EUB/AGS Special Report 74

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

Alberta Energy and Utilities Board
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February 2005

ISBN 0-7785-3834-6



Parks, K., Andriashek, L.D., Michael, K., Lemay, T., Stewart, S., Jean, G., Kempin, E. (2005): Regional groundwater resource appraisal, Cold Lake-Beaver River drainage basin, Alberta; Alberta Energy and Utilities Board, EUB/AGS Special Report 74.

**Published February 2005 by:**
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## Contents

## Tables

## Figures

## Acknowledgments

This work was supported by the Alberta Energy and Utilities Board and Alberta environment - Northern Region. Professor Larry Bentley of the University of Calgary Department of Geology and Geophysics provided guidance on the modeling aspects of this study which was much appreciated. Dan Yoshisaka of Stantec Limited of Edmonton performed the extra modeling study included in Appendix A of this report. This report was improved by the comments of Alan Hingston, Rob George, Jason Pentland, Kate Rich, Bob Savage, Abdi Siad-Omar and Joe Prusak of Alberta Environment.

This report and its companion report on groundwater chemical quality built on the framework of a 1985 hydrogeology study of the Cold Lake area. That study did not achieve wide circulation but the efforts and contributions of our predecessors and former colleagues at AGS who also worked on the Cold Lake area are gratefully acknowledged.

## 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 this work.

This report is divided into six sections:

- Section 1 provides an overview of the scientific framework for regional groundwater-resource evaluation and discusses previous work by others as it relates to this present report.
- Section 2 provides an overview of the physiography and hydrology of the Cold Lake-Beaver River Drainage Basin as they relate to groundwater resources.
- Section 3 discusses the geology of the glacial deposits overlying the bedrock in the Cold Lake-Beaver River Drainage Basin and presents maps and cross-sections showing the geological extents of formations therein.
- Section 4 discusses our observations of regional groundwater flow and groundwater chemical quality.
- Section 5 discusses the development of a numerical simulator of groundwater flow that allows us to estimate groundwater balances and assess the impact of future scenarios of groundwater development.
- Section 6 discusses the output of the simulations as it relates to evaluation of groundwater management options.
- Section 7 discusses regional groundwater-monitoring network design

The key learning of this study is that evidence shows that groundwater in drift aquifers is hydraulically connected to surface water and that groundwater development in drift aquifers could interact with surface water within five years of initiation of pumping. This means that conjunctive management approaches to surface and groundwater management should be considered. The locations and degree of surface-groundwater interactions for each development are not well known and require further study.

# 1 Introduction

Groundwater-resource assessments blend together the theory of flow to a well with the theory of regional groundwater flow. This section briefly reviews the conceptual frameworks of flow to a well and regional groundwater flow. Modern concepts of regional groundwater resource assessments are then explored in order to provide the scientific motivation for the work presented in this report.

## 1.1 Location and Well Distribution

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 (NTS) coordinates, it occupies most of the NTS 73L 1:250000 map sheet with parts overflowing into NTS 73M and in a more minor way onto the other adjoining sheets. In the Canadian Dominion Land Survey Coordinates, the southeast corner of the basin is at approximately Township 56 Range 1W4M and extends northwards as far as Township 78 and westward as far as Range 19 W4M.

The actual physiographic limits extend eastward into Saskatchewan but those parts of the drainage basin are not considered in this report.

The locations of known water-wells in the Cold Lake-Beaver River Basin are shown in Figure 1.2. The estimated amount of total groundwater production by one-mile section of land is shown in Figure 1.3. Details of groundwater use are in presented in Section 6.

Water-source wells drilled and operated by the petroleum industry in deep brackish or saline aquifers are not considered in this report.

## 1.2 Basic Concepts of Flow to Wells

For the reader totally unfamiliar with hydrogeology, a primer of hydrogeological concepts is found in Alley et al. (1999) or in Taylor and Alley (2001), both available at no cost from the United States Geological Survey on the Internet at http://water.usgs.gov/pubs/.

Groundwater is water extracted from wells that have been screened or left open across zones of porous and permeable rock or sediment lying below the water table. The zone below the ground surface but above the water table is termed the unsaturated or vadose zone. All pore and fracture space below the water table is saturated with groundwater (with localized exceptions where the water is displaced by oil, bitumen, or natural gas). Porous and permeable zones or strata below the water table capable of delivering water to a well are called aquifers. Zones or strata that are not capable of delivering water to a well are called aquitards. Aquitards still can transmit groundwater flow over geological time, however. The geology of aquifers and aquitards is reviewed in textbooks like Domenico and Schwartz (1990). The regional geology of aquifers in North America is discussed in detail in Back et al. (1988).

Groundwater flows to a well because pumping in the well reduces the potential energy of the groundwater in the aquifer at the well. This reduction creates the driving force that draws groundwater into the well. The measure of potential energy in an aquifer, pumped or not, is usually expressed in terms of a parameter called hydraulic head, h[L], or simply head. Head is most simply defined as the elevation to which water in a well would rise if allowed to do so. Head can be measured in wells by converting

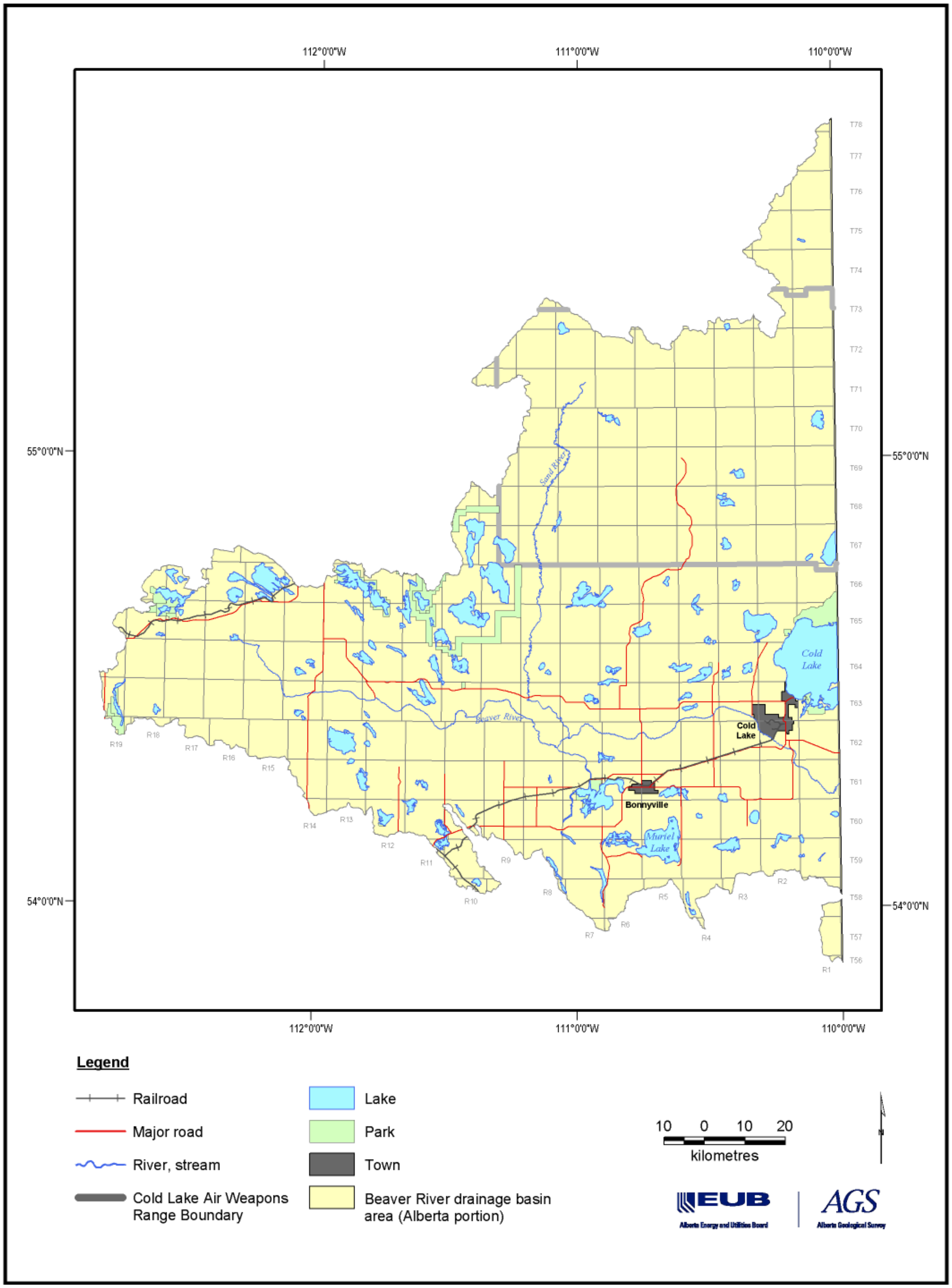



**Figure 1.1. Beaver River Basin study area.**

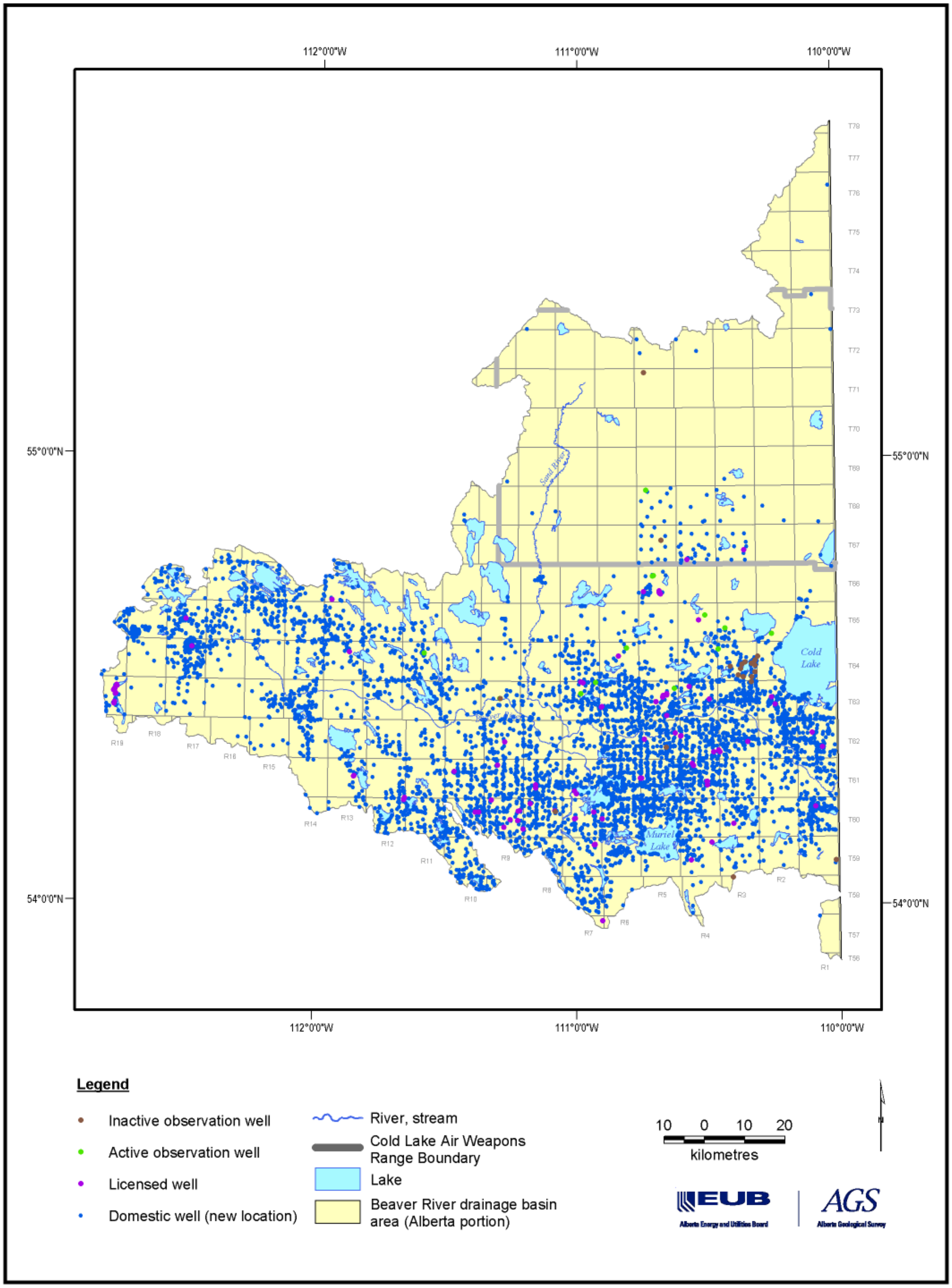



**Figure 1.2. Location of water wells (by type).**

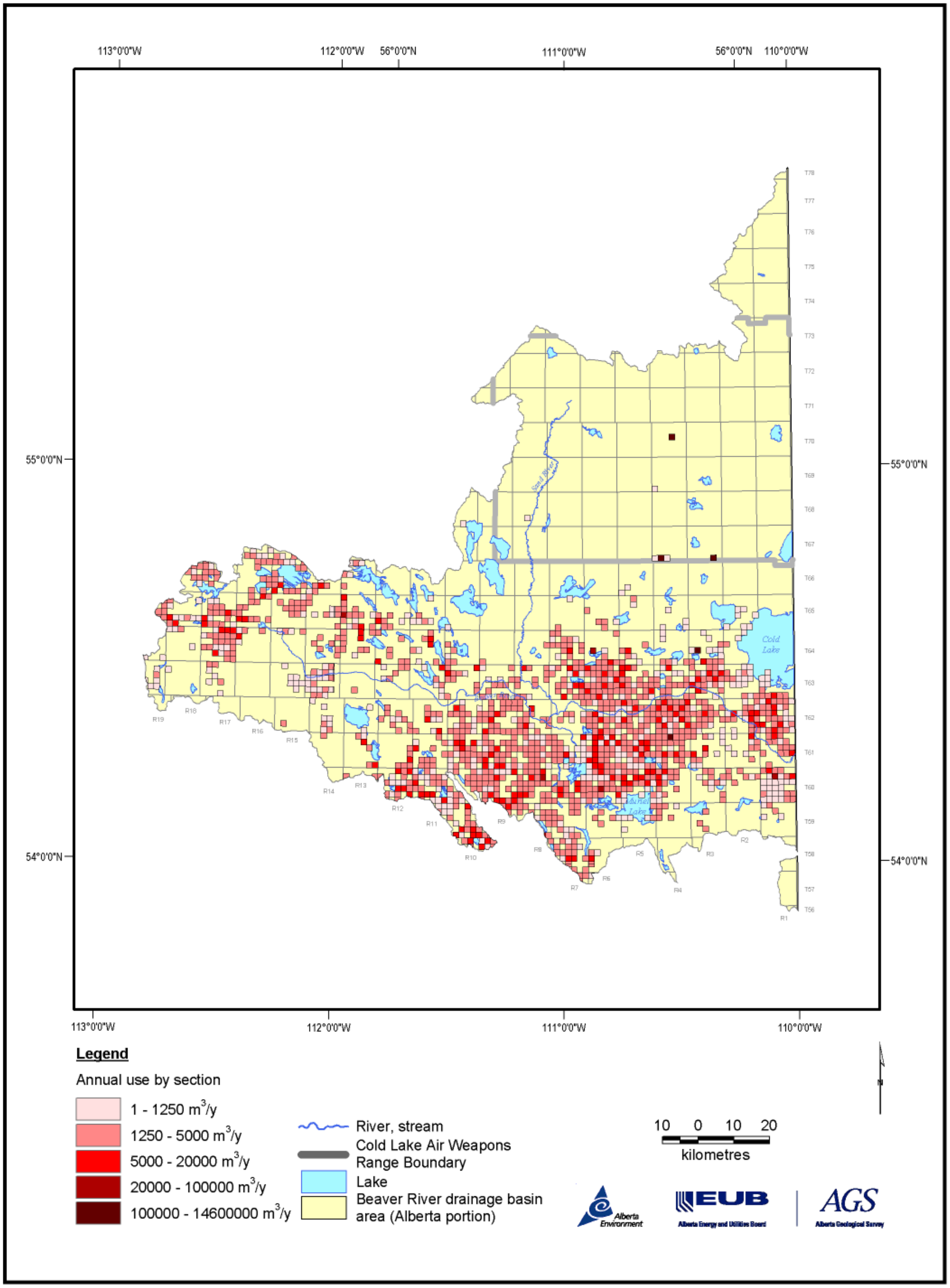



**Figure 1.3. Estimated total groundwater production in the study area by section.**

measurements of depth to water in wells to elevations, provided ground elevation is known. In deep wells, heads can be calculated from pressure measurements by the simple relationship:

$$h = z + P/\rho g \qquad \text{(Equation 1.1)}$$

Where h = hydraulic head [L]; z = elevation of the point of measure [L]; P = fluid pressure [$M^2T^2/L^2$], ρ = fluid density [$M/L^3$]; g = the gravitational constant [$L/T^2$]. In static fluid systems, all hydraulic heads are equal and fluid pressures will increase with depth in proportion to their density. Such pressure conditions are termed hydrostatic.

Hydraulic heads measured and mapped in the vicinity of a pumped well will show a constant increase in head back to non-pumping values away from the well. This pattern is called the cone of depression of a pumped well. The greater the discharge of the well ($Q_w$), the larger and steeper will be its cone of depression, all other things being equal. The other controls on the shape, extent, and rate of growth of the cone of depression are: the aquifer thickness (b), the hydraulic conductivity (K), which measures the ease of transmission of water through the aquifer under head gradients, and the specific storage of the aquifer ($S_s$), which relates the amount of water released by elastic expansion of water and elastic compression of the aquifer when head is reduced to the magnitude of that reduction in head.

The difference between pumping and non-pumping head values anywhere in an aquifer is known as the drawdown. The area around a well that provides water to the well after a given interval of pumping is called the capture zone of the well. The cone of depression and the capture zone are not the same, but both increase over time with continued pumping – quickly at first, then evermore slowly in accordance with the mathematical laws governing flow to the well. When a pumped well is shut off, the heads in an infinite aquifer will recover back to their non-pumping values over time. The drawdown left at any point during recovery is called the residual drawdown. Long-lasting residual drawdown in a pumping well is often the first sign of an unsustainable depletion of an aquifer. Flow to wells and well design is discussed in detail in Driscoll (1986). The mathematical interpretation of drawdown in wells during testing or production is summarized in Kruseman and deRidder (1990).

## 1.3 Basic Concepts of Regional Groundwater Flow

Groundwater does not need the stress of pumping wells to move through aquifers. Natural variations in hydraulic head in the subsurface are in fact the norm. Consequently, most groundwater is in constant motion. The head variations in shallow aquifers are caused primarily by gravity acting to remove topographic variations on the water table that are maintained by precipitation. Regional gravity-flow systems are hydraulically linked to surface-water bodies. Water enters groundwater flow systems by downward-directed percolation of infiltrating precipitation, or in some cases, directly from surface water bodies. Downward-directed, entering flow is called recharge. Water exits groundwater flow systems by upward flow into surface water bodies, marshes, wetlands, springs, etc. Upward-oriented, exiting flow is called discharge.

It is a fundamental axiom of hydrogeology that over geological time all porous or fractured media will conduct flow and transmit fluid pressure (with some possible exceptions like bedded salts). This property of the subsurface is referred to as regional hydraulic continuity. Groundwater flow across aquitards and aquifers is called cross-formational flow (see Toth, 1995, for a summary).

Pore pressures relative to their depth also provide information about groundwater flow. If all groundwater were at rest in the subsurface, the pore pressure would increase with depth in proportion to the density of the groundwater. Such a condition is referred to as the hydrostatic state. In a hydrostatic case, all heads are equal. Pressure-depth gradients associated with such a condition are also termed hydrostatic. The freshwater hydrostatic pore-pressure gradient is 9.8 kPa/m. Mineralized groundwaters have higher hydrostatic pressure-depth gradients due to their greater density. Because groundwater motion is the norm in the earth's subsurface, pore-pressure conditions are not uniformly hydrostatic, but vary from subhydrostatic (<9.8 kPa/m) in areas of downward-directed flow to superhydrostatic (>9.8 kPa/m) in areas of upward-directed flow. Superhydrostatic conditions create artesian wells. Hydrostatic pressure-depth gradients indicate nearly static conditions (rare) or horizontal groundwater flow (common).

The mathematical details of regional, gravity driven, cross-formational groundwater flow in a hydraulically bounded volume of the earth's crust, called a groundwater-drainage basin, in the context of potential-field theory are discussed in textbooks like Domenico and Schwartz (1990). In deeper hydrogeological settings, geomechanical and geochemical forcings like tectonic compression, depositional compaction, dehydration, mineral transformations, pore-dilation due to erosional unloading, glacial loading cycles, or uneven heating may also drive groundwater flow. Neuzil (1995) provides a comprehensive discussion of these driving forces and their manifestations as abnormal subsurface pressures.

Groundwater chemistry changes with flow in drainage basins. The dominant mechanism controlling groundwater chemistry is dissolution of soluble minerals in the rock framework along flow paths. Thus deeper, older groundwaters tend to have higher dissolved solids contents than shallower, younger groundwaters. However, the composition of the dissolved solids and the evolutionary path of groundwater chemistry can be extremely complex. The chemistry of groundwater at any point in a flow system reflects the various mixing, dilution, mineral dissolution, mineral precipitation, ion exchange, organic-reactions, and bacterial processes and their order of interaction during the residence time of the water in the flow system. Discussion of these processes can be found in Drever (1997) as well as Clark and Fritz (1997). More specific discussions of the nature and possible causes of variations in groundwater chemistry in the Cold Lake area are found later in this report.

## 1.4 A Generalized Framework for Regional Groundwater Resource Assessments

Groundwater-resource assessments are performed at all spatial and time scales, ranging from single wells pumping only for weeks to long-term changes in basin flows over geological time. Though each application is unique in terms of geology and purpose, a generalized framework for ground-water assessments has evolved over the past century and has been extensively discussed in the scientific literature.

### 1.4.1 A Few words about Sustainability and Resource Development.

Depending on basin configuration and geological architecture, groundwater resources can be considered as renewable or as non-renewable on a human time-scale. Whenever resources are renewable, there is commonly a desire to quantify a so-called "sustainable" rate at which they can be extracted forever without harm. Alley et al. (1999) use the definition of groundwater sustainability as:

> "the development and use of ground water in a manner that can be maintained for an indefinite time without causing unacceptable environmental, economic, or social consequences."

As discussed below, however, there are situations in which the desired groundwater withdrawal is neither renewable nor sustainable, or the hydraulic behaviour of the system under development cannot be distinguished from an unsustainable development on a human time frame. As well as being difficult to ascertain whether a given groundwater resource is renewable or not, the economic value of groundwater is difficult to quantify. Its value will vary with its degree of "renewability", one's definition of sustainability, local competition for its use, intergenerational value, and so on.

The concepts of sustainability are further discussed by Alley and Leake (2004). The economic value of groundwater that underlie concepts of sustainability will not be discussed in this report. The interested reader is directed to National Research Council (1997) for further information on methods to ascertain the economic value of groundwater.

### 1.4.2 From Single-Well Safe Yields to Concepts of Regional Capture

Single-well safe yields are the most elementary tool for groundwater resource assessment. A single-well safe yield defined as the rate of continuous pumping of a well that will not use all the available drawdown in the well before some defined length of time, assuming no recharge or leakage to a homogeneous, horizontal and unbounded aquifer. Safe yields are very simply calculated from knowledge of local aquifer properties (e.g., Bibby, 1979). In Alberta, a safe-yield time horizon of twenty years is normally used as a norm of evaluating long-term well performance. The groundwater reconnaissance map of the study area (Ozoray et al., 1980) was created with this concept in mind.

Single-well safe yield calculations are not appropriate for quantifying regional groundwater resources or for predicting resource sustainability given multiple, large-scale groundwater developments operating over an indeterminate time horizon. Broader concepts of groundwater-basin yield are used instead.

Theis (1940) first described the source of water from a well in terms of regional groundwater resources. He noted that prior to a well being pumped, the groundwater system is in a dynamic equilibrium with the surface water balance in a groundwater drainage basin. At equilibrium, the hydraulic head field does not change over time and recharge to the groundwater system is balanced by discharge from the groundwater system. This state of nature is captured in the equation:

$$R_o - D_o = 0 \qquad \text{(Equation 1.2)}$$

where $R_o$ is the mean recharge to the groundwater basin under original conditions [$L^3/T$], and $D_o$ is the mean discharge from the groundwater basin under original conditions [$L^3/T$].

When a well is pumped at some steady discharge, Q [$L^3/T$], the hydraulic head field is disturbed and water begins to flow to the well. At first, the water to the well comes out of elastic storage in the basin ($dV/dt$, [$L^3/T$]). As pumping continues, the hydraulic head field evolves towards a new equilibrium with the pumping well by increasing the amount of recharge (induced through falling water tables) and reducing the amount of discharge (by reducing baseflow to streams, lakes, sloughs, etc.). This state of nature can be captured by the equation:

$$(R_o + \Delta R_o) - (D_o + \Delta D_o) - Q + dV/dt = 0 \qquad \text{(Equation 1.3)}$$

When the new equilibrium is reached, there will be no further change in the elastic storage of the basin. The volume of groundwater removed by the well will be balanced by an increase in recharge to the groundwater flow system or a decrease in discharge from the groundwater flow system, or both. Since from Equation 2.2, the original mean recharge is balanced by the original mean recharge, the new state of nature is represented by:

$$\Delta R_o - \Delta D_o - Q = 0 \qquad \text{(Equation 1.4)}$$

Theis called the sum of the increase in recharge and decrease in discharge needed to balance the pumping the “capture” of the well. The increase in recharge may be driven by a reduction in “rejected recharge” or increase in infiltration rates resulting from falling water tables in recharge areas. The decrease in discharge could be manifested by reduction in baseflow to streams, to springs, or upwellings below wetlands, marshes, sloughs, or bogs.

Freeze (1971) used a numerical model to show that there will be an upper limit to the volume of water that can be extracted by a well as capture in a groundwater basin. He called this theoretical upper limit the maximum stable basin yield. In his model, this theoretical limit would be reached when all discharge is captured and the regional fall of water tables has maximized the amount of induced recharge. Past this point, the basin will induce recharge from surface water bodies once fed by discharge and water tables may fall so deep that infiltration evaporates in the vadose zone en route to the water table, rather than providing recharge to the system. Unsustainable and possibly permanent regional groundwater mining will then commence.

Brehehoeft et al. (1982) found it necessary to publish a correction to the then growing practice of using only the total estimated recharge in a groundwater basin (derived from a modeled water balance, for example) as representing the upper limit to groundwater yield of a basin. They underscored that, as Theis and Freeze argued previously, well or well-field capture will be composed of some combination of reduction of discharge as well as an increase in recharge. Moreover, they furthered these ideas with the argument that decreases in discharge will happen before recharge is induced, and that the sustainable yield may well be limited by societal tolerance to reduced discharge to surface water-bodies or falling water levels in wells during the transition from storage to capture, long before some new steady-state is achieved by inducement of extra recharge in some distant future.

Ophori and Toth (1990) investigated the sensitivity of basin yields to position of wellfields in a flow system. Theis had advocated placement of wellfields in recharge areas, to maximize capture of “rejected recharge”, which seemed to presage societal intolerance of reduction of discharge. Ophori and Toth characterized basin responses in terms of the parameters TBY – the transitional basin yield, and SBY – the sustainable basin yield. TBY is defined as the cumulative sum of all the groundwater removed between the time when pumping is initiated to the time when a new steady-state is reached. SBY is defined as the rate of water capture from precipitation into the groundwater system by capture of recharge at the final steady-state condition. In their analyses, they determined that TBY is maximized when wells are placed in discharge areas whereas SBY is maximized (and reduction in discharge is minimized) when wells are placed in recharge areas. Furthermore, they reasoned that industries with high needs for groundwater over long periods of time would optimally place their wells near the midpoint of the unit basin to maximize both TBY and SBY. Like others before them, Ophori and Toth recognized that site-specific analysis, including modeling, would be needed to optimize resource extraction and that the optimal situation could vary in time with changing hydrologic conditions and addition of other groundwater developments in the same groundwater drainage basin.

The values of parameters like TBY, SBY, and the magnitudes and locations of reduced discharge, increased recharge, and change in water-table elevations or hydraulic heads in aquifers are dependent on the number and location of wells, plus any long-term climatic variations experienced by the groundwater basin. Therefore, unique values of sustainable yield have to be forecast by using computer simulations and compared to ongoing monitoring data to have any validity.

The transition of well discharge in a basin from pure mining from elastic storage to pure capture has been developed in detail by several workers. Domenico and Schwartz (1990) note that the time necessary for a new hydraulic head equilibrium to be developed in a homogeneous groundwater basin after steady pumping is initiated is captured by the dimensionless inverse Fourier Number:

$$N_{FO}^{-1} = (r^2S/4T)/t$$

Where r is a characteristic length of the basin [L], S is the representative specific storage [$L^{-1}$], K is the representative hydraulic conductivity [L/T], and t is the time of pumping [T]. If the value of $N_{FO}^{-1}$ is very small (say on the order of 0.001 or less), then drawdowns related to pumping will change only imperceptibly and the system can be considered to be approaching a new equilibrium. This kind of analysis cannot be applied to the Cold Lake-Beaver River Basin because it is not homogeneous.

Balleau and Mayer (1988) used numerical models of realistic groundwater-basin geology to investigate the time of transition from all pumpage being from storage to all pumpage being captured by the definition of Theis, but where the inverse Fourier number suggested by Domenico cannot be easily defined. By examining realistic geologic scenarios, they showed that the transition time from mining storage to reaching pure capture may be so long in some cases that groundwater development would be more akin to mining a non-renewable resource than a renewable one. The time of transition from storage to capture is shown diagramatically on a figure simply called a transition curve. Because transition curves are created by numerical models, it is possible to identify the source of the capture and the geographic distribution. The model of the Cold-Lake Beaver River Basin is discussed in Section 5. Transition curves are used in this report in Section 6.

The concepts of sustainable groundwater yield have been revisited more recently in Sophocleus (1998), Alley et al. (1999). More recently, Alley and Leake (2004) opined that the key challenge in sustained use of groundwater resources is to "frame the hydrologic implications of various alternative development strategies in such a way that their long term implications can be properly evaluated".

### 1.4.3 Groundwater as a Non-Renewable Resource

As shown by Balleau and Mayer (1988), the geometry and geology of a groundwater basin may preclude any new, sustainable steady-state from being re-established on any reasonable human time scale. In such cases, groundwater during pumping will come predominantly from storage in the contained aquifer or from leaking confining aquitards, with little or no true "capture" ever reaching the well. It may also be that the maximum sustainable basin yield has been unknowingly exceeded and the basin will never achieve a new equilibrium, a condition often called groundwater mining. It would be difficult to determine whether a groundwater basin is truly being mined or not, but in both of these cases the groundwater could be assessed as a non-renewable resource. In such a case, the strict concept of groundwater development as "sustainable" discussed above is not applicable. Rather the resource is essentially finite, and the longevity of the resource will be function of number of wells and their discharges. The only uncertainty will be as to how large is the volume of the finite resource and at what rates it can be extracted.

Little attention has been paid in the literature to practical quantification of non-renewable groundwater resources. This omission may reflect our preference to only exploit hydraulically well-connected aquifers because a) they tend to be shallow, keeping drilling and pumping costs down, and b) their short water-residence times result in low dissolved mineral content and relatively high chemical quality. Industrial users, like in-situ oil sands operations, are able to use more brackish to saline water for industrial processes, either with treatment, blending, or as-found – depending on the industrial process. Such groundwater will almost always come from deeper aquifers, increasing the chances that intervening aquitards will essentially isolate them from the surface hydrologic system on a human time scale.

Volumetric assessment of hydraulically isolated aquifers can be easily done by adapting methods of hydrocarbon volume-assessments. At their simplest, hydrocarbon volumes are calculated as the product of drainable pore-volume times hydrocarbon saturation times a formation-volume factor that accounts for elastic expansion of compressible hydrocarbons brought to surface. Because of the commercial value of hydrocarbons and the business needs for managing exploration risks, probabilistic methods of estimating ranges of volumes of original oil-in-place have been developed to a high level of sophistication (e.g., Capen, 1992). The concepts and theories of probabilistic hydrocarbon volume assessment can probably be modified to help assess (practically) non-renewable groundwater resources, but that task is beyond the scope of this project. It should be underscored, however, that resource evaluation techniques exist to evaluate groundwater resources in a non-renewable framework so that nonrenewability does not in itself become the basis for rejecting development scenarios that are acceptable or even desirable on other grounds.

These concepts may be applicable to development of brackish to saline groundwater resources in the Cold Lake Beaver-Basin that lie below thick Cretaceous shales. Those shales are of sufficiently low permeability to essentially isolate the impacts of deep, brackish groundwater development from the drift aquifers in the Cold Lake-Beaver River Basin.

## 1.5 The Role of Simulation in Groundwater Management Studies

Groundwater management is a quantitative science. Calculations can be made to predict the outcome of groundwater developments as a function of space and time on natural groundwater flow conditions or on pre-existing groundwater developments. Relatively simple calculations can be made by hand for low numbers of pumping wells in geologically simple settings. But for regional systems with many wells and complicated geology, more sophisticated computer-based groundwater simulators are needed. Such simulators, also called groundwater models, take the underlying equations of groundwater flow and solve them with powerful computers. The complexities of pumping and geology are captured in the equations being solved. The inputs to a model include numerical maps of geological properties, a mathematical description of the locations and types of natural or assumed hydrological boundaries to the modelled area and information on the locations, durations, and rates of pumping, streamflow, and infiltrating recharge events.

Since regional groundwater systems and river drainage basins are very complex, all models will be a simplification of reality. The challenge to the modeller is to keep the model as simple as possible while capturing all the geological and hydrological elements necessary for the simulator to match historical records of observations of interest, like water levels.

A key output of this study has been the development of a regional groundwater model for the Cold Lake-Beaver River Basin. The model is documented in Section 5 of this report and its outputs are discussed in Section 6.

## 1.6 Review of Prior Modeling Studies

Parts of the Cold Lake-Beaver River Basin in Alberta have been evaluated with numerical groundwater models on a variety of occasions. Traditionally, the models have treated the drift stratigraphy as a layer cake, equating lithostratigraphic units to aquifer-aquitard units. The conceptual model of the relationship between stratigraphy and hydraulic properties is discussed in more detail below in Section 3.

Key historical studies were identified by Alberta Environment for detailed review as part of this project. The goal of this review was to identify lessons drawn from these prior efforts that could possibly assist with the present effort and guide the compilation of data for this study. These lessons are summarized below. Of particular interest were the parameterization of each aquifer and aquitard unit by the modelers, their choices of boundary conditions, and their records of success in calibrating their models. A small number of ancillary model-based studies on file with Alberta Environment and the EUB were also reviewed in hopes that they would also be useful. The models reviewed include:

- Cold Lake-Beaver River Water Management Study Main Report, Planning Division Alberta Environment, December 1983
- Cold Lake-Beaver River Water Management Study Volume 2 Water Supply Appendix A-C
- Appendix B Ground Water Resources, MLM Ground Water Engineering, 1982
- Appendix C Ground Water Modelling, C. Gold and T. Chau, Earth Sciences Division, Alberta Environment, 1983
- Regional Groundwater Assessment of the Cold Lake-Beaver River Study Area, Simco Groundwater Research Ltd., September 1986
- Report of the Cold Lake Beaver River Groundwater Allocations Task Force, November 16, 1987
- Report on the Impact of Groundwater Pumping at Esso Resources, Cold Lake, Terracon Geotechnique Ltd., 15 November, 1991
- Supplement to the Report on the Impact of Groundwater Pumping at Esso Resources, Cold Lake, Terracon Geotechnique, March 2, 1992
- Sustainable Yield of the Empress Unit 1 Aquifer at Imperial Oil Limited Cold Lake, Terracon Geotechnique Ltd., April 1993
- Cold Lake-Beaver River Water Management Study Update, Alberta Environmental Protection, January 1994 (referenced as AEP unpublished report 1993)
- Appendix 3 Availability of Supply – Groundwater Evaluation of the Sustainable Yield of the Empress Unit 1 Aquifer A Modeling Study, Alberta Research Council, September 1993
- Sustainable Yield Evaluation Empress Unit 1 Aquifer A Groundwater Modeling Study, Komex International Ltd., January 1995
- A Groundwater Model to Support Withdrawals from the Sinclair Valley Aquifer System, CH2M Gore & Storey, January 1998
- Groundwater Baseline Investigations Primrose and Wolf Lake Projects, Alberta, CH2M Gore & Storrie Ltd., June 1999 (for AMOCO Canada Petroleum Company Ltd.)
- Canadian Natural Resources Limited Pimrose and Wolf Lake Expansion 2000, Volume V Appendix B - 3-Dimensional Groundwater Flow Model, October 2000

The key lessons derived from this review exercise are as follows.

- Major lake and river levels should be taken into account during calibration and modeling. Some lakes, in particular Cold Lake, have been shown to be well connected to aquifers. Lake-level fluctuations are large enough that they can cause significant changes in aquifer levels that could be misinterpreted as mismatches or false matches when considering transient calibration data.

- The final stratigraphic model and conductivity data should be closely examined for evidence of regions of restrictive flow within the bedrock channel aquifers. Past models have been inconsistent on the existence or lack of channel constrictions. However, these are important features if they exist.
- The final stratigraphic model and conductivity data should be closely examined for a thicker Sand River aquifer section in the area west of Marie Lake. Past studies have indicated that such a feature exists and plays an important role in regional recharge.
- The final stratigraphic model and calibration data should be examined for indications of a thickening of low permeability sediments over the confluence of the Beverly and Helina buried valleys. Komex (1995) indicated a lower recharge in the region due to thickening lacustrine sediments.
- Boundaries of the bedrock channels leaving the domain should be represented by a general head boundary condition to minimize the error due to the interception of cones of depression with the model boundaries.
- A realistic conceptual model needs to be developed for the recharge in the highlands to the north of the study areas. Induced recharge to this area is critical to the long-term model performance, but it is not clear how well understood the mechanisms are. The best approaches to date are found in Simco (1986) and Komex (1995). However, the more constrained the conceptual model, the less reliance on calibration will be required.
- Non-uniqueness is a problem. The more deterministic constraints that can be applied, the less the non-uniqueness problem.
- The model should be calibrated in stages. The first stage should be a series of location specific calibrations for short and intermediate time frames. These exercises will establish hydraulic conductivity, storage and leakage parameters. Other long-term, regional calibrations can be used to establish regional recharge and larger scale features.
- The sources and physics of recharge are key to the long-term predictive capability of the model. There are some general ideas, but no consistent understanding of all aspects of the system. Connectivity of lakes, rivers and boundaries should be looked at locally during calibration to establish as many deterministically as possible and minimize the need for assigning the relationships during large-scale, long-term calibration.
- Baseflows in rivers should be approximated where possible. At a minimum, river flows should be compared to model base flow predictions to assure that the model results remain within reasonable bounds.
- Close attention should be paid to aquifer thickness-hydraulic conductivity relationships. Past studies have implied that the bedrock valley margins are thinner, had more fines and had lower hydraulic conductivity. This relationship seems reasonable and will provide guidance in assigning K-values if it is found to be a good conceptual model. It is also possible that such a relationship could affect the valley flow constrictions and help deterministically model flow barriers.
- Including the Sand River Aquifer will require knowledge of small holding and farm use of groundwater. Groundwater extraction estimates will require some kind of population and land use estimates coupled with groundwater per capita usage estimates. The best example in the documents studied is the Cold Lake-Beaver River Water Management Study Update (1994), but the papers referenced are dated and the data may not be current.

# 2 Physiography and Drainage

## 2.1 Topography and Physiography

A digital elevation model (DEM) of the land surface topography is shown in Figure 2.1. 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 2.1) – 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.

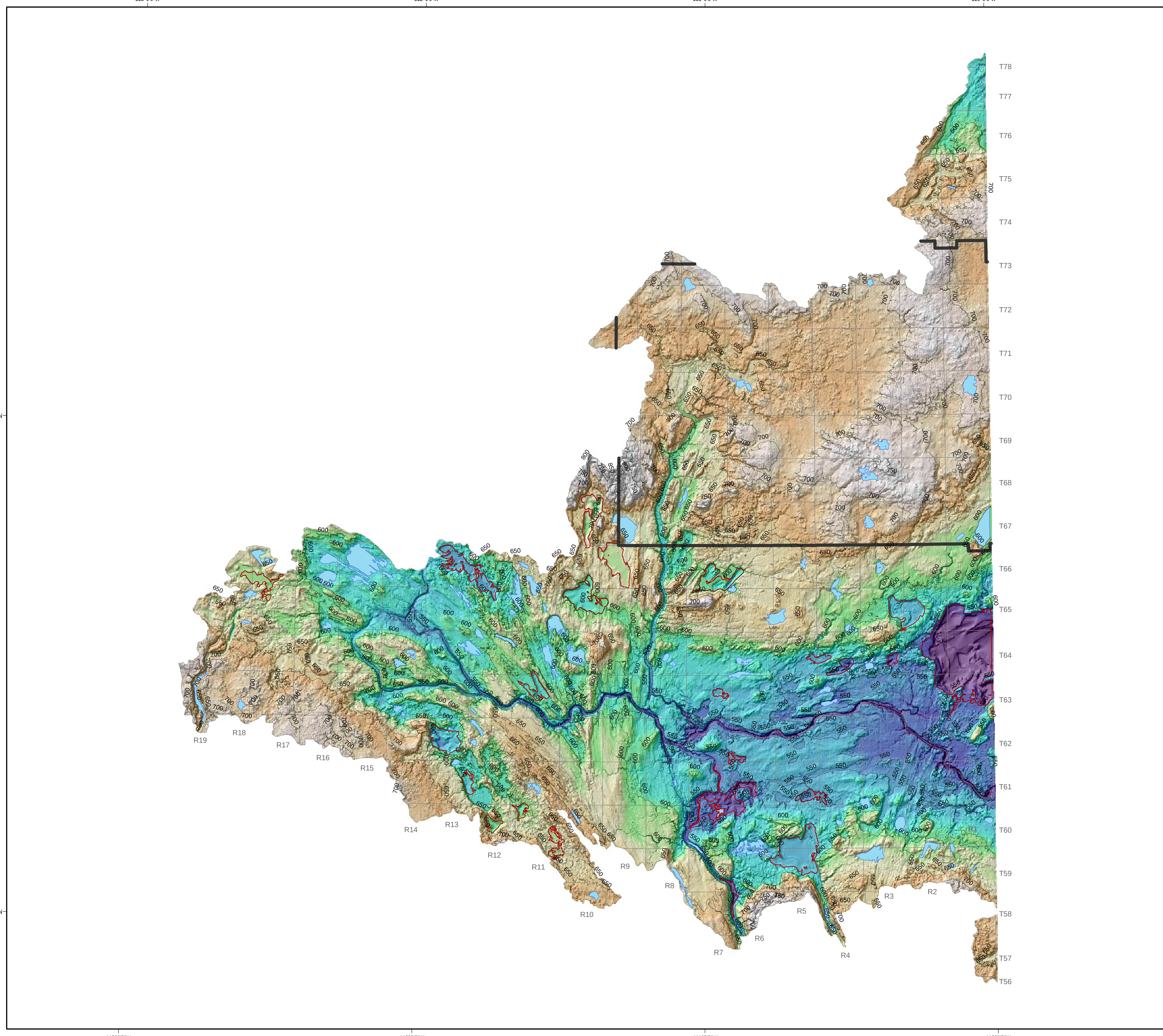
The DEM highlights the major drainage systems. The long axis of the basin is occupied by the Beaver River, which flows west to east. In the uplands of the west, the Beaver River forks into two tributary streams, the south fork being the Amisk River and the north fork still being the Beaver River. Midway down the basin, the Sand River joins the Beaver River from the north. Several other tributary streams join the Beaver River between its junction with the Sand River and the point at which it exits Alberta and flows on into Saskatchewan.

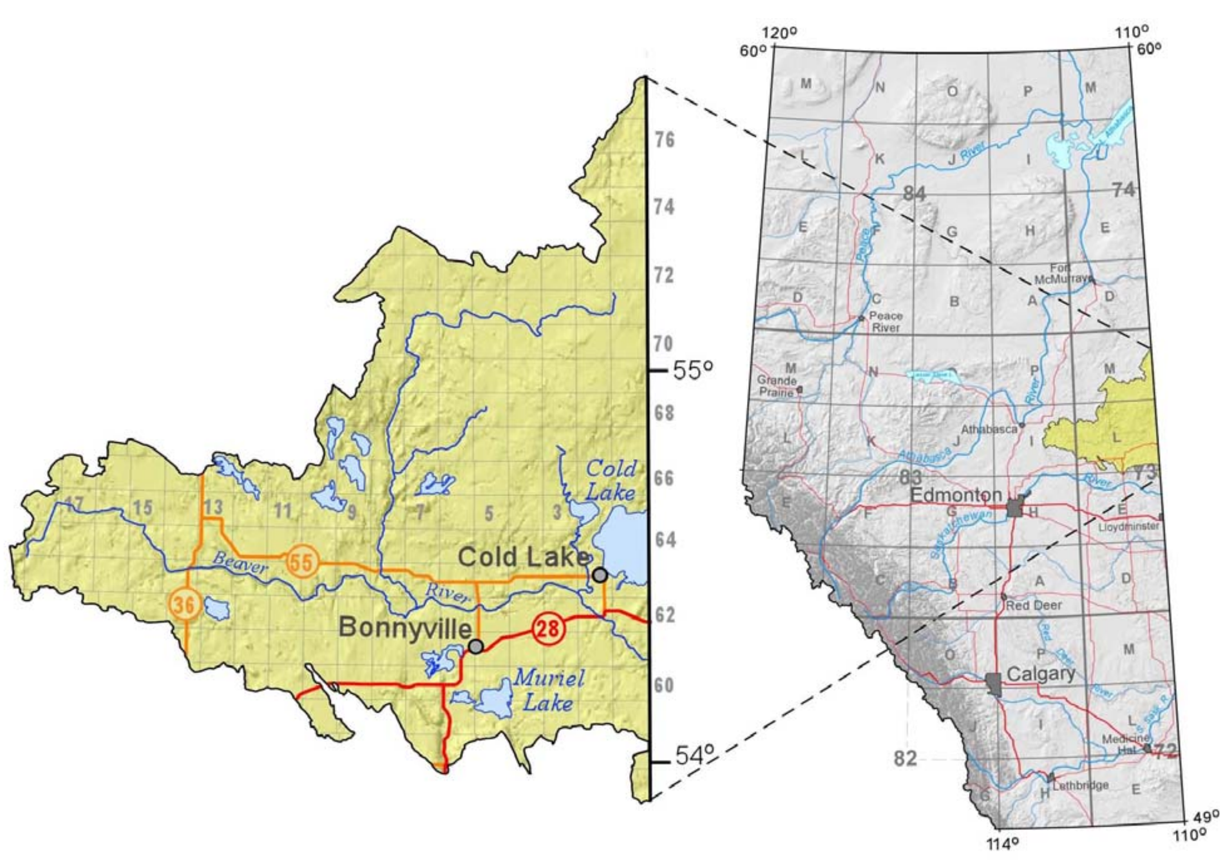
The DEM highlights stream courses and lake beds that are not occupied by present surface water-bodies. For example, there is a stream course that runs north from Moose Lake to the Beaver River that is occupied by small lakes and an underfit stream. This same course extends south where it is partially occupied by Kehiwin Lake. This aspect of physiography is common in formerly glaciated terrains. Unoccupied or underfit stream courses and lake beds reflect drainage during prehistoric times of partial glaciation. Drainage and ponding of glacial meltwaters responded then as much to the distribution of ice as to the topographic gradient. When the ice disappeared completely, many of these stream courses and lake beds were abandoned as drainage once again conformed to topographic gradients and excess glacial meltwaters disappeared.

The DEM also highlights regions of streamlined landforms. These form the seat of the topographic saddle mentioned above. These streamlined landforms were formed during glacial advances and indicate ice-flow direction. These landforms and other glacial features of the Cold Lake-Beaver River Basin are discussed in detail in Andriashek and Fenton (1989).

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.

Pettapeace (1986) further subdivided the Alberta physiographic regions into smaller, sub-regional units based on physiography, local relief, drainage, and elevation. According to the Pettapeace scheme, the Cold Lake-Beaver River Basin is further subdivided into ten physiographic sub-regions. These are shown on Figure 2.2. The main sub-regions include the Moostoos Upland, the Pinehurst Hills, the Beaver River Plain, the Cold Lake Hills, the Elk Point Plain, 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.




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

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

December, 2004

**Figure 2.1 Digital elevation model of land surface and bottom structure of major lakes**

EUB Alberta Energy and Utilities Board | AGS Alberta Geological Survey

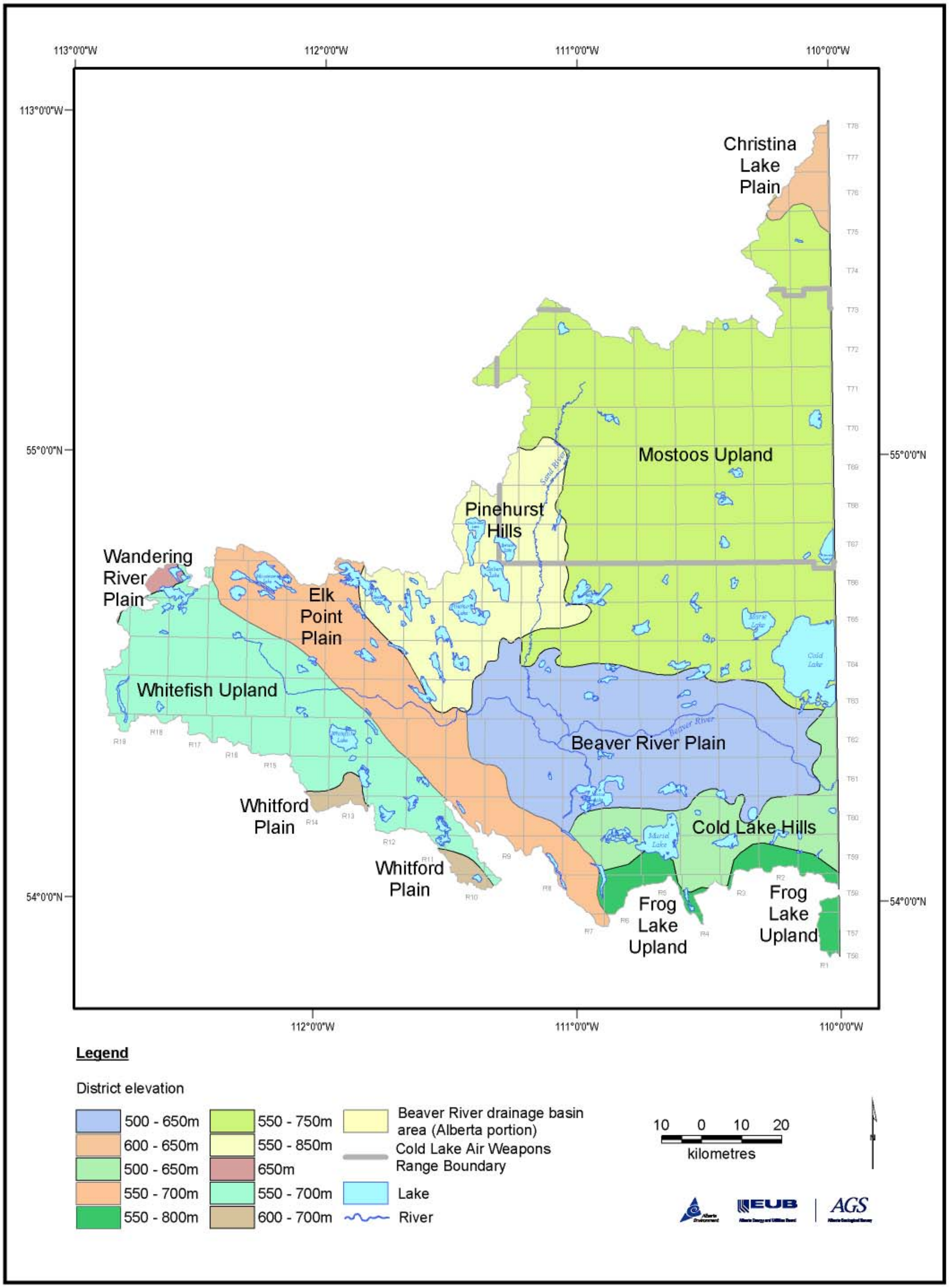



**Figure 2.2. Physiographic subdivisions of Cold Lake-Beaver River Basin (from Pettapiece, 1986).**

Andriashek and Fenton (1989) further subdivided the landscape of that part of the Basin lying within the Sand River 1:250000 NTS map sheet (73L) into local physiographic units based on landforms and surficial geology. Their detailed physiographic subdivision is not discussed in this report.

A generalized soils map of the cultivated part of the basin is shown in Figure 2.3 (Alberta Agriculture, Food and Rural Development, 2003). The soil types are significant to hydrogeologists because their nature and distribution are the product of interplay of climate, parent material, and local water balance. Aspects of long-term water balance provide the hydrogeologist with important clues as to the nature of groundwater-surface water interactions away from lakes and streams. For example, luvisolic soils are characterized by eluviated, or leached, soil profiles and speak to long-term downward groundwater motion. Gleysolic soils, on the other hand, are indicative of poorly drained or perched groundwater conditions at least part of the year whereas organic soils indicate year-round saturated conditions.

Changes in forest cover, land use, and drainage due to settlement will alter the natural drainage patterns, making it difficult for the regional hydrogeologist to use surface indicators of regional groundwater flow for mapping purposes. However, the soil types will tend to persist because they respond to changes over hundreds to thousands of years. This map can thus be used to validate assumptions about natural groundwater flow in the basin as management tools evolve.

## 2.2 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).

There are eleven Environment Canada precipitation stations in the Cold Lake-Beaver River Basin with historical records. The locations of these are shown on Figure 2.4.

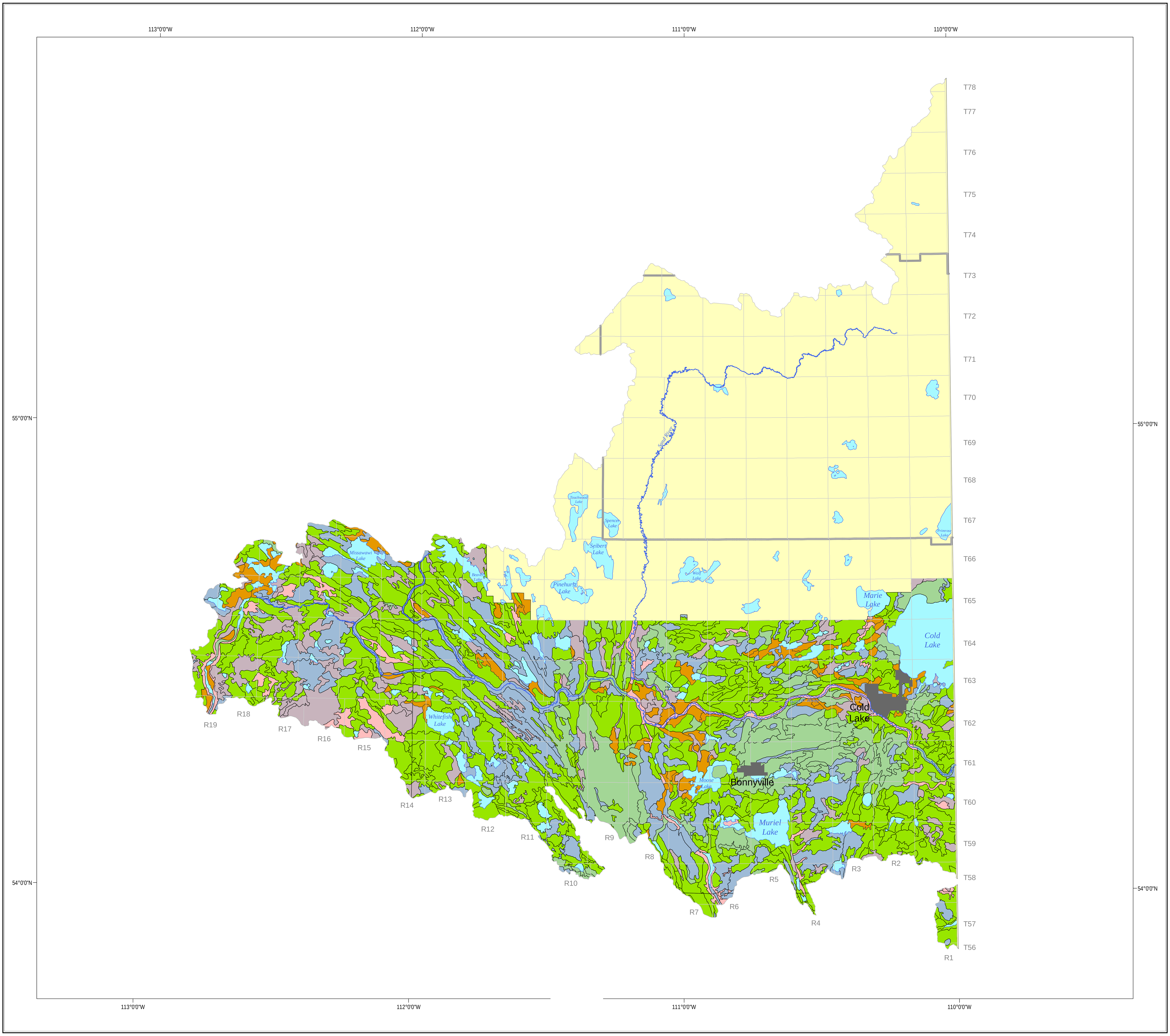
A view of the annual precipitation variation recorded near Cold Lake is provided in Figure 2.5. This view shows the dramatic decrease in both winter and summer precipitation experienced by the Cold Lake-Beaver River Basin during the drought of the 1980s and early 1990s. Further information on the state of precipitation can be found at the drought-watch webpage maintained by the Prairie Farm Rehabilitation Agency at http://www.agr.gc.ca/pfra/drought/index_e.htm.

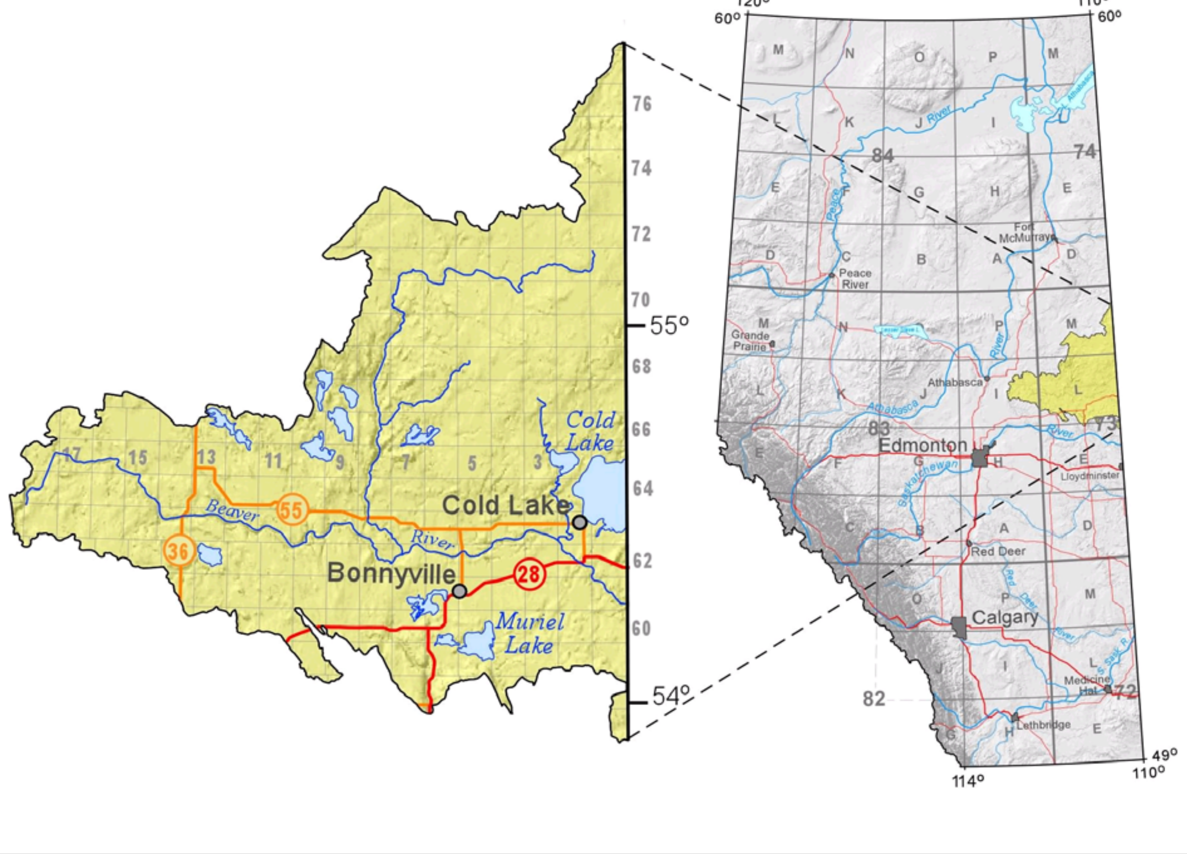
“Real time” precipitation and runoff data (including lake levels) is available at the AENV website (http://www3.gov.ab.ca/env/water/basins/BasinForm.cfm).

## 2.3 Drainage and Streamflow

The Cold Lake-Beaver River Basin in Alberta consists of all land drained by the tributaries and trunk stream of the Beaver River. The drainage basin is approximately 14,500 km$^2$ in area and extends east across the Alberta-Saskatchewan Border. The Beaver River itself is part of the Churchill River Drainage Basin, which ultimately drains into Hudson’s Bay (Environment Canada, 1978). The mean annual discharge of the Beaver River at the Alberta-Saskatchewan border is about 650 e$^6$m$^3$.

There are three major streams in the Cold Lake-Beaver River Basin: the Beaver River itself and two




Scale 1:503356

5 0 5 10 15 20 25 30 Kilometres

5 0 5 10 15 20 25 30 Miles

Projection: UTM Zone 12
Datum: NAD83

December, 2004

**Beaver River Basin Soils**

**Internal drainage characteristics of major Soil Orders**

- Lakes, intermittent water bodies
- Brunisolic soils: very well drained, sandy
- Chernozemic soils: well drained, black to dark grey
- Luvisolic soils: well drained, eluviated, light grey
- Gleysolic soils: wet, high water table
- Organic soils: peat, wet
- Regosoils soils: immature, eroded, newly formed
- River
- Cold Lake Air Weapons Range Boundary
- Town
- Beaver River drainage basin area (Alberta portion)

# Figure 2.3 Drainage of surface materials in the Cold Lake-Beaver River Basin as reflected by major soil types.

**from Agricultural Region of Alberta Soil Inventory Database (AGRASID Version 3.0, 2001)**

Alberta Environment

EUB Alberta Energy and Utilities Board

AGS Alberta Geological Survey

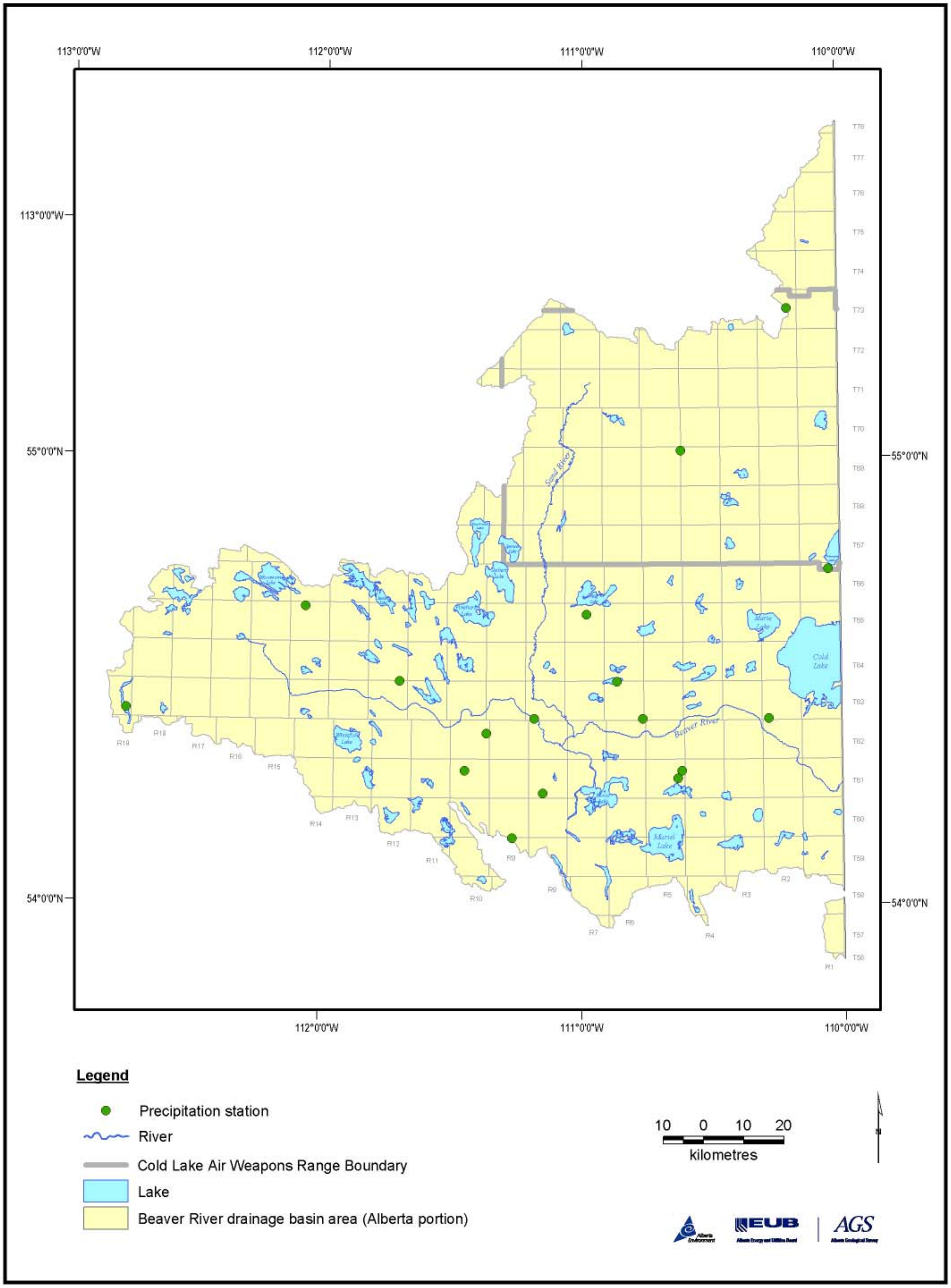



**Figure 2.4. Location of precipitation stations.**

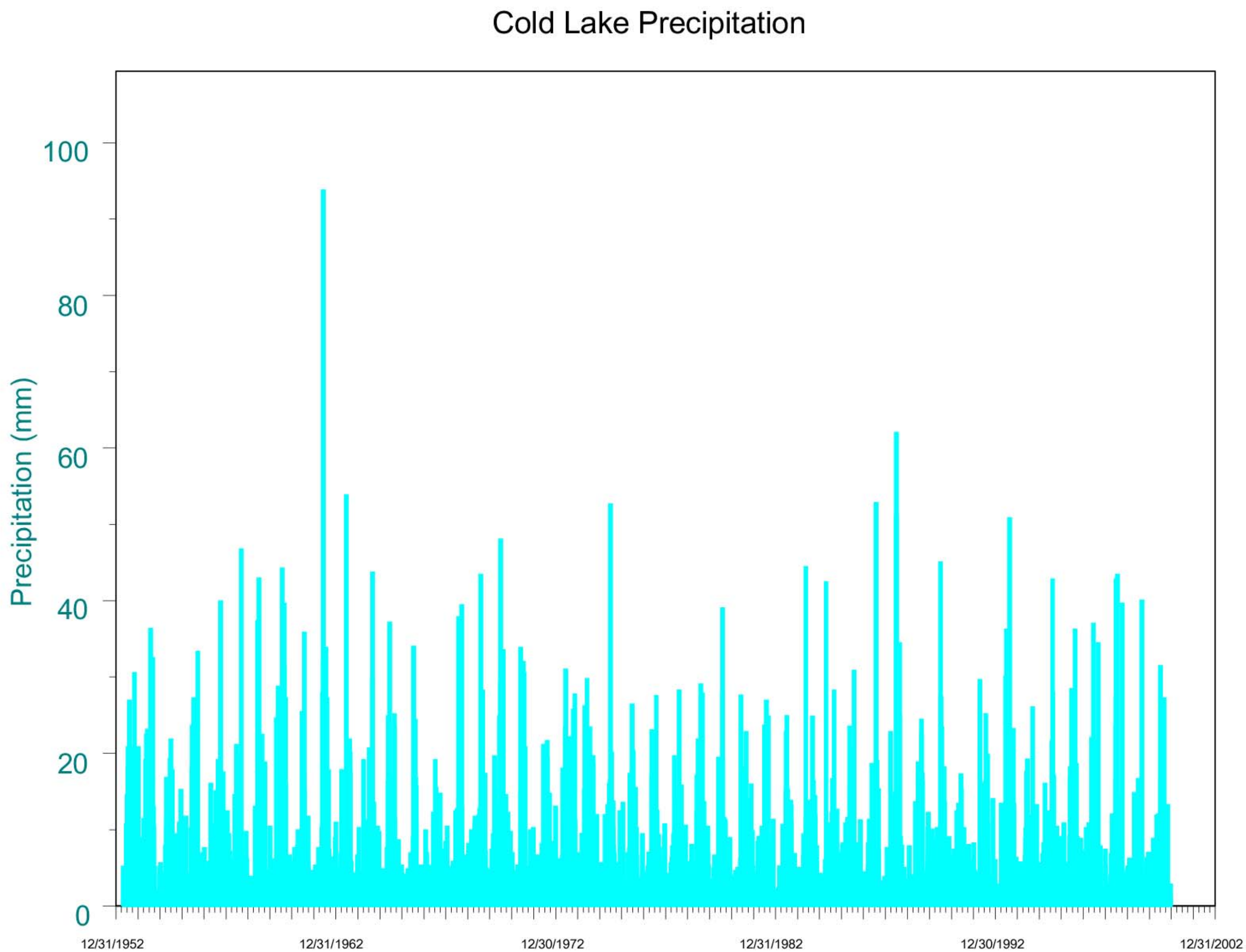



**Figure 2.5. Annual precipitation variation recorded near Cold Lake.**

major tributaries, the Sand River and the Amisk River. Photographs of these rivers are shown in Figure 2.6. The stream network of the Cold Lake-Beaver River Basin is shown in map form in Figure 2.7. Note that there are also numerous perennial and ephemeral streams that feed into the main rivers.

Environment Canada subdivides the Cold Lake-Beaver River Basin into six drainage sub-basins based on surface-water divides. Four are completely in Alberta and two extend east into Saskatchewan. These sub-basins are shown on Figure 2.7 for information purposes.

There are fifteen streamflow-gauging stations in the Cold Lake-Beaver River Basin with historical records available to AGS spanning the years 1952-1997. Their locations are shown on Figure 2.7. Of these 15 stations, only Station 006AD001 (Beaver River at Cold Lake Reserve), Station 006AA001 (Beaver River at Goodridge), Station 006AB001 (Sand River near the mouth), and Station 006AB002 (Wolf River at outlet of Wolf Lake) appear to have good continuous coverage spanning several decades. Detailed study of stream-flow fluctuations and surface hydrology is outside the scope of this report.

A view of the average monthly stream flow recorded at the Beaver River gauging station near Cold Lake is shown in Figure 2.8. This figure shows the dramatic decrease in streamflows recorded for the Beaver River during the drought of 1980s and early 1990s

### 2.3.1 Groundwater Contributions to Streamflow

Continuous discharge measurements of perennial streams can be used to estimate groundwater recharge after precipitation events. These estimates provide an independent check on water-balance calculations derived by models such as discussed in Section 6.

The basic methodology is explained in standard texts like Domenico and Schwartz (1990, p.16). Modern techniques of baseflow separation are discussed in more detail in Nathan and McMahon (1990) and Piggot et al. (2001). In essence, flow in a stream is assumed to come from two sources: surface runoff and groundwater baseflow. Immediately after a precipitation event, most of the stream discharge will be surface runoff with a lesser component of baseflow. After runoff is exhausted, the stream is fed only by continually declining baseflow until the next runoff event occurs. The continual decline of baseflow between recharge events is called the baseflow recession.

The mathematical treatment of baseflow recession underpins methods of recharge estimation. Drainage of an infinite aquifer to a line sink like a stream can be described by a first-order exponential decay law of the form:

$$Q_t = Q_o \exp(-kt) \qquad \text{(Equation 2.1)}$$

where $Q_t$ is the stream discharge at some time t in the hydrological year, $Q_o$ is the initial discharge at the beginning of the hydrological year, and k is a recession constant. Plotting the logarithm of Q versus time may reveal a log-linear relationship whose slope is –k. Integrating the function with respect to time reveals the total potential groundwater discharge to the stream above the gauging station. The difference between remaining-potential discharge at the end of one hydrological cycle and the total-potential discharge at the beginning of the next is a measure of total recharge to the system. Dividing the total recharge obtained through baseflow recession analysis by the drainage area of the basin contributing to stream flow upstream of a gauging station (and assuming that groundwater divides correspond to surface drainage divides) provides a first-order estimate of annual areal recharge rates.

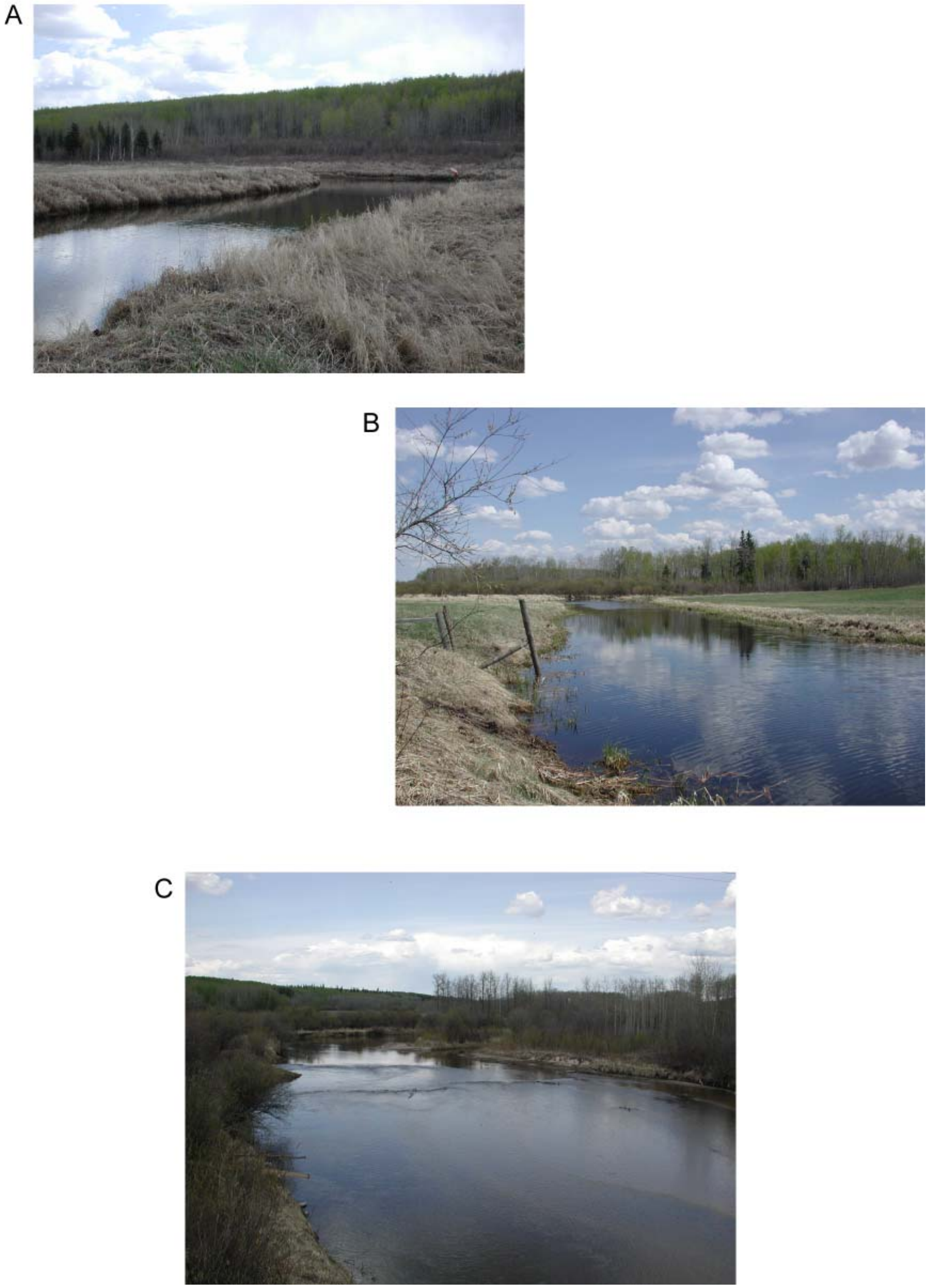


**Figure 2.6. Photographs of the major rivers in the Cold Lake-Beaver River Drainage Basin: A) Amisk River; B) Beaver River and; C) Sand River.**

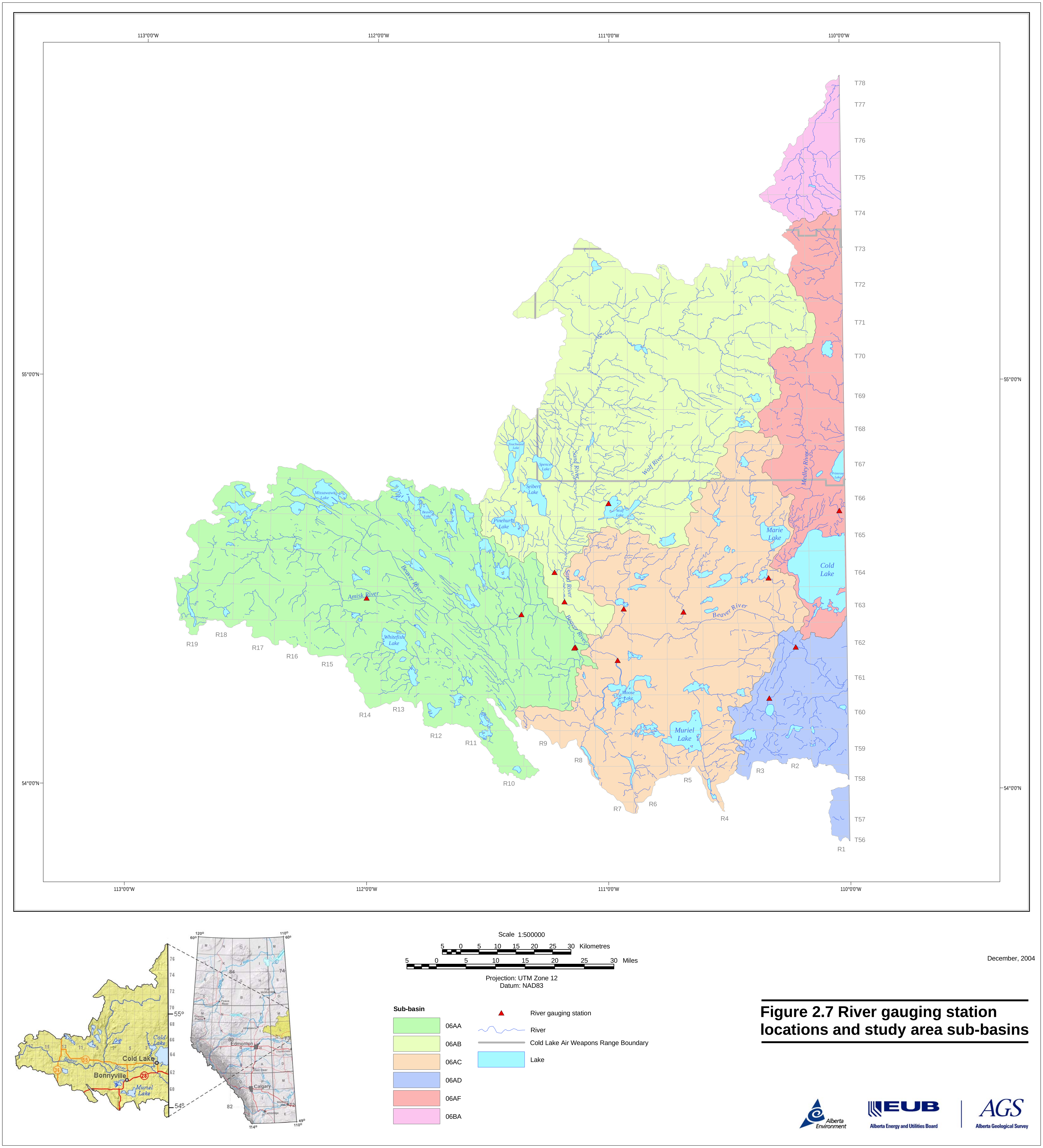



**Figure 2.7 River gauging station locations and study area sub-basins**

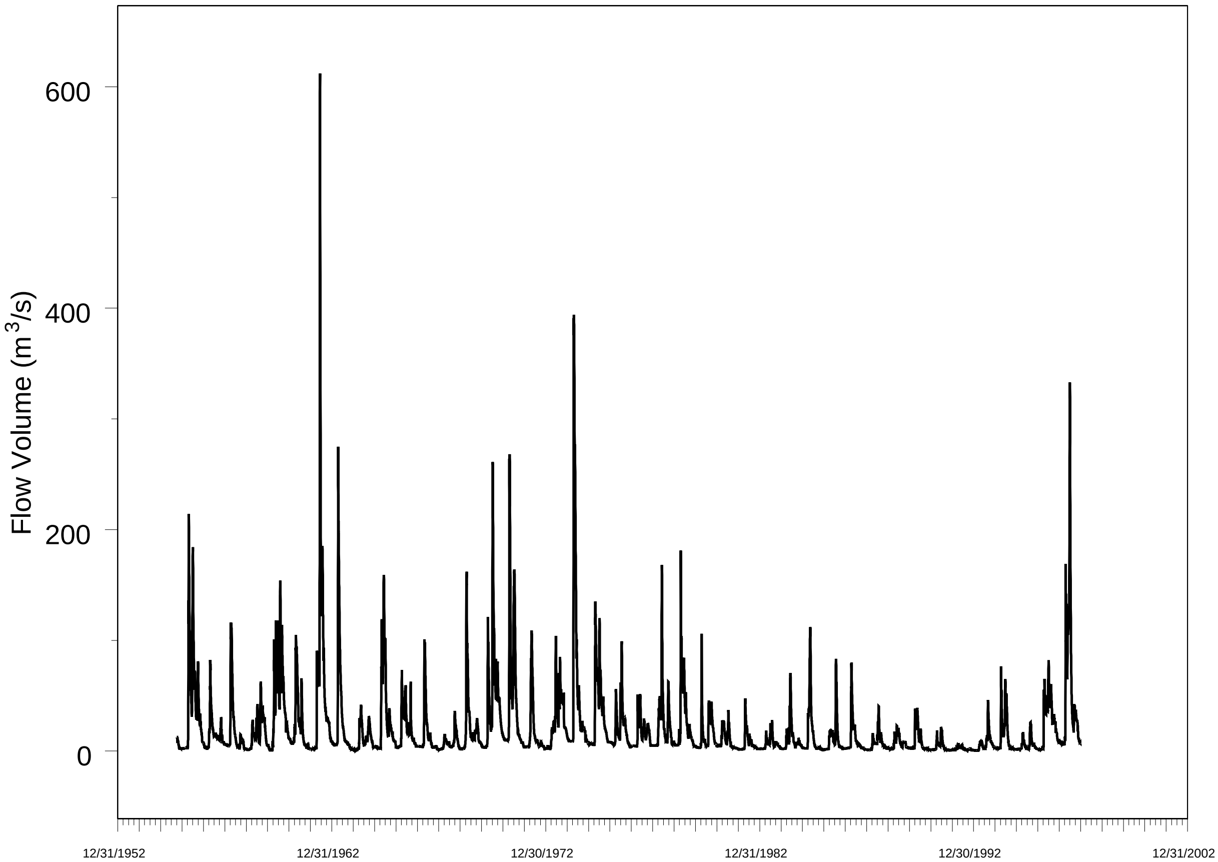



**Figure 2.8. Monthly streamflow recorded at Beaver River gauging station near Cold Lake.**

#### 2.3.1.1 Recharge Estimation by Baseflow Analysis (Rorabaugh Method)

Quantification of baseflow by this method is actually difficult in streams in the boreal regions of Canada for several reasons. Difficulties in baseflow estimation in general are summarized by Halford and Mayer (2000). First, there is often a lot of delayed water-storage in wetlands and beaver dams which is not considered in Equation 2.1. Secondly, there are snowmelt and freeze-thaw dynamics to consider. Third, a lot of gauges either freeze-up or are not operated during the winter even though streams continue to flow under the ice. Fourth, there are empirical correlations used in the more sophisticated methods of baseflow recession that were derived from analysis of watersheds in more temperate regions and in never-glaciated terrains. Lastly, the number and locations of stream gauges in the Cold Lake-Beaver River is not ideal for this kind of analysis, presumably because the network was designed for a different purpose. Despite these drawbacks, an estimate of regional recharge rates by baseflow-recession analysis was made for the Environment Canada stream gauge Station 06AA001 on the Beaver River near Goodridge for this study. This station was selected on the basis of the relative completeness of its stream-discharge record through time and its position close to the outlet of the river's surface catchment area.

The analysis was done using the United States Geological Survey (USGS) programs RECESS and RORA (Rutledge, 1998, 2000). These programs use a particular implementation of baseflow-recession analysis called the Rorabaugh method. These programs were used because they have the capability of automating the recession analysis and independently analyse most of the precipitation events in the stream-flow record. The USGS methodology uses the RECESS process to first define the basin recession constant through interpreter-guided analysis of multiple log-linear stream discharge plots. Then the RORA process automatically identifies peak stream-flow events in the discharge records and these are analysed to define event-specific baseflow-recession intervals. Recharge is calculated between upward shifts of recession curves between successive discharge peaks provided enough days have passed since peak stream discharge for runoff to have subsided. This critical time is based on an empirical formula related to area.

The Rorabaugh method is recommended for small basins with no surface storage or snowpack that may delay runoff. As well, the empirical relationship between area and critical time is recommended for drainage basins of the order of 500 $mi^2$ or less. The upper Beaver River sub-basin is ~1900 $mi^2$ in area and experiences a yearly snowpack, suggesting that caution should be used in using these results. However, there are no alternatives specifically calibrated for Canadian boreal-forest conditions. As well, at the Beaver River near Goodridge, the stream flow is not recorded during winter months, either due to gauge freeze-up or very low flow rates. For these winter months, flow is assumed to be 0.01 $m^3/s$.

A histogram of the estimated recharge rates by year in the Cold Lake-Beaver River Basin above Goodridge calculated with the RORA program is shown in Figure 2.9. The estimated yearly values rise and fall with precipitation and the histogram clearly shows the drought of the 1980s and early 1990s. The median estimated value of recharge in the monitoring period is about 10 mm and the maximum value equates to about 85 mm of recharge. If one assumes a long-term average annual precipitation of 500 mm, these estimates equate to 2 % of annual precipitation and 15% of annual precipitation, respectively.

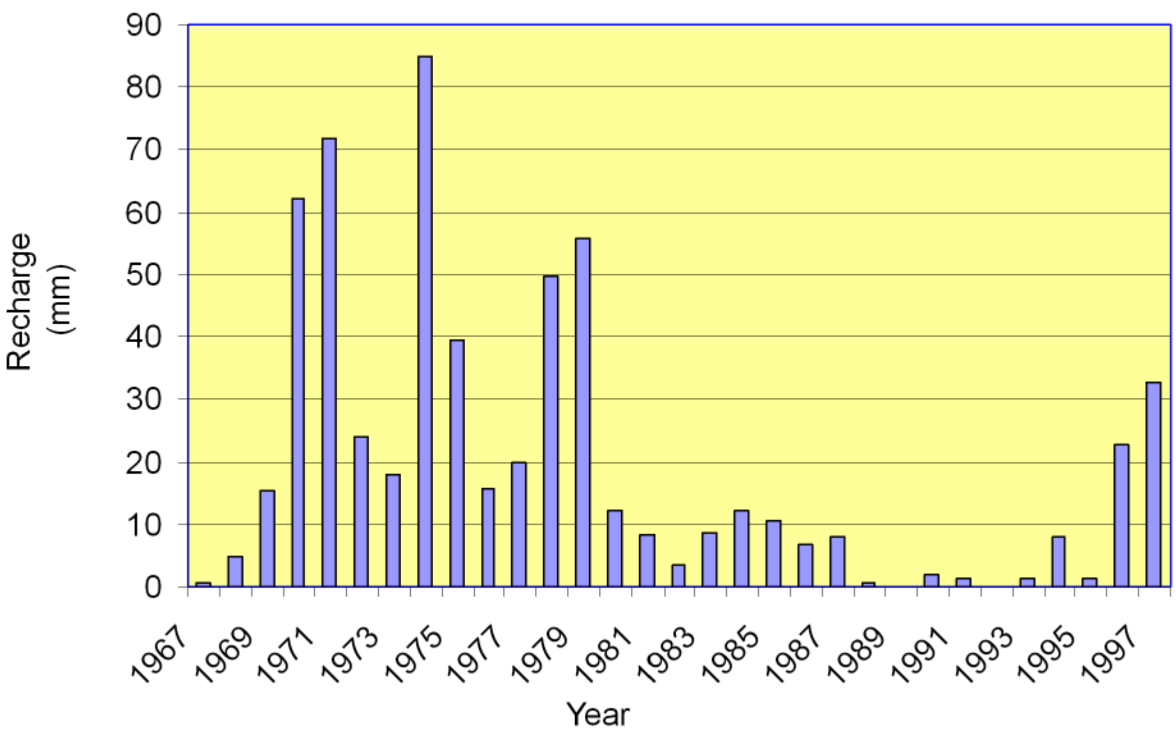



**Figure 2.9. Annual recharge estimate from baseflow-recession analysis of Beaver River streamflow data.**

For comparison, detailed studies of recharge at till-covered sites elsewhere in North America have estimated recharge from 1.5% of precipitation at a site near Dalmeny, Saskatchewan (Fortin et al., 1991) to 9% of precipitation at a site in North Dakota (Rehm et al., 1982). Horgan (1994) estimated recharge to be of the order of 9-12 % of average annual precipitation for a site south of the study area, near Ardmore, Alberta, in the Beaver River-Cold Lake drainage basin. We can conclude that, with the caveats mentioned above, that the annual recharge to groundwater on a regional basis is likely in the order of 2% of annual precipitation in the Cold Lake-Beaver River Basin, very much in keeping with estimates from published detailed studies.

#### 2.3.1.2 Baseflow Estimation by Digital Filtering

An alternate method to estimating groundwater contribution to streamflow is that of a digital recursive filter like that described by Nathan and McMahon (1990). This filtering method essentially removes the high frequency component of the stream discharge record, presumed to be runoff, and leaves the low frequency component, presumed to be baseflow. The lower line shown on the stream hydrograph of the Beaver River in Figure 2.10 represents an estimate of the baseflow contribution to daily discharge estimated using the recursive filtering technique described by Nathan and McMahon (1990). This simple filter is of the form:

$$f_k = \alpha f_{k-1} + (0.5+\alpha/2)(y_k - y_{k-1}) \qquad \text{(Equation 2.2)}$$

where $f_k$ is the filtered response at the kth sampling instance, $y_k$ is the original streamflow, and $\alpha$ is a filter parameter, and the filtered baseflow is $y_k - f_k$. The baseflow index is the ratio of baseflow to streamflow and indicates the proportion of stream flow coming from groundwater at any instance. Nathan and McMahon (1990) show that unlike other baseflow indictors, the baseflow volumes estimated by this technique actually rise when streamflow rises during storm events, rather than staying constant in such sorts of high-frequency perturbations during the annual recession. This has the effect of making the baseflow index more stable.

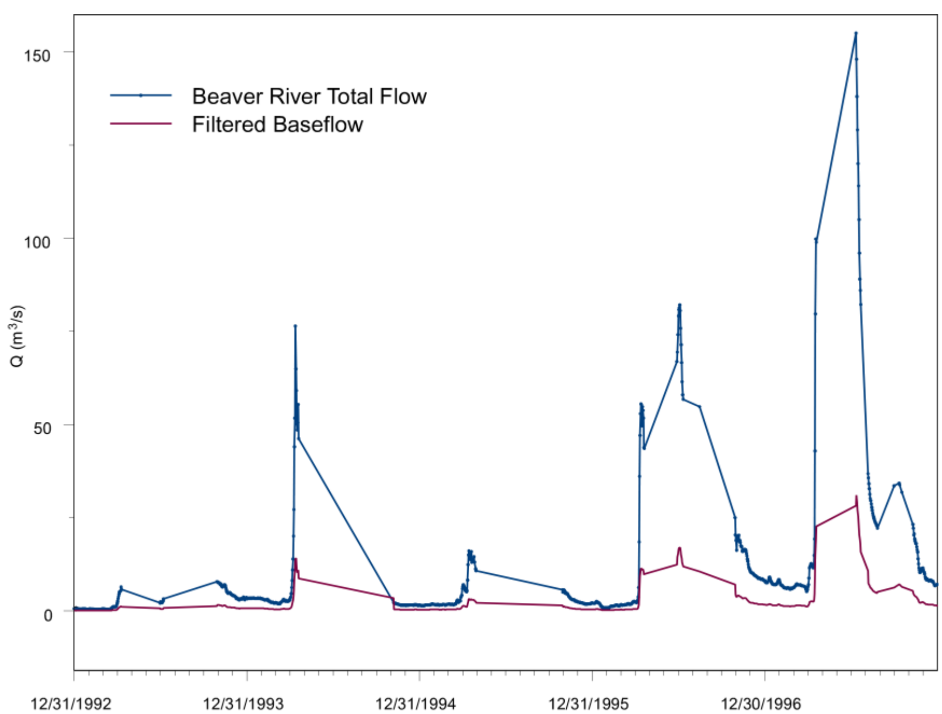



**Figure 2.10. Total streamflow and estimated baseflow of the Beaver River at the Cold Lake Reserve.**

The ratio of baseflow to total stream flow is called the baseflow index. For the Beaver River near Cold Lake, the baseflow index is relatively constant at about 0.20. This compares well to an estimate of baseflow of 25% to a gaining reach of the Athabasca River reported by Hackbarth and Nastasa (1979). This result was used to help calibrate the groundwater flow model in Section 5.

## 2.4 Lakes, Wetlands, and Springs

There are over 2000 lakes mappable at the 1:250 000 scale in the Cold Lake-Beaver River Basin. These lakes are popular recreational destinations as well as important elements of the basin's aquatic ecosystem. Photographs of two of the larger lakes, Bourque Lake in the Moostoos Uplands and Moose Lake in the Beaver River Plain, as they appeared in June 2003 are in Figure 2.11.

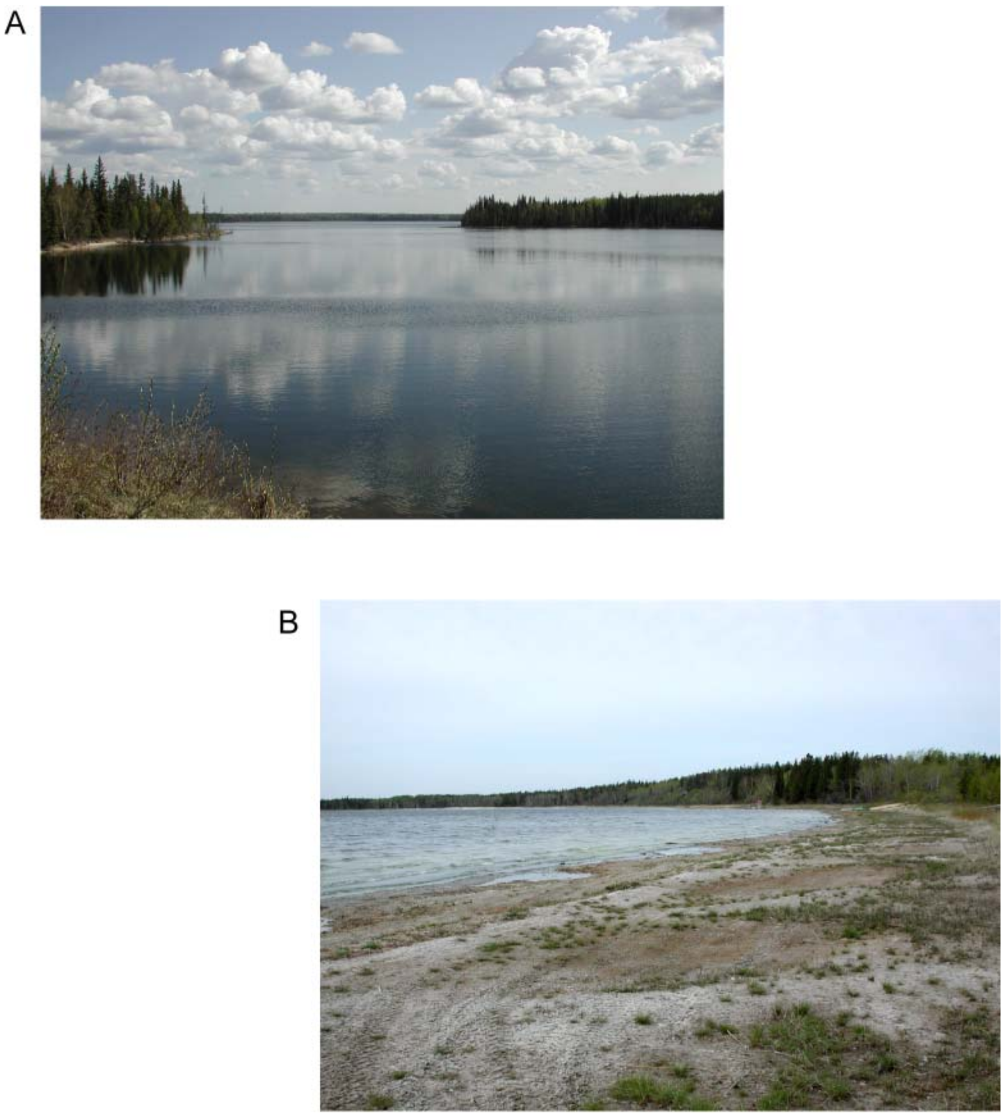



**Figure 2.11. Photographs of two lakes of the Beaver River-Cold Lake Drainage Basin: A) Bourque Lake, B) Moose Lake.**

Lakes in the Cold Lake-Beaver River Basin have three distinct origins. The first kind of lake is characterized by shallow depths, gently-dipping lake-bottom sides, and lake levels sensitive to seasonal and climatic variation. These are mainly typical prairie lakes and sloughs that form in shallow topographic depressions related to landform geometry and relief. In the boreal forest regions of the Moostoos Upland region, these areas may be occupied by wetlands or beaver ponds rather than shallow lakes.

The second kind of lake includes the large, deep and steep-sided lake-bottoms lakes of the area that don't tend to fluctuate widely in lake level from year to year. Members of this second and smaller class of lakes are suspected to have formed from glacial processes that literally excavated deep holes the landscape that later filled with water. These lakes are of particular interest to hydrogeologists because their depth and relatively steep sides makes them likely to intersect and interact with multiple aquifer systems, hence their relative stability in lake level. These lakes can be identified mainly by their steep-walled depth profile and the presence of ice-oriented lakebed features observed on lake-bottom bathymetric surveys.

Ice-carved lakes are also identified by their association with down-ice, elevated features on the land surface. These features that are inferred to represent the ice-excavated material and the landform combination are called hill-hole pairs. Not all ice-carved lakes are necessarily deep and not all deep lakes are necessarily ice-carved, but there does appear to be a strong association of depth and genesis of lakes in the Cold Lake-Beaver River Basin.

The third kind of lake is impoundments of surface water in the bottom of abandoned glacial meltwater channels. Kehiwin Lake is an example of this third kind of lake.

To assist future investigations of lake-groundwater interactions as part of this report, AGS obtained lake-bottom bathymetry data from AENV and had these digitally blended with the land-surface DEM. The resulting DEM shows the land surface as it would appear if the water in the lakes was removed. A close-up of the modified DEM in the area of Cold Lake, the largest of the ice-carved lakes, is in Figure 2.12. In all, twenty-seven lake-bottom bathymetry surveys were integrated into the provincial DEM by AGS. Lakes without lake-bottom bathymetery data are still represented in the DEM by a planar surface of constant elevation representing average lake level.

There are nine Environment Canada lake-level monitoring stations with historical records available to AGS. The locations of these monitoring stations are shown on Figure 2.13. Study of historical lake-level fluctuations requires detailed, local-scale hydrological analysis and is thus outside the scope of the present study.

A significant proportion of the Cold Lake-Beaver River Basin can be classified as a wetland, particularly in the Moostoos Upland. These wetlands include both bogs (recharge and flow-through wetlands) and fenns (discharge and flow-through wetlands). Their distribution is also shown in Figure 2.13.

A review of historical documentation of spring occurrences in the basin area on file with AGS revealed 64 documented major springs, though undocumented springs no doubt exist. The historical documentation has not been reconciled to remove duplicates but a cursory examination of the files suggests that AGS has historical documentation of less than 25 unique springs in the basin. A field excursion by AGS staff in the summer of 2003 was made to ground-truth the existence of documented springs. It was found that the documented spring occurrences were first-order accurate in that a spring was located where previously documented but flows were generally less than those previously reported. The significance of this observation is not known because the time and season of previous observations are not available. Ten springs were field-verified and their locations recorded with a GPS. Photographs of several of these springs are in Figure 2.14. A map of documented and field-checked springs is in Figure 2.15.

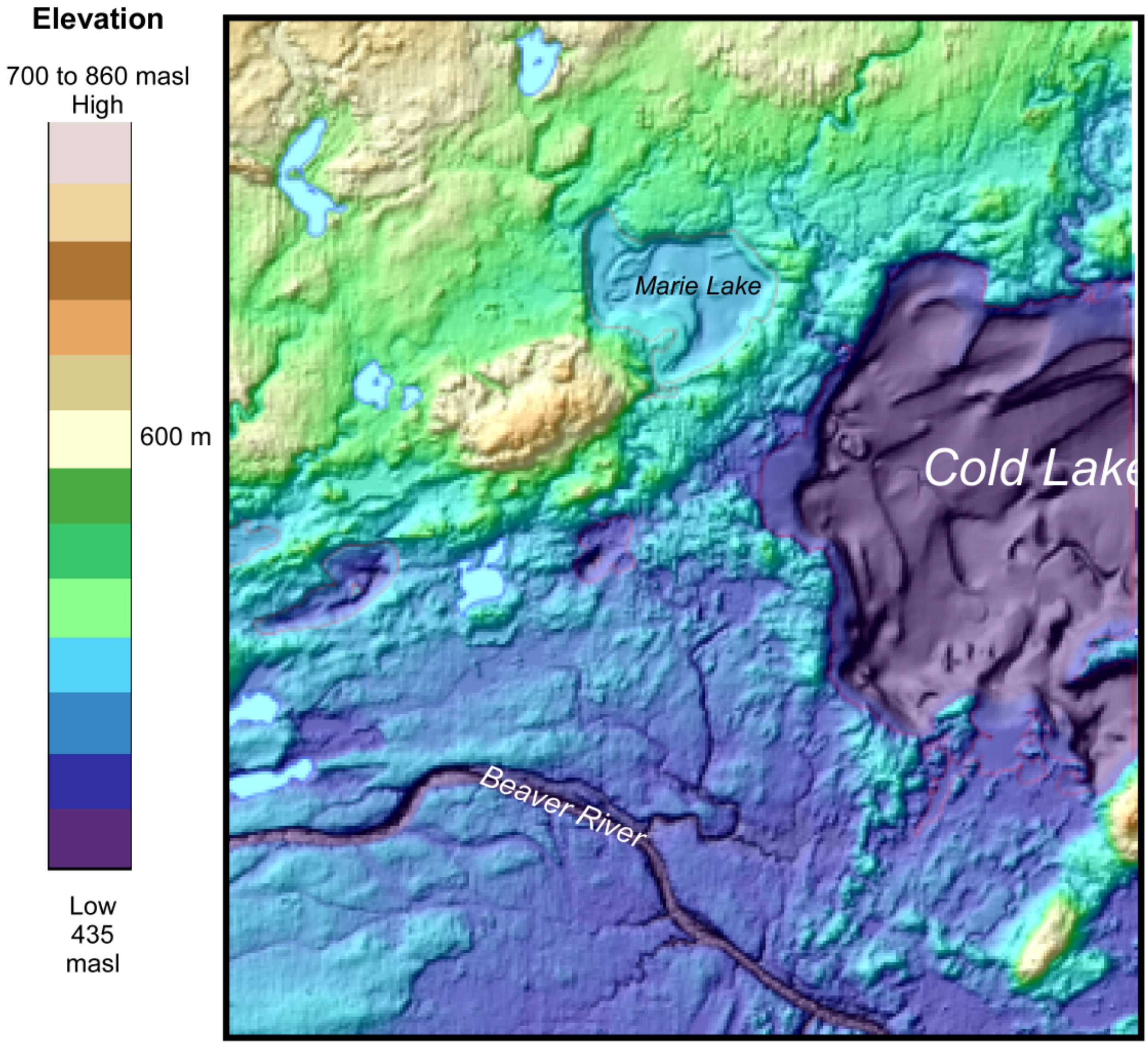
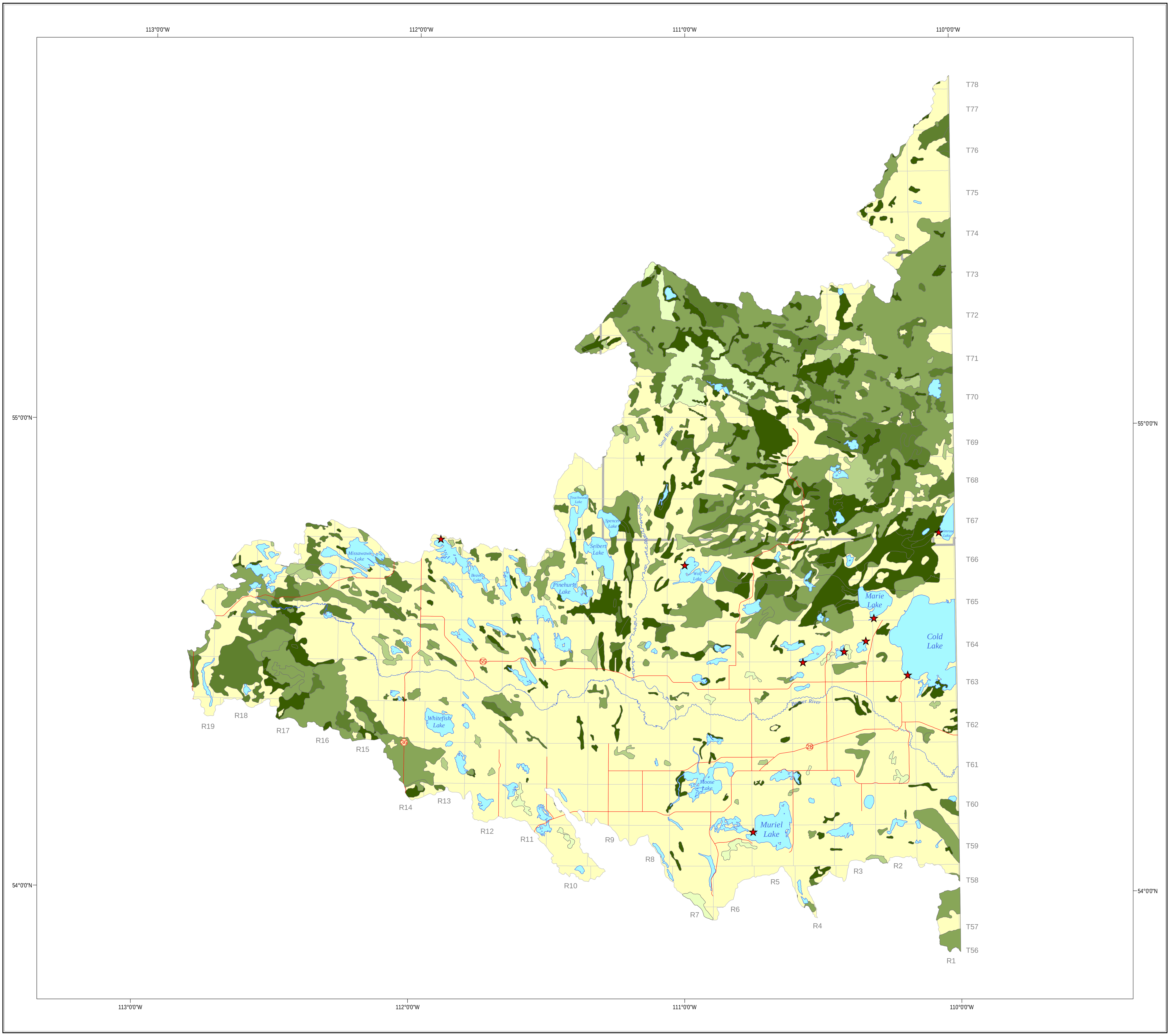
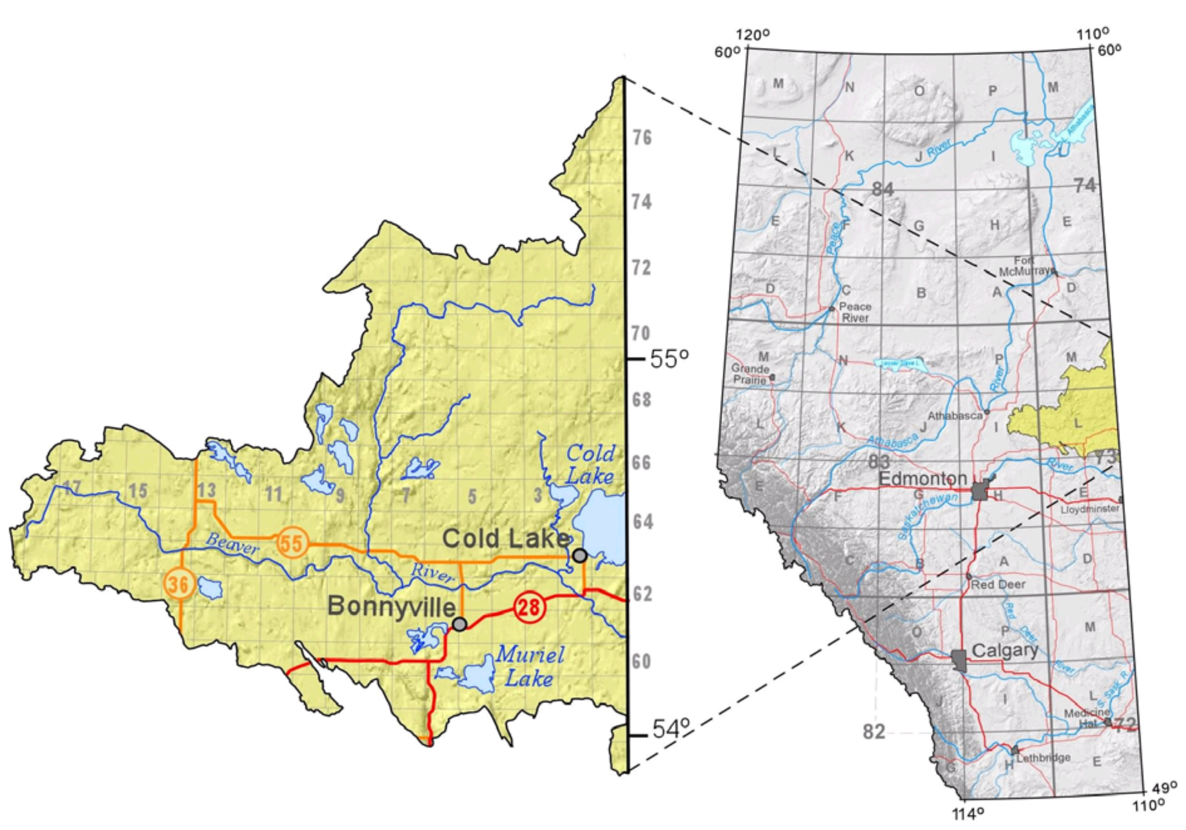



**Figure 2.12. Digital elevation model showing topographic features on the bottom of Cold Lake.**




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

December, 2004

**Wetland mineral levels**

| | | | |
|---|---|---|---|
| 0 - 20% | | ★ | Lake hydrograph station |
| 21 - 40% | | | River |
| 41 - 60% | | | Major road |
| 61 - 80% | | | Cold Lake Air Weapons Range Boundary |
| 81 - 90% | | | Lake |
| | | | Beaver River drainage basin area (Alberta portion) |

## Figure 2.13 Location of lakes, wetlands and gauging stations

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

A

B

Figure 2.14. Photographs of some springs in the Beaver River- Cold Lake Drainage Basin.

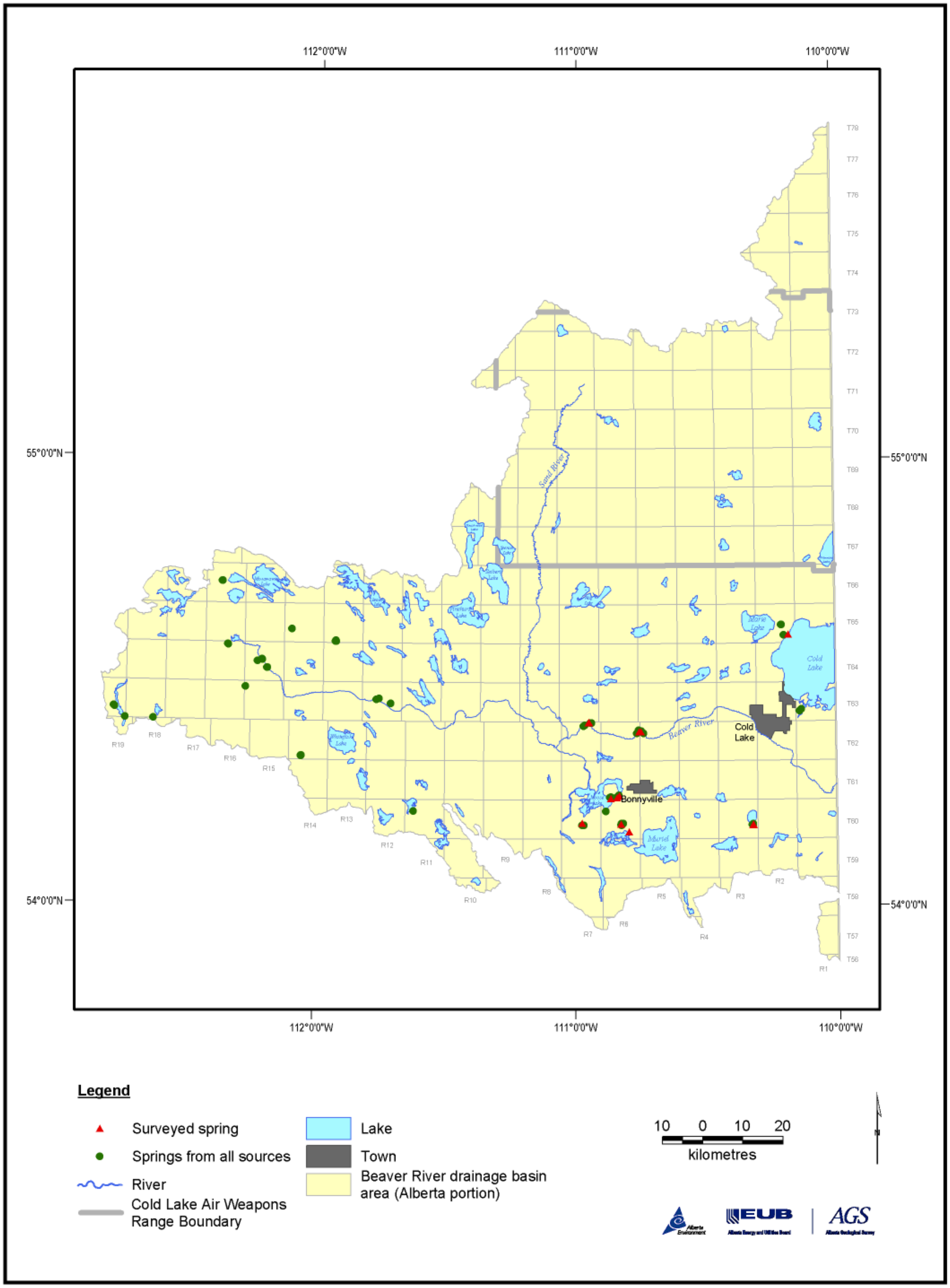



**Figure 2.15. Locations of visited and mapped springs.**

# 3 Geology

## 3.1 General Stratigraphy

The area beneath the Cold Lake-Beaver River Basin is comprised of a succession of Paleozoic (Cambrian) sandstones and (Devonian) limestones resting unconformably atop crystalline Pre-Cambrian shield, in turn overlain by Mesozoic (Cretaceous) sandstones and shales, and in turn overlain by 25 to 225-m of drift made up of Cenozoic (Tertiary?) sands and gravels and (Quaternary) glacial deposits. A general stratigraphic chart is shown in Figure 3.1.

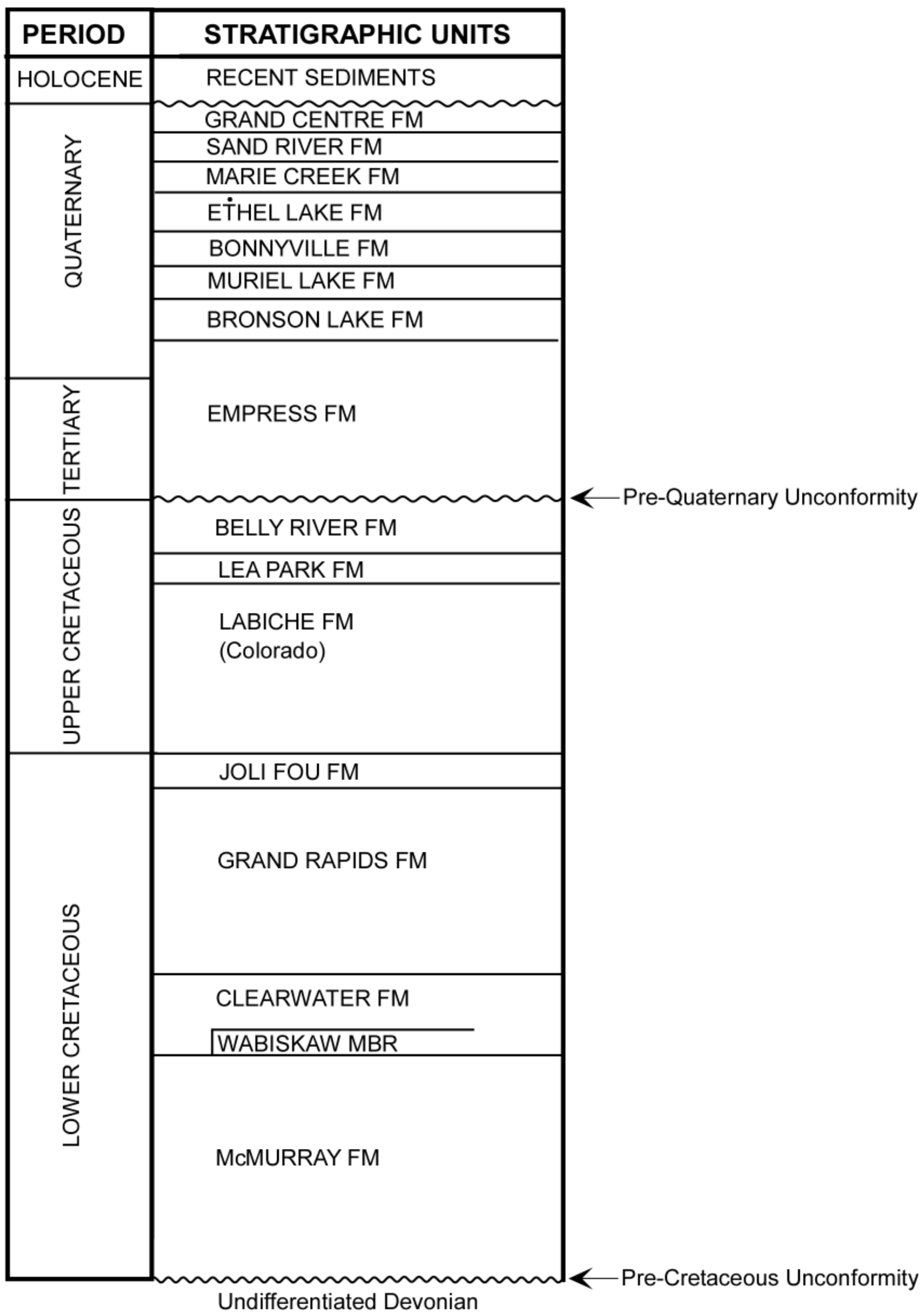



**Figure 3.1. Stratigraphic chart for study area.**

The predominant bedrock lithology in the Cold Lake-Beaver River Basin at the base of the drift is shale of the Colorado and the Lea Park formations. Interbedded sandstone and shale bedrock of the Belly River Formation does occur in the Whitefish Uplands and water wells are completed within those sandstone beds. These bedrock aquifers have not been studied as part of this report. Future work will be required to assess their importance in regional water management but the expectation is that these beds are not a significant contributor to the potable groundwater resource-base nor to surface-groundwater interactions in the basin. Further work will be required on this point. The top of bedrock has therefore been chosen to be the lower limit of the present study.

The focus of this work is the glacial deposits above the bedrock. These are discussed in detail in this section along with maps and cross-sections. Details of water use by formation are in Section 6.

## 3.2 Bedrock Topography

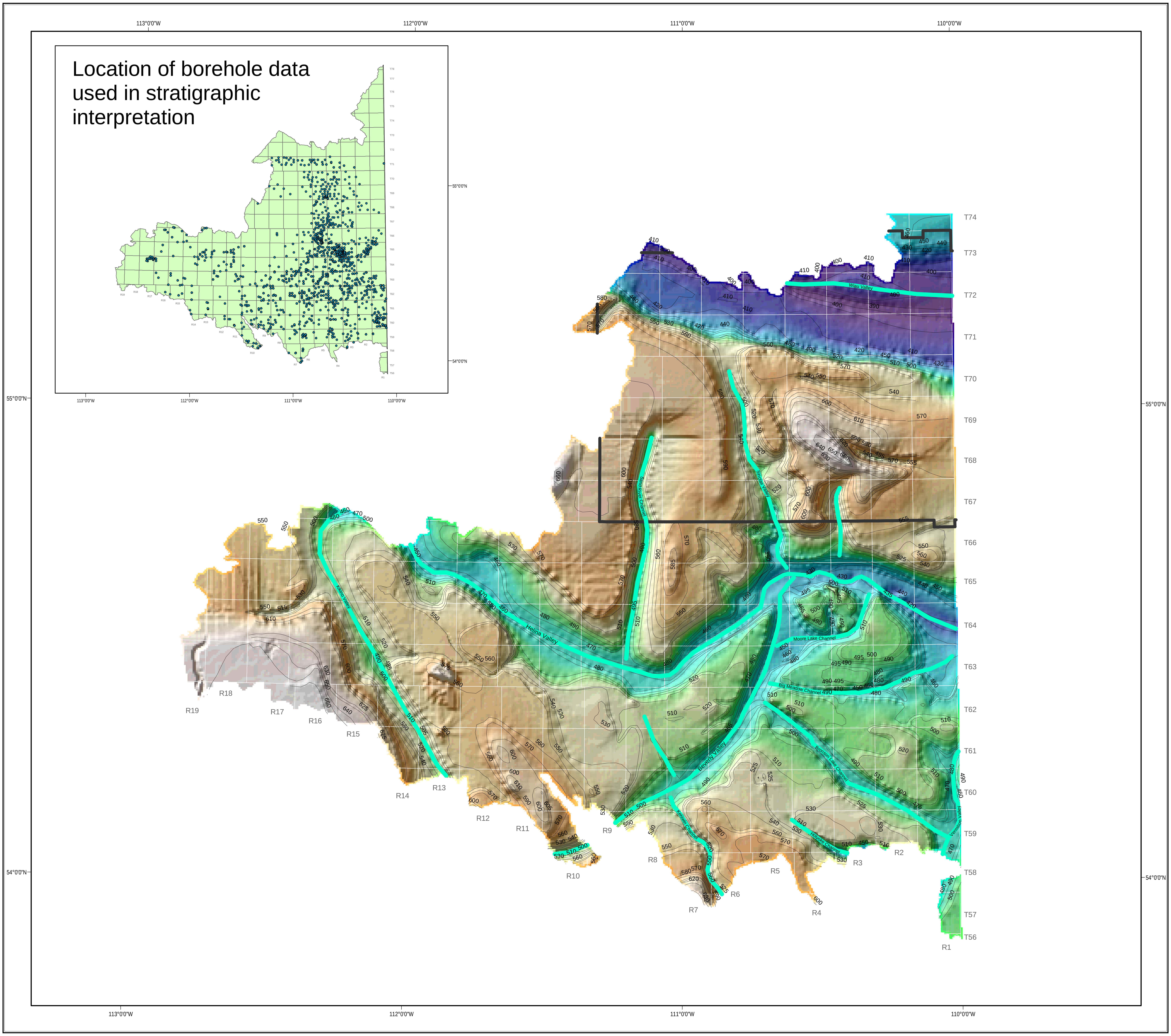
The bedrock topography was initially mapped by Gold et al. (1983) and unofficially revised in subsequent studies by AGS. Bedrock elevations were assessed by rotary drilling and auger holes by the oil and gas industry, by water well drillers, and by scientific investigations. The present view of the bedrock topography is shown in Figure 3.2. Recent advances in 3-D seismic and airborne geophysical methods by the oil and gas industry are known to have improved on the resolution of the bedrock topography where such surveys exist. However these surveys are not in the public domain and have not been used to edit this map. None of the geophysical survey work presented in confidence to AGS during the course of this study has spurred any major revision of Figure 3.2.

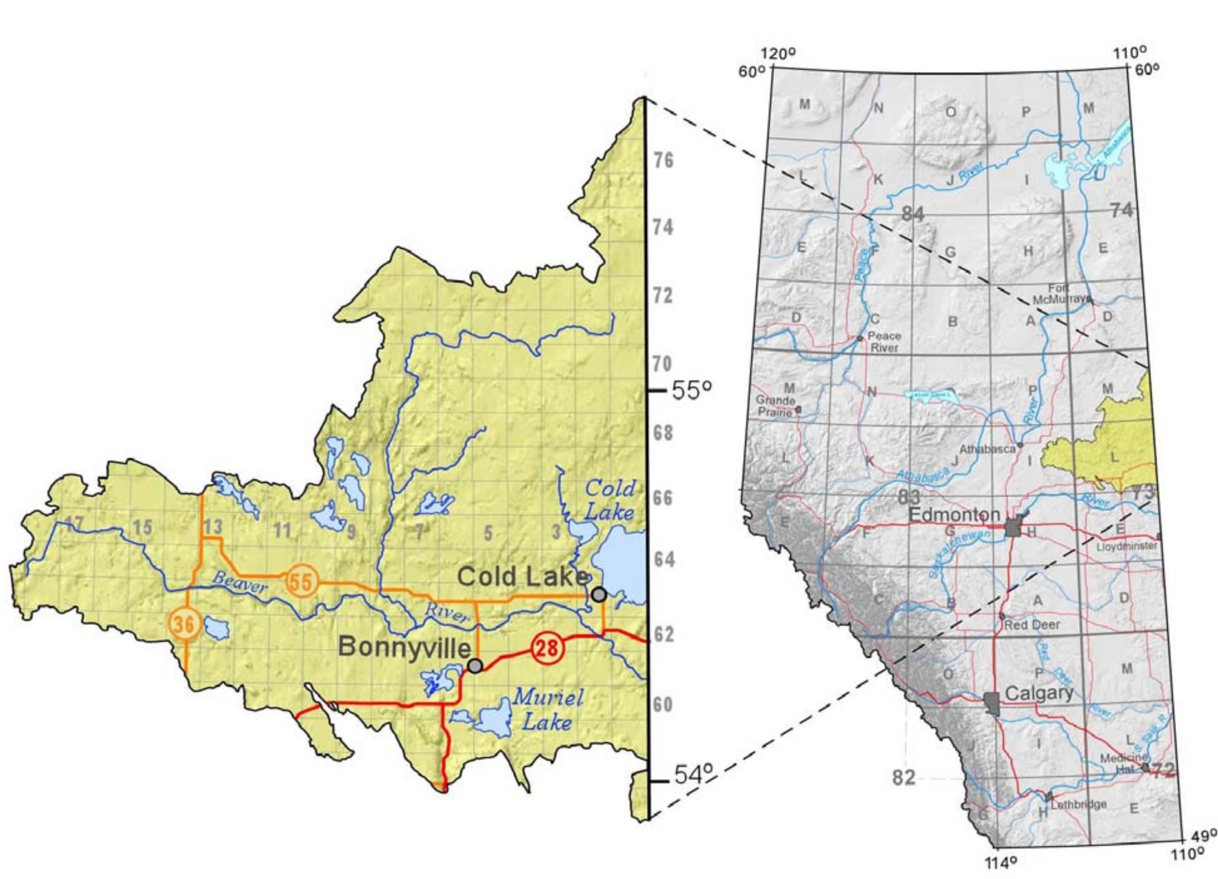
The bedrock topography surface shown in Figure 3.2 is a composite of multiple erosional events and processes acting prior to glaciation and during glacial intervals. The major features are a network of major buried valleys generally oriented west-east. These valleys enter and exit the Cold Lake-Beaver River Basin at locations independent of present-day surface topography. The buried valleys have no present-day surface expression. Andriashek and Fenton (1989) characterized the preglacial valleys as characteristically broad with low gradients and shallow valley-wall slopes. Sediment on preglacial valley walls includes clasts of chert and quartzite derived by eastward flow from the Rocky Mountains. The preglacial valleys on Figure 3.2 include the Helina Valley, the Beverly Valley, the Sinclair Valley, the Wiau Valley, and the Kikino Valley.

Superimposed on the preglacial valleys is a series of glacial channels representing scours formed by glacial meltwater. During earliest interglacials, such scours eroded into the top of the bedrock, creating the buried glacial valleys identified on Figure 3.2 as the Sand River Channel, the Bronson Lake Channel, the Big Meadow Channel, the Moore Lake Channel and the Kehiwin Channel. Glacial channels are distinguished from preglacial valleys by their concave longitudinal profiles, steep channel-wall slope, and the presence of metamorphic and igneous sediment clasts derived from the Canadian Shield.

Though a small part of the Wiau Valley runs below the very northeast part of the Cold Lake-Beaver River Basin, it is not considered in this report. The Wiau Valley is part of the groundwater flow-regime north and outside of the Cold Lake-Beaver River Basin and does likely not contribute in any substantial way to the Cold Lake-Beaver River watershed (Parks and Andriashek, 2002).

There are known localities of glacial-ice disrupted or ice-displaced bedrock throughout the Cold Lake-Beaver River Basin. These localities are commonly referred to as glacial-ice thrusts. Most of the known ice-thrust areas are down-ice of ice-carved lakes as discussed in Section 2. Other ice-thrusts form isolated positive features on the landscape while others are only known from seismic surveys or inferred from borehole evidence.




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

| | |
|---|---|
| High : 630+ | |
| 610 | |
| 590 | |
| 570 | |
| 550 | |
| 530 | |
| 510 | |
| 490 | |
| 470 | |
| 450 | |
| 430 | |
| 410 | |
| Low : 390 (masl) | |

Talwegs of valleys and channels

Cold Lake Air Weapons Range Boundary

December, 2004

## Figure 3.2 Bedrock topography and valley thalwegs

Alberta Energy and Utilities Board

Alberta Geological Survey

## 3.3 Drift Thickness and Stratigraphy

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 thickness is shown in Figure 3.3. The drift is generally, but not always, thicker over bedrock lows and thinner over bedrock highs. The thickness ranges from zero where bedrock is exposed at surface to over 200 m thick in the Sinclair Valley and the Wiau Valley. The greatest thicknesses occur where hills of the Moostoos Upland overlie the centre of buried valleys.

The drift is composed of a series of regionally distinct and mappable units. These units have been recognized as formal geological formations and are named accordingly. A stratigraphic chart showing the names of the drift formations and major glacial events is in Figure 3.4.

The formations were originally mapped and named by Andriashek and Fenton (1989) based on their dominant lithologic character, i.e., sand, gravel, clay, till, etc. As our geological understanding of these formations has grown, we have recognized that the formations are better understood in terms of a genetic stratigraphy, i.e., a stratigraphy based on genesis rather than lithology, for purposes of classifying units as aquifers or aquitards for management purposes. The genetic stratigraphy is discussed later in this section. But because the original Beaver River Water Management Plan and much subsequent geological work in the area has been based on the original lithostratigraphy, the geology and hydrogeology of the drift sediments is herein presented in that more familiar framework.

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 (divided into 3 lithostratigraphic units designated as Empress Fm. Unit 1, Empress Fm. Unit 2, and Empress Fm. Unit 3), the Bronson Lake Formation, the Muriel Lake Formation, the Bonnyville Formation (divided into 3 lithostratigraphic units designated as the Bonnyville Fm. Unit 1 till, the Bonnyville Fm. Unit 1 sand and gravel, and the Bonnyville Fm. Unit 2 till), the Ethel Lake Formation, the Marie Creek Formation, the Sand River Formation, and the Grand Centre Formation.

Previous hydrogeological studies commonly referred to the sand-dominated formations as aquifers and the till-dominated formations as aquitards and considered the stratigraphy as an elementary layer-cake alternation of aquifers and aquitards. This conceptual framework greatly oversimplifies the regional hydrostratigraphy, understates the degrees of lateral and vertical hydraulic connectivity between formations, and leads to self-contradictory interpretations about groundwater flow and production – many water wells are completed in the so-called aquitards, for example. For this reason, these units are referred to only as formations in this report and designations of the units as aquifers or aquitards are avoided as much as possible.

The vertical relationships of the formations are shown in a series of geological cross-sections that run across the Cold Lake-Beaver River Basin. These are in Figures 3.5a-f . An oblique-perspective fence-diagram is shown in Figure 3.6. The cross-sections highlight the complex geological relationships between the drift formations in the area. In places, a relatively straightforward layer-cake stratigraphy is indeed present. But in many other places, thickness changes, stratigraphic pinch-outs and cross-cutting scours create a very complex, three-dimensional labyrinthical architecture. Where lake-bottom bathymetry was available and added to the surface DEM (as discussed in Section 2), the projected outcrops of the drift formations along lake-bottoms could also displayed on the cross-sections.

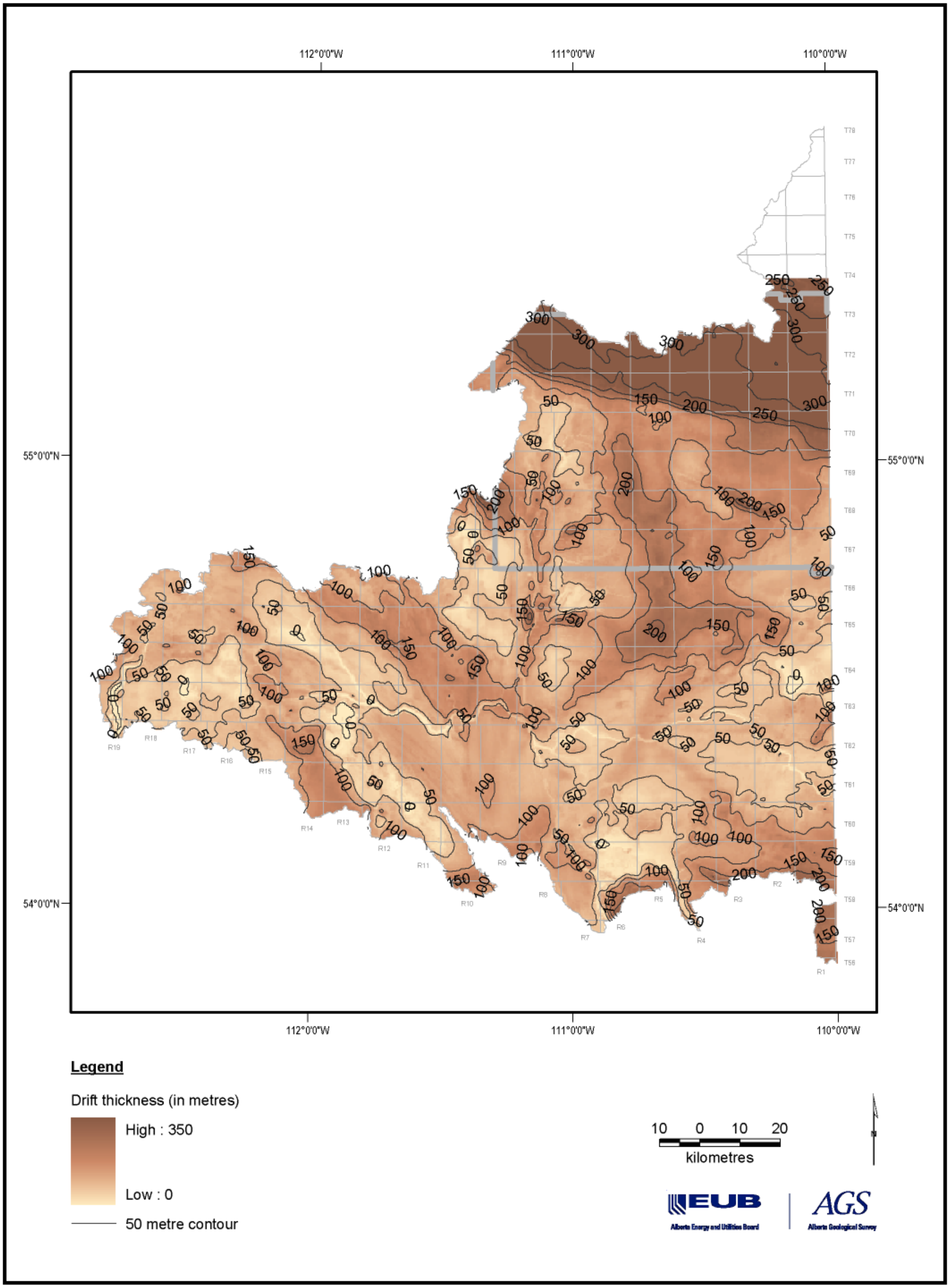



**Figure 3.3. Thickness of drift cover above bedrock.**

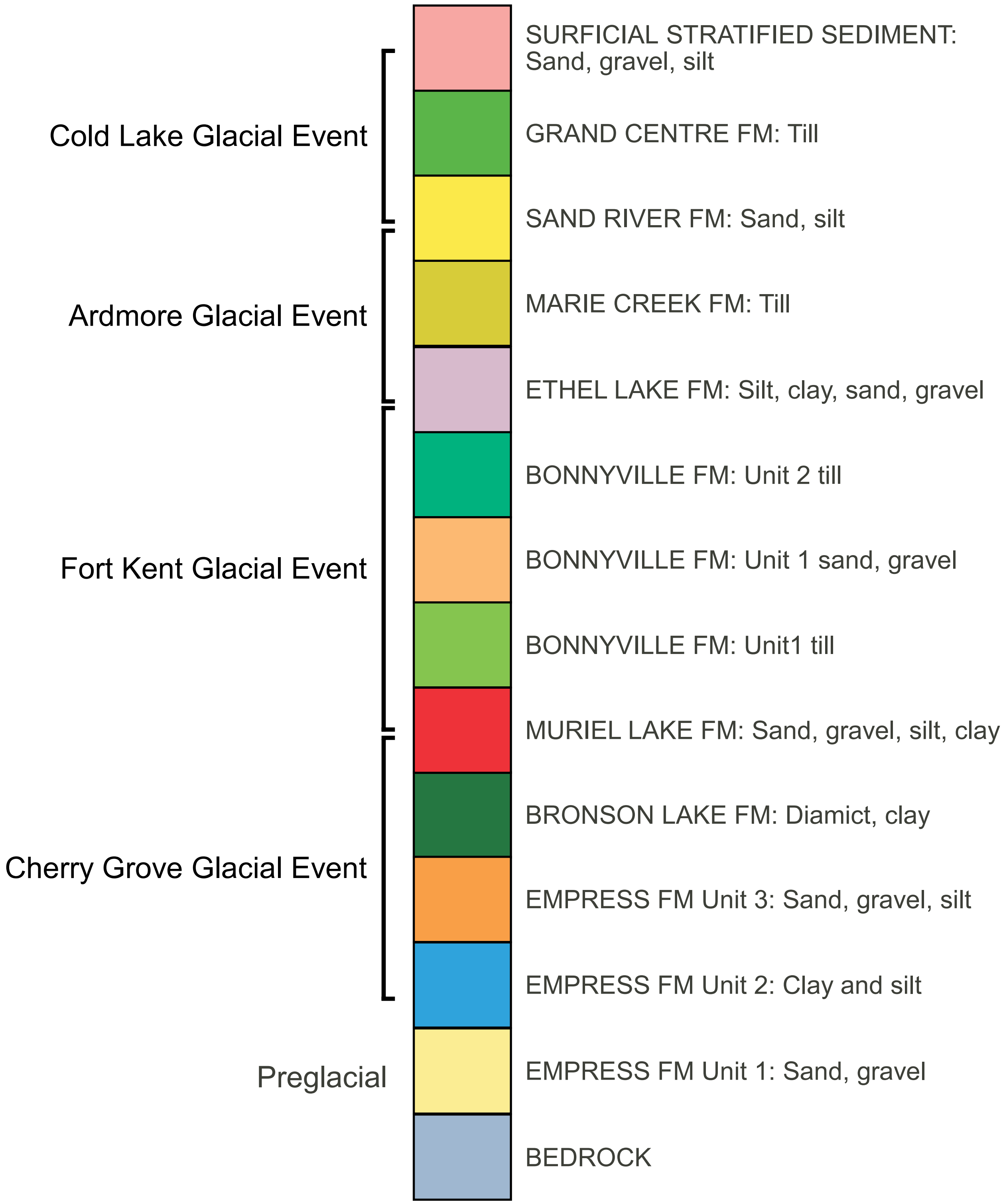
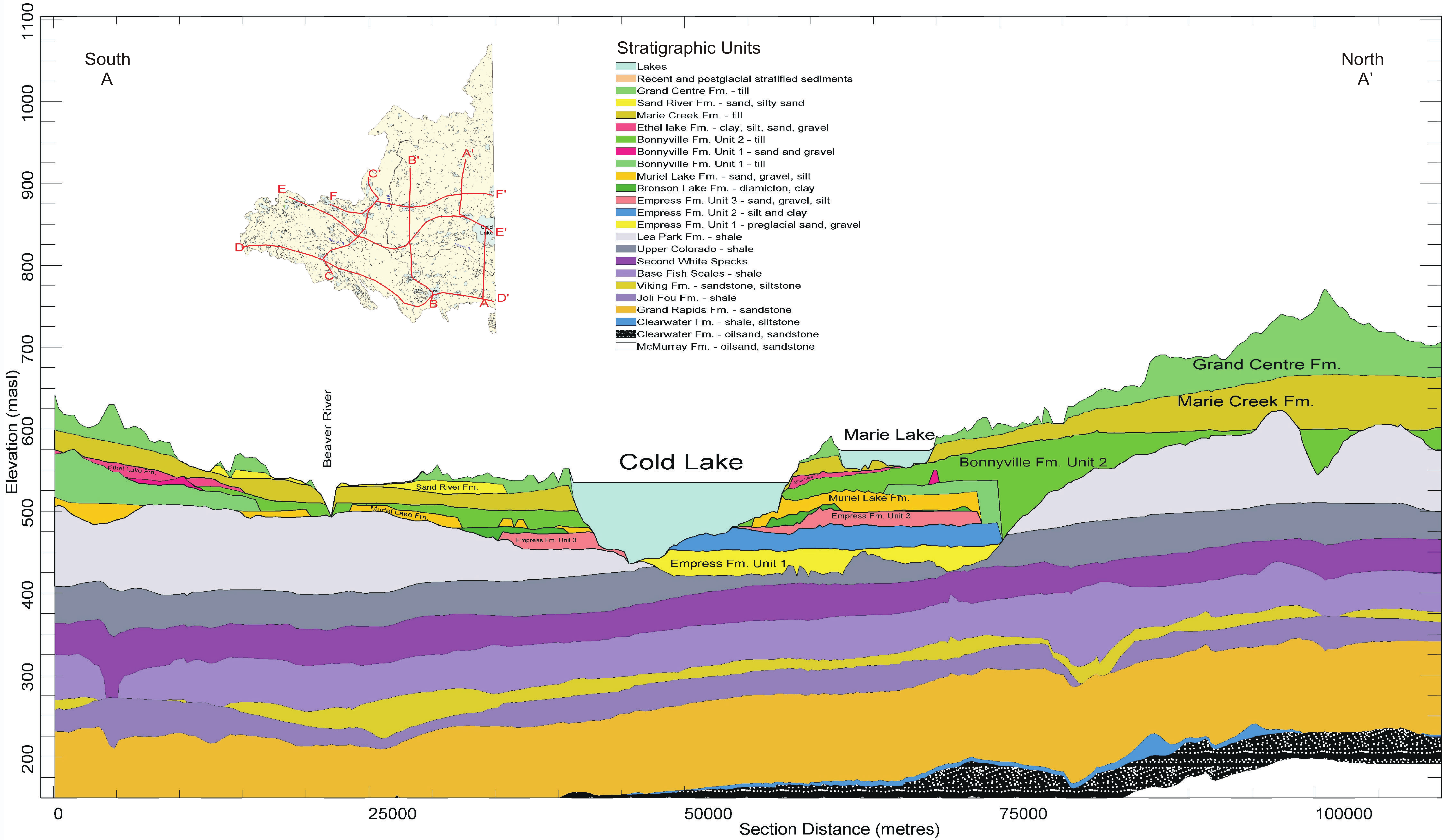


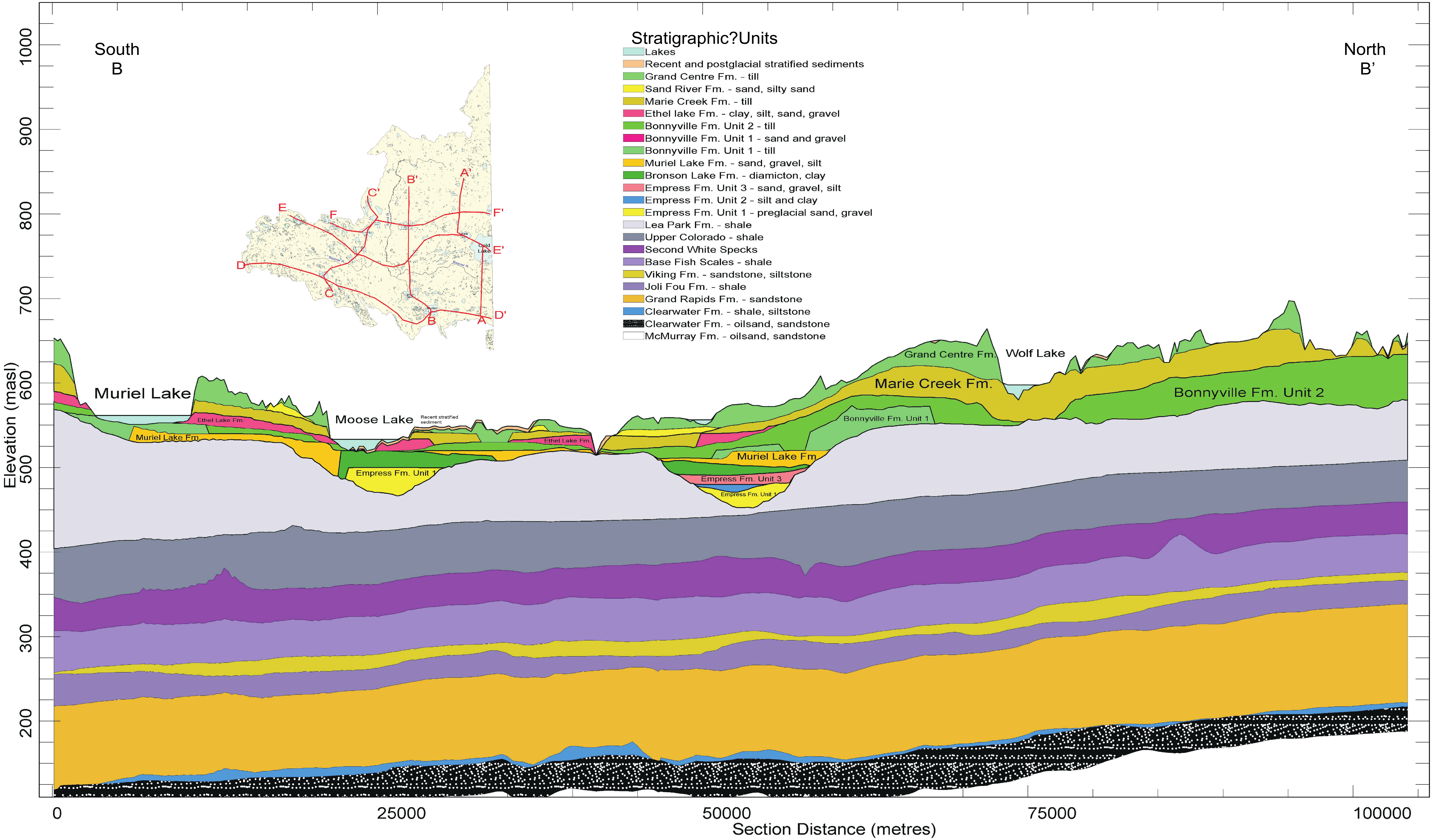

Figure 3.4 Stratigraphic chart showing names of drift formations and major glacial events.




Vertical Exaggeration: 65x's
Map Scale 1:208516
Date: December, 2004
Author: L.D. Andriashek

**Figure 3.5a. Geological cross-section A - A’ (Cold Lake to Marie Lake)**

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




Vertical Exaggeration: 65x's
Map Scale 1:187454
Date: December, 2004
Author: L.D. Andriashek

**Figure 3.5b. Geological cross-section B - B' (Muriel Lake to Wolf Lake)**

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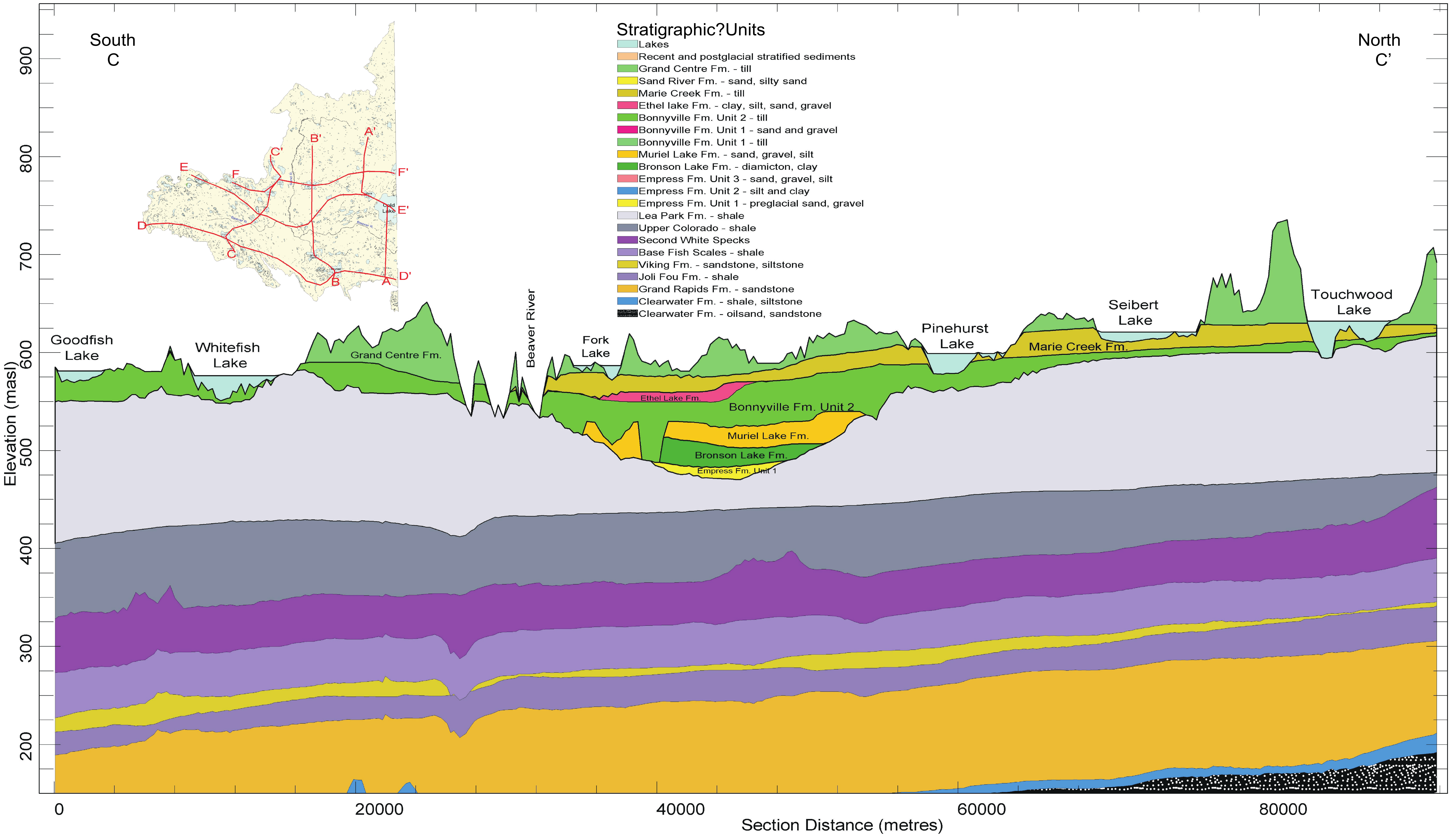


**Figure 3.5c. Geological cross-section C - C' (Goodfish Lake to Touchwood Lake)**

Vertical Exaggeration: 65x's
Map Scale 1:169246
Date: December, 2004
Author: L.D. Andriashek

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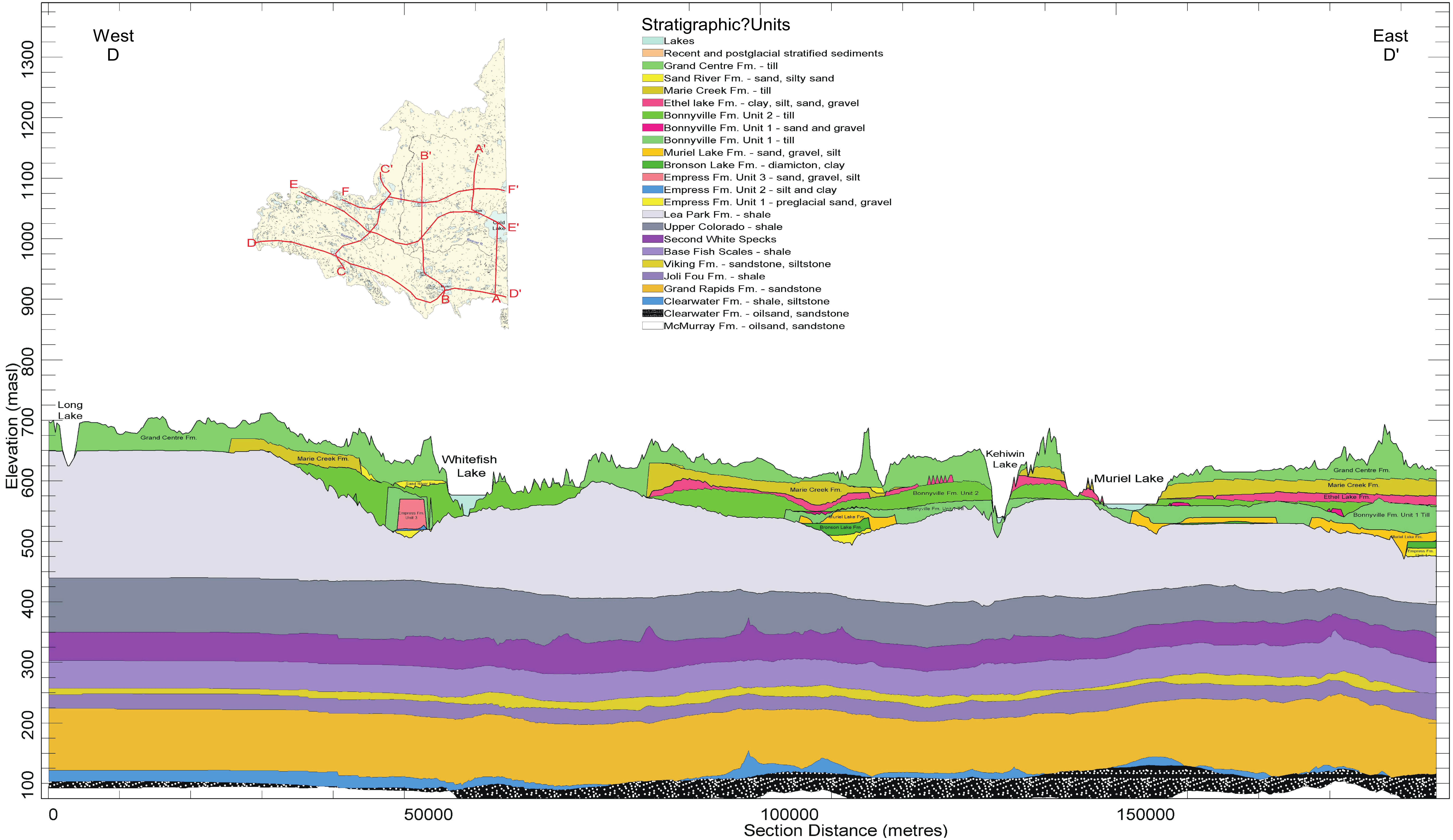


Vertical Exaggeration: 85x's
Map Scale 1:358057
Date: December, 2004
Author: L.D. Andriashek

**Figure 3.5d. Geological cross-section D - D' (Long Lake to Muriel Lake)**

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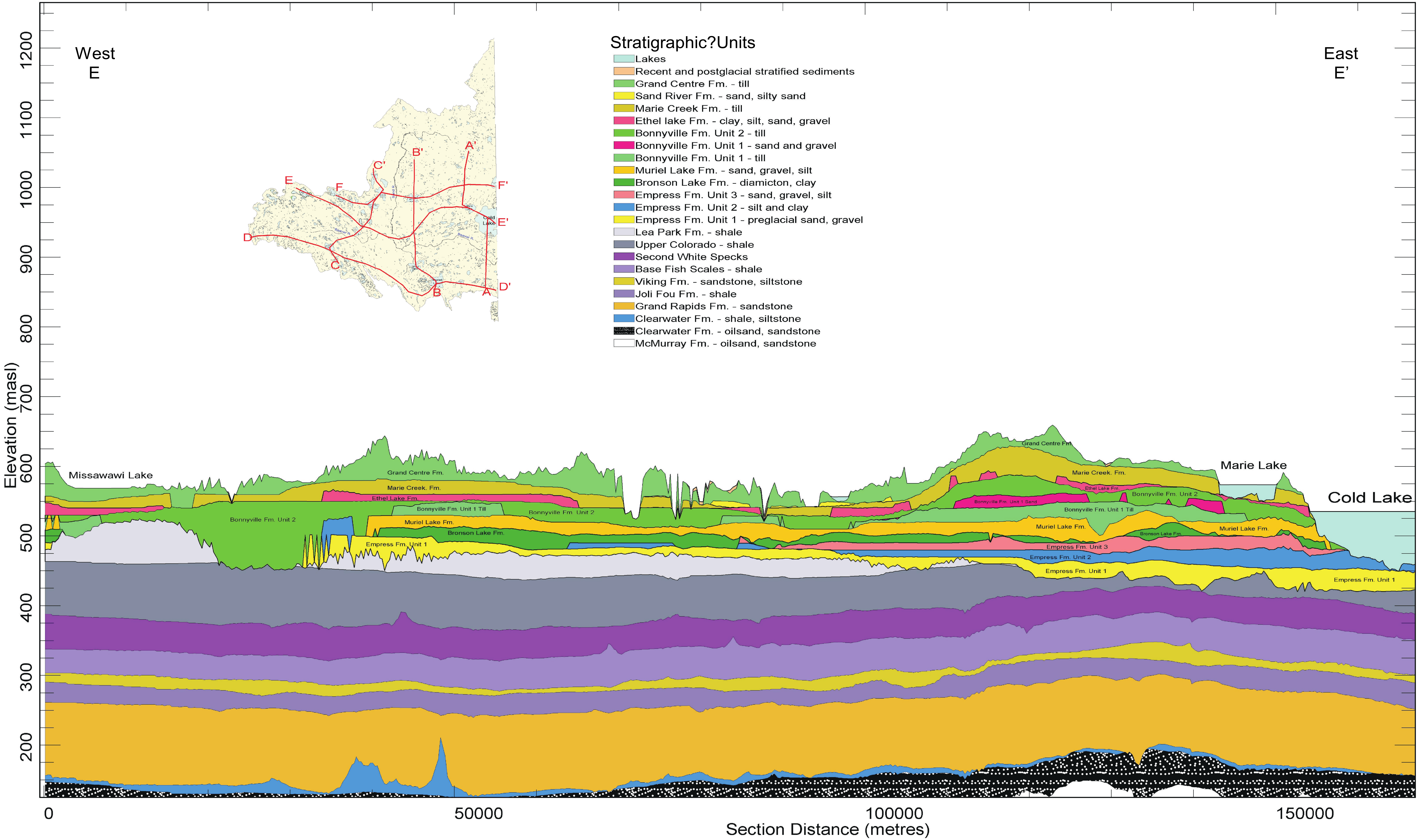
Alberta Geological Survey




Vertical Exaggeration: 85x's
Map Scale1:314023
Date: March, 2004
Author: L.D. Andriashek

**Figure 3.5e. Geological cross-section E - E' (Missawawi Lake to Cold Lake)**

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

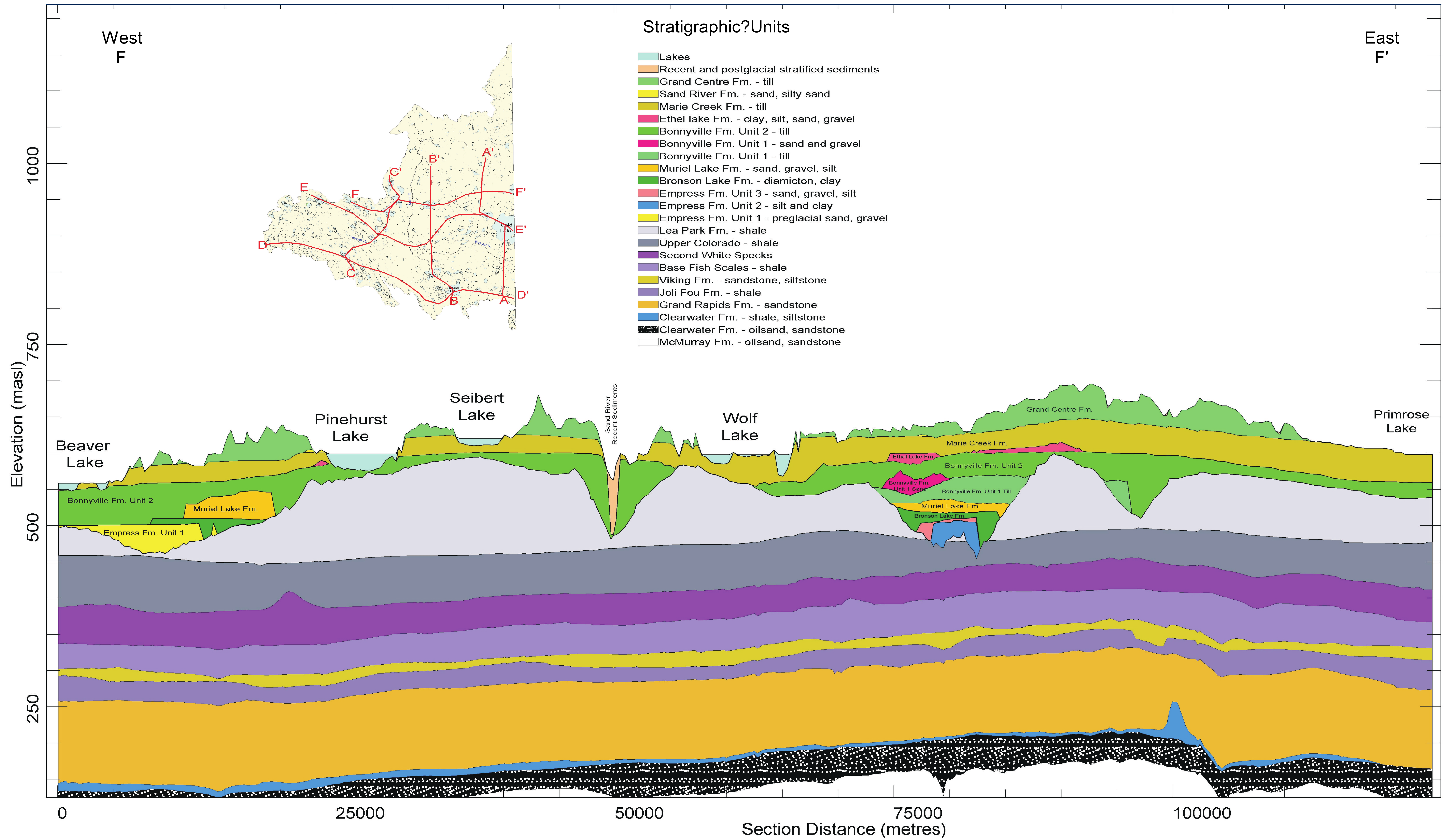
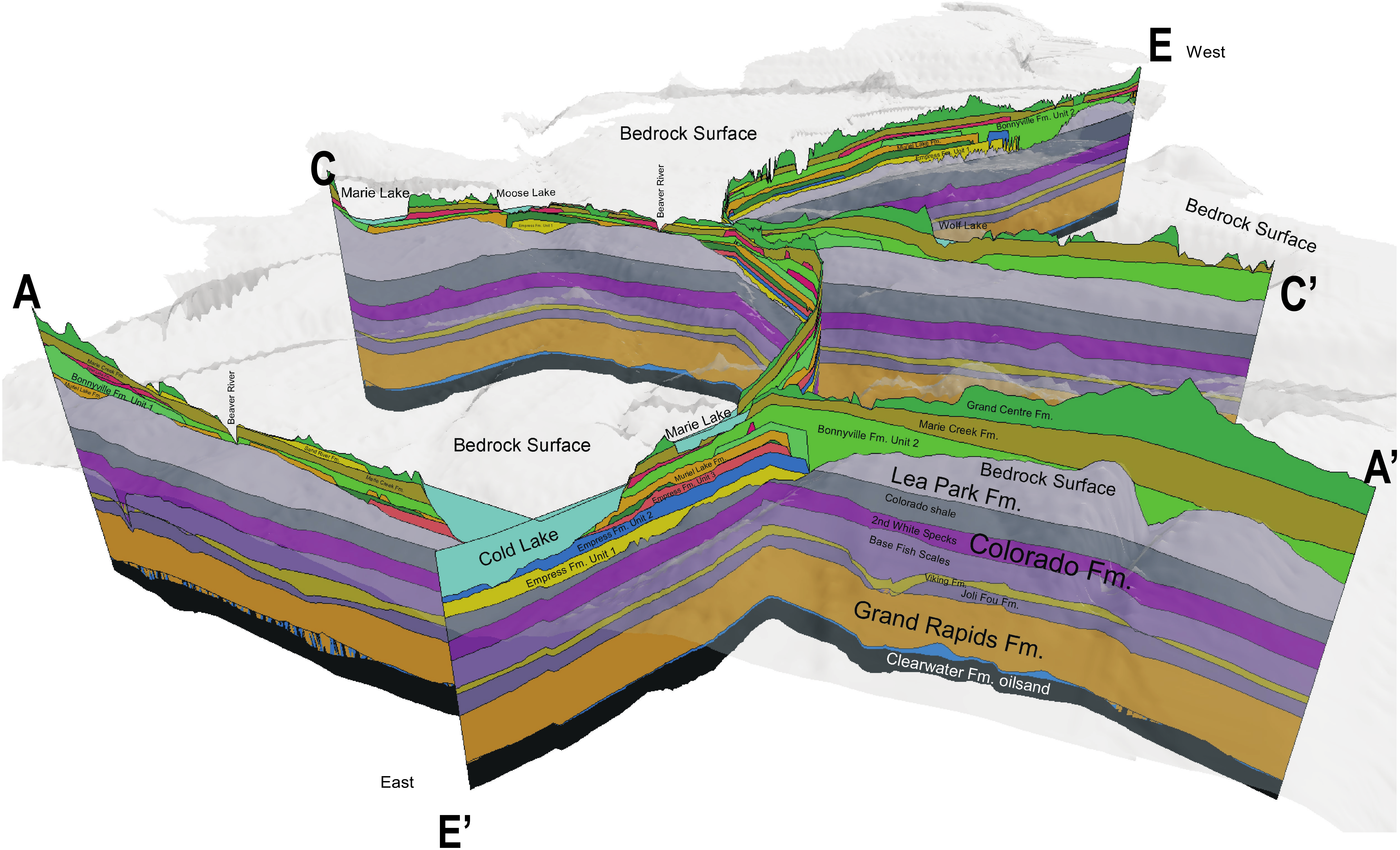



**Figure 3.5f. Geological cross-section F - F' (Beaver Lake to Primrose Lake)**

Vertical Exaggeration: 65x's
Map Scale 1:231684
Date: March, 2004
Author: L.D. Andriashek




Date: December 2004
Author: L.D. Andriashek

**Figure 3.6. 3D view of geological cross-sections.**

The elevation and distribution of each formation is shown in map form on Figures 3.7 to 3.18. These figures are presented as 1:50 000 scale maps with the addition of inset maps showing the calculated isopach (thickness) values for each formation. A summary of the salient features of these maps is given below. Details of the sedimentology and other characteristics of each formation are found in Andriashek and Fenton (1989).

On each map, the distribution of the drift formation is shown in colour atop a gray-shaded backdrop. The gray-shaded backdrop is a reconstructed digital elevation model of the land surface that existed at the time of deposition, not the present day land surface.

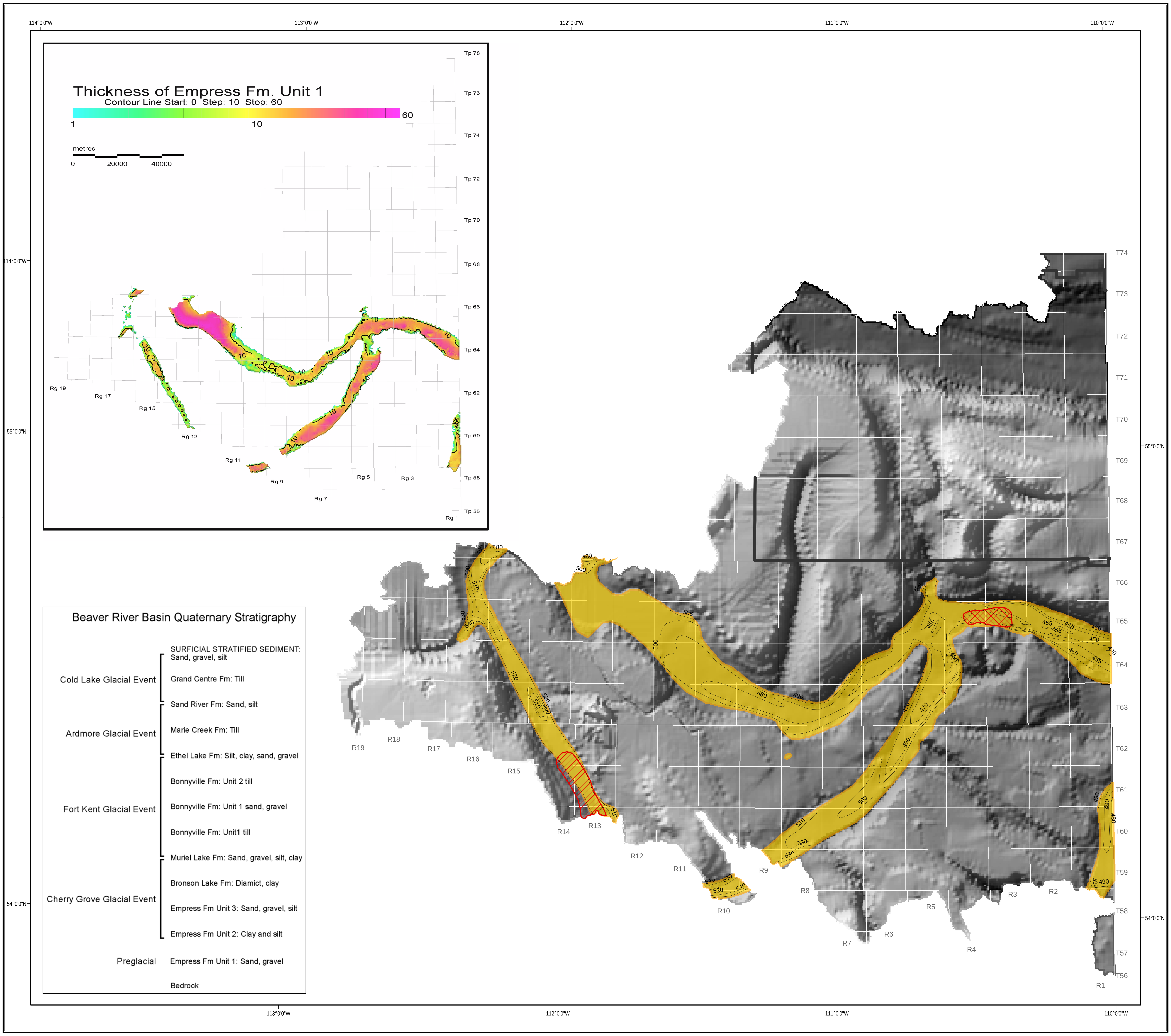
The total area and volume of each formation is presented in Table 3.1

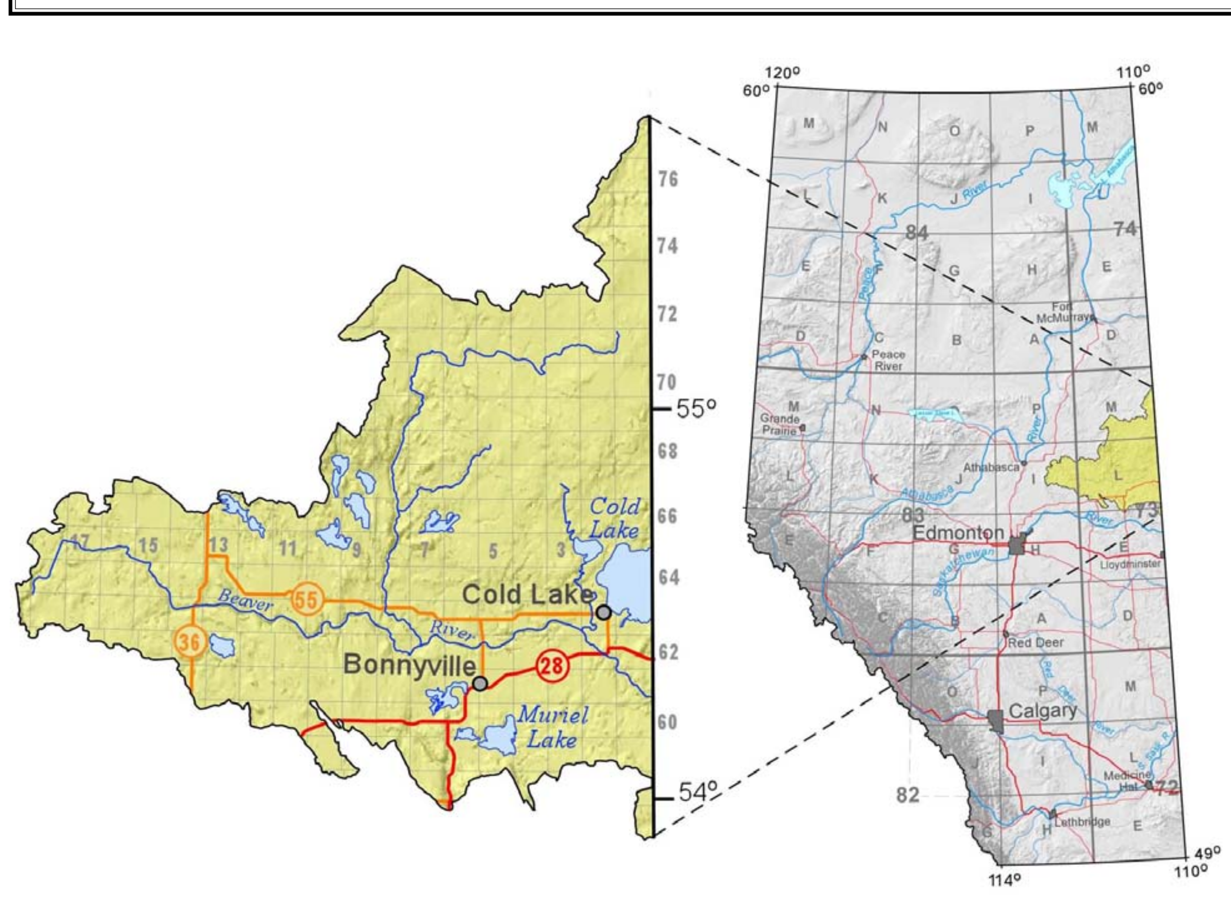
**Table 3.1. Total area and volume of each formation.**

| Formation | Volume ($m^3$) | Volume ($km^3$) | Area ($km^2$) | Thickness Range (m) | Depth to aquifer range (m) |
|---|---|---|---|---|---|
| | | | | | |
| Basin (Drift Cover) | | | 17,395 | 1 - 350 | |
| Sum Formation Volume | 1,704,299,287,471 | 1704.3 | | | |
| Calculated Drift Volume | 1,721,514,520,518 | 1721.5 | | | |
| Bedrock | | | | | 1 - 350 |
| Empress 1 | 21,749,599,624 | 21.8 | 2,214 | 1 - 55 | 5 - 200 |
| Empress 2 | 13,248,820,624 | 13.2 | 1,075 | 1 - 55 | |
| Empress 3 | 18,573,235,249 | 18.6 | 1,571 | 1 - 110 | 1 - 185 |
| Bronson Lake | 33,626,014,740 | 33.6 | 3,217 | 1 - 100 | |
| Muriel Lake | 65,334,951,326 | 65.3 | 4,775 | 1 - 50 | 1 - 185 |
| Bonnyville U1 Till | 77,857,925,442 | 77.9 | 5,243 | 1 - 95 | |
| Bonnyville U1 Sand | 8,347,232,401 | 8.3 | 1,084 | 1 - 65 | 1 - 135 |
| Bonnyville U2 Till | 308,981,491,596 | 309.0 | 12,700 | 1 - 150 | |
| Ethel Lake | 30,992,602,821 | 31.0 | 4,600 | 1 - 65 | 1 - 100 |
| Marie Creek | 303,431,903,840 | 303.4 | 12,034 | 1 - 100 | |
| Sand River | 12,824,086,118 | 12.8 | 4,972 | 1 - 85 | 1 - 100 |
| Grand Centre | 809,331,423,691 | 809.3 | 16,000 | 1 - 150 | |

### 3.3.1 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 the preglacial buried valleys. Three distinct stratified units of the Empress have been recognized in the area. The basal unit, the Empress Fm. Unit 1, is a sand and gravel deposit directly overlying bedrock (Figure 3.7). The next unit, the Empress Fm. Unit 2, is a stratified silt and clay unit that overlies much but not all of the Empress Fm. Unit 2 (Figure 3.8). The third unit, the Empress Fm. Unit 3, is another stratified sand and gravel unit that overlies the Empress Fm. Unit 3 but lies below the till of the overlying Bronson Lake Formation (Figure 3.9). All of the units of the Empress Formation are laterally confined to the preglacial valleys.




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

December, 2004

**Geological Sediments**

Preglacial sand, sand and gravel

Displaced bedrock - area of thick, glacially displaced Belly River Fm.

Deformed stratigraphy - area of glacially faulted and folded Qauternary strata

**Digital Elevation Model Values**

High 660

Low 390 (masl)

Cold Lake Air Weapons Range Boundary

## Figure 3.7 Distribution and structural elevation of Empress Fm. Unit 1 preglacial sand and gravel

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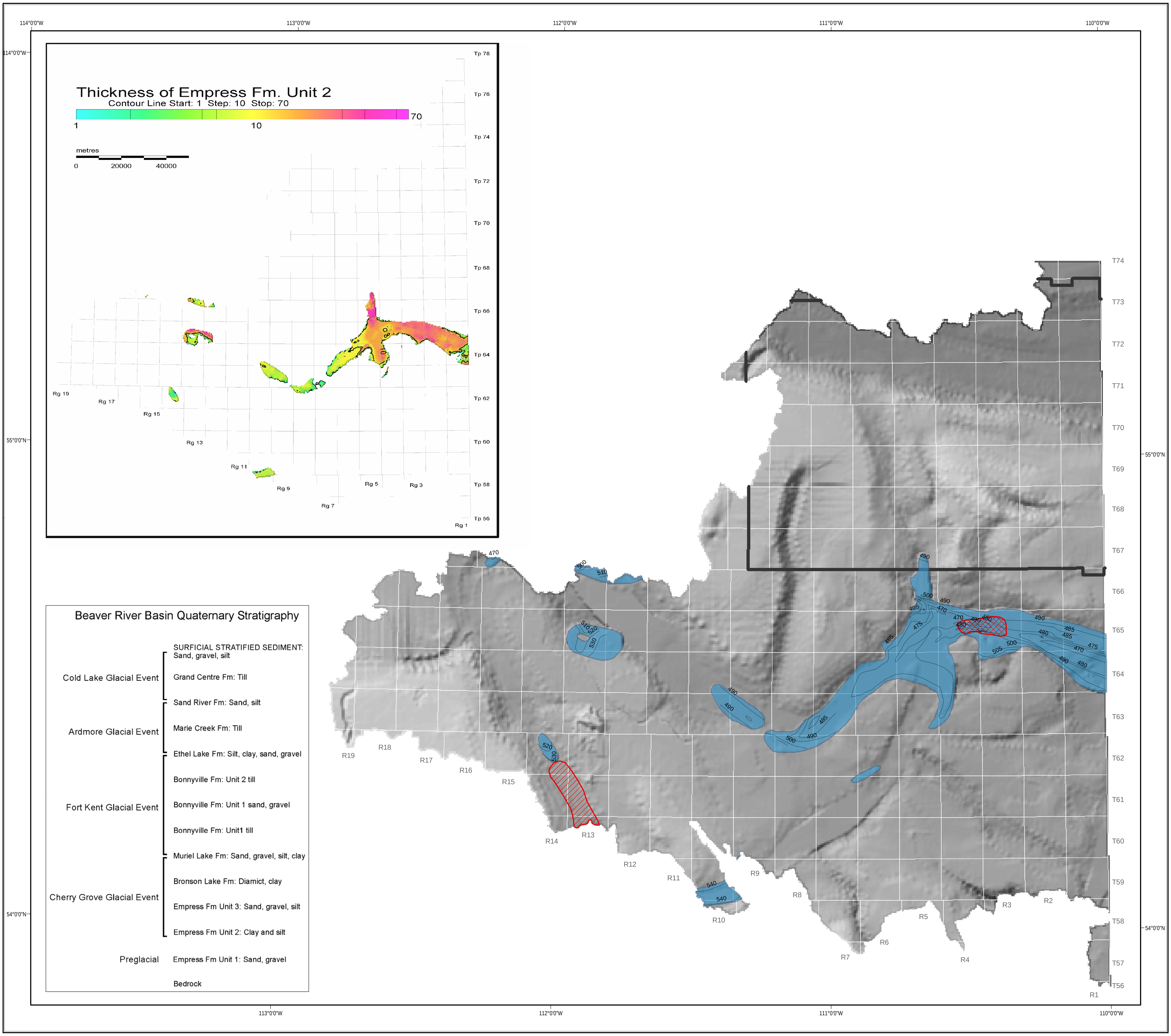
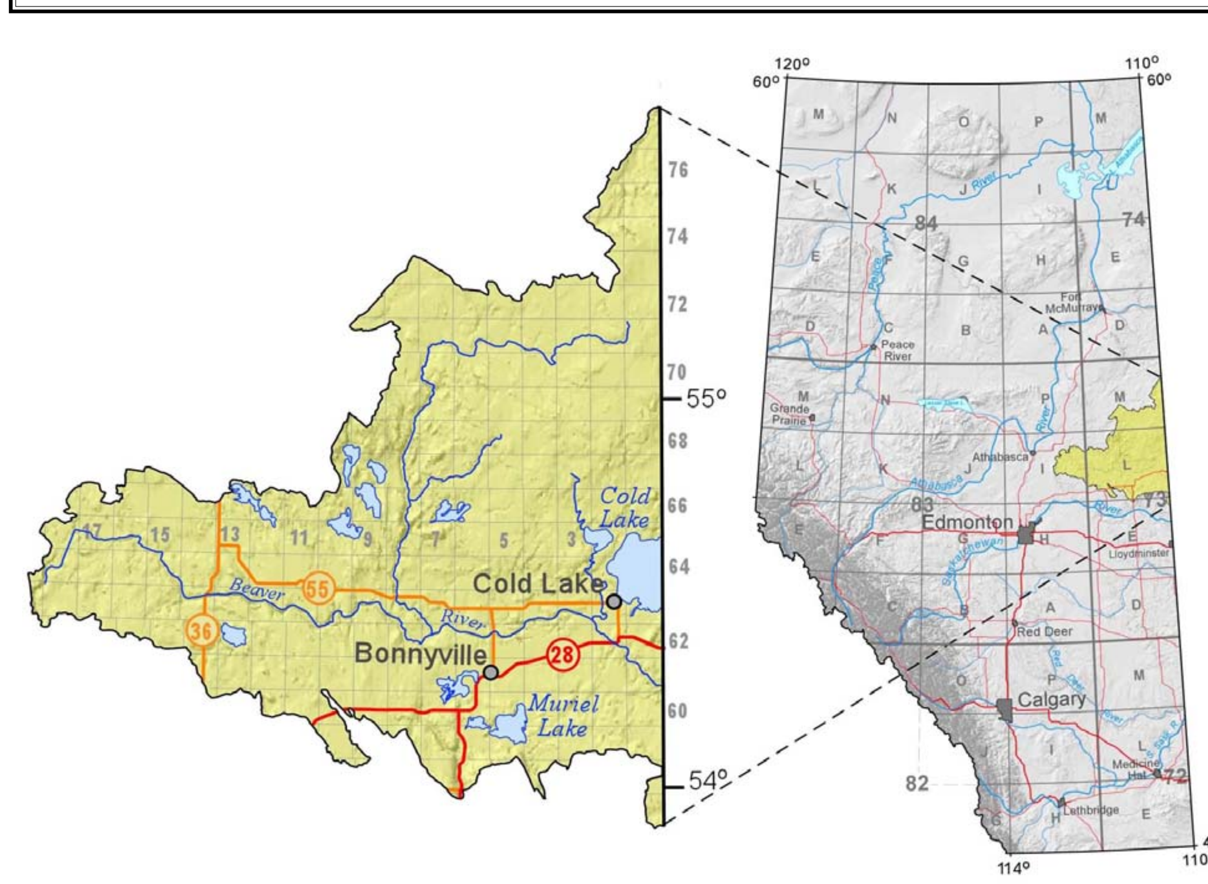



Scale 1:500000

5 0 5 10 15 20 25 30 Kilometres

5 0 5 10 15 20 25 30 Miles

Projection: UTM Zone 12
Datum: NAD83

December, 2004

**Geological Sediments**

Clay and Silt

Displaced bedrock - area of thick, glacially displaced Belly River Fm.

Deformed stratigraphy - area of glacially faulted and folded Quaternary strata

**Digital Elevation Model Values**

High: 660

Low: 390

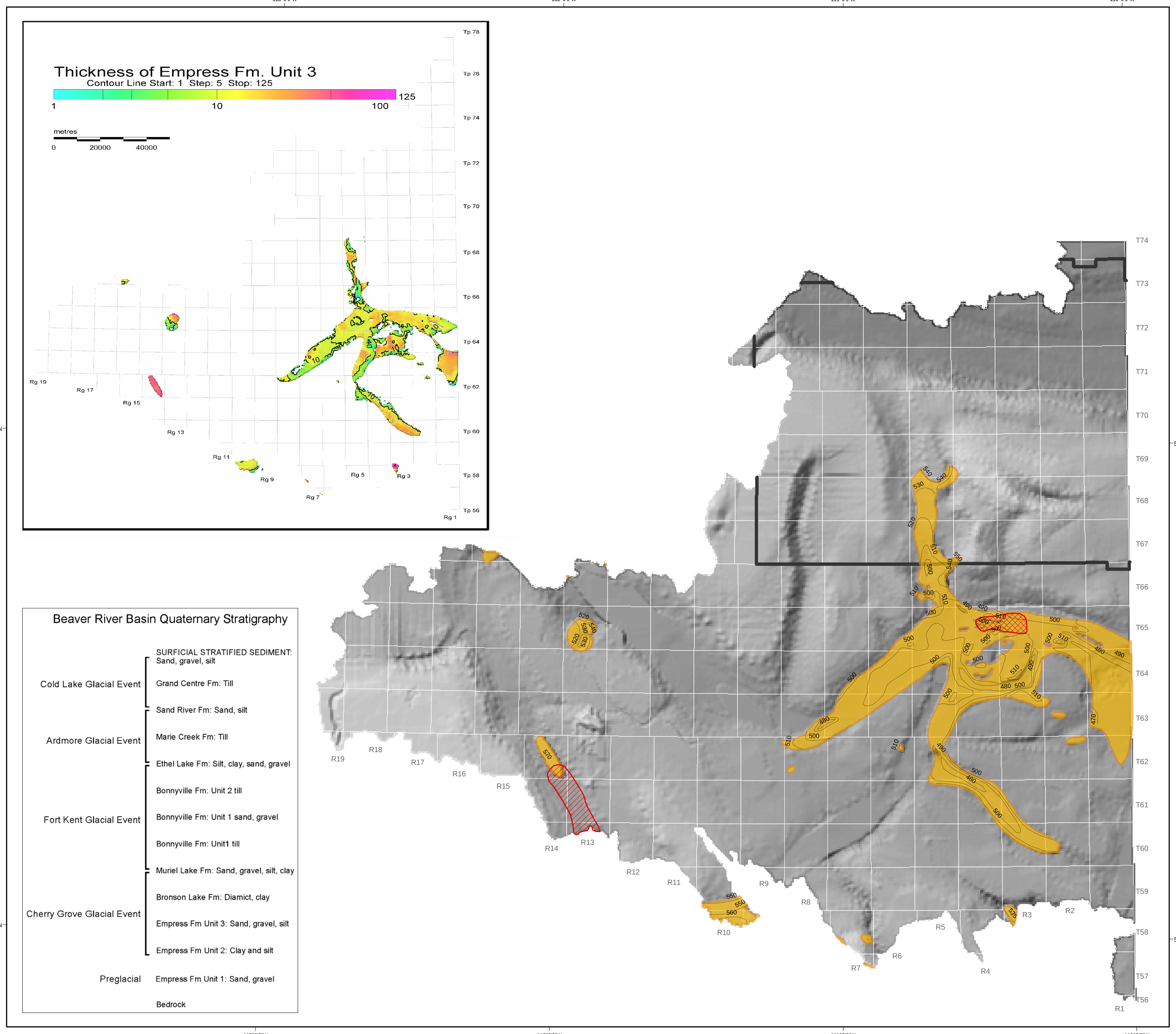
Cold Lake Air Weapons Range Boundary

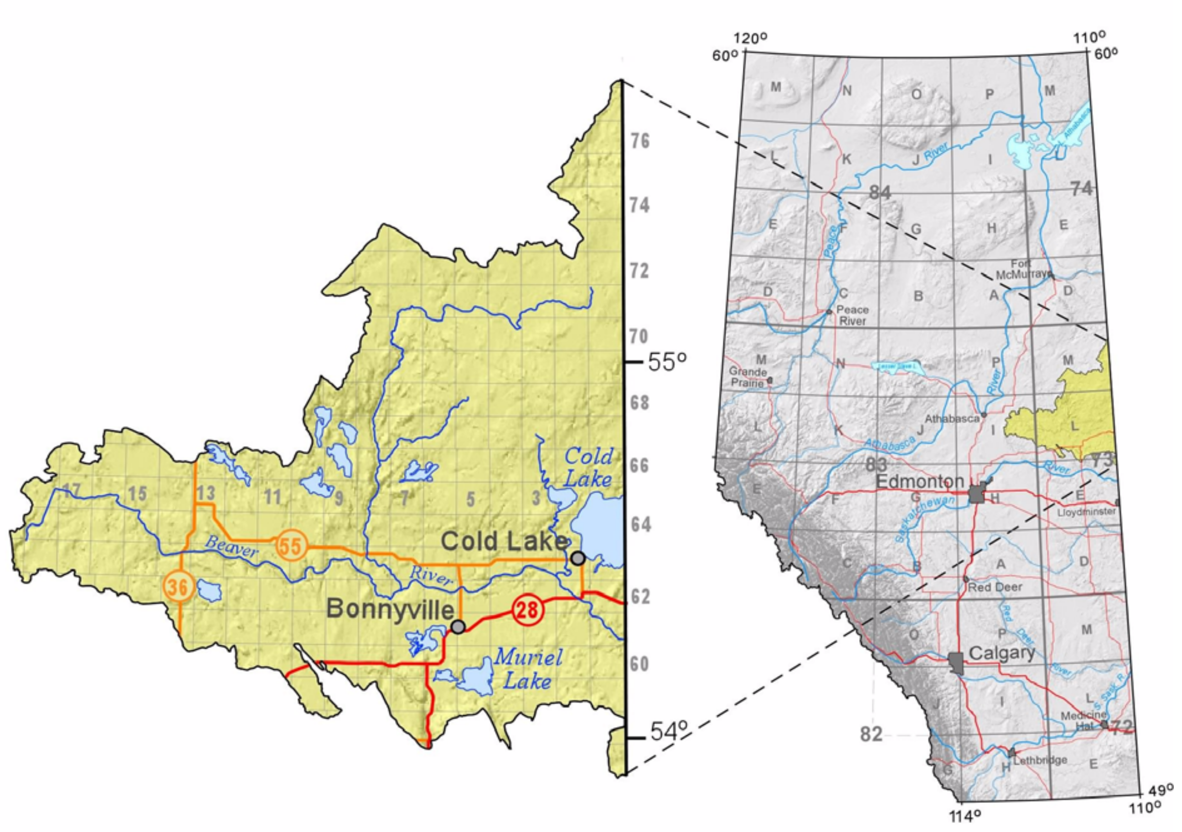
## Figure 3.8 Distribution and structural elevation of Empress Fm. Unit 2 clay and silt deposits

Alberta Environment

EUB Alberta Energy and Utilities Board

AGS Alberta Geological Survey




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

December, 2004

**Geological Sediments**

Sand, gravel, silt

Displaced bedrock - area of thick, glacially displaced Belly River Fm.

Deformed stratigraphy - area of glacially faulted and folded Quaternary strata

**Digital Elevation Model Values**

High: 660

Low: 390

Cold Lake Air Weapons Range Boundary

**Figure 3.9 Distribution and structural elevation of Empress Fm. Unit 3 glacial stratified deposits**

Alberta Environment

EUB Alberta Energy and Utilities Board

AGS Alberta Geological Survey

Where the Empress Fm. Unit 2 is absent, Empress Fm. Unit 1 and Empress Fm. Unit 3 sands and gravels are distinguished by the presence of metamorphic and igneous grains in the Empress Fm. Unit 3. The Empress Fm. Unit 2 is mapped as a regionally continuous blanket where it exists on Figure 3.8. However, it is not unreasonable to expect that downward scour associated with deposition of the Empress Fm. Unit 3 created local holes in the Empress Fm. Unit 2, thereby creating direct hydraulic pathways from the Empress Fm. Unit 1 to the Empress Fm. Unit 3 through sand-on-sand contacts.

In terms of genesis, the Empress Fm. Unit 1 is interpreted to be the fluvial sand and gravels of an eastward flowing drainage system of preglacial age. The Empress Fm. Unit 2 is interpreted to be fluvial-lacustrine silts and clays that may have been deposited throughout the valley system as drainage was blocked by a downstream early ice-advance. The Empress Fm. Unit 3 represents renewed drainage but includes ice-derived sediment clasts from the Canadian Shield brought south by the advancing glaciers and remobilized by meltwaters confined to the valley system.

### 3.3.2 Bronson Lake Formation

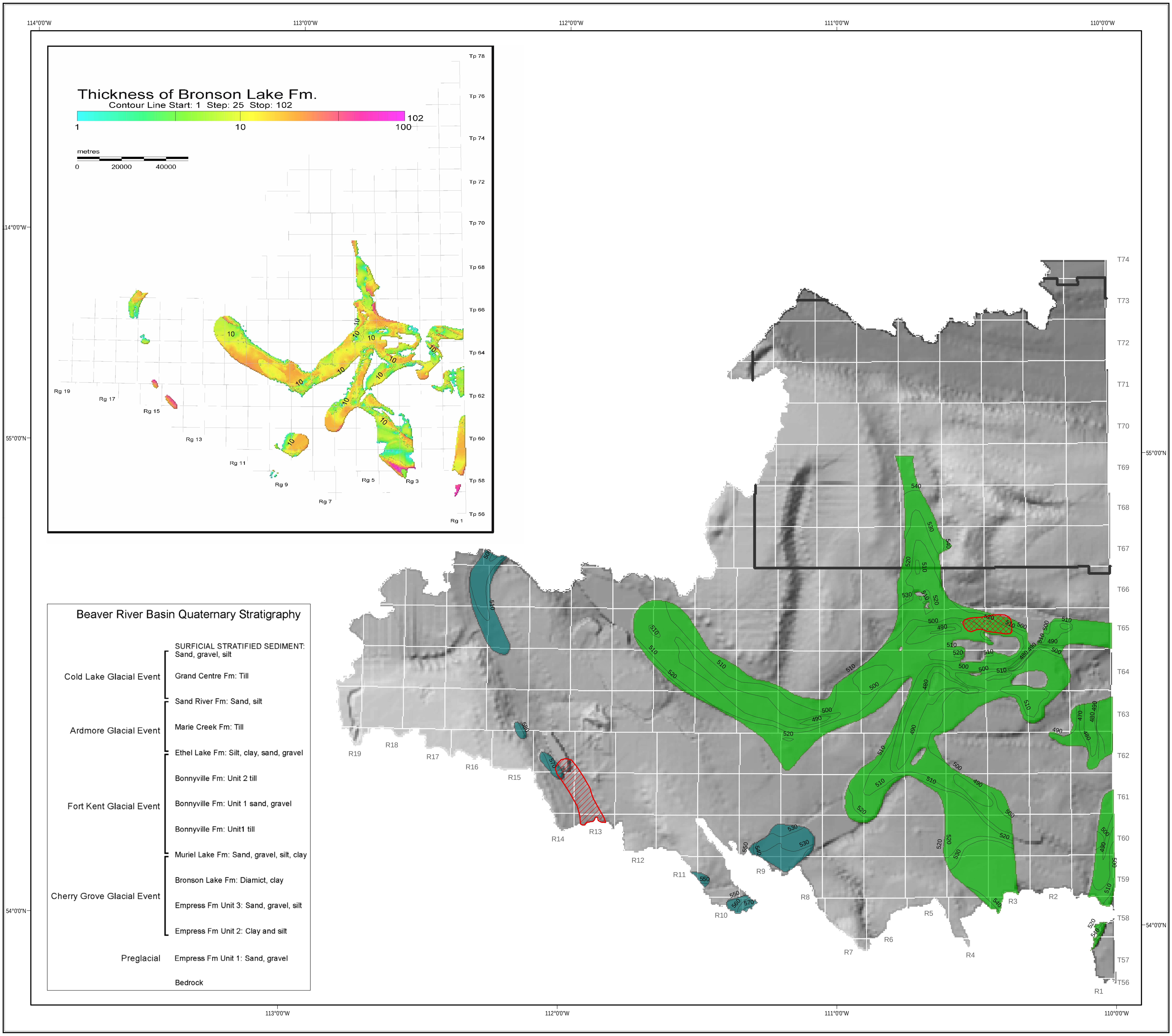
The Bronson Lake Formation is glacial till (or diamict) and diamict mixed with clay. Its areal distribution is shown in Figure 3.10. Like the underlying Empress, the Bronson Lake is mainly confined to the buried preglacial valleys but offlaps some of the valley margins onto higher bedrock elevations. In terms of genesis, the Bronson Lake Formation was formed by the advance and subsequent in-place melt of an ice margin. The Bronson Lake Formation is enriched in clay because the originating ice-sheet would have had much opportunity to have been in direct contact with local shale bedrock.

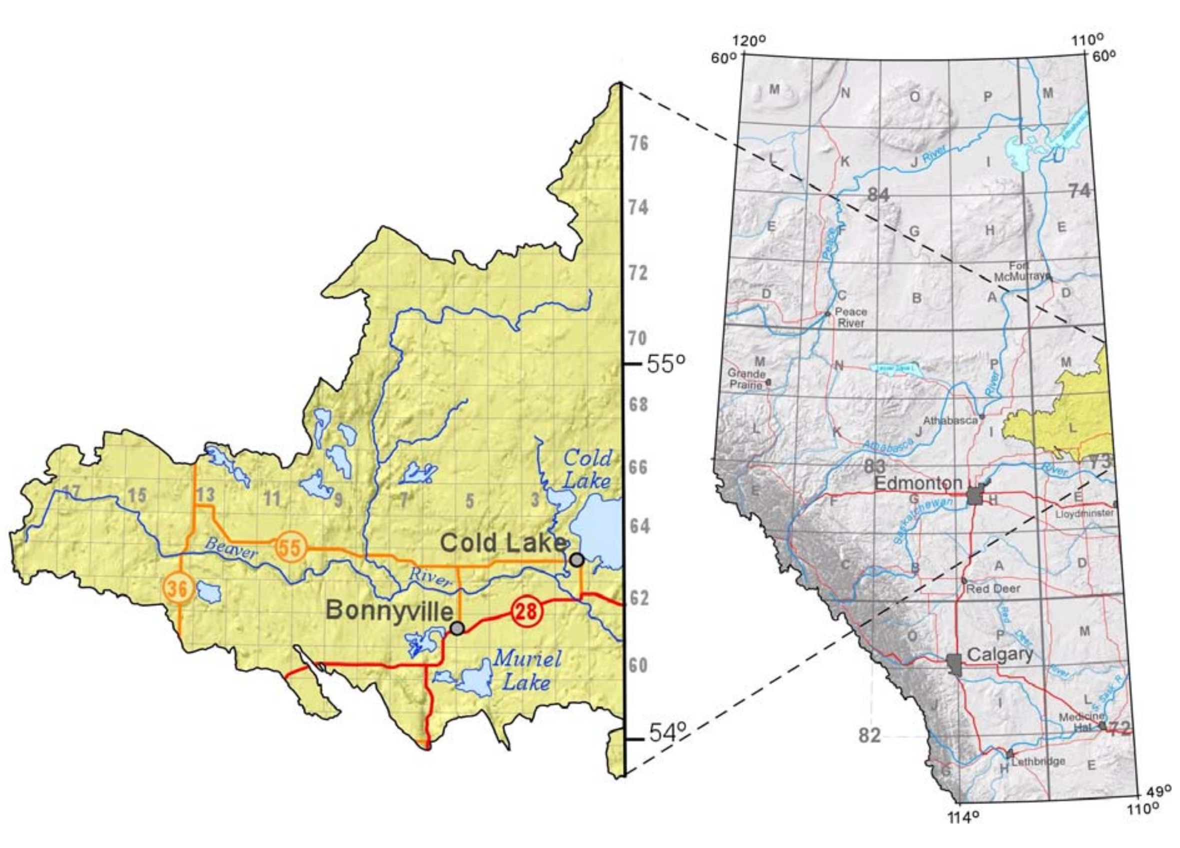
### 3.3.3 Muriel Lake Formation

The Muriel Lake Formation is silt, sand and gravel of glaciofluvial origin. Its distribution is shown in Figure 3.11. The Muriel Lake Formation generally follows the bedrock valleys but like the underlying Bronson Lake Formation, it extends beyond the mapped valley walls. This indicates that during Muriel Lake time, the buried valleys were no longer walled valleys but were still subdued topographic lows that focussed drainage of interglacial meltwaters. Where tills of the underlying Bronson Lake Formation are absent, Empress Fm. Unit 3 is not distinguished and all sand and gravel deposits are mapped together as the Muriel Lake Formation.

### 3.3.4 Bonnyville Formation

The Bonnyville Formation is the first formation that, in its entirety, extends beyond the bounds of the buried valley system. That being said, the Bonnyville Formation has been subdivided into three units: the lowermost Bonnyville Fm. Unit 1 till that has an areal extent comparable to the underlying Muriel Lake Formation which shows influence of the buried valley morphologies (Figure 3.12); the medial Bonnyville Fm. Unit 1 sands and gravels which have an areal distribution generally restricted to the area of confluence of the Helina and Sinclair Valleys (Figure 3.13); and the areally widespread and thick uppermost Bonnyville Fm. Unit 1I till (Figure 3.14). The Bonnyville Fm. Unit 2 till has a much higher proportion of coarse sand than does the underlying Bonnyville I till or the clay-rich Bronson Lake Formation till, though it does become increasingly more clay-rich to the west. The Bonnyville Fm. Unit 2 till forms the core of the Moostoos Upland and thus influenced the depositional extent of water-borne units that came after.




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

**Geological Sediments**

- Diamict (till?)
- Diamict and clay
- Displaced bedrock - area of thick, glacially displaced Belly River Fm.
- Deformed stratigraphy - area of glacially faulted and folded Qauternary strata

**Digital Elevation Model Values**

High: 660

Low: 390 (masl)

Cold Lake Air Weapons Range Boundary

December, 2004

# Figure 3.10 Distribution and structural elevation of Bronson Lake Fm. diamict and clay

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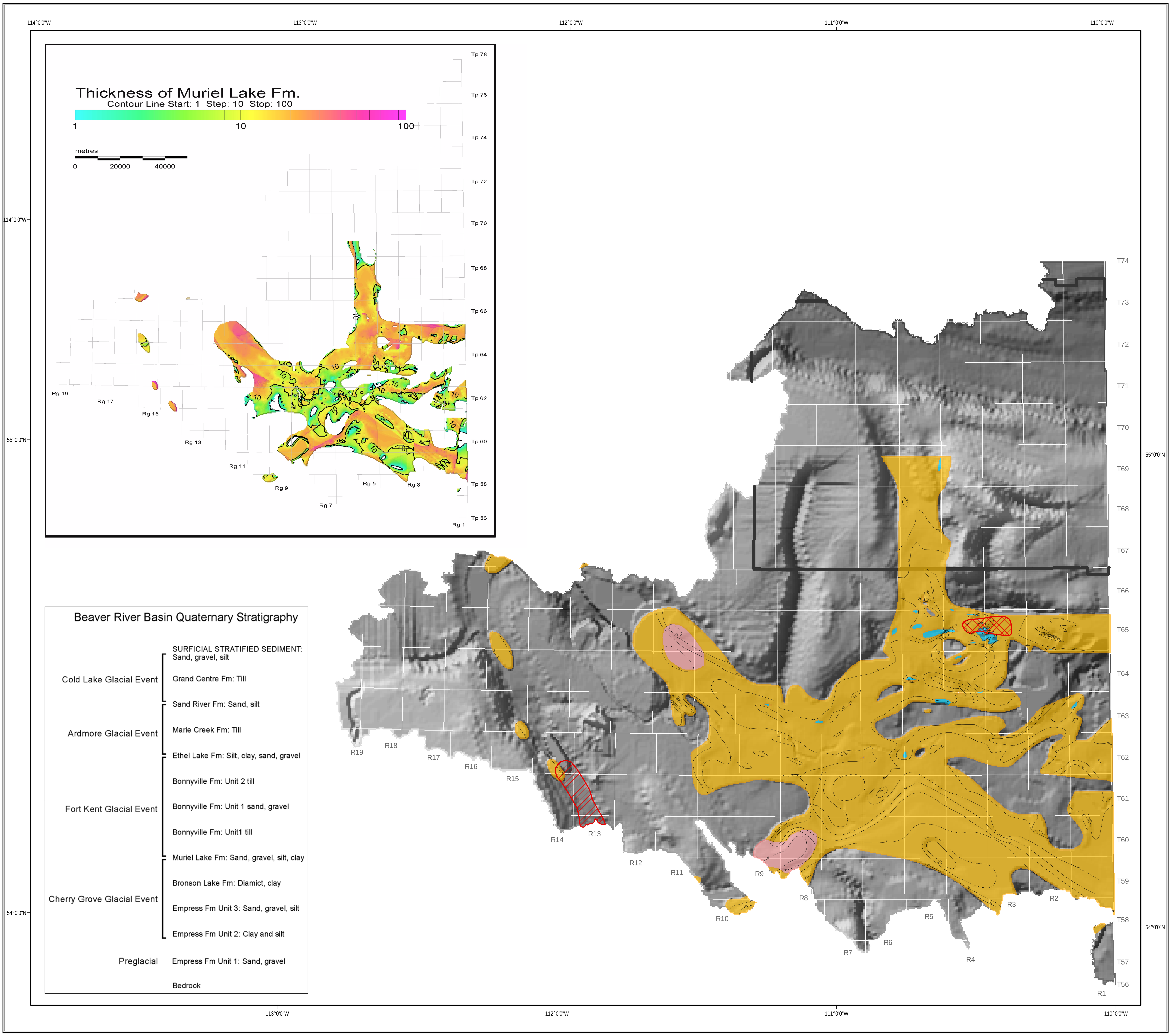


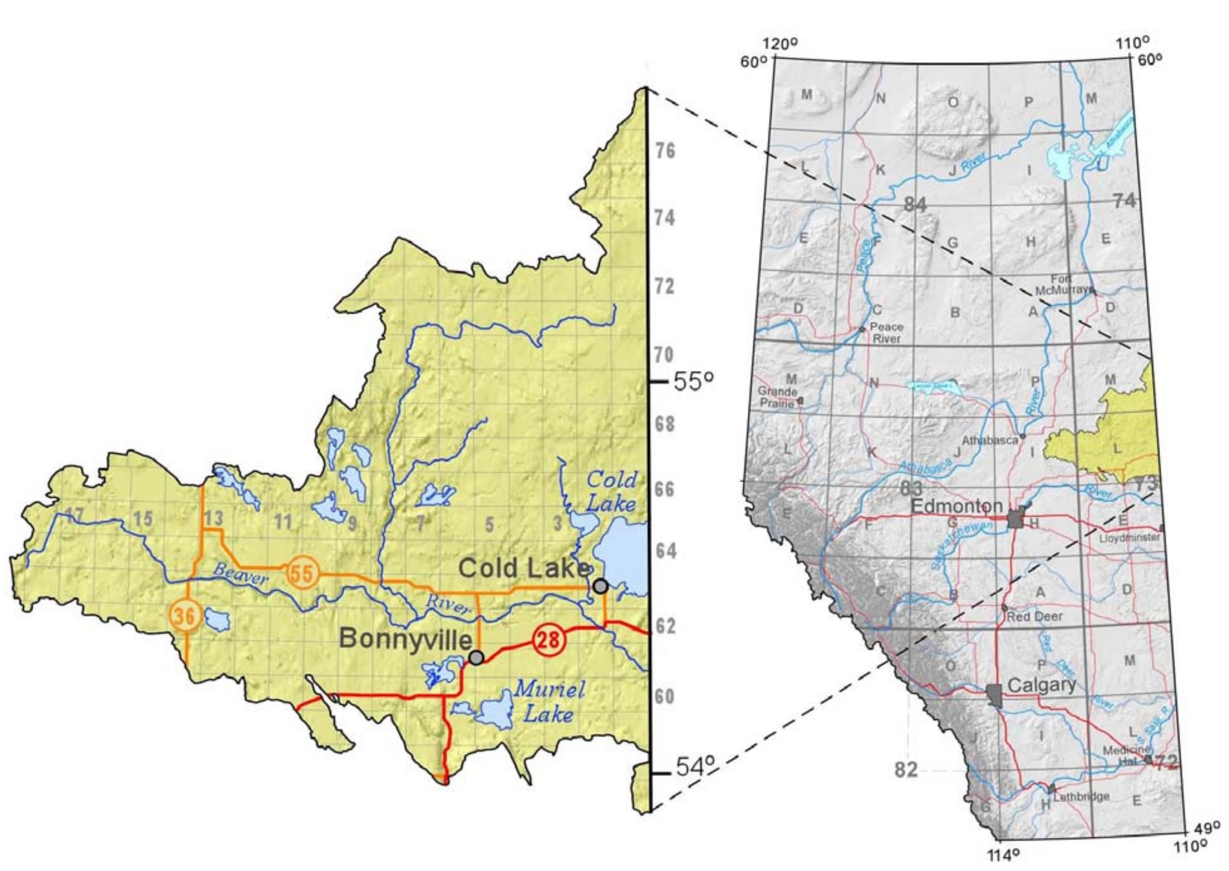


Scale 1:501834

5 0 5 10 15 20 25 30 Kilometres

5 0 5 10 15 20 25 30 Miles

Projection: UTM Zone 12
Datum: NAD83

December, 2004

**Geological Sediments**

- Silt and clay interbedded with sand
- Clay, silt, sand and gravel
- Sand, sand and gravel

Cold Lake Air Weapons Range Boundary

**Digital Elevation Model Values**

High: 660

Low: 390 (masl)

Displaced bedrock - area of thick, glacially displaced Belly River Fm.

Deformed stratigraphy - area of glacially faulted and folded Quaternary strata

# Figure 3.11 Distribution and structural elevation of Muriel Lake Fm. glacial stratified deposits

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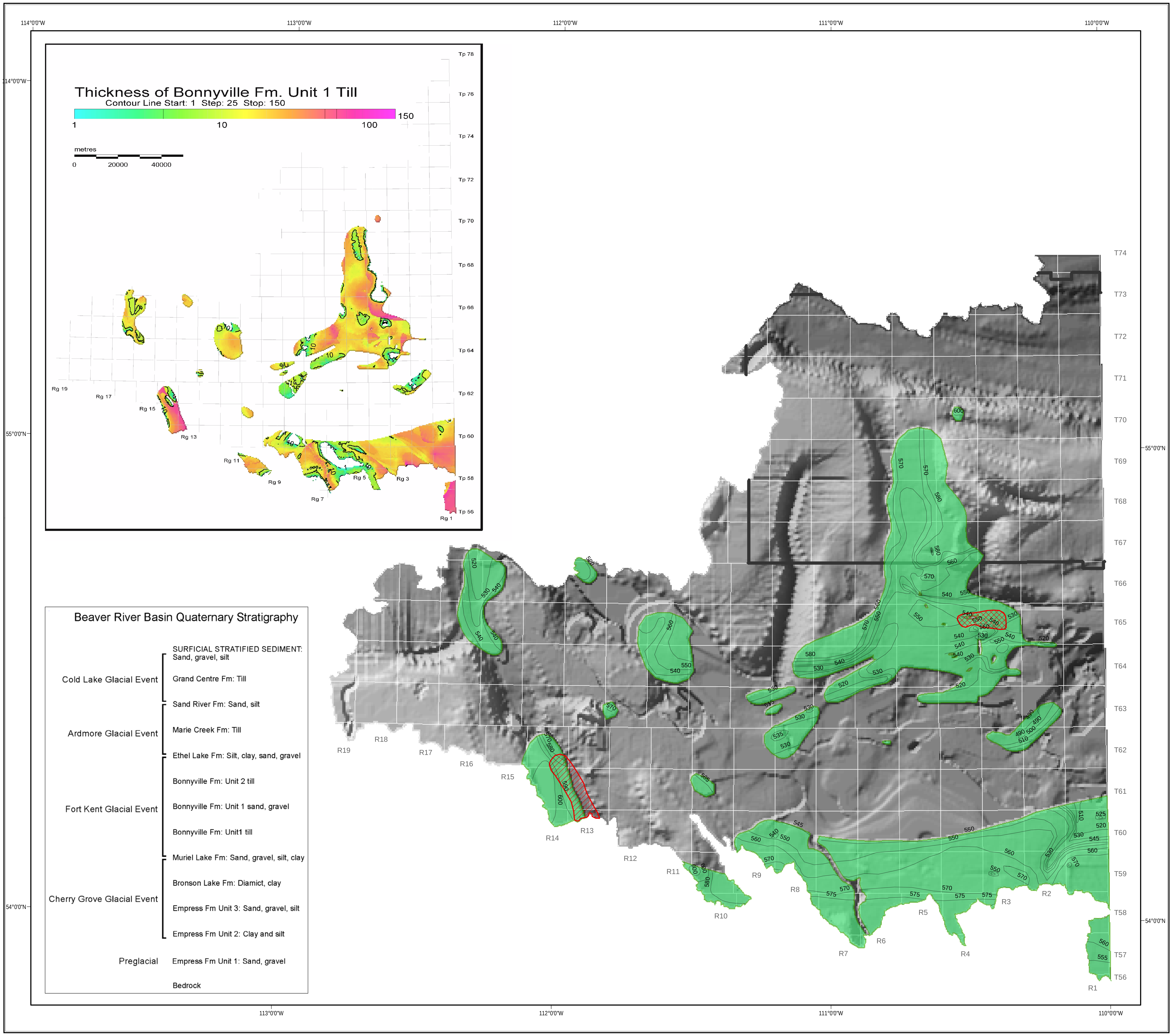
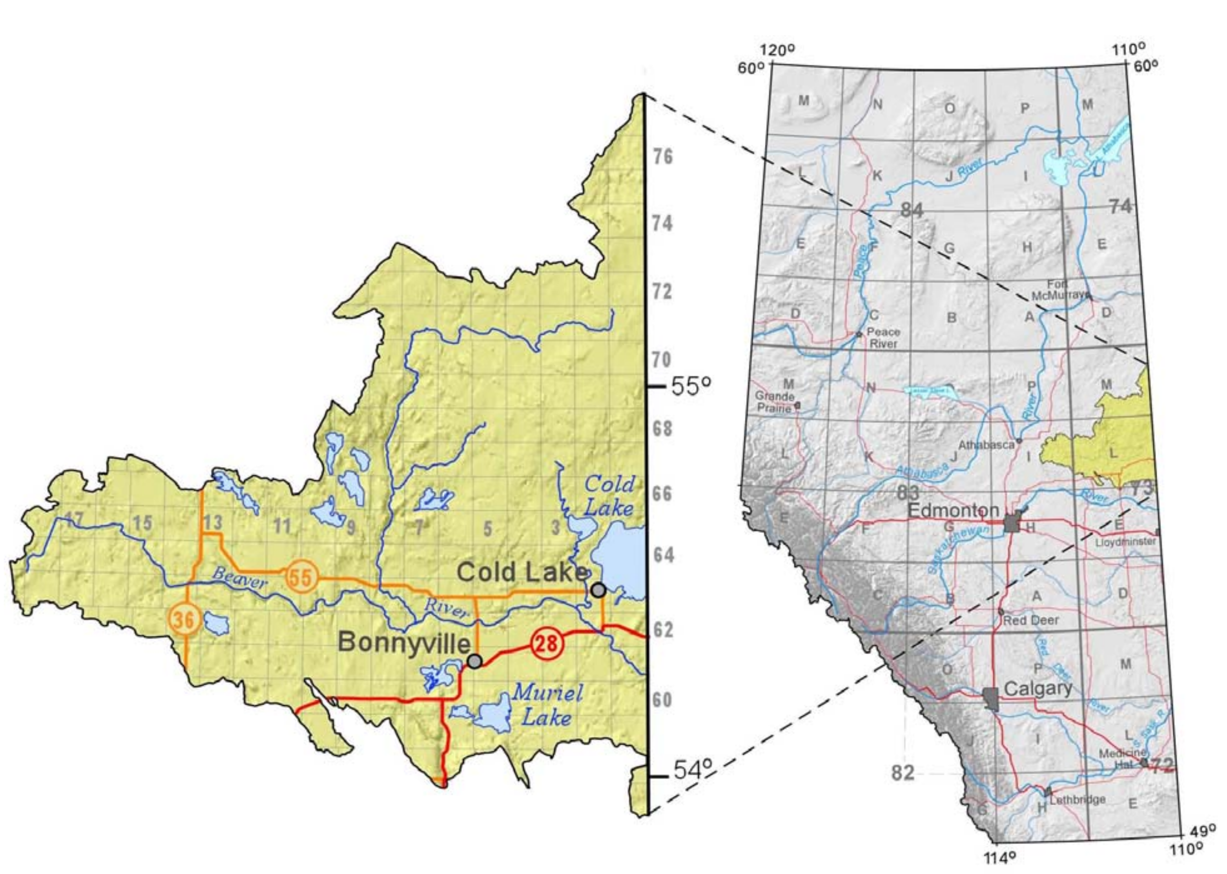
AGS Alberta Geological Survey




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

December, 2004

**Geological Sediments**

Clay-rich till

Displaced bedrock - area of thick, glacially displaced Belly River Fm.

Deformed stratigraphy - area of glacially faulted and folded Quaternary strata

**Digital Elevation Model Values**

High: 660

Low: 390 (masl)

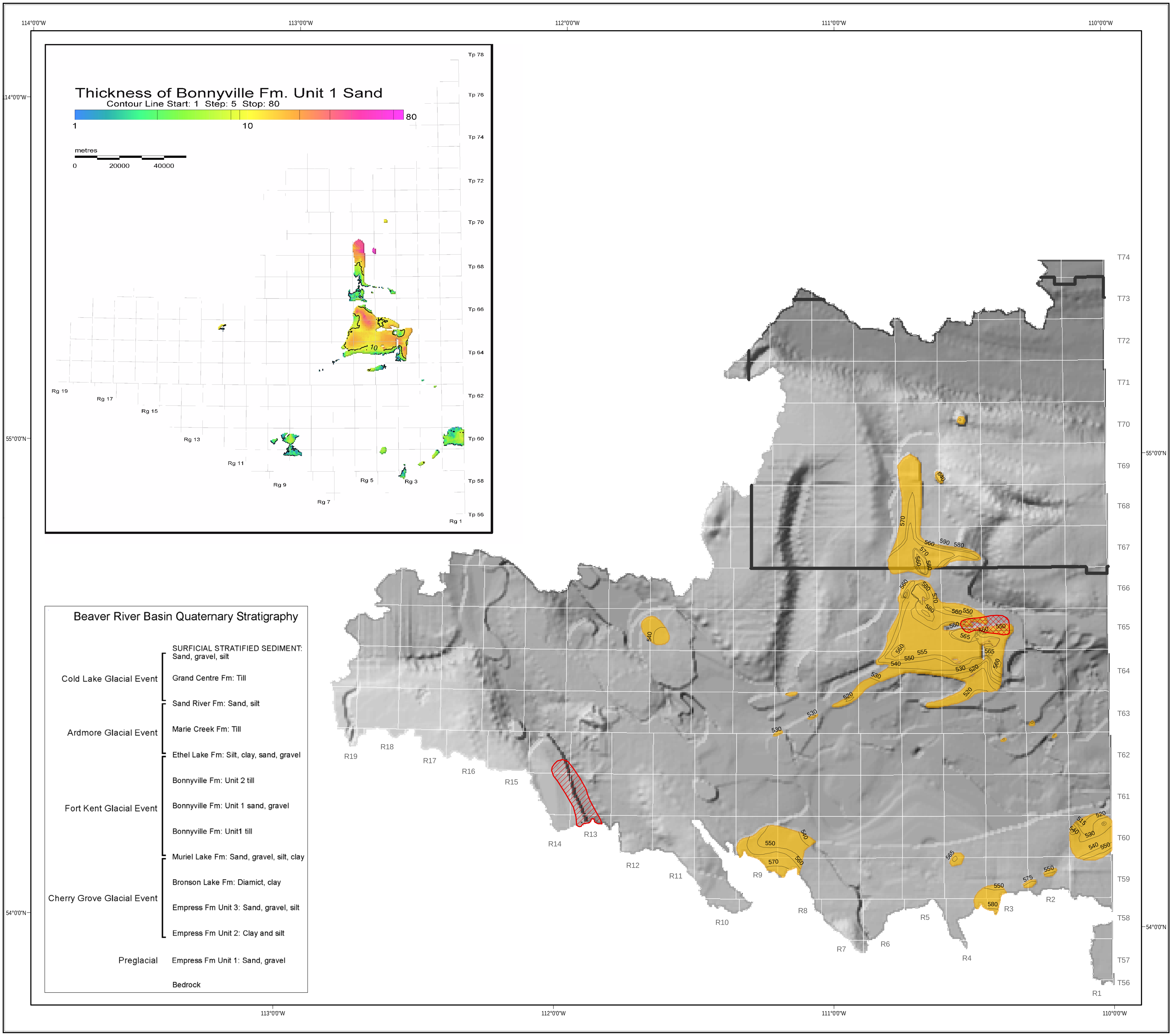
Cold Lake Air Weapons Range Boundary

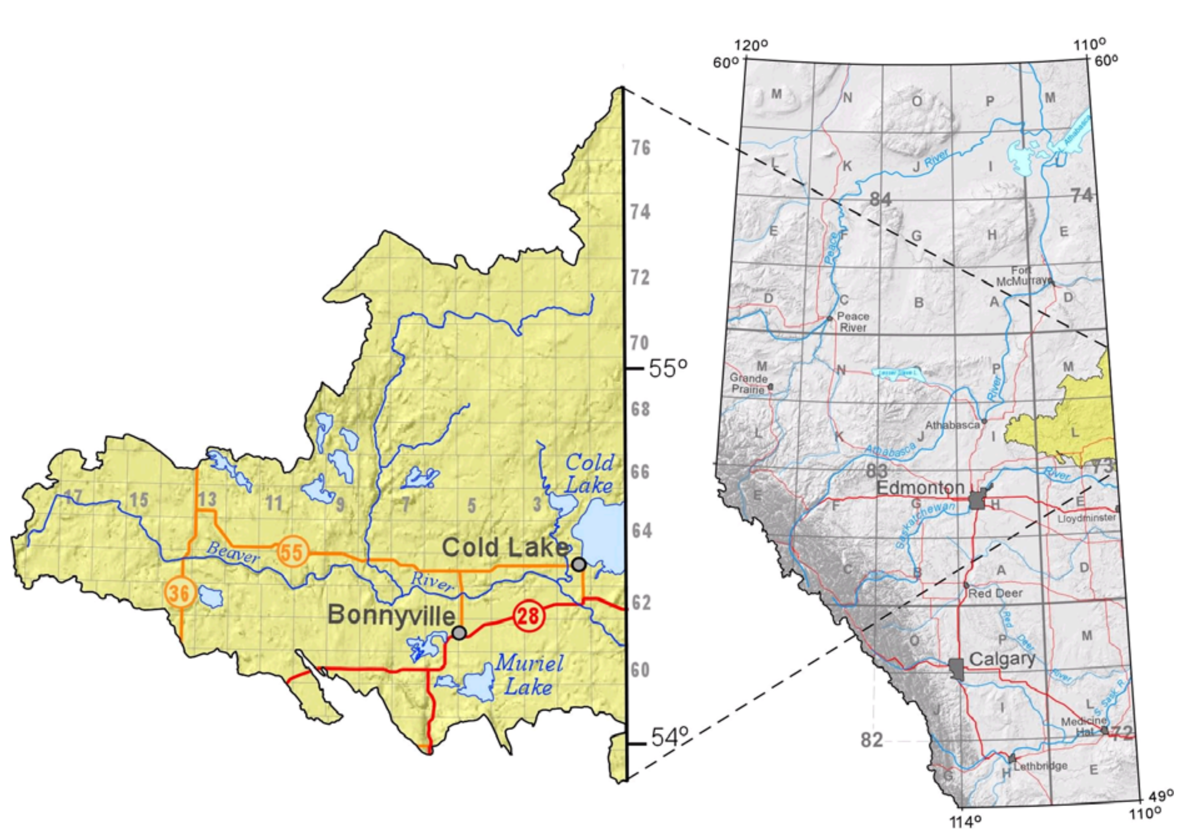
**Figure 3.12 Distribution and structural elevation of Bonnyville Fm. Unit 1 glacial deposits**

Alberta Environment

EUB Alberta Energy and Utilities Board

AGS Alberta Geological Survey




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

December, 2004

**Geological Sediments**

Sand, sand and gravel

Displaced bedrock - area of thick, glacially displaced Belly River Fm.

Deformed stratigraphy - area of glacially faulted and folded Quaternary strata

**Digital Elevation Model Values**

High: 660

Low: 390 (masl)

Cold Lake Air Weapons Range Boundary

## Figure 3.13 Distribution and structural elevation of Bonnyville Fm. Unit 1 glacial sand and gravel deposits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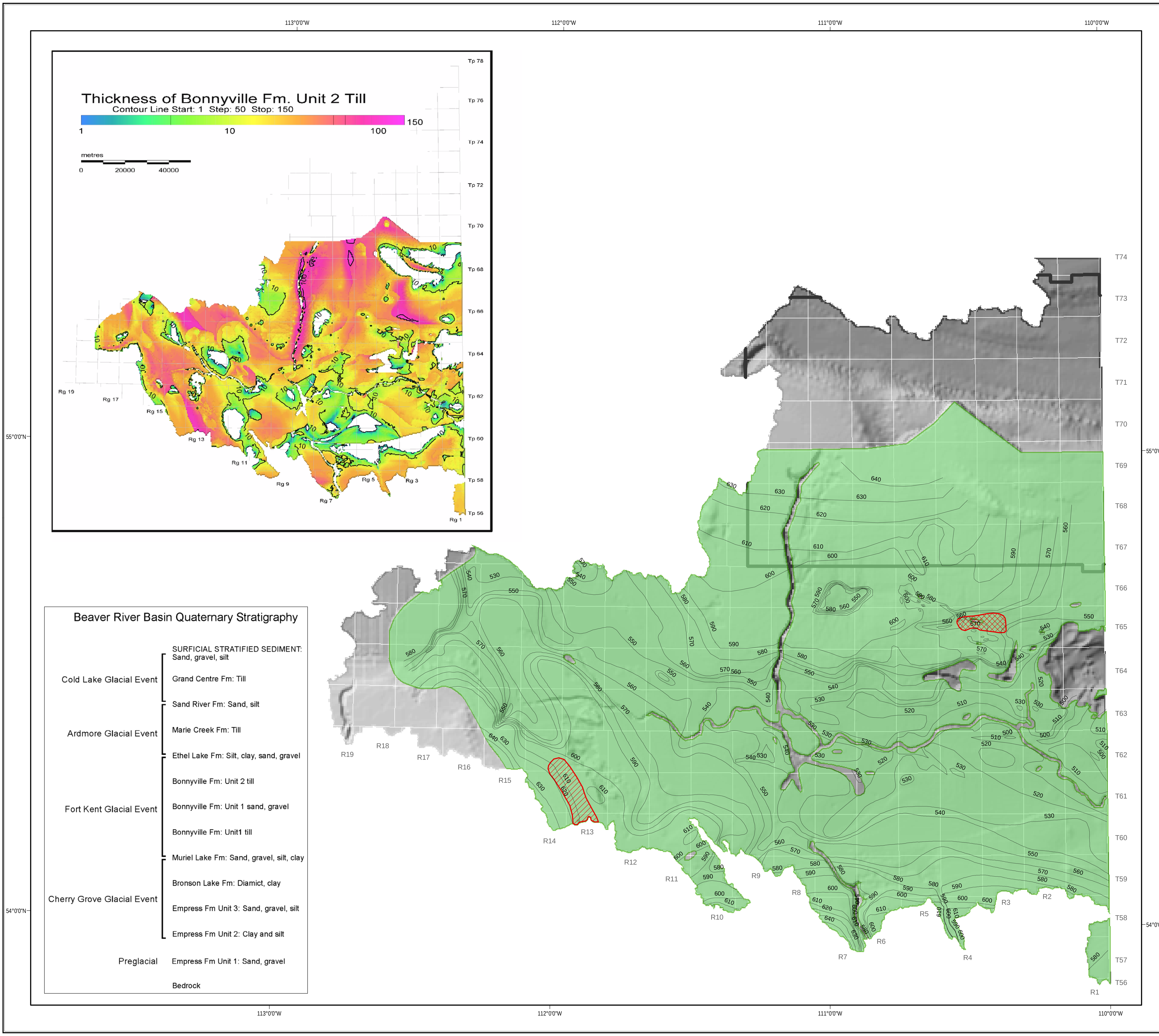
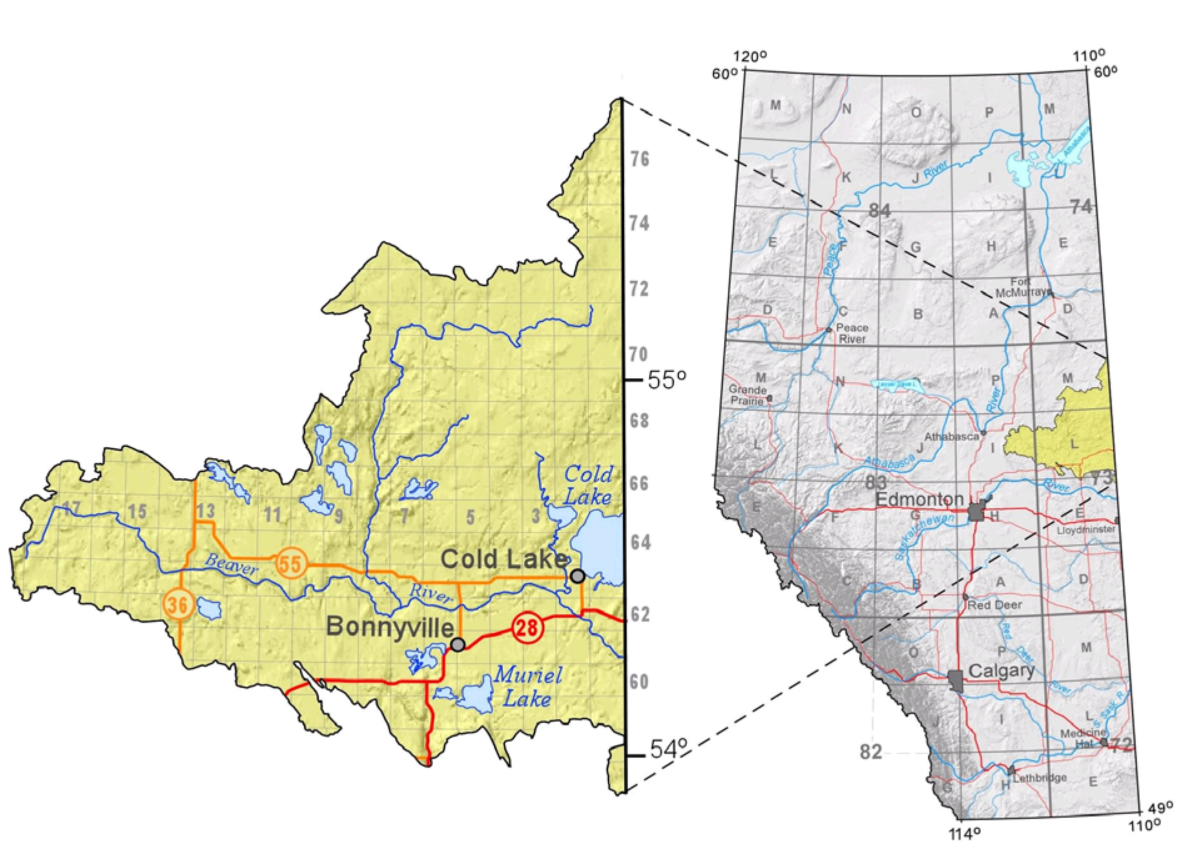
EUB Alberta Energy and Utilities Board
AGS Alberta Geological Survey




Scale 1:500000

5 0 5 10 15 20 25 30 Kilometres

5 0 5 10 20 25 30 Miles

Projection: UTM Zone 12
Datum: NAD83

December, 2004

**Geological Sediments**

Till

Displaced bedrock - area of thick, glacially displaced Belly River Fm.

Deformed stratigraphy - area of glacially faulted and folded Quaternary strata

**Digital Elevation Model Values**

High: 660

Low: 390 (masl)

Cold Lake Air Weapons Range Boundary

# Figure 3.14 Distribution and structural elevation of Bonnyville Fm. Unit 2 glacial deposits

Alberta Environment

EUB Alberta Energy and Utilities Board

AGS Alberta Geological Survey

### 3.3.5 Ethel Lake Formation

The Ethel Lake Formation consists of silt and clay with smaller amounts of sand and gravel. Andriashek and Fenton (1989) interpret it to be of glaciofluvial origin and note that Ethel Lake Formation tends to be associated with isopach thins in the underlying Bonnyville Formation, attesting to regional erosion associated with Ethel Lake deposition. It is found primarily in the south and central parts of the Cold Lake-Beaver River Basin (Figure 3.15) in a drainage basin whose northern limit is defined by the Moostoos Upland.

### 3.3.6 Marie Creek Formation

The Marie Creek Formation consists of till characterized by a very coarse sand-fraction rich in calcareous fragments. The calcareous nature of the Marie Creek Formation is presumed to reflect entrainment of exposed limestone and dolostone bedrock-formations exhumed up-ice by previous glacial advances. The Marie Creek Formation is found over most of the Cold Lake-Beaver River Basin except in the Whitefish Upland area in the southwest (Figure 3.16).

### 3.3.7 Sand River Formation

The Sand River Formation is a stratified sand and gravel formation of glaciofluvial origin. The distribution of the Sand River Formation is shown in Figure 3.17. Like the Ethel Lake Formation, the Sand River Formation is areally restricted to the region south of the Moostoos Upland.

### 3.3.8 Grand Centre Formation and Recent Sediments

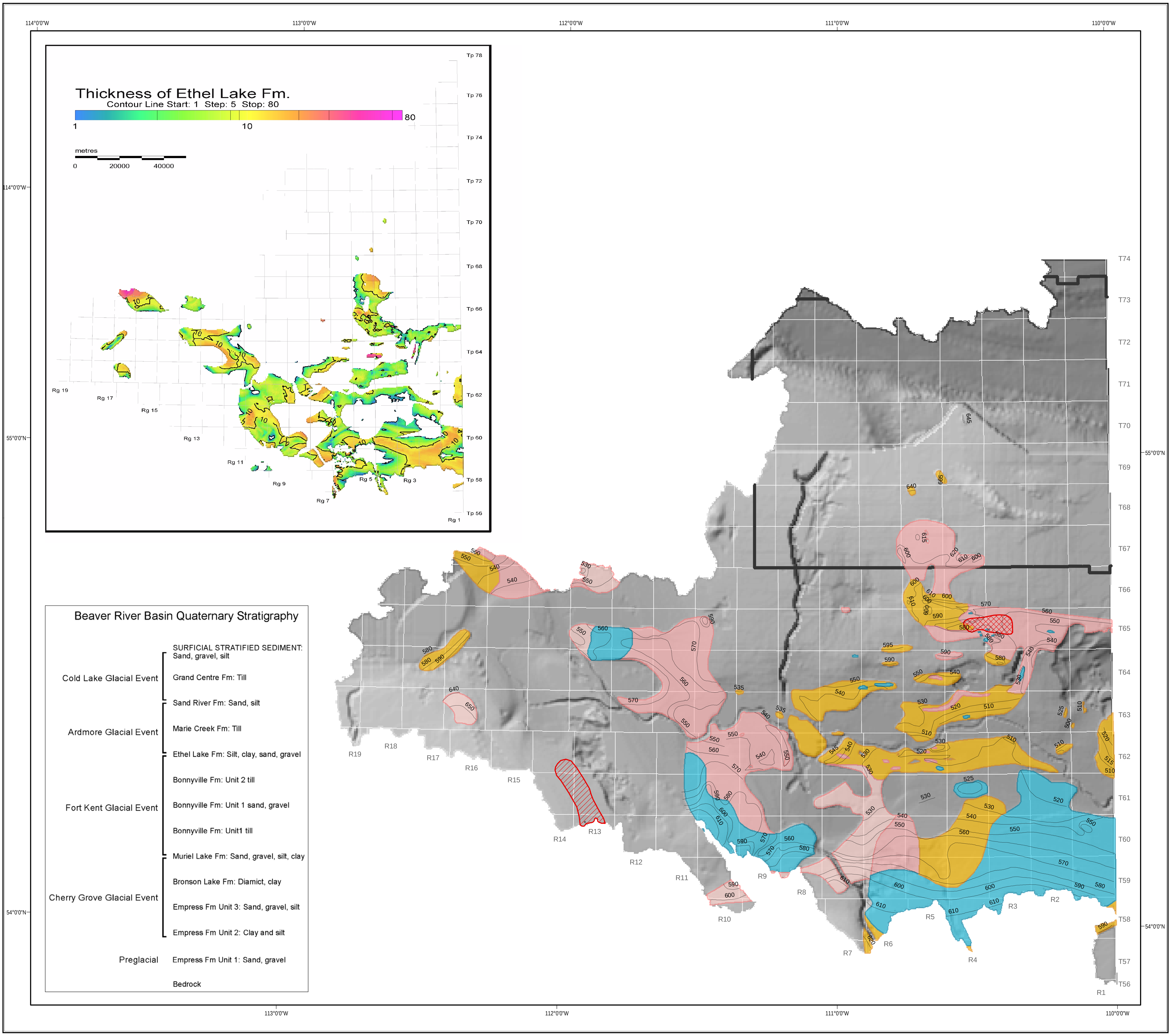
The Grand Centre Formation is the uppermost drift formation in the Cold Lake-Beaver River Formation and extends completely across the area. The Grand Centre Formation is predominantly a till but has locally mappable sand and gravel units within. Its areal distribution is shown in Figure 3.18. The distribution of coarse surficial sediments of Recent origin is also shown on Figure 3.18, mostly being confined to the stream courses of modern rivers and streams. Of particular hyrogeological note is the thick accumulation of sand of presumably Recent age extending from surface to bedrock along the Sand River Channel.

### 3.3.9 Vertical Relationships in Drift Stratigraphy and Local Predictions of Aquifer Quality

The formations discussed above were identified and mapped as distinct regional lithological units on the basis of mineralogy and grain-size. However these units can also be grouped into larger stratigraphic units that reflect their origin as part of a cyclical process. Such a stratigraphic framework is sometimes called a genetic stratigraphy because it groups strata on the basis of their genesis.

The advantage to a genetic-straigraphic approach is that the distribution and connectivity of otherwise unmappable local-scale aquifers become predictable on the basis of their vertical stratigraphic position within the regionally mappable units.

The key to constructing a regional genetic stratigraphy in sedimentary successions is to find regionally correlatable geological markers that essentially represent instantaneous events. In continental glacial successions, highly clay-enriched basal tills are used as such markers (Bleuer, 1999). These beds represent the initial and presumably rapid advance of an ice sheet across the landscape and are relatively





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

December, 2004

**Geological Sediments**

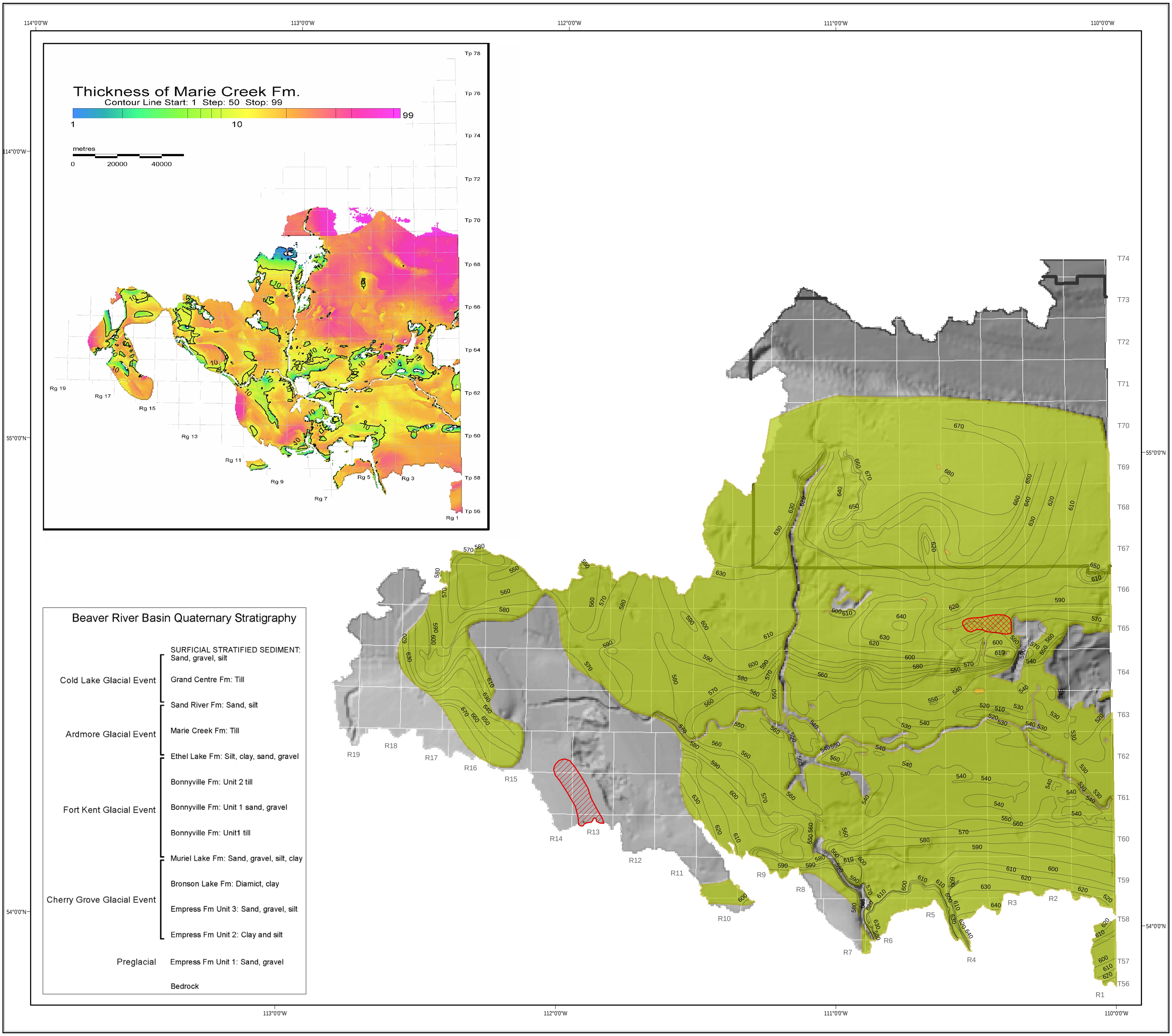
- Clay, silt and clay
- Sand and silt
- Silt, clay, sand and gravel
- Sand, sand and gravel
- Cold Lake Air Weapons Range Boundary

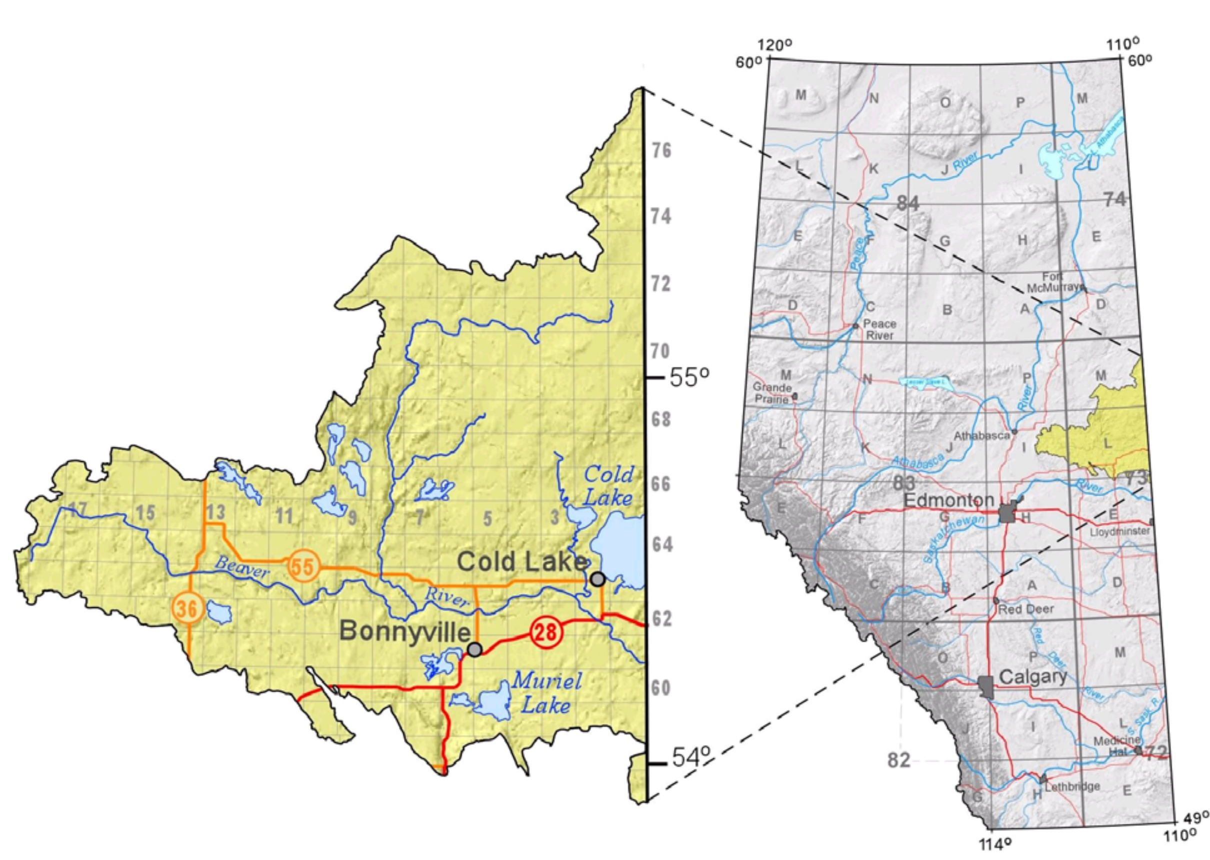
**Digital Elevation Model Values**

- High: 660
- Low: 390 (masl)
- Displaced bedrock - area of thick, glacially displaced Belly River Fm.
- Deformed stratigraphy - area of glacially faulted and folded Quaternary strata

**Figure 3.15 Distribution and structural elevation of Ethel Lake Fm. glacial stratified deposits**

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




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

December, 2004

**Geological Sediments**

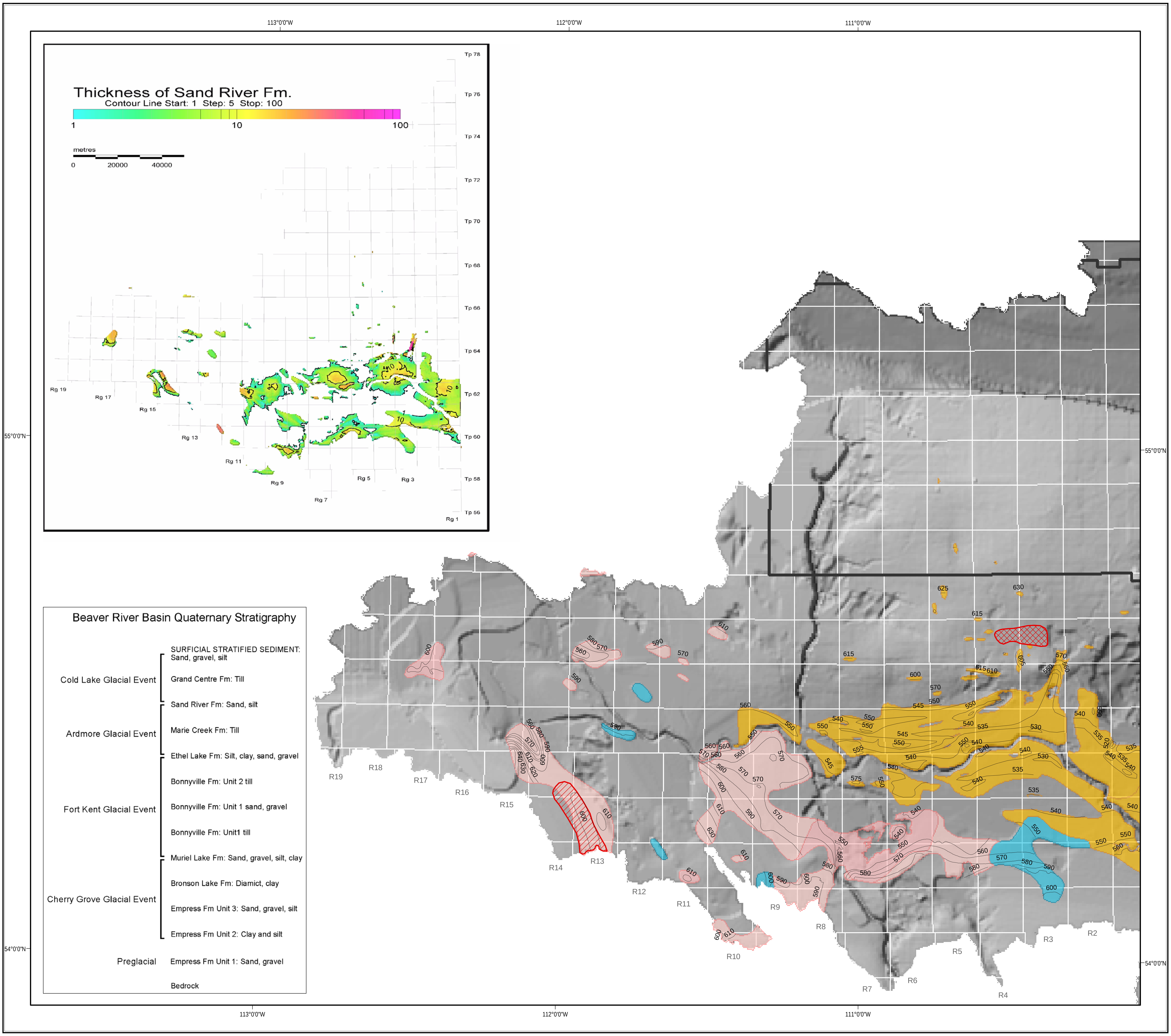
- Till
- Thick (> 1m) sand bodies within till
- Displace bedrock - area of thick, glacially displaced Belly River Fm.
- Deformed stratigraphy - area of glacially faulted and folded Quaternary strata

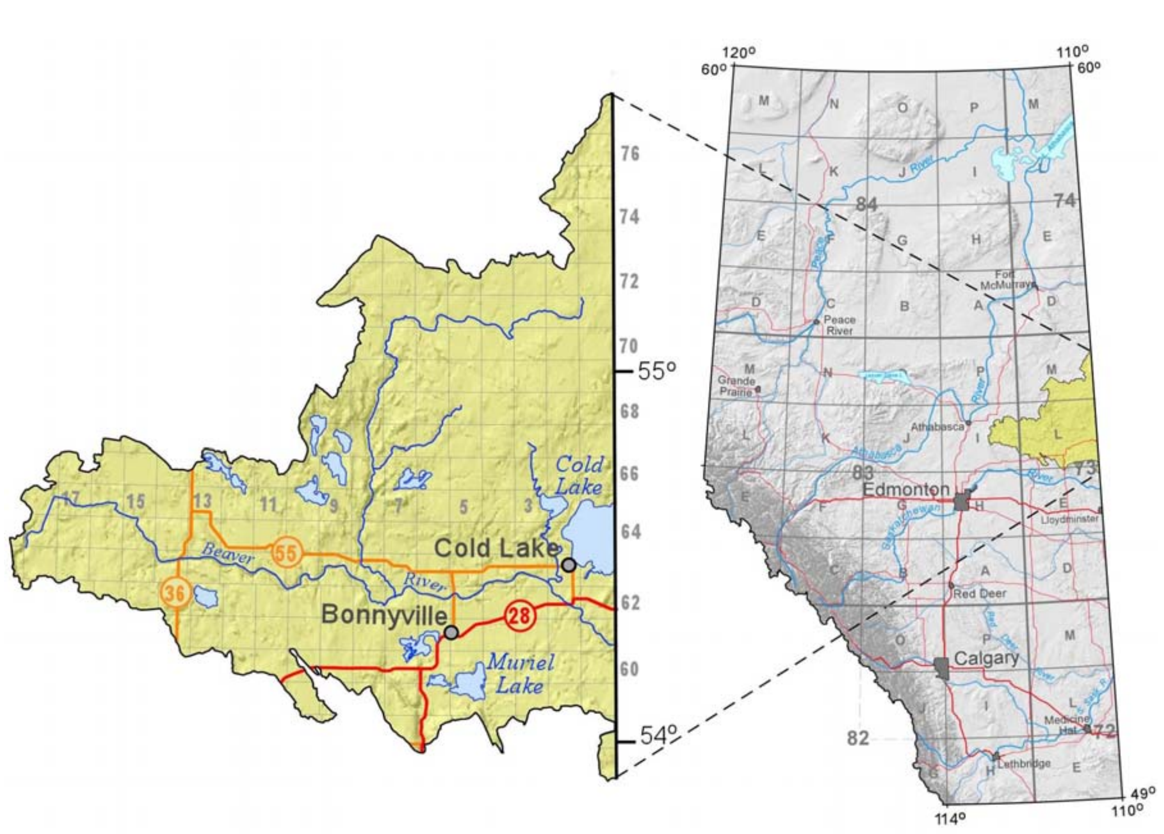
**Digital Elevation Model Values**

- High: 680
- Low: 390 (masl)
- Cold Lake Air Weapons Range Boundary

# Figure 3.16 Distribution and structural elevation of Marie Creek Fm. glacial deposits

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




Scale 1:500944

5 0 5 10 15 20 25 30 Kilometres

5 0 5 10 15 20 25 30 Miles

Projection: UTM Zone 12
Datum: NAD83

December, 2004

**Geological Sediments**

- Clay, silt and clay
- Sand and silt
- Silt, clay, sand and gravel
- Sand, sand and gravel
- Cold Lake Air Weapons Range Boundary

**Digital Elevation Model Values**

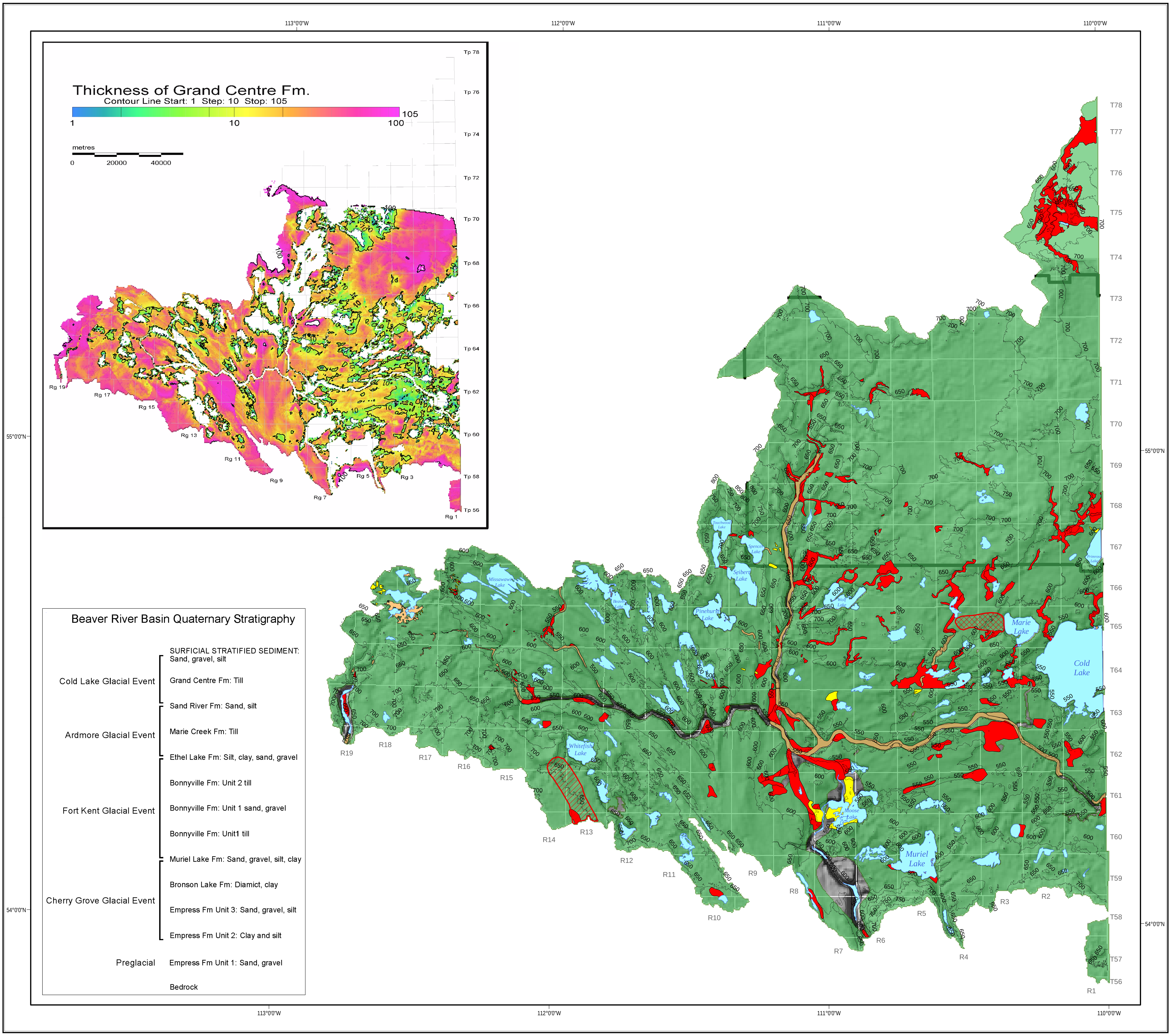
High: 700

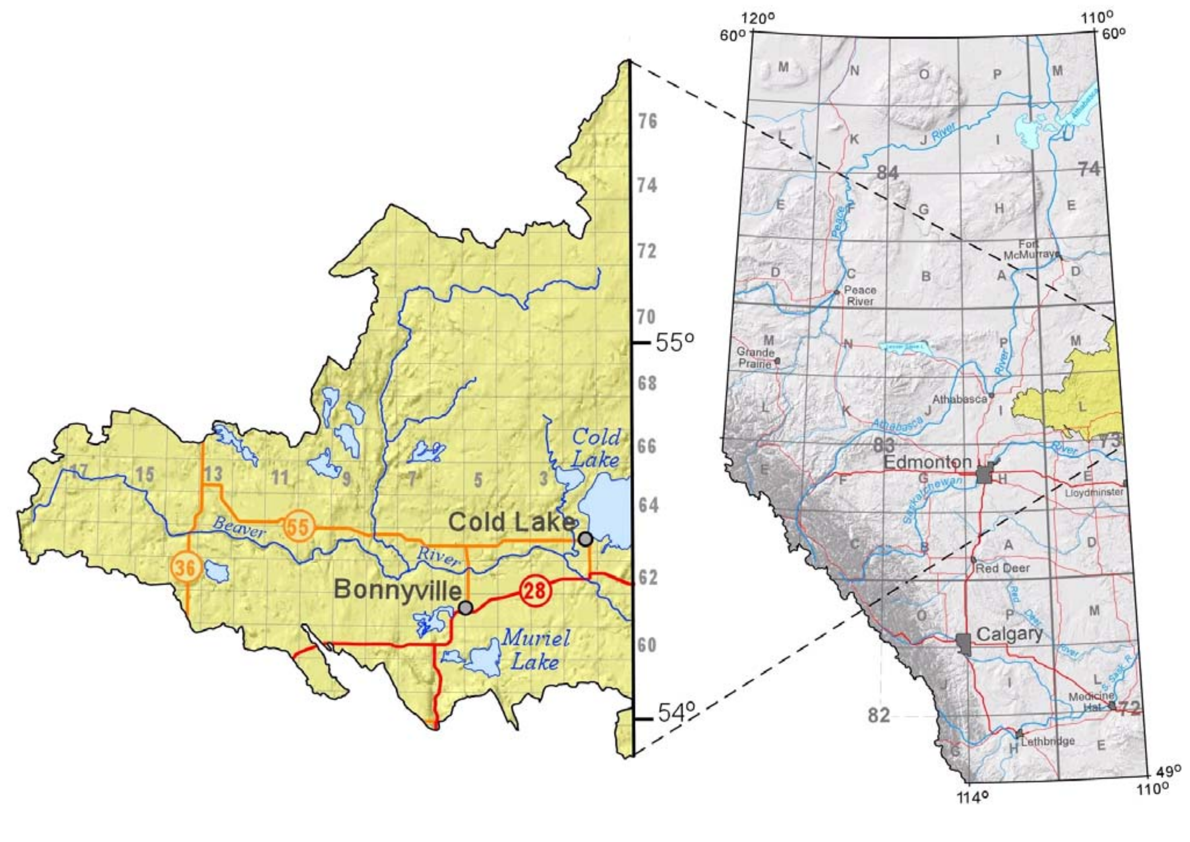
Low: 390 (masl)

- Displaced bedrock - area of thick, glacially displaced Belly River Fm.
- Deformed stratigraphy - area of glacially faulted and folded Quaternary strata

**Figure 3.17 Distribution and structural elevation of Sand River Fm. glacial stratified deposits**

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




Scale 1:501063

5 0 5 10 15 20 25 30 Kilometres

5 0 5 10 15 20 25 30 Miles

Projection: UTM Zone 12
Datum: NAD83

December, 2004

**Geological Sediments**

- Till
- Eolian deposits
- Fluvial deposits
- Glaciofluvial deposits
- Glaciofluvial sand, fine
- Lake
- 50m contour interval
- Cold Lake Air Weapons Range Boundary

**Digital Elevation Model Values**

High: 860

Low: 430 (masl)

- Displaced bedrock - area of thick, glacially displaced Belly River Fm.
- Deformed stratigraphy - area of glacially faulted and folded Quaternary strata

# Figure 3.18 Distribution and structural elevation of Grand Centre Fm. till and postglacial fluvial deposits

Alberta Environment

EUB Alberta Energy and Utilities Board

AGS Alberta Geological Survey

easy to identify in boreholes or on logs because of their high clay enrichment. A single glacial genetic cycle is that period of time represented by the drift between one basal till to the next one above. During this period, the glacier advanced and retreated in a major way only once. Tills deposited above the basal till represent the deposits of stagnating and then increasingly receding ice margins. Because the amount of melting increases, the amount of water sorting increases and the tills become increasingly coarse-grained. Local advances and retreats of the ice-margin may leave very local-scale glaciofluvial and glaciolacustrine deposits.

At the end of the cycle, the glacier melts or recedes completely and all sediment entering the depositional basin in front of the glacier is sorted by wind and by currents and waves in meltwater rivers and lakes. This leads to more areally extensive sand and gravel deposits as well as larger lacustrine deposits. Glacial meltwater scours eroded deep into pre-existing sediments or into bedrock can form during this part of the cycle as large pools of meltwater form beneath or in front of the ice-sheet and are released catastrophically. The degree to which these meltwater scours can create vertical hydraulic conduits across till sheets is thought to be considerable, but their randomly episodic origin makes them impossible to map at a regional scale.

With sufficient time, the area becomes revegetated, soil horizons develop and a nonglacial fluviolacustrine landscape develops. The climax depositional assemblage atop a single glacial cycle can be quite varied and heterogeneous, as demonstrated by our modern landscape. When the next glacial period begins, the next advancing ice-sheet will erode much of the climax landscape assemblage and often leave only some or part of the coarse-grained meltout assemblage preserved beneath the next basal till.

In core and log profiles, this pattern is recognized by the presence of stacked coarsening-upward cycles (with respect to sediment grain-size) atop basal tills, variations in mineralogy between otherwise indistinguishable till sheets reflecting different up-ice sources of pre-till material, and the rare occurrence of buried paleo-soil horizons or their associated oxidized zones. The coarsening upward cycles are illustrated in Figure 3.19.

In terms of the lithostratigraphic units in the Cold Lake-Beaver River Basin, one can group the formations above the Empress Formation into the following glacio-genetic units from oldest to youngest: Bronson Lake-Muriel Lake; Bonnyville I till-Bonnyville I sand and gravel; Bonnyville Fm. Unit 2 till-Ethel Lake; Marie Creek-Sand River; and Grand Centre-Recent.

With respect to local aquifer and aquitard geometry and continuity, the most continuous aquitards will be those associated with basal tills and the lowermost parts of the till sheets of each glacio-genetic unit. The most continuous aquifers will be those in the sand and gravel deposits atop the till sheets and below the climax landscape assemblage (if preserved) or the next basal till (if not). 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. And glacial channels may or may not be aquifers, depending on whether they were backfilled with clay-rich till, sand-rich till, glaciolacustrine clay, or glaciofluvial sand and gravel.

## 3.4 Hydraulic Conductivity Estimates of Geological Materials

Hydraulic conductivity (K) is one measure of the ability of a geological material to pass flow under a hydraulic gradient. Regional estimates of K are needed to parameterize flow models such as the one discussed in Section 5 of this report. Local estimates of K are needed to ascertain deliverability and yield of individual water wells.

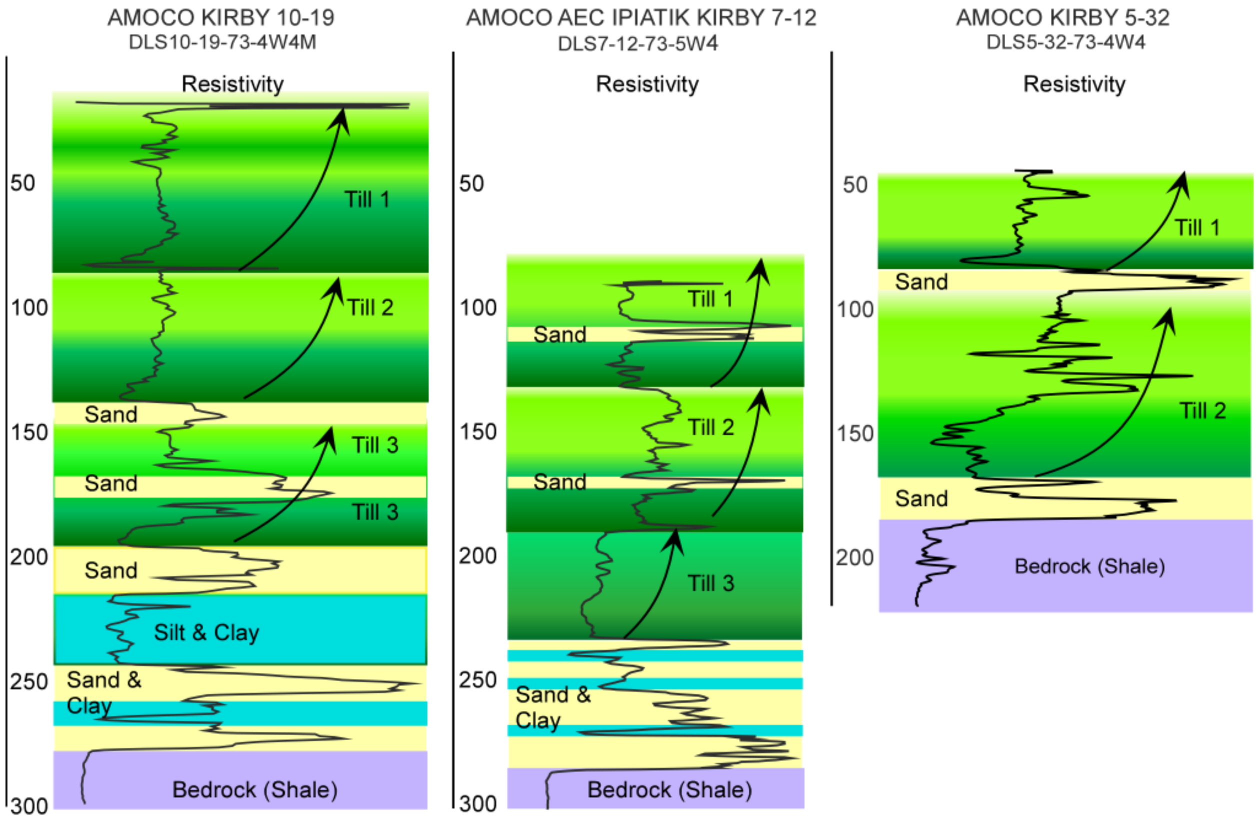


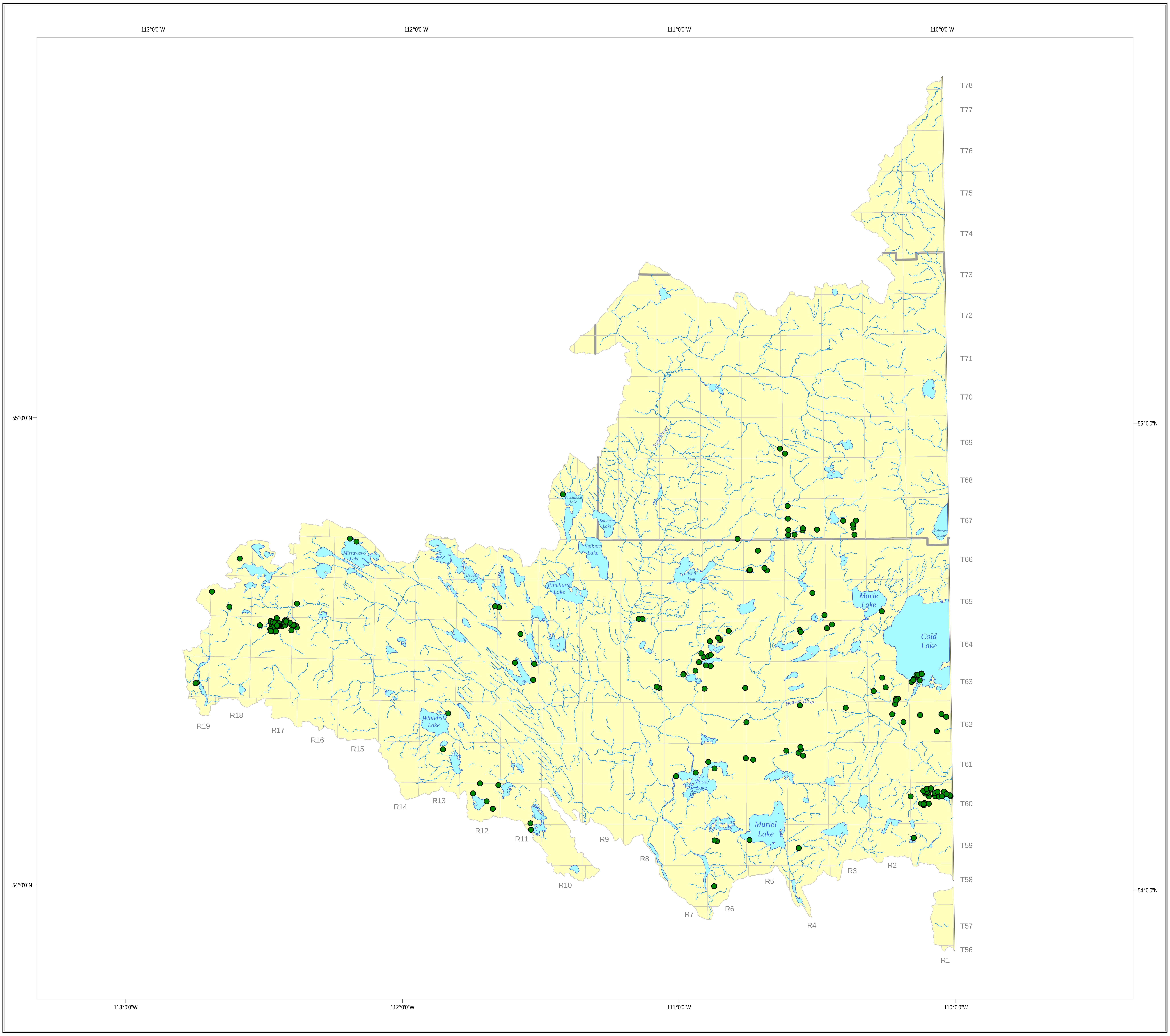

**Figure 3.19. Cyclicity in the petrological logs of the Quaternary stratigraphic succession, illustrating enrichment of fine-grained material at the base of till sheets.**

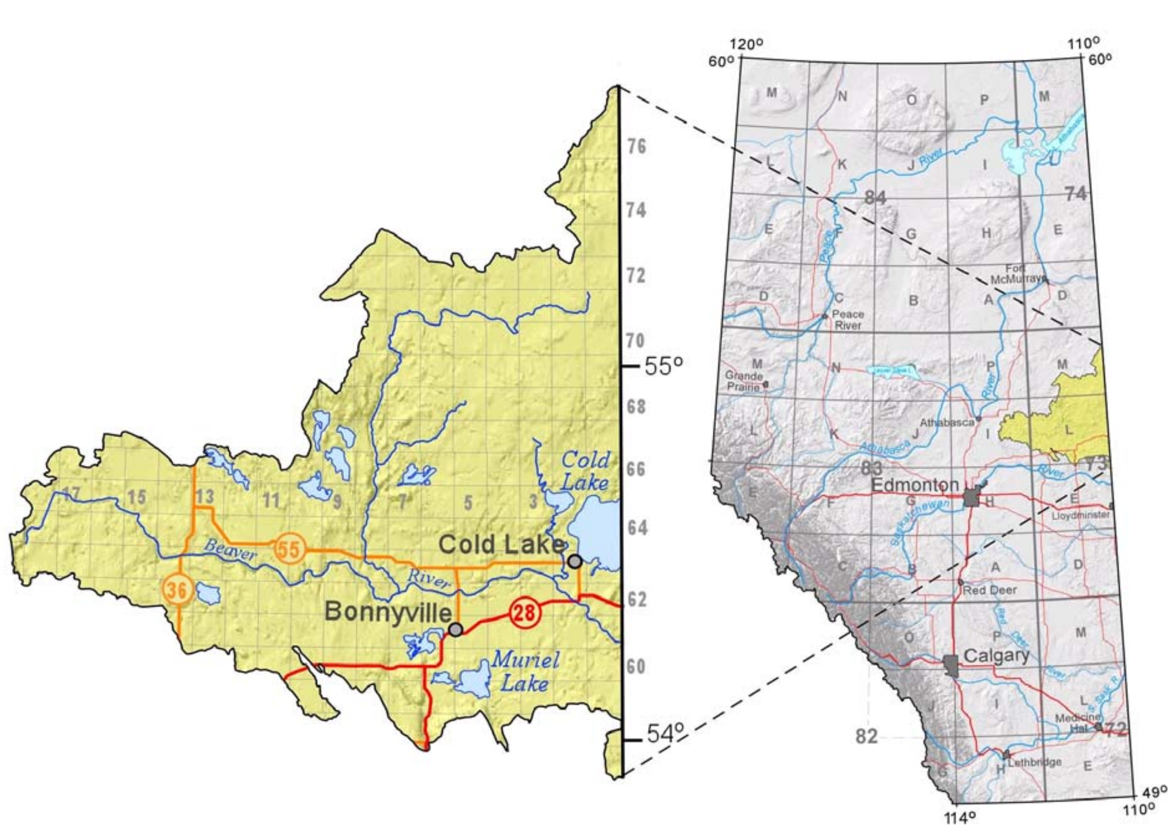
One source of K-estimates is aquifer tests done with production wells. An aquifer test, or pump test, consists of a period of constant production from a well followed by at least that long or more of recovery, during which water-levels in the production well and/or an offsetting observation well are recorded over time. Various mathematical solutions exist to match water-level response to production in order to estimate K around a well. Kruseman and deRidder (1990) is a standard reference on aquifer-test analysis.

Both aquifer-test analyses and uninterpreted aquifer-test data are retained on file with AENV as part of the routine licensing of groundwater production wells. These reports and data were screened as part of this study to gather a set of representative K values for each formation in the drift. Information pertaining to screen-depths and estimates of surface-elevation at presumed well locations were used to determine the formation being tested. Where boundaries were evident on diagnostic time-drawdown plots, pre-boundary K values were selected for compilation.

A map showing distribution of pump-tests compiled by AGS is in Figure 3.20. A comparative notched box-plot of pump-test derived K values is in Figure 3.21. The notched box plot shows the interquartile range of K values in each formation as a gray-shaded box. The narrowed section of each box (i.e., the notch) denotes the 95% confidence interval on the median. When two boxes are compared on the same scale and their notched sections do not overlap, one can say with 95% confidence that the medians of the underlying two populations are different.

Several things of note are illustrated on Figure 3.21. First, there are number of wells in formations that previous workers often contended to be aquitards based on their predominant lithology being till (as




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

Pumping test derived hydraulic conductivity

River

Cold Lake Air Weapons Range Boundary

Lake

Beaver River drainage basin area (Alberta portion)

December, 2004

## Figure 3.20 Location map of pump-test derived K

Alberta Environment

EUB Alberta Energy and Utilities Board

AGS Alberta Geological Survey

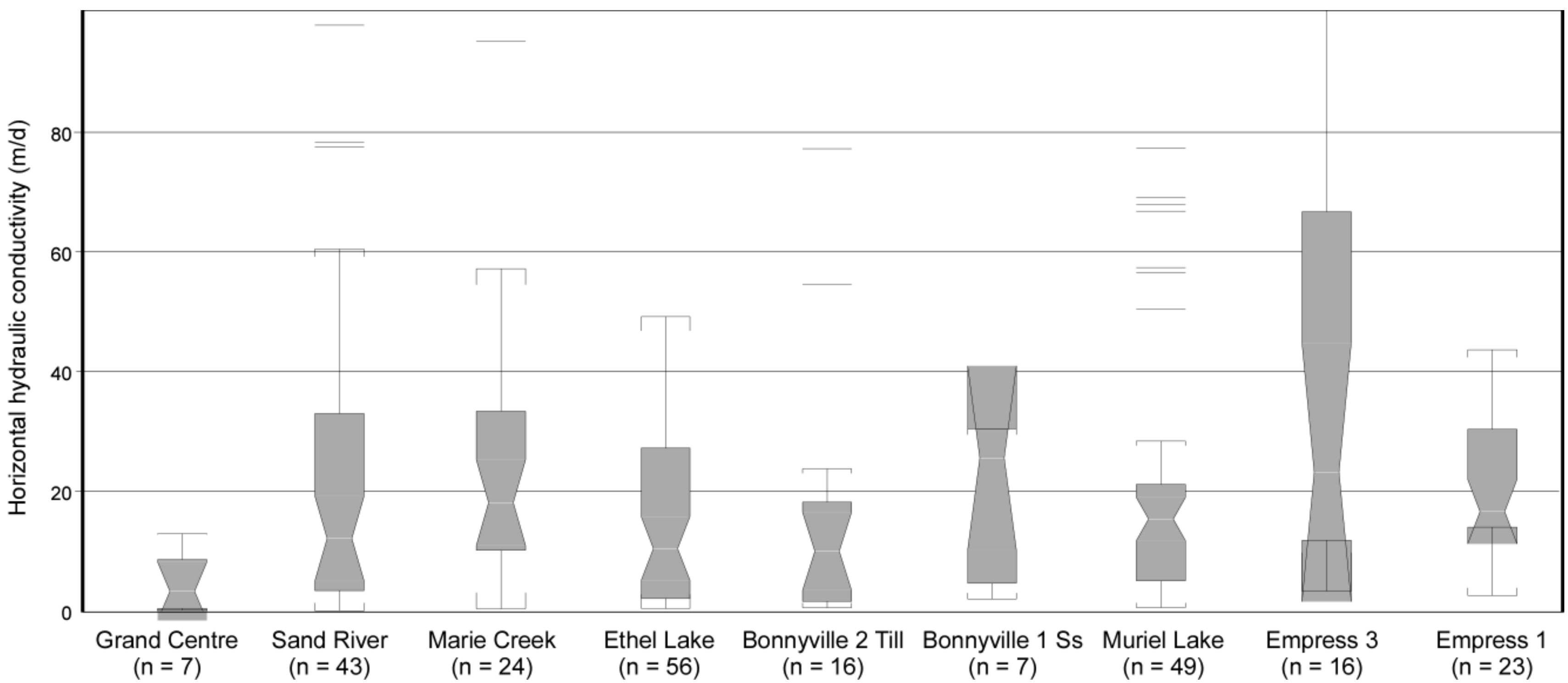



**Figure 3.21. Comparative notched box plots of measured hydraulic conductivity values from pump-tests.**

discussed above), namely the Grand Centre Formation, the Marie Creek Formation and Bonnyville Formation Unit II. Given that the uppermost parts of each till sheet tend to be sandy and that local sand bodies can be formed by glacial processes even within the till-dominated part of each glacio-genetic cycle, it should not be a surprise that water wells are producing from these formations.

Second, the median value of K determined from pumping tests in these formations is typically in the range of 5-30 m/d and does not differ significantly between formations. This range is typical of unconsolidated sand and again is not surprising.

Another important parameter in regional groundwater assessments is lake-bed and stream-bed hydraulic conductance. These values determine the strength of hydraulic connection between surface-water bodies and underlying geological formations. Calculations of conductances need values of K for the stream and lake-bed materials. AGS measured dry lake-bed conductances at a selection of sites in June 2003 using a Guelph field-permeameter. The results are in Table 3.2. Photographs showing the field use of this instrument are in Figure 3.22.

A B

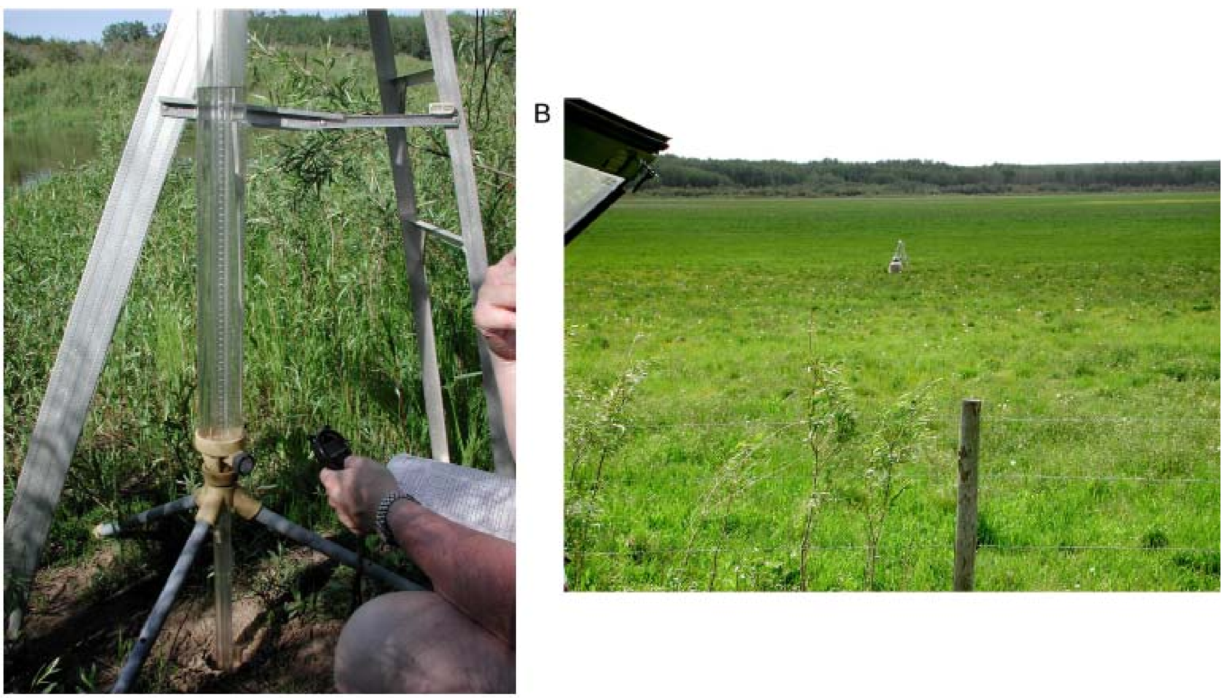


**Figure 3.22. Measuring stream-bed and lake-bed permeability in field with Guelph permeameter.**

Table 3.2. Dry lake- and stream-bed hydraulic conductivity values measured using a Guelph field-permeameter.

| Location Name | A | R | Q | K1fs | Site Average K1fs | Clay Average K1fs | Soil Type | Depth m | UTMN (nad83) | UTME (nad83) |
|---|---|---|---|---|---|---|---|---|---|---|
| Marie Creek 01-18-063-02W4M | 0.00349 | 0.00045833 | 0.0000015996 | 0.0000397087 | 0.0000086503 | 0.0000002185 | oxidized sand | 0.40 | 6033139 | 546253 |
| | 0.00349 | 0.00003333 | 0.0000001163 | 0.0000028876 | | | oxidized sand | 0.40 | | |
| | 0.000217 | 0.00003333 | 0.0000000072 | 0.0000001795 | | | oxidized sandy clay | 0.40 | | |
| | 0.000217 | 0.00001333 | 0.0000000029 | 0.0000000718 | | | oxidized sandy clay | 0.40 | | |
| | 0.000217 | 0.000075 | 0.0000000163 | 0.000000404 | | | oxidized sandy clay | 0.40 | | |
| Beaver River 15-10-062-02W4M | 0.00349 | 0.000105 | 0.0000003665 | 0.000009097 | 1.08600E-04 | | unoxidized silty clayey sand | 0.40 | 6023275 | 551029 |
| | 0.00349 | 0.0029166 | 0.0000101789 | 2.52688E-04 | | | oxidized medium sand | 0.25 | | |
| | 0.00349 | 0.00073888 | 0.0000025787 | 0.000064015 | | | oxidized clayey sand | 0.35 | | |
| Dry Lake Bed 02-18-062-02W4M | 0.00349 | 0.0001444 | 0.000000504 | 0.0000125105 | 0.0000036514 | 0.0000006983 | black silty loam | 0.72 | 6023273 | 546181 |
| | 0.000217 | 0.000127777 | 0.0000000277 | 0.0000006883 | | | unoxidized silty clay | 0.73 | | |
| | 0.000217 | 0.0001 | 0.0000000217 | 0.0000005387 | | | unoxidized silty clay | 0.73 | | |
| | 0.000217 | 0.00016111 | 0.000000035 | 0.0000008679 | | | unoxidized silty clay | 0.72 | | |
| Muriel Lake 05-10-060-05W4M | 0.000217 | 0.0002333 | 0.0000000506 | 0.0000012568 | 0.0000030177 | 0.0000030177 | unoxidized pebbly clay | 0.45 | 6002736 | 521177 |
| | 0.000217 | 0.00004 | 0.0000000087 | 0.0000002155 | | | unoxidized pebbly clay | 0.45 | | |
| | 0.00349 | 0.0000875 | 0.0000003054 | 0.0000075808 | | | unoxidized pebbly clay | 0.45 | | |

Calculations for the Laplace and Gardner Analyses

B = C/2PI(H2)[1+C/2(a/H)2] — C = proportionality constant (1.61)
B = 24.8246 — H = Well head height (.10 m)
a = radius of well (.02 m)

Q = AR — A = annular cross-sectional area between reservoir tube and air-inlet tube ( .000217 m2 or .00349 m2)
R = steady state rate of fall of the liquid surface in the reservoir tube of the GP in m/s

K1fs = BQ — B = constant
Q = steady-state liquid recharge necessary to maintain H in the well in m3/s
K1fs = field saturated hydraulic conductivity determined by the Laplace analysis in m/s

# 4 Regional Groundwater Flow and Chemistry

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 including 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. The documentation of the database structure and contents have been documented in a separate internal report to AENV Northern Region.

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.

This section discusses regional groundwater flow and 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 groundwater chemistry of the Cold Lake-Beaver River Basin is explored in more detail in the companion volume to this report on groundwater quality.

## 4.1 Regional Groundwater Flow

As discussed in Section 1, groundwater flows under gravity from areas of high hydraulic head to areas of low hydraulic head. Areas of downward groundwater motion where water enters the ground are called recharge areas. Areas of upward groundwater motion where water exits the ground are called discharge areas. Large areas of essentially horizontal groundwater flow occur between recharge and discharge areas. Most horizontal flow occurs in the most permeable beds while most vertical cross-formational flow occurs in the least permeable beds. As depth of groundwater penetration into the ground increases, the velocity of groundwater decreases while the length of flow path increases. These relationships are shown diagramatically in Figure 4.1. The mathematical theory of regional groundwater flow is found in standard text books like Domenico and Schwartz (1990).

There are groundwater observation wells with continuous water-level recorders installed in various locations at various points in the Cold Lake-Beaver River Drainage Basin. The locations and formations in which they are completed are shown in Figure 4.2. Some of these observation wells are operated by AENV and some are operated by industry. The hydrographs from these observation wells provide invaluable information on fluctuations in static-water level at a given point over time. These fluctuations provide information on the interconnectivity of formations in the vicinity of the well to neighbouring producing wells as well as to natural conditions at surface or at nearby surface water-bodies. These behaviours are discussed in more detail in Section 7 of this report.

Regional groundwater flow can be mapped using static-water level elevations in water wells and observation wells provided that they are not being affected by pumping. Static water levels reported as depth below top of casing are available on drillers' reports on file with AENV. An acceptable well completion for use in AGS hydraulic-head mapping would include a screen no longer than 3 m and a seal vertically offset from the screen by no more than 6 m. All water wells with acceptable completion details were then cross-indexed with static water-level reports to assemble a final dataset for regional hydraulic head mapping.

Details of the numbers of water-well records with acceptable completion details are in Table 4.1. Details of the numbers of water-well records with acceptable completion details and static water-level reports are in Table 4.2.

After the static-water level data were compiled and assigned to formations, maps of static water level were generated for the coarse-grained formations previously classified as regional aquifers in the Cold Lake-Beaver River Basin. These maps are equivalent to hydraulic head maps and are also called potentiometric surface maps. Hydraulic head maps were produced for the Empress Formation Unit 1, the Empress Formation Unit 3, the Muriel Lake Formation, the Ethel Lake Formation, the Sand River Formation, and the Grand Centre Formation in Figures 4.3 to 4.8, respectively. There were not enough static water-level data of acceptable quality in the other formations to map.

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

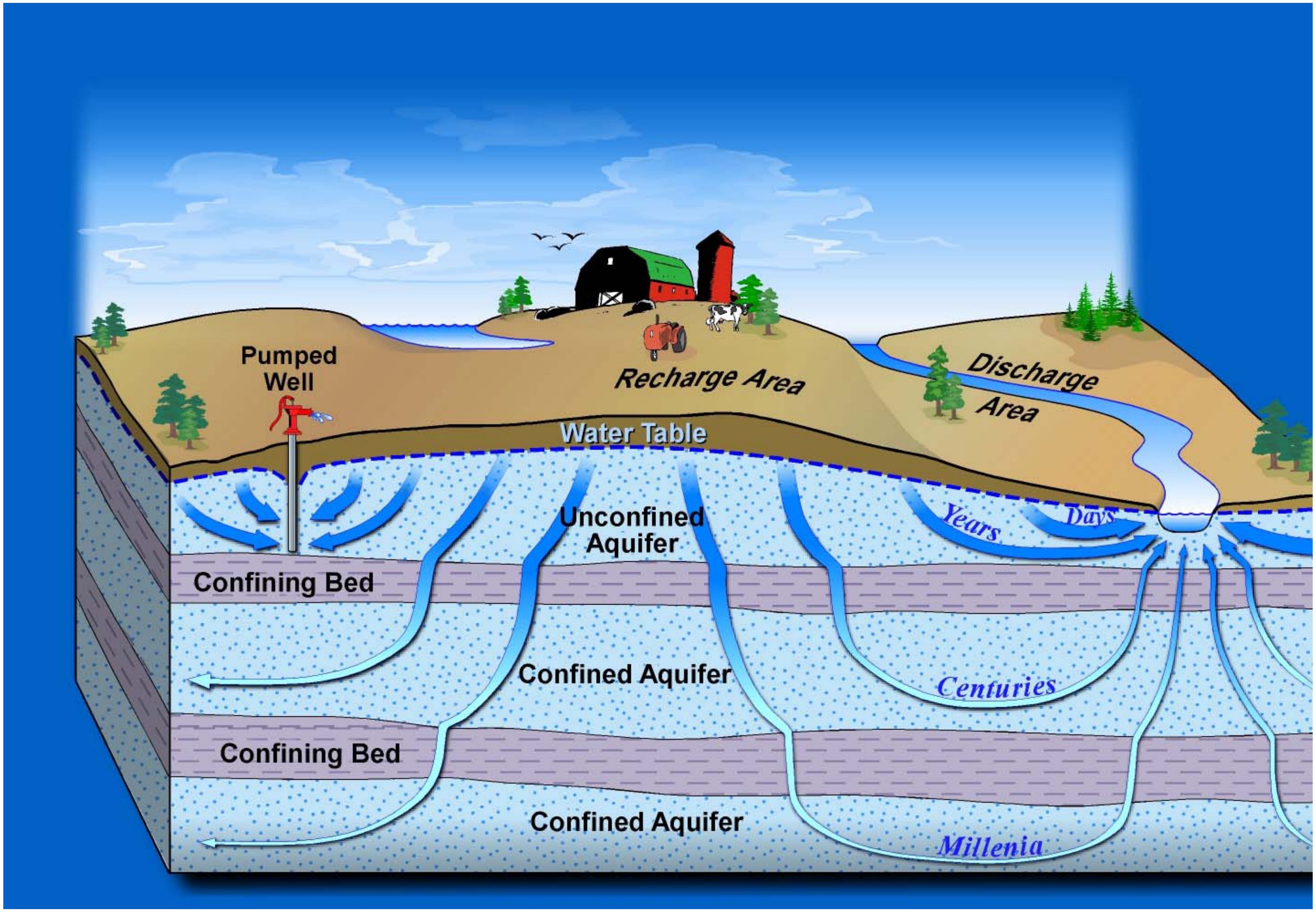



**Figure 4.1. Illustration of groundwater flow-systems.**

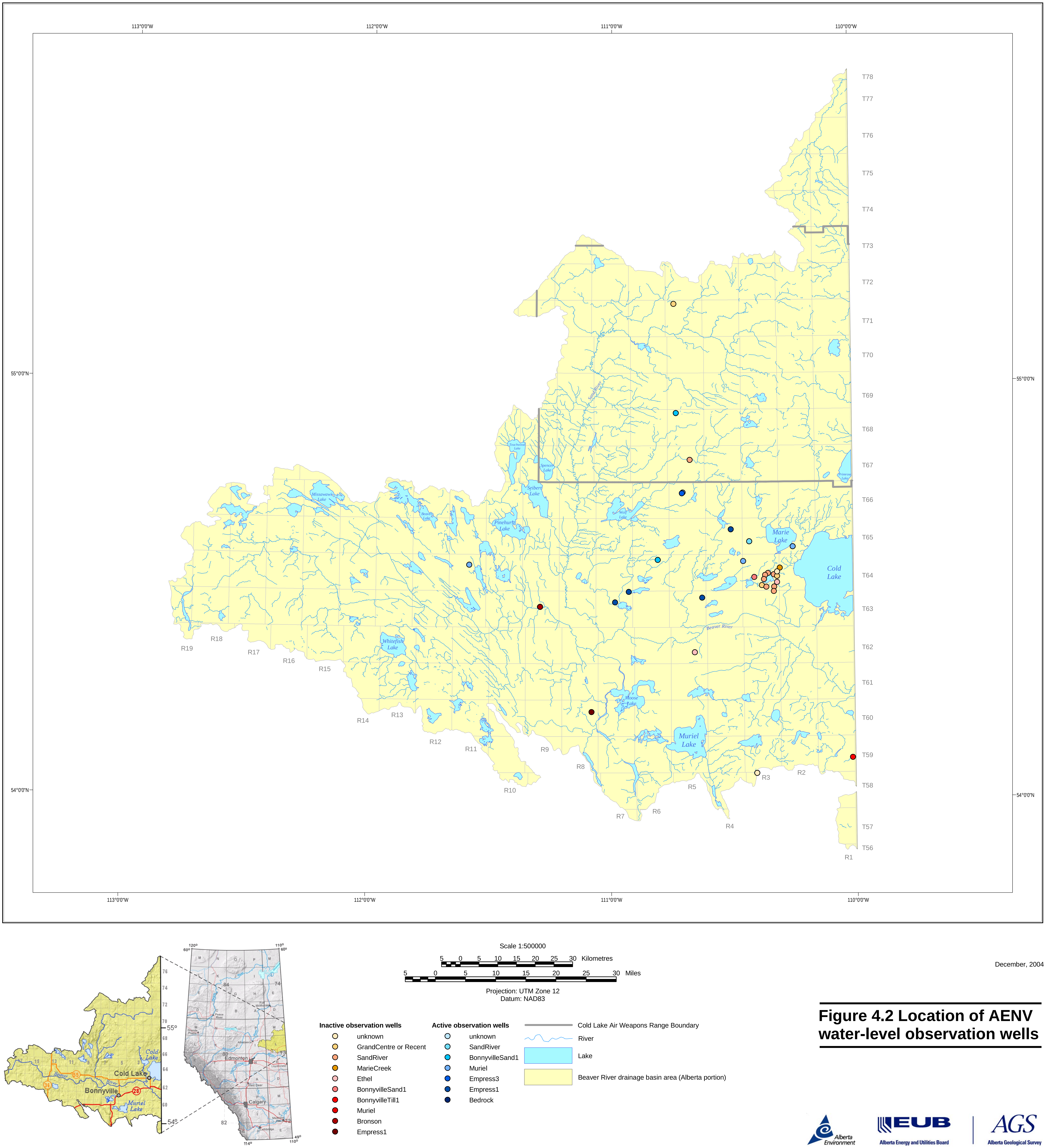



**Figure 4.2 Location of AENV water-level observation wells**

**Table 4.1. Number of water-well screen records by type, quality, flow system.**

| Quality | Flow System SWBR | Flow System NWBR | Flow System SEBR | Flow System NEBR | Flow System Wiau | CLBR study area |
|---|---|---|---|---|---|---|
| In Water_Chemistry.mdb and AENV.mdb | | | | | | |
| Number of water wells with screens | 376 | 375 | 1508 | 1158 | 52 | 3469 |
| Number of water wells stainless steel or plastic screens | 246 | 272 | 1157 | 665 | 5 | 2345 |
| Number of water wells stainless steel or plastic screens and delta seal <6.1m | 100 | 108 | 445 | 263 | 4 | 920 |

Notes:

screen criteria: plastic or stainless steel

casing criteria: plastic, wood, cribbing.

seal criteria: All seal material listed except for sandpack, gravelpack, sand and gravel, unknown, and other.

Delta seal: <= 6.1 metres (20ft) from top of screen or perforation.

**Table 4.2. Number of water-well static water level records by type, quality, flow system.**

| Quality | Flow System SWBR | Flow System NWBR | Flow System SEBR | Flow System NEBR | Flow System Wiau | CLBR study area |
|---|---|---|---|---|---|---|
| In Water_Chemistry.mdb and AENV.mdb | | | | | | |
| Water wells with one or more SWL | 318 | 352 | 972 | 538 | 5 | 2185 |
| wells with more than one SWL | 42 | 62 | 112 | 203 | 1 | 420 |
| wells with SWL and known casing | 77 | 68 | 211 | 171 | 3 | 530 |
| wells with known casing, screen and known seal and SWL's | 17 | 10 | 45 | 128 | 3 | 203 |
| wells with casing, screen, delta seal criteria and SWL's | 14 | 8 | 41 | 114 | 3 | 180 |

Notes:

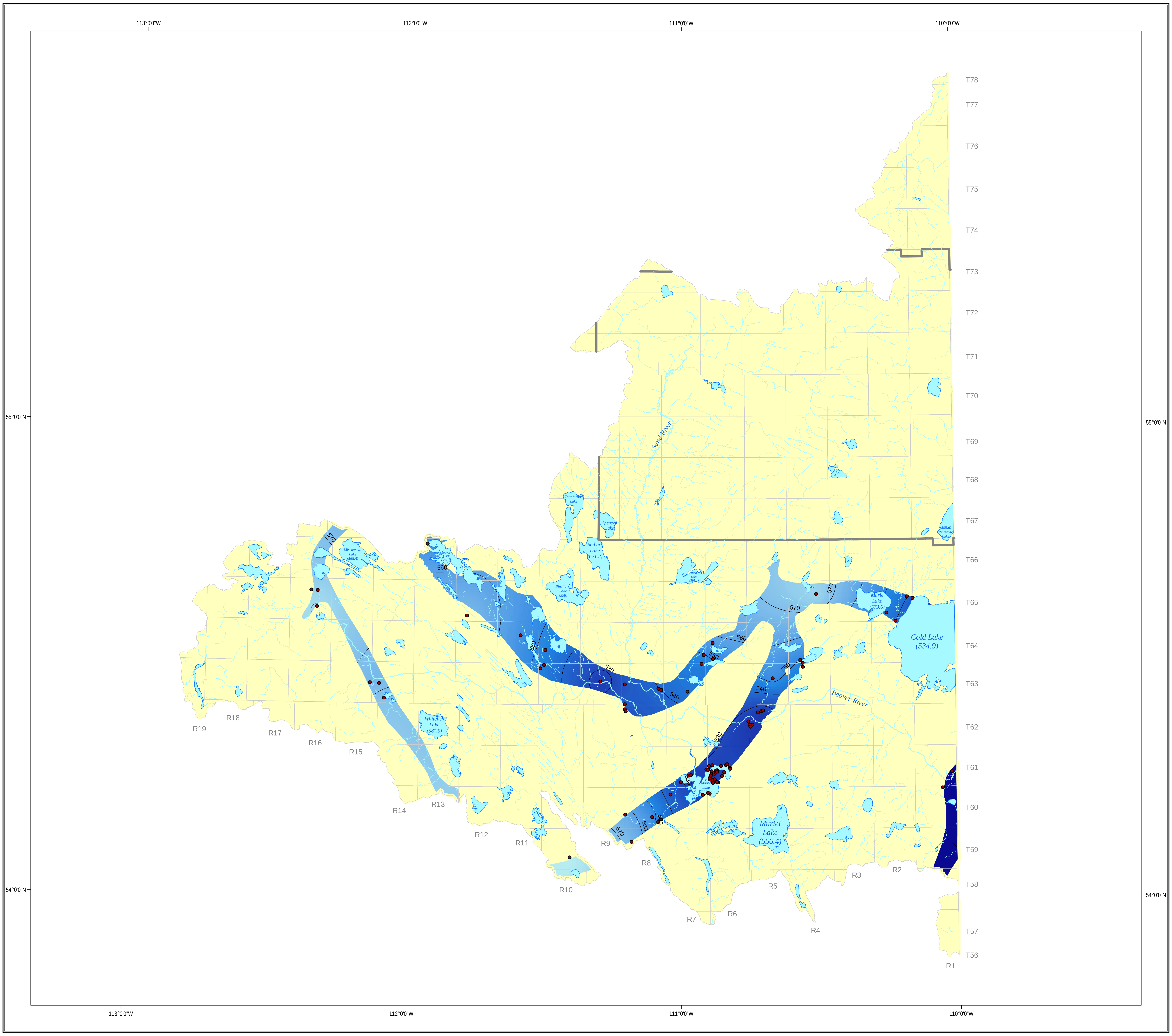
screen criteria: plastic or stainless steel

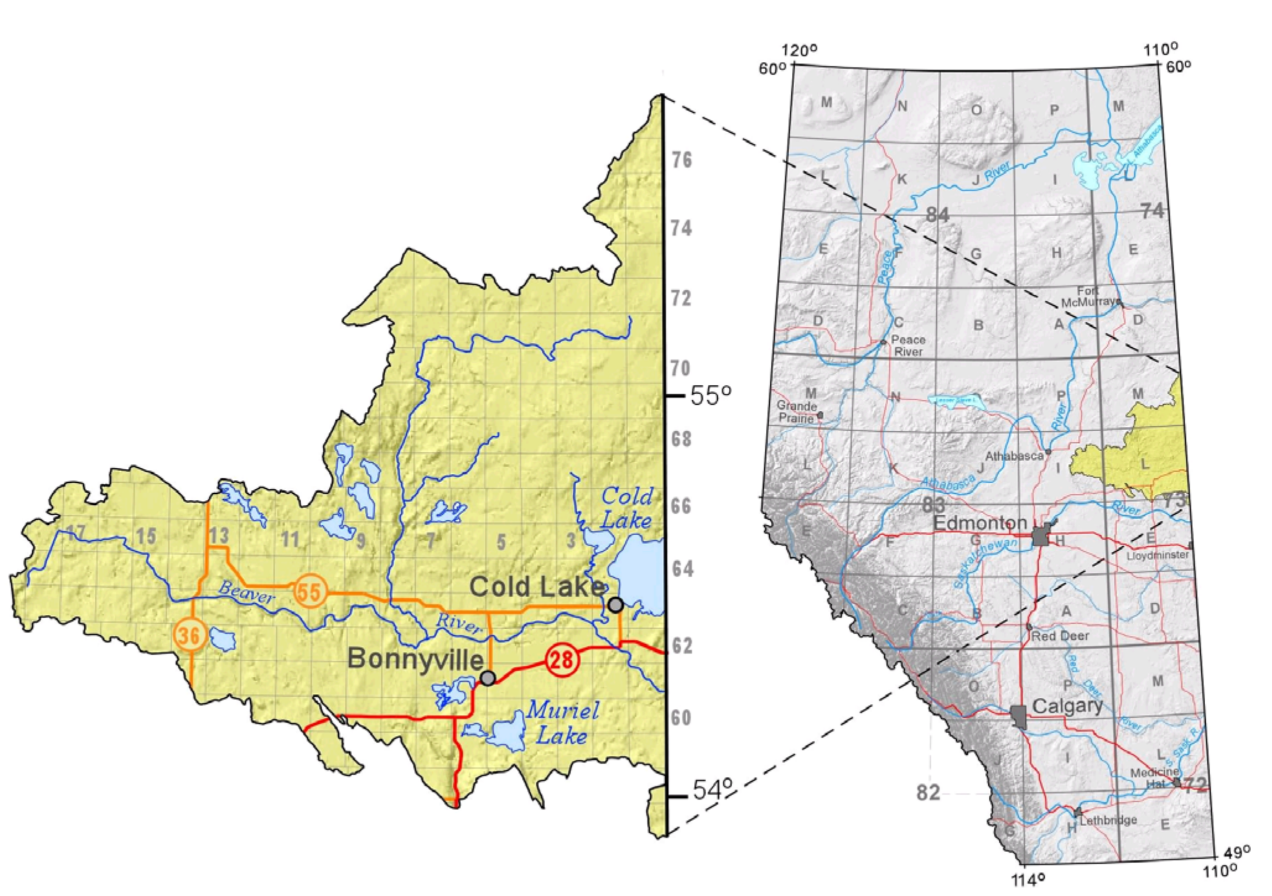
casing criteria: plastic, wood, cribbing.

seal criteria: All seal material listed except for sandpack, gravelpack, sand and gravel, unknown, and other.

Delta seal: <= 6.1 metres (20ft) from top of screen or perforation.

SWL = static water level




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

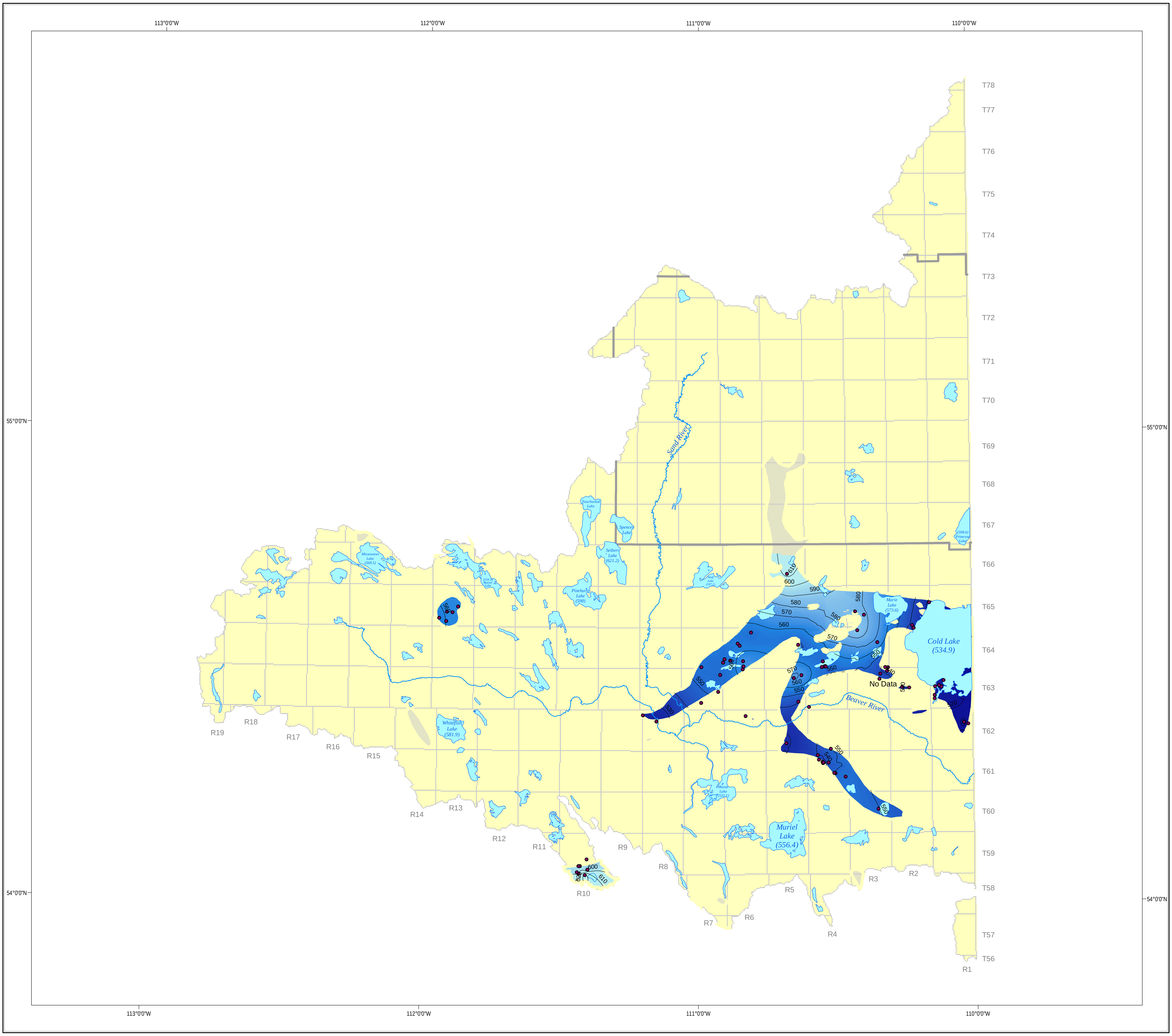
Water well
River
10 metre contour interval
Cold Lake Air Weapons Range Boundary
Lake (elevation in masl)
Beaver River drainage basin area (Alberta portion)

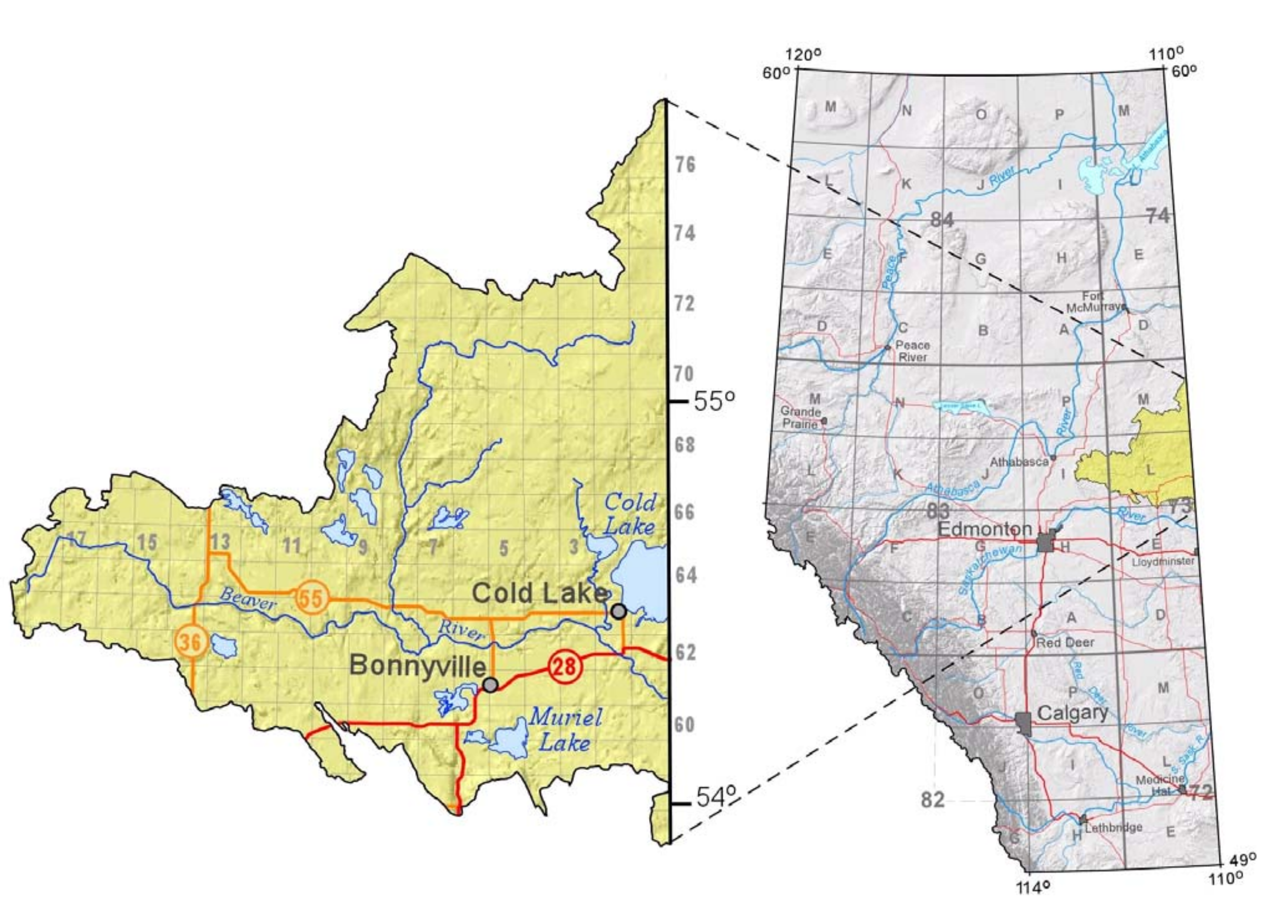
Static water level elevations
High : 585
Low : 495 (masl)
No water level elevation data available

December, 2004

**Figure 4.3 Distribution of static water level elevations in Empress Fm. Unit 1**

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




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

- Water well
- River
- 10 metre contour interval
- Cold Lake Air Weapons Range Boundary
- Lake (elevation in masl)
- Beaver River drainage basin area (Alberta portion)

**Static water level elevation**

High : 625

Low : 517 (masl)

No water level elevation data available

December, 2004

# Figure 4.4 Distribution of static water level elevations in Empress Fm. Unit 3

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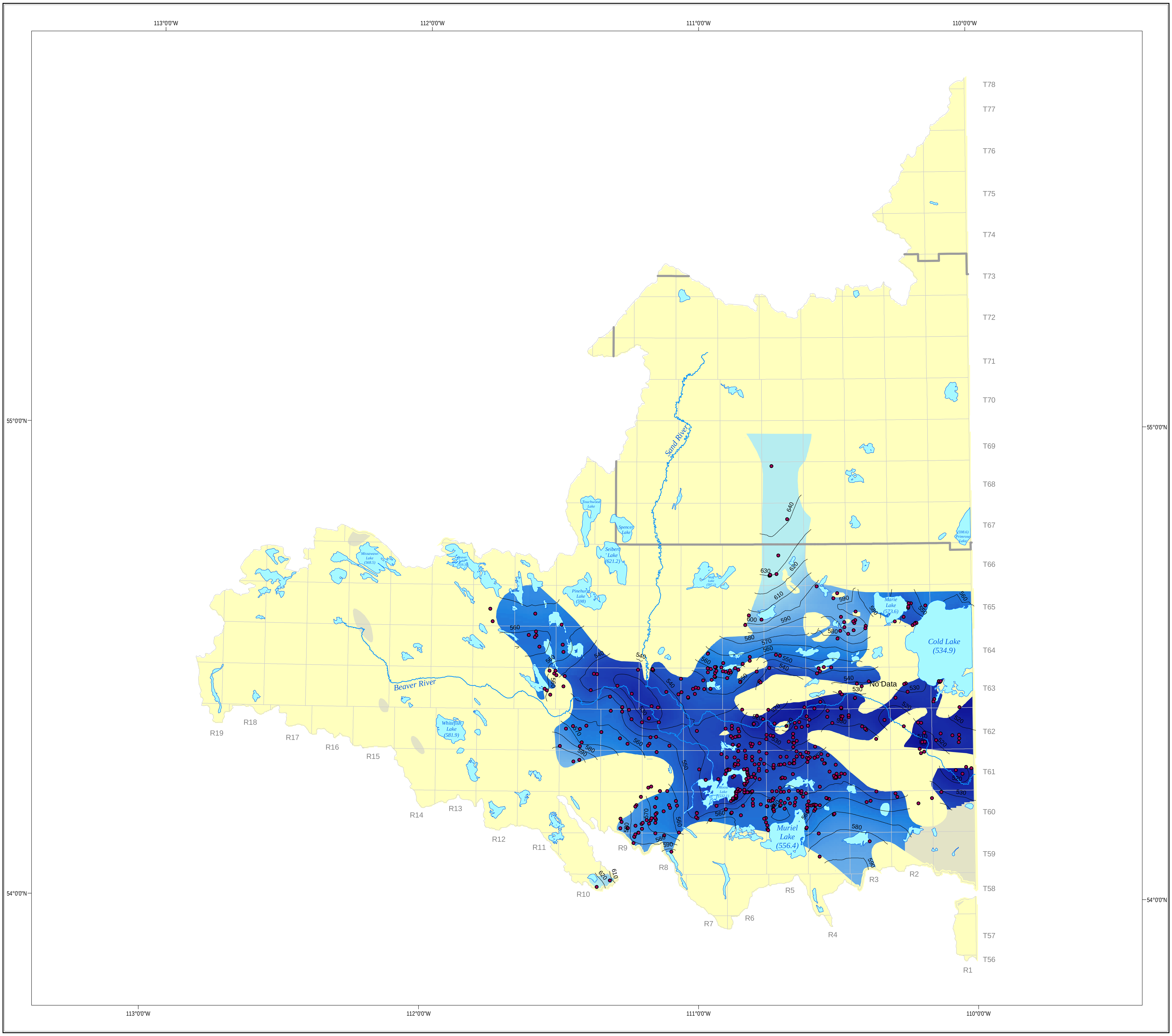


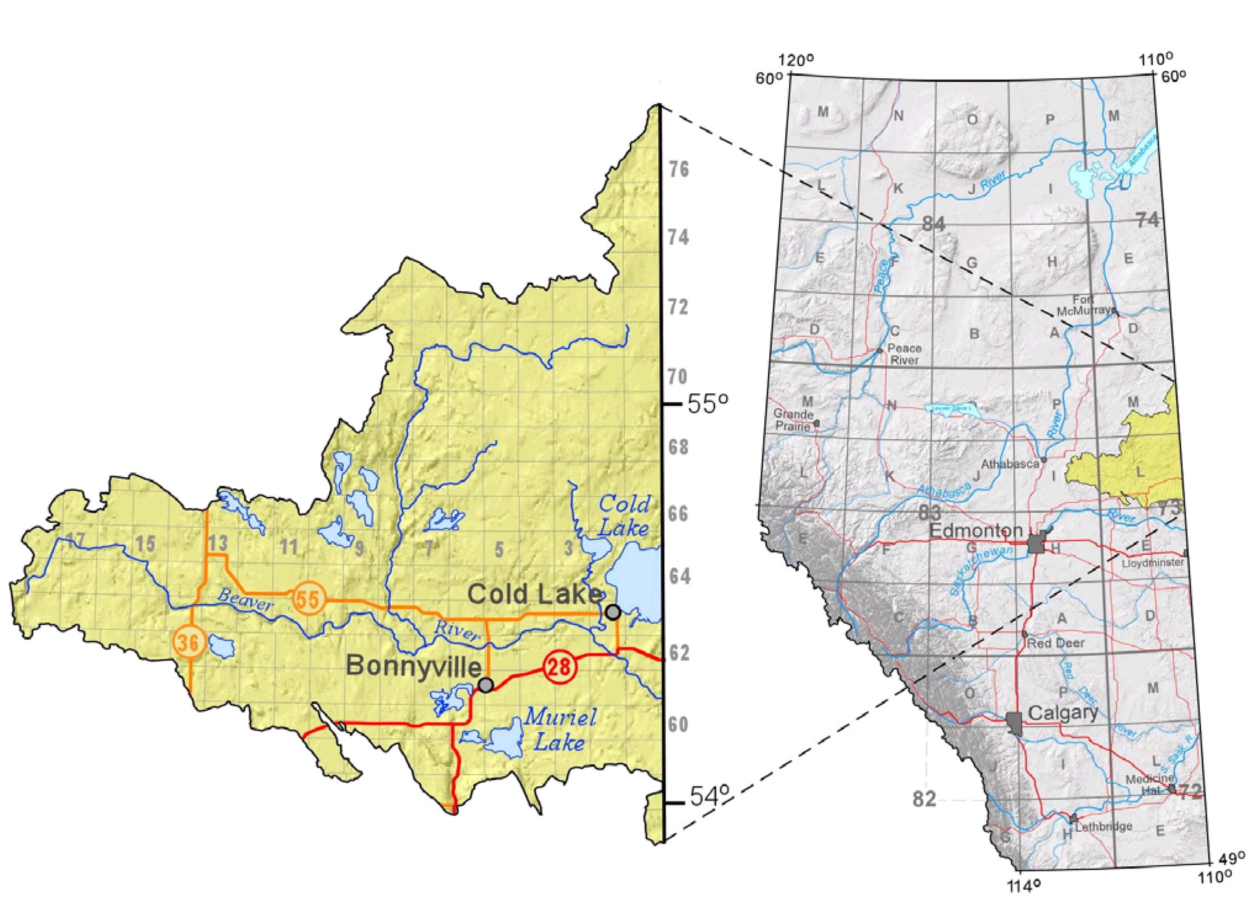


Scale 1:500000

5 0 5 10 15 20 25 30 Kilometres

5 0 5 10 15 20 25 30 Miles

Projection: UTM Zone 12
Datum: NAD83

Water well

River

10 metre contour interval

Cold Lake Air Weapons Range Boundary

Lakes (elevation in masl)

Beaver River drainage basin area (Alberta portion)

**Static water level elevation**

High : 648

Low : 507 (masl)

No water level elevation data available

December, 2004

## Figure 4.5 Distribution of static water level elevations in the Muriel Lake Fm.

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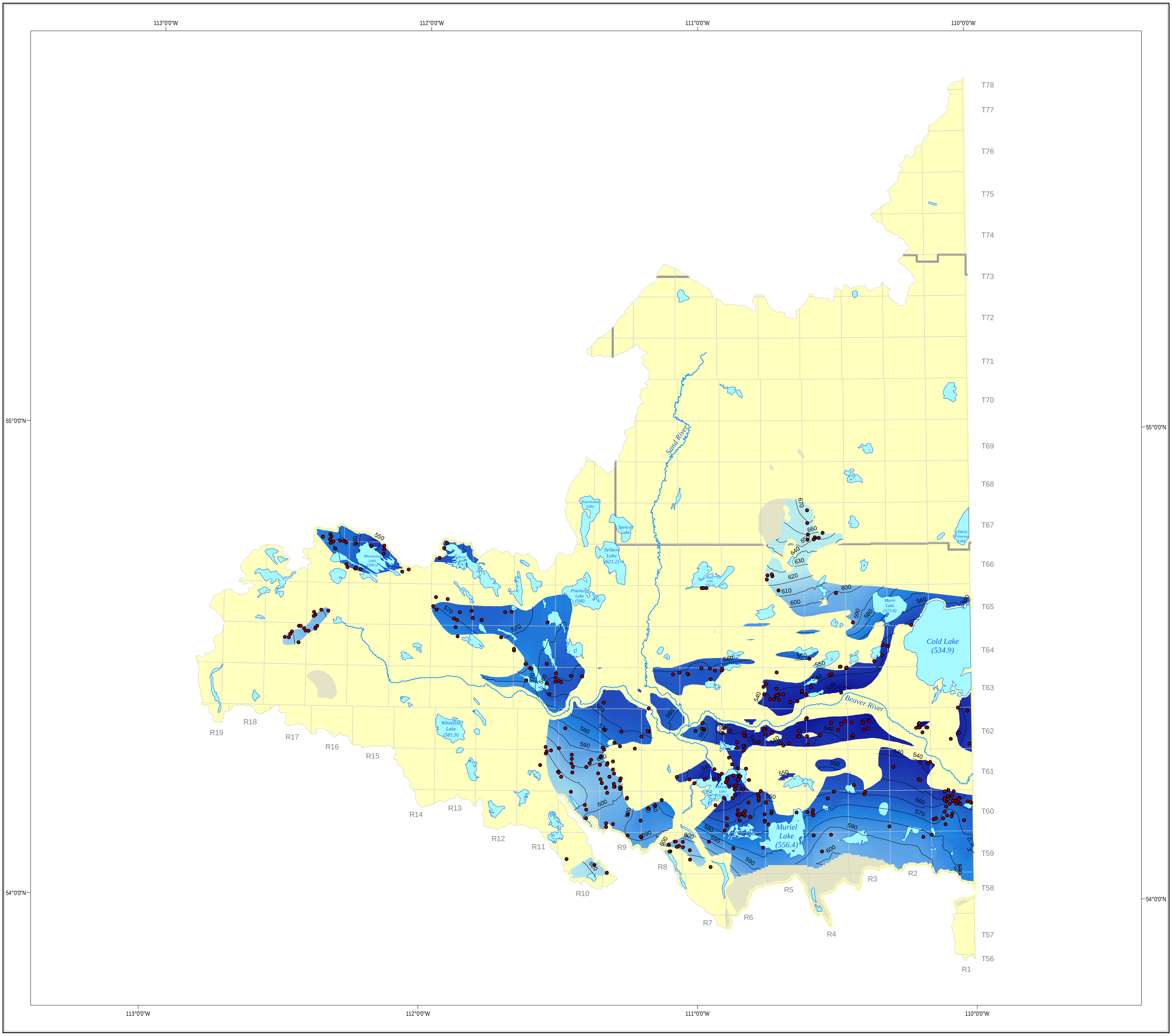
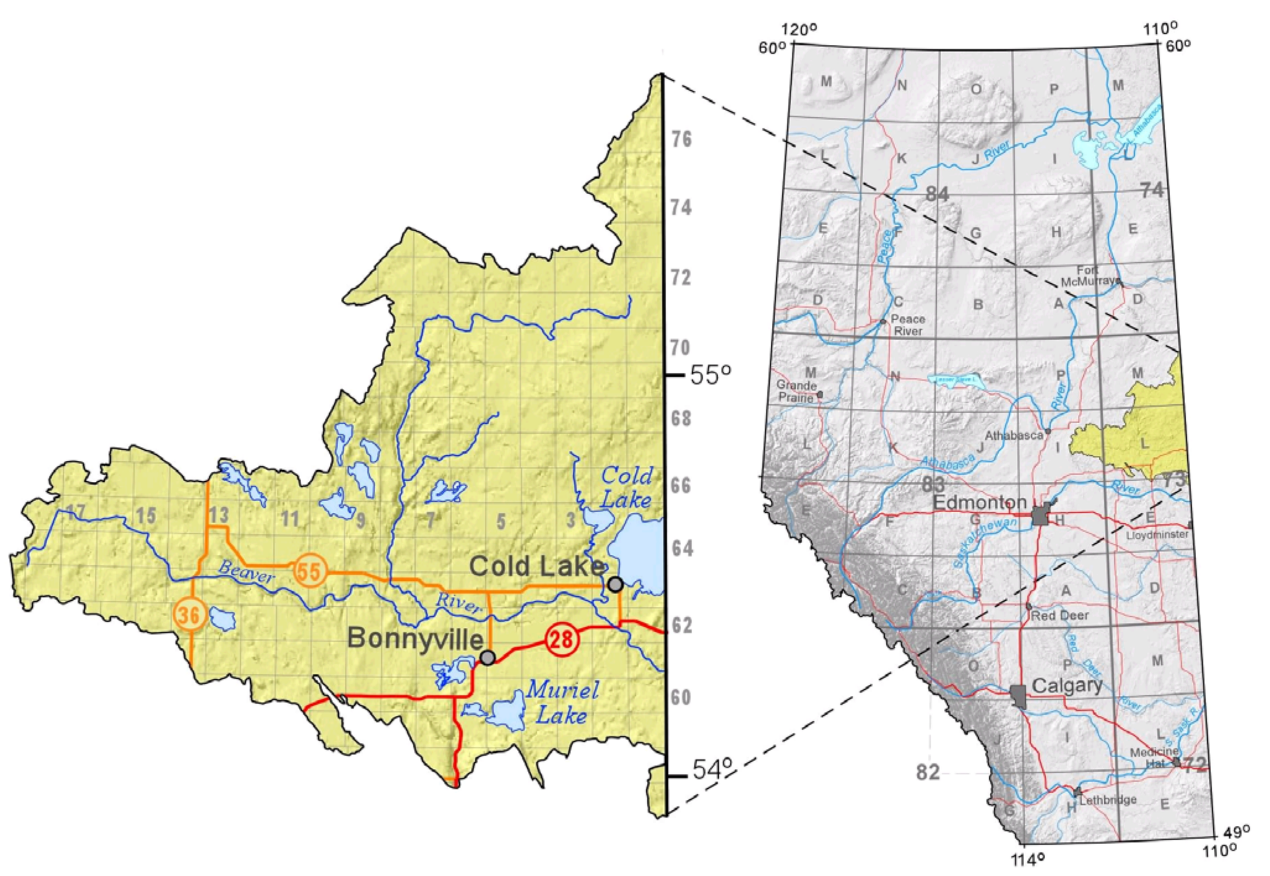




Scale 1:500000

5 0 5 10 15 20 25 30 Kilometres

5 0 5 10 15 20 25 30 Miles

Projection: UTM Zone 12
Datum: NAD83

December, 2004

Water well

River

10 metre contour interval

Cold Lake Air Weapons Range Boundary

Lake (elevations in masl)

Beaver River drainage basin area (Alberta potion)

**Static water level elevation**

High : 674

Low : 525 (masl)

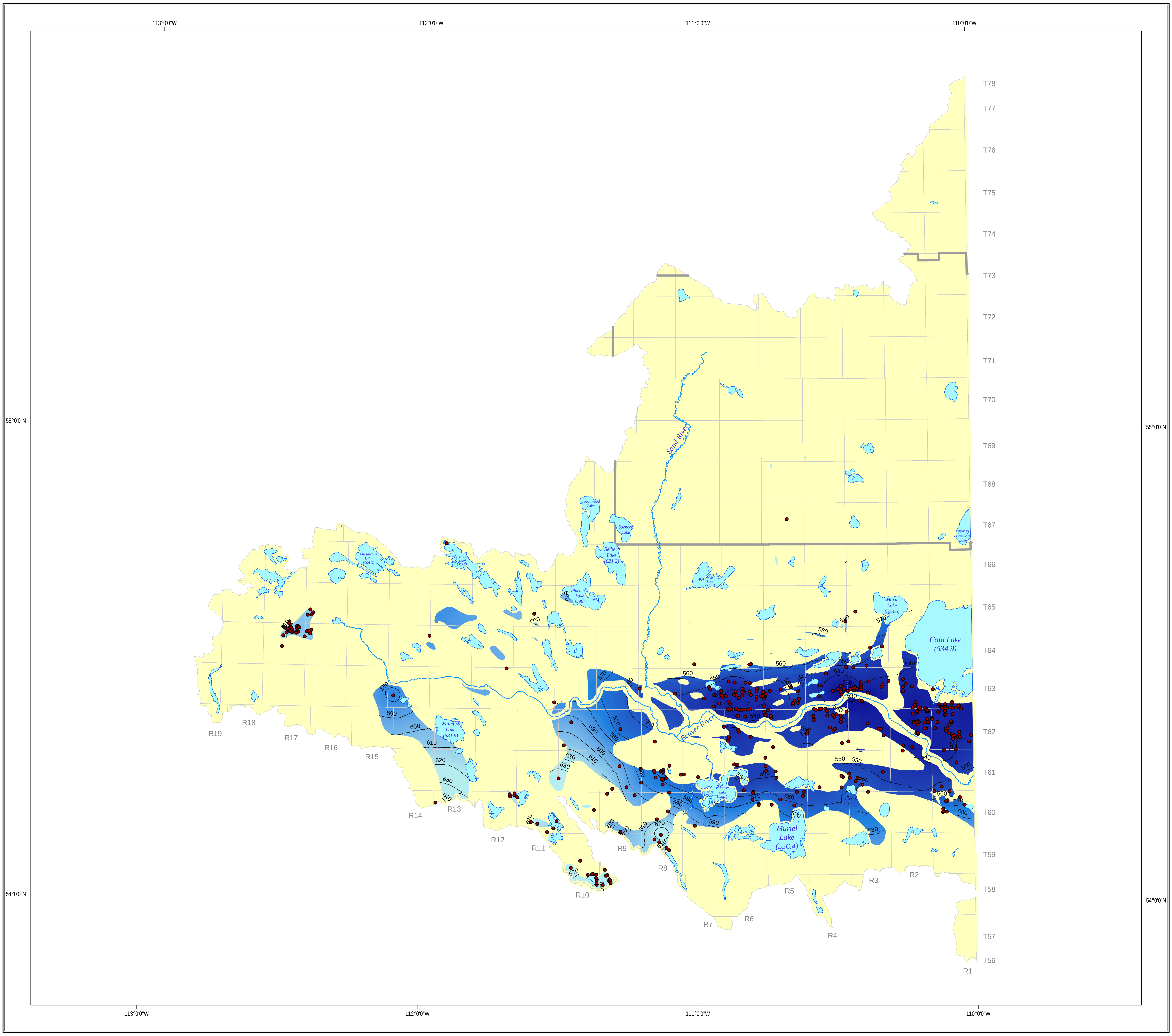
No water level elevation data available

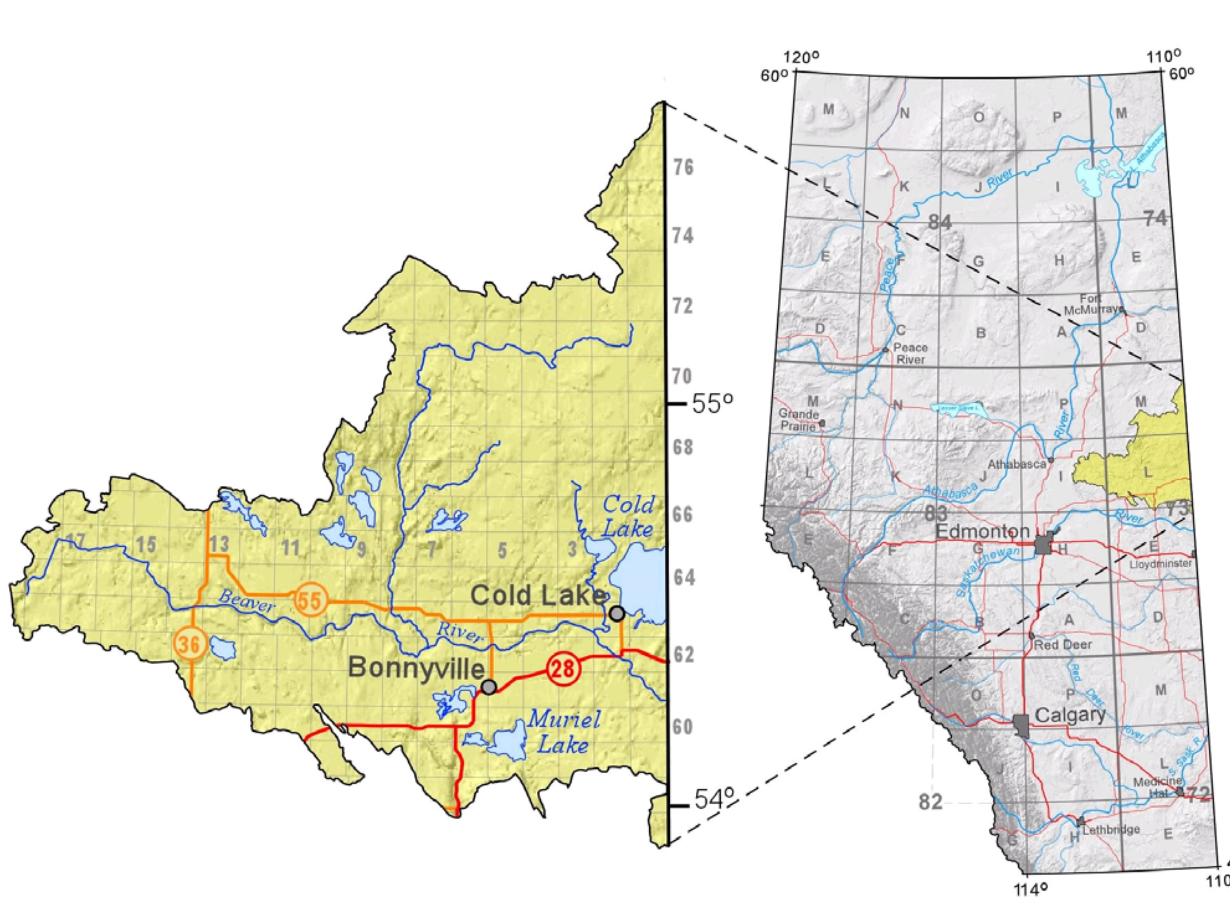
# Figure 4.6 Distribution of static water level elevations in the Ethel Lake Fm.

Alberta Environment

EUB Alberta Energy and Utilities Board

AGS Alberta Geological Survey




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

December, 2004

- Water well
- Rivers
- 10 metre contour interval
- Cold Lake Air Weapons Range Boundary
- Lake (elevation in masl)
- Beaver River drainage basin area (Alberta portion)

**Static water level elevation**

- High : 659
- Low : 527 (masl)
- No water level elevation data available

**Figure 4.7 Distribution of static water level elevations in the Sand River Fm.**

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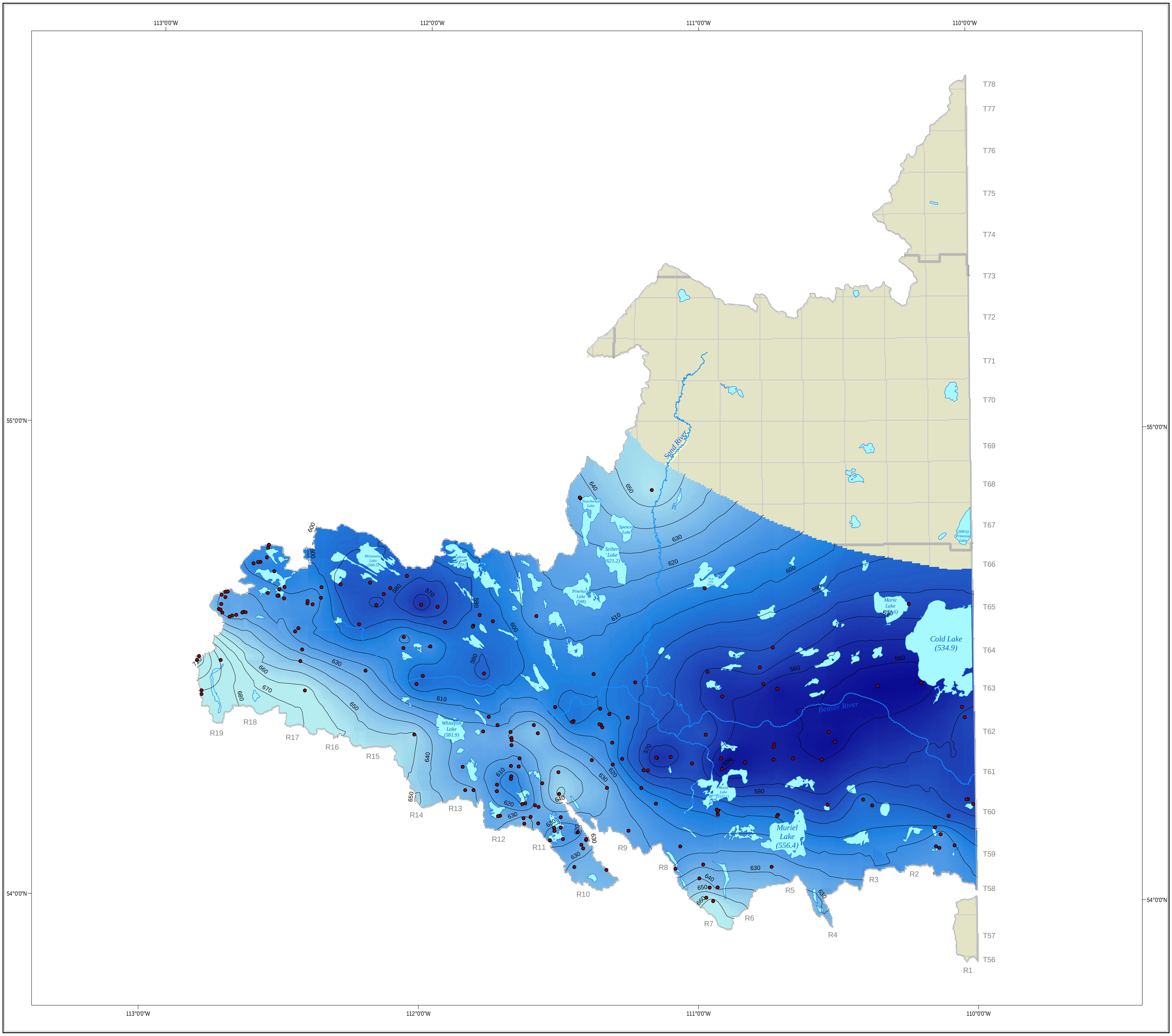
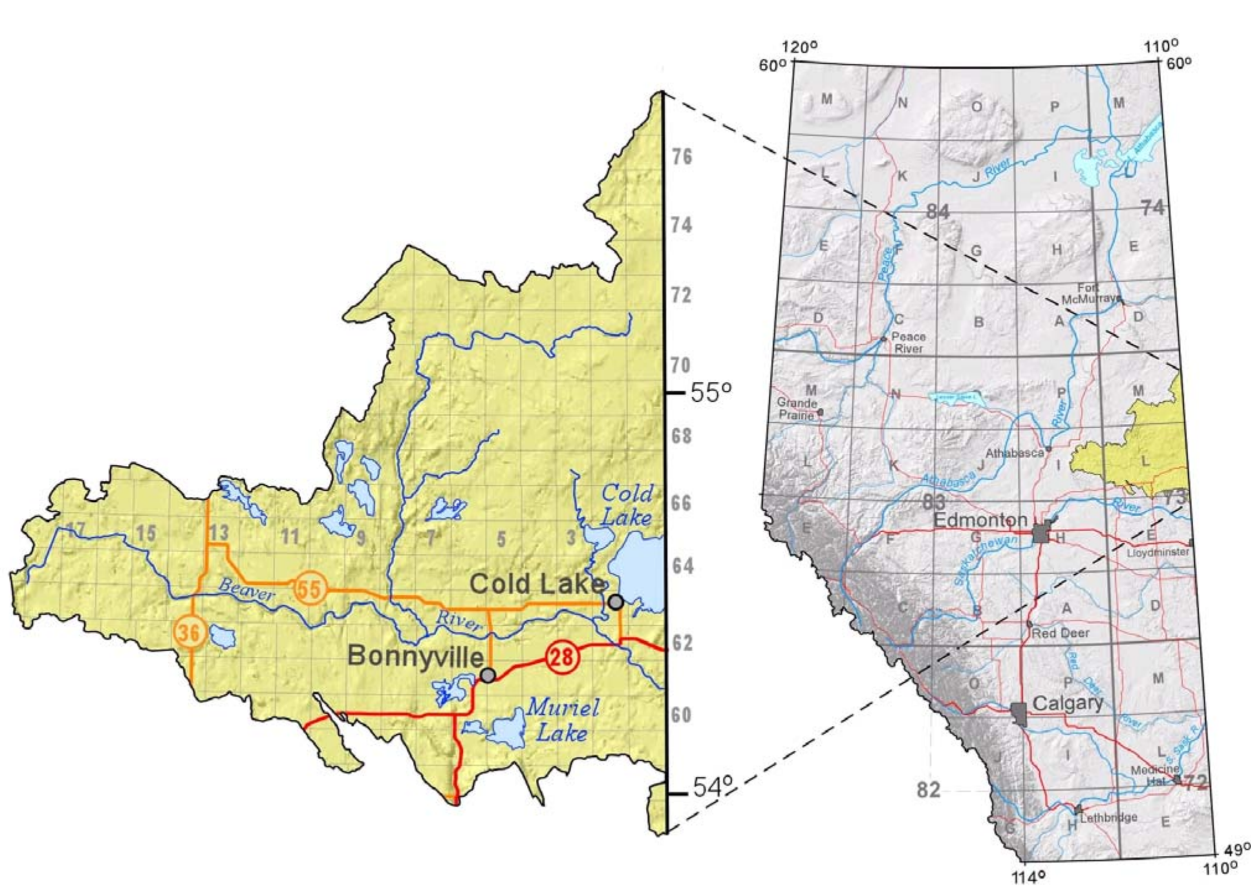
EUB Alberta Energy and Utilities Board
AGS Alberta Geological Survey




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

December, 2004

Water well

River

10 metre contour interval

Cold Lake Air Weapons Range Boundary

Lake (elevation in masl)

**Static water level elevation**

High : 717

Low : 543 (masl)

No water level elevation data available

# Figure 4.8 Distribution of static water level elevations in the Grand Centre Fm.

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AGS Alberta Geological Survey

The natural groundwater flow in the Cold Lake-Beaver River can be divided into five main regional systems that penetrate all of the formations discussed in Section 3. The extents of the five systems are shown in Figure 4.9. 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 mainly 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 divide 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 northwestward 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. This hypothesis requires further investigation.

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.

## 4.2 Regional Groundwater Chemistry

The controls on the chemical quality of groundwater are complex. It depends on the interplay of a number of factors, including:

- the chemical nature of the recharging surface water – be it snowmelt, rainfall, standing or flowing 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 it spent in contact with these materials;
- the order of the materials it came into contact with;
- 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.

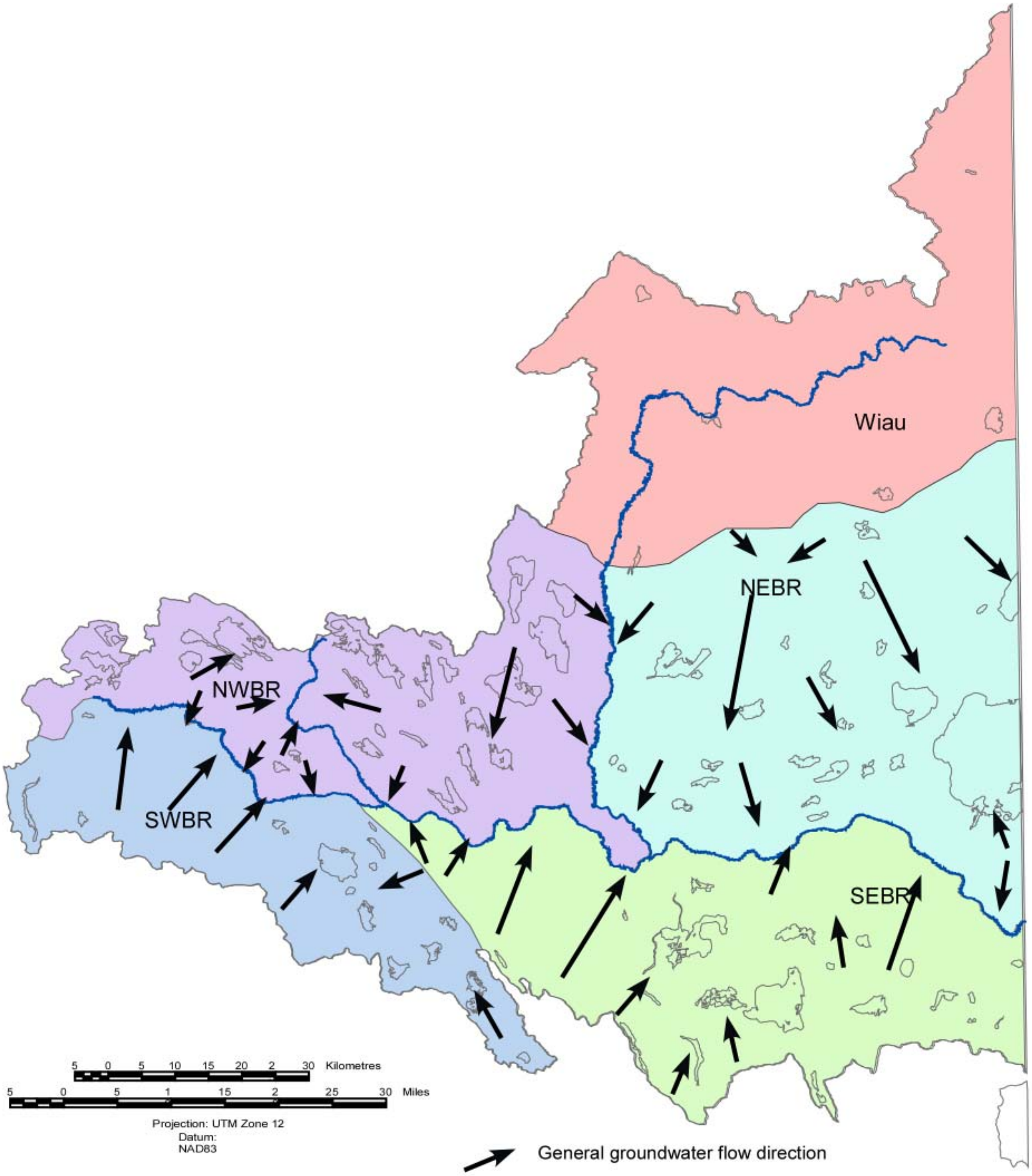



**Figure 4.9. Subdivision of Cold Lake-Beaver River drainage basin into five groundwater flow systems.**

Groundwater chemical quality is usually described in terms of the amount and type of dissolved elements or compounds. The total amount of dissolved solids (TDS) is a first order indicator of salinity of water. The TDS is expressed in units of mg/l. Fresh water generally has TDS between 0 and 1000 mg/l, brackish water has TDS between 1000 and 10000 mg/l, and saline water has TDS from 10000 to 100000 mg/l. Seawater has a TDS of about 35000 mg/l. In Alberta, potable groundwater is considered to be any groundwater with less than 4000 mg/l TDS, though Canadian drinking water quality guidelines recommend 500 mg/l TDS as an upper limit for aesthetic quality.

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%. Where no screen or perforation information was available with the Alberta Health and Wellness data set, the total depth of the well was accepted for a formation assignment. Table 4.3 shows the number of records compiled for this study and how the numbers rapidly diminished as successive screening criteria were applied.

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.

A generalized map of the salinity (i.e., TDS) of groundwater in the entire drift succession is shown in Figure 4.10. This map was generated using AENV water-well chemistry data only. Three observations can be made from this map. First, the groundwater in the drift in the Cold Lake-Beaver River Basin is of reasonable chemical quality everywhere in the basin (though local groundwater sources should always be tested prior to domestic use). Second, there are salinity gradients generally following groundwater flow paths, with the groundwater being most fresh in the recharge areas of the Moostoos Upland and becoming brackish along flow paths towards the Beaver River. An exception to this trend is evident in the south part of the Whitefish Upland and Elk Point Plain where higher salinity is found in recharge areas. This may indicate that groundwater flow paths in this area are lengthy, perhaps because of glacial thrusting or low permeability of sediments. The Bronson Lake, Muriel Lake, and Ethel Lake Formations all become enriched in clay in this area, for example.

The salinity of the Empress to Muriel Lake Formations, the Bonnyville and Ethel Lake Formations, and the Marie Creek to Grand Centre Formations are shown in Figures 4.11 to 4.13. The number of water-chemistry records that passed the quality screening-criteria is relatively low in each formation, which is why the formations were grouped by depth slice to make these maps. The same patterns seen in Figure 4.11 are found in these maps as well.

The major-element geochemistry of groundwater for each regional flow system in the Cold Lake-Beaver River Basin is presented on a Piper tri-linear plot in Figure 4.14. The data points are colour-coded by formation. To make each plot, the relative concentration of the major positively-charged dissolved ions (or cations) are plotted on the triangular field in the bottom left of each Piper plot. The apexes of this triangle

**Table 4.3. Number of chemistry records by type, quality, flow system.**

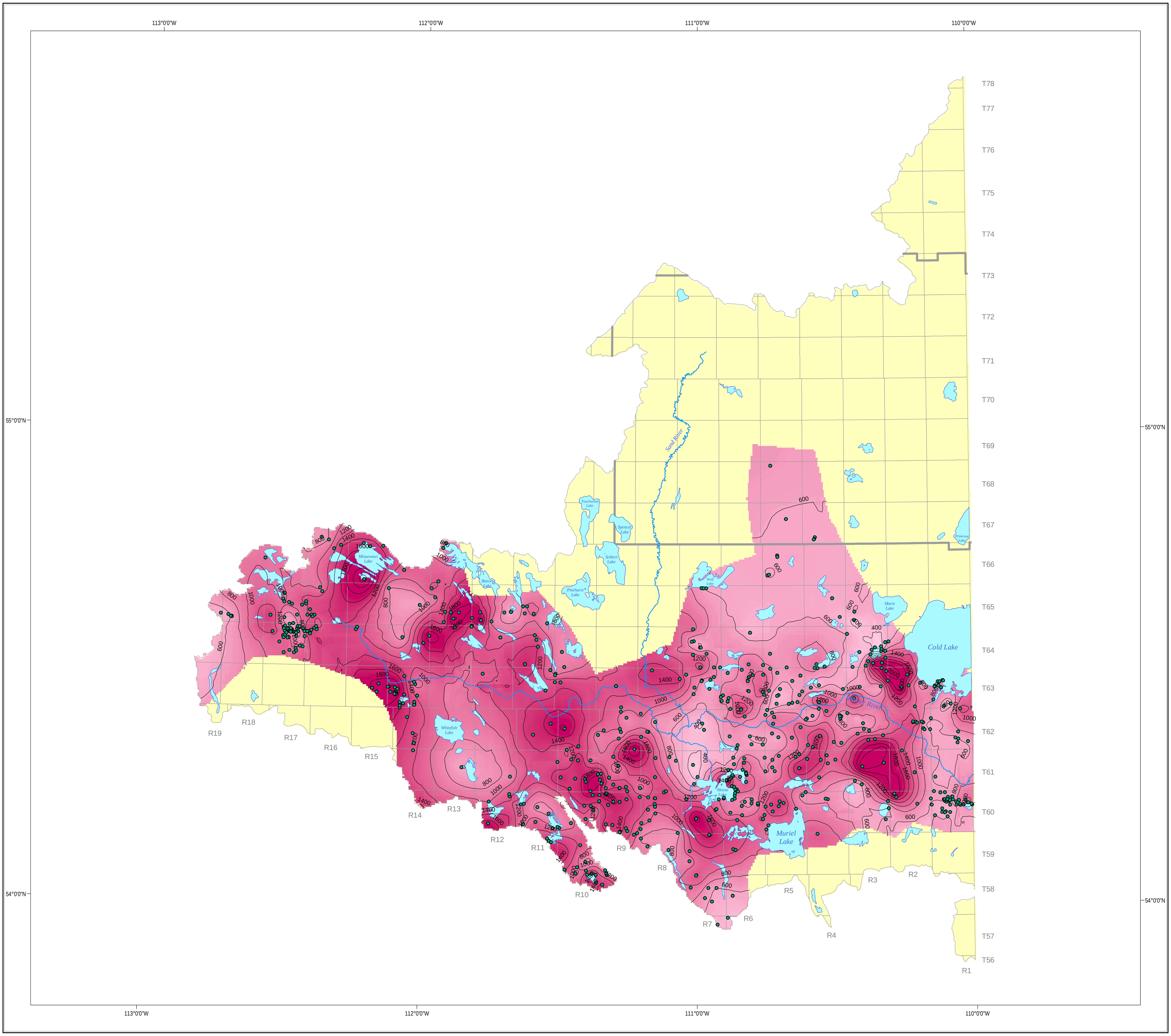
| Quality | Total in Database | Flow System SWBR | Flow System NWBR | Flow System SEBR | Flow System NEBR | Flow System Wiau | CLBR study area |
|---|---|---|---|---|---|---|---|
| Number of chemistries | 5253 | 230 | 168 | 528 | 3699 | 251 | 4876 |
| Number of wells with chemistries | 1326 | 179 | 126 | 440 | 503 | 41 | 1289 |
| Number of Aenv wells with chemistries | 863 | 179 | 126 | 376 | 178 | 3 | 862 |
| Number of industry wells with chemistries | 463 | 0 | 0 | 64 | 325 | 38 | 427 |
| Number of Industry surface chemistries | 7 | 0 | 0 | 0 | 7 | 0 | 7 |
| Number of samples with a charge balance error | 4021 | 201 | 140 | 443 | 2953 | 240 | 3977 |
| Number of wells with a charge balance error | 1148 | 162 | 108 | 381 | 449 | 41 | 1141 |
| Number of wells with a charge balance error between -5 and 5 % | 1062 | 145 | 102 | 337 | 430 | 41 | 1055 |
| Number of wells with a charge balance error between -5 and 5 % and known casing | 637 | 76 | 59 | 236 | 259 | 3 | 633 |
| Number of wells with a charge balance error between -5 and 5 % and known casing and known seal | 274 | 21 | 14 | 66 | 170 | 3 | 274 |
| Number of wells with chemistries and casing, seal criteria and 6m delta seal applied | 154 | 3 | 0 | 24 | 127 | 0 | 154 |
| Alberta Health and Wellness wells with a charge balance | 566 | 5 | 1 | 388 | 172 | 0 | 566 |
| Alberta Health and Wellness wells with a charge balance error -5 and +5 % | 524 | 5 | 1 | 356 | 161 | 0 | 523 |

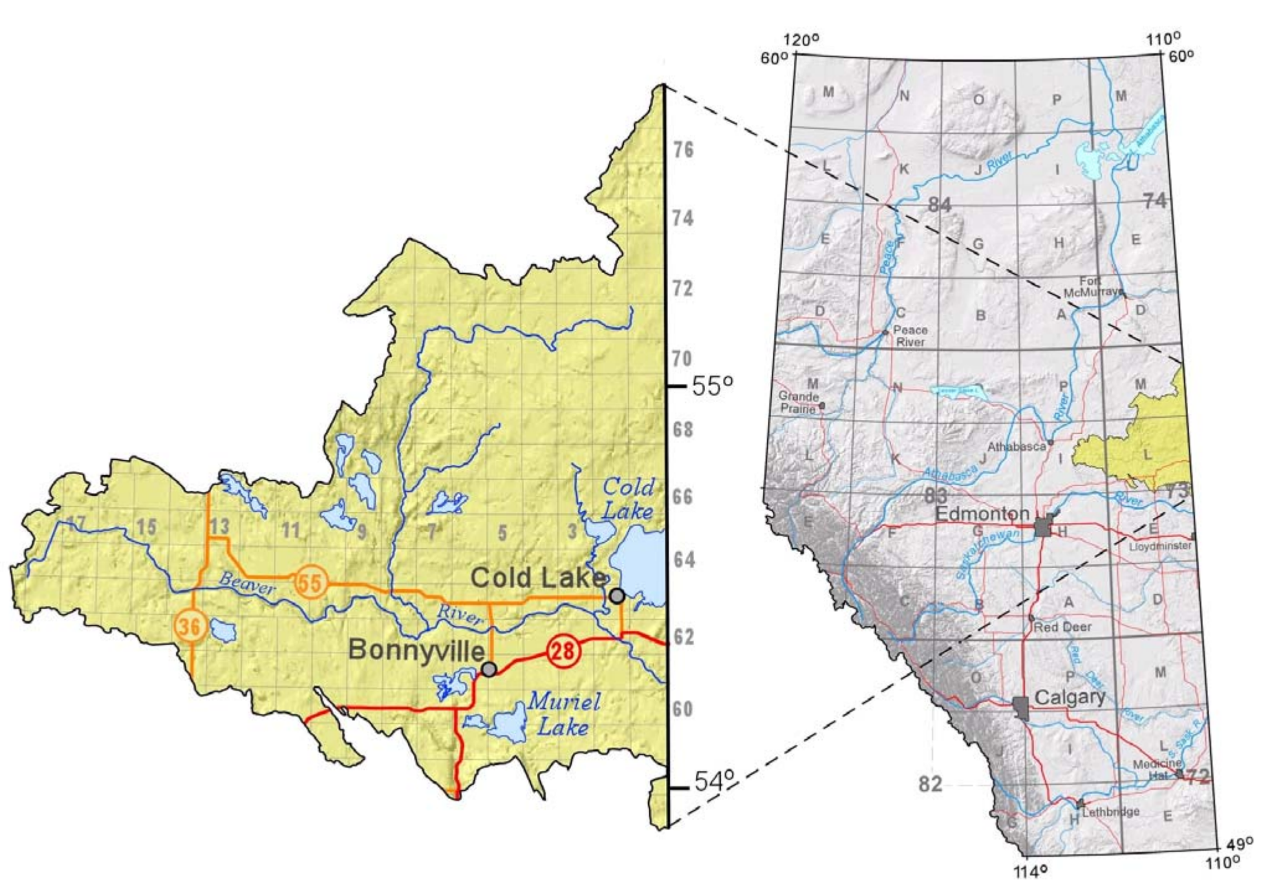
Notes:

casing criteria:  plastic, wood, cribbing.

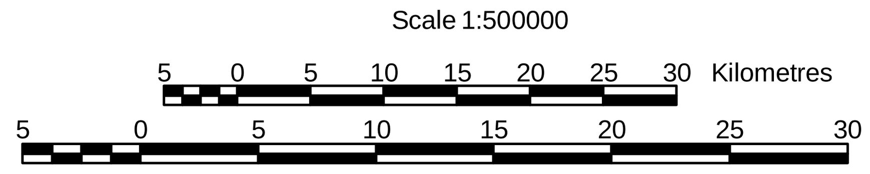
seal criteria: All seal material listed except for sandpack, gravelpack and unknown.

Delta seal: <= 6.1 metres from top of screen or perforation.




Scale 1:500000




Projection: UTM Zone 12
Datum: NAD83

December, 2004

Sample location
River
Salinity in milligrams per litre
Cold Lake Air Weapons Range Boundary
Lake
Beaver River drainage basin area (Alberta portion)

**Ground water salinity (mg/L)**
High : 2300
Low : 300
No salinity data available

## Figure 4.10 Salinity distribution in Quaternary succession

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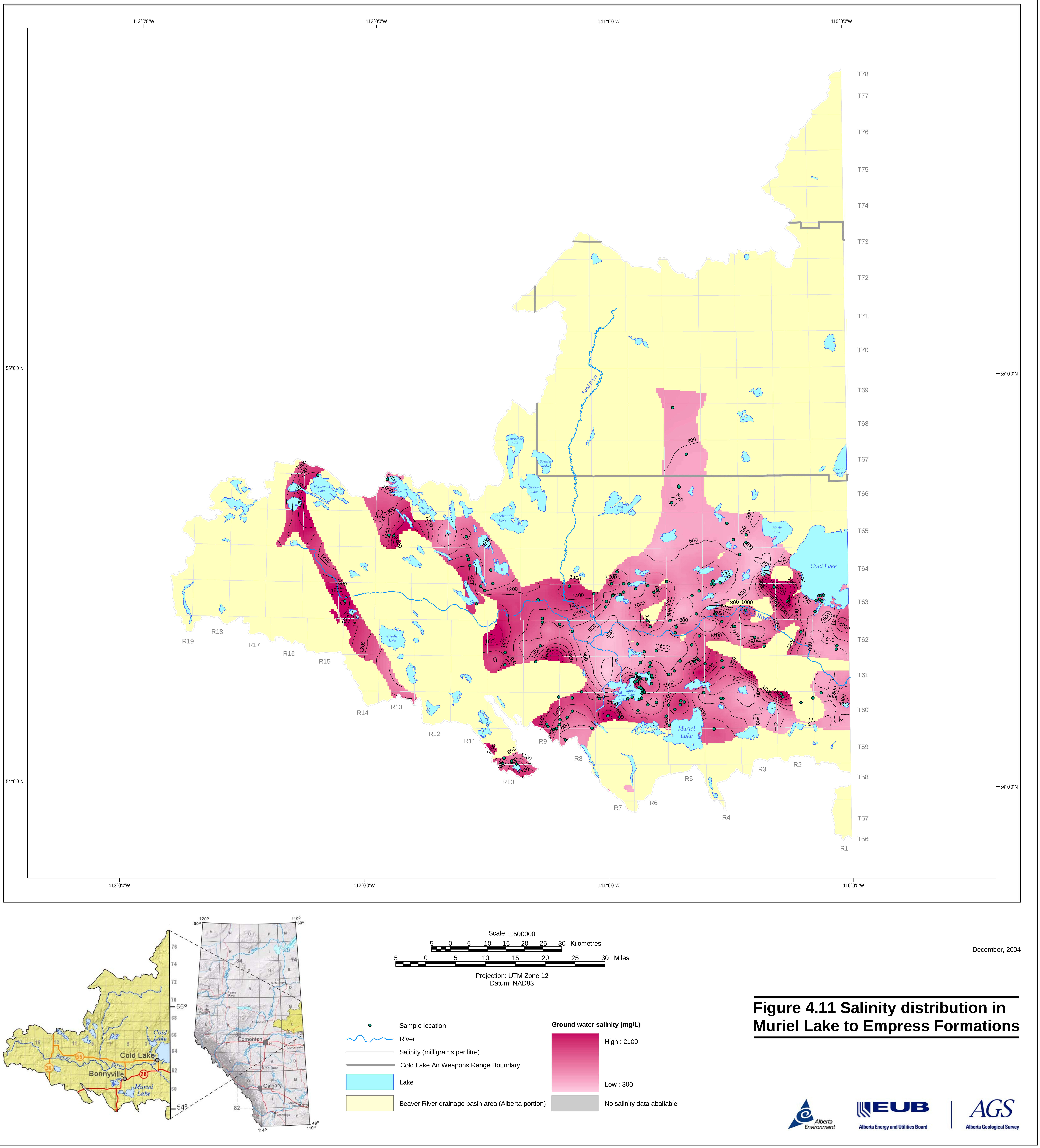
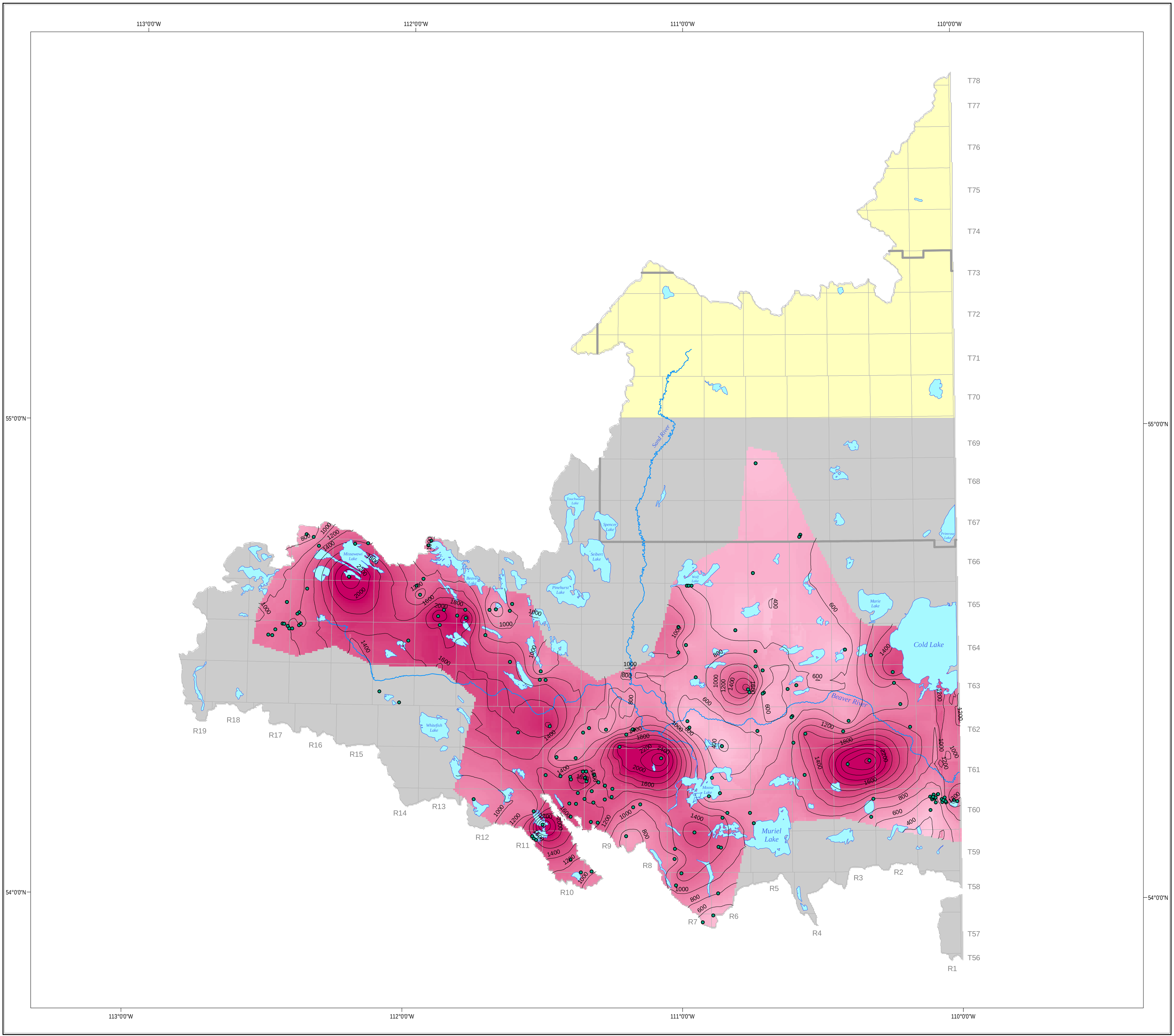
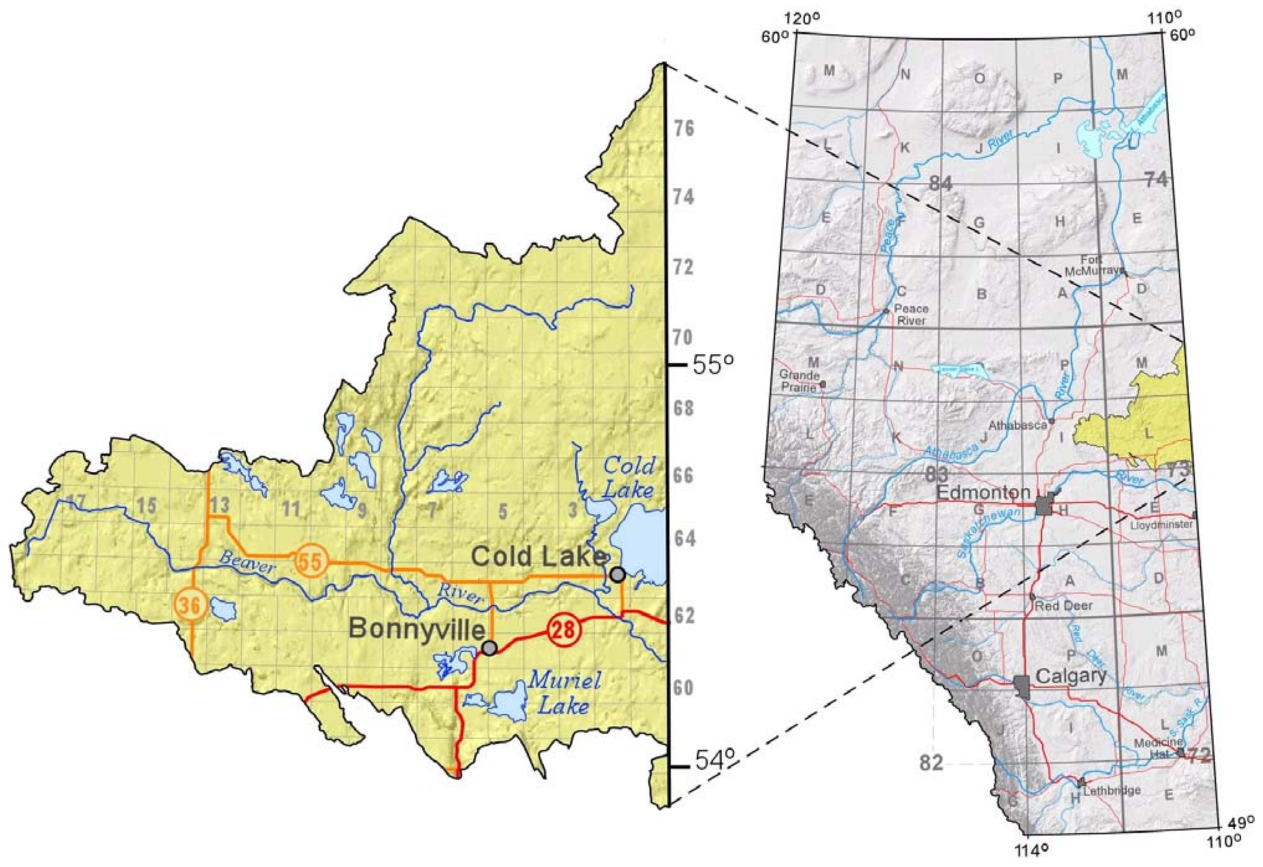



**Figure 4.11 Salinity distribution in Muriel Lake to Empress Formations**




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

December, 2004

Sample location

River

Salinity (milligrams per litre)

Cold Lake Air Weapons Range Boundary

Lake

Beaver River drainage basin area (Alberta portion)

**Ground water salinity**

High : 2500

Low : 300

No salinity data available

# Figure 4.12 Salinity distribution in Ethel Lake to Bonnyville Formations

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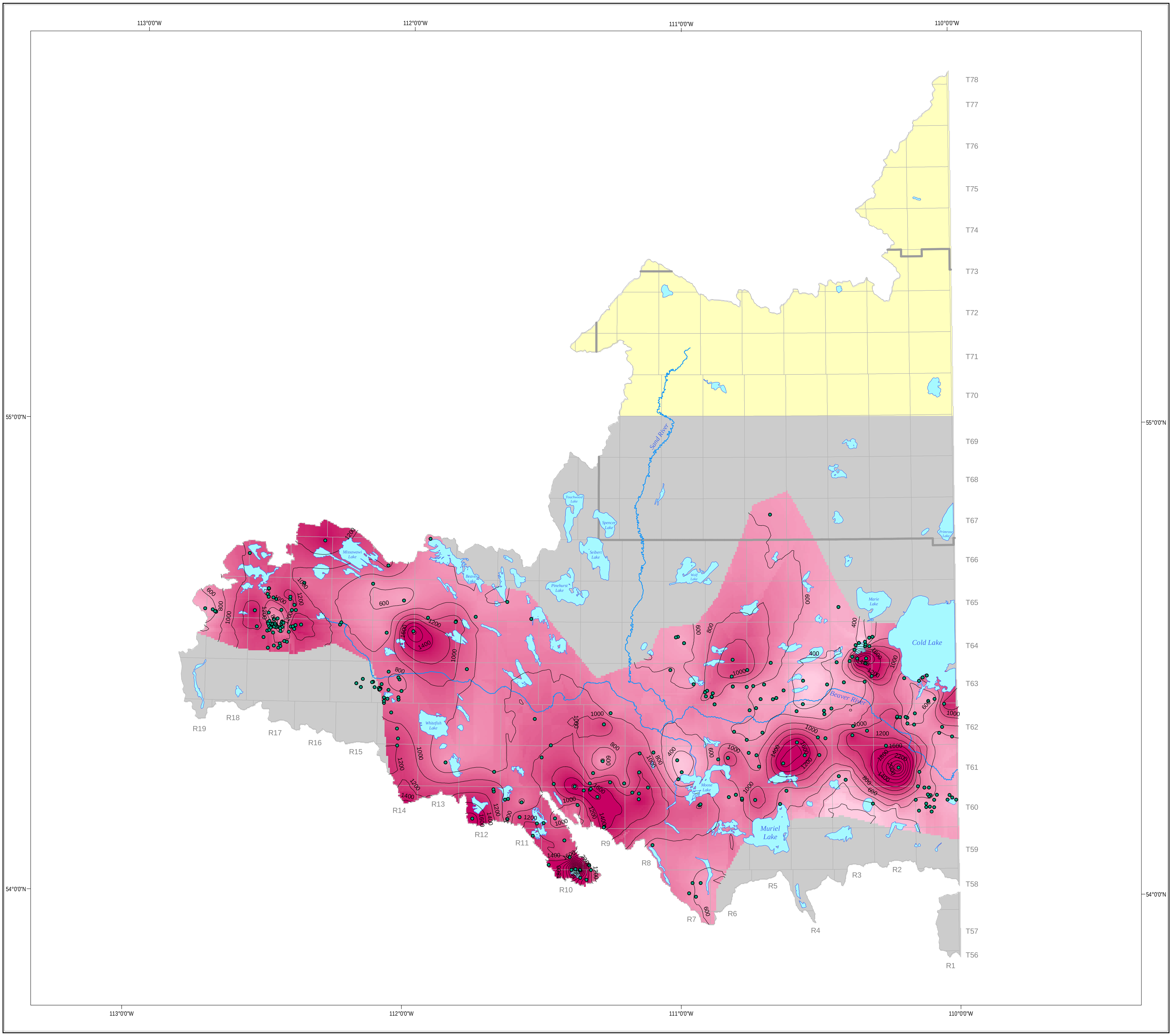
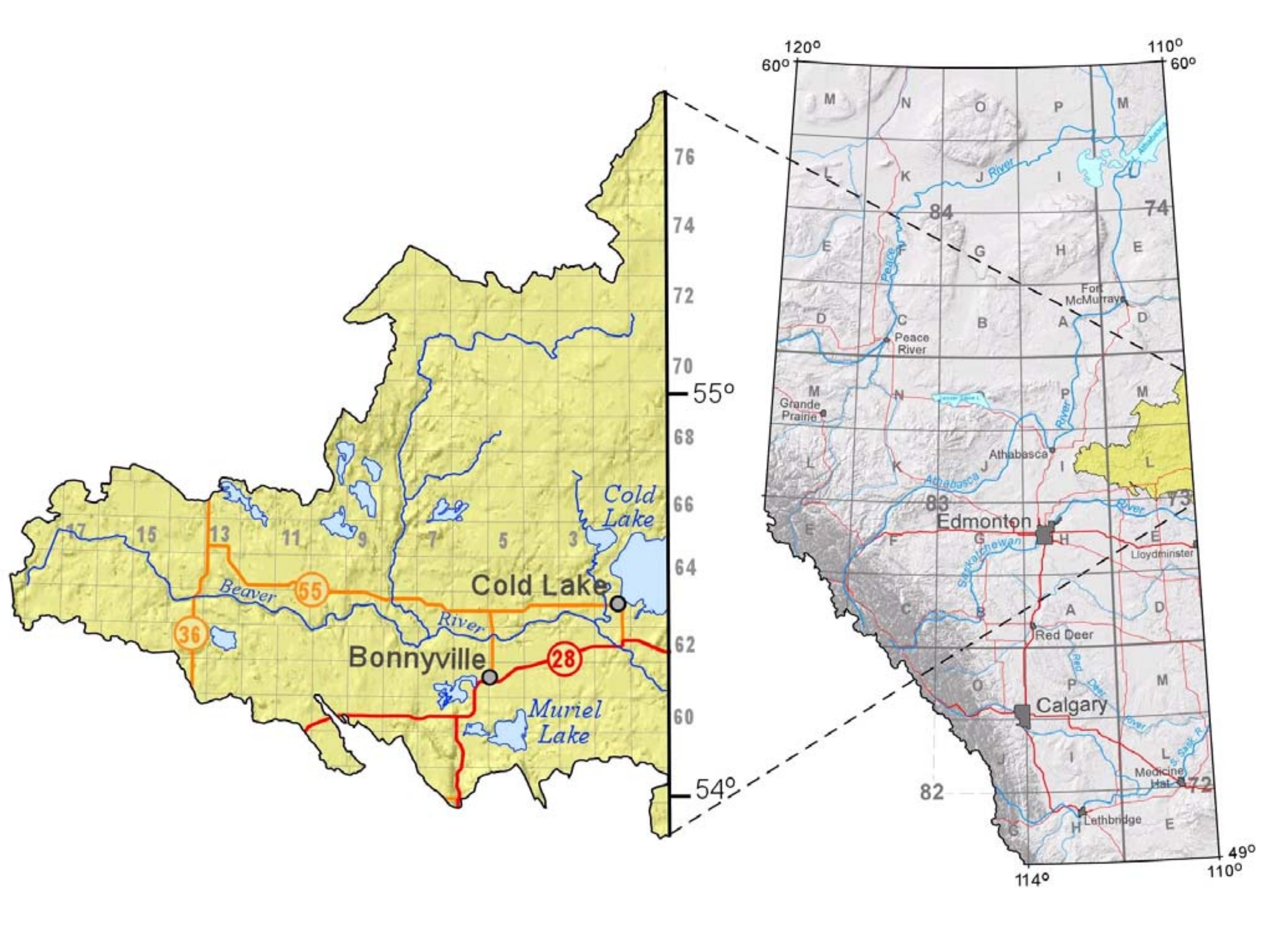
EUB Alberta Energy and Utilities Board

AGS Alberta Geological Survey




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

December, 2004

Sample location

River

Salinity in milligrams per litre

Cold Lake Air Weapons Range Boundary

Lake

Beaver River drainage basin area (Alberta portion)

**Ground water salinity**

High : 4000

Low : 50

No salinity data available

**Figure 4.13 Salinity distribution in Grand Centre to Marie Creek Formations**

Alberta Environment

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AGS Alberta Geological Survey

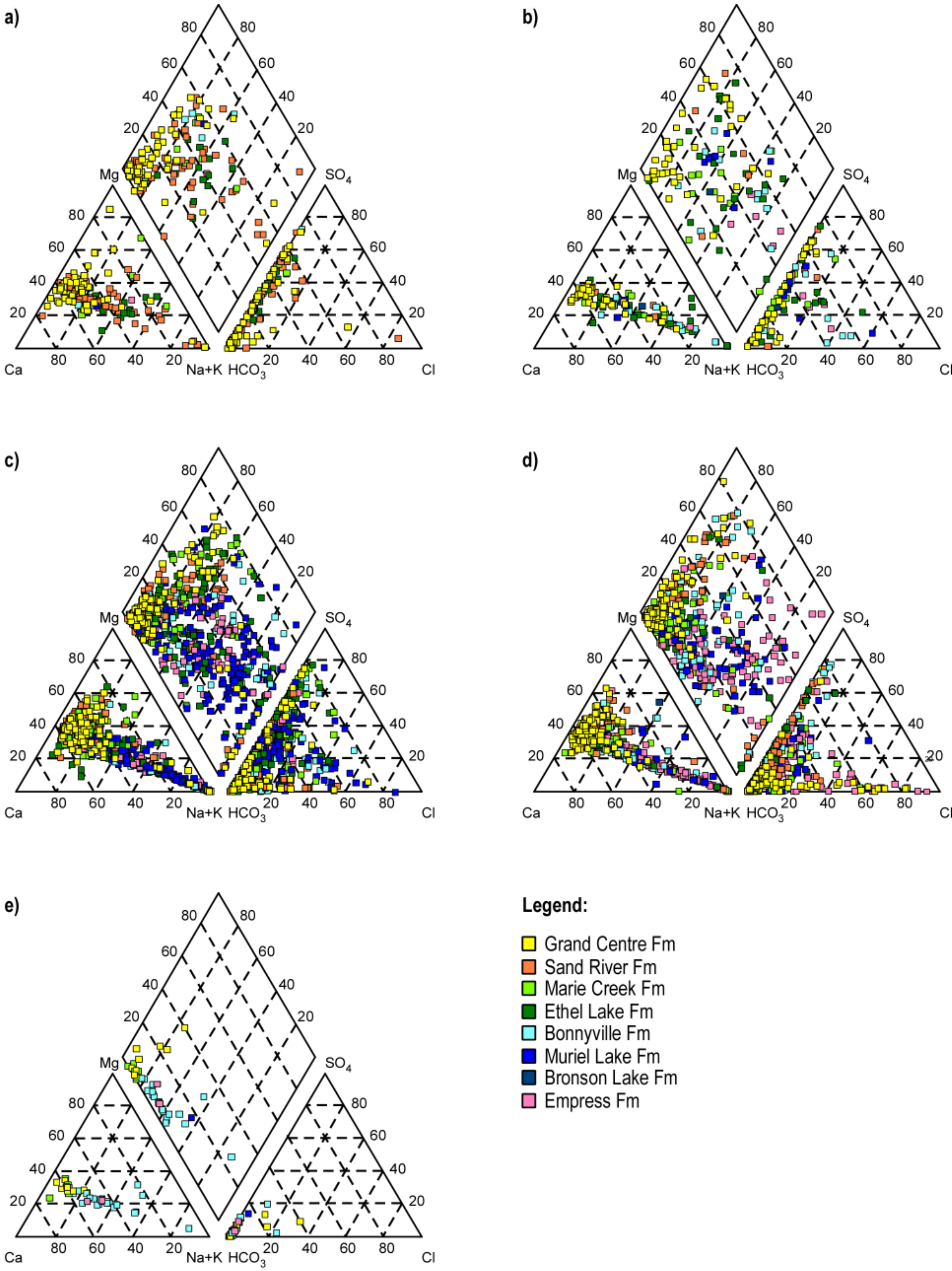



**Figure 4.14. Piper plots by flow system: A) SWBR flow system; B) NWBR flow system; C) SEBR flow system; D) NEBR flow system and; E) Wiau flow system.**

represent 100% end-members of dissolved calcium (Ca), sodium + potassium (Na+K) and magnesium (Mg) in groundwater. Likewise, the bottom right triangle plots the relative concentrations of the major negatively-charged dissolved ions (anions): bicarbonate ($HCO_3$), chloride (Cl), and sulphate ($SO_4$). The projection of the positions in each of the triangular fields into the central diamond field allow for characterization of each groundwater sample by a geochemical "type".

In Figure 4.14a, the chemistry of groundwater in the SWBR flow system shows a systematic variation in cation dominance from a calcium-magnesium groundwater to a sodium groundwater. This is a typical profile in prairie environments and represents natural water-softening along flow paths as easily-dissolved calcium-magnesium in young groundwaters are progressively lost and sodium ions are gained as the groundwater comes into contact with clay minerals. In terms of anions, there is variation from bicarbonate dominance to sulphate dominance. Again, this is typical of prairie groundwaters where bicarbonate originally captured by groundwater in the soil zone during recharge is progressively lost to geochemical reactions while sulphate is progressively gained by dissolution of sulphate minerals like gypsum and through bacterial reactions involving the sulphide minerals like pyrite often entrained in glacial tills. The chemistry of groundwater in the NWBR flow system (Figure 4.14b) is similar to the SWBR flow system.

The chemistry of the SEBR flow system and the NEBR flow system are shown in Piper plots in Figures 4.14c and 4.14d. The chemistries are similar to the previous two systems in that there is a natural water-softening trend in the cations. The two eastern systems are different than the two western systems in that there appears to be more chloride in the system.

The presence of chloride is evident on the anion triangle by the spread of data between the bicarbonate and the chloride apexes. There is some mixing of bicarbonate-sulphate waters in the SEBR flow system but the mixing in the NEBR flow system seems to be more restricted to a more pure bicarbonate-chloride mixing trend and more pure bicarbonate-sulphate mixing trend. In the SEBR system all formations have some moderate to high level of relative chloride contribution whereas in the NEBR system mainly the Empress (the deepest) and the Grand Centre (the shallowest) have higher levels of relative chloride contribution.

The reason for these trends has not yet been identified. Further investigation is required.

The Piper plot for the Wiau flow system is shown in Figure 4.14e. It appears to be more similar to the pattern of groundwater chemistry in the two western systems than the two eastern systems.

# 5 Flow Model Construction

This section provides an overview of the three-dimensional groundwater flow model of the Cold Lake-Beaver River Basin developed for this project. Development of a model is not an end unto itself. Rather it is a tool by which hydrogeologists can test hypotheses about natural groundwater flow and by which water managers can predict the impacts of various regional development scenarios. Flow models improve over time with use so this version of the model should be regarded as only the initial version and it is expected to improve in the future.

This section has three parts. First, there is a summary of lessons learned during previous modeling studies. Second, the numerical model is described. Third, key outcomes of the sensitivity study and calibration of the model are described. Model outputs of immediate use to water managers are described in Section 6.

## 5.1 Lessons from Previous Studies

The following is an attempt to synthesize the lessons learned from the review of previous modeling studies listed in Section 1. All of the reported models implemented recharge, boundary conditions, leakage, etc. differently with different degrees of success. A lot of non-uniqueness existed in the source of recharge to the groundwater system. The previous studies assigned the terms "aquifer" and "aquitard" to formations based on their dominant lithology and this terminology is used in the following discussion.

### 5.1.1 Horizontal Hydraulic Conductivity of Aquifers

The average aquifer horizontal hydraulic conductivity appears to be fairly well constrained for the Empress Unit 1 and Empress Unit 3 but not for the other sand-dominated formations. And since these aquifers exist only in the buried valleys, their areal extent was well constrained but true aquifer thicknesses needed to be used to get realistic transmissivity values.

### 5.1.2 Vertical Conductivity of Aquitards

The measured and calibrated vertical conductivity, $K_v$, of the aquitards was extremely variable For example, values for $K_v$ in the Empress 2 range from 1e$10^{-7}$ m/s to 5e$10^{-11}$ m/s. One study used variable calibrated values for $K_v$, but most other models assumed homogeneous layers or treated aquitards through layer conductance terms. In these cases the layer conductances were mainly based on calibration.

### 5.1.3 Storage Coefficients

The storage coefficients in prior studies were poorly constrained. Part of the difficulty was that there are few primary data. In most cases, models have been run with constant specific storage values, which is inappropriate because the aquifers and aquitards are not of constant thickness. The past models that used layer conductance terms for aquitards did not account for aquitard storage.

### 5.1.4 Lake Levels

Seasonal fluctuations and long term trends in Cold Lake have been shown to be highly correlated with some groundwater head levels. Smaller lake levels have been seen to vary 2 m. It may be necessary to explicitly account for lake level fluctuations in the boundary conditions, especially at Cold Lake which is well connected to the aquifer system. Otherwise near the lakes, calibration targets will be hard to maintain.

### 5.1.5 Horizontal Boundary Conditions

The boundary conditions at the locations where the buried valleys leave the domain historically have not been handled in an manner appropriate for this kind of regional study. The aquifers are hydraulically connected along the valleys and the cones of depression often intersect the domain boundaries. Constant head and no-flow boundaries were found to be an inadequate representation of the flow system when the forcings cause interaction with a physically unconstrained boundary.

It was not clear in previous studies how to assign the northern end of the Sinclair Buried Valley. The main questions were which units pinch out to the north and is the valley connected to the Wiau Buried Valley to the north. The Sinclair Buried Valley is a main source of water for the more southern buried valley systems, so proper definition of recharge and boundary fluxes is important.

### 5.1.6 Bedrock Boundary Condition

Chemistry data presented in prior studies showed that the water down to bedrock is meteoric in origin. Evidence for discharge from deeper formations does not exist. To date, evidence for significant discharge from the surficial sediments to the bedrock does not exist. Given the shaley nature of the bedrock, it seems reasonable to continue the previous assumption that the bedrock is an impermeable boundary either on the bottom or sides of the surficial units.

### 5.1.7 Recharge/Discharge from Lakes, Rivers, Wetlands and Precipitation

Possibly the most difficult task will be to develop a realistic model of the water inputs and outflows from the system. Every legacy model used a different set of boundary conditions. Most were able to reach an acceptable calibration to data, but all had some serious localized discrepancies. Much of the difficulty is due to identifiability, differing time scales and sensitivity.

The boundary at Cold Lake has been modeled as a specified head in all aquifers and it seems to have been a good starting point. The boundary at the smaller lakes is less clear. At times they have been modeled as specified head in the top layer, at other times modeled as third-type boundaries that require specification of a poorly constrained leakance parameter. The northern uplands that contain wetlands is a recharge area and a good hydrologic conceptual model is needed to develop the boundary conditions. Connectivity of rivers to each of the model layers needed improvement. The previous studies indicate that baseflow estimates into rivers or lakes would be extremely useful.

## 5.2 Model Description

In order to simulate groundwater flow under steady state or transient conditions, a dynamic numerical solution of the underlying flow equations, i.e., a “model”, is necessary. For the purposes of this study, the popular U.S. Geological Survey finite-difference model MODFLOW-2000 (Hill et al., 2000) has been chosen. MODFLOW-2000 is very widely used, fully documented, in the public-domain and runs on a variety of computer platforms.

To simulate flow in most cases, the following basic steps must occur:

1. Define the Conceptual Model. The area and depth of interest must be defined. This volume is called the domain of the model. A prior conceptual model of flow within the domain is created by integrated study of subsurface geological and hydrogeological data and observations of hydraulic behaviours of features linked to groundwater like wells, rivers, and lakes.

2. Discretize the Flow Domain. The entire domain is subdivided, or discretized, into grid blocks. Numerical models work by simultaneously solving conservation of mass and other governing flow equations for each block. To implement numerical solutions, each block is considered to have constant hydraulic properties within its volume. Variations between grid blocks allows for geological variability to be embedded in the model. The number of grid blocks will be limited by the available computer memory and processor speed. Because of computational limits, not all the natural geological variability can be captured in the model and some degree of simplification is almost always required. If the domain is discretized into too coarse of a grid, the model will not produce accurate results.

3. Parameterize the Grid Blocks. The average hydraulic properties of each block is defined in a process called parameterization. These are physical properties of the rock or sediment that determine groundwater behaviour. In steady-state simulations using MODFLOW-2000, only the average horizontal and vertical hydraulic conductivity need to be defined for each block. For transient simulations, the average elastic storage properties also need to be specified. Obtaining or estimating average block properties from sparse subsurface data is a significant challenge in any modeling exercise.

4. Define the Appropriate Boundary Conditions. The hydraulic relationships across the boundaries of the domain and the external world need to be defined for each grid cell along the boundary. The relationships are expressed in terms of a limited set of standard mathematical formulations.

5. Calibrate the Numerical Model. At this point, the numerical model has all the elements in place needed to run. If the goal of the model is to predict future hydraulic behaviour of the domain under some kind of stress like pumping or drought, then the modeler will engage in another step called calibration to improve the accuracy of the predictions. In calibration, cell parameters and boundary conditions are systematically varied to better match observed hydraulic behaviours like pump-test responses or static water levels in aquifers. Calibration can be done by simple trial and error or can employ sophisticated automatic calibration techniques. If the calibrated model matches observed behaviours not used in the calibration process, the model is said to have been verified.

The following paragraphs briefly describe how these five steps were implemented in this study.

### 5.2.1 Defining the Conceptual Model of Geology and Groundwater Flow

The conceptual models of geology and groundwater flow in the Cold Lake-Beaver River Basin are described in detail in Sections 2, 3, and 4 of this report. The challenge in modeling is always to simplify the conceptual model sufficiently so the tools of modeling can be applied while still retaining the elements of the conceptual model and geology at sufficient resolution to produce realistic results.

### 5.2.2 Discretizing the Flow Domain

The next step in model development is to mathematically define the top, bottom, and sides of the flow domain and populate the interior model with values of the hydraulic parameters controlling flow according to the geological model. For the Cold-Lake Beaver River Basin, the boundary of the basin was used to define the sides. The DEM of the present-day land surface shown in Figure 2.1 was used to define the top and the top of the bedrock shown in Figure 3.2 was used to define the bottom of the domain.

The volume of the domain was further divided into thirteen layers: one for each formation and major unit described in Section 3 plus an extra layer at the top of the Grand Centre Formation for reasons discussed below. Each grid layer is further divided into 233 equally-spaced rows and 150 equally-spaced columns, creating 800-m square grid cells. The 400-m grid spacing used for constructing the geological models was resampled to 800-m spacing without spatial averaging due to computer limitations. Each grid cell outside of the basin boundary is set to be inactive.

A choice was made to truncate the north part of the basin along an east-west line to eliminate any consideration of the Wiau flow system with this model. That flow system does not contribute water to the Beaver River and indeed is part of a different regional groundwater system lying to the north of the Cold Lake-Beaver River Basin.

The east boundary of the model domain is the Alberta-Saskatchewan border, which coincides with a reasonable hydraulic divide as discussed below.

A plan view of the model grid showing the boundary and grid cells is shown in Figure 5.1. A cross-sectional view through the model is shown in Figure 5.2. Figure 5.2a shows the cross-section as the series of layers of variable transmissivity (hydraulic conductivity times thickness) but constant thickness, which is how the model mathematically treats the input files. Figure 5.2b shows the model in cross-section as we actually conceptualize it and enter it into the model, i.e., as a series of layers of variable thickness and complex geology.

The geology of the basin described in detail in Section 3 was produced in a digital environment that was easily ported into modeling software. For this project, AGS used the GMS™ pre-processing software to produce the MODFLOW-2000 input files. The digital elevation models of the top of each formation surface were imported as arrays marking the layer tops. Where units were not present in the geological model, the surface values of the array were always set to equal the value of the uppermost underlying formation of non-zero thickness, essentially making a zero thickness value.

During the porting of the geological grids into GMS, a small increment of 0.2 m was added to the elevation of every grid cell in each layer. This converted the zero-layer thicknesses to 0.1 m thick layers. This step was necessary because MODFLOW-20000 cannot have zero-thickness layers. Since these layers are generally associated with surface-complexes or buried valley aquifers, wherever these 0.2-m thick cells occur they were be parameterized identically to an adjacent layer.

### 5.2.3 Grid-Cell Parameterization

Parameterization entails assignment of hydraulic properties to each grid block in the model domain. The parameters required depend on the governing equations of flow one wishes to solve. For this study, we are utilizing MODFLOW-2000 to solve the three-dimensional steady-state and transient equations of single-phase, constant temperature and constant density groundwater flow. Transport of dissolved constituents or water-mineral reactions along flow paths cannot be simulated with this code.

To use MODFLOW-20000, the following parameters must be defined for each grid cell: the cell thickness, the cell hydraulic conductivity (K), the vertical anisotropy in K in each cell (the assumed ratio of horizontal K to vertical K which accounts for the difference between flow across bedding and flow along bedding), the specific storage (which defines how much water can be released from elastic storage in the cell given a one-metre decline in hydraulic head), and an estimate of initial head.

Current modeling practice is focussed on use of automated, statistically driven calibration procedures to optimize the values of parameters in each grid cell (e.g., Hill, 1998). The modeling strategy used in this work prepares the foundation for using this type of approach. The grid-cell parameters are initially set as a realistic value but allowed to change during the calibration process. The calibration process aims to minimize the squared difference between field-measured observations and model calculated values. In the list of parameters below, the parameters that are allowed to vary during calibration are distinguished from those that were kept constant.

- The vertical thickness of each grid cell in each layer is defined as the vertical difference between the upper and lower bounding surfaces of each formation as discussed above. Some modifications of the grid were required to obtain better matches to observed heads but this step was not done routinely.

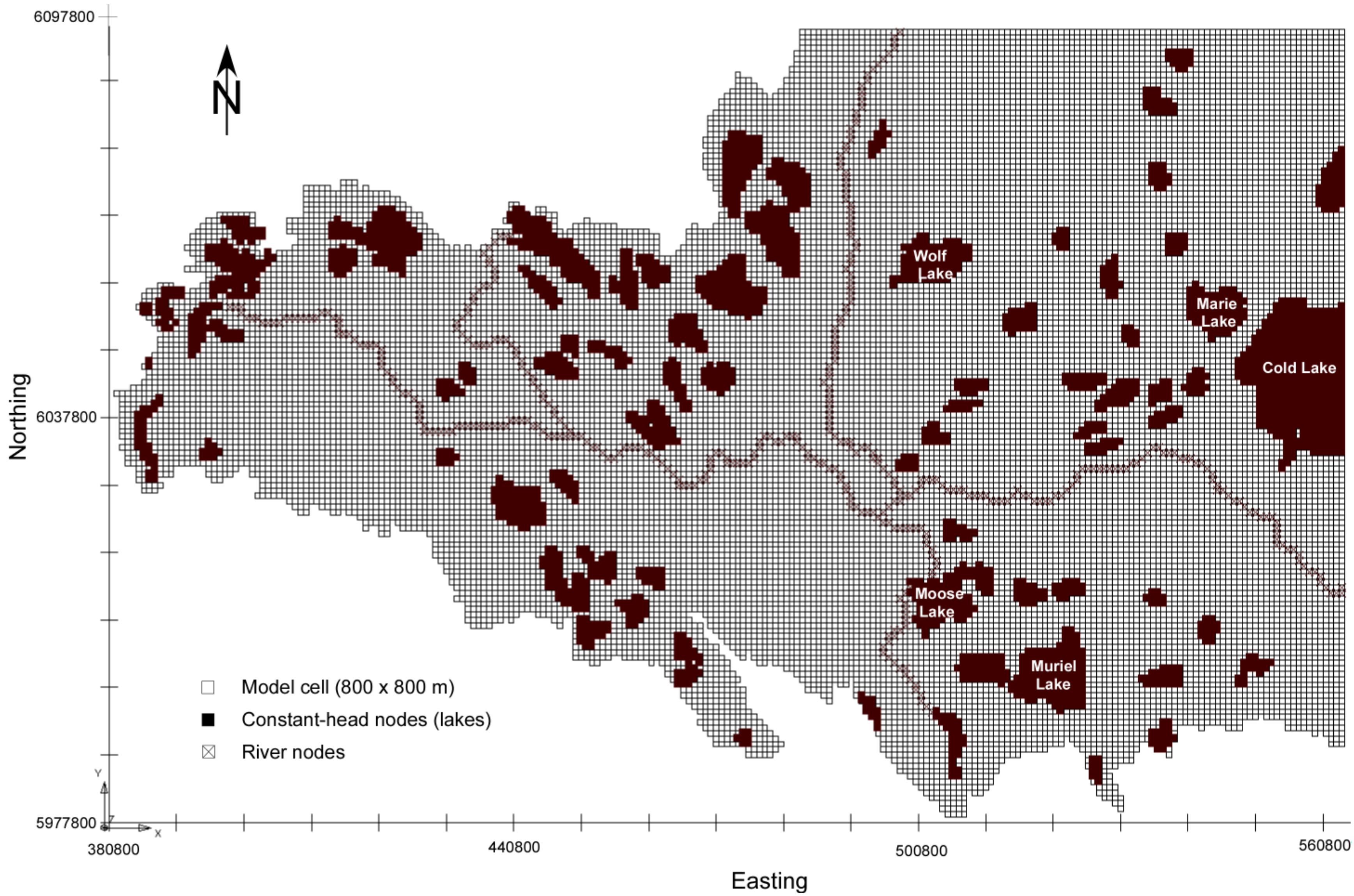



**Figure 5.1. Plan view of model grid showing boundary conditions in upper layer.**

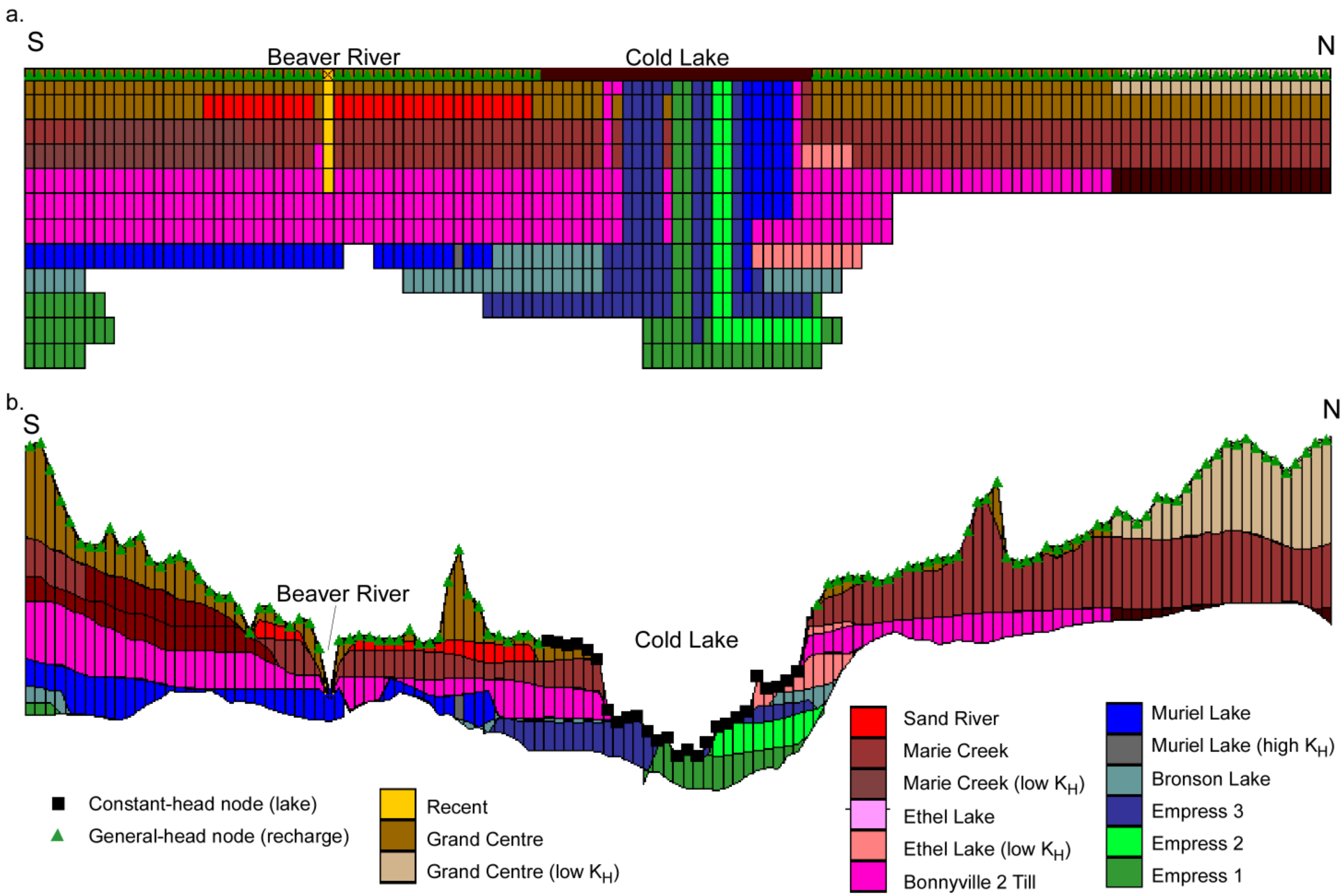



**Figure 5.2. Cross-section view through model grid.**

- The hydraulic conductivity of each formation was initially assumed to be a constant value everywhere that formation has a non-zero thickness. This parameter was allowed to change during calibration.
- The initial K value was 10 m/d for each of the following units.: Empress Unit I, Empress Unit III, Muriel Lake, Bonnyville Unit I sand, Ethel Lake, and Sand River. This initial estimate was based on the distribution of pump-test derived values discussed in Section 3 These values were allowed to vary independently during calibration.
- An initial value of 0.001 m/d was assigned to the clay and till dominated formations: the Empress Fm. Unit 2, the Bronson Lake, the Bonnyville 1 till, the Bonnyville 2, the Marie Creek, and the Grand Centre. These values were allowed to vary independently during calibration.
- An initial constant value of vertical anisotropy of $K_v$:$K_h$ of 1:100 was applied to each till dominated layer. This parameter was allowed to vary during calibration while remaining a single value for all layers.
- The sand-dominated formations were kept isotropic with respect to K. This parameter was allowed to vary during calibration while remaining a single value for all layers.
- An initial constant specific storage value of 1e-5 was applied to each layer. These values were allowed to vary during calibration to transient observations.
- An initial hydraulic-head value for each variable head grid cell was assigned to be equal to the topographic elevation of the land surface above each grid cell. This value is always allowed to vary unless the grid cell was a constant head boundary node, a river node, or a surface general-head boundary node (see below).

### 5.2.4 Assignment of Boundary Conditions

The flow model must be mathematically linked to natural sources and sinks of water to simulate flow. These sources and sinks are collectively called the boundary conditions.

The boundary conditions were chosen as follows:

1. No-flow boundaries are used around the south and west perimeter of the study domain that matched the basin boundary.
2. A straight, north-south no-flow boundary is used along the Alberta-Saskatchewan border north of Cold Lake. This choice presumes that flow along the provincial border north of Cold Lake goes from north-to-south, not an unreasonable choice given that Cold Lake straddles the border.
3. A straight, east-west no-flow boundary was used at the north end of the model where the Wiau flow system begins.
4. General head boundaries are used for the exit points of buried valleys that extend beyond the limits of the Cold Lake-Beaver River Drainage Basin. The reference head in each case is a measured steady state head-value at a well or lake elevation located far outside the boundary. The leakance term was estimated as the layer's conductivity times the distance from the boundary to the reference head location times the width of the cell divided by the thickness of the aquifer at the location of the boundary. This boundary condition is not perfect, because it will not account for induced infiltration or cross formational flow that occurs outside of the domain, but it will allow for a variable head at the boundary and changes in boundary flux. This type of boundary condition definition is illustrated in Figure 5.3.
5. Each major lake is treated as a constant head boundary defined by lake elevation.

6. Each major river is treated with river nodes – these are special grid-cells that act as water sources whenever predicted hydraulic heads in the cell below fall below the predefined elevation of the river node and act as water sinks whenever predicted hydraulic heads in the cell below rise above the predefined elevation of the river node.
7. To create distributed recharge across the uppermost surface, we chose to introduce recharge by dividing the Grand Centre layer into two separate layers and setting the upper layer to be a general-head boundary condition. In this kind of boundary condition, the hydraulic head is specified as the land surface elevation. This is equivalent to assuming that the water table is at the land surface, which is not an unreasonable simplification for a regional model, especially considering the large extent of wetlands and gleysols in the basin . The amount of flux into or out of the bottom of the cell is then calculated as the product of the head difference between the constant head cell and the underlying cell and a conductance term. With this kind of boundary condition, the uppermost layer never dries but rather creates the necessary flux needed to maintain saturation. This flux is recorded and after calibration serves as a model-derived estimate of recharge across the boundary. This boundary condition is illustrated in Figure 5.3.

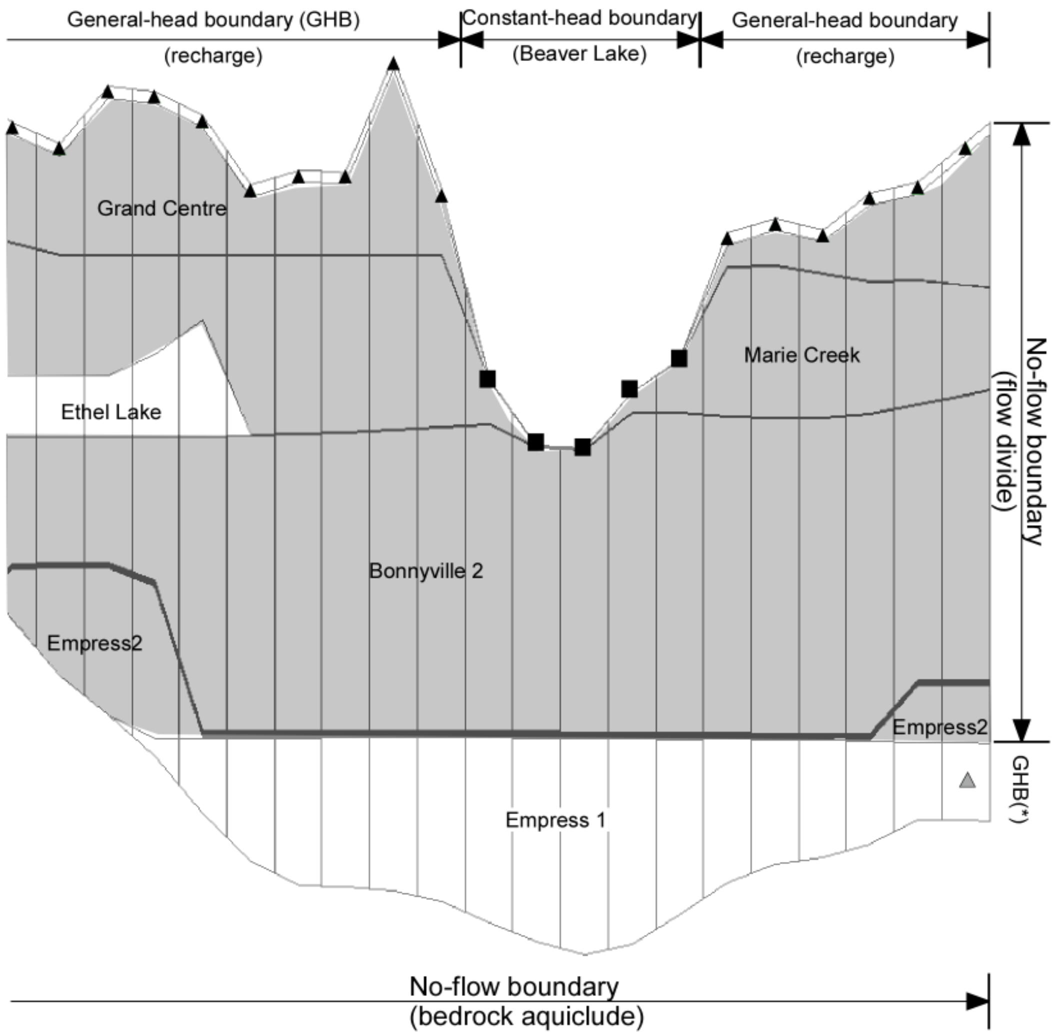
## 5.3 Model Calibration

The step of model calibration involves altering the parameters of the model to minimize descriptive and predictive model error. The measure of success of calibration is usually quantified by some measure of the difference between observed values of hydraulic head or other state variable and those obtained from the model. MODFLOW-2000 has sophisticated capabilities that assist the modeler in the calibration step. These are discussed in detail in Hill (1998) and Hill et al. (2000).

One such capability is the ability to calculate very accurate estimates of model sensitivities to parameter changes. If the model is very sensitive to changes in a given parameter it means that small changes in the value of the parameter may create significant changes in predicted hydraulic heads. This means that the modeler can make changes in that parameter which may help reduce the difference between predicted values and observed values of a state variable like hydraulic head.

In simple models, the modeler can intuitively assess sensitivities by trial and error adjustments of a limited number of parameters, re-running the model after each change and seeing if there is an improvement in predictive capabilities. In complex models such as this one, there are too many parameters to independently adjust and re-run to intuitively gauge sensitivities. In MODFLOW-2000, the sensitivities are automatically calculated by a sophisticated process. The resulting sensitivities of calculated hydraulic head (or other state variable like flux out of a particular boundary) associated with each observation point are scaled (to allow use of different kinds of measurements) and then summed.

The resulting statistic is called the composite scaled sensitivity and indicates the total amount of information provided by the observations for the estimate of each parameter. Large composite scaled sensitivities indicate there is a lot of information in the available observations for improving the estimate of that parameter. Small scaled-sensitivities indicate that there is not much information in the available observations for improving the estimate of that parameter. Large composite scaled sensitivities also indicate what kind of new information would be most useful (by this measure) to collect in future field investigation or monitoring programs. Where such new information would be best collected is discussed in Section 6.




Recharge:

$Q_R = C_R\ (h_b - h)$
$C_R = K_T\ L\ W/M;$

*Extra-basinal flow:

$Q_E = C_E\ (h_b - h)$
$C_E = K_H\ D\ W/T$

where $Q_R$ = recharge as volumetric flux ($m^3$/d); $C_R$ = conductance of soil zone ($m^2$/d); $h_b$ = head at the boundary (set to ground surface elevation) (m); h = head in the aquifer (m); $K_T$ = vertical hydraulic conductivity of zone (m/d); L = length of cell (m); W = width of cell; M = thickness of zone (m);
$Q_E$ = Flow out of/into the model area ($m^3$/d), $C_E$ = term describing the conductance between model boundary and external boundary ($m^2$/d); $K_H$= horizontal hydraulic conductivity of channel aquifer (m/d); D = distance to external boundary; T = thickness of channel aquifer.

**Figure 5.3. Explanation of boundary conditions used to simulate behaviour of buried valley aquifers at model boundary.**

Histograms of the composite scaled sensitivities for the Cold Lake-Beaver River Basin model with respect to observed static water-levels (hydraulic heads) under steady-state and under steady-state pumping conditions are shown in Figure 5.4. The steady-state results show that the model is most sensitive to the hydraulic conductivity of the Muriel Lake Formation, the vertical anisotropy of the till-dominated layers (aquitards) and the conductance term associated with linking the uppermost model layer to the rest of the model. The same is true for the model under steady-state pumping conditions.

The importance of the hydraulic conductivity of the Muriel Lake Formation to overall model performance is believed to be due to its stratigraphic position as the lowest aquifer that still possesses widespread connectivity to lakes and rivers. The degree to which recharge reaches lower units via vertical flow is controlled by how much lateral flow there is in the Muriel Lake Formation. Likewise, the degree of lateral flow in the Muriel Lake Formation determines how vertically well drained the overlying formations are, since it is the lowest widespread drain for everything above it. The other parameters with relatively large composite scaled-sensitivities also have a strong control on groundwater flux through the model.

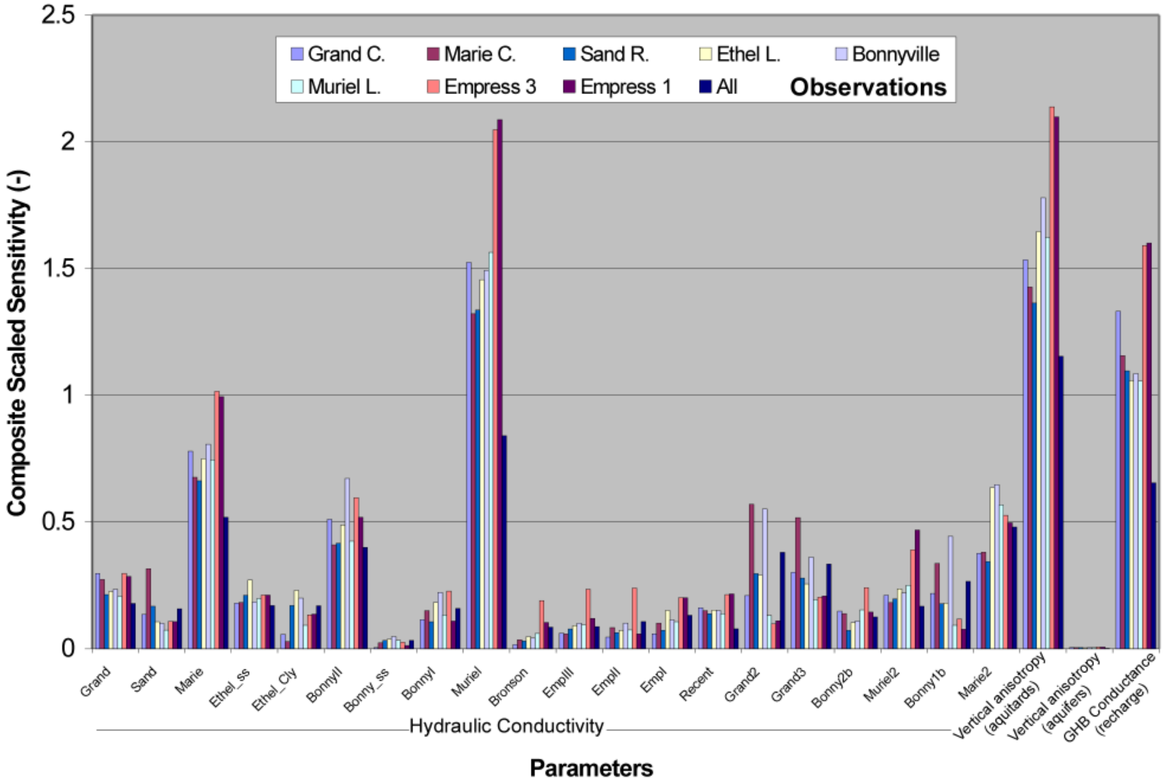
Another capability of MODFLOW-2000 that assists in model calibration is the generation of estimates of pair-wise parameter correlation coefficients. Parameter correlation coefficients indicate whether parameter values estimated by calibration are likely to be unique. That is, if two parameter values are strongly correlated in a given model, then any combination of values of those two parameters that have the same ratio will provide a similar calibration result yet still produce different predicted outcomes. When such a situation arises, a new kind of observation may be needed to reduce the correlation coefficient and thereby produce a more unique result in parameter estimation and calibration. For example, if only heads are available (as in this study), then flux measurements can be gathered to reduce parameter correlation (Poeter and Hill, 1997).

Table 5.1 shows the parameter correlation coefficients in the AGS model. The highest values of parameter correlation are found between the anisotropy of the tills (aquitards), the hydraulic conductivity of the Marie Creek Formation, and the hydraulic conductivity of the Bonnyville Formation Unit 1 till. This means that the additional observations or prior knowledge of one or more of these parameters is required to produce a unique calibration of the model.

The composite-scaled sensitivities and pair-wise parameter correlation coefficients were used to manually calibrate the model in a steady-state mode. To calibrate the model in this step, the model was divided into four sub-models based on flow systems. Each sub-model was manually calibrated to achieve the best fit to a representative subset of observed static water levels in each formation using the composite scaled sensitivities and the pairwise parameter correlation coefficients as guides.

Once an acceptable flow-scale calibration was achieved for all four flow systems, the submodels were reassembled into the single model. Where parameters were comparable, a single or average value was assigned to the formation again. Where parameters were not comparable, the regional model was zoned with respect to that parameter to accommodate the different values. A final global calibration was then done with steady-state observations. Results were deemed to be acceptable if the average error was generally less than 10% of the total hydraulic gradient across the model domain. Graphs showing the computed hydraulic heads versus observed static water levels by formation are in Figure 5.5.

In order for the model to be used for investigation of transient response to pumping, the specific storage values needed to be calibrated. Two multi-year pumping events with good monitoring data and regional drawdown extents in their respective aquifers were chosen for this part of the model calibration. Both of a.




b.

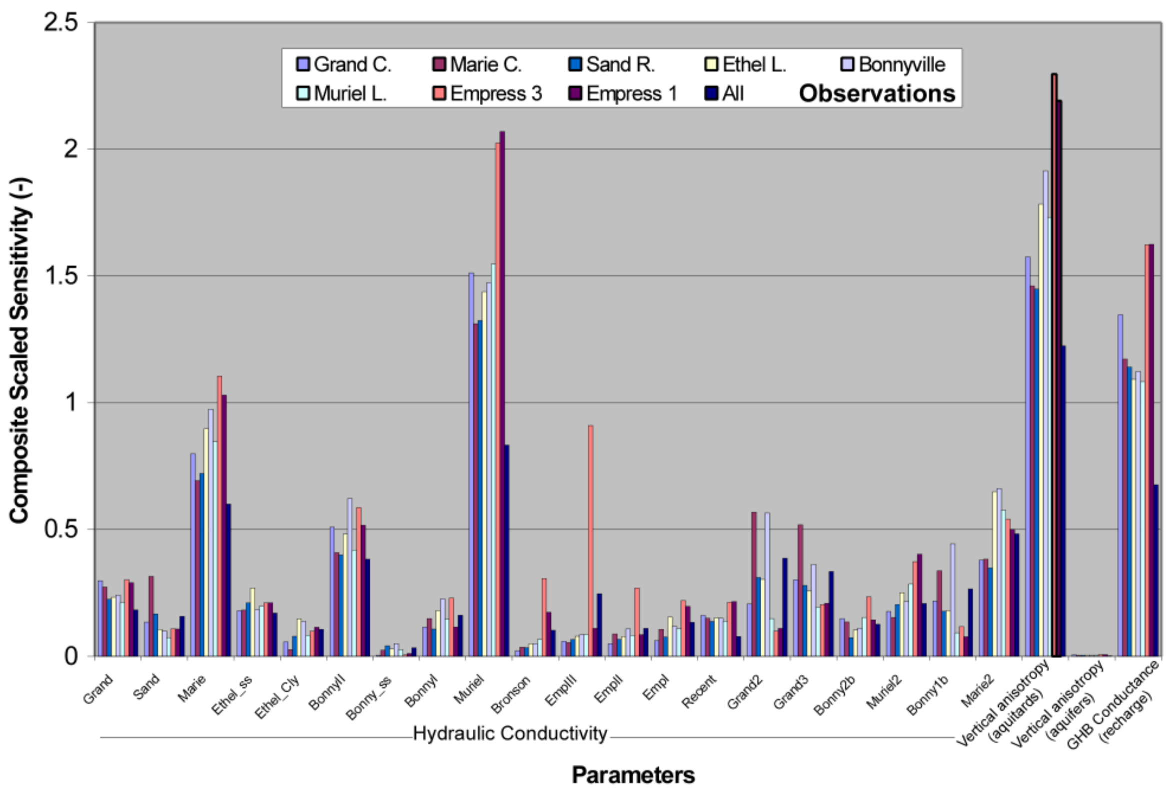



**Figure 5.4. Histogram of composite scaled sensitivities for model parameters with respect to hydraulic heads under A) non-pumping and B) pumping conditions.**

**Table 5.1. Parameter correlation coefficients in the AGS model.**

| | Grand | Sand | Marie | Ethel | BonnyII | Bonny_ss | BonnyI | Muriel | Bronson | EmpIII | EmpII | EmpI | Recent | ANI_aqt | ANI_aqf | GHB |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Grand** | 1.0 | 0.05 | 0.67 | 0.002 | 0.09 | -0.10 | 0.69 | 0.04 | 0.59 | 0.02 | 0.62 | 0.05 | -0.04 | 0.69 | 0.13 | -0.22 |
| **Sand** | | 1.0 | -0.00 | -0.19 | -0.07 | -0.002 | 0.09 | 0.11 | -0.01 | 0.01 | 0.07 | 0.14 | 0.00 | 0.01 | 0.16 | -0.01 |
| **Marie** | | | 1.0 | -0.05 | -0.05 | -0.09 | 0.89 | 0.04 | 0.77 | 0.05 | 0.65 | -0.08 | -0.11 | 0.99 | 0.08 | 0.32 |
| **Ethel** | | | | 1.0 | -0.06 | -0.06 | -0.02 | -0.24 | -0.07 | 0.01 | 0.03 | 0.07 | -0.06 | -0.06 | -0.01 | -0.03 |
| **BonnyII** | | | | | 1.0 | 0.02 | -0.06 | 0.07 | -0.03 | -0.06 | 0.003 | -0.01 | -0.22 | -0.06 | 0.19 | -0.12 |
| **Bonny_ss** | | | | | | 1.0 | -0.17 | 0.01 | -0.12 | -0.03 | -0.09 | 0.05 | -0.08 | -0.11 | -0.06 | -0.03 |
| **BonnyI** | | | | | | | 1.0 | 0.03 | 0.71 | 0.05 | 0.58 | -0.06 | -0.09 | 0.91 | 0.10 | 0.29 |
| **Muriel** | | | | | | | | 1.0 | 0.01 | 0.00 | 0.06 | -0.07 | -0.23 | 0.02 | 0.62 | 0.09 |
| **Bronson** | | | | | | | | | 1.0 | -0.21 | 0.59 | -0.08 | -0.07 | 0.79 | 0.08 | 0.25 |
| **EmpIII** | | | | | | | | | | 1.0 | 0.03 | -0.04 | 0.06 | 0.05 | 0.002 | 0.05 |
| **EmpII** | | | | | | | | | | | 1.0 | -0.31 | -0.10 | 0.66 | 0.14 | 0.11 |
| **EmpI** | | | | | | | | | | | | 1.0 | 0.01 | -0.06 | 0.10 | -0.06 |
| **Recent** | | | | | | | | | | | | | 1.0 | -0.09 | 0.29 | 0.03 |
| **VANI_aqt** | | | | | | | | | | | | | | 1.0 | 0.07 | 0.35 |
| **VANI_aqf** | | | | | | | | | | | | | | | 1.0 | 0.26 |
| **GHB** | | | | | | | | | | | | | | | | 1.0 |

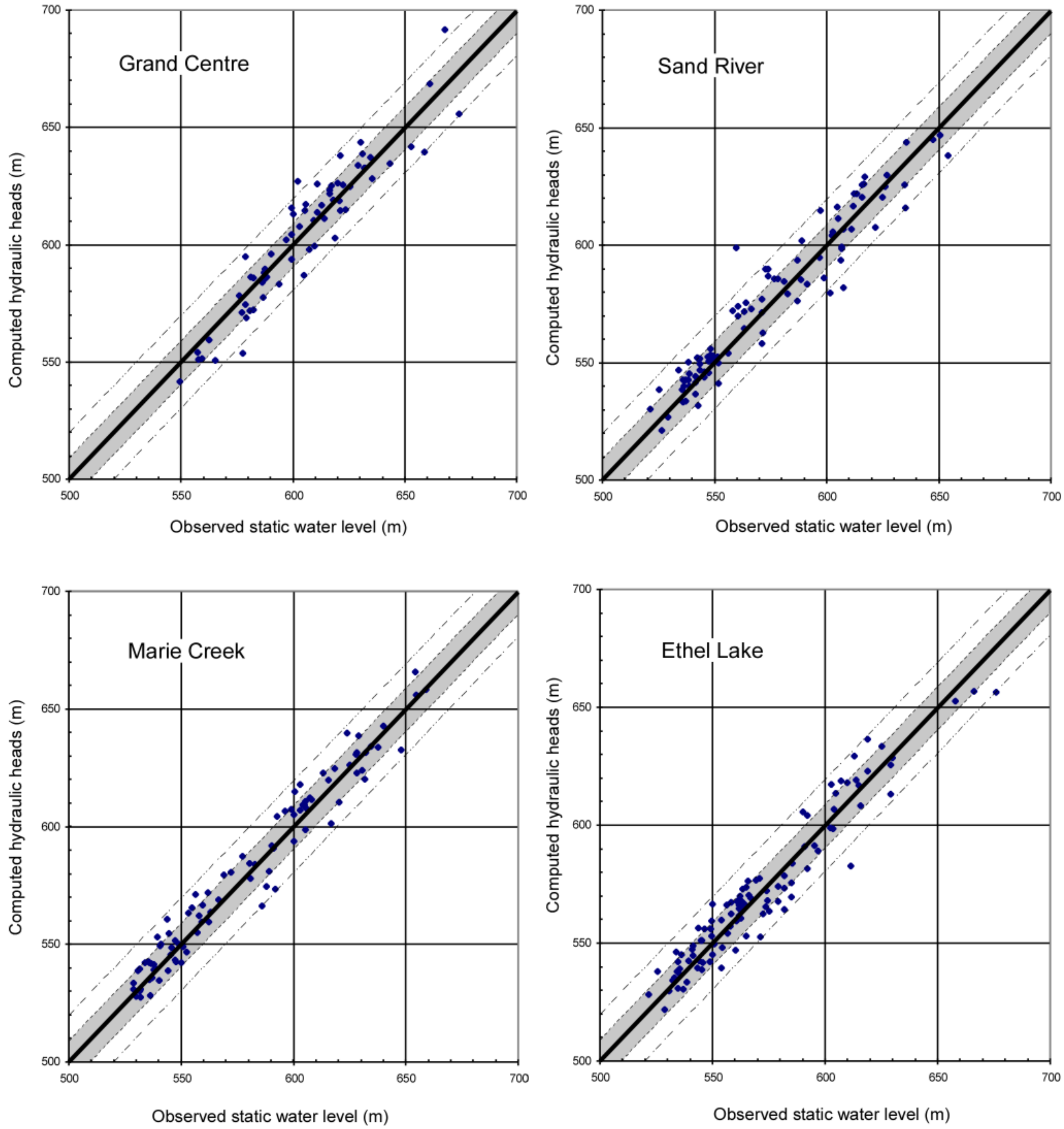



**Figure 5.5. Calibration cross-plots of observed versus predicted hydraulic heads by formation.**

these pumping events were associated with groundwater withdrawal for bitumen production. This step was only conducted for the NEBR submodel. The results of the calibration are in Figure 5.6. The results were deemed to be acceptable.

Figures showing the predicted hydraulic head distributions from the final calibrated model for the Grand Centre Formation, the Sand River Formation, the Ethel Lake Formation, the Muriel Lake Formation, the Empress Formation Unit 3 and the Empress Formation Unit 1 are in Figure 5.7.

Table 5.2 compares the statistics of measured horizontal hydraulic conductivity by aquifer to the calibrated values in the regional model. The calibrated model parameters are compared to the results from selected prior studies in Table 5.3.

### 5.4 Recommendations for Improvement of the Model and Future Work

It should be emphasized that the current numerical flow model of the Cold Lake-Beaver River Basin simulates groundwater flow on a regional scale and therefore does not necessarily account for local heterogeneities that might be important for specific questions and concerns. Also, certain parameters (i.e., aquitard hydraulic conductivity, recharge rates, river baseflow) in the model are not well constrained by field-measured data, which implies that non-uniqueness is a problem. The following suggestions should help to improve the model:

- Additional zoning of hydrostratigraphic units to better match computed to observed hydraulic heads.
- Refinement of the grid in areas of concern (i.e., pump sites).
- Adjust boundaries of the model area to accommodate channel aquifers continuing beyond the current extent of the CLBR Basin, include connectivity to the Wiau Channel to the north, and account for flow across the Alberta-Saskatchewan border.
- Assign a specified-flux boundary to better model recharge and account for seasonal changes in transient model runs.
- Re-visit the stratigraphic interpretation and improve lake/river geometries (additional bathymetry data) in areas of significant divergence of model results from field observations.
- Introduce third-type boundary for lakes and integrate hydraulic data on lake (and riverbed) sediments to better characterize and quantify groundwater – surface water interactions.
- Validate model with new and additional observations and for new pumping scenarios.

## 6 Towards a Regional Groundwater Management Framework

> *Although many people have expressed concerns about the ambiguity of the term sustainability, the fact remains that prudent development of a ground water basin in today's world is a complicated undertaking. A key challenge for sustained use of ground water resources is to frame the hydrologic implications of various alternative development strategies in such a way that their long-term implications can be properly evaluated. Each hydrologic system and development situation is unique and requires an analysis adjusted to the nature of the water issues faced, including the social, economic and legal constraints that must be taken into account*.
>
> W.M. Alley and S.A. Leake, Ground Water, 42, no. 1, p. 16

This quotation underscores the complexity of managing groundwater development in a basin. There are

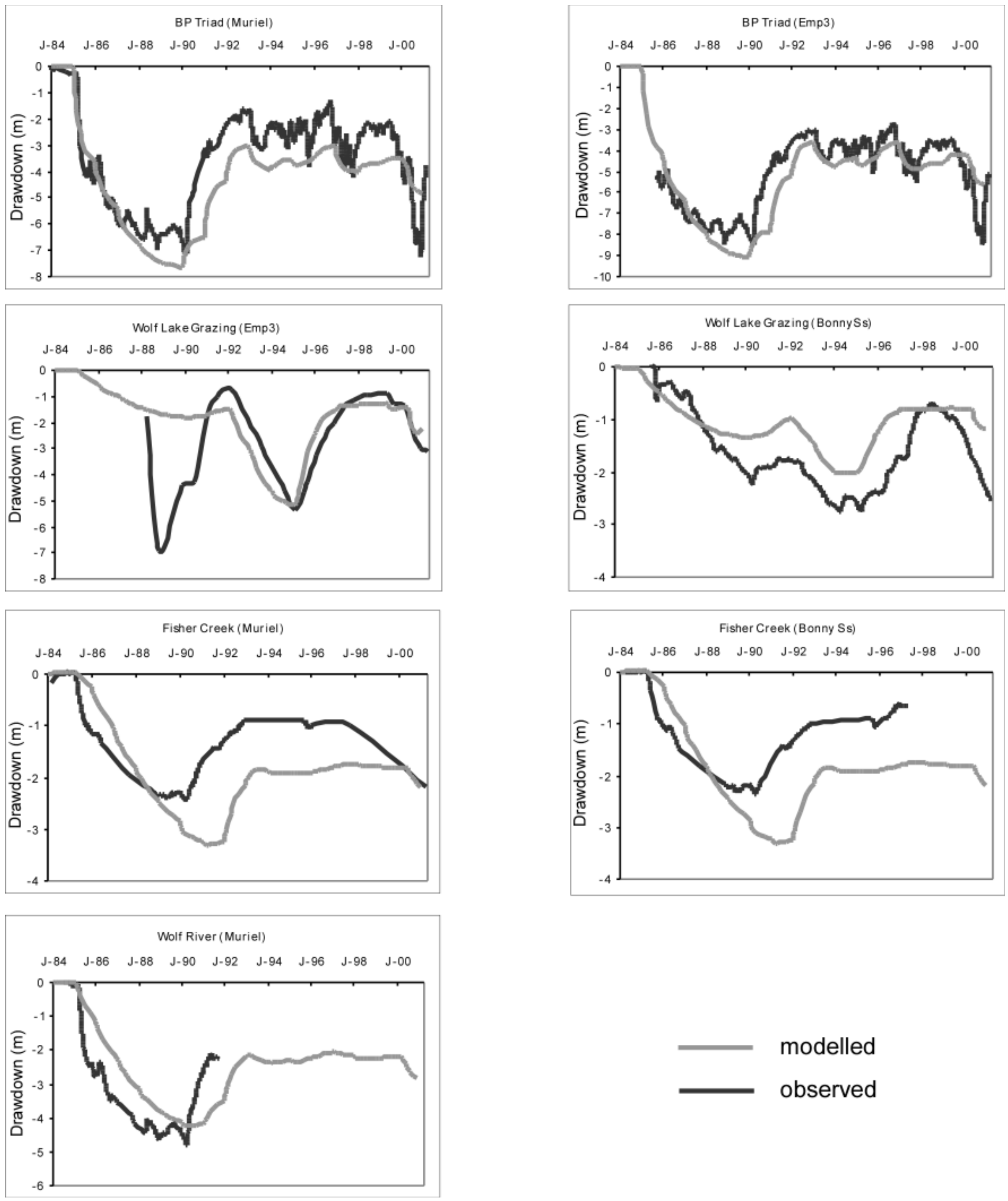



**Figure 5.6. Calibrated versus observed transient hydrographs for observation wells near production wells.**

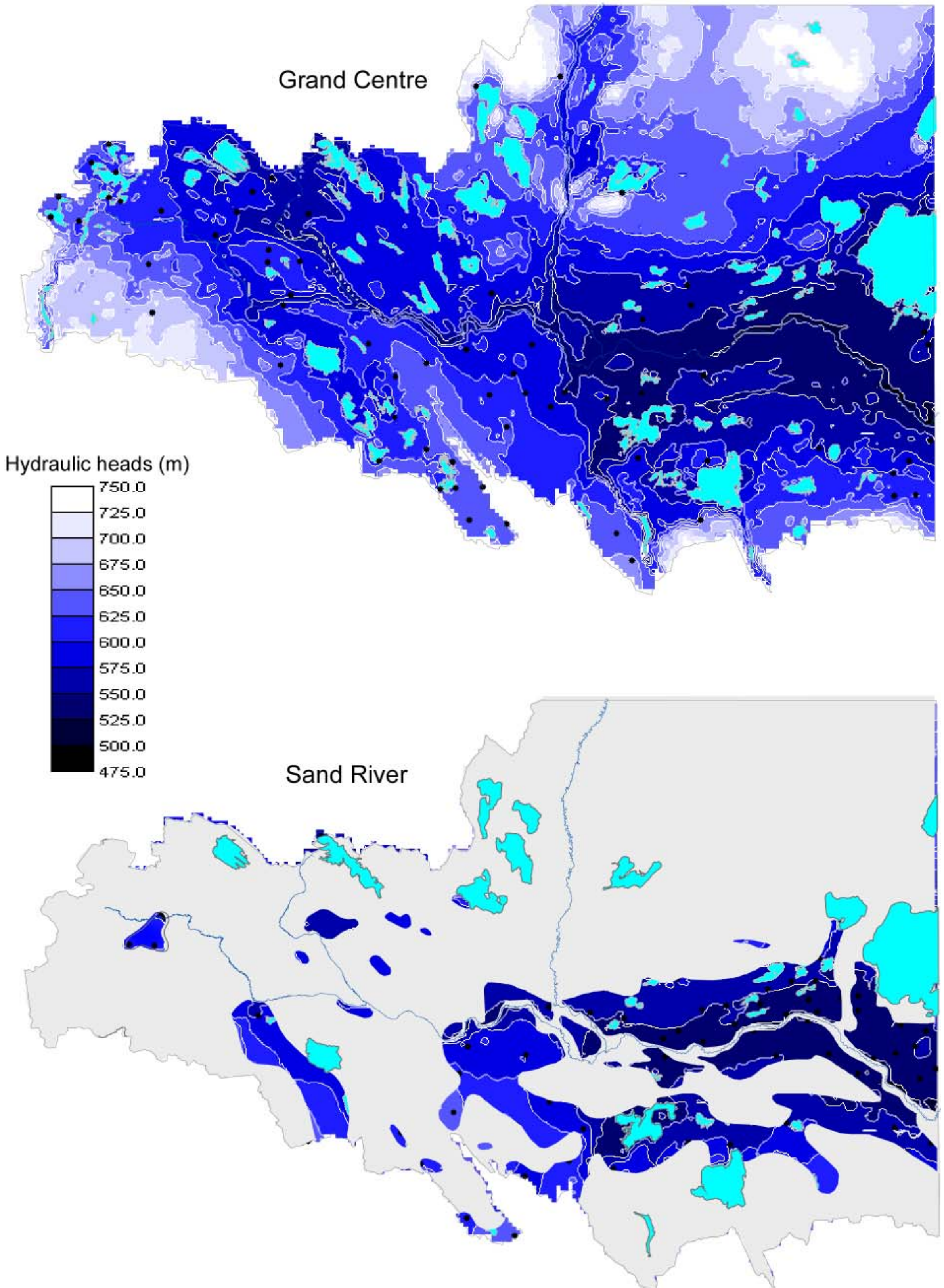



**Figure 5.7a. Predicted steady-state hydraulic head distributions for final calibrated model in the Grande Centre and Sand River formations.**

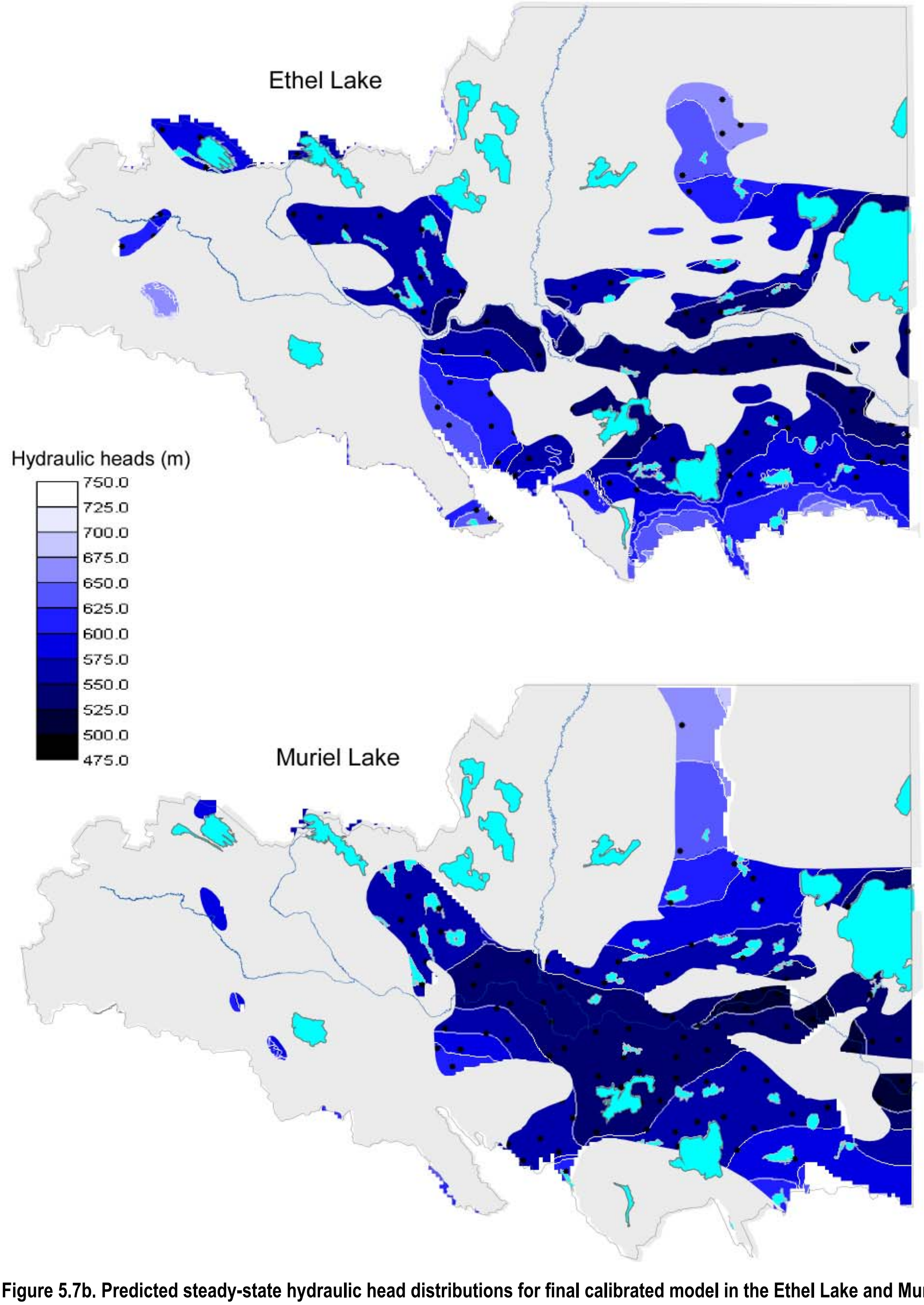



**Figure 5.7b. Predicted steady-state hydraulic head distributions for final calibrated model in the Ethel Lake and Muriel Lake formations.**

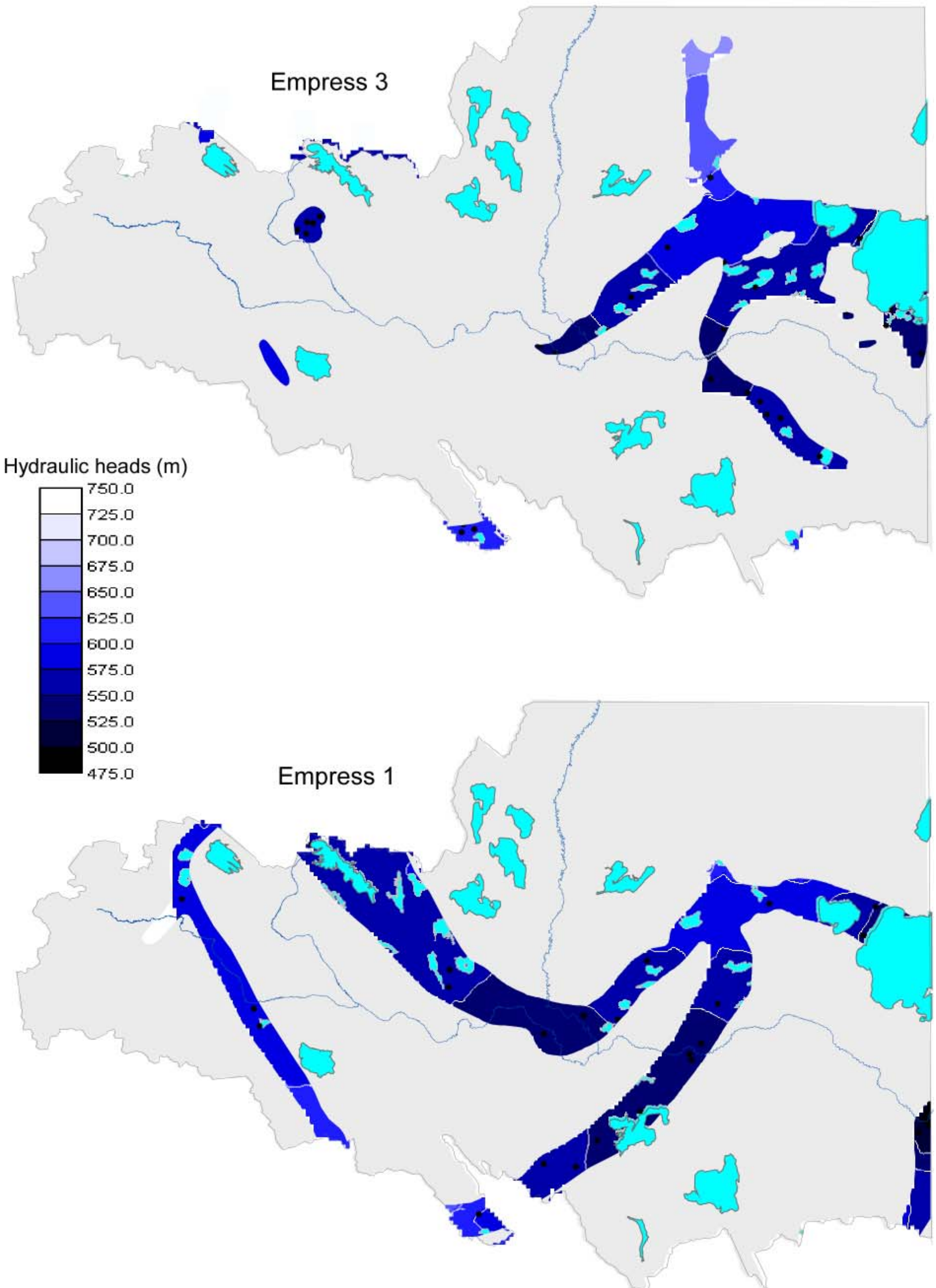



**Figure 5.7c. Predicted steady-state hydraulic head distributions for final calibrated model in the Empress 3 and Empress 1 formations.**

**Table 5.2. Comparison of statistics of horizontal hydraulic conductivity to calibrated model values by formation.**

| | Grand. Centre | Sand. River | Marie. Creek | Ethel. Lake | Bonnyville. Till2 | Bonnyville. Sand1 | Bonnyville. Till1 | Muriel. Lake | Empress. 3 | Empress. 1 | Bedrock |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Min:** | 0.15 | 0.06 | 0.02 | 0.07 | 0.01 | 1.44 | 9.14 | 0.11 | 2.85 | 2.13 | 0.43 |
| **1st Qu.:** | 1.03 | 3.49 | 9.79 | 1.74 | 1.07 | 11.08 | 9.57 | 4.59 | 11.75 | 13.73 | 1.24 |
| **Mean:** | 4.67 | 24.61 | 37.49 | 21.03 | 15.16 | 29.66 | 45.83 | 19.08 | 76.89 | 27.22 | 10.50 |
| **Median:** | 3.29 | 12.11 | 17.75 | 10.03 | 9.38 | 24.88 | 39.65 | 14.91 | 22.75 | 16.15 | 8.85 |
| **3rd Qu.:** | 7.13 | 32.02 | 31.63 | 26.47 | 17.40 | 28.60 | 75.92 | 20.71 | 64.88 | 27.12 | 16.44 |
| **Max:** | 12.92 | 129.06 | 268.06 | 232.93 | 76.24 | 101.95 | 94.89 | 76.97 | 645.93 | 128.68 | 27.80 |
| **Total Values** | 7 | 43 | 26 | 56 | 16 | 7 | 4 | 49 | 16 | 23 | 14 |
| **Variance:** | 22.36 | 986.13 | 3475.86 | 1350.25 | 453.21 | 1139.77 | 1874.19 | 399.92 | 24855.30 | 920.97 | 96.37 |
| **Std Dev.:** | 4.73 | 31.40 | 58.96 | 36.75 | 21.29 | 33.76 | 43.29 | 20.00 | 157.66 | 30.35 | 9.82 |
| **SE Mean:** | 1.79 | 4.79 | 11.56 | 4.91 | 5.32 | 12.76 | 21.65 | 2.86 | 39.41 | 6.33 | 2.62 |
| **LCL Mean:** | 0.29 | 14.95 | 13.67 | 11.19 | 3.81 | -1.56 | -23.05 | 13.33 | -7.12 | 14.09 | 4.83 |
| **UCL Mean:** | 9.04 | 34.28 | 61.30 | 30.87 | 26.50 | 60.88 | 114.72 | 24.82 | 160.90 | 40.34 | 16.17 |

**Table 5.3. Comparison of calibrated model parameters to selected prior studies.**

| Hydraulic Conductivity (m/d) | AGS, 2004 | CNRL, 2000 | Komex, 1995 | Simco, 1986 | Field Measured (Literature) |
|---|---|---|---|---|---|
| Recent | 1 | n.a | n.a | n.a. | n.a. |
| Grand Centre | 0.008<br>0.0001<br>0.00005 | 0.00001 - 0.0004* | 0.00002 - 0.0004* | 0.02* | 0.0002 - 0.6* |
| Sand River | 2 | 1 - 2 | 4 | 2 | 0.02 - 65 |
| Marie Creek | 0.001<br>0.0001 | 0.00002 - 0.004* | 0.00002 - 0.0004* | 0.04* | 0.00008* |
| Ethel Lake | 5 | 1 - 17 | 4 - 40 | 9 | 0.002 - 3200 |
| Bonnyville 2 | 1<br>0.001 | 0.00003 - 0.008* | | | 0.000007 - 0.005* |
| Bonnyville 1 Ss | 2.2 | 2.5 - 17 | 0.009 - 0.0004* | 0.04* | 0.0008 - 10 |
| Bonnyville 1Till | 0.0005<br>0.1 | 0.000004 - 0.003* | | | |
| Muriel Lake | 10<br>25 | 2.5 - 50 | 0.9 - 40 | 17 | 0.04 - 630 |
| Bronson Lake | 0.00008 | 0.00006 - 0.007* | 0.00009* | 0.002* | 0.0001 - 0.03* |
| Empress 3 | 8 | 13 - 50 | 3.5 | 43 | 0.01 - 77 |
| Empress 2 | 0.00008 | 4.0E-08 - 0.0008* | 0.000004 - 0.0004* | 0.009* | 0.00004* |
| Empress 1 | 5 & 25 | 0.2 - 43 | 0.9 - 35 | 26 | 0.2 - 32 |
| | | | | | |
| **Anisotropy (-)** | | | | | |
| Aquifers | 1 | | 1 | | |
| Aquitards | 10 | | n.a. | | |
| | | | | | |
| Conductances (m2/d) | | | | | |
| GHB nodes | 5 | | | | |
| River nodes | 200 | | | | |
| | | | | | |
| Specific Storage (1/m) | | | | | |
| Aquifers | 0.00001 | 0.00001 | 0.0003 - 0.00001 | | 4.0E-07 - 0.00011 |
| Aquitards | 0.0000005 | n.a. | n.a. | | |

* vertical hydraulic conductivity

a multitude of factors that must be considered and each development scenario is likely to be different in terms of impacts on local aquifers, regional interconnections to surface water, and the rights of other users, both human and aquatic.

The purpose of this project has been to build the capacity to manage the groundwater of the Cold Lake-Beaver River Basin through understanding the natural system and being able to query and display the locations of wells and historical static water-levels, map the results of chemical analyses of water, and forecast the possible impacts of future development at the regional scale.

This section provides some of the initial output of this project that supports development of a regional groundwater management plan. Four key elements are presented. First, the groundwater use in the basin as known to AGS through information provided by AENV is described. Second, the model-calculated regional water balances under steady-state conditions are discussed. Third, the transition curves introduced in Section 1 are presented for each major aquifer. Fourth, the basin's steady-state response to licensed pumping stress under the assumed boundary conditions of the model is discussed. We make comments on the design of a regional monitoring network for groundwater quantity in the basin in Section 7.

If sustainability is the goal of the water management plan, then these tools and insights need to be blended with the results of surface water studies to determine the relative contributions and impacts of groundwater developments on surface-water balances. Only in this way can the incremental impact of any given groundwater development, be it domestic or industrial, be measured.

## 6.1 Groundwater Production in the Basin

Total groundwater use in the basin is not known because most of the water-wells are domestic and stock wells and there are no metering or reporting requirements for these wells. Wells with licenses have a maximum groundwater allotment and must report annual groundwater use to AENV in their licence reports. A detailed study of water-well use in the M.D. of Bonnyville was produced for the Prairie Farm Rehabilitation Administration (PFRA) (Hydrogeological Consultants Ltd., 2002). That analysis is not repeated here.

An estimate of groundwater use by well-type and by formation is provided in Table 6.1 for the purpose of completing a regional water balance. The wells are divided into two groups: unlicensed and licensed. Each group is then subdivided by type of use. For unlicensed wells, we used the PFRA estimates that a rural domestic water-well consumes 0.5 $m^3$/d and a stock well produces 5.1 $m^3$/d. Mixed use domestic and stock water-wells are assumed to produce 5.6 $m^3$/d. Licensed water-wells are classified as industrial or municipal. The total production by class is based on licensed diversions, not actual use.

As discussed in Section 4, the water-wells were assigned to formations based on completion details available. Where completion details were not available or of sufficient quality to make a formation assignment, the total depth of the water-well was used to make the formation assignment. The formation assigned by AGS in this study may not match a formation assignment on the formal well license. Likewise, if an industry monitoring well had a formation assignment AGS used its own geological model to re-do the formation assignment for internal consistency. Reconciliation of formation-assignment conflicts are outside the scope of this study.

Reasonable efforts were made to reduce double-counting of well-records for the production estimates but it is likely that some wells have been counted twice. This is because well-records for the same well in the

**Table 6.1. Estimated groundwater production by well type and formation.**

| **Sum of Q_m3/y** | | **Formation** | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Licensed or Domestic Well | Proposed Use | GrandCentre or Recent | SandRiver | MarieCreek | Ethel | Bonny-villeTill2 | Bonny-villeSand1 | Bonnyvil-leTill1 | Muriel | Bronson | Em-press3 | Em-press2 | Em-press1 | Bed-rock | Grand Total |
| Domestic | Domestic | 76103 | 88330 | 26280 | 42340 | 13505 | 2738 | 4198 | 43435 | 9125 | 5475 | 365 | 17520 | 31938 | 361350 |
| | Domestic & Stock | 441504 | 525308 | 233016 | 331128 | 141036 | 40880 | 42924 | 441504 | 6132 | 38836 | 4088 | 49056 | 122640 | 2418052 |
| | Stock | 193596 | 260610 | 115413 | 188012 | 68876 | 7446 | 20477 | 225242 | | 14892 | | 13031 | 46538 | 1154130 |
| Domestic Total | | 711203 | 874248 | 374709 | 561480 | 223417 | 51064 | 67598 | 710181 | 15257 | 59203 | 4453 | 79607 | 201115 | 3933532 |
| Licensed | Injection | | | | 1803840 | | 547500 | | 3656633 | | 2751272 | | 3653156 | | 12412401 |
| | Municipal | | 2470 | | | | | | 3700 | | | | 14556 | 7154 | 27880 |
| Licensed Total | | | 2470 | | 1803840 | | 547500 | | 3660333 | | 2751272 | | 3667712 | 7154 | 12440281 |
| Grand Total | | 711203 | 876718 | 374709 | 2365320 | 223417 | 598564 | 67598 | 4370513 | 15257 | 2810475 | 4453 | 3747319 | 208269 | 16373813 |

**Number of Wells**

| **Licensed or Domestic Well** | **Proposed Use** | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Domestic | Domestic | 417 | 484 | 144 | 232 | 74 | 15 | 23 | 238 | 50 | 30 | 2 | 96 | 175 | 1980 |
| | Domestic & Stock | 216 | 257 | 114 | 162 | 69 | 20 | 21 | 216 | 3 | 19 | 2 | 24 | 60 | 1183 |
| | Stock | 104 | 140 | 62 | 101 | 37 | 4 | 11 | 121 | | 8 | | 7 | 25 | 620 |
| Domestic Total | | 737 | 881 | 320 | 495 | 180 | 39 | 55 | 575 | 53 | 57 | 4 | 127 | 260 | 3783 |
| Licensed | Injection | | | | 5 | | 1 | | 5 | | 5 | | 4 | | 20 |
| | Municipal | | 1 | | | | | | 1 | | | | 1 | 1 | 4 |
| Licensed Total | | | 1 | | 5 | | | | 6 | | 5 | | 5 | 1 | 24 |
| Grand Total | | 737 | 882 | 320 | 500 | 180 | 40 | 55 | 581 | | 62 | 4 | 132 | 261 | 3807 |

AENV database can occur with different unique identifiers for various reasons. Likewise we also found it difficult to match licenses to drillers' reports on file with AENV to reduce double-counting because these datasets have never been linked. In addition, the degree of completeness of the AENV drillers' report database is not known and there are no records of when wells are abandoned or replaced.

Table 6.1 shows that the total allocation of groundwater from all wells is on the order of 16,400,000 $m^3$/year. Of this volume, 12,400,000 $m^3$/yr is licensed allocation from industrial and municipal wells and about 4,000,000 $m^3$/yr is assumed production from unlicensed domestic and stock wells. Actual production is likely to be a portion of this volume since few industrial wells regularly produce their total allocation.

The number of water wells and estimated volume of production are also shown in Table 6.1. One can see from this table that there is no clearly favoured formation for well completions, though numbers do decline with depth.

The total number of wells drilled by year are shown in Figure 6.1. The average depth of wells drilled by year are shown in Figure 6.2. These graphs were prepared to see if there are any historical trends in water-production that should be considered when forecasting groundwater use over the next decades. There is an apparent increase in the number of wells drilled from the 1970s to the 1980s. Presumably this growth reflects both population increase and response to drought. There is an apparent decrease in the number of drilled wells in the late 1990s. It is not known if this reflects actual practice or reflects incompleteness of the database relative to recent records.

The yearly number of domestic wells drilled in all basins peaked in the late 1980s and early 1990s, probably as a result of drought and of government assistance programs. No consistent trends in the depth of domestic water wells are apparent on the graphs, though one could surmise that some of the time intervals of deeper drilling coincided with drought response.

Table 6.1 shows that most of the licensed industrial and municipal production comes from the Ethel Lake Formation, the Muriel Lake Formation, and the Empress Formation Unit 1 and Unit 3. Figures 6.1 and 6.2 show that most of these wells were drilled in the 1980s and 1990s as the bitumen industry northwest of Cold Lake began to grow significantly.

## 6.2 Steady-State Water Balance

The steady-state water balances without and with currently licensed allocations (ignoring domestic and stock wells) calculated by the model are shown in Table 6.2. The table shows the calculated flux of water moving in and out of the groundwater system on an average annualized basis expressed as daily volumes. The results suggest that the majority of water entering the groundwater system would be derived from recharge due to infiltration from wetlands or precipitation (~232,000 $m^3$/d or 7 mm/year), while minor amounts of water would be provided by leakage from recharging lakes (~30,000 $m^3$/d). Recharge rates are highest in the northeast and southeast of the study area (13.2 mm/year and 7.6 mm/year, respectively) and are lower than 5 mm/year in the west of the drainage basin. Overall, recharge rates predicted by the model amount to approximately 2% of annual precipitation. This result agrees well with the average value estimated from baseflow recession analyses of the Beaver River near Goodridge but falls at the lower end of values reported in the literature discussed in Section 2. If recharge is areally concentrated to regions of luvisolic soils (Figure 2.3) and highland wetlands (Figure 2.6) the average recharge predicted by the model would rise.

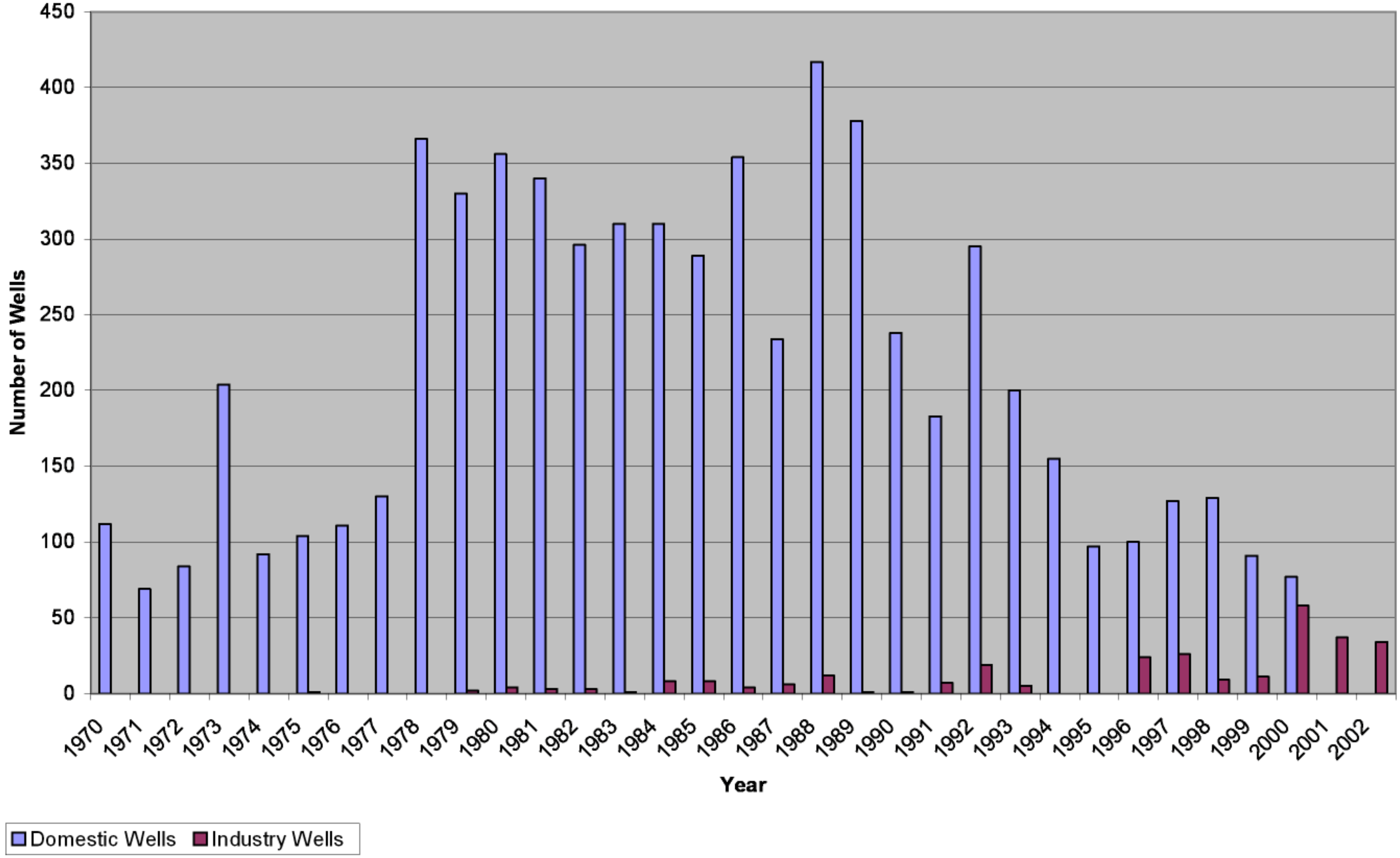



**Figure 6.1. Total number of water wells drilled by year.**

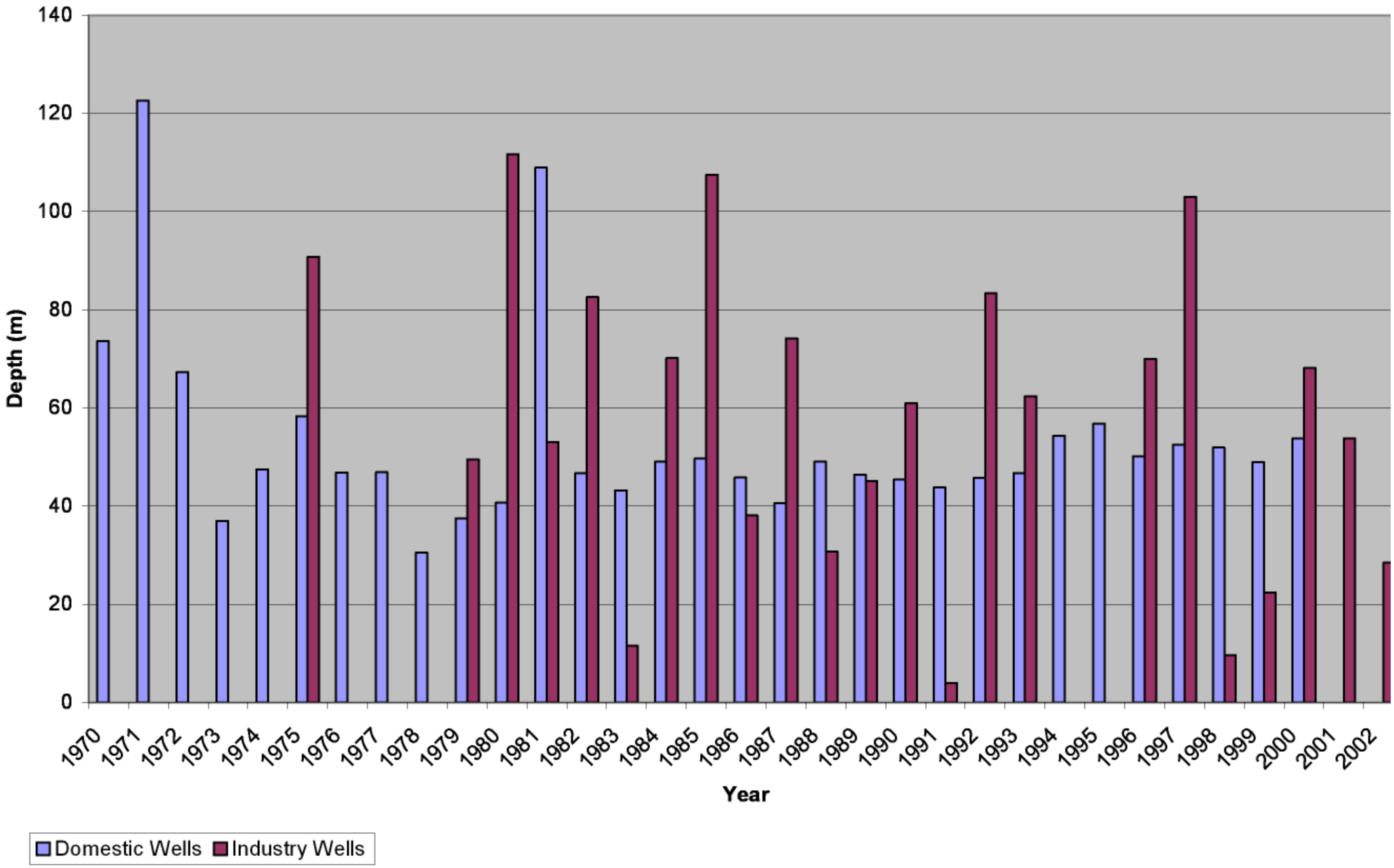



**Figure 6.2. Average depth of wells drilled by year.**

**Table 6.2. Calculated steady-state water balances with and without pumping.**

| | No Pumping Stresses | | | | | With Currently Licensed Pumping | | | Total Change | % Change | % of Production |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | Total | NWBR | NEBR | SWBR | SEBR | Total | NEBR | SEBR | | | |
| **Recharge** | 232404 | 18139 | 91266 | 8022 | 114976 | 251977 | 110451 | 115364 | 19573 | 8.4 | 67 |
| *Recharge (mm/year)* | *7.1* | *4.7* | *7.6* | *1.5* | *13.2* | *7.7* | *9.2* | *13.2* | *0.6* | *8.4* | |
| **Lakes (In)** | 30718 | 1826 | 13702 | 1845 | 13344 | 33354 | 16274 | 13406 | 2636 | 8.6 | 9 |
| **Lakes (Out)** | -87143 | -1478 | -42829 | -4839 | -37996 | -83925 | -39791 | -37824 | 3218 | -3.7 | 11 |
| **Beaver River (+ Amisk)** | -110983 | -9029 | -42755 | -969 | -58231 | -109598 | -41425 | -58143 | 1385 | -1.2 | 5 |
| **Sand River** | -13734 | -7350 | -6384 | 0 | 0 | -13582 | -6313 | 0 | 152 | -1.1 | 0.5 |
| **Kehiwin River** | -18845 | 0 | 0 | 0 | -18845 | -18741 | 0 | -18741 | 104 | -0.6 | 0.4 |
| **Other drainage** | -29764 | -1551 | -12946 | -1707 | -13560 | -27505 | -10787 | -13497 | 2259 | -7.6 | 8 |
| **Intra-basin flow** | -4061 | -404 | 0 | -2266 | -1391 | -4052 | 0 | -1382 | 9 | -0.2 | 0.03 |
| **Pumping** | 0 | 0 | 0 | 0 | 0 | -29154 | -28298 | -856 | -29154 | | |
| **Total In** | 263122 | -19812 | -104913 | -9781 | -130024 | 285331 | 126725 | 128770 | 22209 | 8.4 | |
| **Total Out** | -264530 | 19970 | 104976 | 9869 | 128334 | -286557 | -126614 | -130443 | -22027 | 8.3 | |
| **Water balance (error)** | -1408 | | | | | -1226 | | | | | |
| **Water balance (% error)** | -0.54 | | | | | -0.43 | | | | | |

Values are in $m^3$/day if not otherwise noted.

Discharge of groundwater under steady-state non-pumping conditions occurs through the major rivers (~143,000 $m^3$/d), secondary drainage at surface nodes representing surface discharge and minor streams (~30,000 $m^3$/d) and through discharge to lakes (~87,000 $m^3$/d). Approximately 4000 $m^3$/d leave the drainage basin through lateral groundwater flow in known buried valleys extending beyond the basin boundaries. The calculated amount of baseflow to the nodes representing the Beaver River amounts to ~111,000 m3/d.

The steady-state model can be used to help identify lakes that may be contributing to the groundwater flow (recharge lakes) and those that may be fed by groundwater flow (discharge lakes). Table 6.3 shows the groundwater leakage to or from the major lakes included in the model. The estimated leakage for those lakes with digital bathymetry should be regarded as more reliable than those lakes that were incorporated as constant-head boundary conditions on the uppermost model layer.

The results show that under steady-state conditions without pumping, the main lakes recharging water into the groundwater system are Marie Lake (1600 $m^3$/d) and Margueritte Lake (1100 $m^3$/d) in the northeast part of the basin. With respect to discharge lakes, by far greatest discharge occurs into Cold Lake (~ 20,000 $m^3$/d). Other important discharge lakes are Moose Lake, Muriel Lake, and Kehiwin Lake (~ 8000 $m^3$/d each). It is important to note that these numbers are derived from a regional scale model. Whether a lake is predominantly a recharge lake or a discharge lake is controlled by its position in the landscape. The classifications indicated by Table 6.3 are therefore probably reliable statements over the long-term. However, the actual water-balances for any given lake calculated using a local-scale model that is integrated with surface water inflows and outflows and accounting for seasonal effects are likely to differ from these regional calculations.

## 6.3 Production Effects

### 6.3.1 Transition Curve Sensitivity Analysis

The concept of a transition curve as a means of defining the appropriate planning horizon for groundwater management of a given development in a basin is discussed in Section 1. Recall that transition curves track the time to go from all water produced at a well to come from elastic storage to all water produced at a well to be captured regional flow in the form of induced or formerly rejected recharge and/or reduced discharge. Developments with transition curves on the scale of years or less should be considered as candidates for joint surface-groundwater management schemes while developments with transition curves on the scale of decades or more might not need such attention, depending on the proposed duration of development. Developments with transition curves on the scale of century to millenia are particularly susceptible to groundwater mining and may be managed as a non-renewable resource with a formal depletion plan.

The AGS flow model can be used to define the transition curves for any development the Cold Lake – Beaver River Basin. Figure 6.3a shows the transition curves for ten hypothetical groundwater developments in six different formations. In all cases, the transition curve proceeds from 100% produced water from storage to practically 100% capture in 1000 days (3 years) or less. This analysis suggests that all groundwater developments in the drift formations will potentially achieve a new steady-state in 3 years or less if sufficient surface water can be captured through an increase in recharge or a decrease in discharge or both.

For example, the transition curve of a single hypothetical well completed in the Empress Formation Unit 1 south of Bourque Lake is shown in Figure 6.3b. The transition from storage to capture is essentially

Table 6.3. Calculated steady-state groundwater leakage to/from selected major lakes.

| | No pumping ($m^3$/d) | With pumping $m^3$/d | Difference ($m^3$/d) | % Change |
|---|---|---|---|---|
| Cold Lake | -20959 | -20330 | -628 | 3.0 |
| Marie Lake* | 1622 | 3349 | -1727 | -106.5 |
| Wolf Lake | -671 | -624 | -48 | 7.1 |
| Marguerite* | 1116 | 1437 | -321 | -28.8 |
| Ethel | -1474 | -1339 | -134 | 9.1 |
| Hilda | -2298 | -1894 | -404 | 17.6 |
| Moore | -1209 | -938 | -270 | 22.4 |
| Tucker | -2526 | -2017 | -509 | 20.2 |
| Bourque | -26 | 259 | -285 | 1103.3 |
| Leming* | 137 | 256 | -119 | -86.5 |
| Sinclair* | 52 | 571 | -518 | -990.8 |
| Primrose | -346 | -346 | -1 | 0.2 |
| Burnt Lake (W) | -11 | -10 | -1 | 9.1 |
| May Lake* | 114 | 323 | -209 | -182.6 |
| Moose Lake | -8726 | -8658 | -68 | 0.8 |
| Chickenhill | -267 | -267 | -0 | 0.1 |
| Muriel Lake | -7956 | -7794 | -162 | 2.0 |
| Reita* | 304 | 309 | -5 | -1.8 |
| Angling | -63 | -60 | -3 | 5.1 |
| Garner N | -1415 | -1411 | -4 | 0.3 |
| Cushing* | 370 | 371 | -1 | -0.4 |
| Jessie | -95 | -92 | -3 | 3.6 |
| Charlotte | -86 | -83 | -3 | 3.8 |
| Thompson* | 119 | 121 | -1 | -1.2 |

* recharging lakes
bold indicates lakes with bathymetry

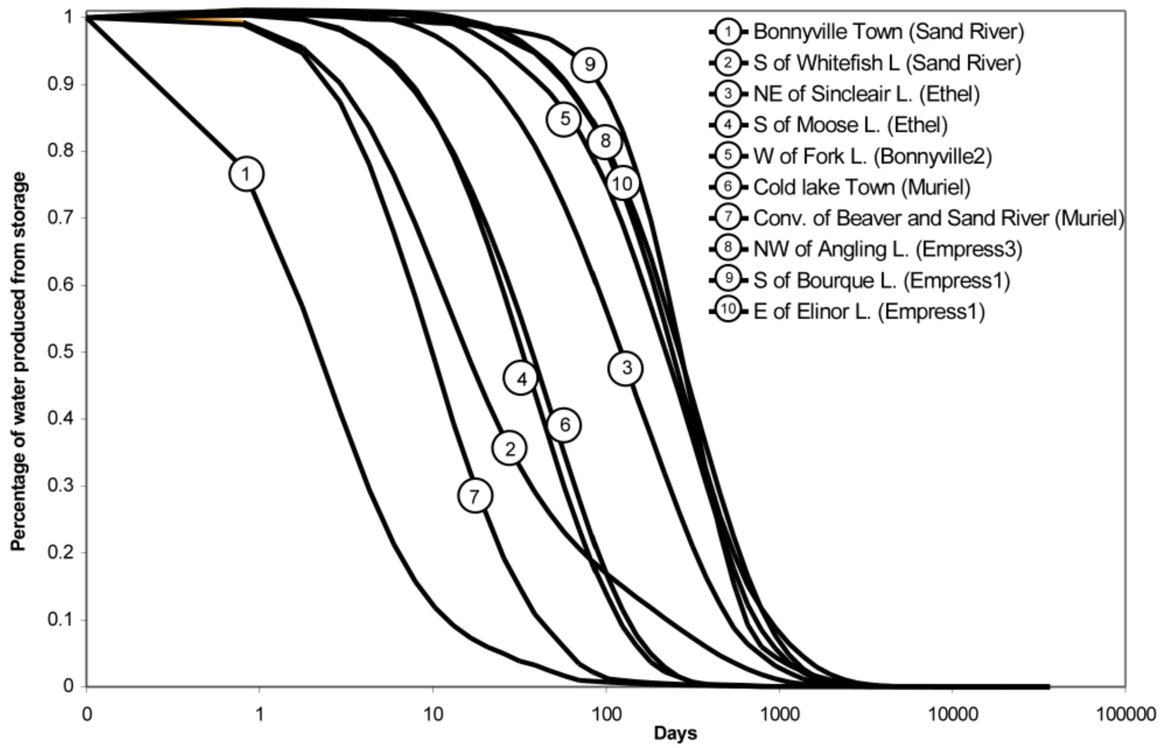



Figure 6.3a: Transition curves for various pumping scenarios at selected locations. Formation names in brackets denote pumped aquifer.

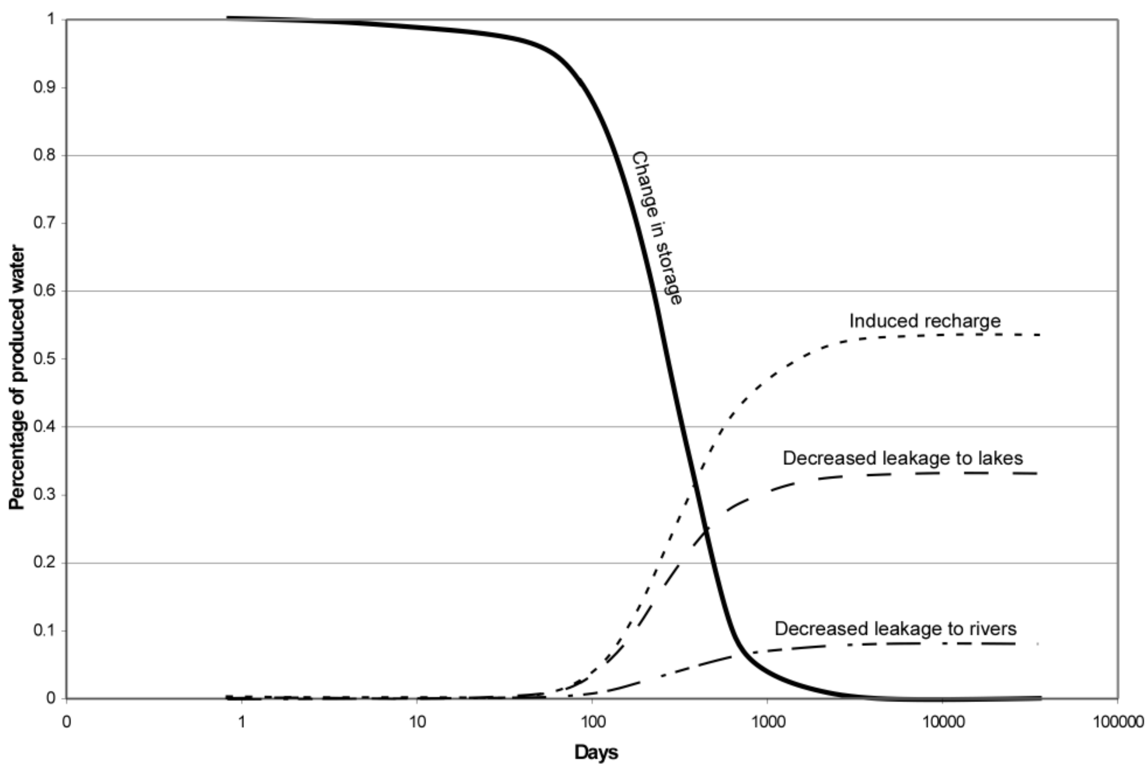



Figure 6.3b: Graph showing an example of the effect of pumping (from Empress 1, S of Bourque Lake) on the change in storage and leakage from surface water bodies

**Figure 6.3. Transition curves for ten hypothetical wells in six different formations showing similar response times.**

complete after 1000 days. The model was used to identify where the capture was coming from. These curves are shown on Figure 6.3b and indicate that just over half of the capture is coming from induced recharge while the remaining is coming from decreased discharge to lakes and rivers. The actual distribution and magnitude of these changes could be predicted with a model to assist in monitoring design for this hypothetical project.

Note that while the time of transition will be independent of the magnitude of production, the impact of the induced recharge or reduced discharge at the affected boundaries will be directly correlated with the magnitude of production. Whether that impact is tolerable or not depends on how it is spatially distributed and how it adds to the distributed impacts of concurrent production from other production well.

AGS retained Stantec Consulting Ltd. to run the model using a second series of hypothetical wells. These hypothetical wells were introduced into the model to assess the sensitivity of boundaries to pumping from wells in selected formations and selected locations. The results are shown in detail in Appendix A. The results show how varied the transition curves will be as a function of location and geology. This supports the contention that the impact of each well on the basin will be unique and needs to be assessed in the context of location, local geology, and pre-existing pumping stresses.

### 6.3.2 Simulated Effects of Licensed Pumpage

The regional model was run in a steady-state mode with all licensed groundwater allocation in the NEBR and SEBR flow systems to show the incremental impacts of these developments on the regional steady-state water-balance. The model was also used to examine the spatial distribution of their incremental effect on regional static water levels. Then the model was run in a transient mode to evaluate the impact of historical pumping using reported production volumes instead of allocations. Third, a preliminary forecast of future groundwater production was input into the model and the impact on water balances and drawdown was evaluated.

Domestic and stock-wells were not included in this analysis because they are not directly regulated under most conditions, they are dispersed throughout the basin, and the amount of production from these wells is very poorly constrained. Their capture zones are also expected to be smaller than our model's grid blocks and therefore cannot be evaluated individually at the scale of the regional model. In addition, by our best estimates their total production amounts to less than 25% of the groundwater allocation of the basin so this first-order analysis using only licensed wells will cover the majority of groundwater production at this time. As well, since they are concentrated in the south side of the basin, their cumulative effects will be greatest south of the Beaver River, in the SEBR and SWBR flow systems, away from most of the licensed wells. However, their cumulative impact should not be ignored, and improvements on our state of knowledge of domestic and stock-water groundwater use should be a very high priority for future study.

The results of this analysis are shown in Tables 6.2 and Tables 6.3. In terms of total water balance, the groundwater allocations of licensed users (assuming they use all of their licensed allocations on a continual basis) amounts to about 10% of the original steady-state water basin balance. The model does not consider any return-flow of this production so the basin responds to production by increasing recharge and decreasing discharge. About 67% of the licensed production is being sourced by an increase in simulated recharge at the land surface and about 8% is sourced by a decrease in simulated discharge at the land surface relative to simulated, steady-state natural conditions. About 11% of licensed allocation would come from a decrease in simulated discharge to the major discharge lakes and 9% would come from an increase in simulated recharge from the major recharge lakes. About 5% would be matched by a decrease in simulated baseflow to the Beaver River.

The steady-state drawdowns by formation at continuous maximum licensed production are shown in Figure 6.4. In most formations the predicted heads do not fall below the top of the formation at steady-state, indicating that no unsustainable mining of aquifers would be occurring if full allocations were to be produced, domestic production notwithstanding. One should note that, in reality, groundwater mining at such locations would be prevented during actual production by a restrictive condition in the groundwater licence issued by AENV. Calculated heads falling below the tops of formations are observed in the Grand Centre Formation and Recent sediments, but this is to be expected since they are at the land surface and as such are regionally unconfined. Because of our choice in the upper boundary condition, our upper layers do not become unsaturated but under real conditions a falling water table would be observed in conjunction with these falling heads.

AGS retained Stantec Consulting Ltd. to run the model was using historical production volumes from licensed wells rather than allocations. Production volumes from the time interval 1985 to 2003 were provided by AENV. Examination of the transient simulation results suggested that the major aquifer systems responsed relatively quickly to changes in system stresses and that residual drawdowns were minimal in years after production for various wells was discontinued. The transient simulation results also revealed that the cones of influence surrounding production wells did not extend across the basin and were generally limited to the vicinity of the production wells. This is consistent with the response of regional observation wells discussed in Section 7. The impacts of 2004-2020 projected industrial groundwater use were also investigated by Stantec Consulting Ltd. and are included in their report. The complete Stantec report is found in Appendix A.

All of the results of the modeling of hypothetical transition-curve responses and actual licensed-well allocations and historical productions show that the location and timing of groundwater production are key factors in understanding the potential responses of the Cold Lake-Beaver River Basin to groundwater development. As well, since the results indicate that the system responds quickly to pumping and that wells in drift aquifers interact with surface boundary conditions, one must integrate the results of groundwater simulation and analysis with surface-water management in order to identify the sustainable limits of the groundwater resource.

The relatively rapid response time of the basin and variability in transition curves suggests that the transitional basin yield (TBY as discussed in Section 1) of the basin will be small and that the sustainable basin yield (SBY, that proportion of capture contributed by induced recharge as discussed in Section 1) will be dependent on the location of the pumping wells.

If induced recharge cannot be demonstrated to occur for a given development, then one may want consider that all groundwater capture is coming from reduced discharge to be conservative when considering regional management options. This approach will reduce the risk of double-counting of total water resources in the basin but essentially fixes the value of SBY at zero. If this approach is too conservative to meet societal and industrial needs, then extra scientific work will be required to assess induced recharge under pumping conditions in the various landscapes and climatic zones of the Cold Lake-Beaver River Basin. Total available groundwater resources can also be increased by examining deep, brackish groundwater resources where the TBY will be large even though SBY will be negligible over the timescales of decades to centuries.

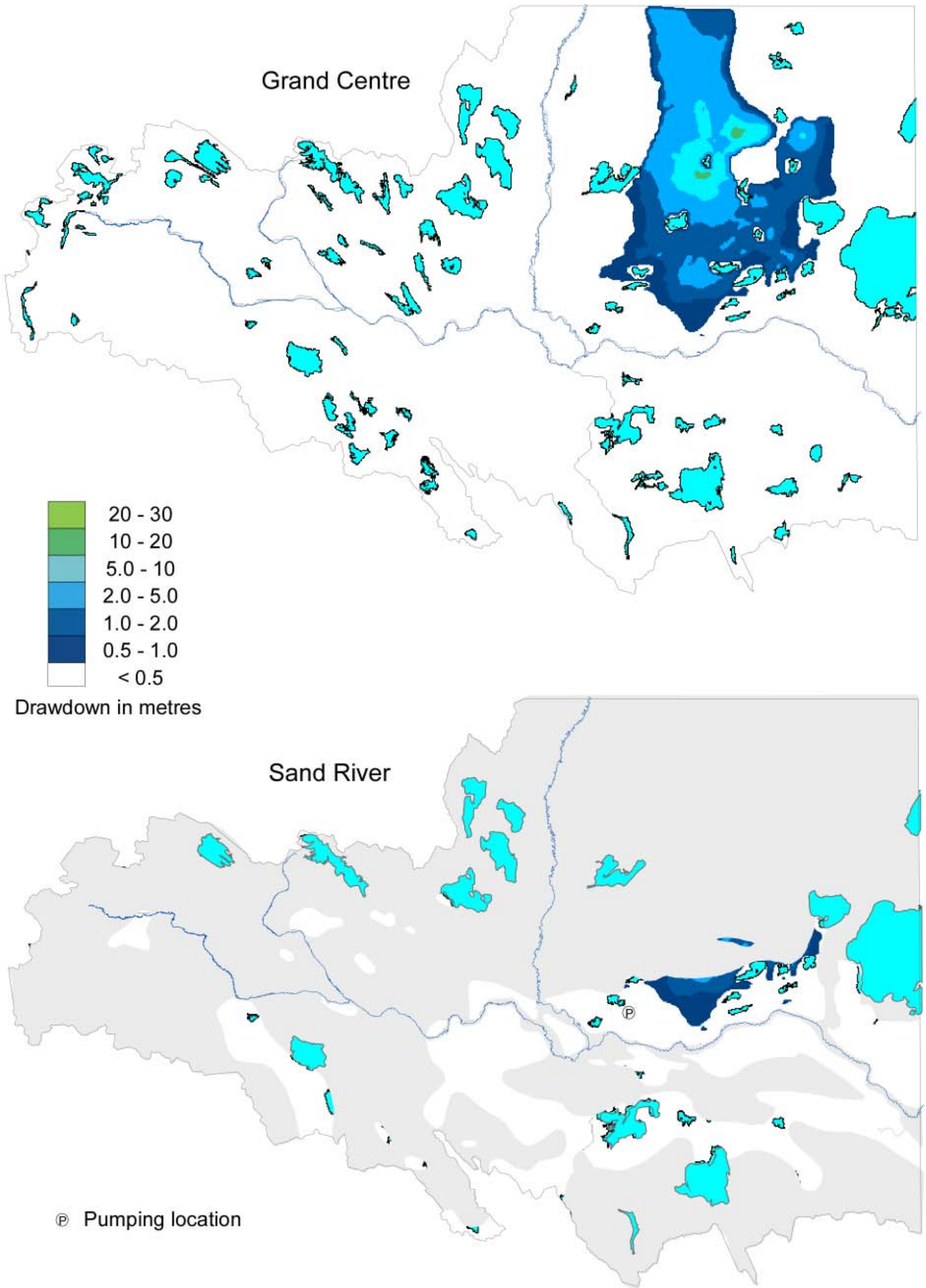



**Figure 6.4a. Simulated steady-state drawdowns assuming all licensed wells pumping continuously at maximum allocated rates.**

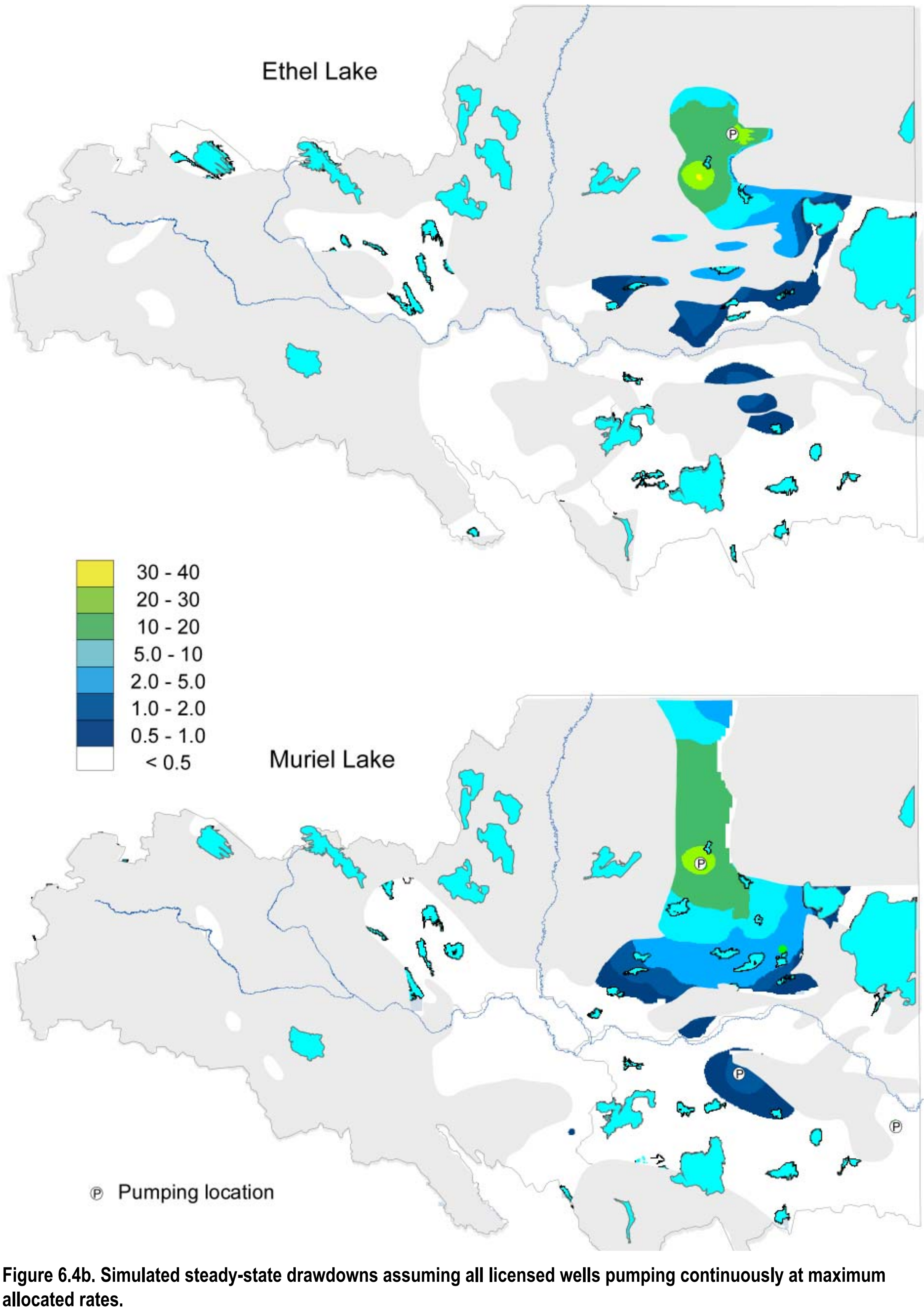



**Figure 6.4b. Simulated steady-state drawdowns assuming all licensed wells pumping continuously at maximum allocated rates.**

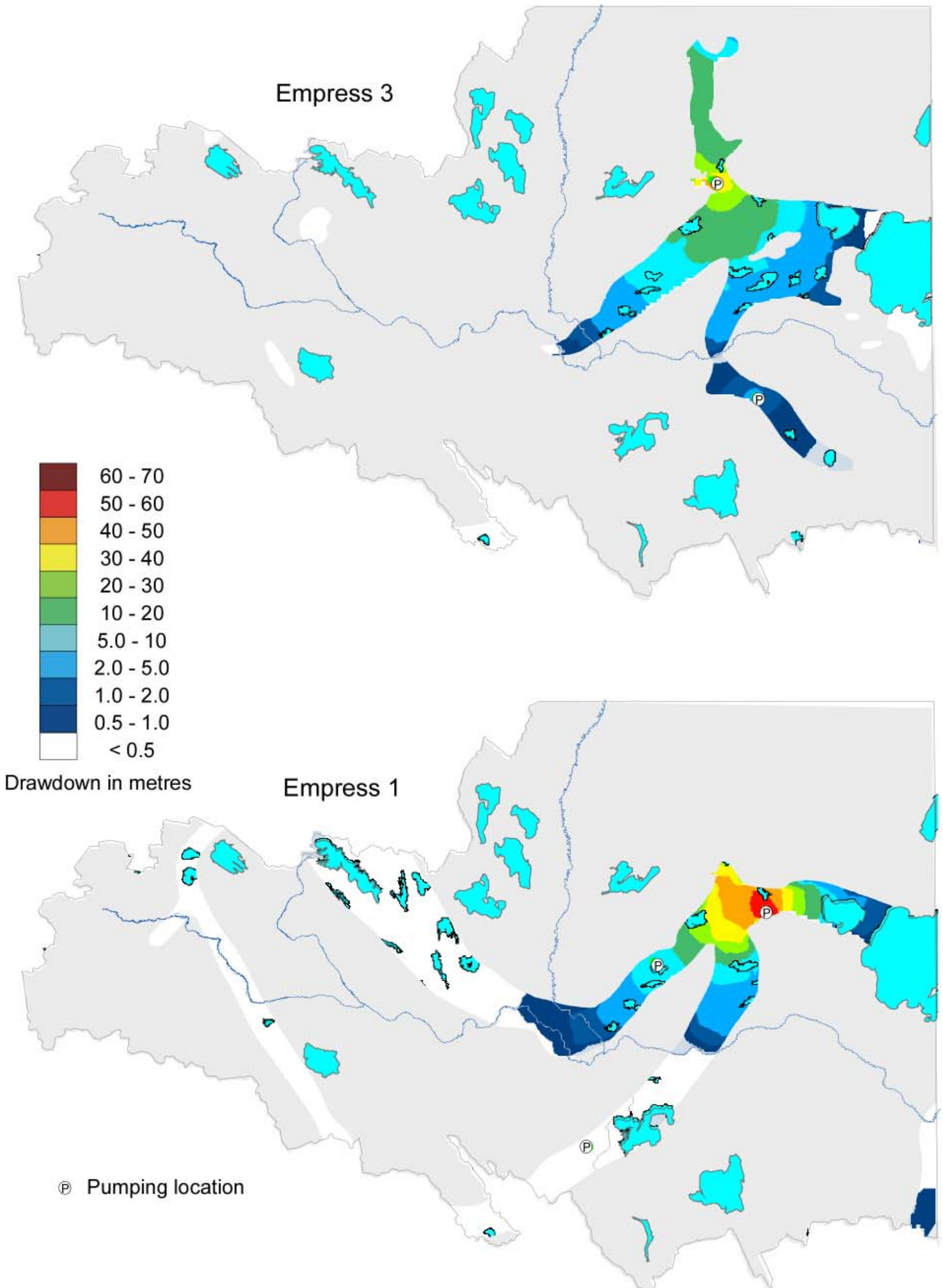



**Figure 6.4c. Simulated steady-state drawdowns assuming all licensed wells pumping continuously at maximum allocated rates.**

# 7 Regional Monitoring Network Analysis

This section evaluates the locations of active groundwater observation-wells in light of this work and proposes new locations to augment the existing network. At present there are twenty-four dedicated government water-level observation wells and six dedicated government quality-observation wells in the Cold Lake Beaver-River Drainage Basin. In addition there are numerous monitoring wells in the Basin owned by industry but these were not considered in this analysis.

Rivera et al. (2003) describe the following roles for groundwater monitoring programs:

1. Monitor ambient groundwater quality and water levels on a regional scale;
2. Assist in the management of groundwater during periods of problems;
3. Assist in the protection of sensitive and important areas of groundwater recharge;
4. Assess the impact of development and land-use activities on groundwater resources; and
5. Distinguish between short-term and transient natural fluctuations (e.g., seasonal) and long-term impacts due to anthropogenic activities.

Moreover, they state that a regional groundwater monitoring network must be integrated with study of the overall hydrologic cycle to be effective.

Uil et al. (1999) catergorize observation-well networks as being strategic, operational, or surveillance in purpose. Strategic networks seek to characterize the natural system or generally inform water-management policy. These networks establish the baseline conditions against which long-term trends or anthropogenic impacts can be identified. Operational networks monitor compliance with regulations or policy regarding groundwater withdrawals, groundwater protection, or protection of sensitive areas linked to groundwater use. Surveillance networks are specifically designed to give early warning of regional change in groundwater conditions

Monitoring networks are distinguished by the parameters measured, the locations and depths of monitoring wells, the areal density of the wells, the duration of monitoring, and the frequency of observation at each well. The design of a network depends first on the general purpose and second on the specific technical objectives of the network. Whereas the general purpose is a qualitative statement of the monitoring design, the technical objectives should be expressed in terms of quantifiable or probabilistic performance measures. For example, a surveillance network's general purpose may be to provide early warning of drought conditions while the technical objective may be to identify non-seasonal declines within a pre-defined statistical tolerance of accuracy and precision.

Loaiciga et al. (1992) discuss two main approaches to groundwater monitoring network design. Hydrogeological approaches rely on expert opinion based on conceptual models, geological inference, and analytical or simulation-based calculations to identify best locations of monitoring wells. Hydrogeological approaches are best suited to preliminary network designs when little is known about a site or region. They are also well suited for regional investigatory programs driven by geological considerations.

Geostatistical approaches, on the other hand, look to integrate multiple sources of information in a probabilistic framework to select monitoring well locations. If a geostatistical approach is used, then optimization algorithms can be employed to select a network design out of a collection of alternative designs which best satisfies the quantitative technical objectives given a set of budgetary constraints.

Much of current research into groundwater monitoring network design has focussed on application of optimization methods to minimize network costs. Examples of network optimization with single objectives related to groundwater quantity are discussed by Andrevic (1990) as well as Winter et al. (1999). Examples of network optimization with single or multiple objectives related to groundwater quality are discussed by Storck et al. (1997) and Reed and Minsker (2004).

The design of a regional monitoring network for the Cold Lake-Beaver River Basin can only be optimized after the completion of a water-management plan that sets out specific technical goals related to water-management objectives. Therefore the observation-well locations discussed in this report are by necessity evaluated hydrogeologically rather than geostatistically, although some geostatical analyses are presented as they are useful in informing hydrogeological judgement.

## 7.1 Evaluation of Active Water-Level Observation Wells

According to information provided to AGS, Alberta Environment presently maintains twenty-four active water-level observation wells in the Cold Lake-Beaver River Drainage Basin. A map showing the active well locations on the same map as licensed production wells is in Figure 7.1. In addition, there are an additional twenty-four wells that are inactive or abandoned. These inactive or abandoned wells were not considered as part of this evaluation but are shown on Figure 7.1 for completeness.

Water-level, location and downhole completion data for each of the active water-level observation wells were obtained from AENV. Water-level observations were plotted on hydrographs and inspected for trends. In addition, lake-level hydrographs for monitored lakes were prepared using data from Environment Canada for comparison. As well, reported annual production from licensed industrial and municipal wells was obtained from Alberta Environment- Northern Region and plotted against time. The purpose of these plots was to examine hydrogeological responses of the wells to known local and regional stresses.

The AGS formation assignment is based on the reported surface elevation, the reported completion depth of each observation well, and the local details of the regional geological model as described in Section 3. Linkages between observed water-level behaviours, groundwater pumping, and/or lake-level fluctuations are based on visual comparisons between observation-well hydrographs, water-well production graphs, and relative well locations.

After review of the observation wells, it appears that many of the wells are responding to pumping activity associated with bitumen or heavy oil production in the northeast part of the Basin. Those not responding to pumping are responding either directly to lake-level fluctuations or to recharge events that cause those lake-level fluctuations. The two cannot be easily distinguished. However, based on the geological results reported in Section 3, we believe it is more likely that the water-level fluctuations in the latter group are lake-level controlled rather than precipitation-controlled. This is because the lateral hydraulic connectivity of subsurface formations to deep lakes is presumed to be better than the vertical hydraulic connectivity to the surface at most points in the basin. This point requires further investigation. Table 7.1 provides details on AGS' evaluation of each presently active AENV water-level observation well. Each well is identified by unique AENV identification number and a general location is given. The formation assignment is based on the AGS geological model of the area plus the location and elevation data provided to AGS by AENV. The preliminary evaluation of the controlling stressors on each well's long-term water-level behaviours is given and cross-referenced to the related comparative hydrograph. Comparative hydrographs are found in Figures 7.2 to 7.10. These show the water-level response of active AENV water-level observation wells plus either reported groundwater withdrawals from licenced water-wells or lake-level hydrographs as appropriate.

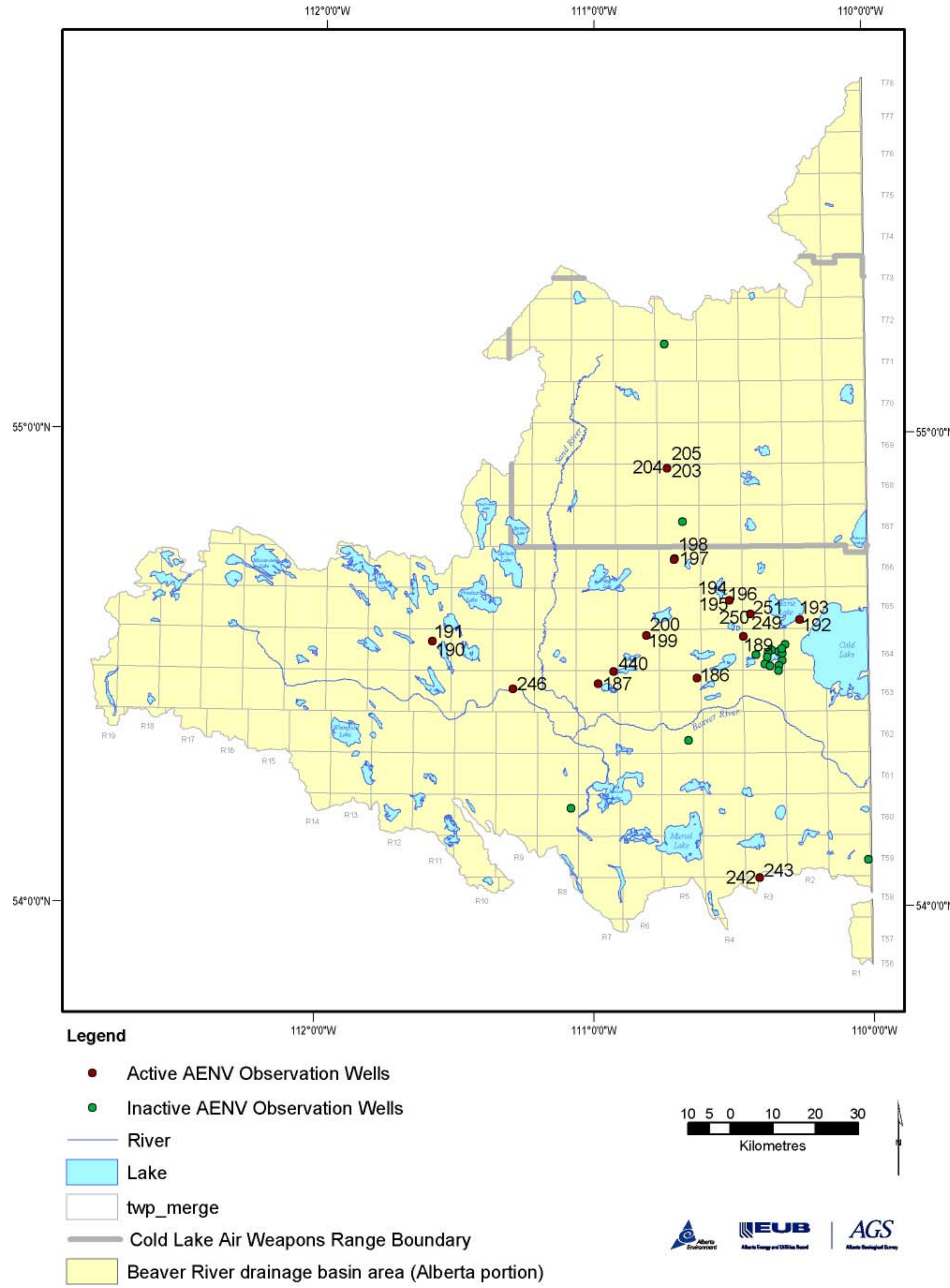



**Figure 7.1. Active and inactive AENV water-level observation wells.**

**Table 7.1. Evaluation of active AENV water-level observation wells.**

| Water-Level Observation Well | General Location | AGS Formation Assignment | Comments |
|---|---|---|---|
| A186 | South of Tucker Lake | Empress Formation Unit I | Water levels respond to pumping at IOL Cold Lake project (Figure 7.2) |
| A187 | West of Manatokan Lake | Empress Formation Unit I | Water levels respond to pumping at IOL Cold Lake project (Figure 7.2) |
| A189 | Between Leming and Hilda Lake | Muriel Lake Formation | Water levels track water-level hydrograph of nearby Hilda Lake (Figure 7.3) |
| A190 | Northwest of Rich Lake | Empress Formation Unit I | Well distal to any reported licensed production wells. Ongoing decline trend and seasonality compares with hydrograph of Lac La Biche (Figure 7.4), which drains the Northwest Beaver River Flow-System. |
| A191 | Northwest of Rich Lake | Muriel Lake Formation | Well distal to any reported licensed production wells. Ongoing decline trend and seasonality compares with hydrograph of Lac La Biche (Figure 7.4), which drains the Northwest Beaver River Flow-System. |
| A192 | East side of Marie Lake | Empress Formation Unit I | Water-level fluctuations track Marie Lake hydrograph (Figure 7.5) |
| A193 | East side of Marie Lake | Muriel Lake Formation | Water-level fluctuations track Marie Lake hydrograph (Figure 7.5) |
| A194 | Near Bourque Lake | Empress Formation Unit I | Water levels respond to pumping at IOL Cold Lake project (Figure 7.6) |
| A195 | Near Bourque Lake | Muriel Lake Formation | Water levels respond to pumping at IOL Cold Lake project (Figure 7.6) |
| A196 | Near Bourque Lake | Empress Formation Unit I | Water levels respond to pumping at IOL Cold Lake project (Figure 7.6) |
| A197 | West of Sinclair Lake | Muriel Lake Formation | Water levels respond to pumping at CNRL Wolf Lake project (Figure 7.7) |
| A198 | West of Sinclair Lake | Empress Formation Unit 3 | Water levels respond to pumping at CNRL Wolf Lake project (Figure 7.7) |
| A199 | Wolf Lake Grazing Lease | Empress Formation Unit 3 | Water levels respond to pumping at both IOL Cold Lake project and CNRL Wolf Lake Project (Figure 7.8) |
| A200 | Wolf Lake Grazing Lease | Bonnyville Formation Unit I | Water levels respond to pumping at both IOL Cold Lake project and CNRL Wolf Lake Project (Figure 7.8) |
| A203 | Fisher Creek, Air Weapons Range | Muriel Lake Formation | Water levels respond to pumping at CNRL Wolf Lake Project (Figure 7.9) |
| A204 | Fisher Creek, Air Weapons Range | Bonnyville Formation Unit I Sand | Water levels respond to pumping at CNRL Wold Lake Project (Figure 7.9) |
| A205 | Fisher Creek, Air Weapons Range | Bonnyville Formation Unit I Sand | Water levels respond to pumping at CNRL Wold Lake Project (Figure 7.9) |
| A242 | Near Cushing Lake | Empress Formation Unit I (?) | Not a close offset to reported licensed well in Cold Lake-Beaver River Drainage Basin. Could be responding to pumping stresses outside the Basin and/or local lake levels in an unmonitored lake. |
| A243 | Near Cushing Lake | Recent (?) | Not a close offset to reported licensed well in Cold Lake-Beaver River Drainage Basin. Could be responding to pumping stresses outside the Basin and/or local lake levels in an unmonitored lake. |
| A246 | Upper Beaver River | Bedrock, Lea Park Formation (?) | None |
| A249 | West of Marie Lake | Empress Formation Unit III | Possible recorder malfunction. |
| A250 | West of Marie Lake | Muriel Lake Formation | Water levels respond to pumping at IOL Cold Lake project (Figure 7.6) |
| A251 | West of Marie Lake | Sand River Formation | Water levels respond to Marie Lake or Cold Lake or correlated local precipitation events (Figure 7.10). |
| 440 | West of Osborne Lake | Empress Formation Unit 1 | Short hydrograph. Water levels apparently respond to pumping but well not identifiable from information received. |

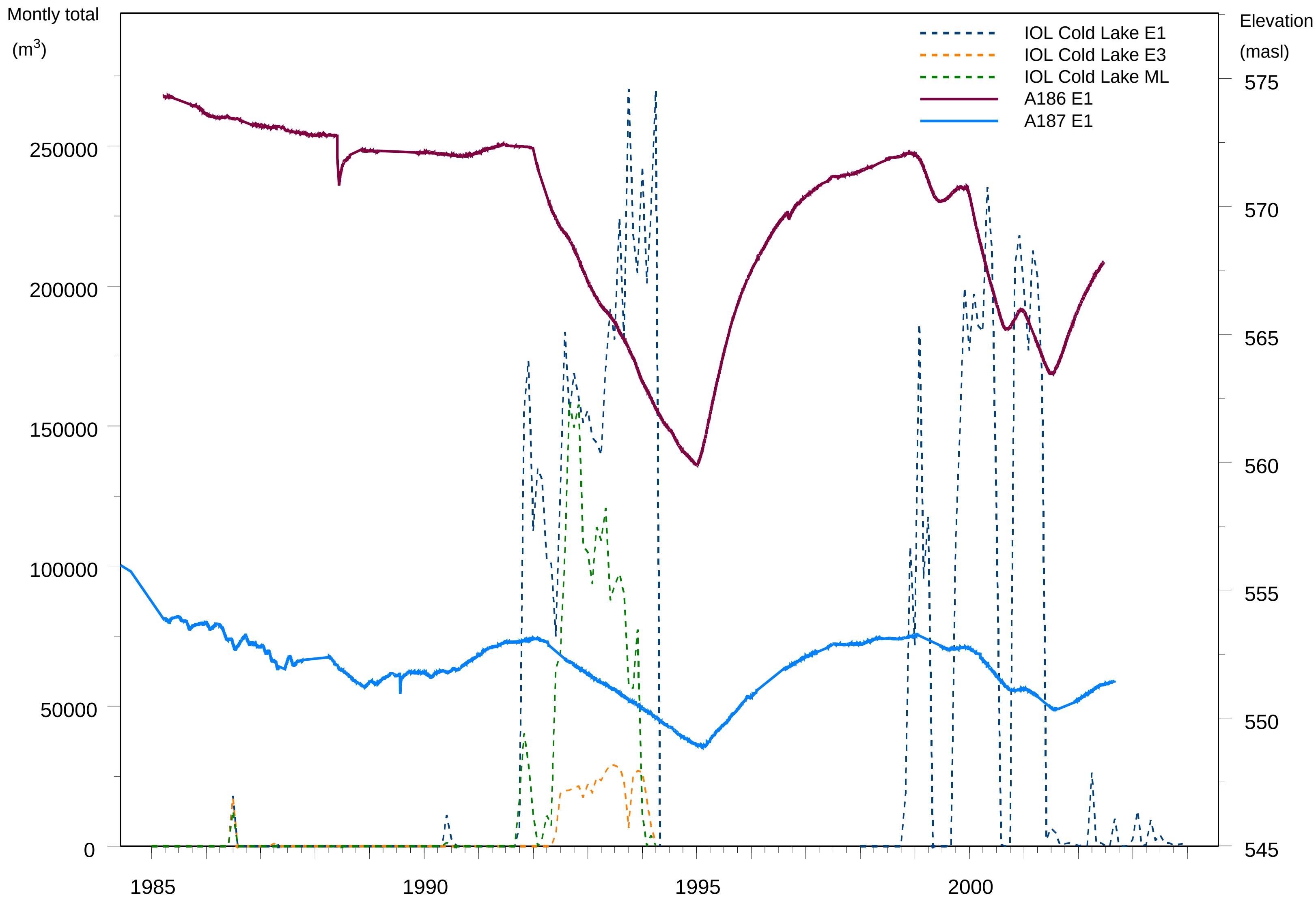



**Figure 7.2. Comparative hydrographs, AENV water-level observation wells A186,A187 vs. IOL Cold Lake pumping.**

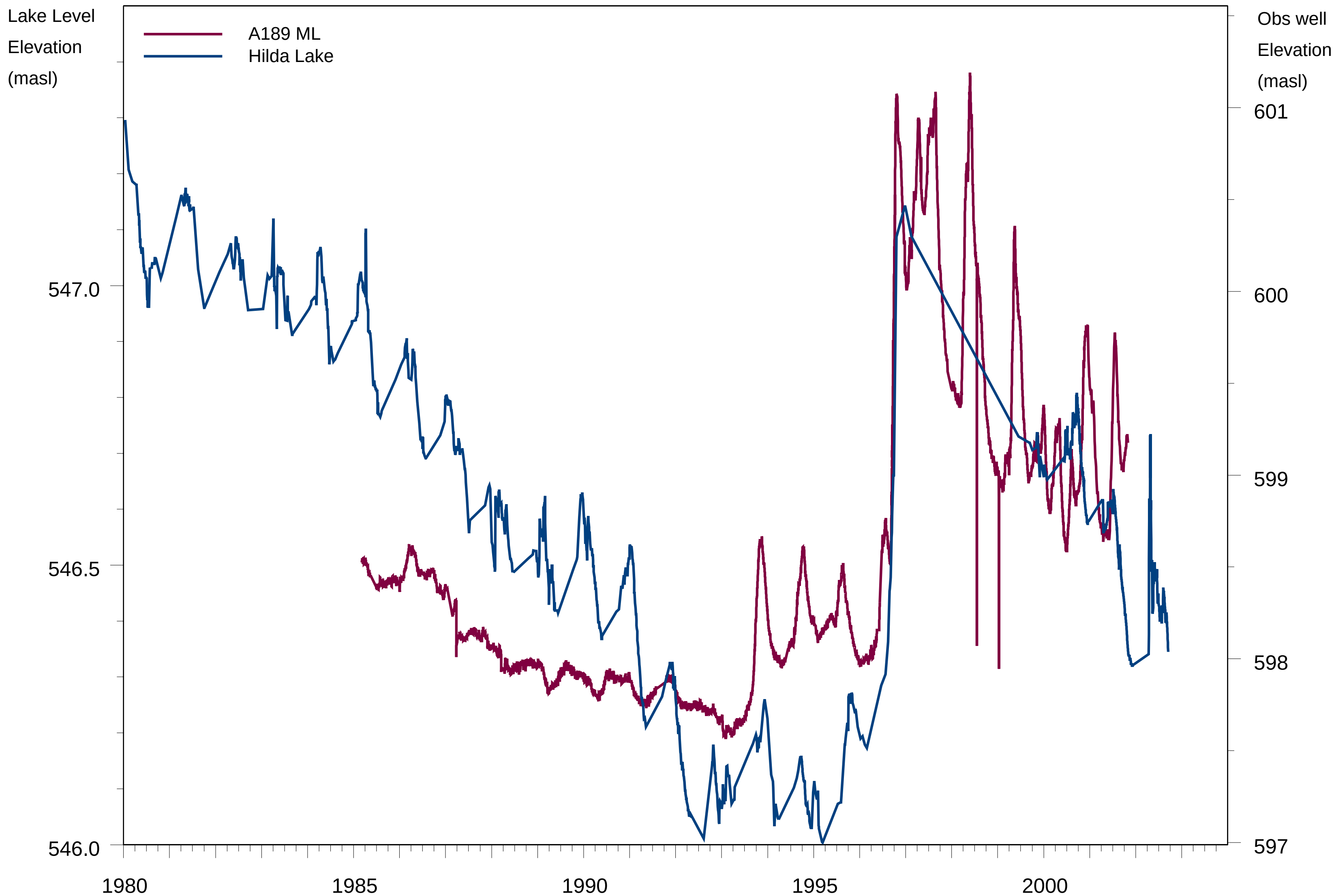



**Figure 7.3. Comparative hydrographs, AENV water-level observation well A189 vs. Hilda Lake water-levels**

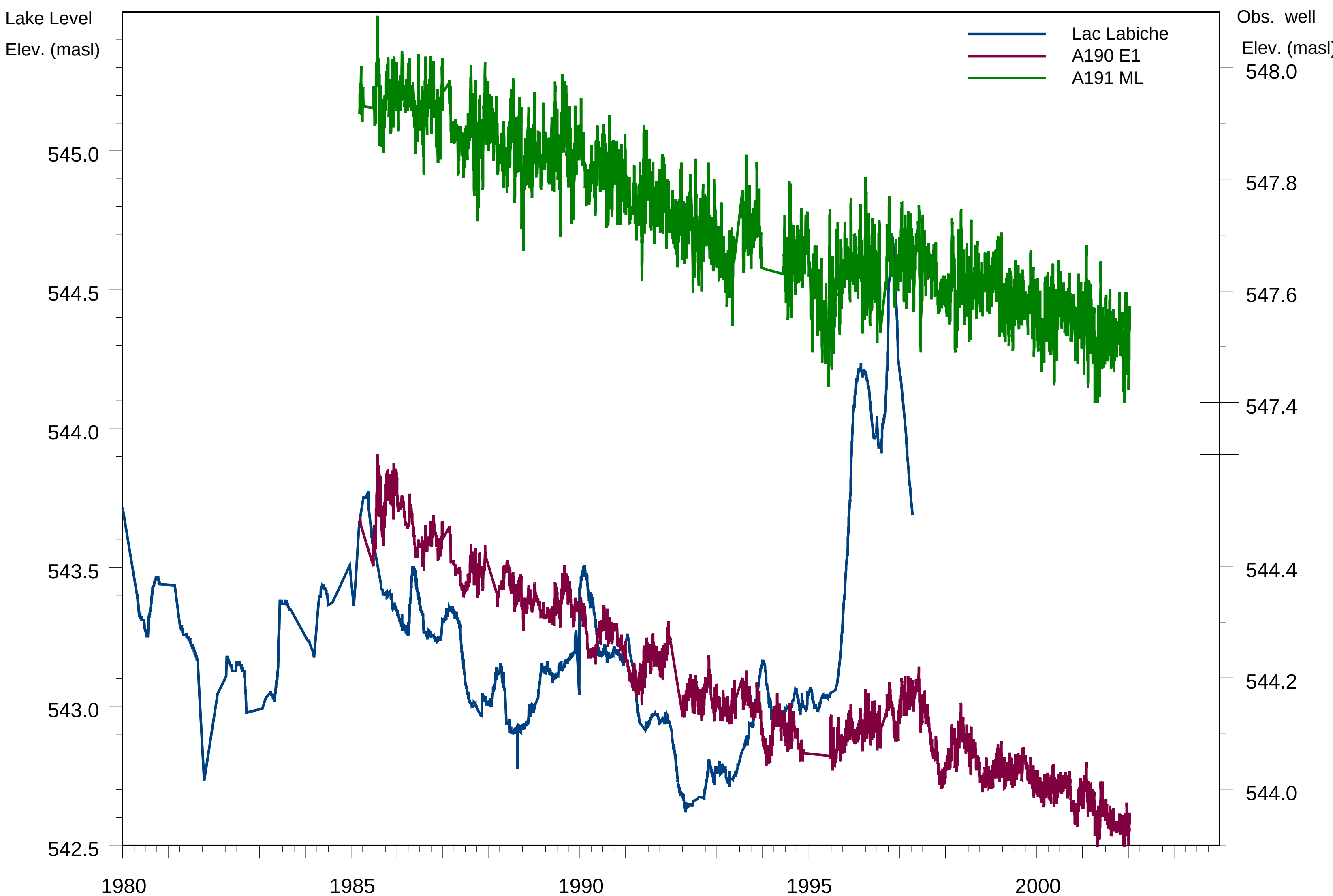



**Figure 7.4. Comparative hydrographs, AENV water-level observation wells A190, A191 v.s. Lac La Biche water-levels.**

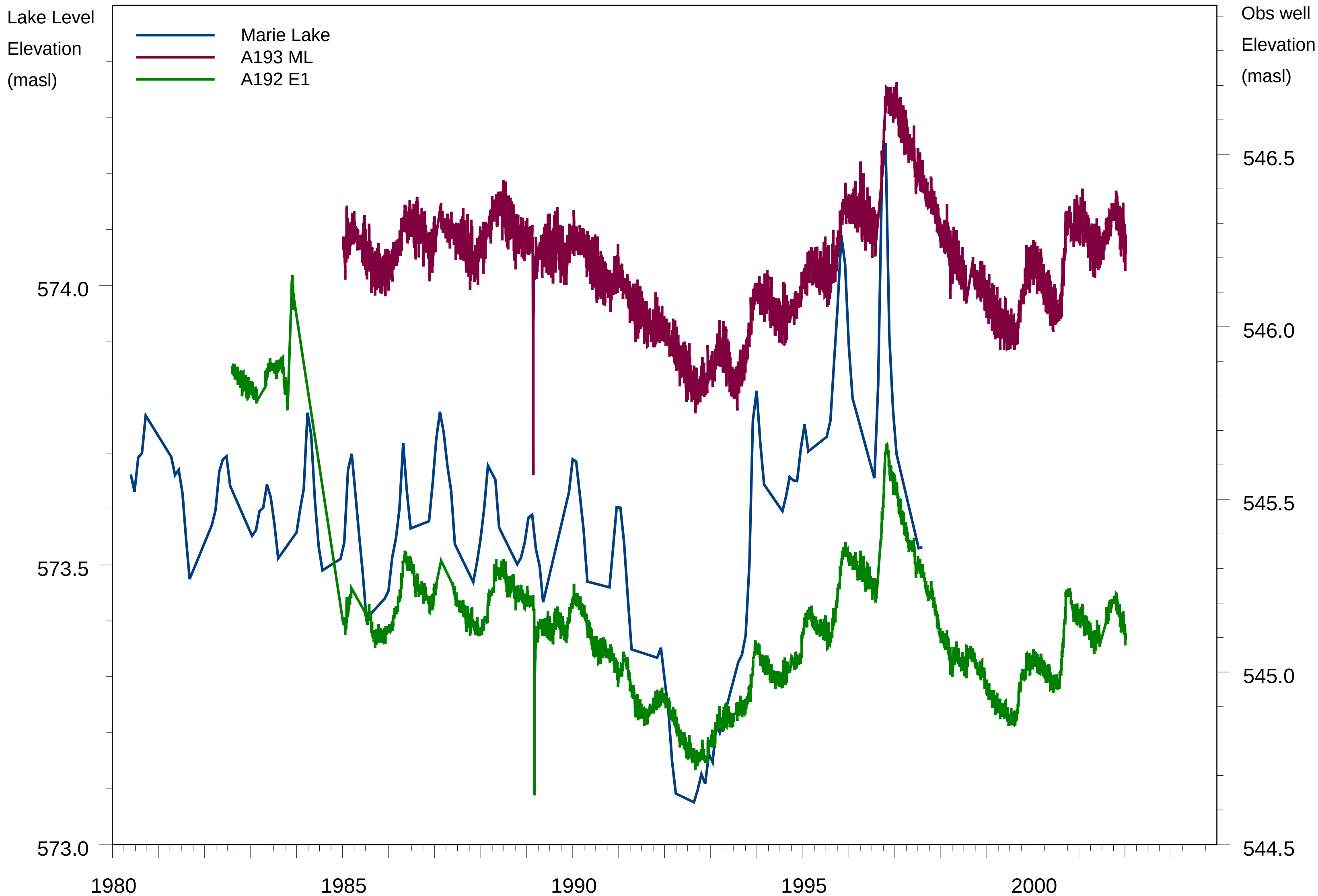



**Figure 7.5. Comparative hydrographs, AENV water-level observation wells A192, A193 vs. Marie Lake water-levels.**

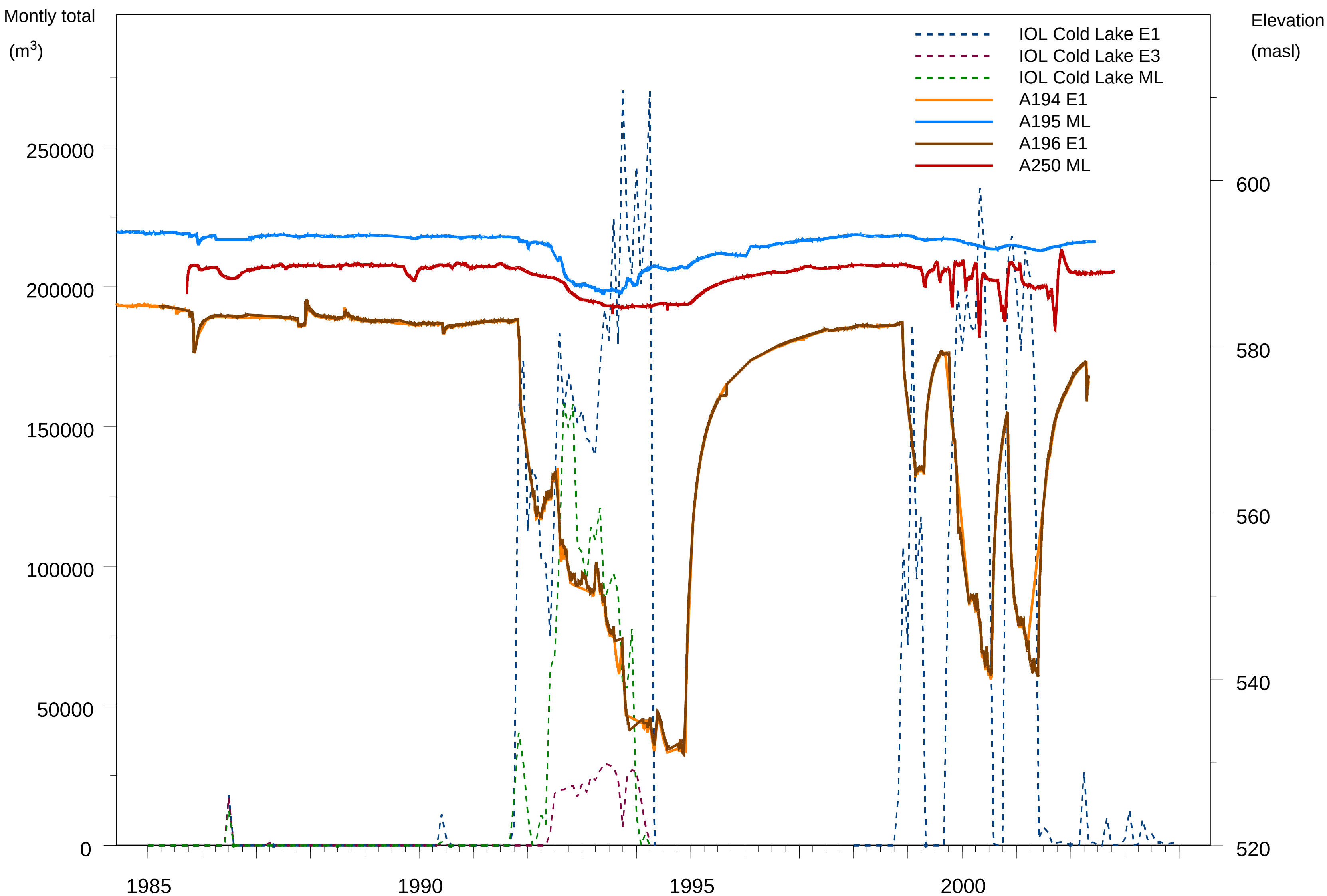



**Figure 7.6. Comparative hydrographs, AENV water-level observation wells A194, A195, A196, A250 vs. IOL Cold Lake pumping.**

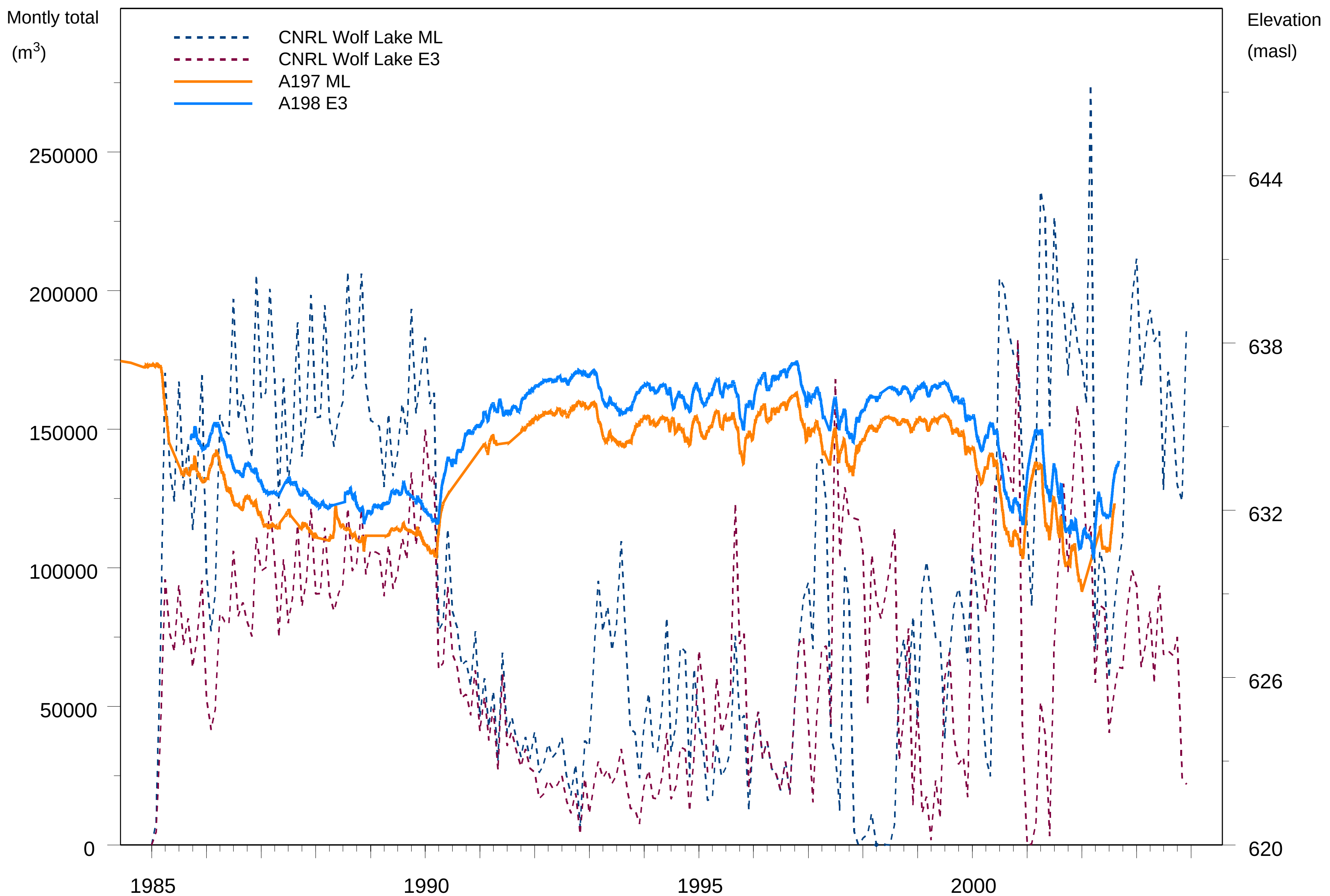



**Figure 7.7. Comparative hydrographs, AENV water-level observation wells A197, A198 and CNRL Wolf Lake pumping.**

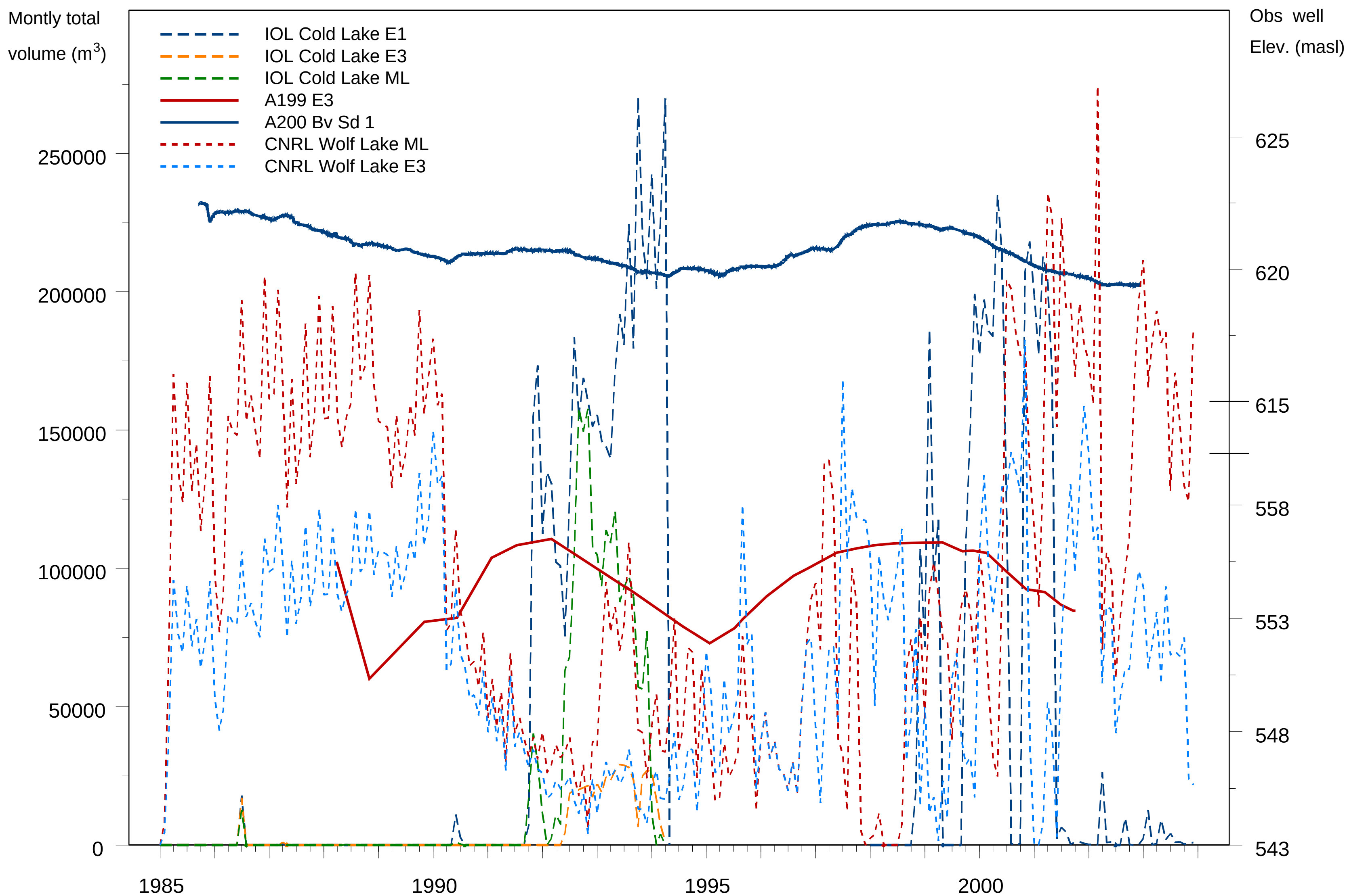



**Figure 7.8. Comparative hydrographs, AENV water-level observation wells A199, A200 vs. IOL Cold Lake and CNRL Wolf Lake pumping**

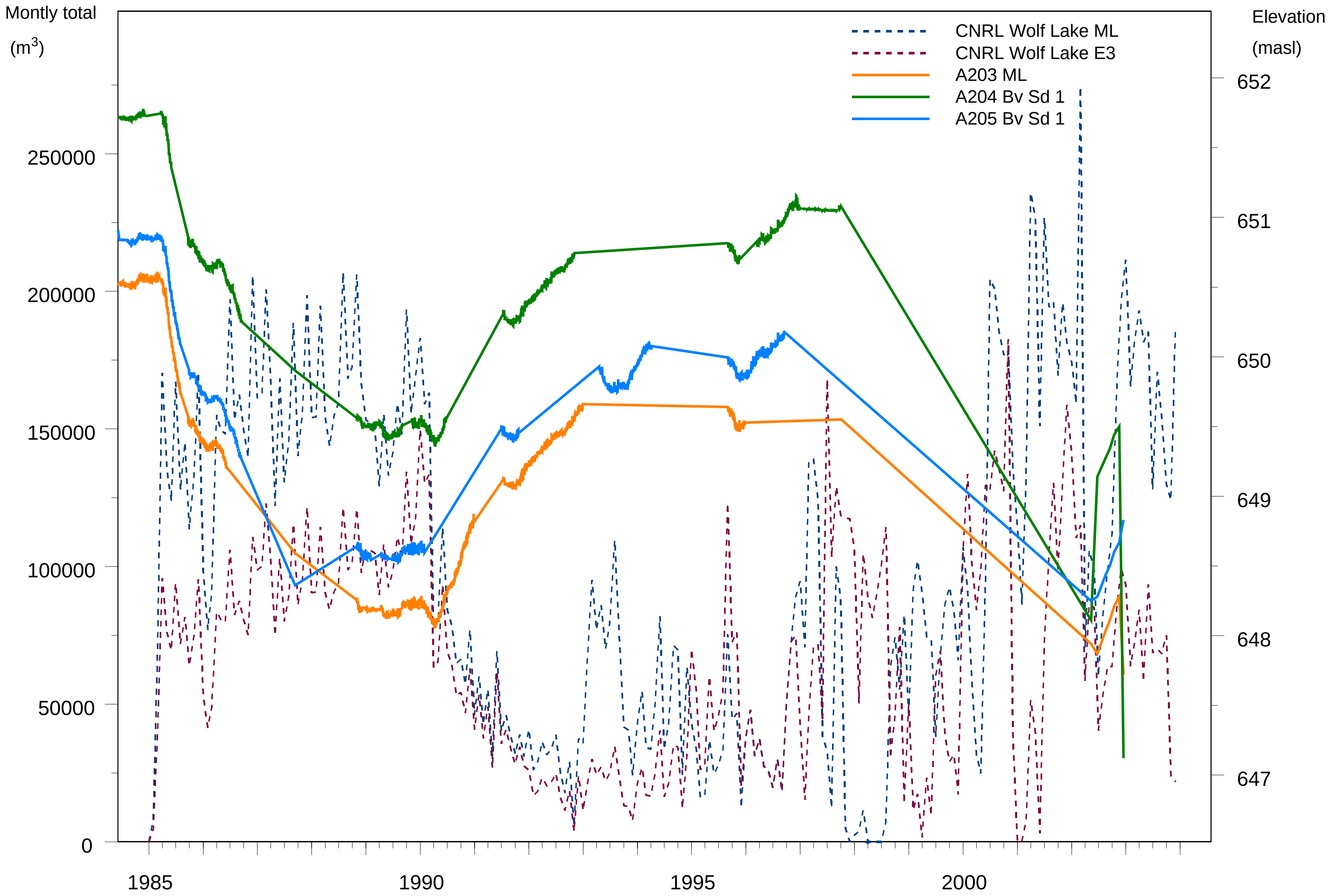



**Figure 7.9. Comparative hydrographs, AENV water-level observation wells A203, A204, A205 vs. CNRL Wolf Lake pumping.**

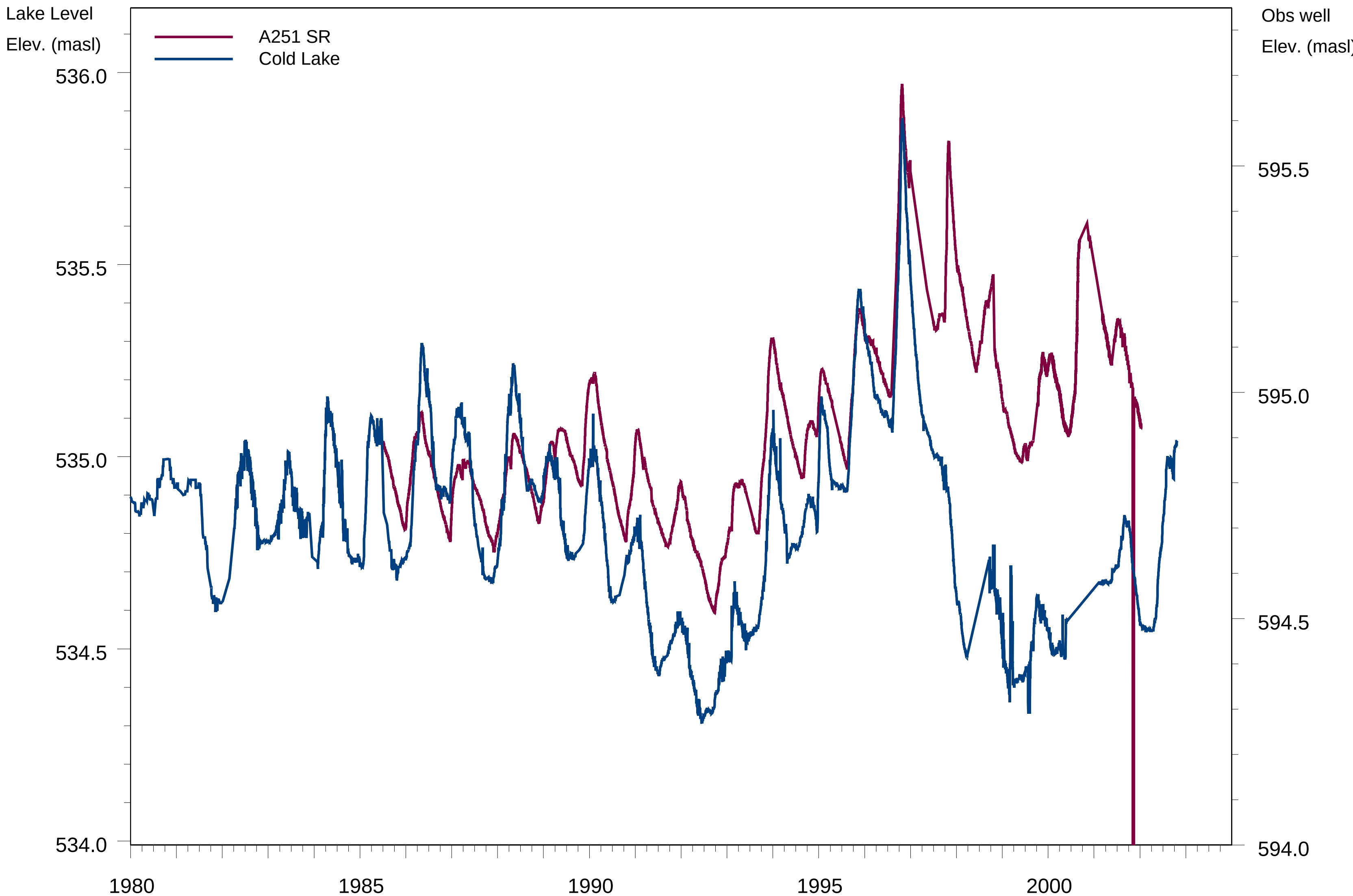



**Figure 7.10. Comparative hydrograph, AENV water-level observation well A251 vs. Cold Lake water levels.**

## 7.2 Opportunities to Augment Existing Water-Level Monitoring Network

The water-level monitoring network consisting of existing wells appear to do a good job of capturing aquifer response to large pumping stresses in the northeast part of the Cold Lake-Beaver River Drainage Basin. In addition, those water-level observation wells located near large lakes and distal to groundwater production wells show strong control by lake-level fluctuations.

In the terms of Uil et al. (1999) the existing monitoring network can be viewed as a mixed strategic-compliance network. The monitoring wells were installed over time in response to fundamental data needs and to ensure compliance of large industrial groundwater-production licenses. Though multi-objective networks are possible to design, they do not produce results superior to single-objective designs. Therefore, the recommended network augmentations discussed below are separated into their single-objective components.

It should be noted that there are redundancies in the present water-level observation well network. Where these redundancies occur, one or more wells could be considered for suspension, depending on the amount of spatial coverage, i.e., two wells may respond to the same production well but are both worth keeping because they are spatially located far apart from one another. Redundant well pairs include: A186 and A187, A194 and A196, A204 and A205.

### 7.2.1 Strategic Network Augmentation

Strategic networks provide baseline information about the natural system. The most optimal locations for new observation wells are therefore coincident with the existence of knowledge gaps. Identification of these locations can be done through hydrogeological judgement and through quantitative means.

#### 7.2.1.1 Monitoring Wells Near Lakes

Simulations of regional groundwater flow under natural and pumping scenarios indicate a signficant proportion of regional groundwater discharge goes into the lakes (although the groundwater contribution relative to surface water inflows and outflow is very small). However, there is little hydrogeological information available about the lake-groundwater dynamics in the basin. Therefore, a logical set of locations to augment the strategic monitoring network would be adjacent to the major lakes of the area. The purpose of these wells will be to gather baseline data about their interactions with groundwater and to quantify the strength of aquifer-lake interactions. The actual locations should be placed as far away from existing wells as possible, preferably on the far side of each lake from rural or urban developments.

Alberta Observation Wells A192, A193 and A189 already exist near Marie Lake and Hilda Lake, respectively. As well, two observation wells (A190 and A191) appear to respond to Lac La Biche to the northwest of the Cold Lake-Beaver River Basin, albeit with a substantially subdued response related to their distance from Lac La Biche. New locations for new water-level monitoring wells should go to lakes already equipped with lake-level gauges. Recommended locations for montoring well nest near the major lakes are shown in Figure 7.11, namely at Wolf Lake, Beaver Lake, and Muriel Lake.

The formations best monitored at each location would need to be evaluated on a site-specific basis given the heterogeneity of the drift formations and presence of ice thrusts around the major lakes. However, the first choice would be an aquifer-bearing unit that appears to be hydraulically connected to the the lakes at the chosen location based on the regional geological model. At Beaver Lake, this would be probably

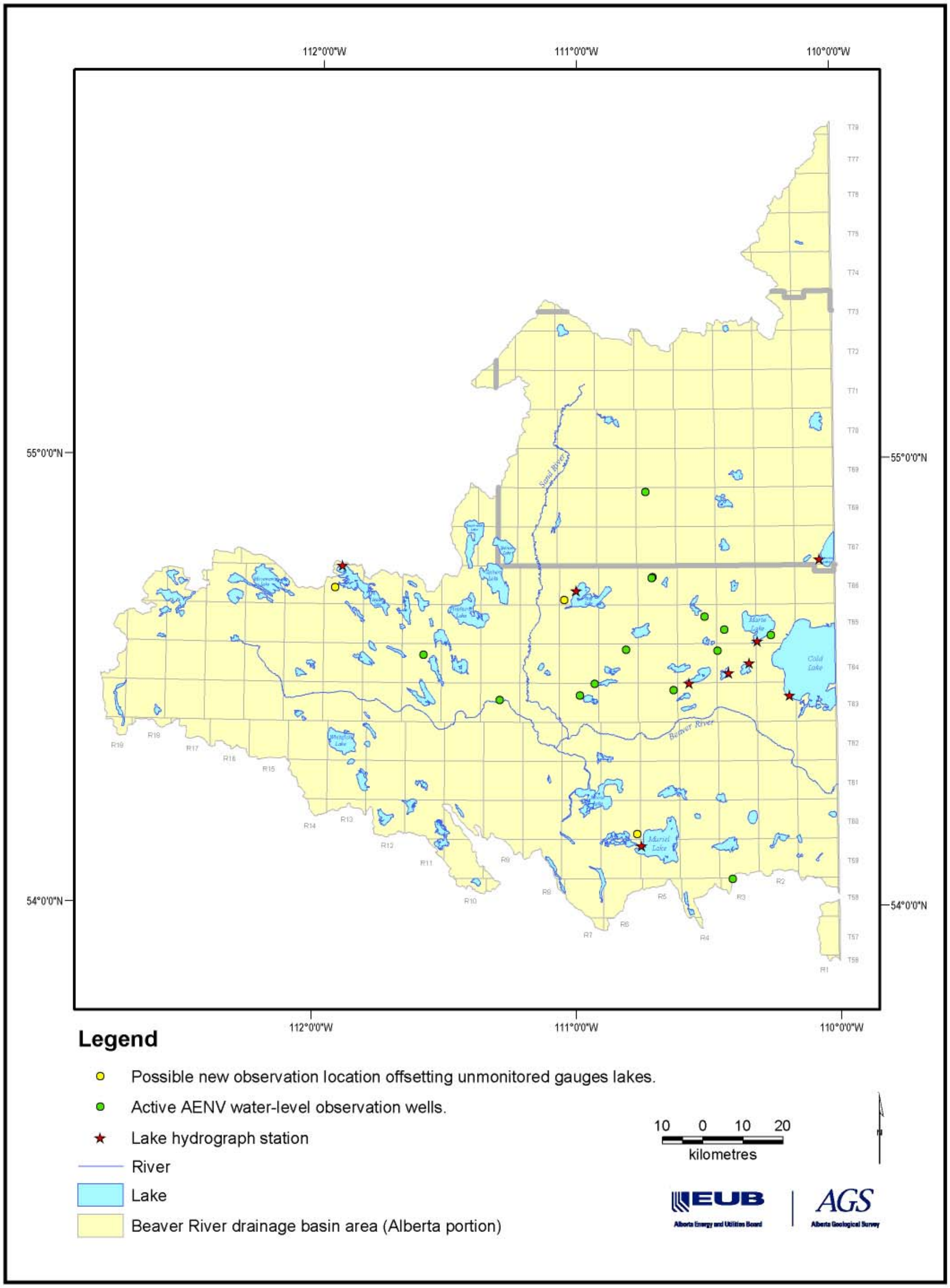



**Figure 7.11. Locations of possible observation wells offsetting gauged lakes.**

be the Grand Centre Formation, at Wolf Lake this would be the Sand River Formation Formation, and at Muriel Lake this would probably be the Grand Centre Formation and the Ethel Lake Formation.

The results of analyses of lake-aquifer interactions from these six sites could then be extended to unmonitored lakes in the basin with similar geological settings.

#### 7.2.1.2 Monitoring Wells in Buried Valleys

Our quantitative knowledge of groundwater flow into and out of the basin along buried valley aquifers is poorly constrained. Therefore new water-level monitoring locations completed in the Empress Formation would be most useful at the places where the buried valleys enter/exit the Basin boundaries. Similarly, the connection between the Muriel Lake Formation along the Sinclair Valley at the northernmost extent of the basin would benefit from a similar monitoring site. Recommended sites for new monitoring well-nests at the entry/exit points of buried valleys are shown in Figure 7.12.

#### 7.2.1.3 Montoring Wells Nests in Recharge Areas

Another poorly constrained parameter needed to manage the Basin is an estimate of groundwater recharge rate. Though quantification of recharge is difficult and confounded by multiple site-specific factors operating at a number of different spatial and temporal scales, monitoring well nests can provide valuable data to constrain first-order estimates of recharge rates. These data include vertical hydraulic gradients from water-level observations, vertical age-date profiles from sediment-core and groundwater chemistry, vertical leakance estimates from well-tests, and recharge estimates from hydrograph separation techniques. Ideally, there should be at least one site in the regional recharge areas for each of the five flow-systems identified by Section 4. Care must be taken to select sites that are not on ice-thrust ridges as these areas are more hydraulically compartmentalized and would lead to biased-low estimates of recharge. In general, a nested installation consisting of one water-table well completed in surficial sediments and one or two shallow observation-wells in the Grand Centre Formation would be recommended at each location to investigate recharge rates.

Possible sites for well nests in recharge areas are shown in Figure 7.13. One site in each regional flow system is placed overtop a buried valley and at least one is placed away from any buried valley. The underdrain effect of the buried valley aquifers may increase recharge along their axes but this effect has never been investigated in the Cold Lake-Beaver River Drainage Basin. The off-valley locations were chosen to be in areas of strong vertical gradients (where possible) as calculated by the regional steady-state flow model discussed in Section 5. The exact locations need to be further investigated by field visits to see if they are indeed useable for this purpose.

#### 7.2.1.4 New Locations to Improve Regional Estimates of Potentiometric Surfaces

Water-level observations can be compared to historical or baseline potentiometric surface maps to identify areas of hydraulic head change. The significance of observed change will depend, in part, on the quality of the baseline estimate of hydraulic head. Geostatistical interpolation and simulation techniques offer a way to estimate uncertainty in predicted values at unsampled locations. These estimates can guide the selection of new observation points that will add the most information to baseline potentiometric surface maps.

Potentiometric surfaces of the Grand Centre Formation, Sand River Formation, and the Ethel Lake. Formation are discussed in Section 4. These maps were constructed from static water-level measurements

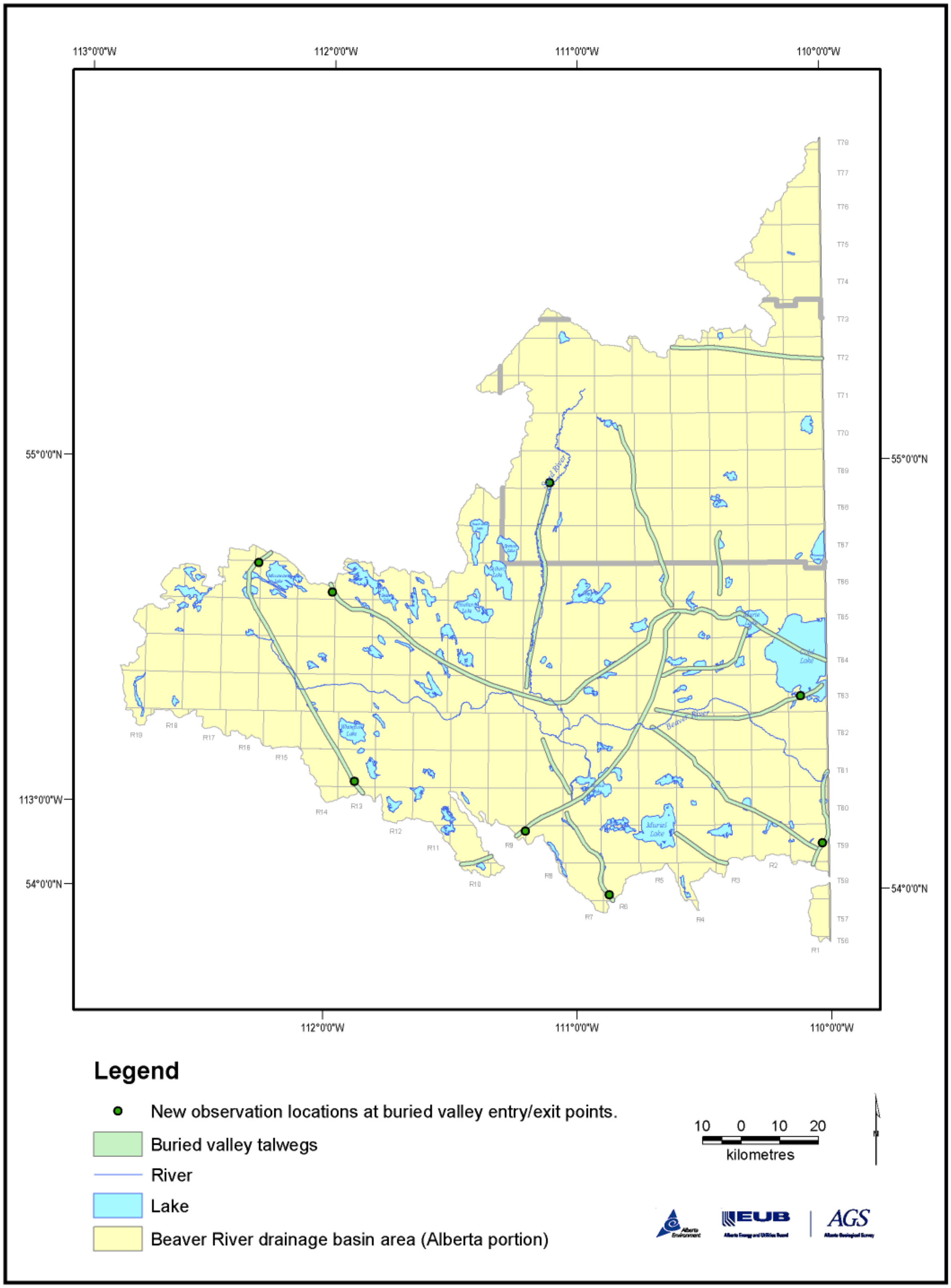



**Figure 7.12. Potential sites for observation wells at buried valley entry/exit points.**

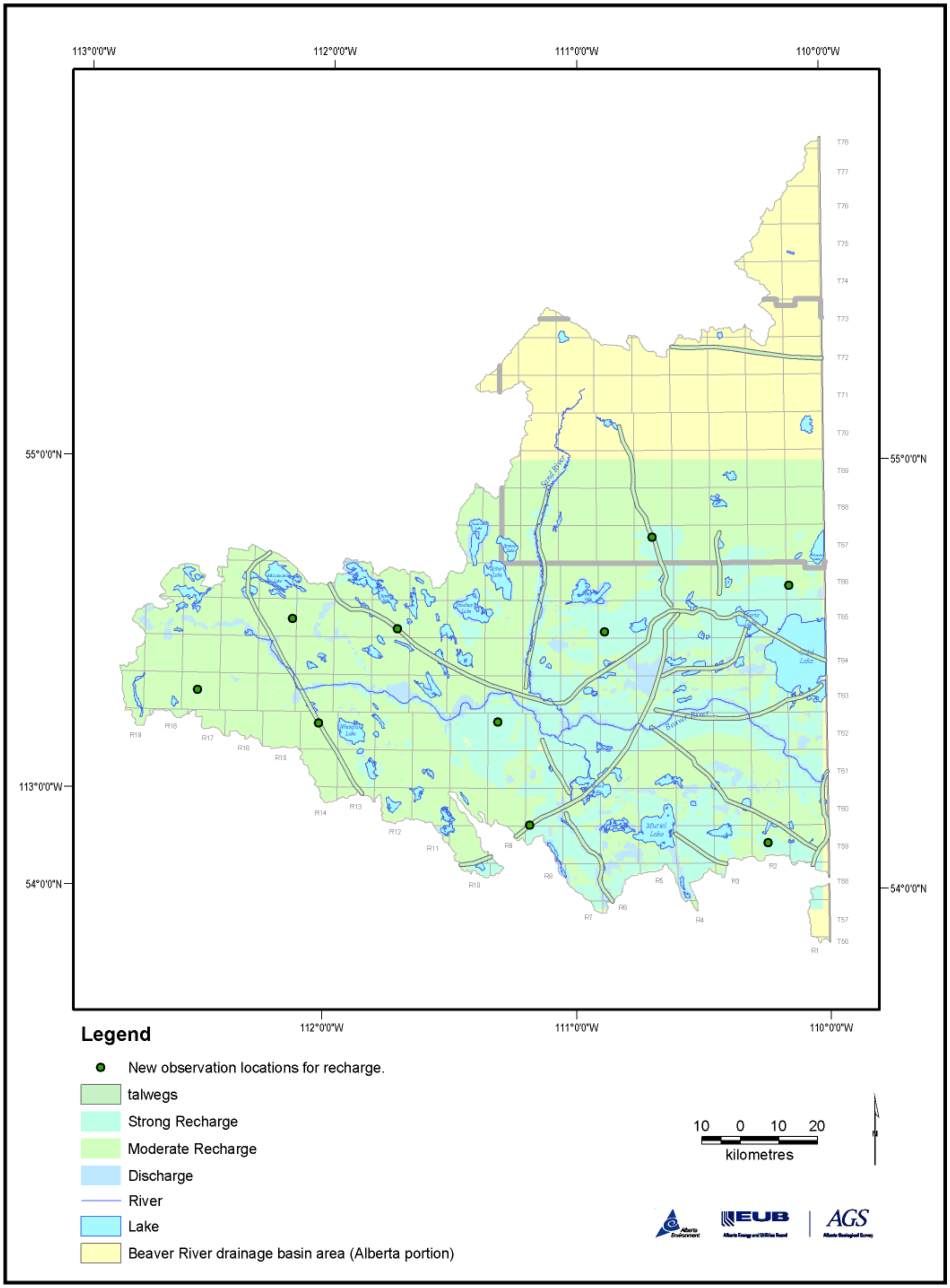



**Figure 7.13. Potential sites for recharge monitoring.**

reported on driller's reports on file with Alberta Environment. For the purposes of this analysis, the same static water-level measurements were detrended, converted to normal-score values, and then kriged using simple kriging to calculate the error variance of estimate in Gaussian units on each potentiometric surface and thereby identify potential locations for new water-level observation wells. These maps were backtransformed into normal units of head measurements using an appropriate backtransform technique to provide interquartile (i.e., $P_{75}$-$P_{25}$) ranges of estimate in the potentiometric residuals. The areas of greatest interquartile range in estimate would benefit greatest from additional observations.

The maps of interquartile ranges for the Grand Centre, Sand River and Ethel Lake are shown in Figure 7.14 to 7.16, respectively. There were not enough data in the other formations to do this kind of analysis. Areas of highest values indicate where the relative uncertainty in estimations of hydraulic head on the potentiometric surface maps is greatest and therefore where additional head measurements would be valuable in improving the regional potentiometric maps

#### 7.2.1.5 New Locations to Improve Regional Numerical Model

The calibrated numerical model of regional groundwater flow of the Cold Lake-Beaver River Drainage Basin is discussed in Section 5. As with any numerical model, this one is a simplified version of reality and as such would benefit from incorporation of new field observations. An improved model would benefit future water-management decisions made with its assistance.

Sensitivity analysis using inverse-modeling technology provides a way to identify which new field observations would most improve the model and where they should be taken. One of the outcomes of the modeling study was such an analysis of the sensitivity of model parameter estimates (e.g., formation hydraulic conductivity) to additional observations of hydraulic head using the inverse-modeling capabilities of MODFLOW2000 (Hill et al., 2000).

The overall sensitivity is captured in a statistic called the composite scaled-senstivity, or *css* (Hill, 1998). The parameters associated with high *css* values are most likely to be successfully estimated by an inverse-modeling procedure because their estimation is sensitive to field observations. Putting it another way, field observations have high value to estimation of parameters with associated high *css* values. A histogram of the css values for the numerical model parameters is shown in Figure 5.4. This histogram shows that the model calibration to hydraulic head values is most sensitive to the conductivity term associated with the uppermost boundary condition representing recharge, the vertical anisotropy of hydraulic conductivity in the till-dominated formations (presumed regional aquitards), and the horizontal hydraulic conductivity of the Muriel Lake Formation.

Once the most sensitive parameters have been identified by calculation of the *css* statistic, another statistic called the one-percent scaled sensitivity, or *dss*, can be calculated and mapped (Hill, 1998). This statistic captures how much a simulated value would change given a one-percent increase in the value of a model parameter. Any point with a high value of *dss* would be important to estimation of the model parameter during an inversion process. Therefore any point of high *dss* without a real observation point is a good candidate for a new observation that would improve the model.

Three one-percent sensitivity maps are presented in Figures 7.17 to 7.19. These include maps of the sensitivity of calculated heads in the Sand River Formation to the conductivity term embedded in the surface boundary condition, the sensitivity of calculated heads in the Muriel Lake Formation to the estimated hydraulic conductivity of the Muriel Lake Formation, and the sensitivity of the calculated heads in the Muriel Lake Formation to the vertical anisotropy of the till-dominated formations in the Basin.

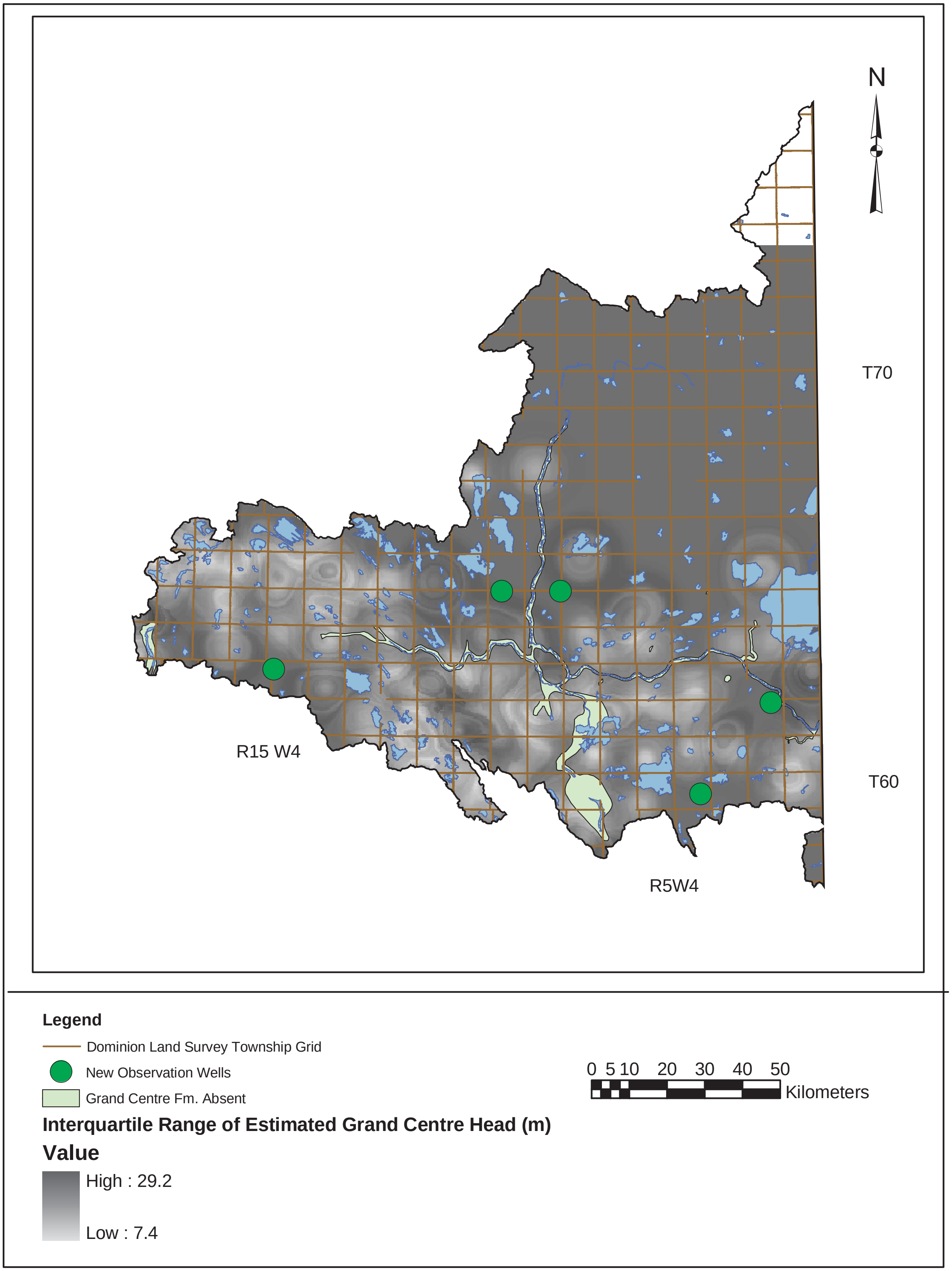



**Figure 7.14. Locations of possible observation wells relative to the interquartile range of estimated local distributions of hydraulic head, Grand Centre Formation.**

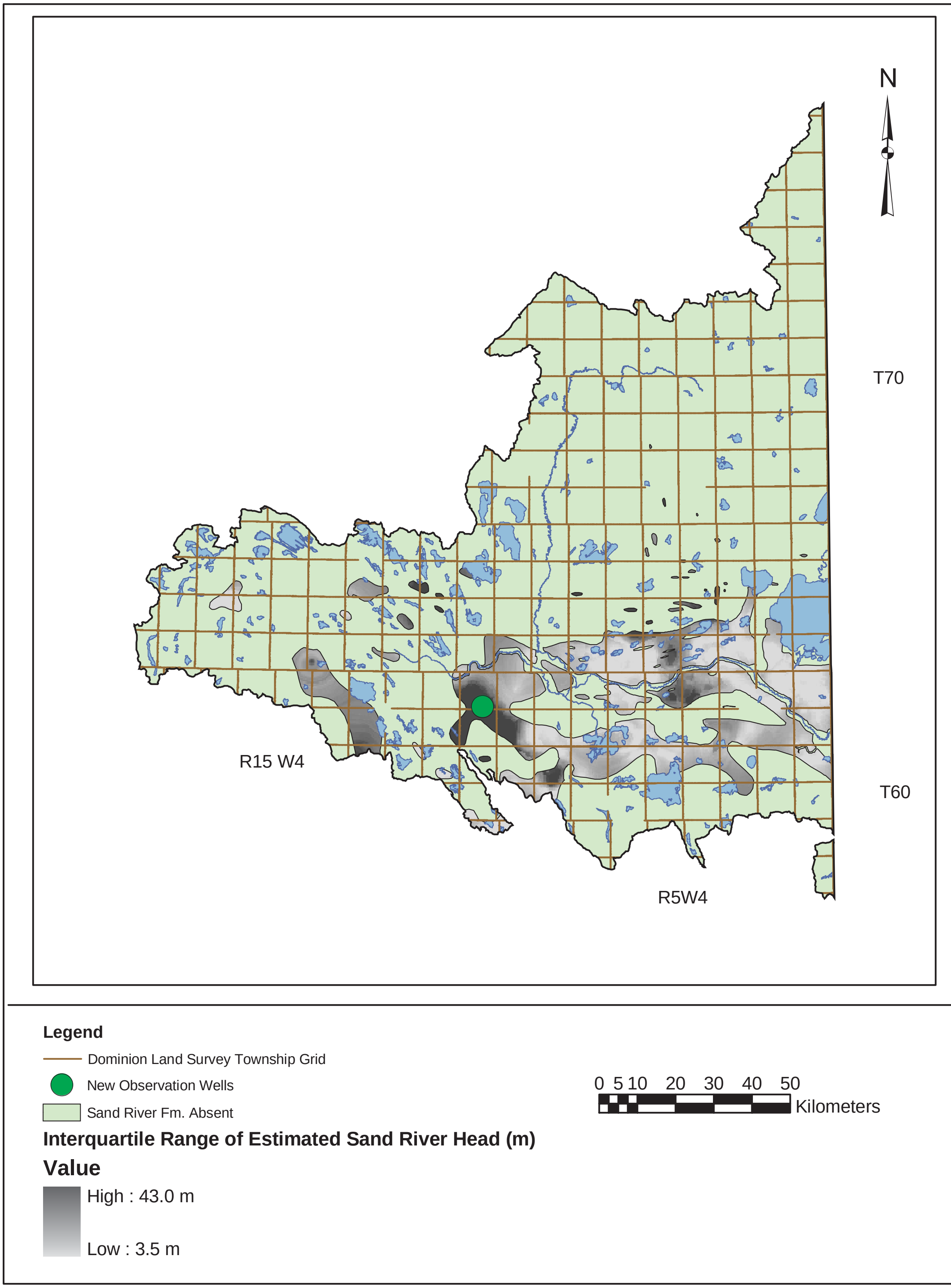



**Figure 7.15. Locations of possible observation wells relative to the interquartile range of estimated local distributions of hydraulic head, Sand River Formation.**

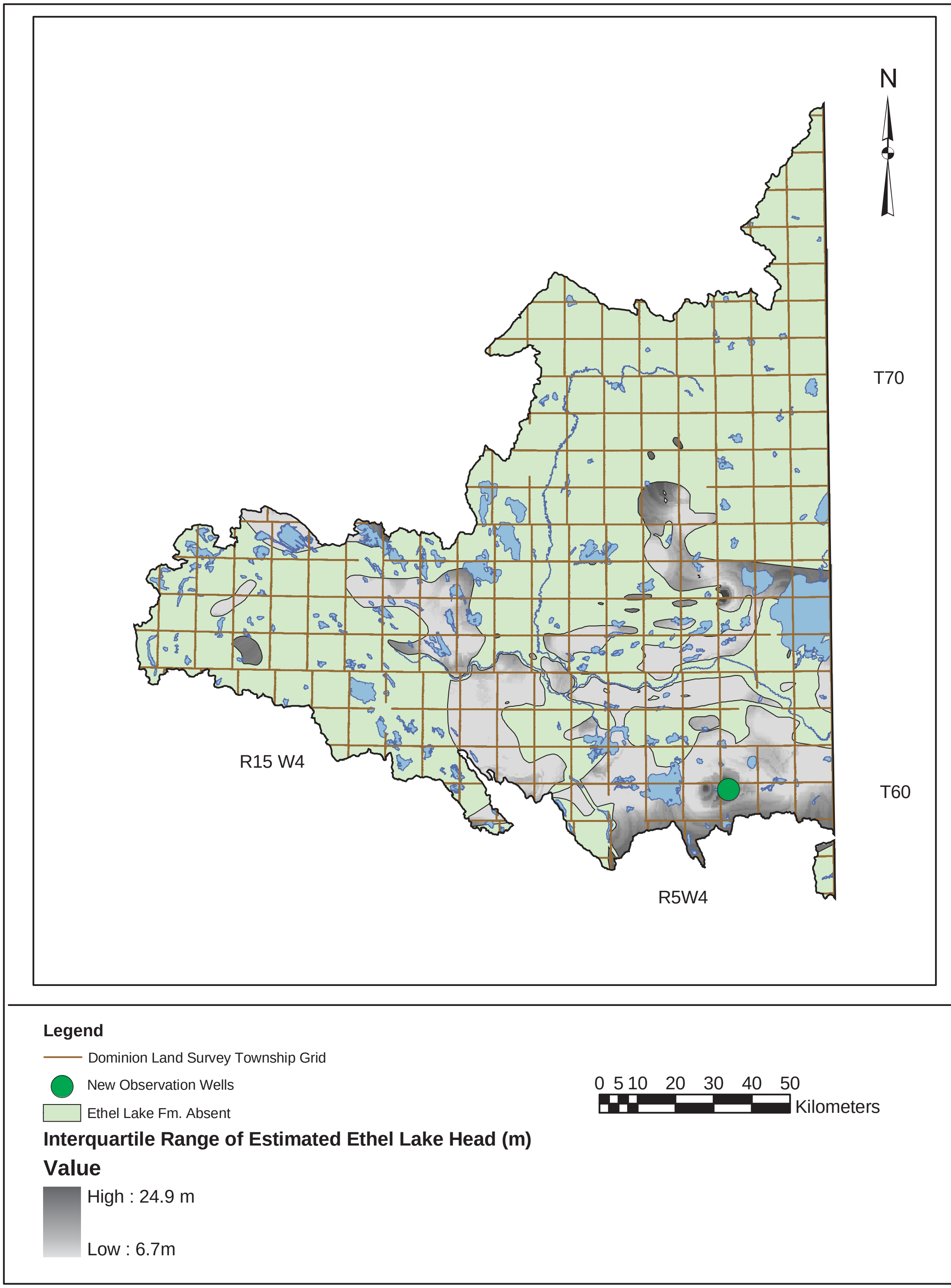



**Figure 7.16. Locations of possible observation wells relative to the interquartile range of estimated local distributions of hydraulic head, Ethel Lake Formation.**

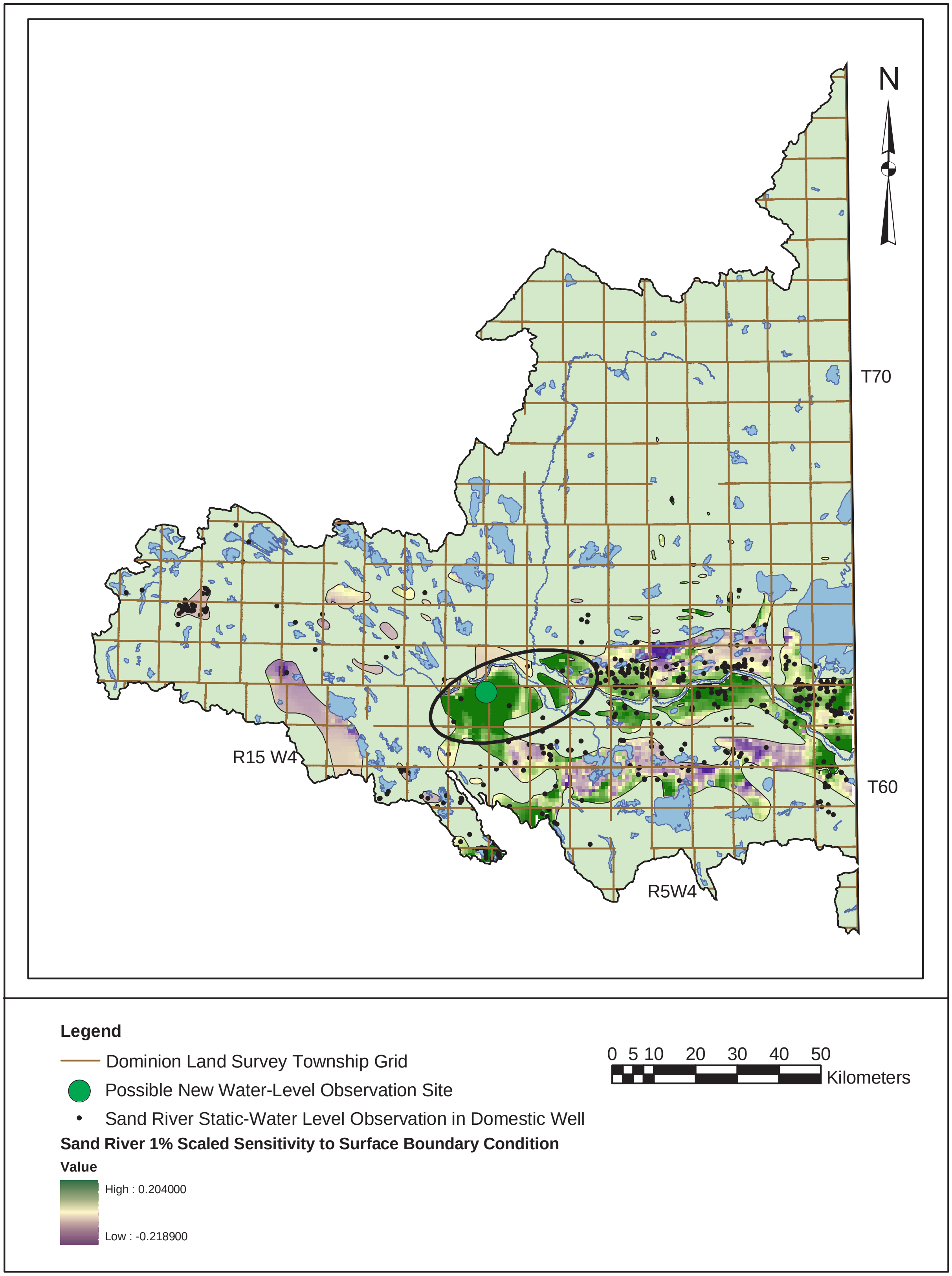



**Figure 7.17. One-percent scaled-sensitivities in the model Sand River Fm. highlighting areas where model has high sensitivity to the surface boundary condition.**

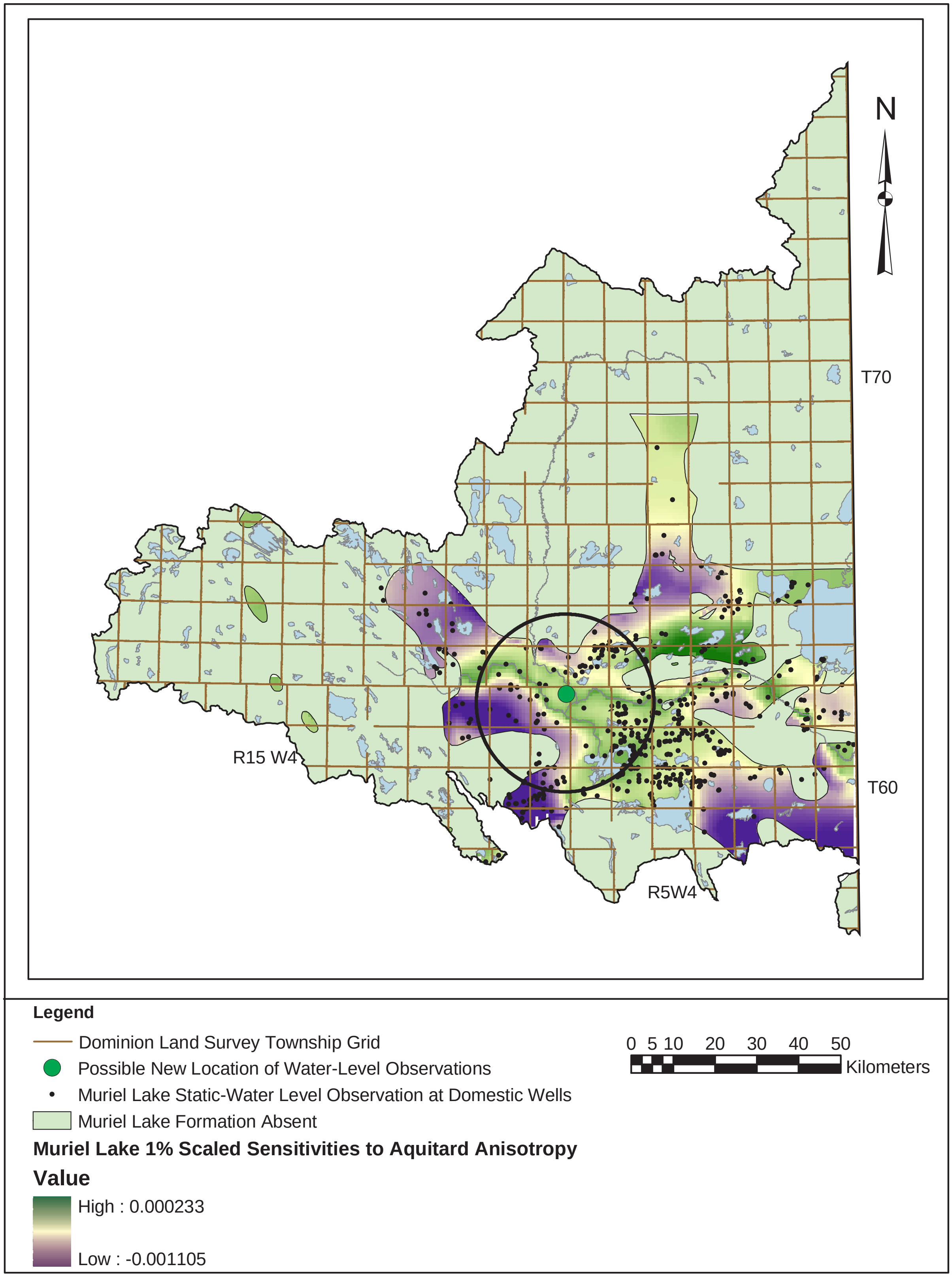



**Figure 7.18. One-percent scaled-sensitivities in the model Muriel Lake Fm. highlighting areas where model has high sensitivity to the vertical anisotropy of aquitards.**

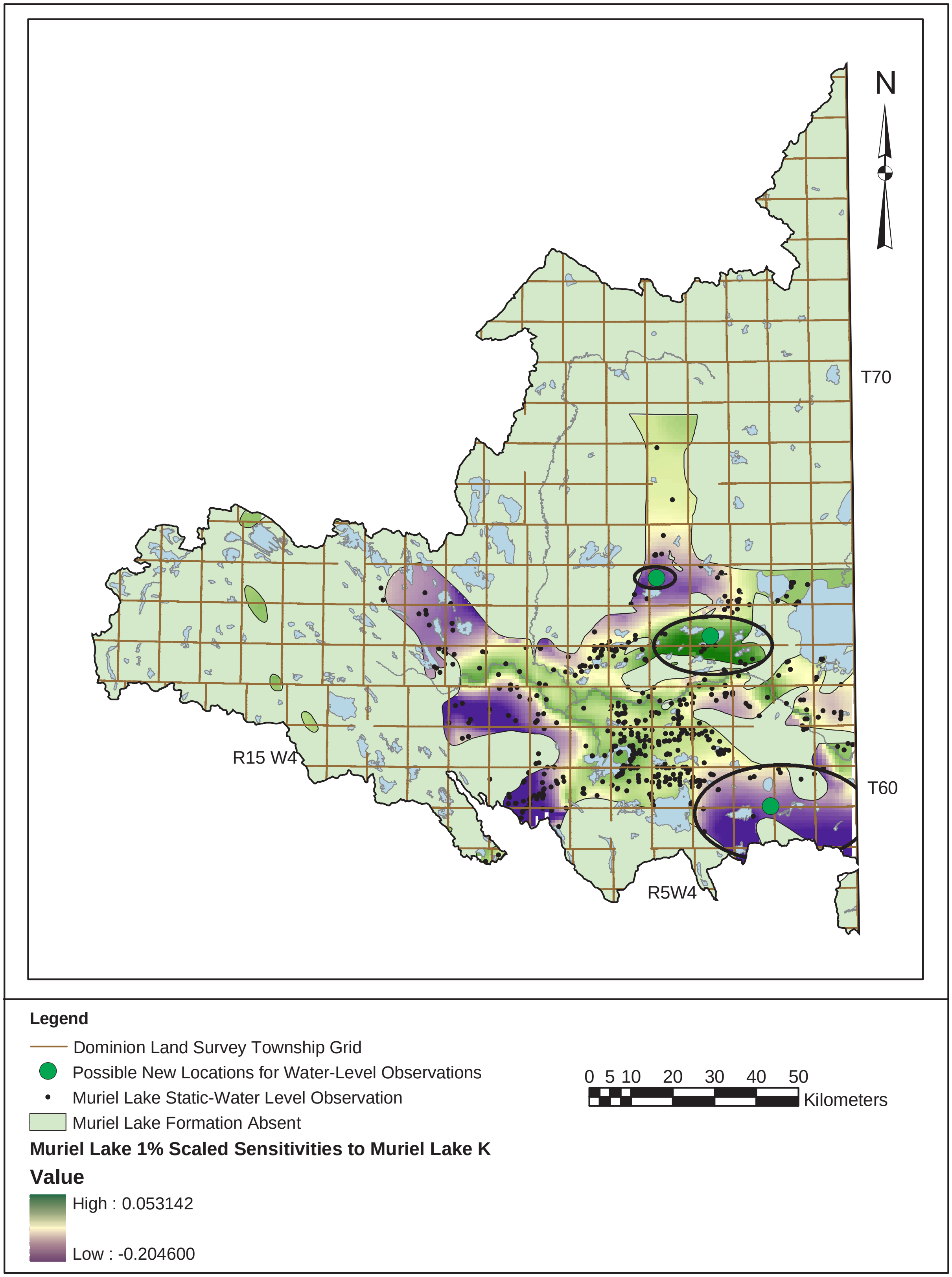



**Figure 7.19. One-percent scaled-sensitivities in the model Muriel Lake Fm. highlighting areas where model has high sensitivity to the hydraulic conductivity of the Muriel Lake Fm.**

On each map is a circled area where the *dss* tends to be high in absolute magnitude and where head observations are sparse. New water-level observation wells in these circled areas would benefit future model improvement the most.

### 7.2.2 Compliance Network Augmentation

Licensed water wells have water-level reporting requirements from the production well and/or a closeby dedicated observation well. These water-levels are used to ensure compliance with regulations and license requirements for the specific wells. Regional water-level monitoring wells can be used in a similar fashion to ensure that the cumulative impact of all production is not exceeding the capacity of the Basin to sustain the production. This can be done by ensuring that the water-level declines and related changes in regional hydraulic gradients do not create changes in recharge or discharge areas that exceed limits set in a water-management plan.

The placement of such regional compliance monitoring wells can be guided by maps of the predicted drawdown in all aquifers given a predefined set of production wells and their maximum allowable production. Regional compliance wells can be set at locations away from production wells but at locations were unambiguous drawdown is predicted to occur from cumulative production.

For example, the cumulative drawdown in all drift formations in the Cold Lake-Beaver River Basin from all presently licensed groundwater production wells was calculated and mapped using the numerical model as discussed in Section 6. The cumulative drawdown was calculated assuming all licensed wells produced at their maximum allowable rate until the Basin reached a new steady-state. Unlicensed domestic and stock-well production was not considered.

If the present licensed capacity were to be used as the basin limit, then the drawdown maps shown in Section 6 could be used to select new compliance water-level observation locations to monitor cumulative effects of production. For this purpose, new water-level observation wells should be placed somewhere along the 5-m predicted drawdown contours in each formation. Five metres of drawdown would be a clear signal of production effects because short-term drawdowns of this magnitude should be easy to distinguish from background water-level fluctuations.

The predicted maximum drawdown at steady-state are shown for the Empress, Muriel Lake, Ethel Lake, Sand River, and Grand Centre formations in Figures 7.20 to 7.24, respectively. New water-level observation sites are shown on each figure at one or more points along the predicted 5-m drawdown contour, depending on the formation. The presence of AENV water-level observation wells and reported industry observation wells was taken into account when selecting these sites to avoid duplication. If water-level declines are observed at these locations in excess of five metres, then one could conclude that the maximum changes in recharge and discharge fluxes distributed across the basin as calculated by the model would be exceeded.

For any future well licensed in the Basin, the model would need to be re-run to test the adequacy of the regional compliance network. Should the extent of the new cone of depression in any formation enter areas not already covered by an existing or recommended new water-level observation well location, an additional new water-level observation location may need to be considered to monitor regional scale cumulative effects.

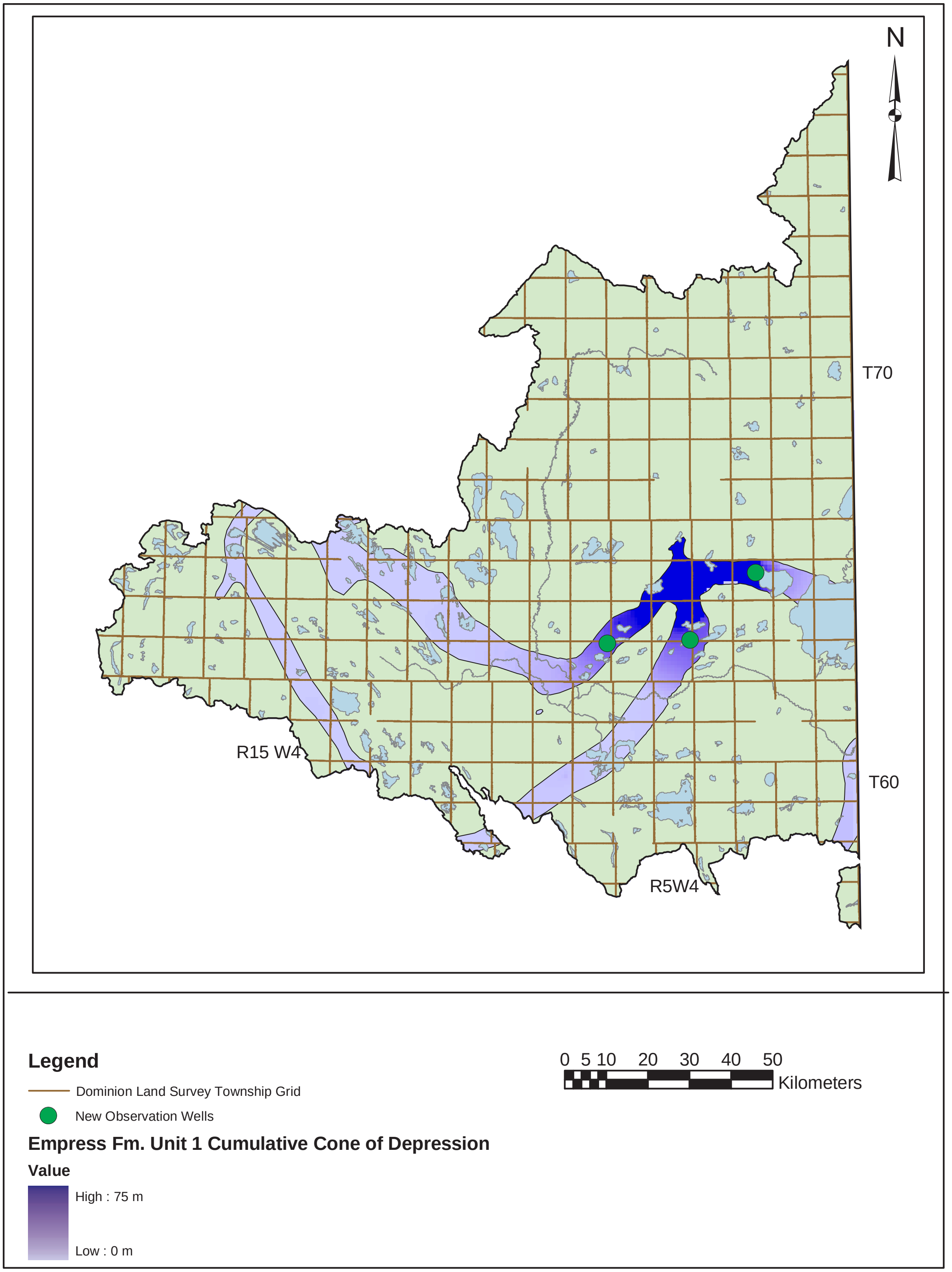



**Figure 7.20. Locations of possible additional water-level observation wells relative to maximum extent of predicted drawdown in the Empress Formation Unit I due to pumping all licensed wells at licensed maximum.**

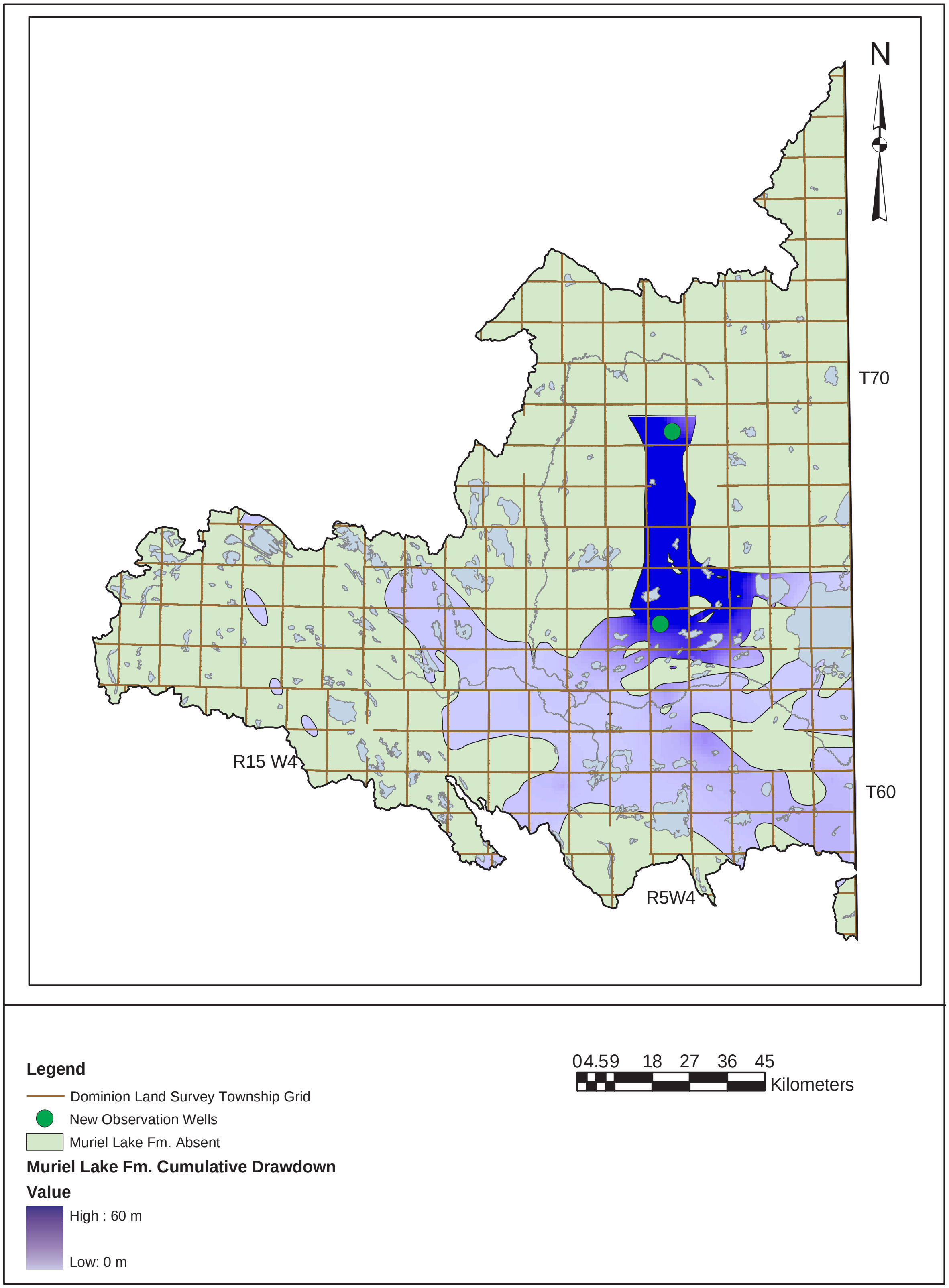



**Figure 7.21. Locations of possible additional water-level observation wells relative to maximum extent of predicted drawdown in the Muriel Lake Formation due to pumping all licensed wells at licensed maximum.**

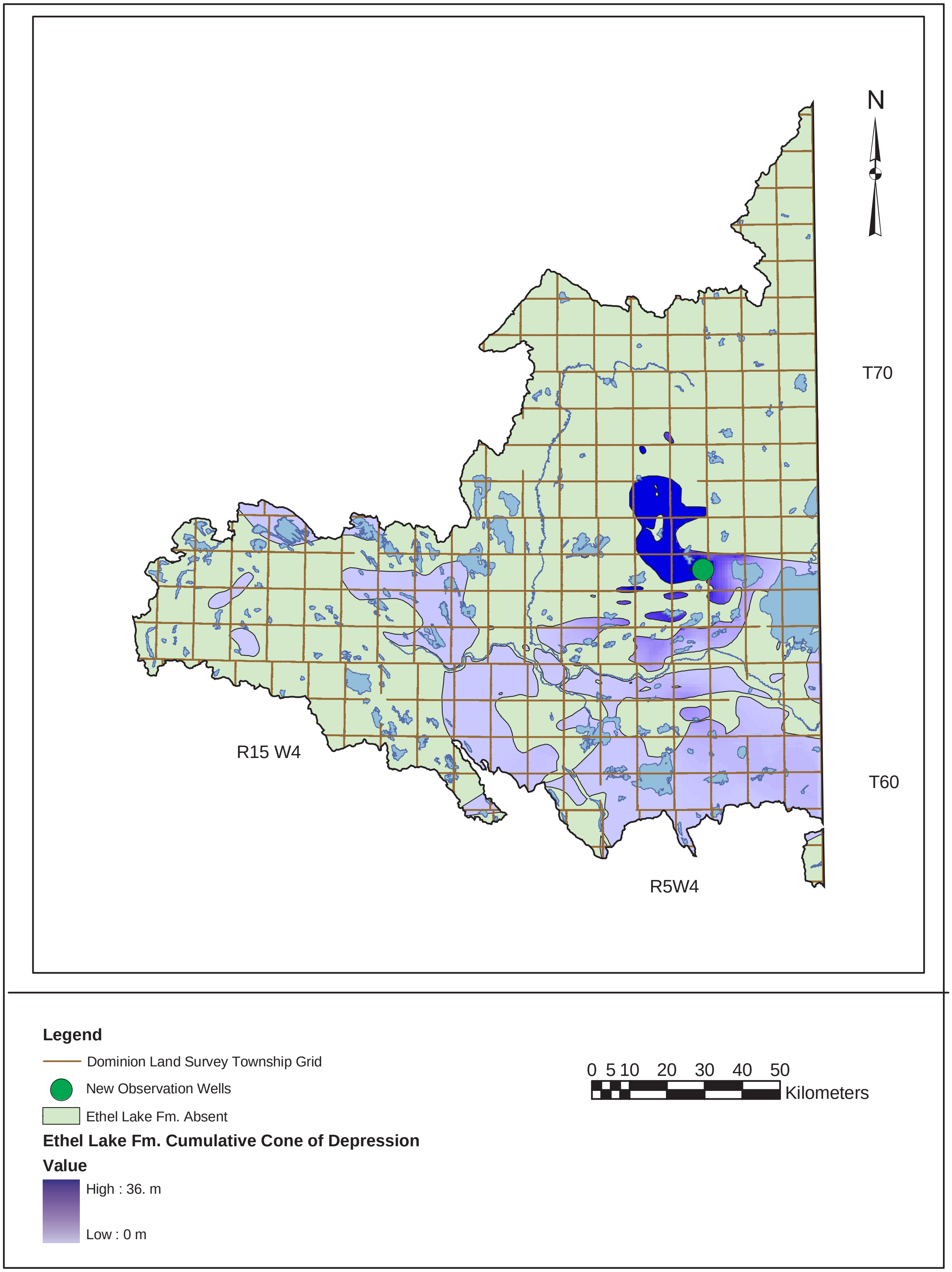



**Figure 7.22. Locations of possible additional water-level observation wells relative to maximum extent of predicted drawdown in the Ethel Lake Formation due to pumping all licensed wells at licensed maximum.**

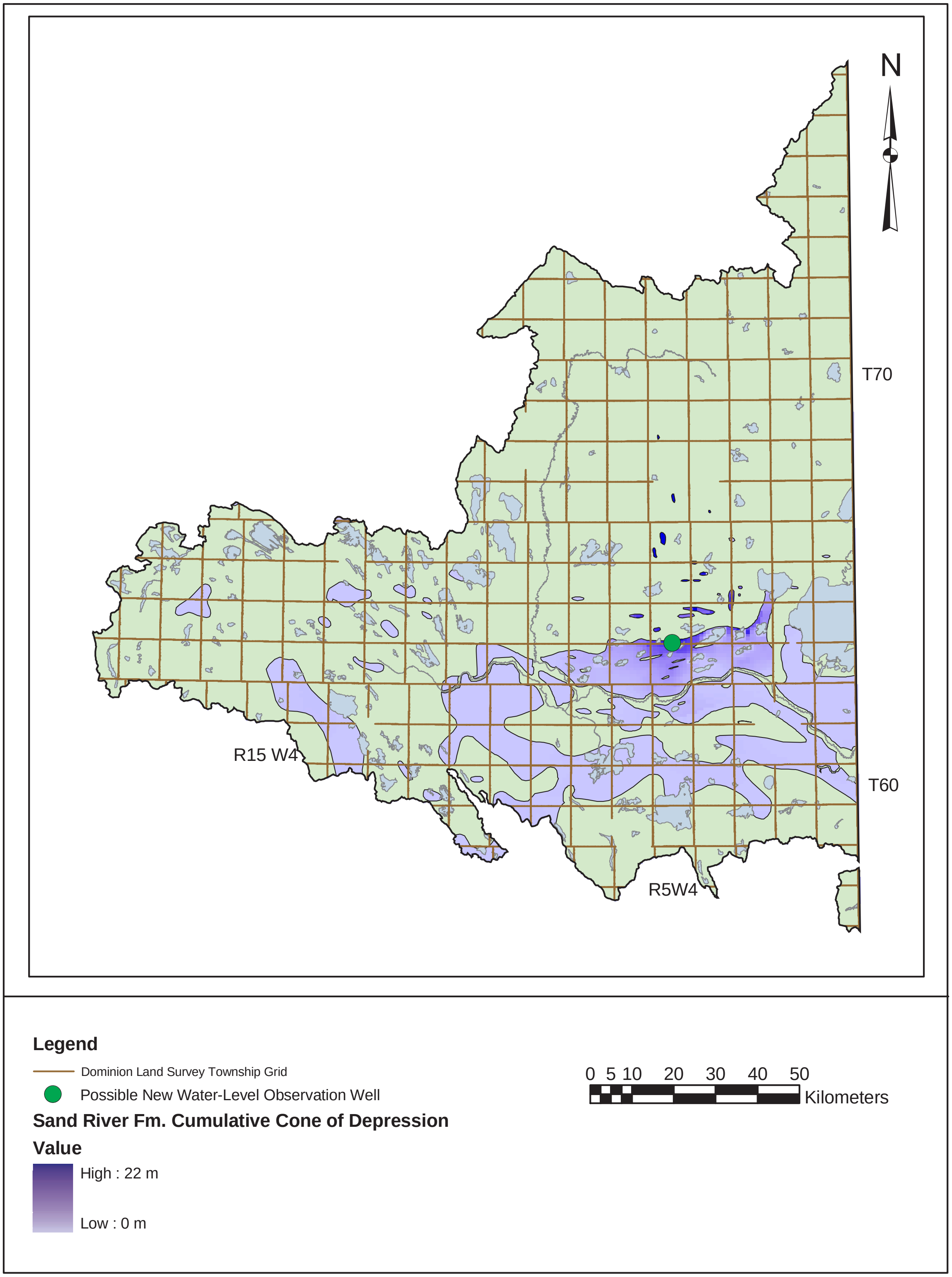



**Figure 7.23. Locations of possible additional water-level observation wells relative to maximum extent of predicted drawdown in the Sand River Formation due to pumping all licensed wells at licensed maximum.**

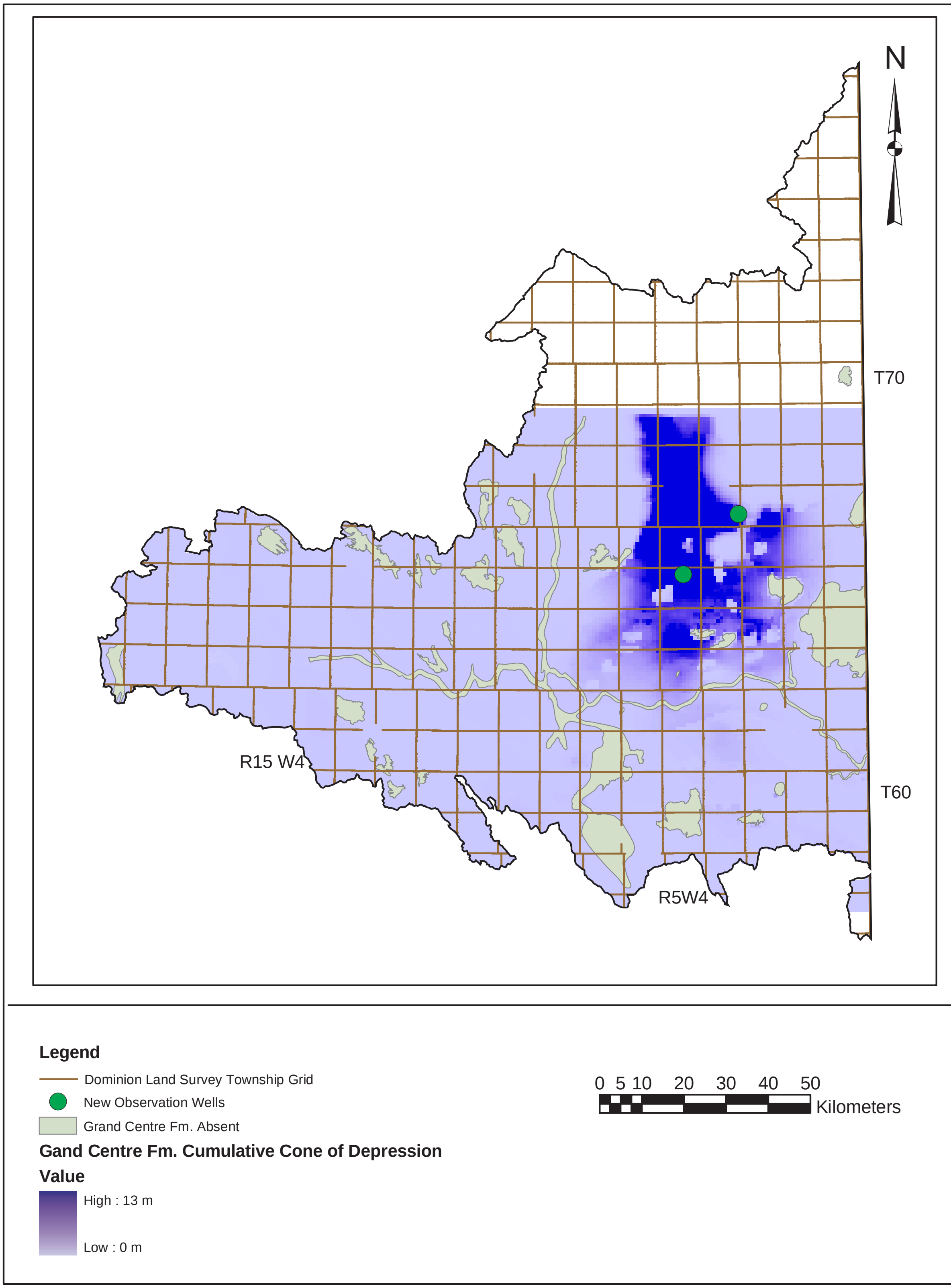



**Figure 7.24. Locations of possible additional water-level observation wells relative to maximum extent of predicted drawdown in the Grand Centre Formation due to pumping all licensed wells at licensed maximum.**

## 7.3 Redundancy Analysis of Augmented Sites

The discussion above enumerates a number of possible sites for augmenting the regional network based on various goals. There is considerable overlap in the possible sites so an analysis was performed to see which new locations could be combined into single multipurpose locations and, of those, which could be potentially be replaced by an existing industry or domestic well on record.

Table 7.2 lists all the possible new locations and formations for monitoring. Locations that are redundant or could be replaced by existing wells are flagged. This process reduces the number of possible new locations worth monitoring from 44 to 29 locations.

New monitoring wells can be dual purpose for water level and groundwater chemical quality monitoring. Designs can be modified to include dedicated sampling tubes for quality monitoring that do not interfere with downhole water-level recorder apparatus. A qualified well-drilling contractor with knowledge of local drilling conditions would be able to provide current cost-estimates based on depth and location.

**Table 7.2. Recommended locations for new water-level observations.**

| Location Number | EUTMZ12N83 | NUTMZ12N83 | Report Section | Motive | Formation | Redunancy Analysis |
|---|---|---|---|---|---|---|
| 1 | 440061.87 | 6063075.99 | 7.2.1.1 | Offsetting Beaver Lake Lake-Level Gauging Station | Grand Centre | |
| 2 | 515123.69 | 6001757.96 | 7.2.1.1 | Offsetting Muriel Lake Lake-Level Gauging Station | Ethel Lake | |
| 3 | 497025.58 | 6059895.83 | 7.2.1.1 | Offsetting Wolf Lake Lake-Level Gauging Station | Sand River | |
| 4 | 436588.76 | 6060867.37 | 7.2.1.2 | Buried Valley Exit Point | Empress I | |
| 5 | 486617.39 | 5998976.29 | 7.2.1.2 | Buried Valley Exit Point | Empress I | Redundant- covered by domestic well 295183 |
| 6 | 508279.28 | 5982472 | 7.2.1.2 | Buried Valley Exit Point | Empress I | |
| 7 | 557792.15 | 6034047.91 | 7.2.1.2 | Buried Valley Exit Point | Empress I | |
| 8 | 492806.5 | 6089234.12 | 7.2.1.2 | Buried Valley Exit Point | Empress I | |
| 9 | 417505.67 | 6068603.76 | 7.2.1.2 | Buried Valley Exit Point | Empress I | |
| 10 | 442262.11 | 6011870.25 | 7.2.1.2 | Buried Valley Exit Point | Empress I | |
| 11 | 563465.5 | 5995881.73 | 7.2.1.2 | Buried Valley Exit Point | Empress I | |
| 12 | 433144.72 | 6027087.04 | 7.2.1.3 | Recharge Area Above Buried Valley | Grand Centre | |
| 13 | 401884.96 | 6035677.51 | 7.2.1.3 | Recharge Area Not Above Buried Valley | Grand Centre | |
| 14 | 426463.25 | 6054051.58 | 7.2.1.3 | Recharge Area Not Above Buried Valley | Grand Centre | |
| 15 | 453666.4 | 6051426.71 | 7.2.1.3 | Recharge Area Above Buried Valley | Grand Centre | |
| 16 | 487789.65 | 6000599.76 | 7.2.1.3 | Recharge Area Above Buried Valley | Grand Centre | |
| 17 | 549508.71 | 5996104.42 | 7.2.1.3 | Recharge Area Not Above Buried Valley | Grand Centre | |
| 18 | 519526.65 | 6075050.5 | 7.2.1.3 | Recharge Area Above Buried Valley | Grand Centre | |
| 19 | 554843.02 | 6062642.04 | 7.2.1.3 | Recharge Area Not Above Buried Valley | Grand Centre | |
| 20 | 507247.76 | 6050552.20 | 7.2.1.3 | Recharge Area Not Above Buried Valley | Grand Centre | |
| 21 | 479562.23 | 6027287.30 | 7.2.1.3 | Recharge Area Not Above Buried Valley | Grand Centre | |
| 22 | 419278.32 | 6028127.03 | 7.2.1.4 | Grand Centre Fm. Head Estimation Error | Grand Centre | Redundant - covered by Location 13 |
| 23 | 479945.71 | 6048868.01 | 7.2.1.4 | Grand Centre Fm. Head Estimation Error | Grand Centre | |
| 24 | 495501.46 | 6048868.01 | 7.2.1.4 | Grand Centre Fm. Head Estimation Error | Grand Centre | Redundant - covered by Location 20 |
| 25 | 551502.13 | 6019312.11 | 7.2.1.4 | Grand Centre Fm. Head Estimation Error | Grand Centre | |
| 26 | 532835.24 | 5994941.45 | 7.2.1.4 | Grand Centre Fm. Head Estimation Error | Grand Centre | Redundant - covered by Location 17 |

Table 7.2. Recommended locations for new water-level observations continued.

| Location Number | EUTMZ12N83 | NUTMZ12N83 | Report Section | Motive | Formation | Redunancy Analysis |
|---|---|---|---|---|---|---|
| 27 | 473207.66 | 6020638.16 | 7.2.1.4 | Sand River Fm. Head Estimation Error | Sand River | |
| 28 | 536977.13 | 6000477.17 | 7.2.1.4 | Ethel Lake Fm. Head Estimation Error | Ethel Lake | Redundant - covered by Location 2 |
| 29 | 551220 | 5999219.32 | 7.2.1.4 | Muriel Lake Fm. Head Estimation Error | Muriel Lake | Redundant - covered by Locaton 34 |
| 30 | 481957.59 | 6036951.83 | 7.2.1.4 | Muriel Lake Fm. Head Estimation Error | Muriel Lake | Redundant - covered by Location 35 |
| 31 | 476268.4 | 6028227.00 | 7.2.1.5 | Max dss - Sand River Fm, GHB Conductance | Sand River | Redundant - covered by Location 27 |
| 32 | 517025.63 | 6055594.41 | 7.2.1.5 | Max dss - Muriel Lake Fm, Muriel Lake K | Muriel Lake | Redundant - covered by well 294724 |
| 33 | 529923.89 | 6041664.29 | 7.2.1.5 | Max dss - Muriel Lake Fm, Muriel Lake K | Muriel Lake | Redundant - covered by an industry observation well. |
| 34 | 544369.95 | 6000905.76 | 7.2.1.5 | Max dss - Muriel Lake Fm, Muriel Lake K | Muriel Lake | Redundant - covered by domestic well 232310 |
| 35 | 495354.7 | 6027738.12 | 7.2.1.5 | Max dss - Muriel Lake Fm, Aquitard Anisotropy | Muriel Lake | |
| 36 | 524601.14 | 6039609.76 | 7.2.2 | 5-m Steady-State Drawdown Cone - Empress I Fm | Empress I | Redundant - covered by domestic well 217690 |
| 37 | 504700.49 | 6038759.55 | 7.2.2 | 5-m Steady-State Drawdown Cone - Empress I Fm | Empress I | |
| 38 | 540434.78 | 6055756.86 | 7.2.2 | 5-m Steady-State Drawdown Cone - Empress I Fm | Empress I | Redundant - covered by an industry observation well. |
| 39 | 533371.68 | 6054654.74 | 7.2.2 | 5-m Steady-State Drawdown Cone - Ethel Lake Fm | Ethel Lake | |
| 40 | 521106.74 | 6091090.20 | 7.2.2 | 5-m Steady-State Drawdown Cone - Muriel Lake Fm | Muriel Lake | |
| 41 | 518268.78 | 6045367.54 | 7.2.2 | 5-m Steady-State Drawdown Cone - Muriel Lake Fm | Muriel Lake | Redundant - covered by Location 41 |
| 42 | 520895.06 | 6057041.75 | 7.2.2 | 5-m Steady-State Drawdown Cone - Grand Centre Fm | Grand Centre | Redundant - covered by Location 42 |
| 43 | 533964.53 | 6071463.24 | 7.2.2 | 5-m Steady-State Drawdown Cone - Grand Centre Fm | Grand Centre | |
| 44 | 520618.64 | 6039436.16 | 7.2.2 | Maximum Steady-state Drawdown Cone-Sand River Fm | Sand River | |

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# Appendix A - Cold Lake Beaver River Basin Numerical Groundwater Model Report

**Cold Lake Beaver River Basin Numerical Groundwater Model**

Prepared for:

Alberta Geological Survey

Prepared by:

Stantec Consulting Ltd.

February 2005
1102-17043

# Table of Contents

## LIST OF TABLES

**Page / Following**



## LIST OF FIGURES

**Page / Following**

# 1.0 Introduction

Alberta Environment (AENV) is in the process of updating the 1985 Cold Lake Beaver River Basin Water Management Plan (WMP). The updated WMP will address four key issues identified through stakeholder consultation in the area:

- Surface Water Quality
- Surface Water Quantity
- Groundwater Quality
- Groundwater Quantity

One of the subtasks of the Groundwater Quantity component involves characterizing groundwater resources in the Beaver River Basin. The development of a tool to support groundwater management decisions in the basin was also identified as a key objective. To achieve this objective, AENV retained Alberta Geological Survey (AGS) to develop a numerical groundwater flow model for the basin. AGS developed and calibrated the numerical model using the MODFLOW2000 code coupled with the Groundwater Modeling System (GMS) interface.

Stantec Consulting Ltd. (Stantec) was subsequently retained by AGS to run the calibrated model with several scenarios developed in consultation with AENV. The scope of work for this project involved:

- Familiarization with the numerical model and its limitations
- Running steady state and transient simulations of various scenarios developed in consultation with AENV
- Conducting transition curve analysis at various locations and Formations in the Basin
- Documenting the development, calibration, and simulation runs of the model

# 2.0 Model Domain

Typically the first task in a numerical groundwater modeling exercise would be to develop a conceptual geologic model to serve as a basis for the model. In the Cold Lake area, a three dimensional stratigraphic model had already been developed, and this stratigraphic model became the primary basis for the numerical model described herein.

In addition to the stratigraphic model, the extent of the groundwater model domain has been defined with the following considerations:

- The hydrologic extent of the Beaver River Basin
- Geopolitical boundaries
- Regional hydrogeological flow divides
- Bedrock interactions

The numerical model boundaries are defined as “no flow” boundaries (exceptions are described below) that groundwater cannot be transmitted across. The southern, western, and northwestern boundaries of the model domain coincide with the extent of the Beaver River Basin. The eastern boundary of the model domain coincides with the Alberta/Saskatchewan border. Available data suggests that groundwater flow direction in the vicinity of the Alberta/Saskatchewan border is predominantly parallel to the border and strongly controlled by flow towards Cold Lake. As such, defining the border as a “no flow” boundary seemed reasonable considering the regional scale of the model. The northern boundary of the model domain coincides with the Wiau Channel, which is a major buried valley system that is considered to be a regional groundwater flow divide.

Areas of the model exist where the “no flow” boundary condition does not appear to be maintained. These are areas of the model boundary where major buried valley aquifer systems extend far beyond the limits of the model domain, and as such “no flow” conditions cannot be assumed. In such cases, the groundwater inflows/outflows from the model domain are modeled through use of general head or constant head boundary conditions (Refer to Section 4.0).

The vertical extents of the model domain were bounded by the ground surface at the top of the model, and by the bedrock surface at the bottom of the model. The Lea Park Formation shales are the uppermost bedrock formation throughout much of the Beaver River Basin. These shales possess extremely low hydraulic conductivities, and as such were defined as the lower “no flow” boundary for the model domain.

# 3.0 Model Discretization

## 3.1 VERTICAL DISCRETIZATION

The groundwater model domain has been vertically discretized into 13 model layers. Twelve of the model layers represent different hydrostratigraphic units, as defined in the three dimensional stratigraphic model. Table 3.1 presents the various model layers as defined in the numerical model.

**Table 3.1**
**Vertical Discretization of the Model Domain**

| Model Layer | Hydrostratigraphic Unit |
|---|---|
| 1 (pseudo) | Grand Centre |
| 2 | Grand Centre |
| 3 | Sand River |
| 4 | Marie Creek |
| 5 | Ethel Lake |
| 6 | Bonnyville Unit 2 Till |
| 7 | Bonnyville Unit 1 Sand |
| 8 | Bonnyville Unit 1 Till |
| 9 | Muriel Lake |
| 10 | Bronson |
| 11 | Empress 3 |
| 12 | Empress 2 |
| 13 | Empress 1 |

One of the layers (Layer 1) is a conceptual pseudo-layer defined for the purposes of model calibration. Material properties assigned to Layer 1 were the same as properties assigned to Layer 2 (Grand Centre). By defining a pseudo-layer of constant thickness (2 m) across the entire domain of the model, constant cell dimensions for all cells in Layer 1 could be attained. This allowed for easier parameterization and zoning of the conductance values during model calibration, since the variables affecting conductance were then reduced to the hydraulic conductivity of the geologic material in Layer 1 (i.e. cell length, width, and height were constant).

All model layers were set as confined layers in the Layer Property Flow (LPF) package. Top of layer elevations were defined based on elevations from the 3D stratigraphic model. Grid files of structure elevations were imported from the 3D stratigraphic model into the GMS interface in order to assign layer elevations. In instances where a particular geological unit was not present (internal boundary), the thickness of the layer was set to 20 cm and the material properties of the cells were set equal to the properties of the underlying or overlying layer.

## 3.2 HORIZONTAL DISCRETIZATION

The model domain has been horizontally discretized into a regularly spaced grid consisting of 150 rows and 233 columns, for a total of 34,950 cells per model layer. The horizontal cell dimensions are constant throughout the model domain at 800 m by 800 m. Active and inactive model cells were defined in the IBOUND array. Positive values in the array represent an active cell, while zero values in the array represent an inactive cell. Figure 3.1 presents a plan view map of Layer 13 of the model domain, indicating active and inactive cells.

ArcView shapefiles exported from the 3D stratigraphic model were imported into the GMS interface. Shapefiles indicating the horizontal distribution of geological units were used to define the active/inactive regions of a particular model layer. The shapefiles were also used to define material property zones where the material properties for a particular layer were modeled as nonhomogeneous (Refer to Section 5.3).

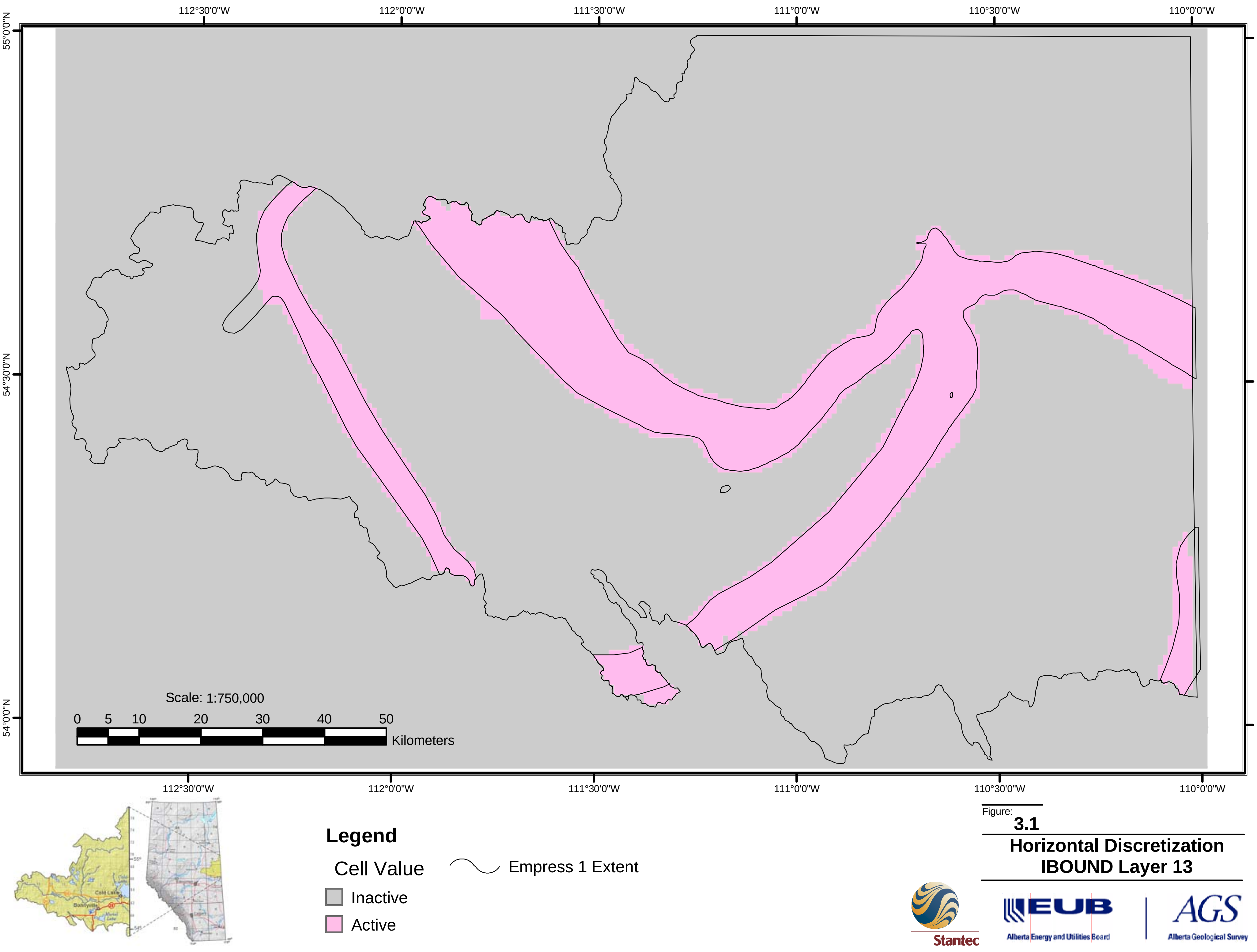



Figure: 3.1

Horizontal Discretization IBOUND Layer 13

# 4.0 Boundary Conditions and Stresses

## 4.1 GENERAL HEAD BOUNDARIES

The general head boundary (GHB) conditions were implemented in the model through use of the GHB1 package in MODFLOW2000. Flow through GHB cell boundaries is proportional to the conductance of the boundary and the difference between specified head and the calculated head. Numerically, the volumetric flux (in this case, external recharge or basin inflow/outflow) can be expressed as:

$$Q_r = C_r(h_b - h_0)$$

Where:

$Q_r$ is the volumetric flux across the cell boundary ($m^3$/d)

$C_r$ is the conductance of the soil ($m^2$/d)

$h_b$ is the head at the boundary (m)

$h_o$ is the head in the aquifer (m)

In this model, the GHB condition was utilized to represent external recharge into the regional groundwater system. All grid cells in Layer 1 were assigned GHB conditions (with the exception of the cells representing lakes, refer to Section 4.2) and head elevations were set to equal the ground elevation at that cell location. 18,726 model cells in Layer 1 were assigned GHB conditions. Ground elevations were obtained from the DEM for the area. Figure 4.1 presents Layer 1 of the model domain, indicating cells defined as GHB cells.

Rationale for utilizing GHB cells to model external recharge include observations that wetlands cover much of the model domain, indicating that the water table is at or near the ground surface. Additionally, GHB cells allow water to leave the groundwater system in instances where the calculated heads are greater than the specified heads (set equal to ground surface elevation), simulating discharge areas.

GHB conditions were also used to simulate flow in/out of the model domain in areas where “no flow” conditions were not applicable. The major buried valley systems extend well beyond the model domain, and as such volumetric fluxes were simulated across the boundaries of the model. In particular, the sands and gravels of the Empress 1 formation are continuously distributed through the buried valley systems. As such, 67 model cells in Layer 13 (Empress 1) were assigned GHB conditions to represent inflows/outflows from the basin via the major buried valley systems.

## 4.2 CONSTANT HEAD BOUNDARIES

Constant head boundary (CHB) conditions were implemented in the model through use of the IBOUND array in MODFLOW2000. Negative values were assigned in the IBOUND array where CHB conditions prevailed.

CHB cells were used to represent the hydraulic influence of lakes on the groundwater system. In general, water levels in lakes in the model domain vary within a few metres. In consideration of the regional scale of the numerical model, it was deemed that CHB cells would adequately simulate the influence of lakes.

ArcView shapefiles of lake polygons in the model domain were directly imported into the GMS interface. The coverage was then selected and CHB conditions were applied to all cells intersected by or falling within the lake polygons. Some manual refinement of cells was also conducted. In total, 2,763 CHB cells were defined in Layer 1 of the model. Figure 4.1 presents Layer 1 of the model domain, indicating cells defined as CHB cells.

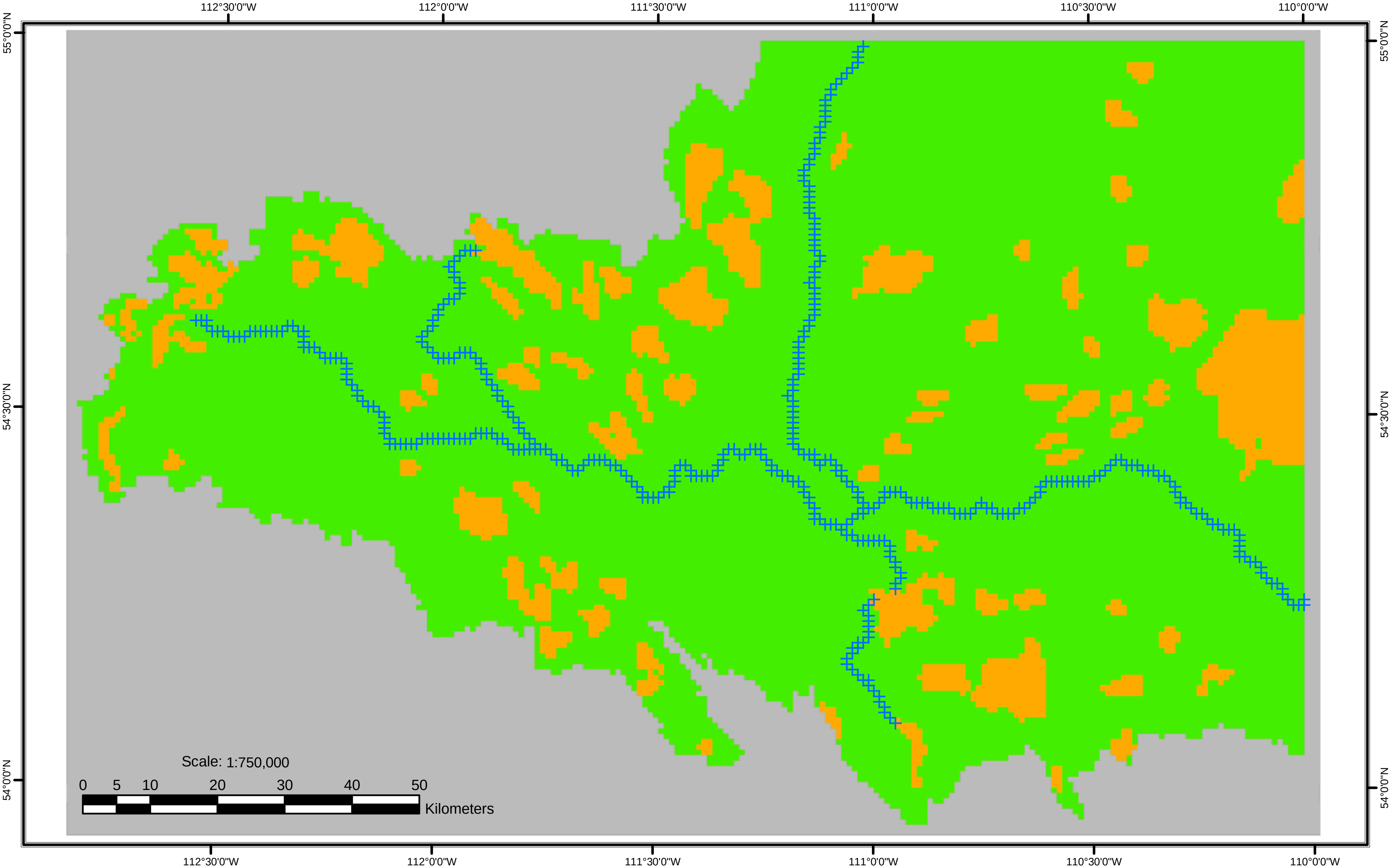
Lake bathymetries, where available, were used to define the lake bed surface elevations. The top elevation of the CHB cells in Layer 1 were specified by subtracting bathymetry data from the elevations in the digital elevation model. In this manner, outcrops of hydrostratigraphic units at lake beds and the associated groundwater/lake interactions could be more accurately represented.

## 4.3 RIVER BOUNDARIES

River boundary conditions (RIV) were implemented in the model through use of the RIV1 module in MODFLOW2000. Similar to GHB cells, flow through RIV cell boundaries is proportional to the conductance of the boundary and the difference between specified head (river stage elevation) and the calculated head. RIV cells allow for water to leave the groundwater system (simulating gaining reaches) where upward gradients exist. RIV cells also allow water to enter the groundwater system (simulating losing reaches) where downward gradients exist.

ArcView shapefiles of the major rivers in the basin (Beaver, Amisk, Sand, and Kehiwin) were directly imported into the GMS interface. The coverage was then selected and RIV conditions were applied to all cells intersected by the river polylines. In total, 427 RIV cells were defined in Layer 1 of the model. Figure 4.1 presents Layer 1 of the model domain, indicating cells defined as RIV cells.

River stage elevations at each end of the river polylines were obtained from a topographic map of the area. River bed and stage elevations were then automatically interpolated between end points assuming and average stage of 5 m. The interpolated elevations were then assigned to the RIV cells. Manual refinement of river bed and stage elevations was required in several instances where interpolated values conflicted with elevations in the digital elevation model (interpolated elevations above ground surface elevations in the digital elevation model).




## Legend

**Layer 1 - Cell Type**

- Inactive
- Constant Head
- General Head

+ River Nodes

Figure: **4.1**

**Model Boundary Conditions Layer 1**

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

Recent fluvial deposits were explicitly represented in the model through use of a separate material property (named “Recent”). The degree of connection between aquifers and rivers in the model was adjusted during calibration by increasing or decreasing the extent of the “Recent” deposits.

## 4.4 PUMPING WELLS

Pumping wells were implemented in the model through use of the WEL1 module in MODFLOW2000. Well completion intervals were assigned to the appropriate model layer. In instances where several production wells were located within the same model cell, the flow rates for the wells were summed and only a single well was input into the WEL1 module. Groundwater production was denoted as a negative rate (outflow from the system) in the WEL1 module.

The number, location, and model layer of wells varied depending on the calibration or simulation run. A more thorough description of pumping rates and schedules used for calibration and simulation runs can be found in Sections 5 and 6, respectively.

# 5.0 Model Calibration

## 5.1 STEADY STATE CALIBRATION

The numerical model was first calibrated to steady state conditions. Initially the model domain was subdivided into four sub-domains, and each of the sub-domains were calibrated separately. Once the four sub-domains had been adequately calibrated, they were recombined into the original model domain.

Major municipal and industrial production wells were modeled in the steady state calibration run. Licensed annual groundwater allocations provided by AENV were converted to average daily production rates and input into the WEL1 module. Table 5.1 presents the well locations and pumping rates specified in the WEL1 module. Table 5.2 presents the MODFLOW2000 settings used in the steady state calibration.

**Table 5.1**
**Production Well Locations and Pumping Rates Used in the Steady State Calibration**

| Name | Row | Column | Layer | Pumping Rate ($m^3$/d) |
|---|---|---|---|---|
| WR-20478 | 81 | 158 | 3 | 7 |
| WSW 15-5 | 34 | 185 | 5 | 774 |
| WSW 10-5 | 35 | 185 | 5 | 517 |
| Burntlake | 35 | 202 | 6 | 1500 |
| WSW 02&5 | 45 | 176 | 9 | 5862 |
| WSW 03&4 | 46 | 177 | 9 | 3555 |
| WSW 16-17 | 67 | 197 | 9 | 600 |
| WR-17888 | 98 | 186 | 9 | 51 |
| WR-20638 | 111 | 225 | 9 | 100 |
| WSW 06 | 45 | 176 | 11 | 3478 |
| WSW 01 | 45 | 176 | 11 | 2370 |
| WSW 04E3 | 46 | 177 | 11 | 1185 |
| Well # 434 | 99 | 187 | 11 | 505 |
| FW1-1 & FW1-2 | 54 | 188 | 13 | 8200 |
| WID 154556 | 67 | 160 | 13 | 250 |
| WR-19580 | 113 | 144 | 13 | 200 |

**Table 5.2**
**MODFLOW2000 Settings Used in Steady State Calibration Runs**

| | |
|---|---|
| **Stress Periods** | N/A |
| **Total Timesteps** | N/A |
| **Packages Used** | LPF1, SOR1, WEL1, RIV1, GHB |
| **Flow Package Settings** | All layers confined<br>Interblock transmissivity: Harmonic mean<br>Cell Wetting: OFF |
| **Solver Settings** | SOR1 Solver<br>Max Iterations = 5000<br>Convergence Criteria = 0.001<br>Prevent Cell Drying: ON<br>Minimum saturated thickness = 0.1 |

Static water level measurements obtained from the AENV Water Well Database were utilized for the steady state calibration. Water level measurements were provided relative to ground level, and as such water level elevations (relative to mean sea level) needed to be calculated using ground elevations interpolated from the digital elevation model. Errors in the interpolated ground elevations at the well locations were estimated to be up to +/- 10 m. In turn, the errors in the specified water level elevations were estimated to be up to +/- 10 m.

A subset of 614 well records in the following Formations were used during model calibration:

- 66 wells in the Grande Centre Formation
- 93 wells in the Sand River Formation
- 95 wells in the Marie Creek Formation
- 104 wells in the Ethel Lake Formation
- 93 wells in the Bonnyville Formation
- 101 wells in the Muriel Lake Formation
- 32 wells in the Empress 3 Formation
- 30 wells in the Empress 1 Formation

Observation well coverages were defined in the GMS interface for each of the above Formations. Once the observation points were defined, MODFLOW2000 then calculated the simulated head elevation at those points. The calculated head elevation at the observation point is estimated using a bilinear interpolation of the head values from the four adjacent cells. These computed head elevations from the calibration run were then compared to the observed head elevations calculated from the AENV data. Figures 5.1 through 5.8 present graphs comparing the simulated head elevations of the final steady state calibration run to the observed head elevations.

**Figure 5.1**
**Comparison of Simulated vs. Observed Heads for the Grande Centre Formation**

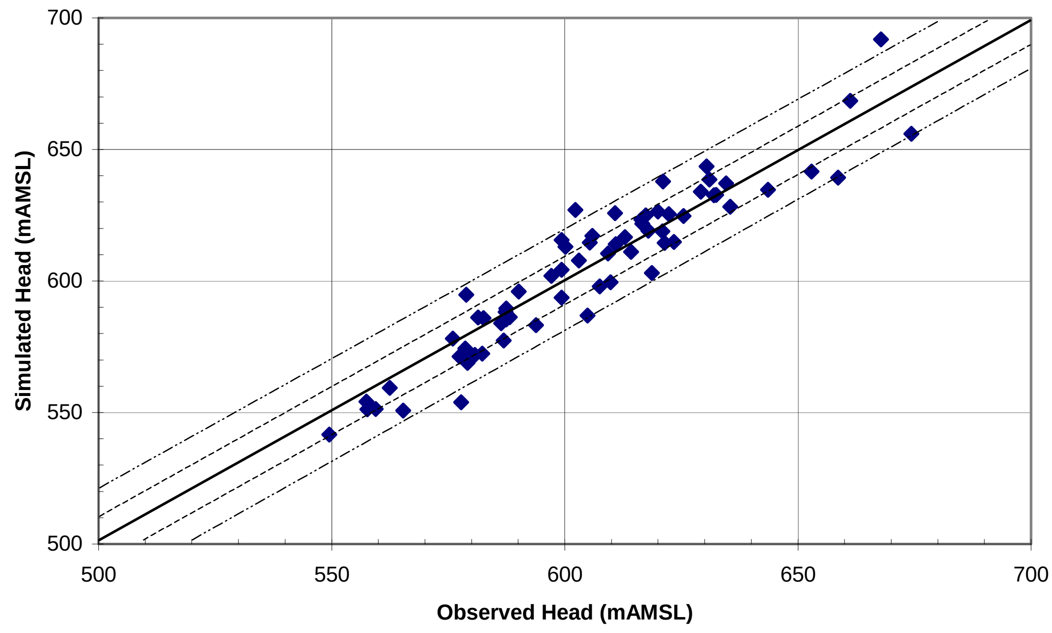



**Figure 5.2**
**Comparison of Simulated vs. Observed Heads for the Sand River Formation**

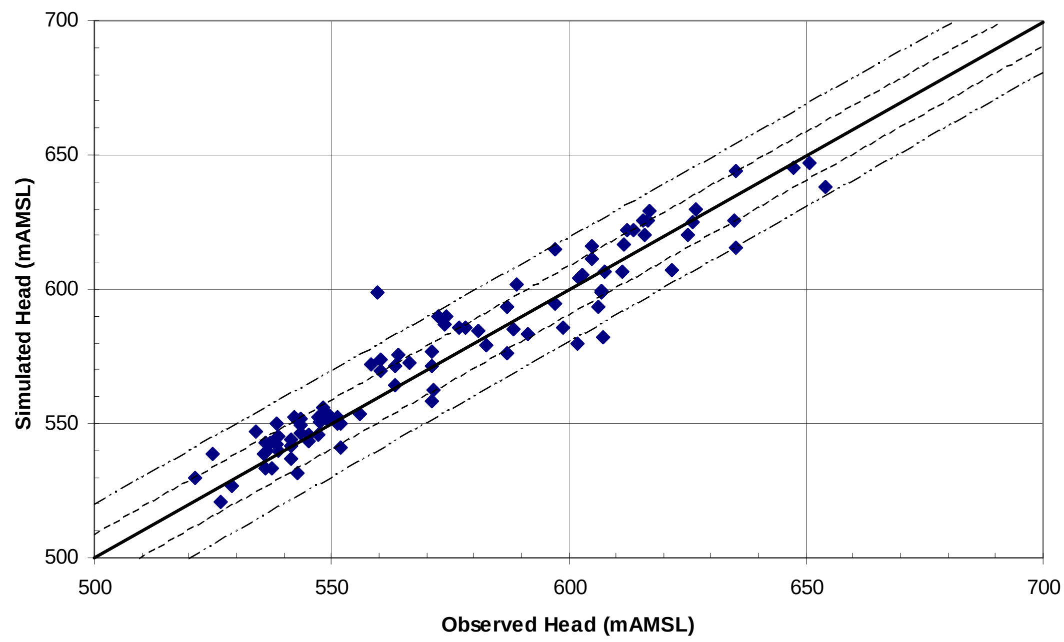


**Figure 5.3
Comparison of Simulated vs. Observed Heads for the Marie Creek Formation**

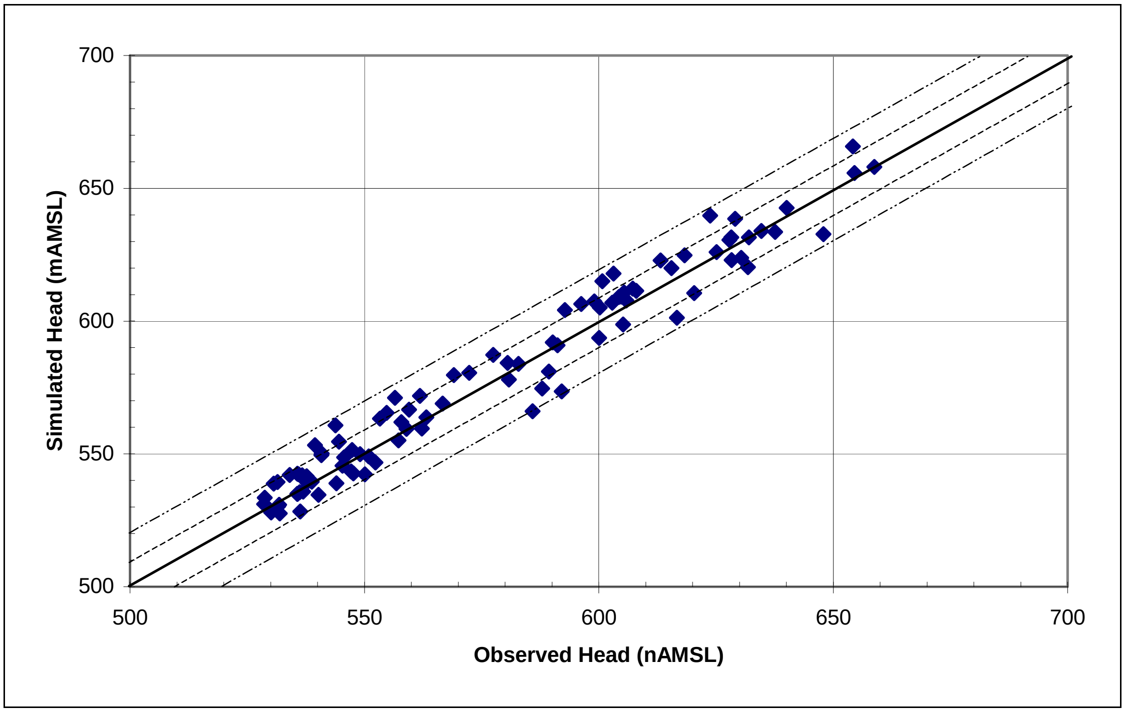



**Figure 5.4
Comparison of Simulated vs. Observed Heads for the Ethel Lake Formation**

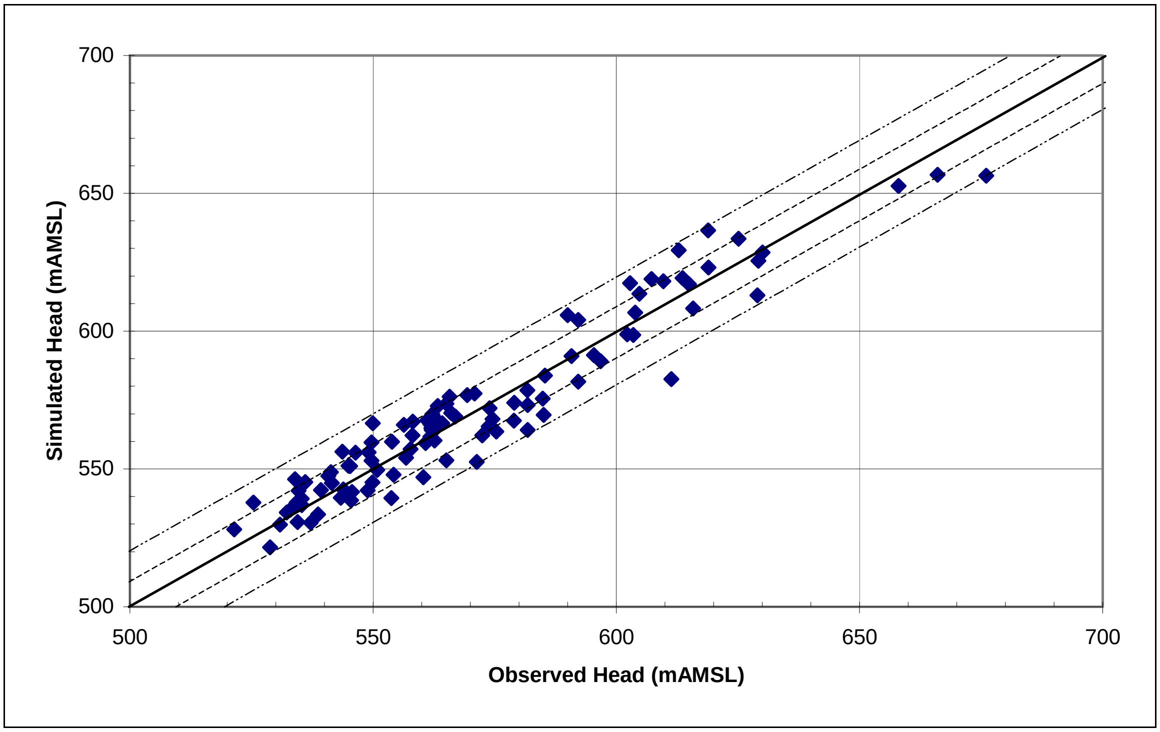


**Figure 5.5**
**Comparison of Simulated vs. Observed Heads for the Bonnyville Formation**

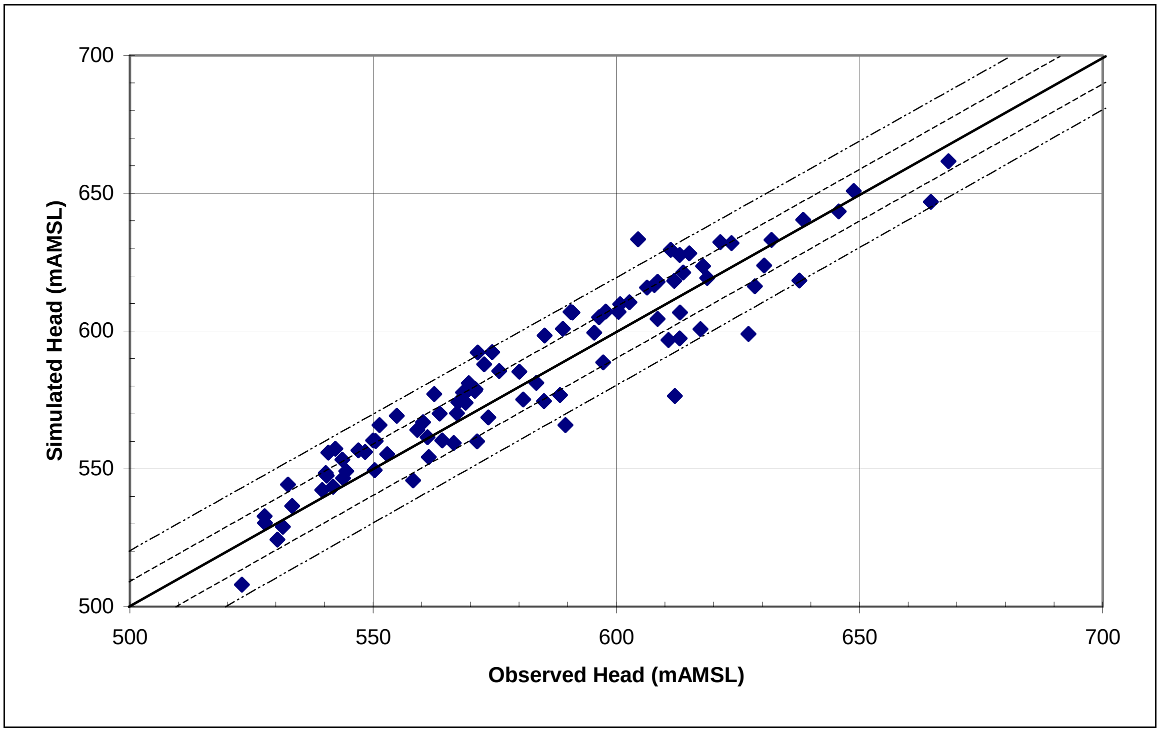



**Figure 5.6**
**Comparison of Simulated vs. Observed Heads for the Muriel Lake Formation**

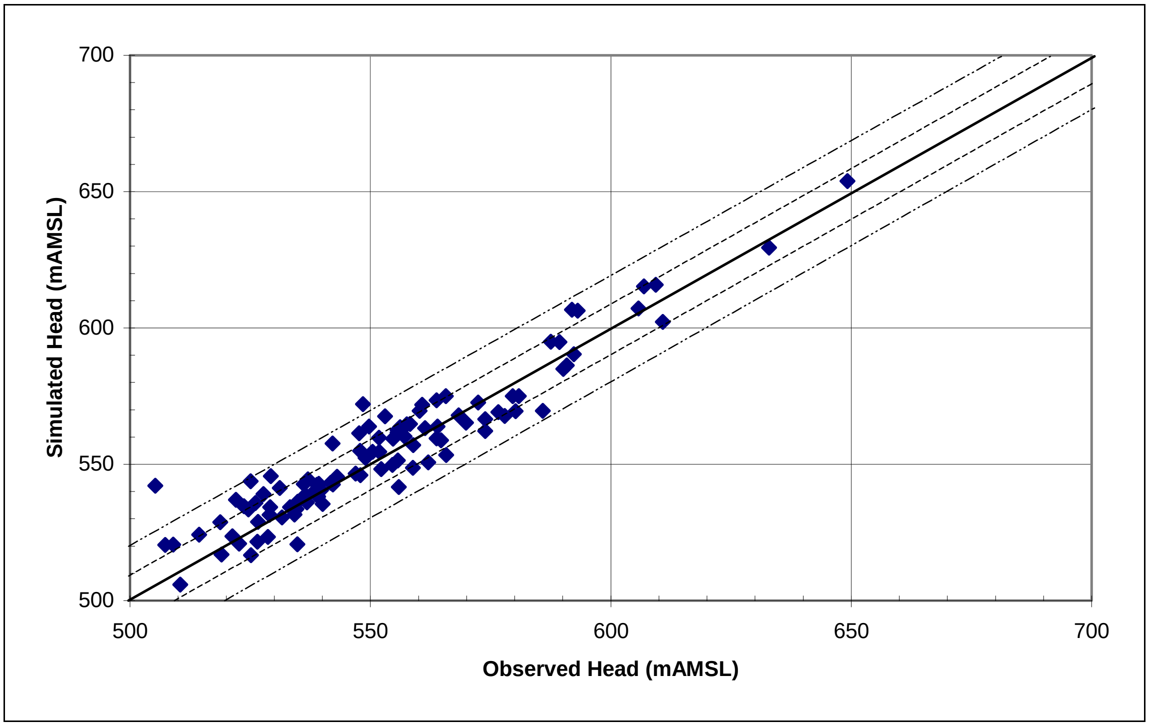


**Figure 5.7**
**Comparison of Simulated vs. Observed Heads for the Empress 3 Formation**

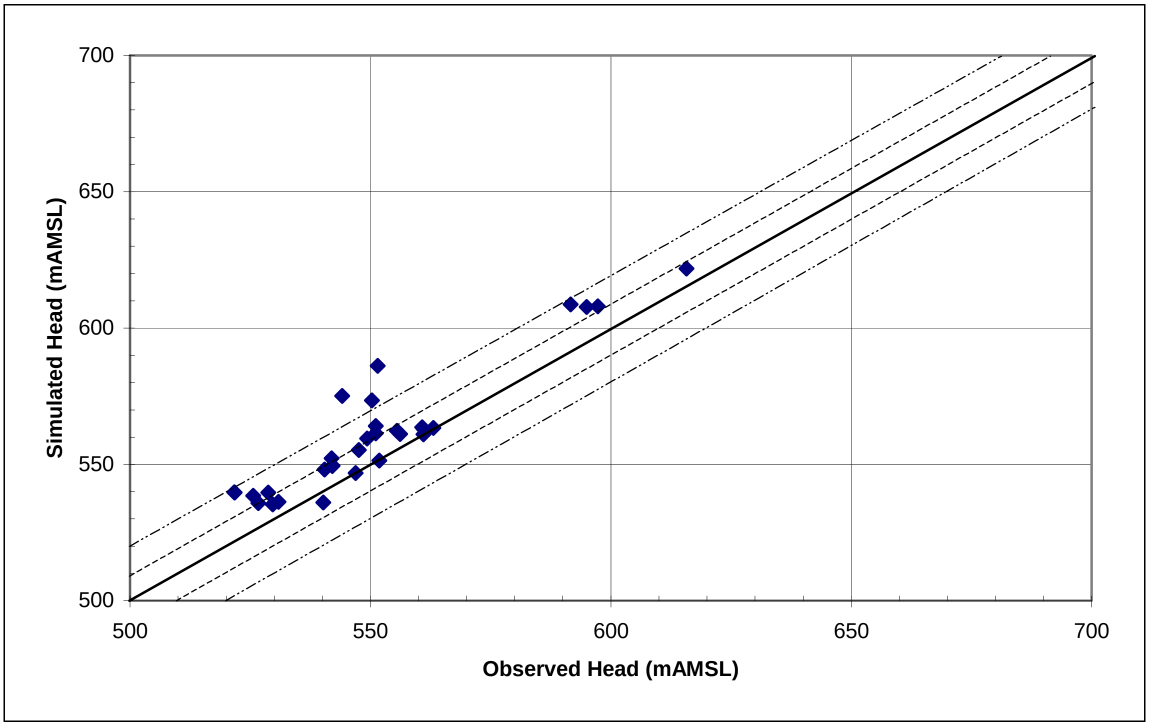
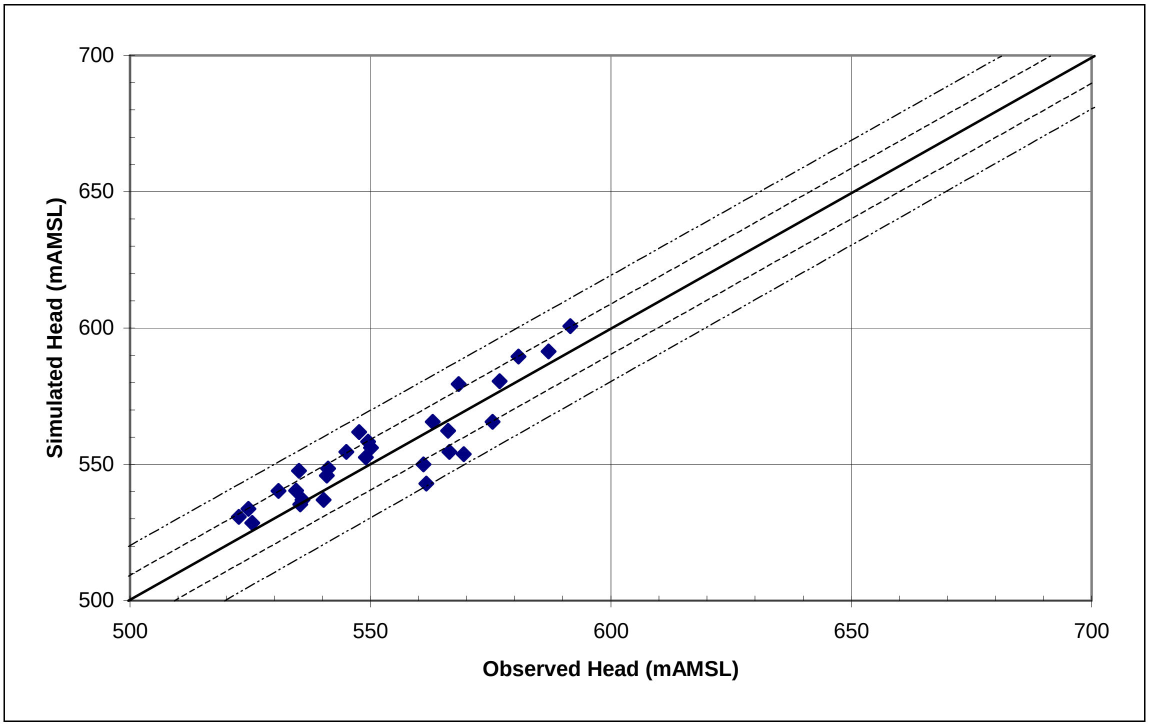



**Figure 5.8**
**Comparison of Simulated vs. Observed Heads for the Empress 1 Formation**



The dotted lines on Figures 5.1 through 5.8 have been included for reference purposes. The inner and outer dotted lines indicate the +/- 10 m and +/- 20 m intervals, respectively.

During the steady state calibration, composite scaled sensitivities were utilized to determine the parameters with the largest influence on the simulated hydraulic heads. Results of the sensitivity analysis suggested that the model was most sensitive to the vertical anisotropy and hydraulic conductivity of the shallow aquitards and the hydraulic conductivity of the Muriel Lake Formation.

The results of preliminary calibration runs suggested that the hydraulic parameters of the shallow till aquitards controlled the vertical flow of recharge derived water into the deeper hydrostratigraphic units. It also appeared that the hydraulic conductivity of the Muriel Lake Formation governed the lateral flow and drainage to discharge areas, due largely to its broad extent, continuity, and degree of connection to rivers and lakes. Thus, the primary parameters that were adjusted during subsequent calibration runs included the vertical anisotropy of the aquitards, the hydraulic conductivity of the Grand Centre and Marie Creek Formations, and the degree of connection between buried channel sediments and surface water bodies.

Connectivity between buried channel sediments and surface water bodies was adjusted by changing the extent (vertical and/or horizontal) of the fluvial deposits (represented by the “Recent” material property) in the vicinity of lakes and rivers. The relative distribution of aquifer and aquitard materials underlying surface water bodies was also adjusted to improve the calibration results.

## 5.2 TRANSIENT CALIBRATION

Transient calibration was conducted for the northeast sub-region of the numerical model. Production and observation well data from CNRL’s Wolf Lake operations and Imperial Oil’s Cold Lake operations were utilized to examine the transient response of the numerical model. Other areas of the model could not be calibrated with transient data due to lack of a suitable transient data set.

Forward transient runs were modeled from 1984 to 2000 using historical pumping rates reported by CNRL and Imperial Oil. Table 5.3 presents the modeled production well locations and pumping schedules specified in the transient WEL1 module. All pumping rates specified in the WEL1 module were annual average daily rates. Table 5.4 presents the MODFLOW2000 settings used in the transient calibration runs.

**Table 5.4**
**MODFLOW2000 Settings Used in Transient Calibration Runs**

| | |
|---|---|
| **Stress Periods** | 19 |
| **Total Timesteps** | 190 |
| **Packages Used** | LPF1, SOR1, WEL1, RIV1, GHB |
| **Flow Package Settings** | All layers confined<br>Interblock transmissivity: Harmonic mean<br>Cell Wetting: OFF |
| **Solver Settings** | SOR1 Solver<br>Max Iterations = 5000<br>Convergence Criteria = 0.01<br>Prevent Cell Drying: ON<br>Minimum saturated thickness = 0.1 |

Three dimensional grids of calibrated heads from the steady state calibration (Section 5.1) were loaded into the simulation as initial heads. The model was then run and the calibration parameters were adjusted between runs until a visual fit between measured drawdowns (at various observation wells historically monitored by CNRL and Imperial Oil) and simulated drawdowns was observed. Figures 5.9 and 5.10 present graphs comparing the measured drawdowns at observation wells with the simulated drawdowns in the numerical model. These graphs are provided as examples of the transient observation data sets and the simulated drawdowns.

Examination of Figures 5.9 and 5.10 suggests that the dynamic response of the model adequately represents the actual response of the groundwater system observed in the vicinity of the simulated industrial groundwater production wells. Some discrepancies between simulated and observed heads do exist, however, these discrepancies are generally within the level of error expected in hydraulic head measurements used during model calibration.

Following the transient calibration of the northeast sub-domain of the model, the four sub-domains were reassembled and another transient calibration run was completed to account for potential boundary effects associated with the smaller extent of the sub-domains.

## Table 5.3: Transient Calibration Production Well Locations and Pumping Rates

| | | | Pumping Rates for Simulated Year ($m^3$/d) | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Row** | **Column** | **Layer** | **1984** | **1985** | **1986** | **1987** | **1988** | **1989** | **1990** | **1991** | **1992** | **1993** | **1994** | **1995** | **1996** | **1997** | **1998** | **1999** | **2000** |
| 45 | 176 | 9 | 0 | 2332 | 2833 | 3480 | 3480 | 3080 | 2169 | 848 | 0 | 107 | 0 | 161 | 863 | 1206 | 473 | 1074 | 1074 |
| 46 | 177 | 9 | 0 | 1474 | 1534 | 1842 | 2029 | 2102 | 1202 | 545 | 818 | 1690 | 1462 | 1292 | 580 | 1119 | 515 | 855 | 855 |
| 53 | 194 | 9 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1100 | 650 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 54 | 183 | 9 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 100 | 2100 | 2000 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 45 | 176 | 11 | 0 | 1340 | 1893 | 2187 | 2445 | 2628 | 1856 | 1217 | 818 | 1133 | 920 | 1495 | 1081 | 2547 | 2028 | 1312 | 1312 |
| 46 | 177 | 11 | 0 | 791 | 1039 | 1098 | 1092 | 987 | 722 | 130 | 0 | 107 | 0 | 130 | 19 | 302 | 285 | 237 | 237 |
| 54 | 188 | 11 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 550 | 650 | 1100 | 0 | 0 | 0 | 0 | 0 | 0 |
| 54 | 188 | 13 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 900 | 4600 | 7000 | 8150 | 0 | 0 | 0 | 320 | 2400 | 0 |

**Figure 5.9**
**Comparison of Observed vs. Simulated Drawdowns at Borque Lake (Empress 1)**

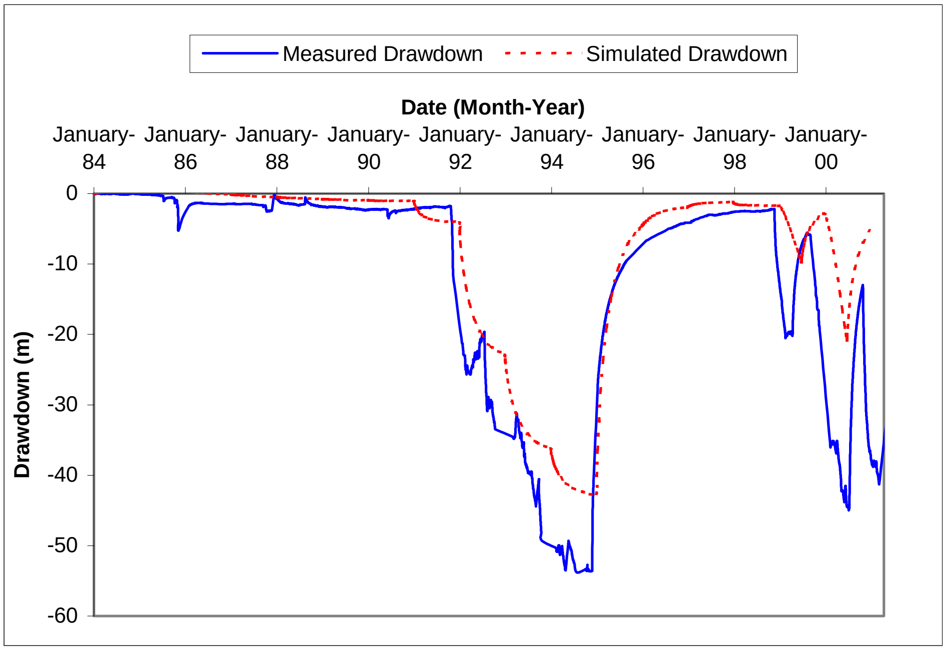
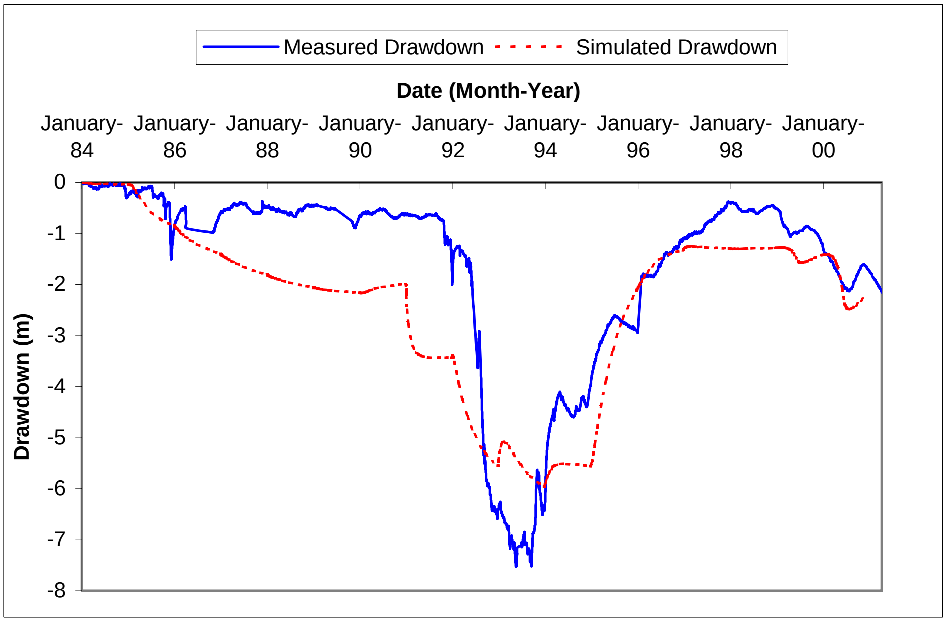



**Figure 5.10**
**Comparison of Observed vs. Simulated Drawdowns at Borque Lake (Muriel Lake)**



## 5.3 FINAL CALIBRATION AND HYDRAULIC PARAMETERS

A final steady state calibration was run once the four sub-domains had been reassembled. Calibrated hydraulic parameters from each of the four sub-domains were compared, and in cases where the parameter values were similar, the average parameter value was assigned to the entire model domain. In instances where the parameter values significantly differed between sub-domains, these parameters were zoned and assigned different values in each of their respective zones. Parameters requiring zoning included the horizontal hydraulic conductivity of the Grande Centre, Marie Creek, Bonnyville 1 tills, Bonnyville 2 tills, and the Muriel Lake Formation. Table 5.5 presents the final calibrated hydraulic parameters for the various material properties used in the model.

**Table 5.5**
**Calibrated Hydraulic Parameters of Modeled Materials**

| Material Name | Description | Horizontal Hydraulic Conductivity (m/d) | Horizontal Anisotropy | Vertical Anisotropy | Specific Storage ($m^{-1}$) |
|---|---|---|---|---|---|
| Bonny1b | Bonnyville Formation - Unit 1 Tills - Zone 2 | 0.1 | 1 | 10 | 5.00E-07 |
| Bonny2 | Bonnyville Formation - Unit 2 Zone 1 | 1 | 1 | 10 | 0.00001 |
| Bonny2b | Bonnyville Formation - Unit 2 Zone 2 | 0.001 | 1 | 10 | 5.00E-07 |
| BonnySs | Bonnyville Formation - Unit 1 Sandstone | 2.2 | 1 | 1 | 0.00001 |
| Bonnytill | Bonnyville Formation - Unit 1 Tills - Zone 1 | 0.0005 | 1 | 10 | 5.00E-07 |
| Bronson | Bronson Formation | 0.00008 | 1 | 10 | 5.00E-07 |
| Clay | Ethel Lake Formation - Clays | 5 | 1 | 10 | 0.00001 |
| Emp1 | Empress 1 Formation | 5 | 1 | 1 | 0.00001 |
| Emp2 | Empress 2 Formation | 0.00008 | 1 | 10 | 5.00E-07 |
| Emp3 | Empress 3 Formation | 8 | 1 | 1 | 0.00001 |
| Ethel | Ethel Lake Formation | 5 | 1 | 1 | 0.00001 |
| Grand | Grande Centre Formation - Zone 1 | 0.008 | 1 | 10 | 5.00E-07 |
| Grand2 | Grande Centre Formation - Zone 2 | 0.0001 | 1 | 10 | 5.00E-07 |
| Grand3 | Grande Centre Formation - Zone 3 | 0.00005 | 1 | 10 | 5.00E-07 |
| Marie | Marie Creek Formation | 0.001 | 1 | 10 | 5.00E-07 |
| Marie2 | Marie Creek Formation - Zone 2 | 0.0001 | 1 | 10 | 5.00E-07 |
| Muriel | Muriel Lake Formation | 10 | 1 | 1 | 0.00001 |
| Muriel2 | Muriel Lake Formation - Zone 2 | 25 | 1 | 1 | 0.00001 |
| Recent | Recent Fluvial Deposits | 1 | 1 | 1 | 0.00001 |
| Sand | Sand River Formation | 2 | 1 | 1 | 0.00001 |

# 6.0 Model Simulations and Output Analysis

## 6.1 1985 – 2003 INDUSTRIAL GROUNDWATER USE – STEADY STATE RUN

A steady state simulation was first run in order to verify the original steady state calibration. This run utilized historical industrial groundwater usage rates provided by AENV. Groundwater production rates from the industrial wells were averaged over the 1985 – 2003 time period and converted to average daily production rates. In instances where multiple production wells were situated in the same model cell, their production rates were summed and only a single well was specified in the WEL1 module. Table 6.1 presents the production well locations and rates used in the steady state simulation. Table 6.2 presents MODFLOW2000 settings used in steady state simulation runs.

**Table 6.2**
**MODFLOW2000 Settings Used in Steady State Simulation Runs**

| | |
|---|---|
| **Stress Periods** | N/A |
| **Total Timesteps** | N/A |
| **Packages Used** | LPF1, SOR1, WEL1, RIV1, GHB |
| **Flow Package Settings** | All layers confined<br>Interblock transmissivity: Harmonic mean<br>Cell Wetting: OFF |
| **Solver Settings** | SOR1 Solver<br>Max Iterations = 5000<br>Convergence Criteria = 0.01<br>Prevent Cell Drying: ON<br>Minimum saturated thickness = 0.1 |

Figure 6.1 presents the final steady state head distribution for the Empress 1 Formation. Steady state head distributions from the calibration run are also presented for comparison. In general, it appears that the head distributions from the steady state run are in agreement with the head distributions from the steady state calibration run. Small discrepancies between the head contours are visible near the pumping wells. This was expected however, as the pumping rates utilized in the steady state rum were actual historical groundwater production rates that differed from the licensed allocations utilized for the calibration run. The discrepancies between the two sets of contours appears to decrease as the distance from the area of pumping increases, to the point where the two sets of contours appear to be coincident.

## 6.2 1985 – 2003 INDUSTRIAL GROUNDWATER USE – TRANSIENT RUN

A transient forward simulation was run using historical industrial groundwater production rates provided by AENV. This simulation was conducted primarily to gain further understanding of the dynamic response of the groundwater system to historical groundwater production in the Beaver River Basin.

Annual groundwater production rates were converted to average daily production rates and were then specified in the WEL1 module. Three dimensional grids of the head distribution from the 1985 – 2004 steady state simulation (Section 6.1) were loaded into the simulation as initial heads.

Table 6.3 presents the industrial production wells simulated and their respective pumping schedules. Figure 6.2 graphically presents the simulated pumping schedules of the industrial production wells. Table 6.4 presents the MODFLOW2000 settings used in the transient simulation.

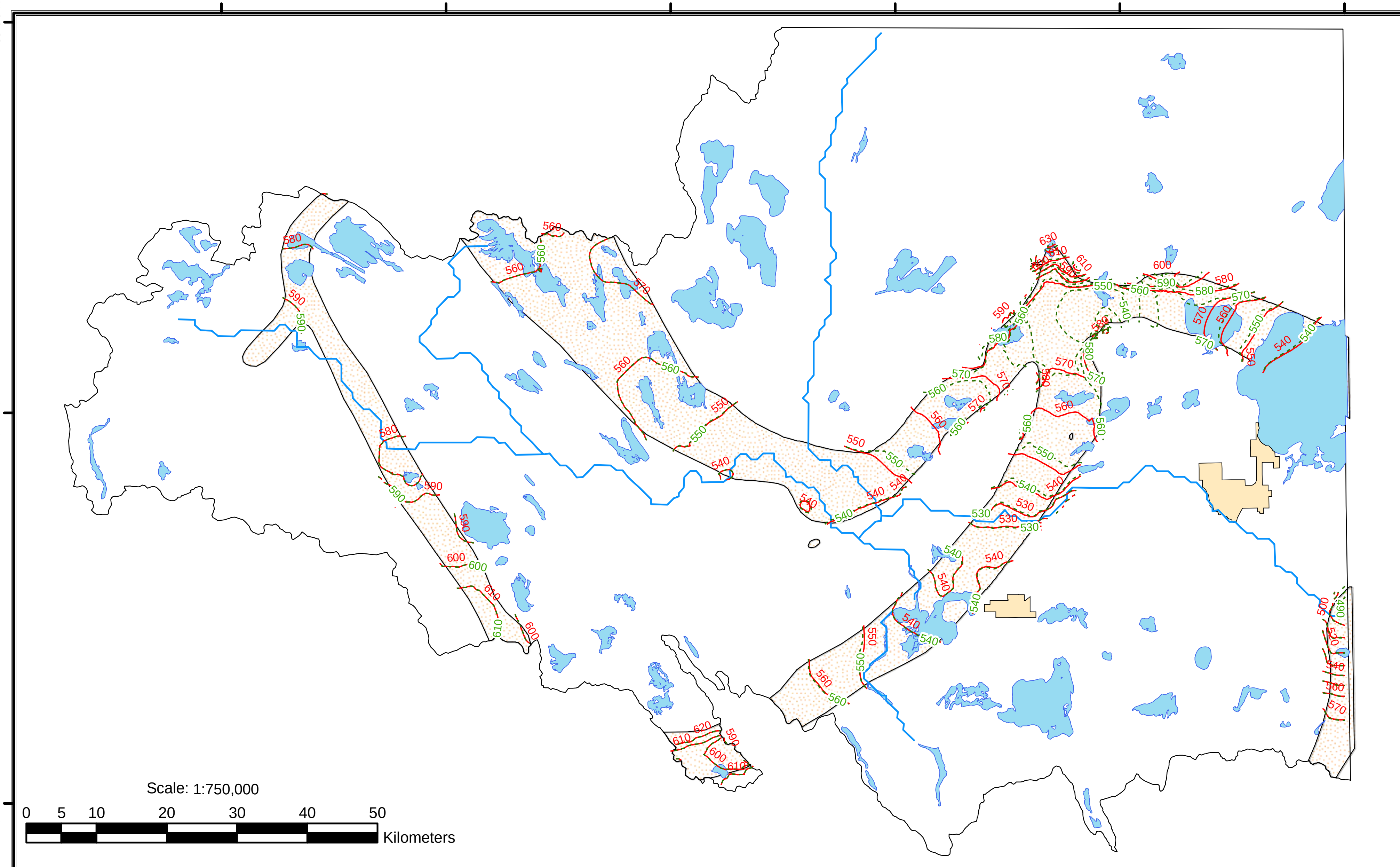
**Table 6.4**
**MODFLOW2000 Settings Used in Transient Simulation (1985 – 2003) Runs**

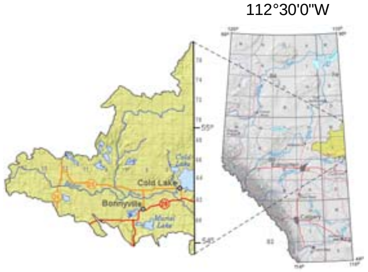
| | |
|---|---|
| **Stress Periods** | 19 |
| **Total Timesteps** | 190 |
| **Packages Used** | LPF1, SOR1, WEL1, RIV1, GHB |
| **Flow Package Settings** | All layers confined<br>Interblock transmissivity: Harmonic mean<br>Cell Wetting: OFF |
| **Solver Settings** | SOR1 Solver<br>Max Iterations = 5000<br>Convergence Criteria = 0.1<br>Prevent Cell Drying: ON<br>Minimum saturated thickness = 0.1 |

Examination of the transient simulation results suggested that the major aquifer systems utilized in the basin for industrial production (Empress 1 Formation, Empress 3 Formation, and Muriel Lake Formation) responded relatively quickly to changes in system stresses. Figure 6.3 presents a comparison of simulated drawdown contours for the Empress 1 Formation from the years 1994 and 1996. Groundwater production from the Empress 1 Formation peaked over the 1992 to 1994 time period (Refer to Figure 6.2). Drawdown contours for the year 1994 show marked drawdown (approximately 24 m) in the vicinity of the FWE1-1 and FWE1-2 wells. However, examination of the 1996 drawdown contours in the same vicinity suggest that two years following the peak production period between 1992 to 1994, residual drawdowns were limited to approximately 2 m. It also appeared that the center of the cone of depression had moved from the FWE wells to the vicinity of WSW3 and WSW4.

**Table 6.1**
**Well Locations and Pumping Rates Used in Steady State Simulation**

| Project | Well ID | LSD | Section | Township | Range | Meridian | UTM Northing | UTM Easting | Aquifer | Model Row | Model Column | Model Layer | Adjusted Rate ($m^3/d$) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Wolf Lake | WSW2 | 12 | 10 | 65 | 5 | 4 | 6051607.6 | 520448.7 | Muriel Lake | 57 | 176 | 9 | 858 |
| Wolf Lake | WSW3 | 6 | 10 | 66 | 5 | 4 | 6060917.2 | 520809.4 | Muriel Lake | 46 | 176 | 9 | 1717 |
| Wolf Lake | WSW4 | 6 | 10 | 66 | 5 | 4 | 6060917.2 | 520809.4 | Muriel Lake | 46 | 176 | 9 | |
| Wolf Lake | WSW5 | 12 | 10 | 66 | 5 | 4 | 6061317.2 | 520401.2 | Muriel Lake | 45 | 176 | 9 | 858 |
| Wolf Lake | WSW1 | 12 | 10 | 65 | 5 | 4 | 6051607.6 | 520448.7 | Empress 3 | 57 | 176 | 11 | 763 |
| Wolf Lake | WSW4 | 6 | 10 | 66 | 5 | 4 | 6060917.2 | 520809.4 | Empress 3 | 46 | 177 | 11 | 763 |
| Wolf Lake | WSW6 | 13 | 10 | 66 | 5 | 4 | 6061719.6 | 520399.0 | Empress 3 | 45 | 176 | 11 | 763 |
| Marguerite Lake | W1 | 9 | 7 | 66 | 5 | 4 | 6061300.2 | 516749.1 | 124.4 | 45 | 171 | 11 | 510 |
| Marguerite Lake | W2 | 9 | 7 | 66 | 5 | 4 | 6061300.2 | 516749.1 | 124.4 | 45 | 171 | 11 | |
| Burnt Lake | NW-2-67-3-4 | NW | 2 | 67 | 3 | 4 | 6068539.1 | 541882.1 | Bonnyville 1 | 36 | 203 | 6 | 10 |
| Primrose | WSW15-5 | 14 | 5 | 67 | 4 | 4 | 6069840.4 | 526951.7 | Ethel Lake | 34 | 184 | 5 | 136 |
| Primrose | WSW10-5 | 10 | 5 | 67 | 4 | 4 | 6069437.8 | 527362.2 | Ethel Lake | 35 | 185 | 5 | 136 |
| Hilda Lake | WSW16-17 | 16 | 17 | 63 | 3 | 4 | 6034320.5 | 538100.7 | Muriel Lake | 79 | 198 | 9 | 161 |
| Cold Lake | FWE1-1 | 5 | 22 | 65 | 4 | 4 | 6054498.8 | 530189.8 | Empress 1 | 54 | 188 | 13 | 1351 |
| Cold Lake | FWE1-2 | 5 | 22 | 65 | 4 | 4 | 6054498.8 | 530189.8 | Empress 1 | 54 | 188 | 13 | |
| Cold Lake | FWE3-1 | 5 | 22 | 65 | 4 | 4 | 6054498.8 | 530189.8 | Empress 3 | 54 | 188 | 11 | 205 |
| Cold Lake | BSDU1 | 9 | 12 | 65 | 4 | 4 | 6051697.4 | 534688.3 | Muriel Lake | 57 | 194 | 9 | 313 |
| Cold Lake | BSDU2 | 9 | 12 | 65 | 4 | 4 | 6051697.4 | 534688.3 | Muriel Lake | 57 | 194 | 9 | |
| Cold Lake | BSDU3 | 9 | 12 | 65 | 4 | 4 | 6051697.4 | 534688.3 | Muriel Lake | 57 | 194 | 9 | |
| Soars Lake | 88-04-07-01 | 14 | 19 | 59 | 1 | 4 | 5997261.6 | 555805.2 | Muriel Lake | 125 | 220 | 9 | 25 |
| Soars Lake | 88-04-07-02 | 14 | 19 | 59 | 1 | 4 | 5997261.6 | 555805.2 | Muriel Lake | 125 | 220 | 9 | |
| Ft. Kent | W4-33 | SW | 33 | 61 | 4 | 4 | 6019096.6 | 530549.5 | Empress 3 | 98 | 189 | 11 | 86 |




## Legend

- Major Rivers
- Towns
- Major Lake
- Empress 1 Formation
- Calibration Run
- Steady State Simulation

Figure:
**6.1**

**Calibrated vs. Simulated Heads**
**Empress 1 Formation**

Stantec

Alberta Energy and Utilities Board

Alberta Geological Survey

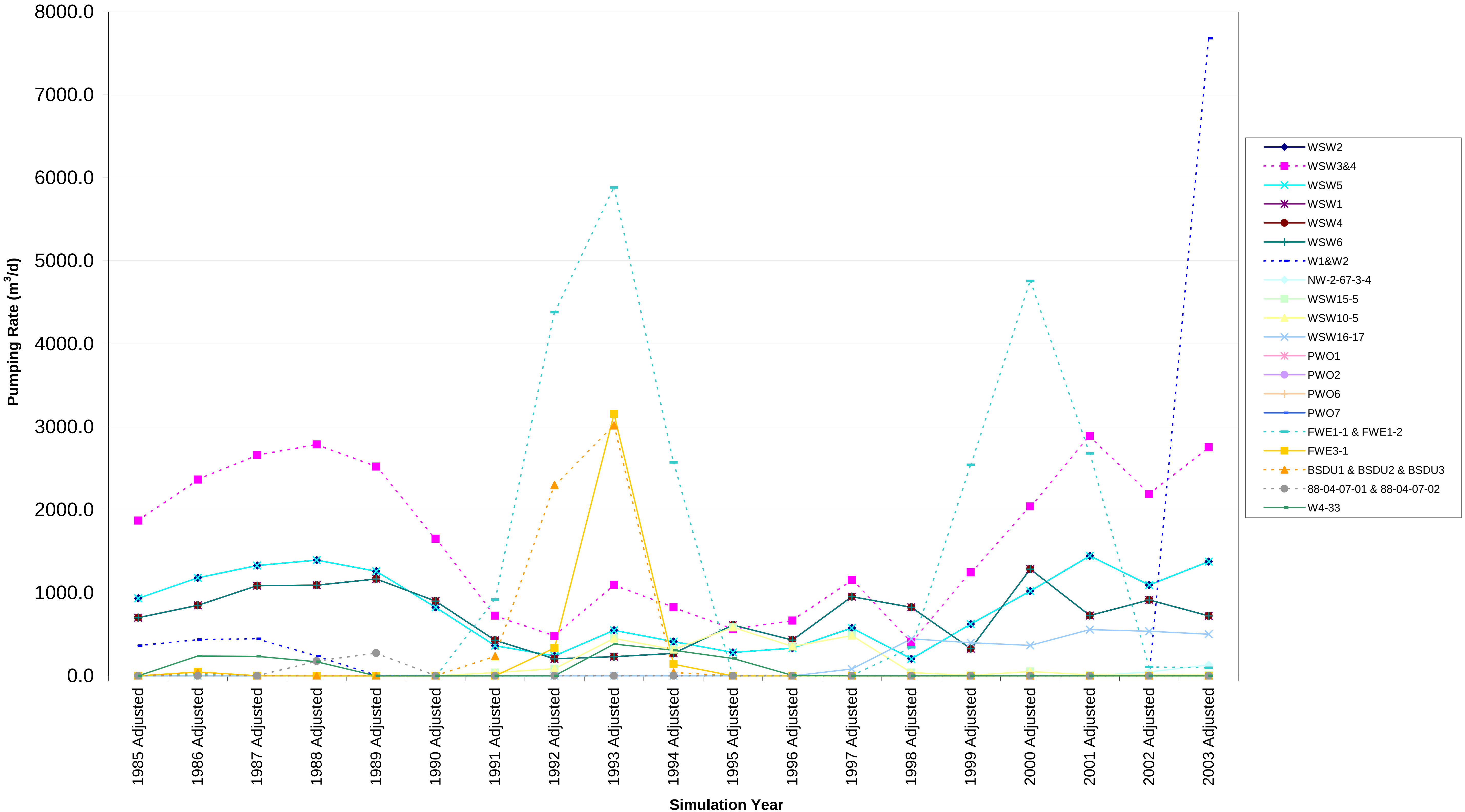
**Table 6.3: Transient Simulation 1985 - 2003 Industrial Production Well Locations and Pumping Rates**

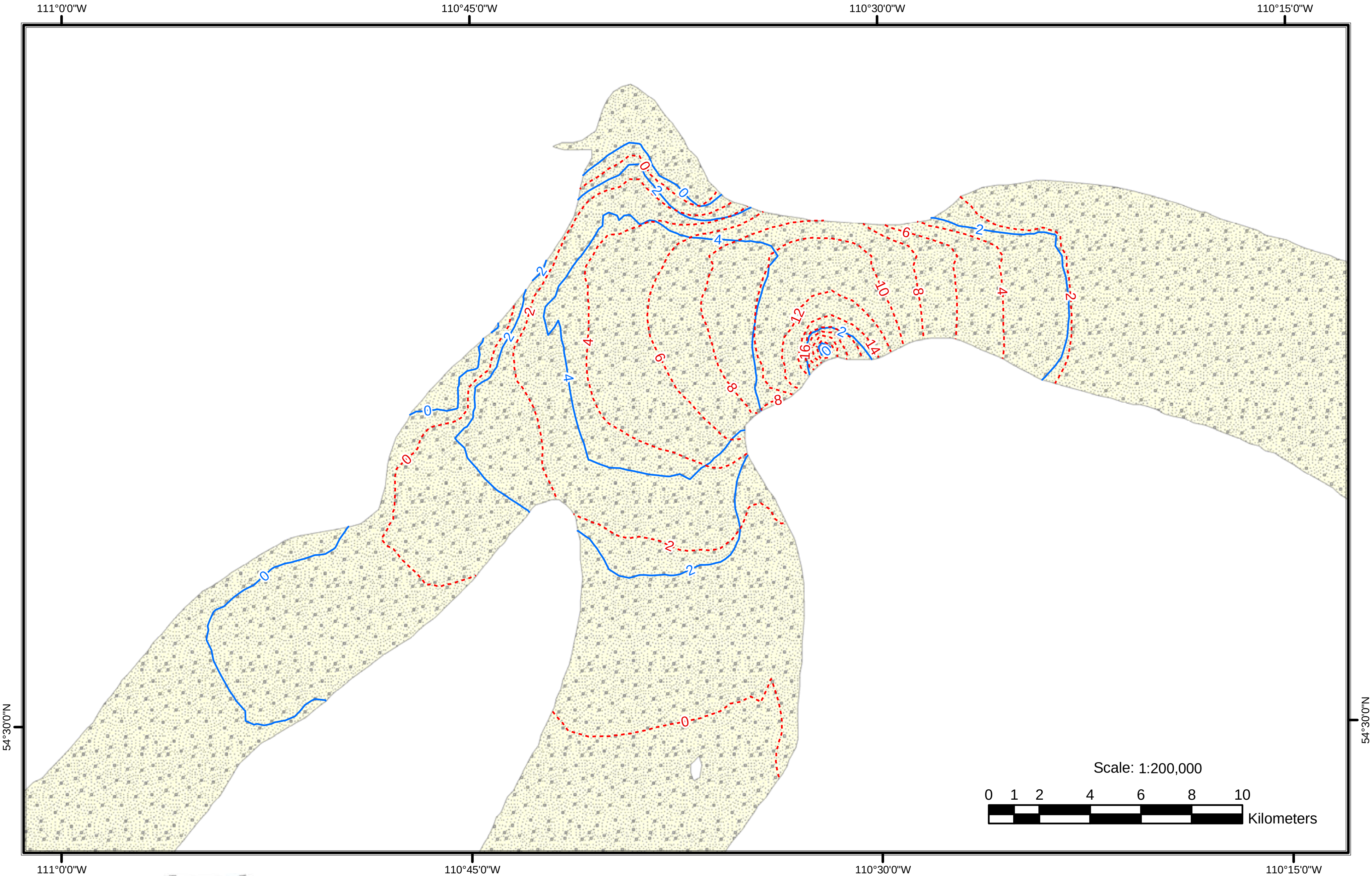
| Project | Well ID | UTM Northing | UTM Easting | UTM Zone | Aquifer | Model Row | Model Column | Model Layer | 1985 | 1985 Adjusted | 1986 | 1986 Adjusted | 1987 | 1987 Adjusted | 1988 | 1988 Adjusted | 1989 | 1989 Adjusted | 1990 | 1990 Adjusted | 1991 | 1991 Adjusted | 1992 | 1992 Adjusted | 1993 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Wolf Lake | WSW2 | 6051607.6 | 520448.7 | 12 | Muriel Lake | 57 | 176 | 9 | 935.5 | 935.5 | 1182.2 | 1182.2 | 1329.8 | 1329.8 | 1394.1 | 1394.1 | 1260.4 | 1260.4 | 825.5 | 825.5 | 362.8 | 362.8 | 240.5 | 240.5 | 548.5 |
| Wolf Lake | WSW3 | 6060917.2 | 520809.4 | 12 | Muriel Lake | 46 | 176 | 9 | 935.5 | 1870.9 | 1182.2 | 2364.4 | 1329.8 | 2659.5 | 1394.1 | 2788.3 | 1260.4 | 2520.7 | 825.5 | 1650.9 | 362.8 | 725.7 | 240.5 | 481.0 | 548.5 |
| Wolf Lake | WSW4 | 6060917.2 | 520809.4 | 12 | Muriel Lake | 46 | 176 | 9 | 935.5 | | 1182.2 | | 1329.8 | | 1394.1 | | 1260.4 | | 825.5 | | 362.8 | | 240.5 | | 548.5 |
| Wolf Lake | WSW5 | 6061317.2 | 520401.2 | 12 | Muriel Lake | 45 | 176 | 9 | 935.5 | 935.5 | 1182.2 | 1182.2 | 1329.8 | 1329.8 | 1394.1 | 1394.1 | 1260.4 | 1260.4 | 825.5 | 825.5 | 362.8 | 362.8 | 240.5 | 240.5 | 548.5 |
| Wolf Lake | WSW1 | 6051607.6 | 520448.7 | 12 | Empress 3 | 57 | 176 | 11 | 701.6 | 701.6 | 848.8 | 848.8 | 1086.7 | 1086.7 | 1091.7 | 1091.7 | 1167.8 | 1167.8 | 900.5 | 900.5 | 429.0 | 429.0 | 205.0 | 205.0 | 231.0 |
| Wolf Lake | WSW4 | 6060917.2 | 520809.4 | 12 | Empress 3 | 46 | 177 | 11 | 701.6 | 701.6 | 848.8 | 848.8 | 1086.7 | 1086.7 | 1091.7 | 1091.7 | 1167.8 | 1167.8 | 900.5 | 900.5 | 429.0 | 429.0 | 205.0 | 205.0 | 231.0 |
| Wolf Lake | WSW6 | 6061719.6 | 520399.0 | 12 | Empress 3 | 45 | 176 | 11 | 701.6 | 701.6 | 848.8 | 848.8 | 1086.7 | 1086.7 | 1091.7 | 1091.7 | 1167.8 | 1167.8 | 900.5 | 900.5 | 429.0 | 429.0 | 205.0 | 205.0 | 231.0 |
| Marguerite Lake | W1 | 6061300.2 | 516749.1 | 12 | 124.4 | 45 | 171 | 11 | 181.3 | 362.6 | 218.0 | 436.0 | 223.5 | 447.0 | 119.4 | 238.7 | 2.6 | 5.2 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Marguerite Lake | W2 | 6061300.2 | 516749.1 | 12 | 124.4 | 45 | 171 | 11 | 181.3 | | 218.0 | | 223.5 | | 119.4 | | 2.6 | | 0.0 | | 0.0 | | 0.0 | | 0.0 |
| Burnt Lake | NW-2-67-3-4 | 6068539.1 | 541882.1 | 12 | Bonnyville 1 | 36 | 203 | 6 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Primrose | WSW15-5 | 6069840.4 | 526951.7 | 12 | Ethel Lake | 34 | 184 | 5 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 39.8 | 39.8 | 86.5 | 86.5 | 453.2 |
| Primrose | WSW10-5 | 6069437.8 | 527362.2 | 12 | Ethel Lake | 35 | 185 | 5 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 39.8 | 39.8 | 86.5 | 86.5 | 453.2 |
| Hilda Lake | WSW16-17 | 6034320.5 | 538100.7 | 12 | Muriel Lake | 79 | 198 | 9 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Cold Lake | FWE1-1 | 6054498.8 | 530189.8 | 12 | Empress 1 | 54 | 188 | 13 | 0.0 | 0.0 | 0.0 | 24.5 | 0.8 | 1.5 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 532.4 | 919.0 | 1975.1 | 4382.4 | 2942.3 |
| Cold Lake | FWE1-2 | 6054498.8 | 530189.8 | 12 | Empress 1 | 54 | 188 | 13 | 0.0 | | 24.5 | | 0.8 | | 0.0 | | 0.0 | | 0.0 | | 386.6 | | 2407.3 | | 2942.3 |
| Cold Lake | FWE3-1 | 6054498.8 | 530189.8 | 12 | Empress 3 | 54 | 188 | 11 | 0.0 | 0.0 | 46.8 | 46.8 | 2.4 | 2.4 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 335.8 | 335.8 | 3156.1 |
| Cold Lake | BSDU1 | 6051697.4 | 534688.3 | 12 | Muriel Lake | 57 | 194 | 9 | 0.0 | | 11.6 | | 0.0 | | 0.2 | | 0.0 | | 0.0 | | 79.2 | | 766.8 | | 1005.6 |
| Cold Lake | BSDU2 | 6051697.4 | 534688.3 | 12 | Muriel Lake | 57 | 194 | 9 | 0.0 | 0.0 | 11.6 | 34.7 | 0.0 | 0.0 | 0.2 | 0.7 | 0.0 | 0.0 | 0.0 | 0.0 | 79.2 | 237.6 | 766.8 | 2300.4 | 1005.6 |
| Cold Lake | BSDU3 | 6051697.4 | 534688.3 | 12 | Muriel Lake | 57 | 194 | 9 | 0.0 | | 11.6 | | 0.0 | | 0.2 | | 0.0 | | 0.0 | | 79.2 | | 766.8 | | 1005.6 |
| Soars Lake | 88-04-07-01 | 5997261.6 | 555805.2 | 12 | Muriel Lake | 125 | 220 | 9 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 89.2 | 178.3 | 137.5 | 274.9 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Soars Lake | 88-04-07-02 | 5997261.6 | 555805.2 | 12 | Muriel Lake | 125 | 220 | 9 | 0.0 | | 0.0 | | 0.0 | | 89.2 | | 137.5 | | 0.0 | | 0.0 | | 0.0 | | 0.0 |
| Ft. Kent | W4-33 | 6019096.6 | 530549.5 | 12 | Empress 3 | 98 | 189 | 11 | 0.0 | 0.0 | 240.0 | 240.0 | 234.6 | 234.6 | 170.3 | 170.3 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 382.8 |

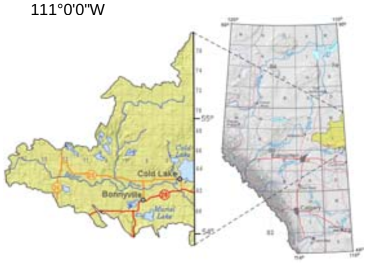
**Table 6.3: Transient Simulation 1985 - 2003 Industrial Production Well Locations and Pumping Rates**

| Project | Well ID | 1993 Adjusted | 1994 | 1994 Adjusted | 1995 | 1995 Adjusted | 1996 | 1996 Adjusted | 1997 | 1997 Adjusted | 1998 | 1998 Adjusted | 1999 | 1999 Adjusted | 2000 | 2000 Adjusted | 2001 | 2001 Adjusted | 2002 | 2002 Adjusted | 2003 | 2003 Adjusted |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Wolf Lake | WSW2 | 548.5 | 412.8 | 412.8 | 281.6 | 281.6 | 333.2 | 333.2 | 577.6 | 577.6 | 205.9 | 205.9 | 623.6 | 623.6 | 1020.5 | 1020.5 | 1445.6 | 1445.6 | 1094.6 | 1094.6 | 1377.5 | 1377.5 |
| Wolf Lake | WSW3 | 1097.0 | 412.8 | 825.7 | 281.6 | 563.2 | 333.2 | 666.3 | 577.6 | 1155.2 | 205.9 | 411.8 | 623.6 | 1247.1 | 1020.5 | 2041.1 | 1445.6 | 2891.3 | 1094.6 | 2189.3 | 1377.5 | 2755.1 |
| Wolf Lake | WSW4 | | 412.8 | | 281.6 | | 333.2 | | 577.6 | | 205.9 | | 623.6 | | 1020.5 | | 1445.6 | | 1094.6 | | 1377.5 | |
| Wolf Lake | WSW5 | 548.5 | 412.8 | 412.8 | 281.6 | 281.6 | 333.2 | 333.2 | 577.6 | 577.6 | 205.9 | 205.9 | 623.6 | 623.6 | 1020.5 | 1020.5 | 1445.6 | 1445.6 | 1094.6 | 1094.6 | 1377.5 | 1377.5 |
| Wolf Lake | WSW1 | 231.0 | 271.1 | 271.1 | 612.5 | 612.5 | 431.5 | 431.5 | 954.1 | 954.1 | 825.6 | 825.6 | 328.1 | 328.1 | 1285.8 | 1285.8 | 726.7 | 726.7 | 915.1 | 915.1 | 724.0 | 724.0 |
| Wolf Lake | WSW4 | 231.0 | 271.1 | 271.1 | 612.5 | 612.5 | 431.5 | 431.5 | 954.1 | 954.1 | 825.6 | 825.6 | 328.1 | 328.1 | 1285.8 | 1285.8 | 726.7 | 726.7 | 915.1 | 915.1 | 724.0 | 724.0 |
| Wolf Lake | WSW6 | 231.0 | 271.1 | 271.1 | 612.5 | 612.5 | 431.5 | 431.5 | 954.1 | 954.1 | 825.6 | 825.6 | 328.1 | 328.1 | 1285.8 | 1285.8 | 726.7 | 726.7 | 915.1 | 915.1 | 724.0 | 724.0 |
| Marguerite Lake | W1 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 3841.0 | 7682.1 |
| Marguerite Lake | W2 | | 0.0 | | 0.0 | | 0.0 | | 0.0 | | 0.0 | | 0.0 | | 0.0 | | 0.0 | | 0.0 | | 3841.0 | |
| Burnt Lake | NW-2-67-3-4 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 48.2 | 48.2 | 131.7 | 131.7 |
| Primrose | WSW15-5 | 453.2 | 318.5 | 318.5 | 584.9 | 584.9 | 355.1 | 355.1 | 486.4 | 486.4 | 38.8 | 38.8 | 6.7 | 6.7 | 53.4 | 53.4 | 11.0 | 11.0 | 10.9 | 10.9 | 10.0 | 10.0 |
| Primrose | WSW10-5 | 453.2 | 318.5 | 318.5 | 584.9 | 584.9 | 355.1 | 355.1 | 486.4 | 486.4 | 38.8 | 38.8 | 6.7 | 6.7 | 53.4 | 53.4 | 11.0 | 11.0 | 10.9 | 10.9 | 10.0 | 10.0 |
| Hilda Lake | WSW16-17 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 83.4 | 83.4 | 446.8 | 446.8 | 399.2 | 399.2 | 366.9 | 366.9 | 557.0 | 557.0 | 538.3 | 538.3 | 500.9 | 500.9 |
| Cold Lake | FWE1-1 | 5884.5 | 1139.6 | 2571.5 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 291.3 | 344.4 | 1103.0 | 2543.4 | 2466.0 | 4756.9 | 1459.3 | 2678.6 | 65.6 | 107.4 | 58.1 | 95.9 |
| Cold Lake | FWE1-2 | | 1431.9 | | 0.0 | | 0.0 | | 0.0 | | 53.0 | | 1440.4 | | 2290.9 | | 1219.3 | | 41.8 | | 37.8 | |
| Cold Lake | FWE3-1 | 3156.1 | 141.1 | 141.1 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Cold Lake | BSDU1 | | 13.6 | | 0.0 | | 0.0 | | 0.0 | | 0.0 | | 0.0 | | 0.0 | | 0.0 | | 0.0 | | 0.0 | |
| Cold Lake | BSDU2 | 3016.8 | 13.6 | 40.8 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Cold Lake | BSDU3 | | 13.6 | | 0.0 | | 0.0 | | 0.0 | | 0.0 | | 0.0 | | 0.0 | | 0.0 | | 0.0 | | 0.0 | |
| Soars Lake | 88-04-07-01 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Soars Lake | 88-04-07-02 | | 0.0 | | 0.0 | | 0.0 | | 0.0 | | 0.0 | | 0.0 | | 0.0 | | 0.0 | | 0.0 | | 0.0 | |
| Ft. Kent | W4-33 | 382.8 | 308.8 | 308.8 | 208.5 | 208.5 | 6.3 | 6.3 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |

Figure 6.2: Transient Simulation 1985 - 2003 Pumping Schedule





## Legend

Simulated 1994 Drawdown Contour

Simulated 1996 Drawdown Contour

Empress 1 Extent

Figure:
6.3

**Transient Simulation 1985 - 2003**
**Empress 1 Drawdown Contours**

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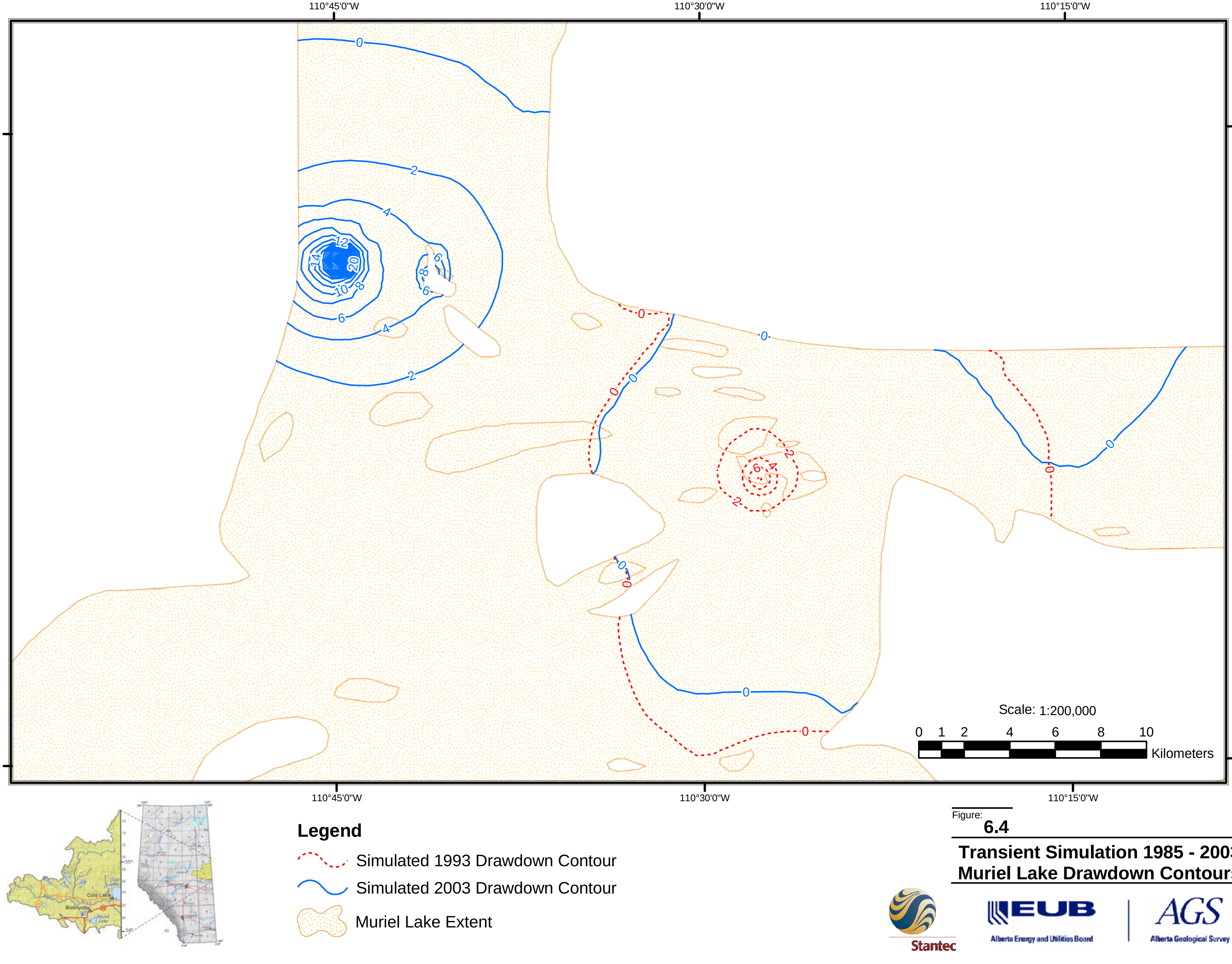


## Legend

- Simulated 1993 Drawdown Contour
- Simulated 2003 Drawdown Contour
- Muriel Lake Extent

Figure: 6.4

**Transient Simulation 1985 - 2003**
**Muriel Lake Drawdown Contours**

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The transient simulation results also revealed that cones of influence surrounding production wells generally did not extend across the basin and were limited to the vicinity of the production wells.  Figure 6.4 presents a comparison of simulated drawdown contours for the Muriel Lake Formation.  Examination of the simulated 1993 drawdown contour revealed a cone of depression centered around the BSDU1-3 wells, corresponding to their peak production rate in 1993 (Refer to Figure 6.2).  Examination of the simulated 2003 drawdown contours revealed a cone of depression centered around the W1 and W2 wells, corresponding to their peak production rate in 2003.  Interference effects due to residual drawdowns from 1993 were not observed in the 2003 drawdown contours.

The transient simulation results suggested that the location and timing of groundwater production in the basin were important factors in understanding the potential responses to hydrogeologic stresses in the system.  Impacts from groundwater production appear to be affected by groundwater production rates, spatial separation of production wells, and temporal separation of peak production rates.

## 6.3 2004 – 2020 PROJECTED INDUSTRIAL GROUNDWATER USE – TRANSIENT RUN

A transient forward simulation was run using projected industrial groundwater pumping rates provided by AENV.  This simulation was run to examine the dynamic response of the hydrogeologic system to projected groundwater production from foreseeable industrial projects in the basin.  The simulation period began in 2004 and extended to the year 2020.  The various industrial operators, in response to requests from AENV, provided the projected groundwater production rates used in this simulation.

Annual groundwater production rates were converted to average daily production rates and were then specified in the WEL1 module.  Table 6.5 presents the well locations and pumping schedules specified in the WEL1 module.  Three dimensional grids of final simulated heads from the 1985 – 2004 transient simulation (Section 6.2) were loaded into the simulation as initial heads.  Table 6.6 presents the MODFLOW2000 settings used in the transient simulation.

**Table 6.6**
**MODFLOW2000 Settings Used in Transient Simulation (2004 – 2020) Runs**

| | |
|---|---|
| **Stress Periods** | 17 |
| **Total Timesteps** | 170 |
| **Packages Used** | LPF1, SOR1, WEL1, RIV1, GHB |
| **Flow Package Settings** | All layers confined<br>Interblock transmissivity: Harmonic mean<br>Cell Wetting: OFF |
| **Solver Settings** | SOR1 Solver<br>Max Iterations = 5000<br>Convergence Criteria = 0.1<br>Prevent Cell Drying: ON<br>Minimum saturated thickness = 0.1 |

Examination of the 2004 – 2020 transient simulation results corroborates the dynamic response of the model observed during the 1985 – 2003 simulation, in general. Again, examination of the transient simulation results suggested that the major aquifer systems utilized in the basin for industrial production responded relatively quickly to changes in system stresses.

Figure 6.5 presents a comparison of drawdown contours for the Empress 1 Formation in the years 2009 and 2020. Projected groundwater production rates for the Empress 1 Formation peak in the year 2009 (Refer to Table 6.5). Examination of the 2009 drawdown contours revealed a cone of depression centered around the FWE1-1 and FWE1-2 wells, with a maximum drawdown of approximately 84 m. Projected groundwater production rates in the Empress 1 Formation decline after the year 2017. Simulated drawdown contours for the year 2020 indicated that the cone of depression remained centered around the FWE1-1 and FEW 1-2 wells. However the maximum drawdown had decreased to approximately 44 m. It was also noted that the overall extent of the cone of depression appeared similar to the extent observed in the 2009 contours, although the magnitude of drawdown was reduced.

Figure 6.6 presents a comparison of drawdown contours for the Empress 3 Formation in the years 2009 and 2020. Similar to the Empress 1 Formation, projected groundwater production rates in the Empress 3 Formation peak in the year 2009 (Refer to Table 6.5). Production rates then declined and remained constant until the end of the simulation in the year 2020. Comparison of the 2009 and 2020 drawdown contours revealed that the overall extent of the drawdown contours appeared similar, yet the magnitude of drawdowns in 2020 was reduced.

## 6.4 TRANSITION CURVE ANALYSIS

Transition curve analysis was conducted for the study area in order to gain further understanding of the potential interactions between surface water and the groundwater system and changes to regional water balances in response to groundwater production. During the initial stages of groundwater production, water comes primarily from aquifer storage. However,

## Table 6.5 2004 - 2020 Transient Simulation Industrial Production Well Locations and Pumping Rates

| Project | Well ID | UTM Northing | UTM Easting | UTM Zone | Aquifer | Model Row | Model Column | Model Layer | 2004 | 2004 Adjusted | 2005 | 2005 Adjusted | 2006 | 2006 Adjusted | 2007 | 2007 Adjusted | 2008 | 2008 Adjusted | 2009 | 2009 Adjusted |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Wolf Lake | WSW2 | 6051607.6 | 520448.7 | 12 | Muriel Lake | 57 | 176 | 9 | 1027.9 | 1027.9 | 284.9 | 284.9 | 1305.9 | 1305.9 | 743.1 | 743.1 | 284.9 | 284.9 | 1705.7 | 1705.7 |
| Wolf Lake | WSW3 | 6060917.2 | 520809.4 | 12 | Muriel Lake | 46 | 176 | 9 | 1027.9 | 2055.9 | 284.9 | 569.9 | 1305.9 | 2611.8 | 743.1 | 1486.3 | 284.9 | 569.9 | 1705.7 | 3411.3 |
| Wolf Lake | WSW4 | 6060917.2 | 520809.4 | 12 | Muriel Lake | 46 | 176 | 9 | 1027.9 | | 284.9 | | 1305.9 | | 743.1 | | 284.9 | | 1705.7 | |
| Wolf Lake | WSW5 | 6061317.2 | 520401.2 | 12 | Muriel Lake | 45 | 176 | 9 | 1027.9 | 1027.9 | 284.9 | 284.9 | 1305.9 | 1305.9 | 743.1 | 743.1 | 284.9 | 284.9 | 1705.7 | 1705.7 |
| Wolf Lake | WSW1 | 6051607.6 | 520448.7 | 12 | Empress 3 | 57 | 176 | 11 | 1027.9 | 1027.9 | 284.9 | 284.9 | 1305.9 | 1305.9 | 743.1 | 743.1 | 284.9 | 284.9 | 1705.7 | 1705.7 |
| Wolf Lake | WSW4 | 6060917.2 | 520809.4 | 12 | Empress 3 | 46 | 177 | 11 | 1027.9 | 1027.9 | 284.9 | 284.9 | 1305.9 | 1305.9 | 743.1 | 743.1 | 284.9 | 284.9 | 1705.7 | 1705.7 |
| Wolf Lake | WSW6 | 6061719.6 | 520399.0 | 12 | Empress 3 | 45 | 176 | 11 | 1027.9 | 1027.9 | 284.9 | 284.9 | 1305.9 | 1305.9 | 743.1 | 743.1 | 284.9 | 284.9 | 1705.7 | 1705.7 |
| Primrose | WSW15-5 | 6069840.4 | 526951.7 | 12 | Ethel Lake | 34 | 184 | 5 | 9.7 | 9.7 | 2.7 | 2.7 | 12.4 | 12.4 | 7.0 | 7.0 | 2.7 | 2.7 | 16.2 | 16.2 |
| Primrose | WSW10-5 | 6069437.8 | 527362.2 | 12 | Ethel Lake | 35 | 185 | 5 | 9.7 | 9.7 | 2.7 | 2.7 | 12.4 | 12.4 | 7.0 | 7.0 | 2.7 | 2.7 | 16.2 | 16.2 |
| Hilda Lake | WSW16-17 | 6034320.5 | 538100.7 | 12 | Muriel Lake | 79 | 198 | 9 | 300.0 | 300.0 | 300.0 | 300.0 | 300.0 | 300.0 | 300.0 | 300.0 | 35.6 | 35.6 | 35.6 | 35.6 |
| Cold Lake | FWE1-1 | 6054498.8 | 530189.8 | 12 | Empress 1 | 54 | 188 | 13 | 5304.3 | 10608.6 | 5346.1 | 10692.2 | 5502.3 | 11004.6 | 5493.5 | 10987.0 | 5504.0 | 11007.9 | 5403.8 | 10807.6 |
| Cold Lake | FWE1-2 | 6054498.8 | 530189.8 | 12 | Empress 1 | 54 | 188 | 13 | 5304.3 | | 5346.1 | | 5502.3 | | 5493.5 | | 5504.0 | | 5403.8 | |
| Tucker Lake | | 6046801.6 | 528618.8 | 12 | Empress 1 | | | | 20.0 | 20.0 | 20.0 | 20.0 | 20.0 | 20.0 | 20.0 | 20.0 | 20.0 | 20.0 | 20.0 | 20.0 |

### Table 6.5 2004 - 2020 Transient Simulation Industrial Production Well Locations and Pumping Rates

| 2010 | 2010 Adjusted | 2011 | 2011 Adjusted | 2012 | 2012 Adjusted | 2013 | 2013 Adjusted | 2014 | 2014 Adjusted | 2015 | 2015 Adjusted | 2016 | 2016 Adjusted | 2017 | 2017 Adjusted | 2018 | 2018 Adjusted | 2019 | 2019 Adjusted | 2020 | 2020 Adjusted |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 919.4 | 919.4 | 510.3 | 510.3 | 427.4 | 427.4 | 427.4 | 427.4 | 427.4 | 427.4 | 427.4 | 427.4 | 427.4 | 427.4 | 427.4 | 427.4 | 427.4 | 427.4 | 427.4 | 427.4 | 427.4 | 427.4 |
| 919.4 | 1838.7 | 510.3 | 1020.7 | 427.4 | 854.8 | 427.4 | 854.8 | 427.4 | 854.8 | 427.4 | 854.8 | 427.4 | 854.8 | 427.4 | 854.8 | 427.4 | 854.8 | 427.4 | 854.8 | 427.4 | 854.8 |
| 919.4 | | 510.3 | | 427.4 | | 427.4 | | 427.4 | | 427.4 | | 427.4 | | 427.4 | | 427.4 | | 427.4 | | 427.4 | |
| 919.4 | 919.4 | 510.3 | 510.3 | 427.4 | 427.4 | 427.4 | 427.4 | 427.4 | 427.4 | 427.4 | 427.4 | 427.4 | 427.4 | 427.4 | 427.4 | 427.4 | 427.4 | 427.4 | 427.4 | 427.4 | 427.4 |
| 919.4 | 919.4 | 510.3 | 510.3 | 427.4 | 427.4 | 427.4 | 427.4 | 427.4 | 427.4 | 427.4 | 427.4 | 427.4 | 427.4 | 427.4 | 427.4 | 427.4 | 427.4 | 427.4 | 427.4 | 427.4 | 427.4 |
| 919.4 | 919.4 | 510.3 | 510.3 | 427.4 | 427.4 | 427.4 | 427.4 | 427.4 | 427.4 | 427.4 | 427.4 | 427.4 | 427.4 | 427.4 | 427.4 | 427.4 | 427.4 | 427.4 | 427.4 | 427.4 | 427.4 |
| 919.4 | 919.4 | 510.3 | 510.3 | 427.4 | 427.4 | 427.4 | 427.4 | 427.4 | 427.4 | 427.4 | 427.4 | 427.4 | 427.4 | 427.4 | 427.4 | 427.4 | 427.4 | 427.4 | 427.4 | 427.4 | 427.4 |
| 8.7 | 8.7 | 4.8 | 4.8 | 4.1 | 4.1 | 4.1 | 4.1 | 4.1 | 4.1 | 4.1 | 4.1 | 4.1 | 4.1 | 4.1 | 4.1 | 4.1 | 4.1 | 4.1 | 4.1 | 4.1 | 4.1 |
| 8.7 | 8.7 | 4.8 | 4.8 | 4.1 | 4.1 | 4.1 | 4.1 | 4.1 | 4.1 | 4.1 | 4.1 | 4.1 | 4.1 | 4.1 | 4.1 | 4.1 | 4.1 | 4.1 | 4.1 | 4.1 | 4.1 |
| 35.6 | 35.6 | 35.6 | 35.6 | 35.6 | 35.6 | 35.6 | 35.6 | 35.6 | 35.6 | 35.6 | 35.6 | 35.6 | 35.6 | 35.6 | 35.6 | 35.6 | 35.6 | 35.6 | 35.6 | 35.6 | 35.6 |
| 3132.9 | 6265.7 | 4723.8 | 9447.6 | 4199.0 | 8398.0 | 4536.6 | 9073.2 | 2150.0 | 4300.0 | 4624.1 | 9248.2 | 4273.5 | 8547.0 | 4529.0 | 9058.0 | 2150.0 | 4300.0 | 2045.0 | 4090.0 | 1895.0 | 3790.0 |
| 3132.9 | | 4723.8 | | 4199.0 | | 4536.6 | | 2150.0 | | 4624.1 | | 4273.5 | | 4529.0 | | 2150.0 | | 2045.0 | | 1895.0 | |
| 20.0 | 20.0 | 20.0 | 20.0 | 20.0 | 20.0 | 20.0 | 20.0 | 20.0 | 20.0 | 20.0 | 20.0 | 20.0 | 20.0 | 20.0 | 20.0 | 20.0 | 20.0 | 20.0 | 20.0 | 20.0 | 20.0 |

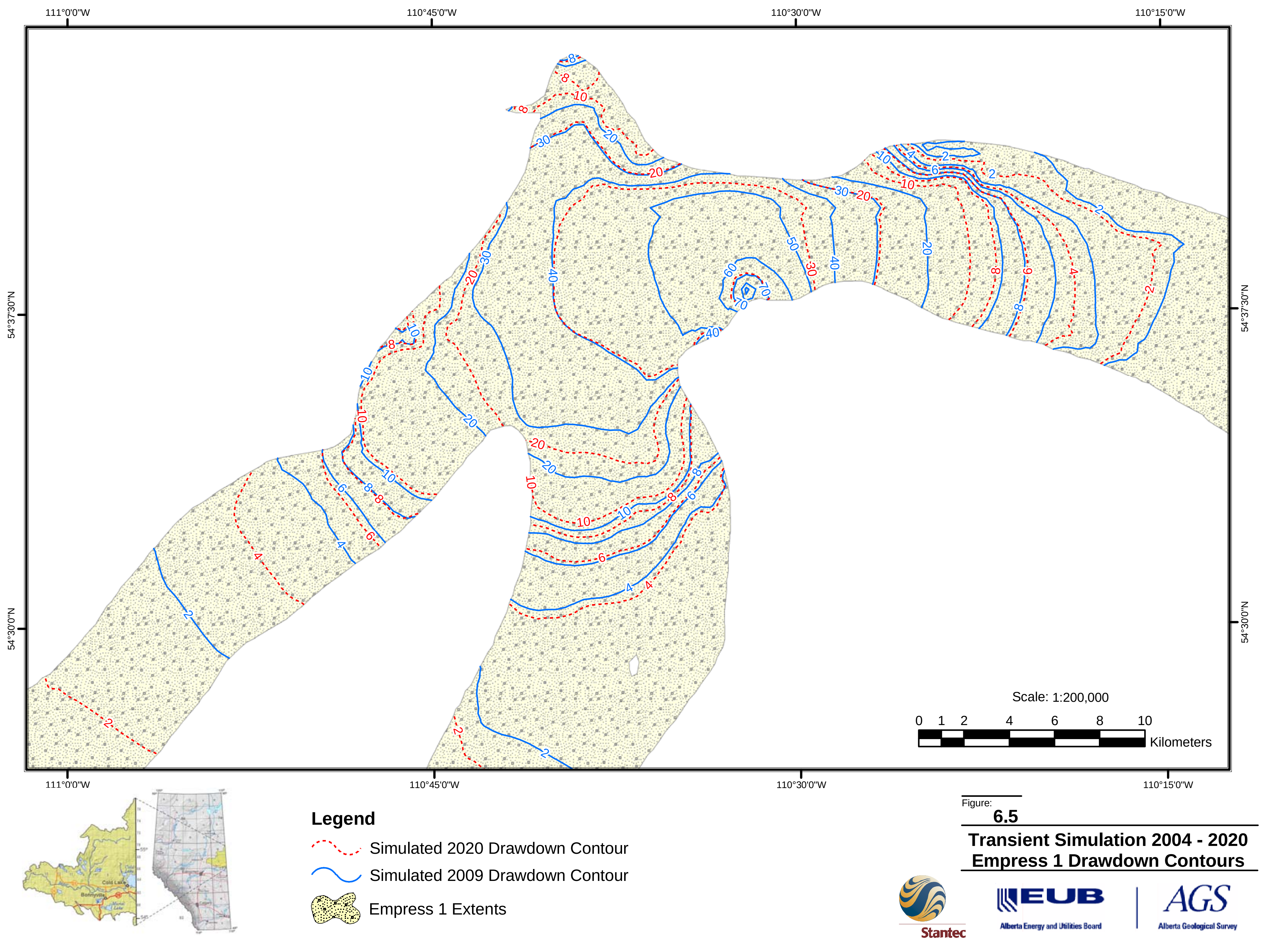
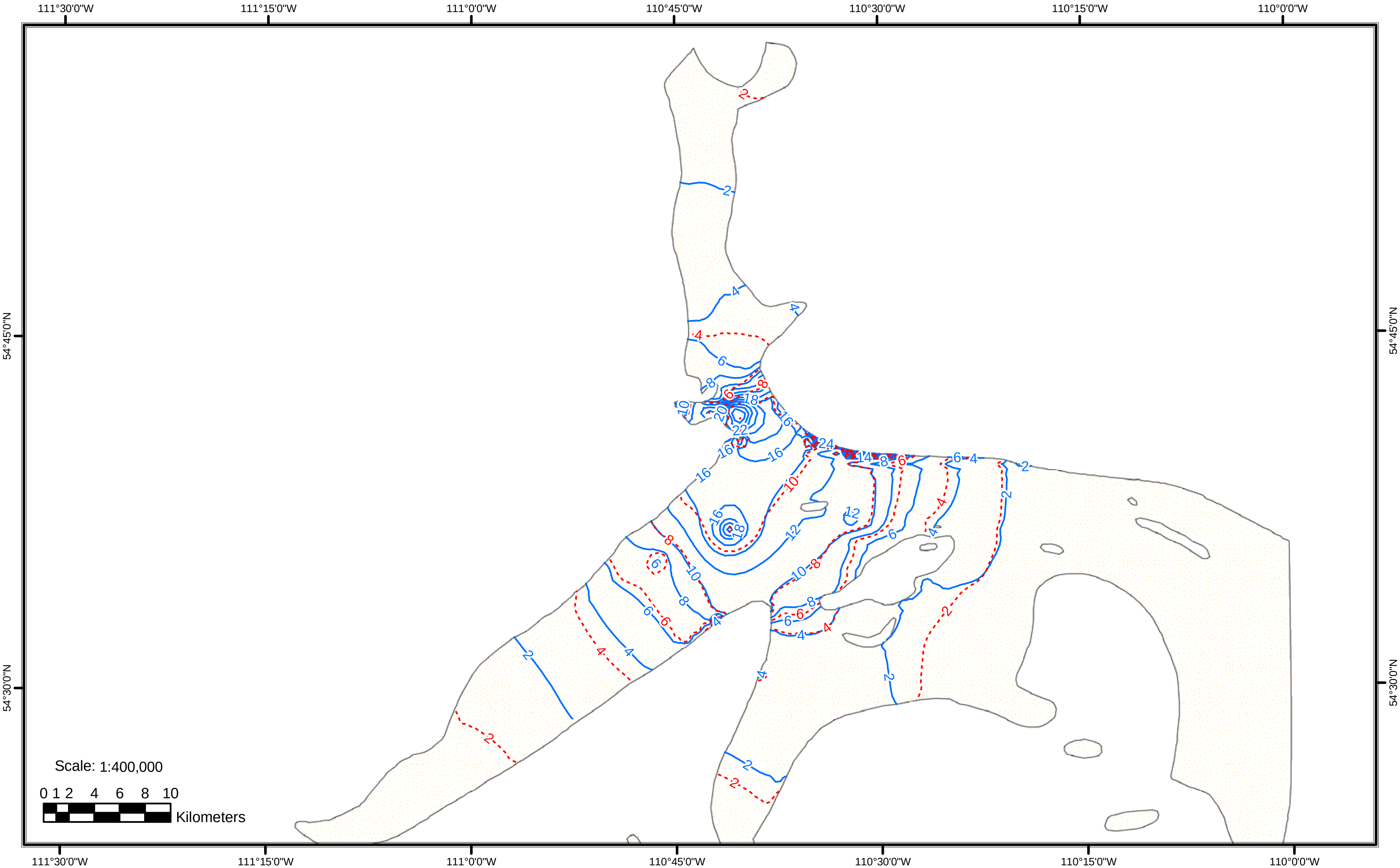



Figure: 6.5

**Transient Simulation 2004 - 2020**
**Empress 1 Drawdown Contours**




## Legend

Simulated 2009 Drawdown Contour

Simulated 2020 Drawdown Contour

Empress 3 Extent

Figure: 6.6

**Transient Simulation 2004 - 2020**
**Empress 3 Drawdown Contours**

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continued production will eventually be derived from induced recharge of water from surface water bodies. Timing of the change from reliance on groundwater storage to reliance on induced recharge will depend to a large degree on local hydrologic/hydrogeologic conditions.

It was known that groundwater production would cause changes to the regional water balances in response to the external stresses applied to the hydrogeologic system. The transition curve analysis seeked to define the range of system responses that could reasonably be expected over the study area. In total, 23 transient simulations were run for the transition curve analysis. Each model run simulated the influence of a single hypothetical production well pumping at a constant rate of 10,000 $m^3$/d over a period of 100 years. The location and completion formation were varied for each of the runs in order to span a range of reasonably expected system responses. Table 6.7 presents the MODFLOW2000 setting used in the transition curve analysis simulations.

**Table 6.7**
**MODFLOW2000 Settings Used in Transition Curve Runs**

| | |
|---|---|
| **Stress Periods** | 10 |
| **Total Timesteps** | 100 |
| **Packages Used** | LPF1, SOR1, WEL1, RIV1, GHB |
| **Flow Package Settings** | All layers confined<br>Interblock transmissivity: Harmonic mean<br>Cell Wetting: OFF |
| **Solver Settings** | SOR1 Solver<br>Max Iterations = 5000<br>Convergence Criteria = 0.1<br>Prevent Cell Drying: ON<br>Minimum saturated thickness = 0.1 |

Output control options were set to write volumetric budget data for each timestep (100 irregularly spaced timesteps in total) in the transient simulation. Following each of the runs, volumetric budget data were extracted directly from the MODFLOW2000 output file. Volumetric budgets were calculated for the entire model domain for the CHB cells (representing lakes), RIV cells (representing rivers), and GHB cells (representing external recharge).

Twelve model runs were conducted with hypothetical production wells completed in the Empress 1 Formation. Figure 6.7 presents the locations of the 12 wells simulated in the Empress 1 Formation. Ten of the hypothetical wells were placed from west to east along the thalweg of the Beverly Channel. The remaining two wells were placed adjacent to the Beaver River and Moose Lake, respectively. 5 model runs were conducted with hypothetical production wells completed in the Muriel Lake Formation. Figure 6.8 presents the locations of the 5 wells in the Muriel Lake Formation. 3 model runs were conducted with hypothetical production wells completed in the Ethel Lake Formation. Figure 6.9 presents the locations of the 3 wells in the Ethel Lake Formation. Finally, 3 model runs were conducted with hypothetical production wells completed in the Sand River Formation. Figure 6.10 presents the locations of the 3 wells in the Sand River Formation.

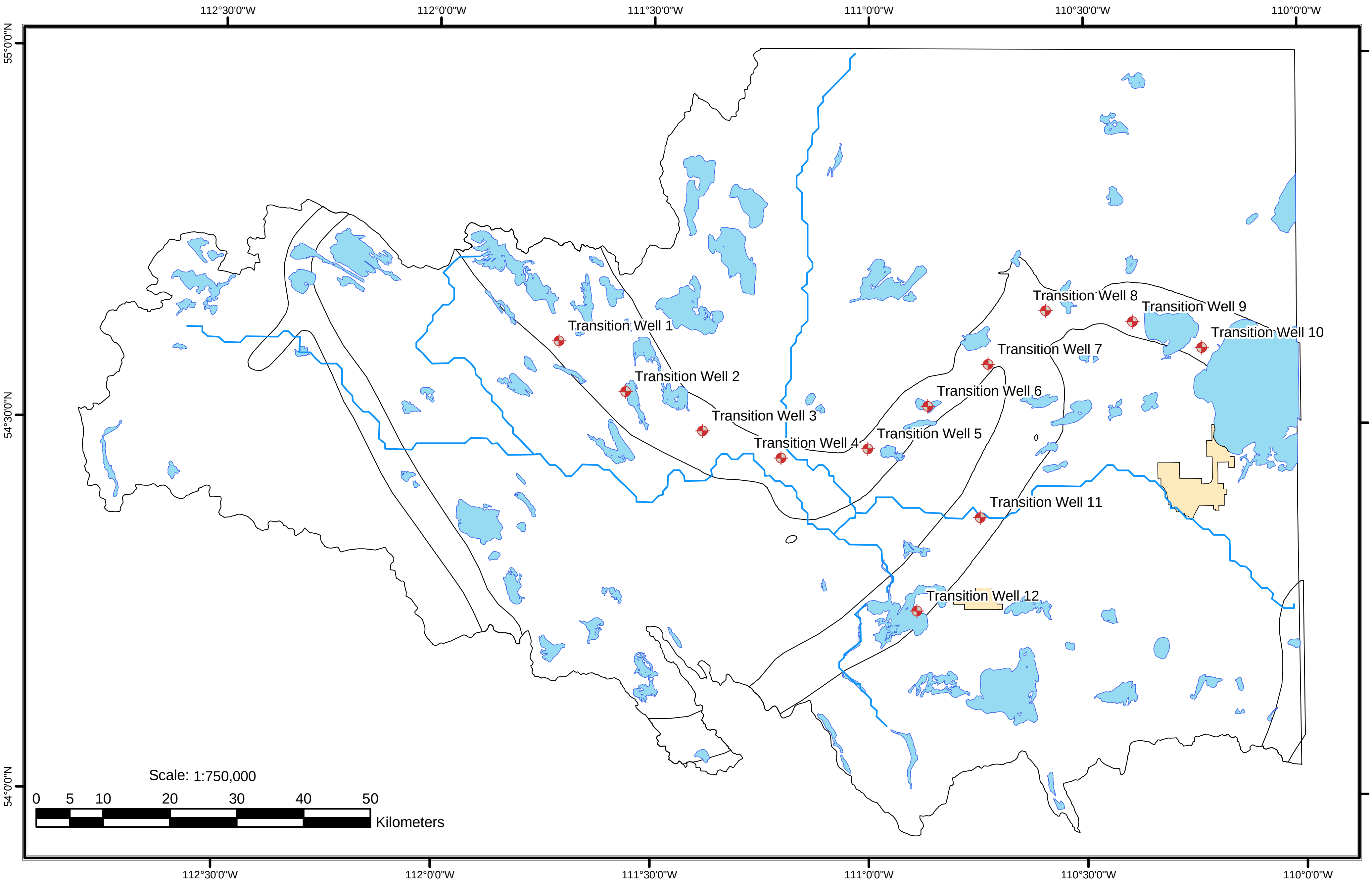
Transition curves generated for each of the 23 simulation runs are presented in Appendix A for reference. Examination of the transition curves reveals that changes in regional water balances due to groundwater production are highly dependent on the location of the production well. It was also noted that the transition time (the time taken for the derivation of production volumes to switch from aquifer storage to other sources) also appears to be highly dependent on the location of the production well.

When the simulated production well was situated adjacent to a major lake (i.e. Transition Wells 9 and 10) it was observed that as production continued over time, the origin of water changed from primarily aquifer storage, to induced recharge from lakes. The calculation of such changes did not differentiate between water derived from increased seepage and water derived from decreased lake discharge. It was also noted during the Transition Curve analysis that the connection between aquifers and surface water bodies did not need to be direct for changes in water balances to occur. Indirect connections through overlying aquifers or vertical continuity of recent fluvial deposits appeared to have similar effects, albeit with lower magnitudes or transition times.

Comparison of the transition curves for Transition Wells 9 and 10 suggested that the proportion of water originating from lakes depended of the degree of connection (direct and indirect) between the lake and the aquifer being produced. For Transition Well 10, situated adjacent to Cold Lake, it was observed that following the transition period, approximately 85 % of production volumes were being derived from induced recharge from lakes. This was expected since there is a high degree of connection between the Empress 1 formation and Cold Lake in the model. For Transition Well 9, situated adjacent to Marie Lake, it was noted that following the transition period approximately 50 % of production volumes were being derived from induced recharge from lakes. This lower proportion was expected since Marie Lake is not as well connected to the Empress 1 Formation as Cold Lake is.

Transition curves for production wells situated adjacent to major rivers (i.e. Transition Well 4) revealed that as production continued over time, the origin of water changed from primarily aquifer storage, to induced recharge from rivers. Again, the calculation of such changes did not differentiate between water derived from increased seepage and water derived from decreased river discharge. For Transition Well 4, it was observed that following a transition period of approximately 900 days, 70 % of the production volumes were being derived from induced recharge from rivers.

Observations of transition curves for production wells not well connected to surface water bodies (i.e. Transition Well 17) revealed that as groundwater production continued over time, the origin of water changed from primarily aquifer storage to increased capture of rejected atmospheric recharge. For Transition Well 17, it was observed that following a transition period of approximately 350 days, 85 % of the production volumes were being derived from induced recharge from atmospheric water.




## Legend

Empress 1 Wells

Major Rivers

Towns

Major Lake

Empress 1 Extent

Figure: 6.7

**Transition Curve Analysis**
**Empress 1 Formation**

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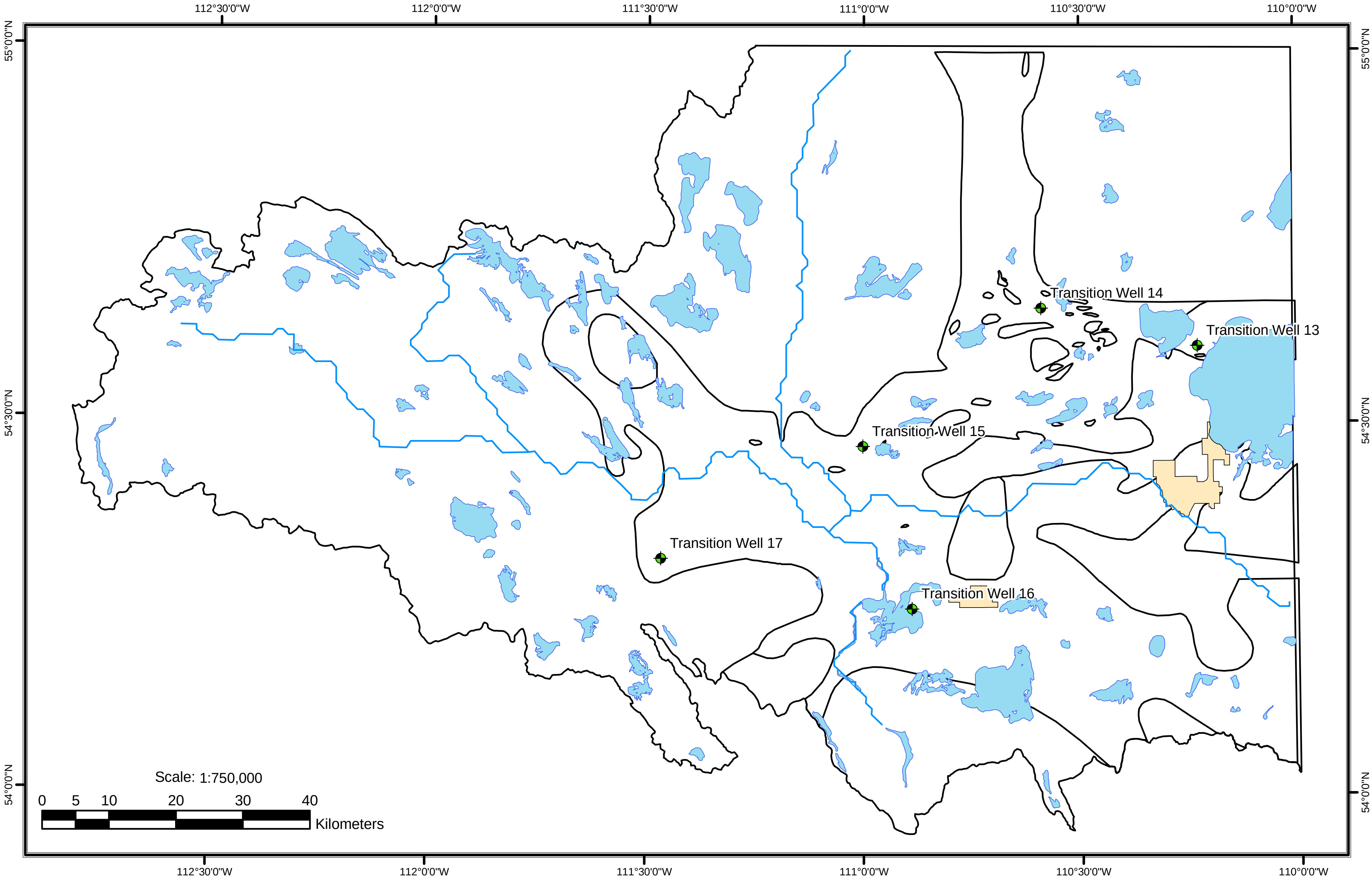
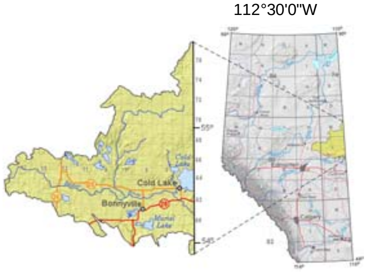
AGS Alberta Geological Survey



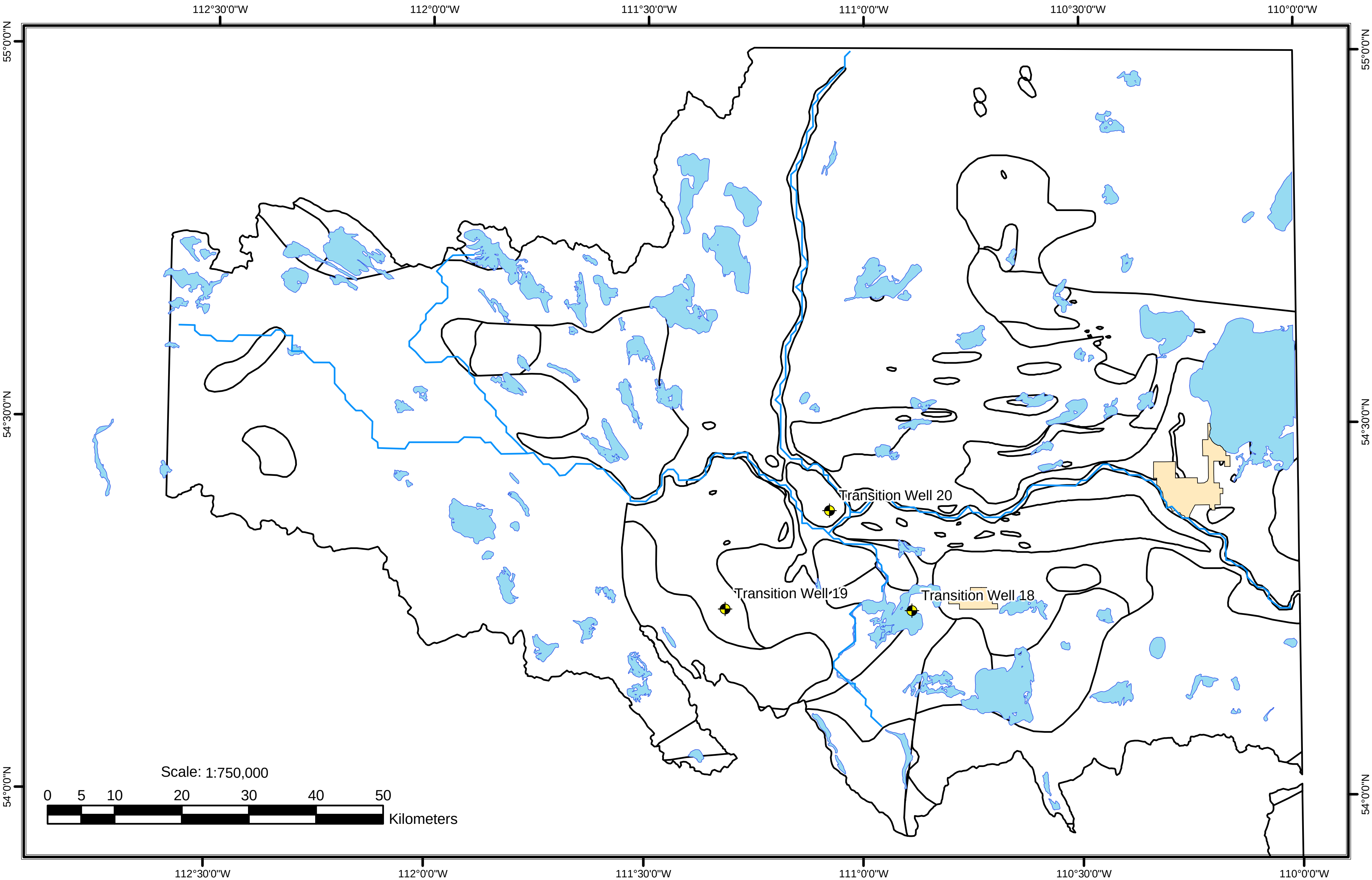
**Legend**

- Muriel Lake Wells
- Major Rivers
- Towns
- Major Lake
- Muriel Lake Extent

Figure: **6.8**

**Transition Curve Analysis**
**Muriel Lake Formation**

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



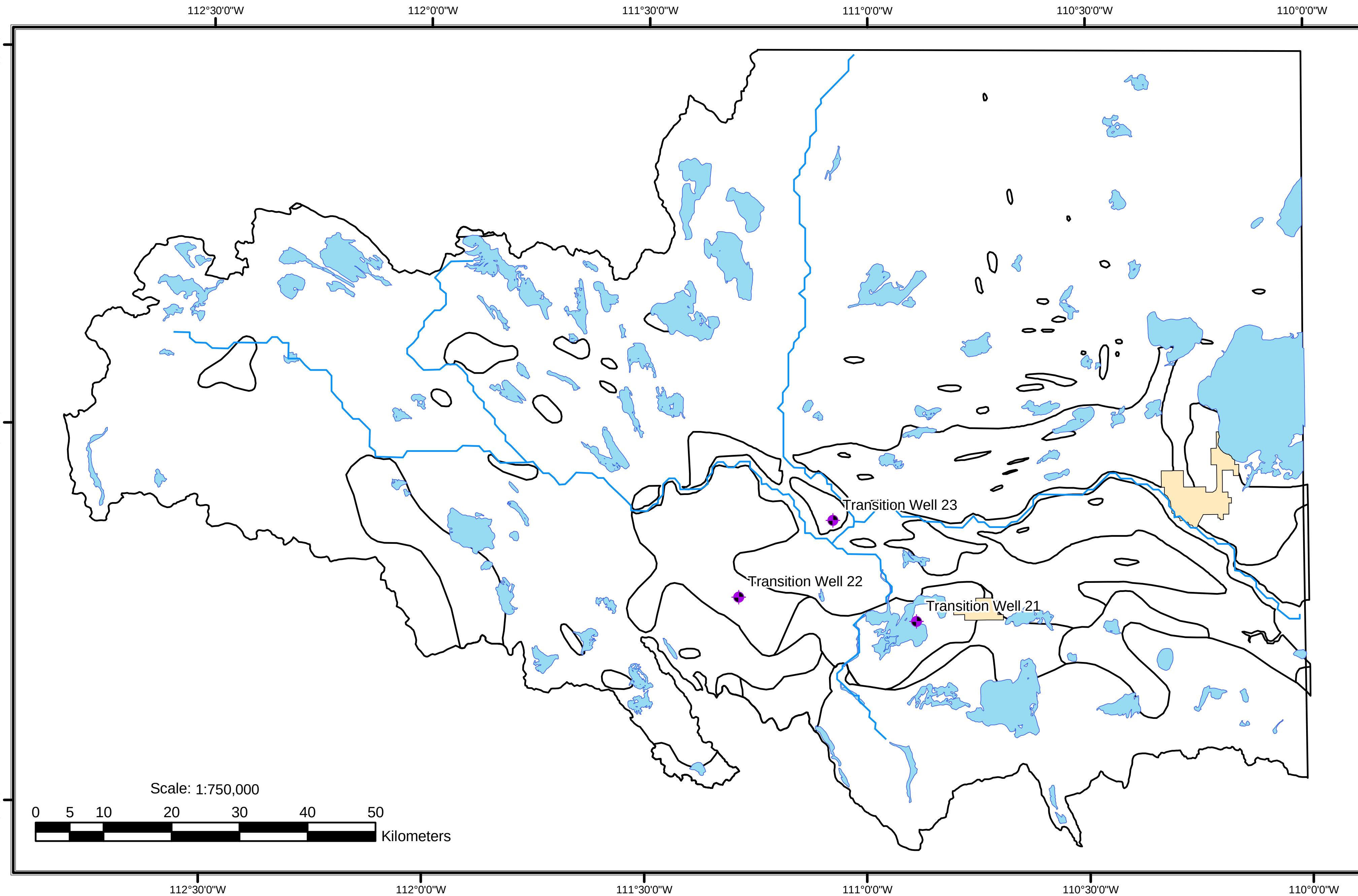

**Legend**

- Ethel Lake Wells
- Major Rivers
- Towns
- Major Lake
- Ethel Lake Extent

Figure: **6.9**

**Transition Curve Analysis**
**Ethel Lake Formation**

Stantec
EUB Alberta Energy and Utilities Board
AGS Alberta Geological Survey




**Legend**

Sand River Wells
Major Rivers
Towns
Major Lake
Sand River Extent

Figure: **6.10**

**Transition Curve Analysis**
**Sand River Formation**

Stantec
EUB Alberta Energy and Utilities Board
AGS Alberta Geological Survey

# 7.0 Limitations and Recommendations

The numerical groundwater flow model documented in this report is a regional scale model developed to gain understanding of regional water balances and groundwater flow regimes. The model was also developed for use as an analysis tool to support basin scale water management decisions. The model was not intended to provide site specific assessments of groundwater flow regimes. It should be noted that the model cell size is 800 m by 800 m, and a single cell roughly represents a quarter section of land. At this level of resolution, the model cannot be expected to accurately describe local groundwater flow systems. However, modelers interested in site specific assessment of groundwater flow conditions could extract a sub domain out of the regional model, and refine model grid and parameters with site specific values.

Transient calibration of several regions of the model should be revisited when adequate transient data sets are available. Currently, transient calibrations have been completed for northeast portions of the model domain only (in the vicinity of Imperial Oil and CNRL's developments). Further transient calibrations would confirm that the simulated dynamic response of the model accurately depicts actual system response in areas yet to undergo transient calibrations.

The model currently utilizes a regularly spaced finite difference grid. This approach was adopted primarily to simplify calibration of the model, as all cell geometries would be consistent for a layer of constant thickness (i.e. Layer 1 of the model). The model grid could be refined in areas of major industrial groundwater production or in areas where the distribution of geological features is rapidly changing. Refinement of the grid would allow for more accurate simulation of hydraulic heads in areas under external hydraulic stresses.

RIV cells were utilized in the model to simulate the effects of major rivers in the model domain. RIV cells allow water to leave or enter the cell, simulating seepage from the river (losing reaches) or groundwater discharge (gaining reaches), respectively. However, RIV cells do not account for river stage or discharge rates, and could in theory provide infinite volumes of water seepage to the model. Alternatively, the Streamflow Routing package (STR) could also be used to simulate the effects of major rivers in the domain. STR cells are similar to RIV cells, by allowing water to seep from or discharge to the river. However, STR cells also consider river stage and discharge relationships of open channel hydraulics. This may allow for more accurate calculation of water balances, particularly in areas where the rivers are modeled as being well connected to major aquifer systems.

The ability of underlying model layers to receive recharge is primarily dependent on the conductance of the GHB cells. The volumes of recharge are also proportional to the head difference in the GHB cell. The use of specified flux boundary conditions instead of GHB conditions for simulating the effects of recharge could be examined to determine the effects on simulated head distributions.

Certain cells in the model are currently incorrectly assigned as inactive in the IBOUND array. This is primarily an artifact of the discretization of the model domain, where grid files were used to assign layer elevations. Manual inspection and correction of individual cells should be undertaken to improve the overall numerical stability of the model. This may also correct the behaviour of cells observed in the vicinity of the aforementioned inactive cells.

# 8.0 Stantec Quality Management Program

This report, entitled **"Cold Lake Beaver River Basin Numerical Groundwater Model",** ***was*** produced by:

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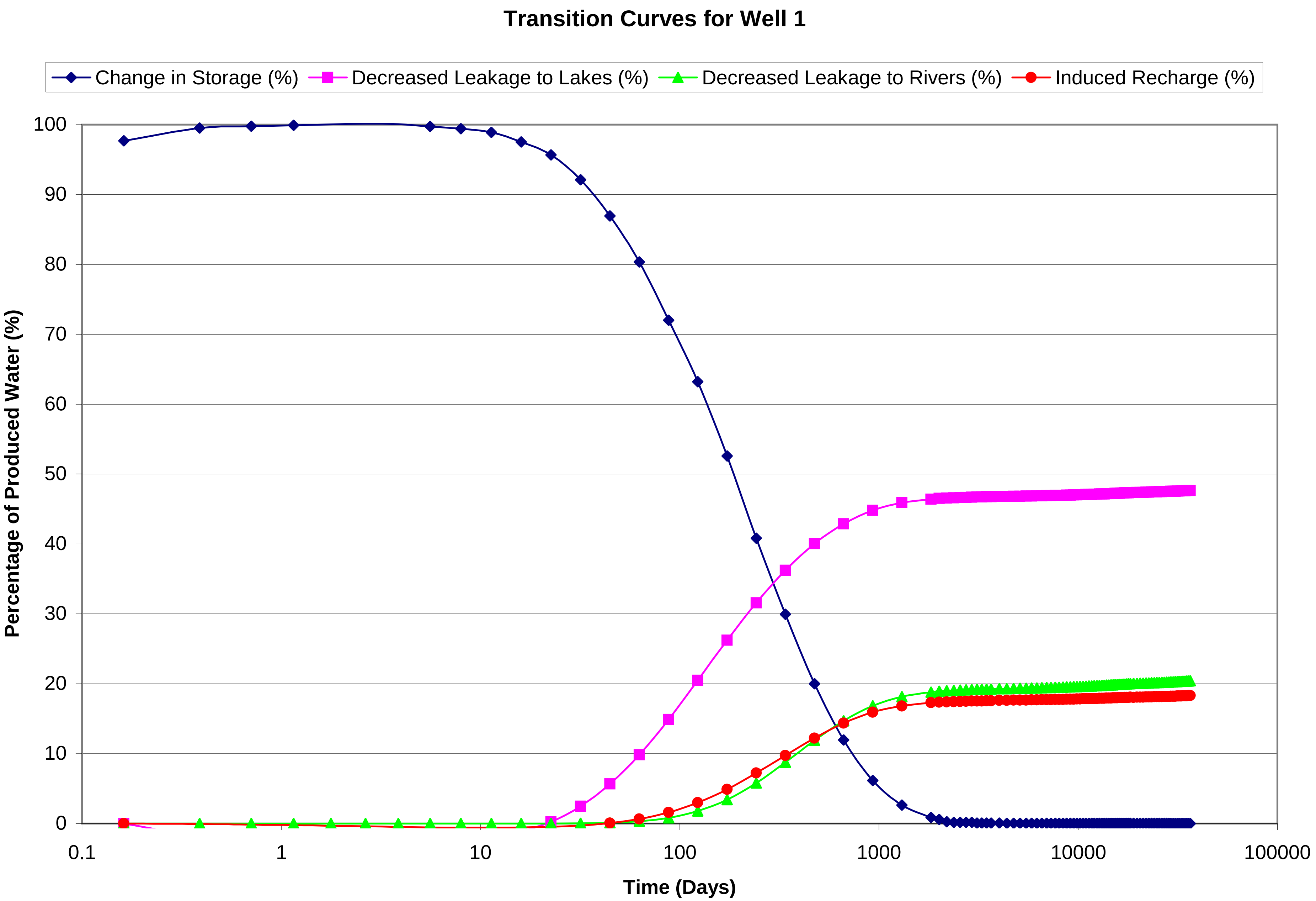
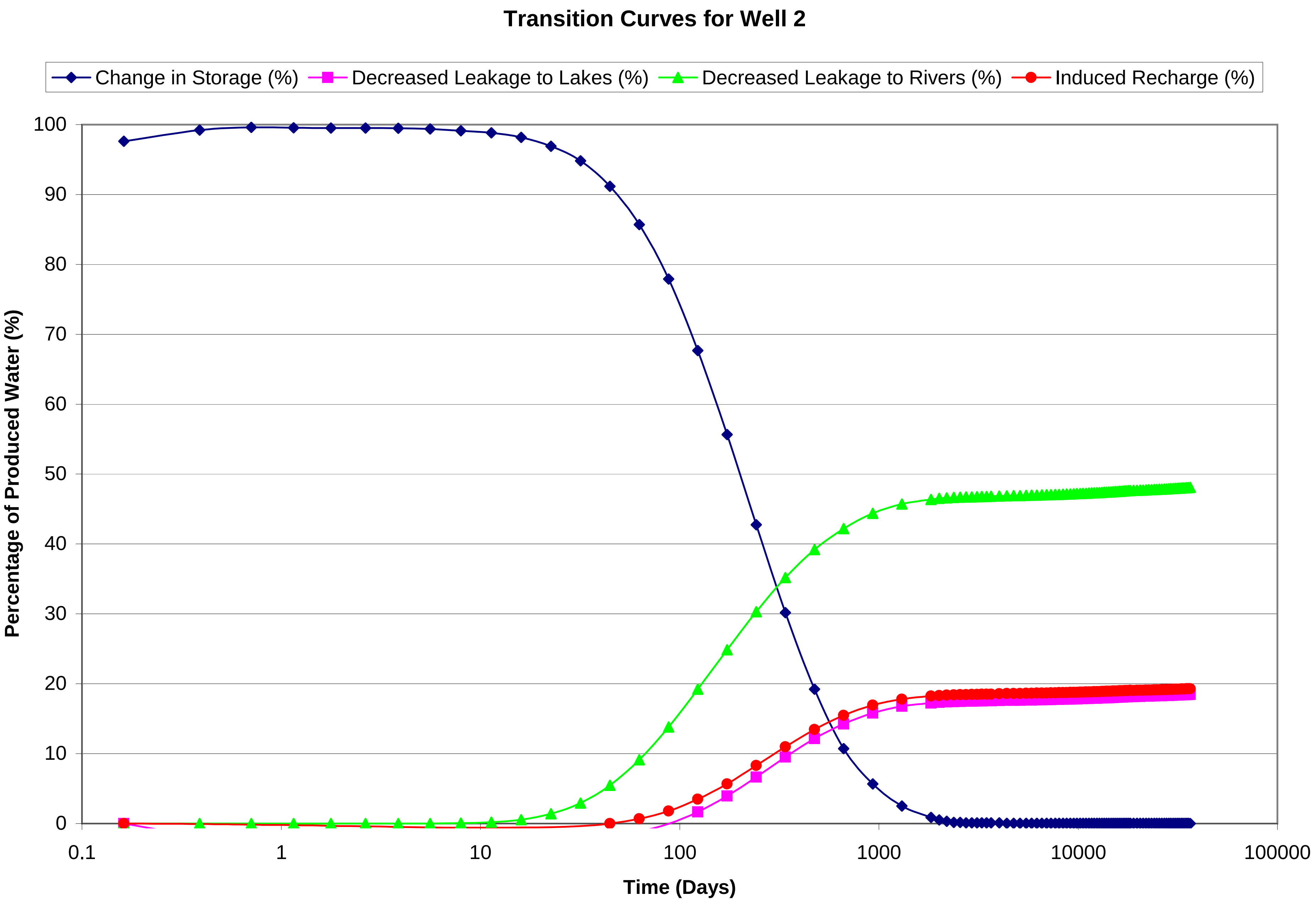
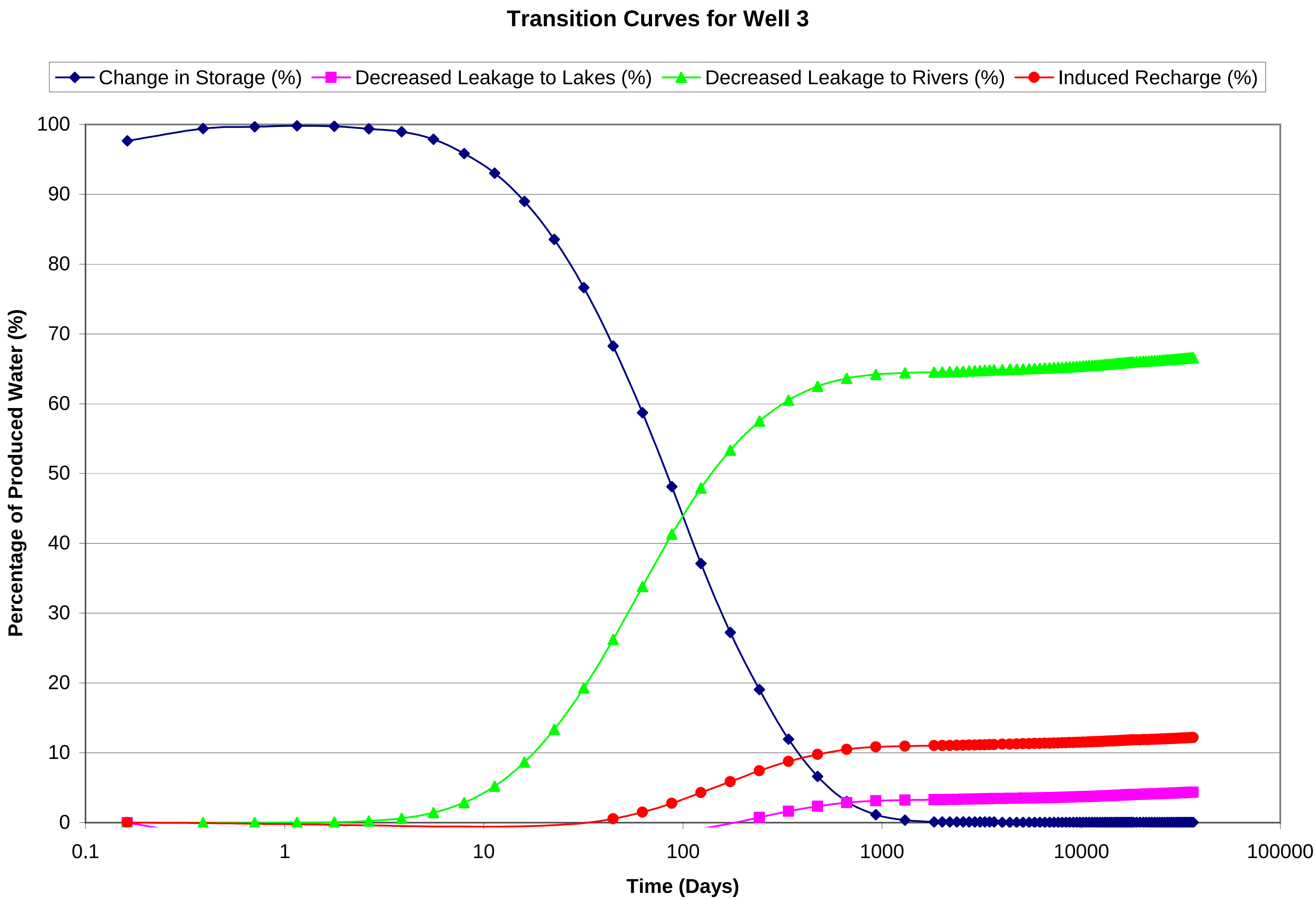
# APPENDIX A
# TRANSITION CURVES

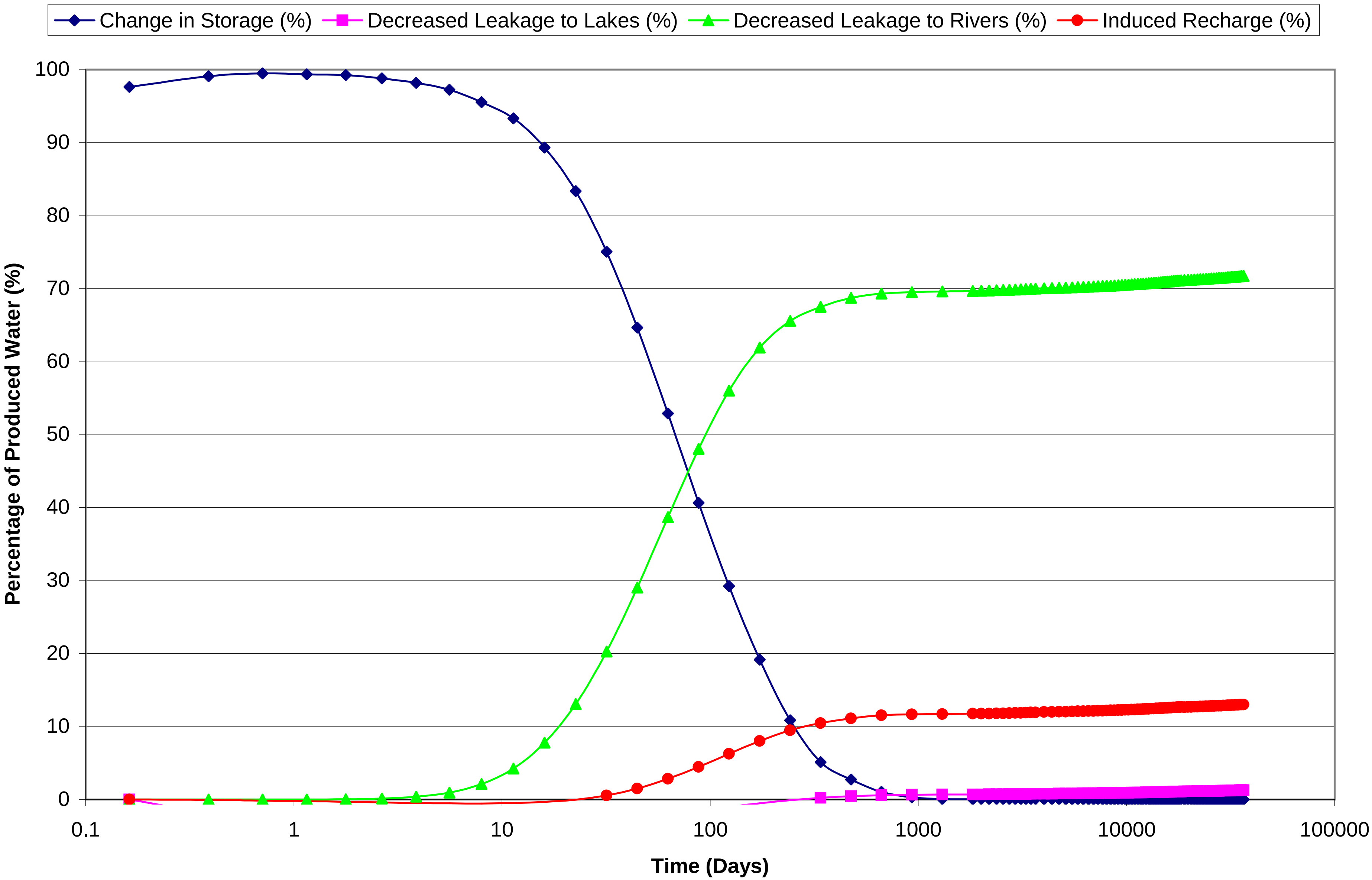

Transition Curves for Well 1
Change in Storage (%)
Decreased Leakage to Lakes (%)
Decreased Leakage to Rivers (%)
Induced Recharge (%)
Percentage of Produced Water (%)
100
90
80
70
60
50
40
30
20
10
0
0.1
1
10
100
1000
10000
100000
Time (Days)



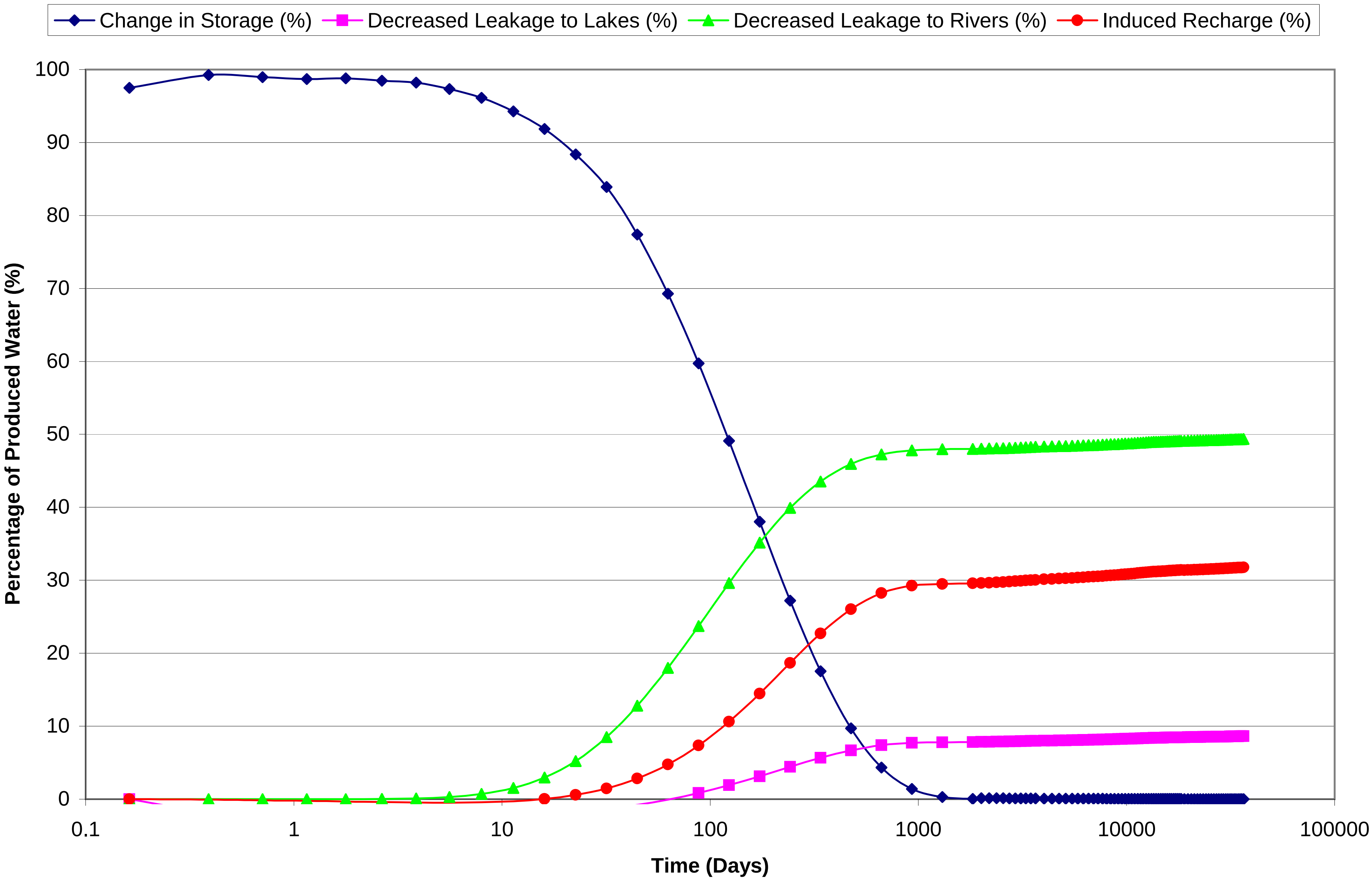
Transition Curves for Well 2
Change in Storage (%)
Decreased Leakage to Lakes (%)
Decreased Leakage to Rivers (%)
Induced Recharge (%)
Percentage of Produced Water (%)
100
90
80
70
60
50
40
30
20
10
0
0.1
1
10
100
1000
10000
100000
Time (Days)

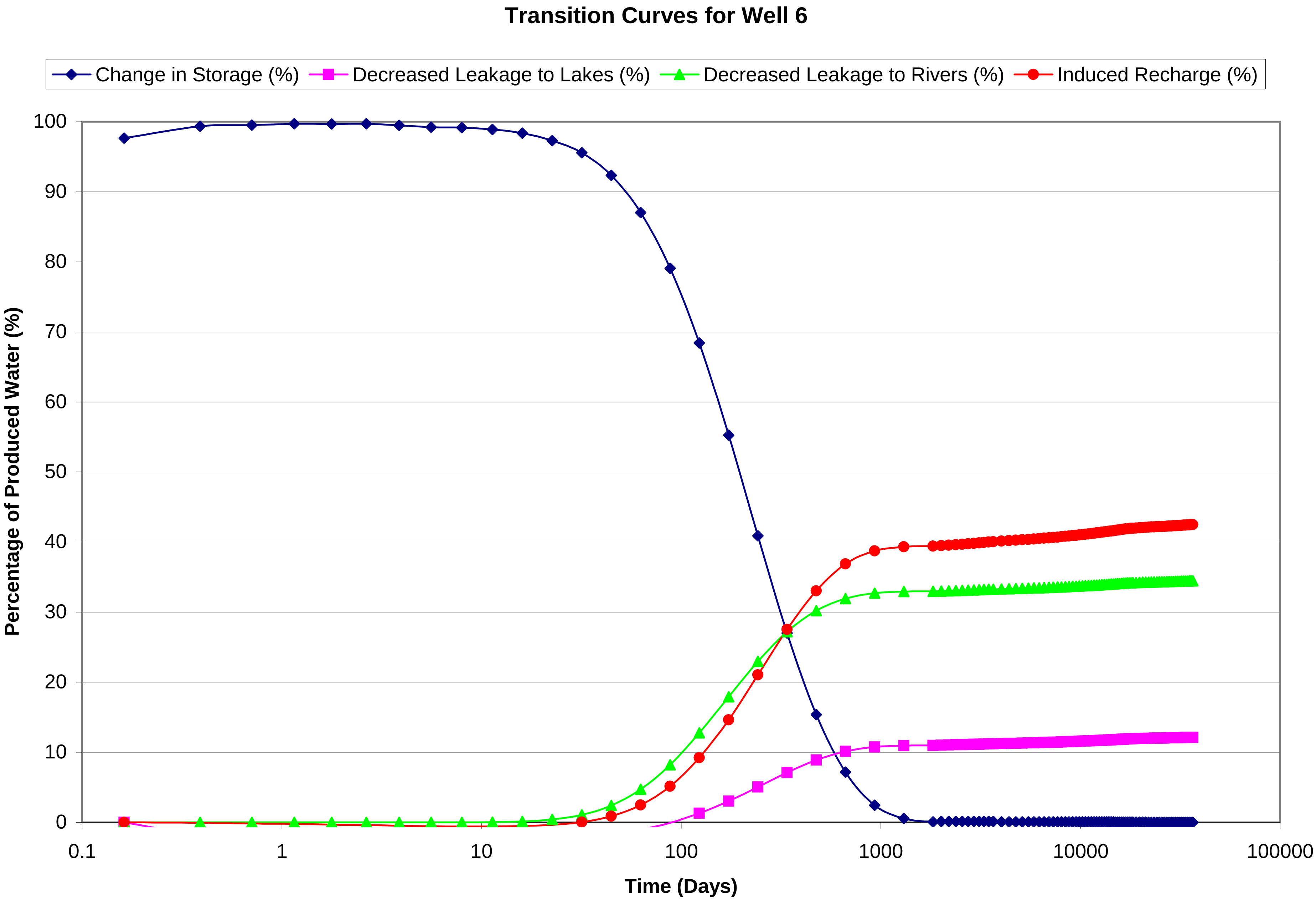

Transition Curves for Well 3
Change in Storage (%)
Decreased Leakage to Lakes (%)
Decreased Leakage to Rivers (%)
Induced Recharge (%)
Percentage of Produced Water (%)
Time (Days)
100
90
80
70
60
50
40
30
20
10
0
0.1
1
10
100
1000
10000
100000

## Transition Curves for Well 4

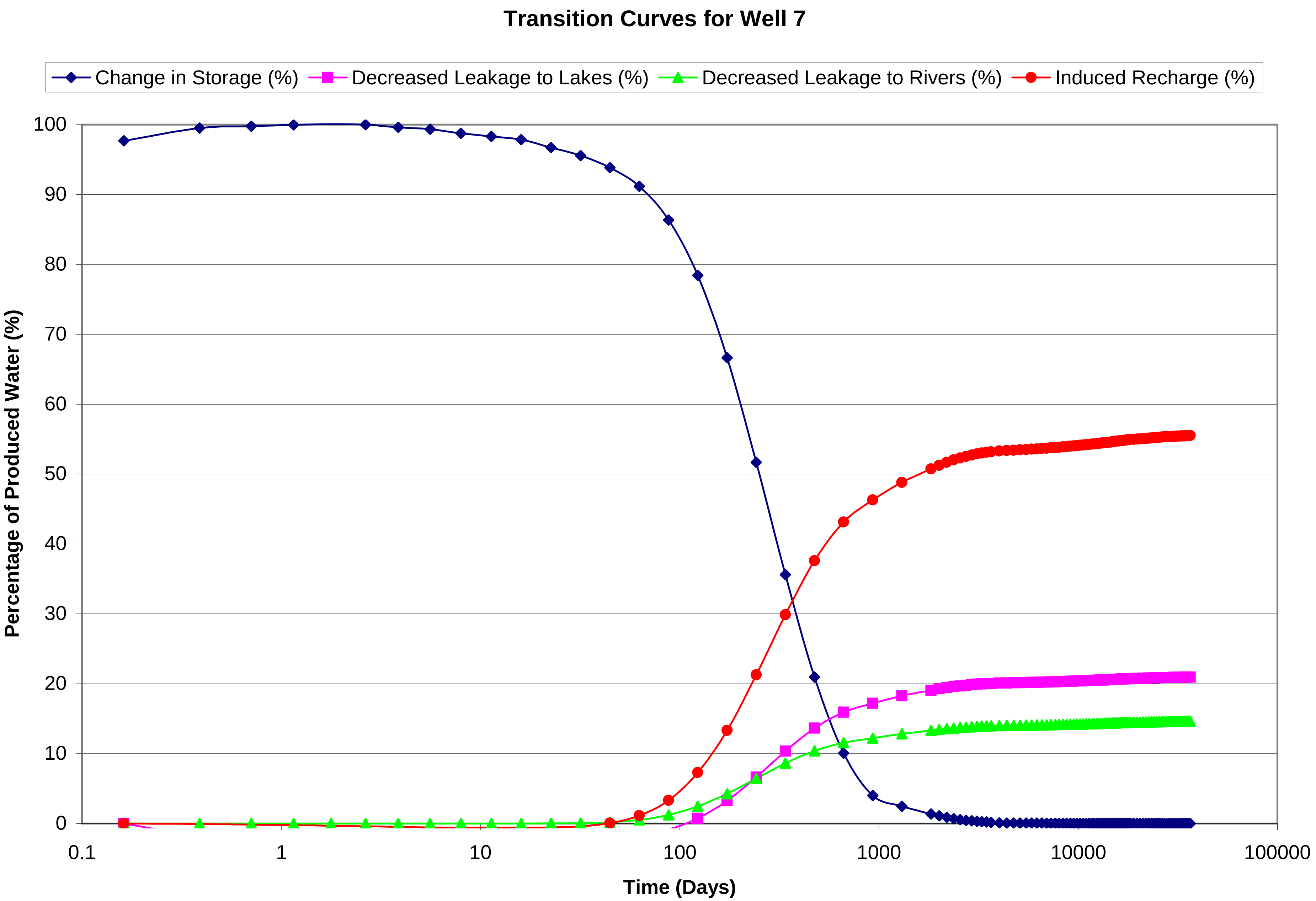


# Transition Curves for Well 5

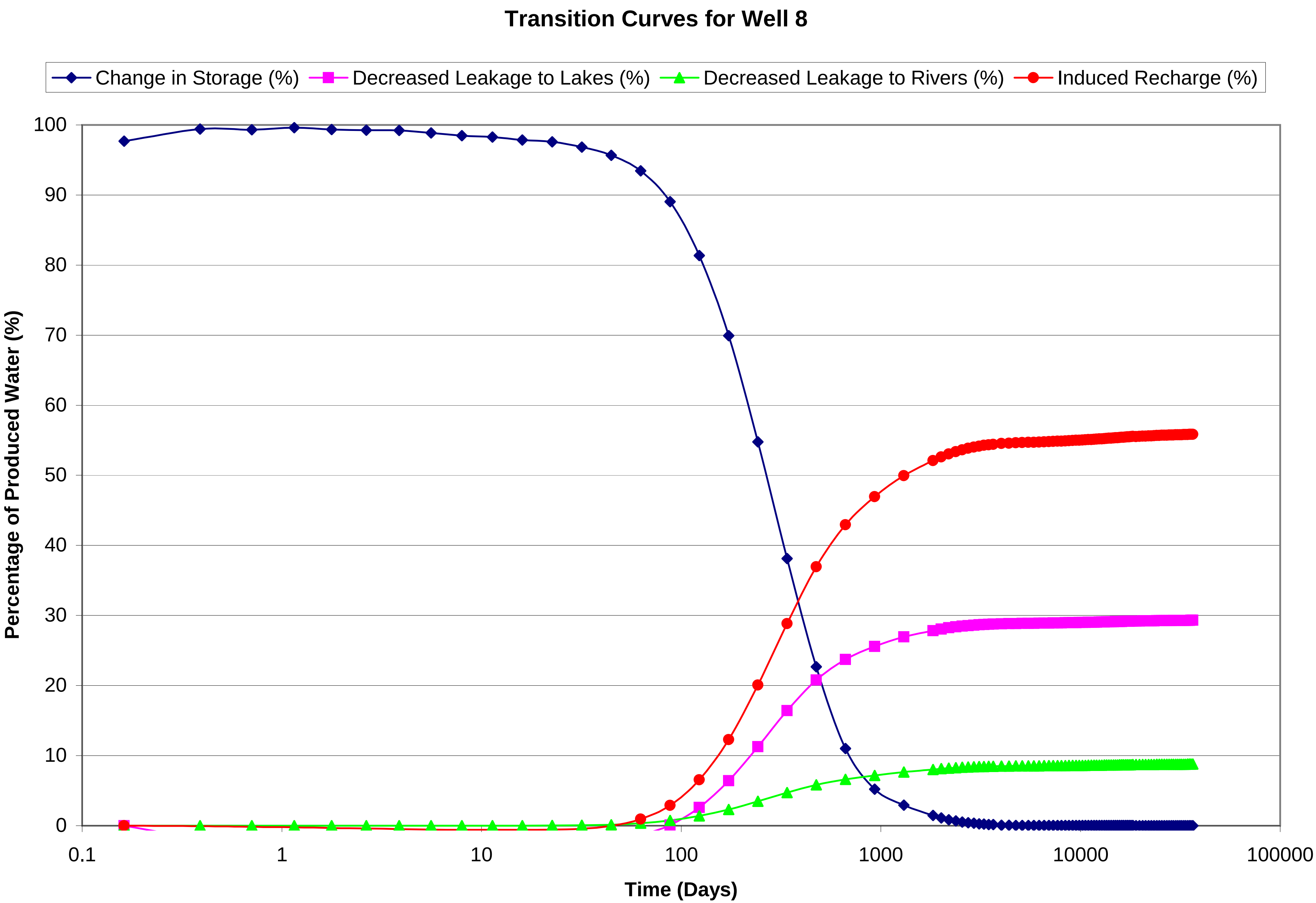




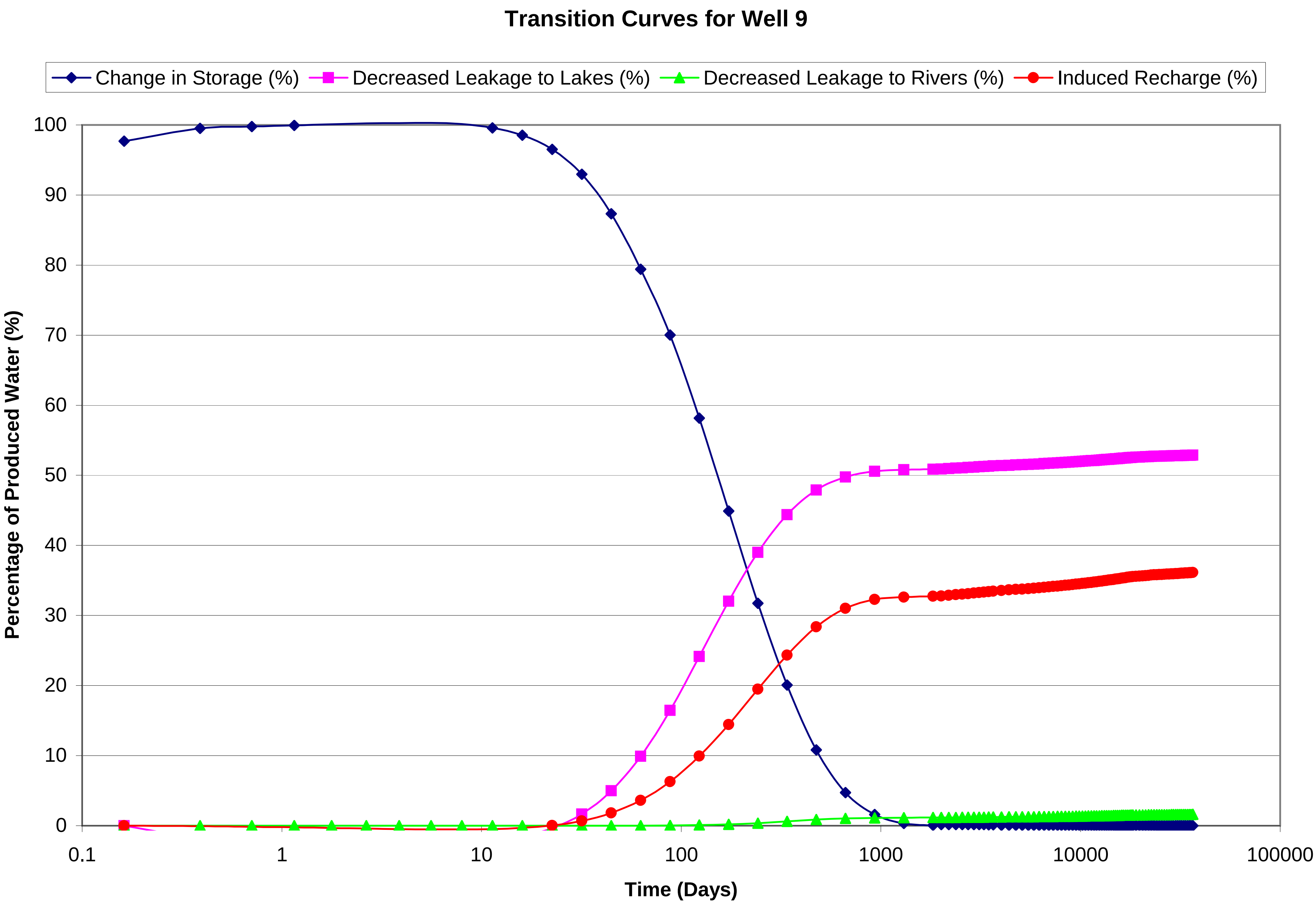
Transition Curves for Well 6
Change in Storage (%)
Decreased Leakage to Lakes (%)
Decreased Leakage to Rivers (%)
Induced Recharge (%)
Percentage of Produced Water (%)
100
90
80
70
60
50
40
30
20
10
0
0.1
1
10
100
1000
10000
100000
Time (Days)



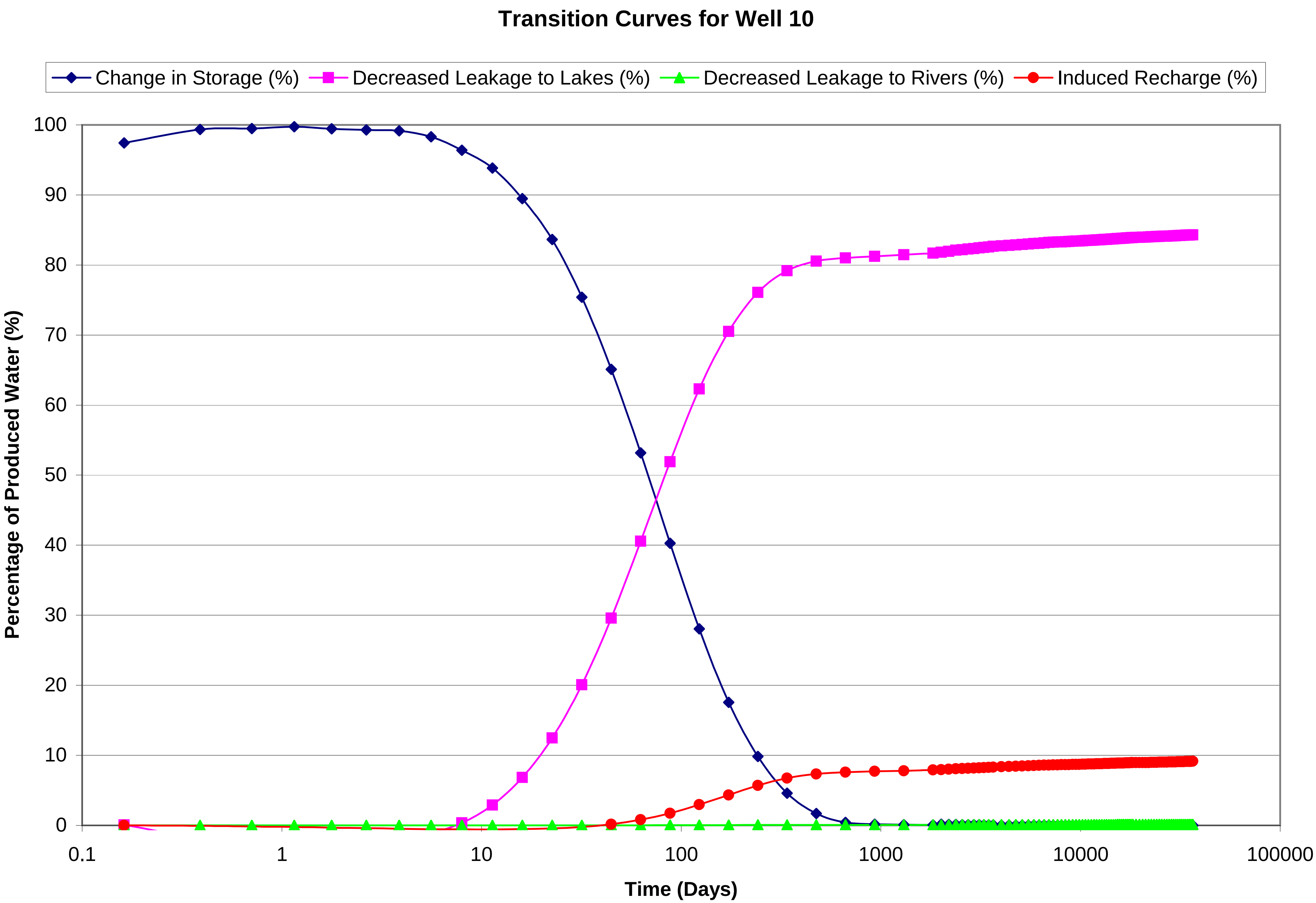
Transition Curves for Well 7
Change in Storage (%)
Decreased Leakage to Lakes (%)
Decreased Leakage to Rivers (%)
Induced Recharge (%)
Percentage of Produced Water (%)
0
10
20
30
40
50
60
70
80
90
100
0.1
1
10
100
1000
10000
100000
Time (Days)



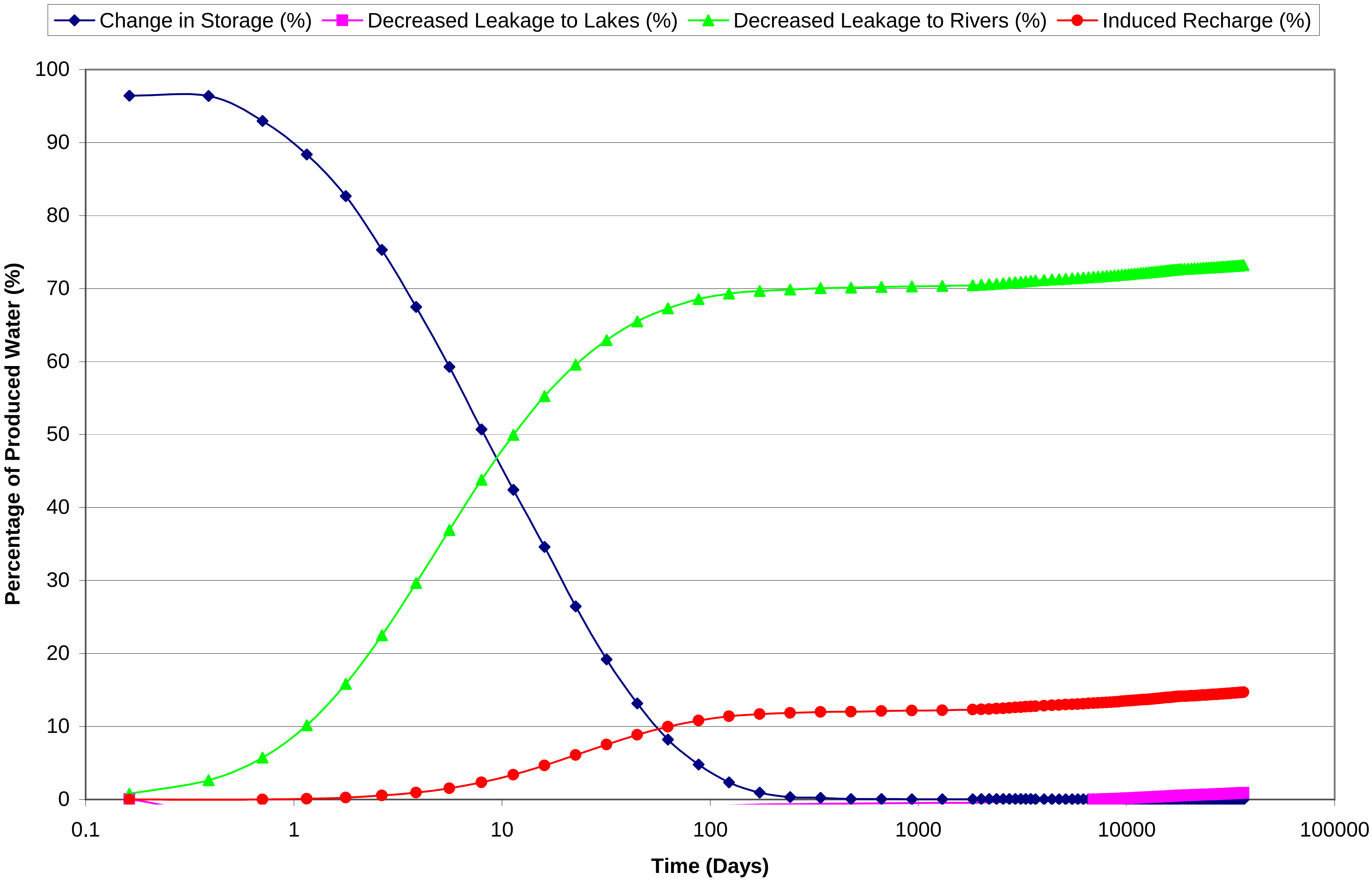
Transition Curves for Well 8
Change in Storage (%)
Decreased Leakage to Lakes (%)
Decreased Leakage to Rivers (%)
Induced Recharge (%)
Percentage of Produced Water (%)
100
90
80
70
60
50
40
30
20
10
0
0.1
1
10
100
1000
10000
100000
Time (Days)

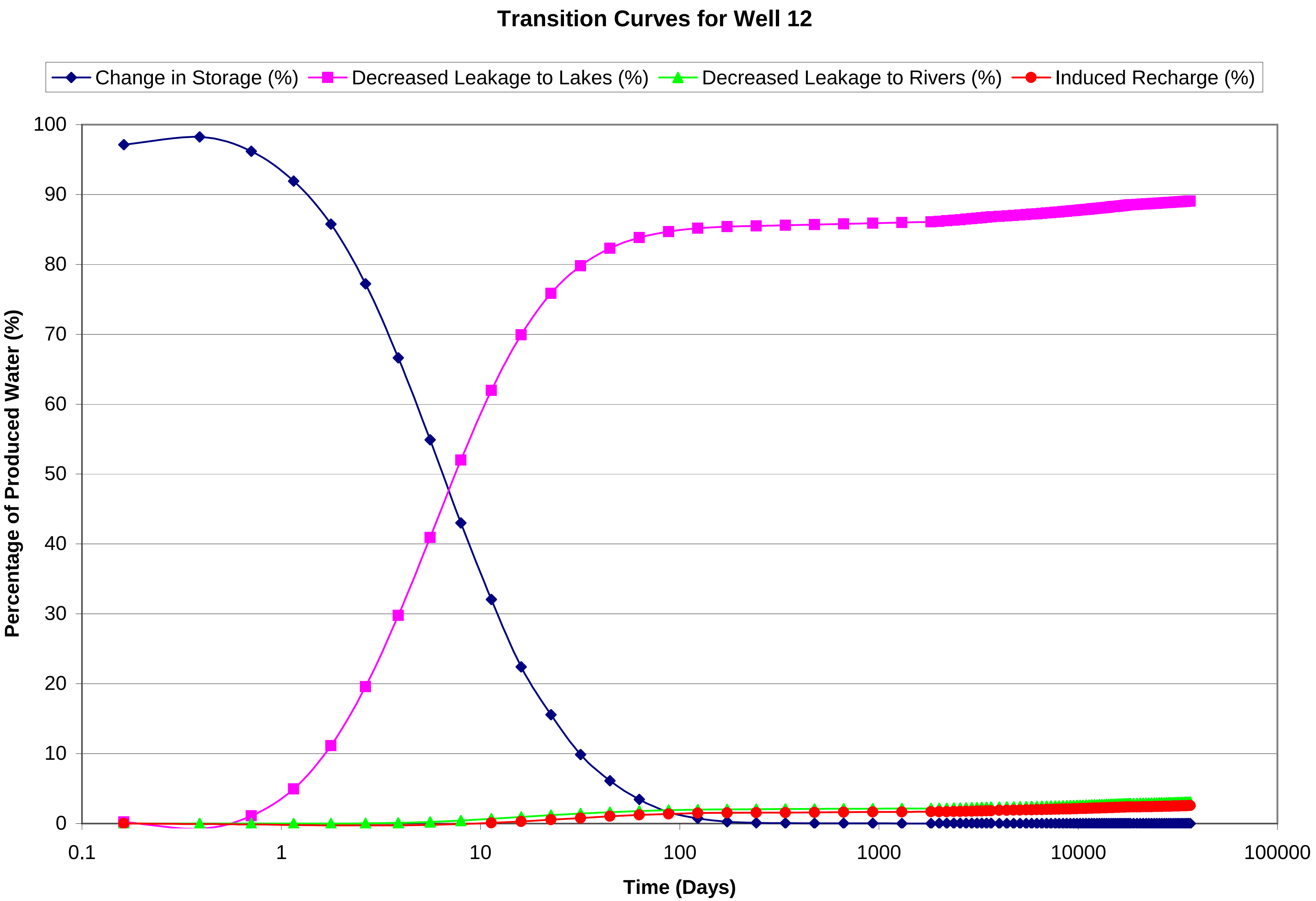


Transition Curves for Well 9
Change in Storage (%)
Decreased Leakage to Lakes (%)
Decreased Leakage to Rivers (%)
Induced Recharge (%)
Percentage of Produced Water (%)
100
90
80
70
60
50
40
30
20
10
0
0.1
1
10
100
1000
10000
100000
Time (Days)

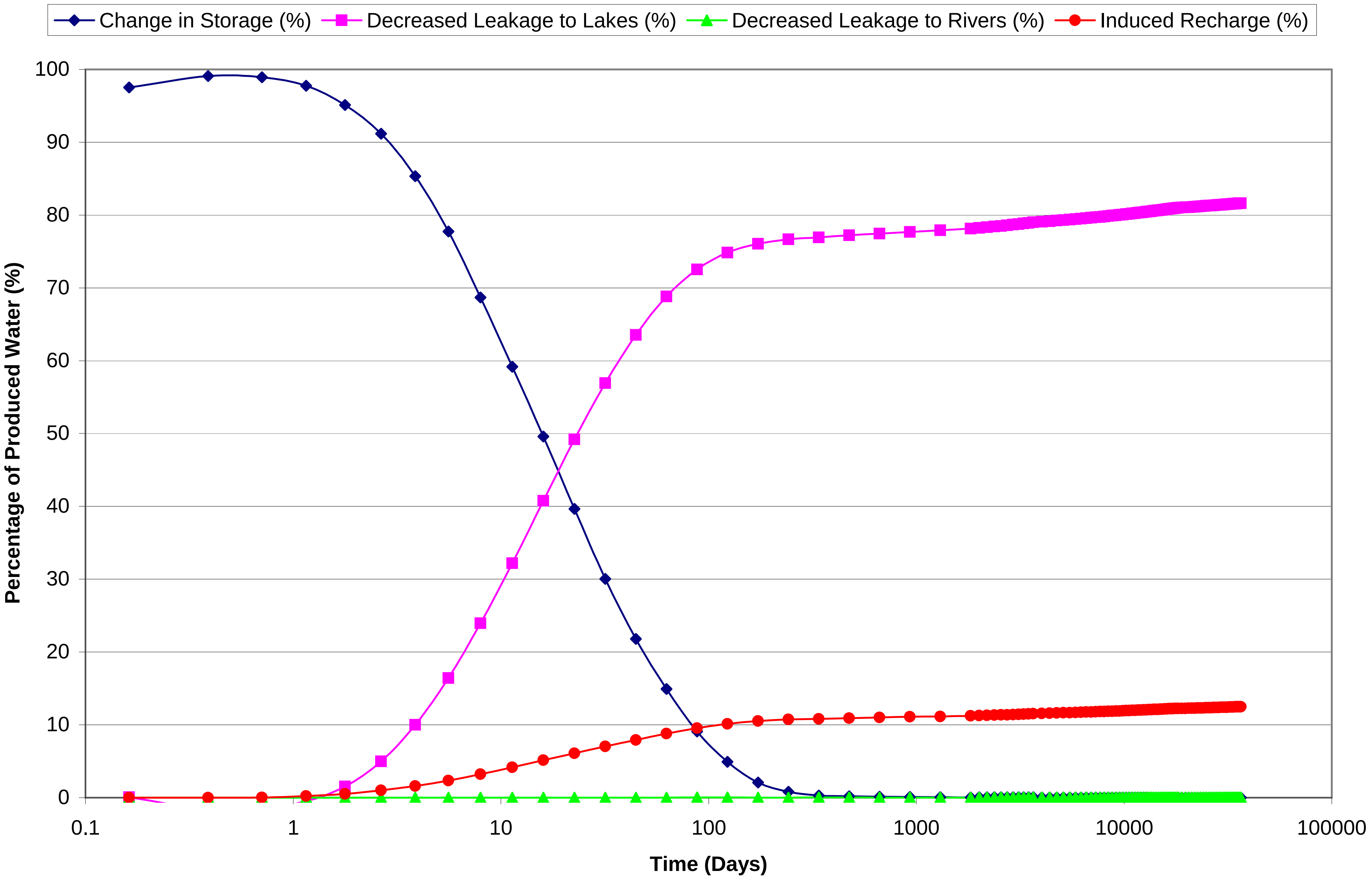

Transition Curves for Well 10
Change in Storage (%)
Decreased Leakage to Lakes (%)
Decreased Leakage to Rivers (%)
Induced Recharge (%)
Percentage of Produced Water (%)
100
90
80
70
60
50
40
30
20
10
0
0.1
1
10
100
1000
10000
100000
Time (Days)

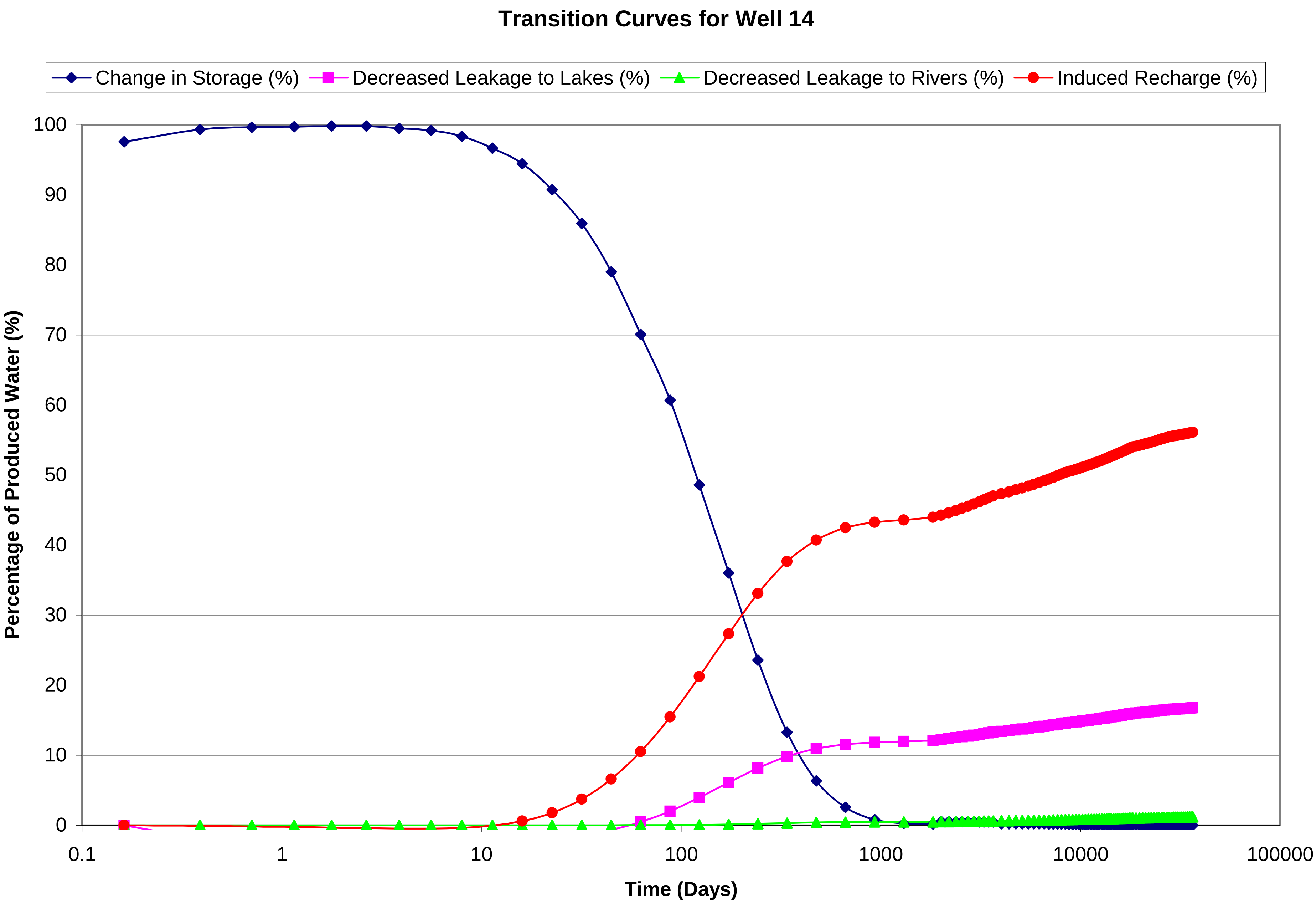
# Transition Curves for Well 11

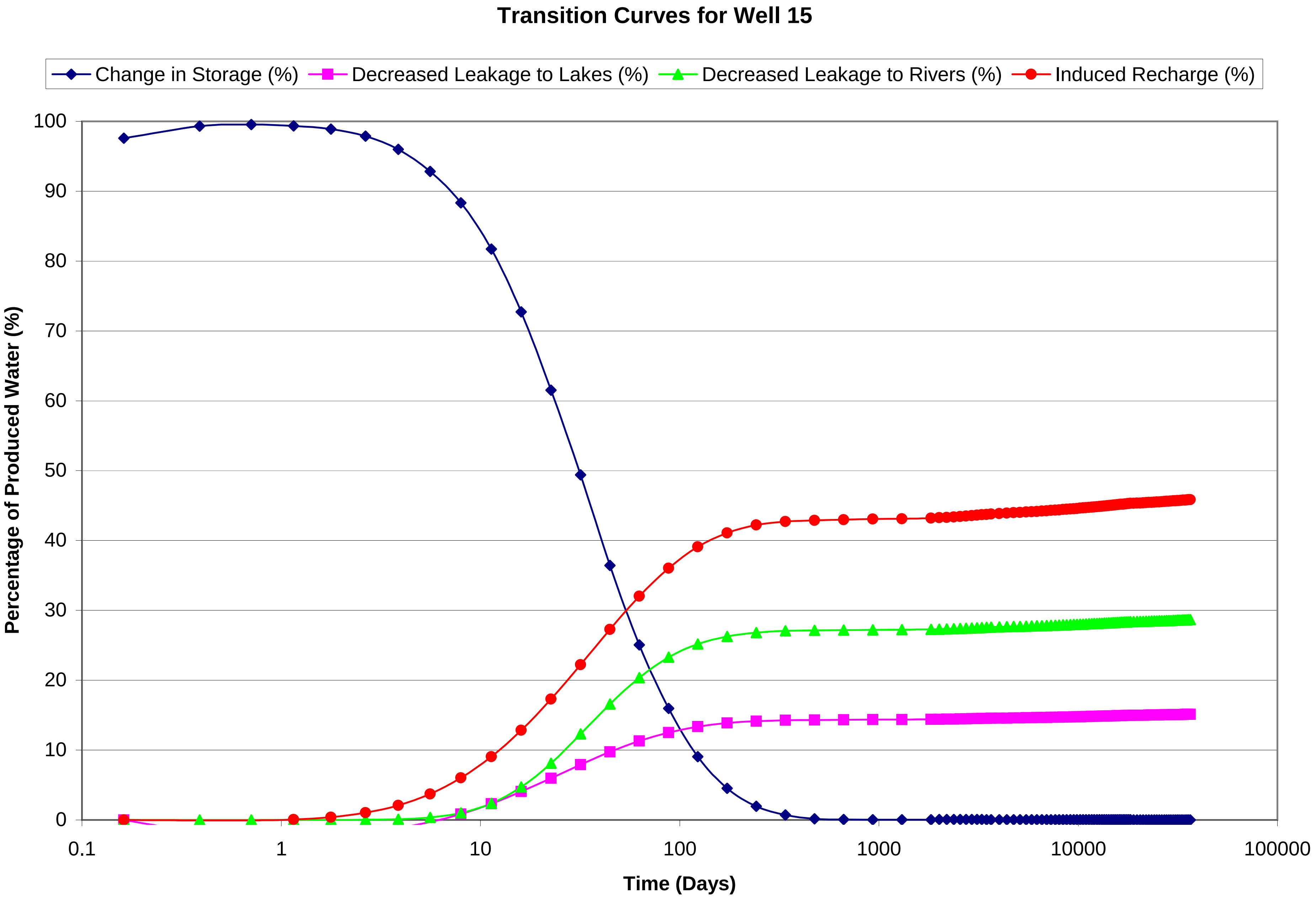



Transition Curves for Well 12
Change in Storage (%)
Decreased Leakage to Lakes (%)
Decreased Leakage to Rivers (%)
Induced Recharge (%)
Percentage of Produced Water (%)
0
10
20
30
40
50
60
70
80
90
100
0.1
1
10
100
1000
10000
100000
Time (Days)

Transition Curves for Well 13

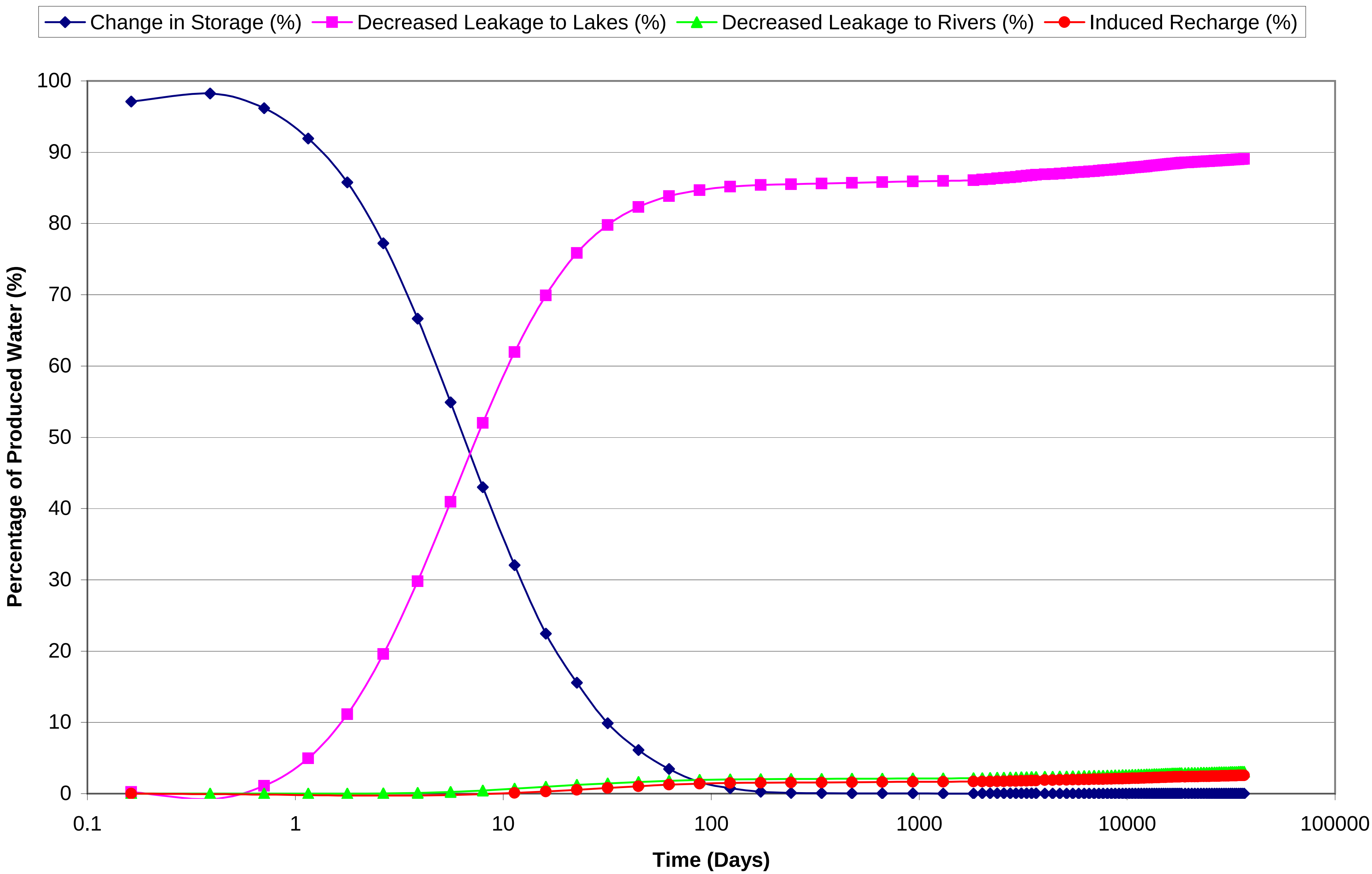


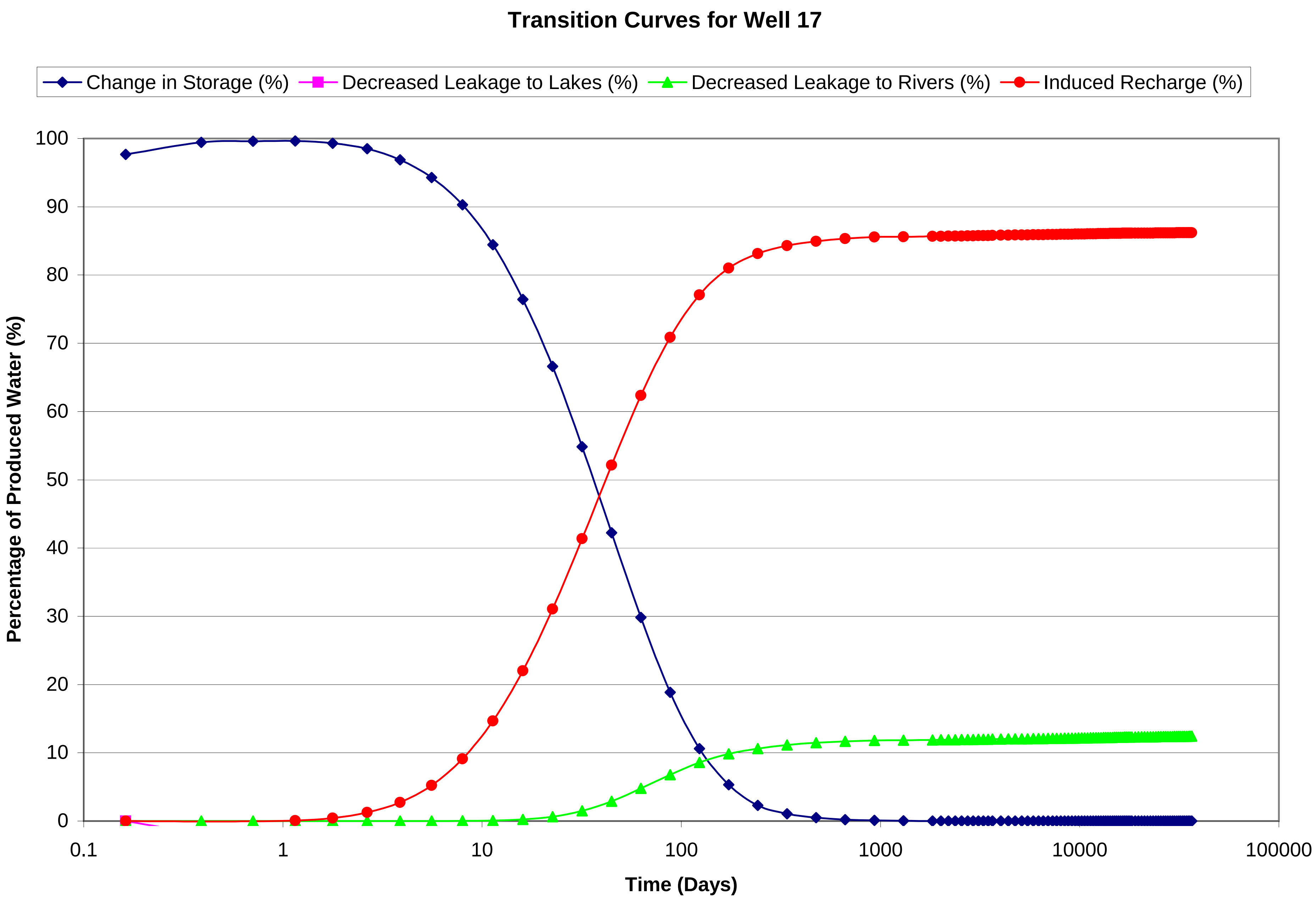

Transition Curves for Well 14
Change in Storage (%)
Decreased Leakage to Lakes (%)
Decreased Leakage to Rivers (%)
Induced Recharge (%)
Percentage of Produced Water (%)
100
90
80
70
60
50
40
30
20
10
0
0.1
1
10
100
1000
10000
100000
Time (Days)

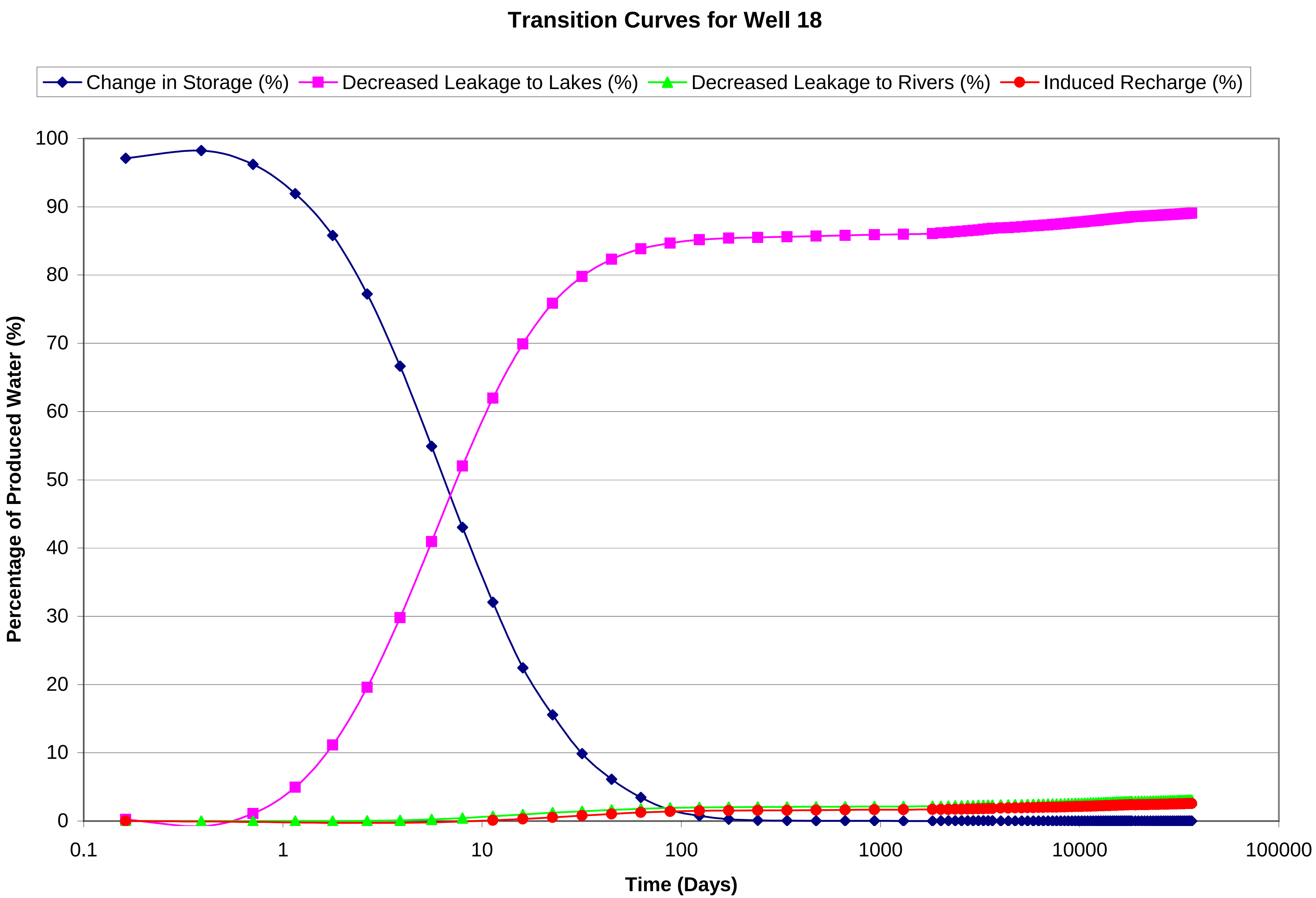


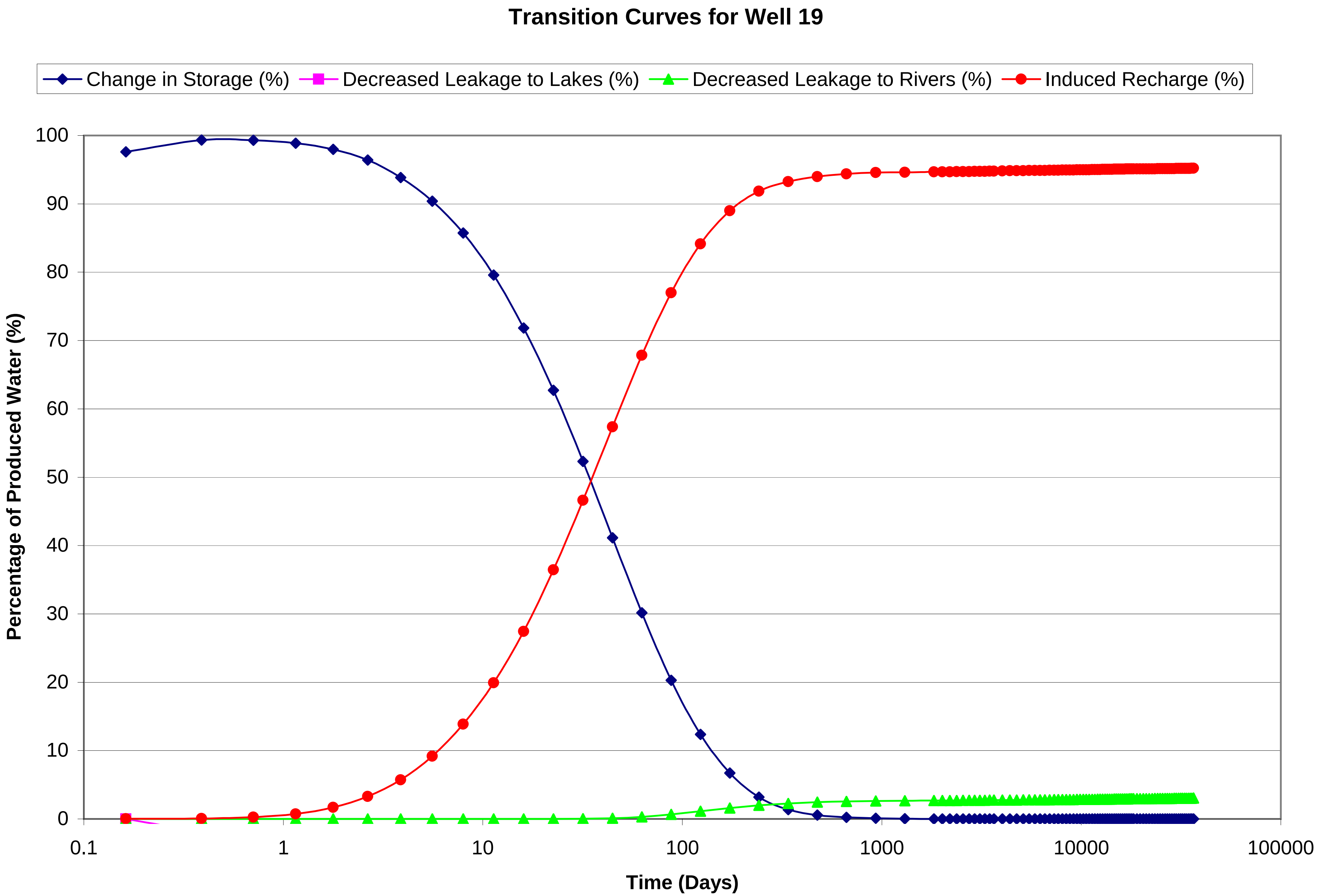
Transition Curves for Well 15
Change in Storage (%)
Decreased Leakage to Lakes (%)
Decreased Leakage to Rivers (%)
Induced Recharge (%)
Percentage of Produced Water (%)
100
90
80
70
60
50
40
30
20
10
0
0.1
1
10
100
1000
10000
100000
Time (Days)

## Transition Curves for Well 16

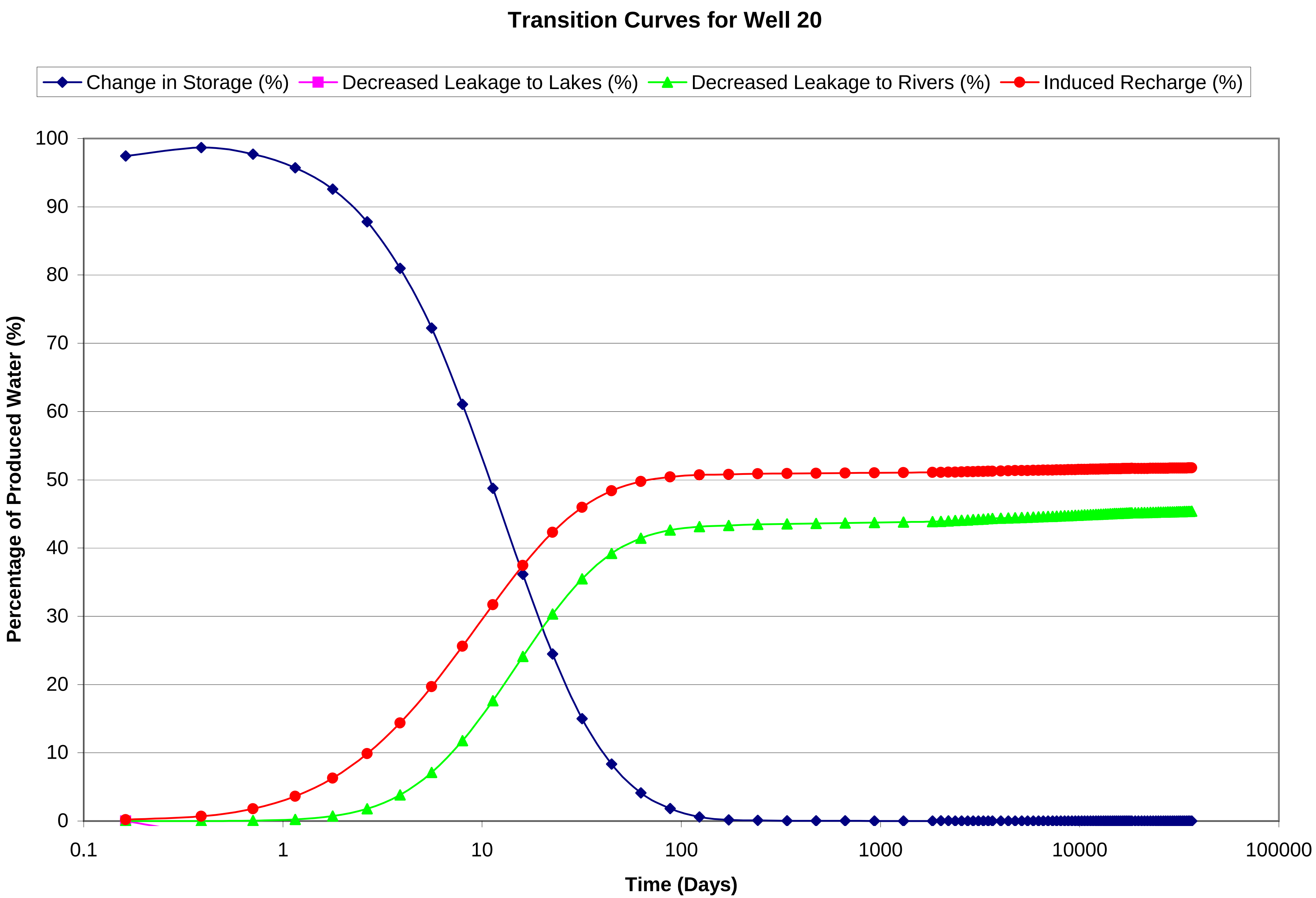


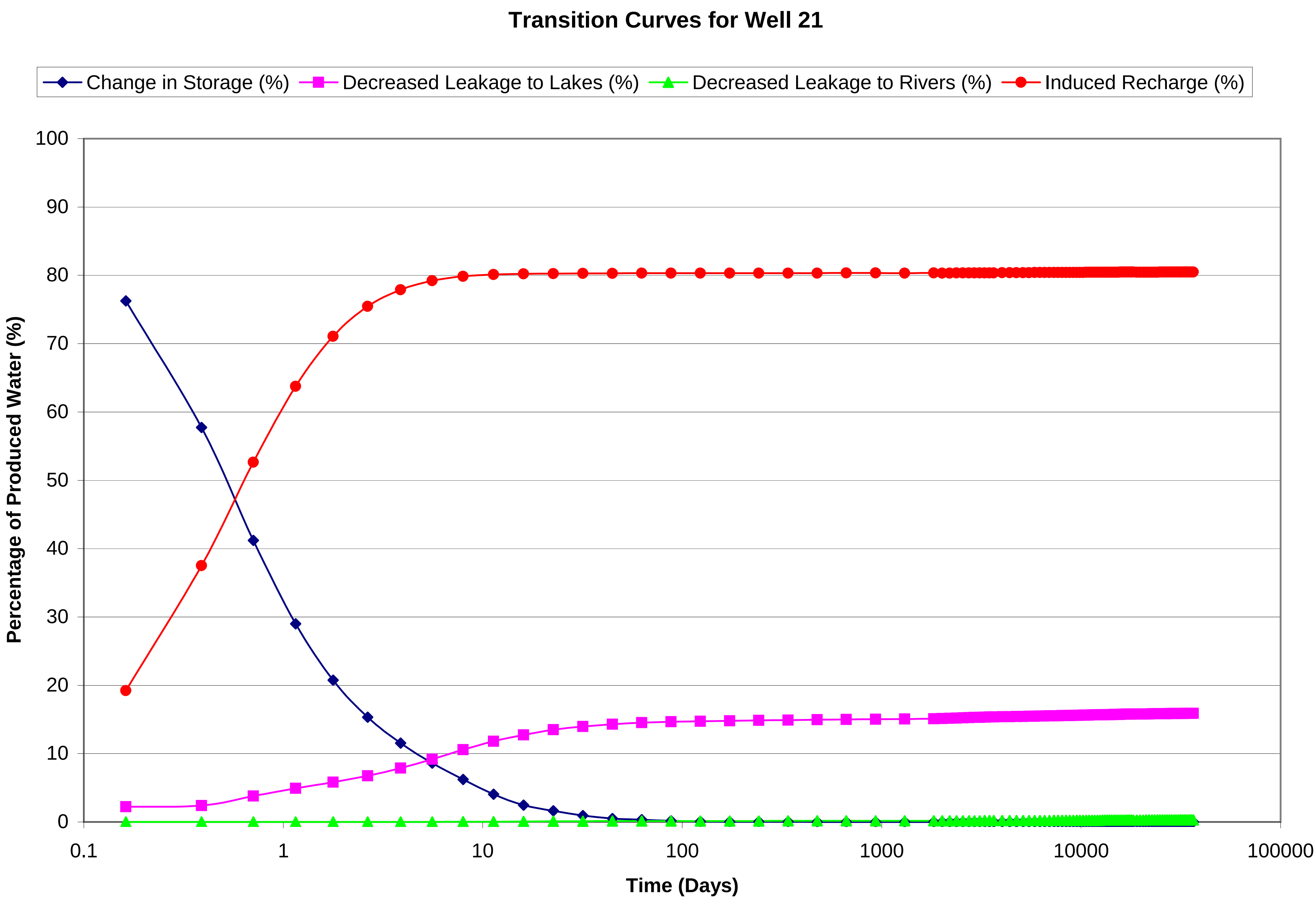

Transition Curves for Well 17
Change in Storage (%)
Decreased Leakage to Lakes (%)
Decreased Leakage to Rivers (%)
Induced Recharge (%)
Percentage of Produced Water (%)
100
90
80
70
60
50
40
30
20
10
0
0.1
1
10
100
1000
10000
100000
Time (Days)

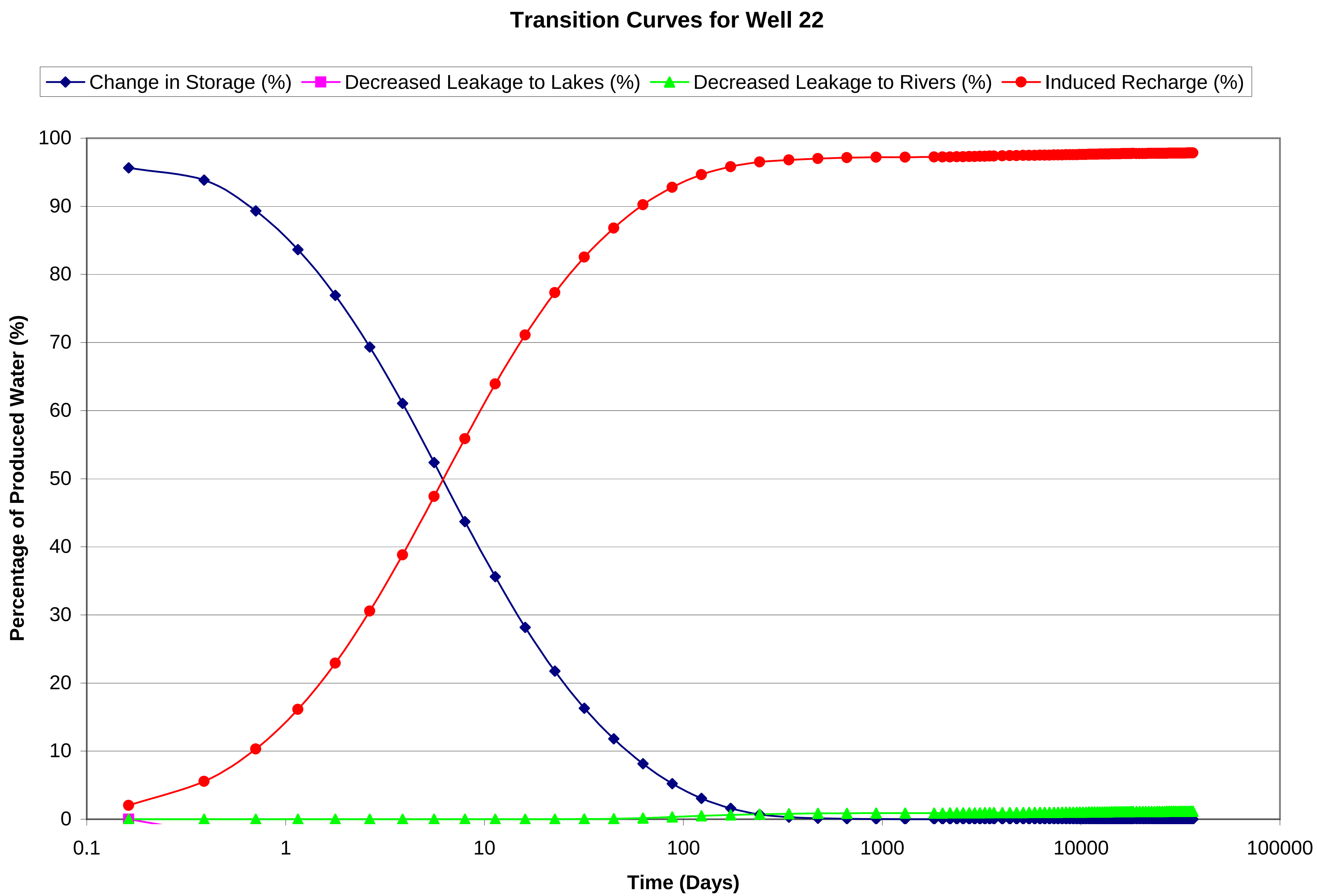

Transition Curves for Well 18
Change in Storage (%)
Decreased Leakage to Lakes (%)
Decreased Leakage to Rivers (%)
Induced Recharge (%)
Percentage of Produced Water (%)
100
90
80
70
60
50
40
30
20
10
0
0.1
1
10
100
1000
10000
100000
Time (Days)



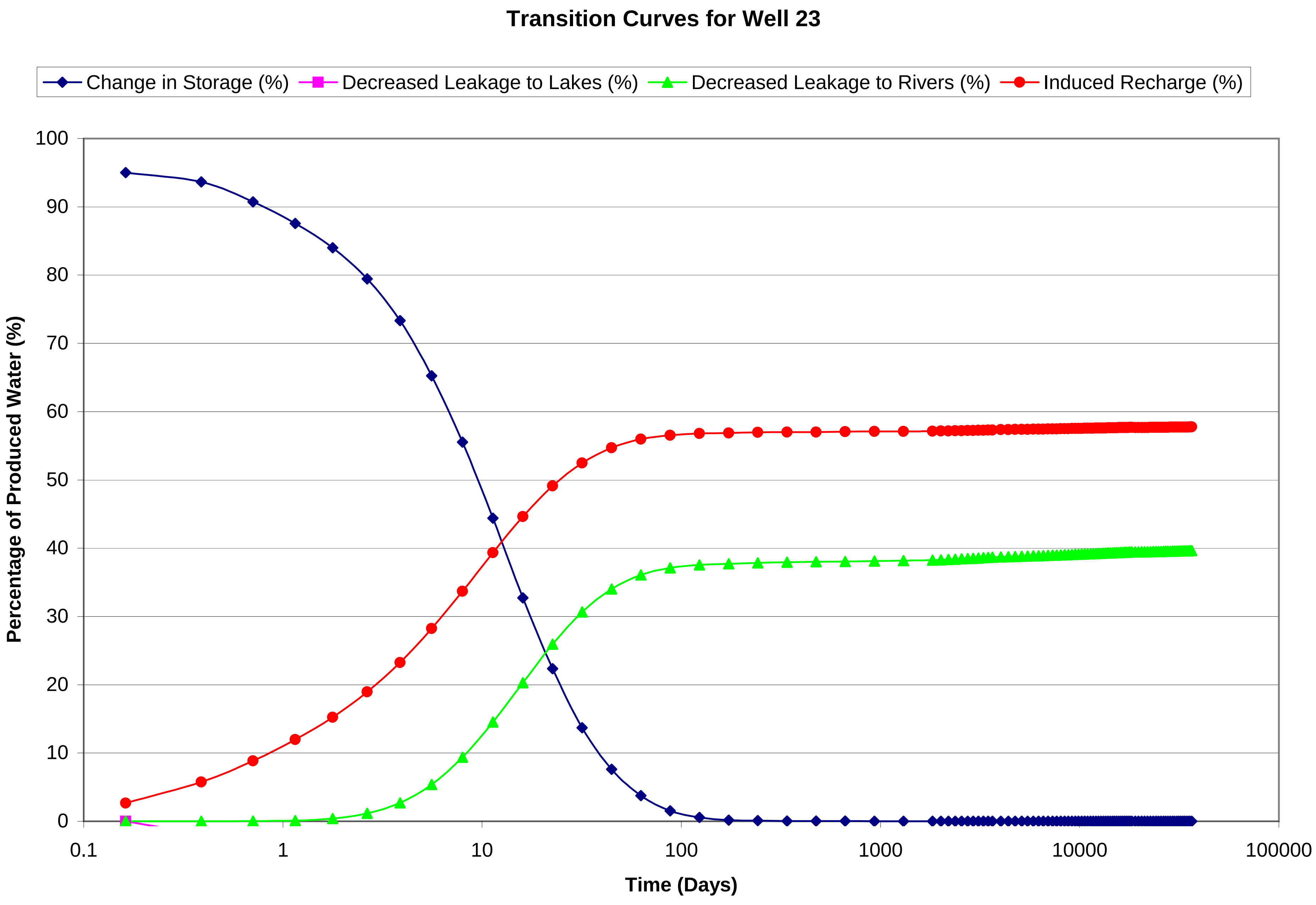
Transition Curves for Well 19
Change in Storage (%)
Decreased Leakage to Lakes (%)
Decreased Leakage to Rivers (%)
Induced Recharge (%)
Percentage of Produced Water (%)
0
10
20
30
40
50
60
70
80
90
100
0.1
1
10
100
1000
10000
100000
Time (Days)


Transition Curves for Well 20
Change in Storage (%)
Decreased Leakage to Lakes (%)
Decreased Leakage to Rivers (%)
Induced Recharge (%)
Percentage of Produced Water (%)
100
90
80
70
60
50
40
30
20
10
0
0.1
1
10
100
1000
10000
100000
Time (Days)


Transition Curves for Well 21
Change in Storage (%)
Decreased Leakage to Lakes (%)
Decreased Leakage to Rivers (%)
Induced Recharge (%)
Percentage of Produced Water (%)
100
90
80
70
60
50
40
30
20
10
0
0.1
1
10
100
1000
10000
100000
Time (Days)



Transition Curves for Well 22
Change in Storage (%)
Decreased Leakage to Lakes (%)
Decreased Leakage to Rivers (%)
Induced Recharge (%)
Percentage of Produced Water (%)
0
10
20
30
40
50
60
70
80
90
100
0.1
1
10
100
1000
10000
100000
Time (Days)


Transition Curves for Well 23
Change in Storage (%)
Decreased Leakage to Lakes (%)
Decreased Leakage to Rivers (%)
Induced Recharge (%)
Percentage of Produced Water (%)
100
90
80
70
60
50
40
30
20
10
0
0.1
1
10
100
1000
10000
100000
Time (Days)