PRELIMINARY EVALUATION OF GEOCHEMICAL AND HYDRODYNAMIC EFFECTS OF DEEP INJECTION OF RESIDUAL WATER AT THE AOSTRA UNDERGROUND TEST FACILITY

Prepared For
Conservation and Protection, Environment Canada

by

Stefan Bachu
J.R. Underschultz

and

E.H. Perkins

ALBERTA GEOLOGICAL SURVEY
EDMONTON, ALBERTA, CANADA

Open File Report 1996-15

1993-03-01

DISCLAIMER

This report was prepared as an account of work sponsored by the Alberta Research Council and Environment Canada, Conservation and Protection. Every possible effort was made to ensure that the work conforms to accepted scientific practice. However, neither the Alberta Research Council (ARC), nor any of its employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favouring by the ARC. The views and opinions of the authors expressed herein do not necessarily state or reflect those of the ARC.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

EXECUTIVE SUMMARY

This report presents the results of a preliminary evaluation of the geochemical and hydrodynamic effects of deep injection of residual water at the Underground Test Facility (UTF) being expanded by the Alberta Oil Sands Technology and Research Authority (AOSTRA) to a pilot operation. AOSTRA is proposing to inject over a period of two years up to 900,000 m^3 of produced, blowdown and regeneration water into the thin Cretaceous Wabiskaw sands, until a long term disposal solution is found. Environment Canada and the Alberta Research Council initiated in 1990 a collaborative study on the hydrogeological effects of deep injection of residual water at the UTF site, with data support and cooperation from AOSTRA. As part of this effort, the baseline hydrogeological and geochemical conditions at the site were previously identified and described starting from the regional scale and zooming-in to the local UTF scale. Numerical modelling of the geochemical and hydrodynamic processes related to the deep injection of residual water were used in the present study to analyze the effects of injection and the suitability for disposal of all the aquifers in the sedimentary succession at the UTF site.

The results of the analysis confirm that the Wabiskaw aquifer is the only suitable one capable of accepting the proposed injection volumes. All the Devonian aquifers (Winnipegosis, Slave Point, Calumet and Moberly) have low porosity and permeability. These aquifers also have a relatively high potential for formation plugging by precipitation

of silica, dolomite and calcite. Mineral precipitation resulting from geochemical reactions between the injected water and the formation water and rocks will lead to a further decrease in porosity and permeability. Because of the low permeability of rocks in these aquifers, the pressure will increase rapidly, probably reaching the fracturing threshold in several weeks. The regulations for deep disposal of residual water require that the injection pressure be less than 90% of the fracturing pressure, thus excluding these aquifers as potential host zones for the projected volumes. The only available Cretaceous aquifer, the Wabiskaw, has very high porosity and permeability. The numerical simulations indicate that the pressure induced by injection will diffuse rapidly, with the effect that the pressure buildup will most probably remain at all times below the fracturing threshold. The radius of influence (pressure buildup) is estimated to be approximately 4000 m from the injection well at the end of the disposal operation. Geochemically, the Wabiskaw aquifer has the lowest potential and probable rates of mineral precipitation. It is expected that any mineral precipitation will occur far from the injection well and will not significantly alter the porosity and permeability of the Wabiskaw aquifer.

INTRODUCTION

The environmentally safe and economically affordable management of produced water from enhanced oil recovery (EOR) plants is fundamental to their economic success. Once the fresh water needs of these plants exceed 500,000 m^3/yr, the Energy Resources Conservation Board (ERCB) regulations require the implementation of a produced-water recycling scheme. Pilot-scale in-situ operations are small producers of heavy oil or bitumen, their primary purpose being to test a specific technology for hydrocarbon production. However, these operations can produce significant volumes of fluids. Because of the small size and demonstration level of the pilot plants, the cost of implementing a water recycling scheme is generally prohibitive. In such cases, deep well injection generally provides the most cost effective, technically feasible and environmentally safe option for the disposal of produced water and has been the preferred method by the oil industry (Sadler, 1991). Currently, nearly 90% of oil-field waste and residual waters in Alberta are disposed of by deep injection (CPA, 1990).

The Alberta Oil Sands Technology and Research Authority (AOSTRA) has been developing an Underground Test Facility (UTF) near Fort McMurray in Alberta (Figure 1), for the extraction of bitumen from the near-surface Athabasca oil sand deposits using a steam-assisted gravity drainage (SAGD) recovery process. The concept and technology proved to be successful and the facility is currently being expanded to pilot stage, with plans to go commercial in a few years. Over an initial period of two years, AOSTRA

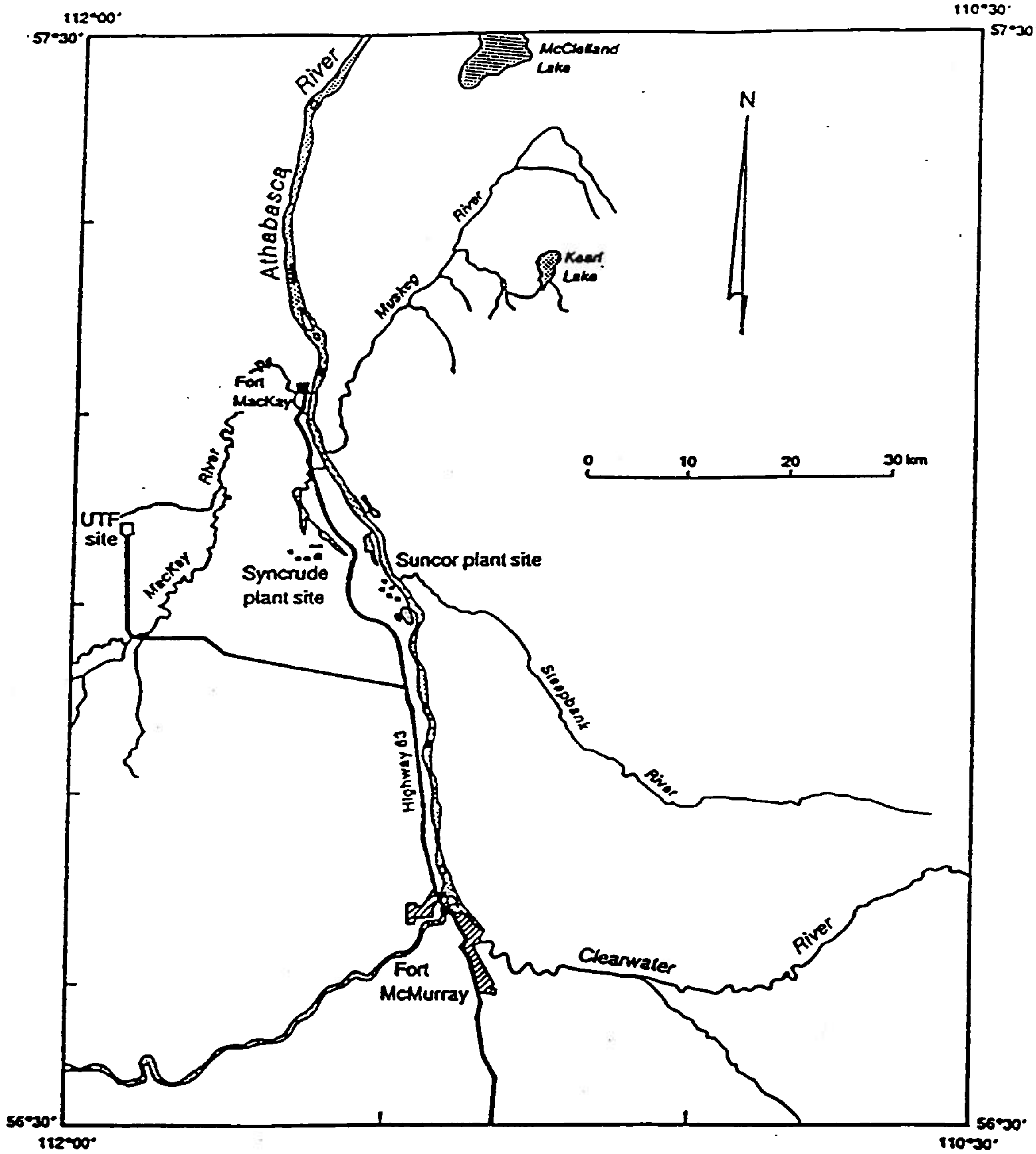


Figure 1. Location map of the UTF site in northeast Alberta.

plans to dispose of 900,000 m^3 of residual water by injecting it into a deep formation. During this time, various water recycling alternatives will be examined. AOSTRA is addressing environmental concerns relating to the issue of deep injection of residual water, satisfying all the requirements imposed by Alberta regulatory agencies (ERCB and Alberta Environment). However, the expansion of the UTF operations provides an opportunity to study and monitor the hydrogeological effects of deep injection of residual water as they develop. This will allow for development of strategies and guidelines applicable to future similar activities. Thus, Environment Canada and the Alberta Research Council initiated a collaborative study regarding the geochemical and hydrodynamic effects of deep injection of residual water at the UTF site, with data support and cooperation from AOSTRA. This report presents preliminary results of this study.

The a priori evaluation of the geochemical and hydrodynamic effects of deep injection of residual water is based on predictive numerical modelling, for which the baseline hydrogeological conditions need to be known. An initial feasibility study (Basin Analysis Group, 1988) identified a general lack of hydrogeological data around the UTF and recommended a "zoom-in" or scaling-down approach to site characterization. Accordingly, the hydrogeological regime was evaluated successively from larger to smaller scales, such that, in absence of data at any given scale, information could be retrieved through interpolation from the respective distributions at the larger scales. A regional-scale hydrogeological study was completed first (Petroleum Geology and Basin Analysis Group, 1991, 1992a) for an area defined by Tp. 70-103, all ranges W4 Mer, covering approximately 76,000 km^2 in northeast Alberta (Figure 2). All the aquifers in the Phanerozoic hydrostratigraphic succession were characterized in terms of distributions of formation water chemistry and hydraulic head, and aquifer porosity and permeability. Subsequently, an intermediate-scale study was performed (Petroleum Geology and Basin Analysis Group, 1992b). Because of different data distributions, two intermediate-scale study areas were defined (Figure 2), one for the Paleozoic strata (Tp. 90-97, R 10-14, W4 Mer) and one for the Cretaceous strata (Tp. 92-95, R 11-14, W4 Mer). These study areas represent respectively the smallest areas with sufficient hydrogeological information for the delineation of Paleozoic and Cretaceous hydrostratigraphy and the analysis of the flow of formation waters in the entire succession. Finally, a local-scale study area, defined by Tp. 92-94, R 12-13, W4 Mer and covering approximately 500 km^2 (Figure 3), was chosen for preliminary modelling of geochemical and hydrodynamic effects of injection. The area was selected to include the Dover and MacKay rivers which form natural hydrogeological boundaries. It is a priori assumed that the effects of injection will not propagate beyond this area, an assumption which has to be verified a posteriori. Based on available lithostratigraphic and well data, the hydrostratigraphy and petrophysical characterization of the Cretaceous strata in the local-scale study area were further refined (Petroleum Geoscience Section, 1993). In addition, three representative aquifers were characterized in terms of their mineralogy, for the study of possible geochemical reactions between the injected water and the formation water and rocks.

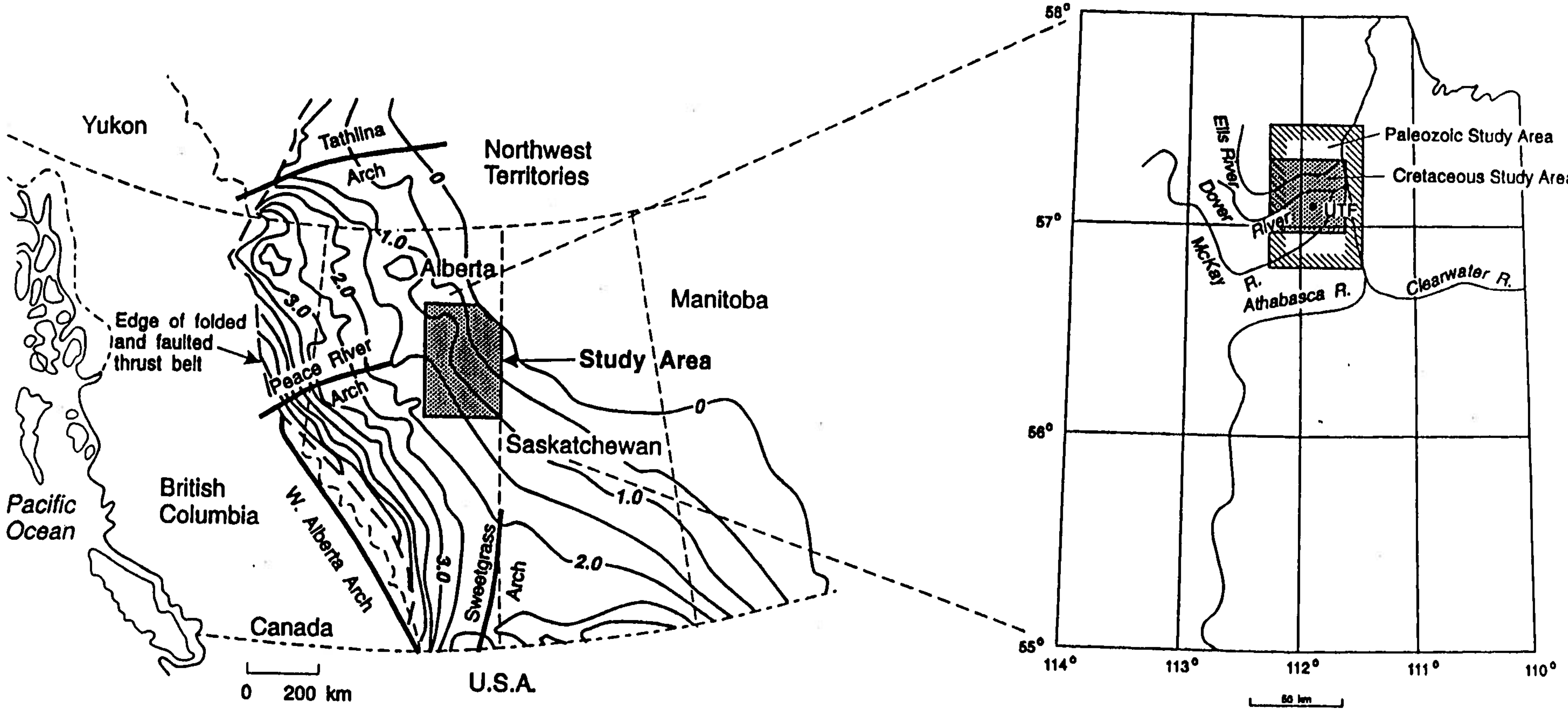


Figure 2. Regional- and intermediate-scale study areas in northeast Alberta around the UTF site.

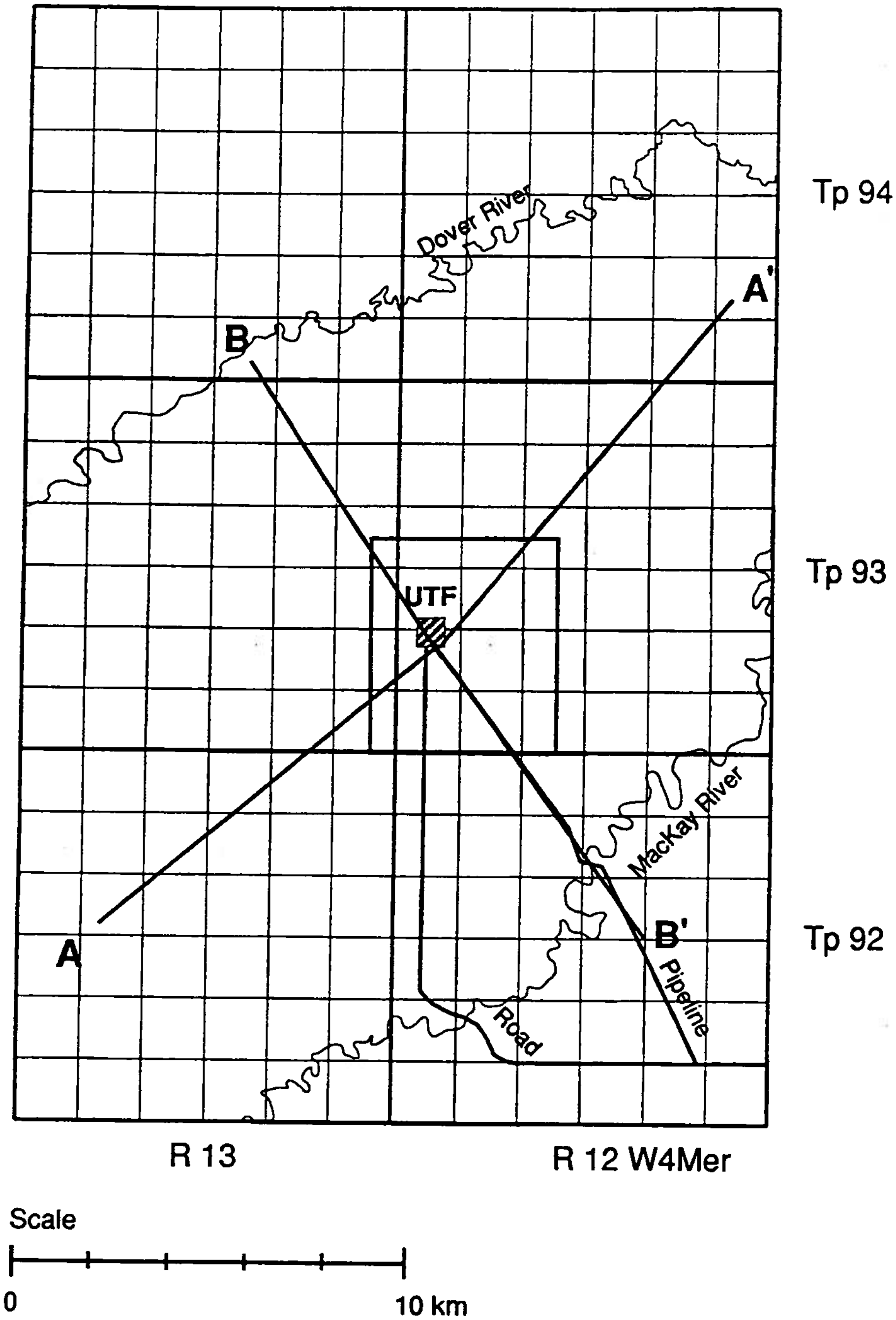


Figure 3. Local-scale study area around the UTF site.

In 1992 AOSTRA made an application to ERCB for approval to dispose of the UTF residual water in the Wabiskaw Formation based on an in-house evaluation (AOSTRA, 1992). Although recognizing AOSTRA's decision as valid, the present preliminary study of the geochemical and hydrodynamic effects of deep disposal of residual water at the UTF site evaluates in quantitative terms these effects for other theoretically potential injection units, and validates AOSTRA's decision to inject in the Wabiskaw Member. The present study will determine the area of influence of the projected injection operation, in order to validate the assumption that the effects of injection will not spread beyond the confines of the chosen local-scale study area. The intended numerical modelling is limited to well-scale geochemical effects and to local-scale, coarse resolution hydrodynamic effects. Fine resolution modelling of fluid flow and contaminant transport is needed in order to assess fully the hydrogeological effects of injection of residual water at the UTF site.

BASELINE CONDITIONS

GEOLOGY

The sedimentary succession in the local-scale study area around the UTF is broadly divided into Paleozoic passive-margin strata and Cretaceous foreland-basin strata (Table 1), separated by the regionally significant sub-Cretaceous angular unconformity. The Paleozoic strata consist of the Elk Point and Beaverhill Lake groups, with the latter subcropping at the sub-Cretaceous unconformity everywhere throughout the area. Only Lower Cretaceous Mannville Group strata are present, with younger strata being completely removed from the area by erosion. A veneer of Pleistocene-age drift and other sediments of recent geological age, comprised primarily of unconsolidated sands and gravels, covers the bedrock. Several areas of thick drift accumulations are present in the form of valley fill deposits. Figures 4 and 5 present dip and strike stratigraphic cross-sections, respectively.

Paleozoic Succession

The Paleozoic succession consists of Lower to Upper Devonian strata from the Elk Point and Beaverhill Lake groups (Table 1), bounded unconformably at the base by the Precambrian basement and at the top by the sub-Cretaceous unconformity. Overlying the Precambrian basement is the Granite Wash followed by the Lower Elk Point

EON	ERA	Period		Group		Formation
Phanerozoic	Cenozoic	Quaternary Tertiary				Pleistocene deposits
	Mesozoic	Cretaceous	Lower	Mannville		Grand Rapids
						Clearwater
						McMurray
		Jurassic				
		Triassic				
	Paleozoic	Permian				
		Carboniferous				Sub-Cretaceous Unconformity
		Devonian	Upper	Beaverhill Lake		Waterways
						Slave Point
						Fort Vermilion
			Middle	Elk Point	Upper	Watt Mountain
						Prairie
						Winnipegosis (Keg River)
					Lower	Contact Rapids
			Lower			Ernestina
						Granite Wash
		Silurian				
		Ordovician				
		Cambrian				
Pre-cambrian						

Table 1. Stratrigraphic succession and nomenclature at the UTF site.

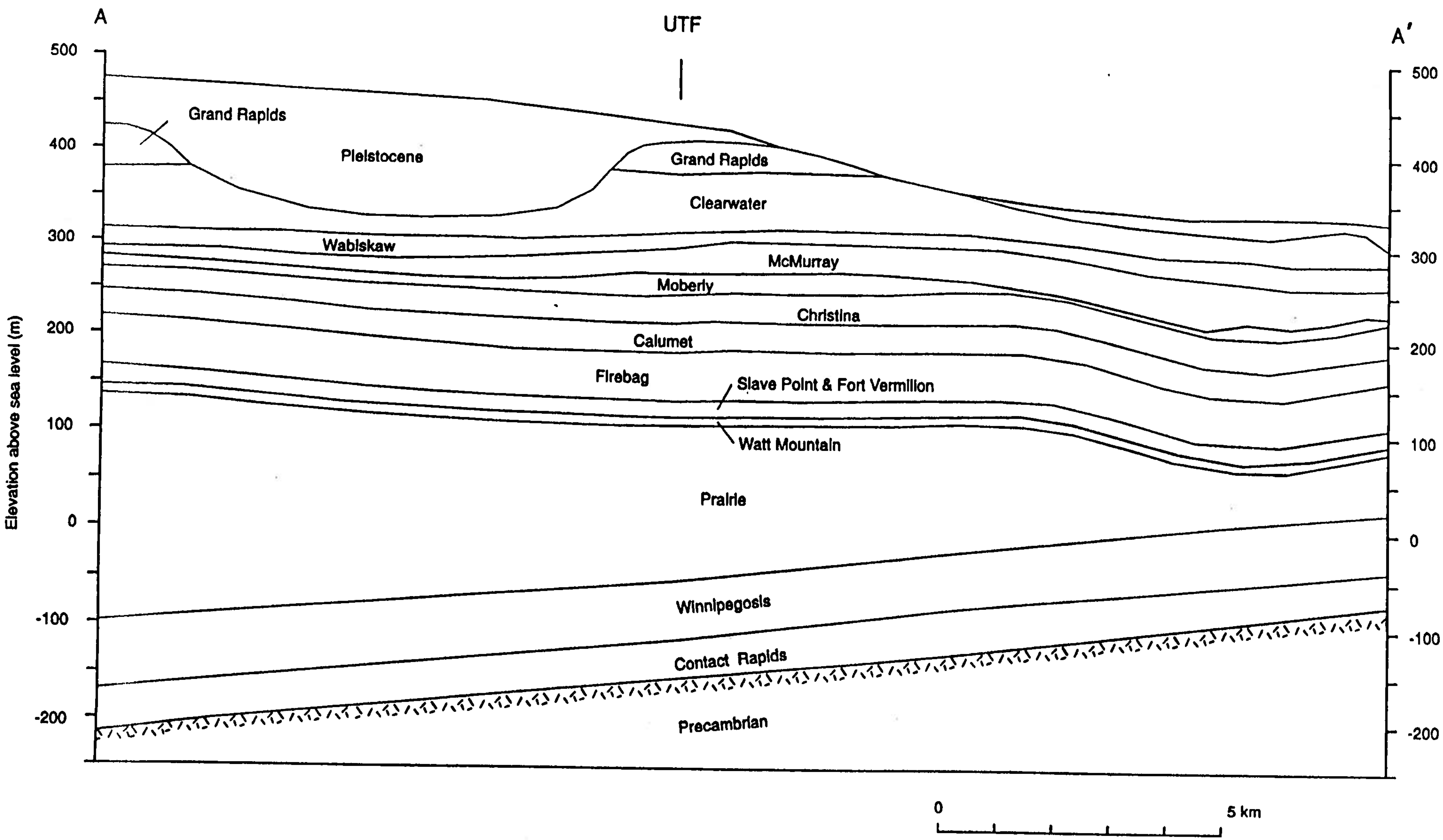


Figure 4. Stratigraphic dip cross-section A-A' of the Phanerozoic succession.

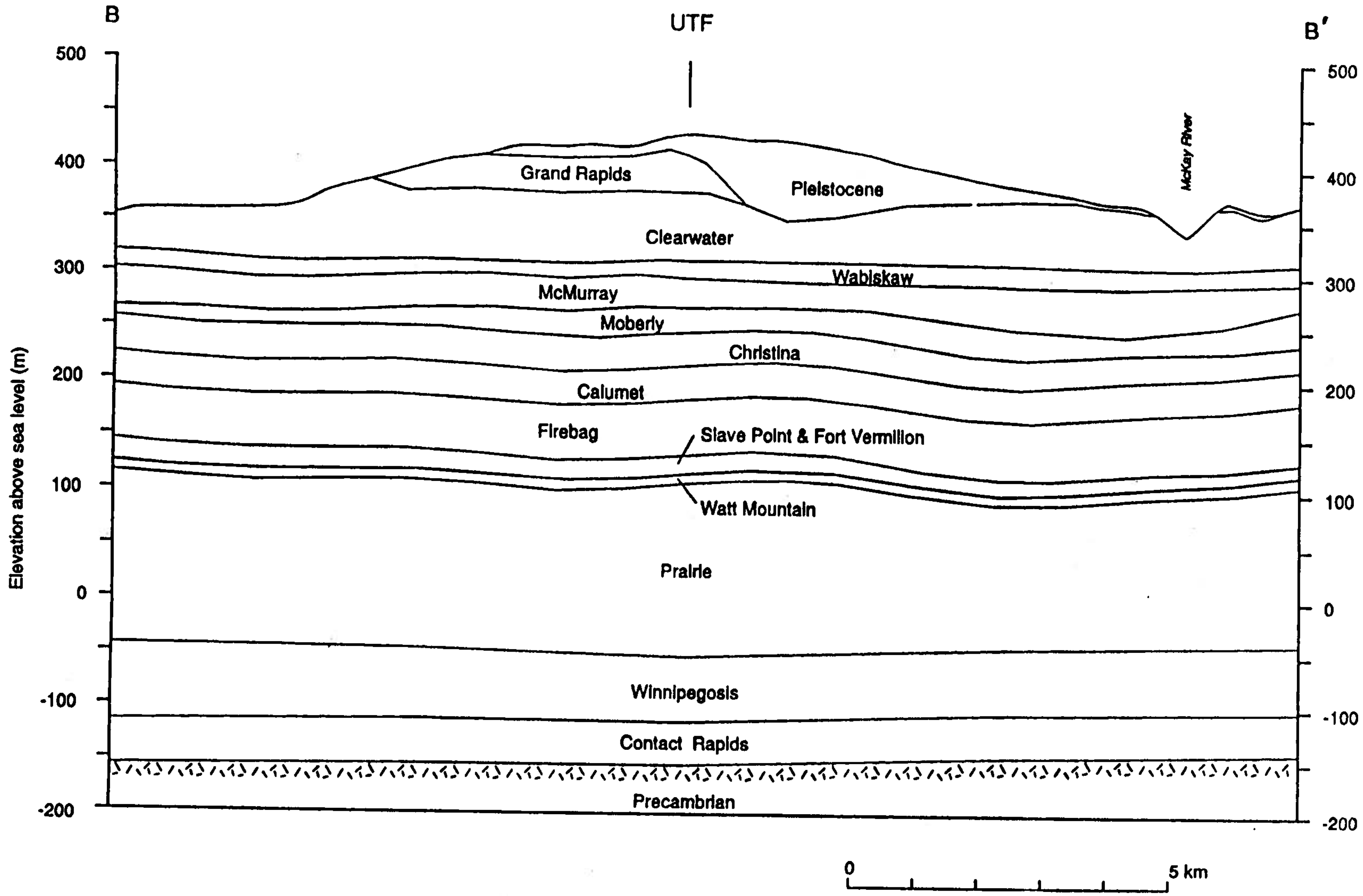


Figure 5. Stratigraphic strike cross-section B-B' of the Phanerozoic succession.

Subgroup consisting of the Ernestina Lake and Contact Rapids formations. The Granite Wash, known also as the LaLoche Formation, generally consists of regolithic, arkosic sandstones and conglomerates. The Ernestina Lake consists of dolomitic shale, anhydritic limestone and anhydrite. The Contact Rapids Formation, consisting of argillaceous dolomite and dolomitic shale, overlies the Ernestina Lake Formation. The Contact Rapids Formation marks the boundary between the Lower and Upper Elk Point subgroups.

The Upper Elk Point Subgroup consists, in ascending order, of the Winnipegosis, Prairie and Watt Mountain formations. The Winnipegosis Formation is generally comprised of reef and non-reef carbonates, becoming increasingly argillaceous towards the base. Most of the pore space in the upper Winnipegosis strata has been filled with halite from the overlying Prairie Formation (Glaister, 1991). The Prairie Formation is a thick succession of strata consisting mostly of evaporites (halite and anhydrite), with minor shales capped by carbonate. The thin Watt Mountain Formation, consisting predominantly of dolomitic shale, disconformably overlies the Prairie Formation.

The Beaverhill Lake Group is comprised, in ascending order, of the Fort Vermilion, Slave Point and Waterways formations. The Fort Vermilion Formation consists of anhydrite thinly interbedded with dolomites and limestones. The overlying Slave Point Formation is comprised of limestone, silty limestone and siltstone. The sparse well control and lack of adequate geophysical logs did not allow for an accurate pick of the boundary between the two units.

The overlying Waterways Formation, bounded at the top by the sub-Cretaceous unconformity, is subdivided into the Firebag, Calumet, Christina and Moberly members. The lower portion of the Firebag member is comprised of interbedded shale and argillaceous limestone, while the upper portion is dominated by shale with minor thin carbonate-rich beds. The Calumet Member is comprised of two distinct limestone units separated by a relatively thick shale, the lower unit being more argillaceous. The Christina Member is comprised mainly of shales, with argillaceous limestone also present. The overlying Moberly Member consists of alternating argillaceous limestone and shale combined with limestone. The top of the Moberly Member forms the surface of the sub-Cretaceous unconformity.

Mesozoic Succession

The Lower Cretaceous Mannville Group strata, bounded at the base by the sub-Cretaceous erosional unconformity and at the top by Cenozoic glacial drift deposits, generally consist of interbedded siliciclastics comprised of sand, shale and silt. Paleo-topography on the sub-Cretaceous unconformity influenced the distribution of sediments, especially within the lower strata, while post-Cretaceous erosional events account for most of the variation in geometry within Mannville stratigraphy. The Mannville Group is comprised of, in ascending order, the McMurray, Clearwater and Grand Rapids formations (Table 1).

The McMurray Formation sediments infill the erosional topography on the sub-Cretaceous unconformity. The sediments are comprised mainly of thick, relatively clean, fining upward, bitumen-saturated sandy successions. Erosional events during the deposition of the overlying Wabiskaw Member of the Clearwater Formation have also affected the thickness of the McMurray Formation.

The Wabiskaw Member (Clearwater Formation), which disconformably overlies the McMurray Formation, can be subdivided into four units. The lowermost one is a basal erosional channel consisting of two localized sandy deposits saturated with bitumen. Above them there is a wedge of sandy shale, named the lower shale wedge, which thickens and becomes progressively shaley to the southwest. Overlying this shale wedge is an upward coarsening, biouturbated sand which thins gradually from southwest to northeast. A uniformly thick, black, often sandy/silty shale, overlies the upper sand. This shale is named the upper marine shale, and defines the top of the Wabiskaw Member within the Clearwater formation.

The remainder of the Clearwater formation above the Wabiskaw Member consists mainly of shale interbedded with thin, very fine-grained sand and silt. A relatively thick shale overlies the Wabiskaw Member. Above it there are two stacked coarsening-upward cycles, each grading from shale at the base to very fine sand or silt at the top. Each cycle is capped by a shale layer. Post-Cretaceous erosional events have removed significant portions of the Clearwater Formation within the study area.

The Clearwater Formation, where not eroded, is conformably overlain by the Grand Rapids Formation, which consists of sands interbedded with thin shales. Mostly unconsolidated sands and gravels of Pleistocene and more recent age cover the Mannville Group sediments.

HYDROSTRATIGRAPHY AND HYDROGEOLOGY

The hydrostratigraphy provides a breakdown of strata according to certain hydrogeological characteristics. The hydrostratigraphic nomenclature is defined as follows: an aquifer is a layer, formation or group of formations saturated with water and with a degree of permeability that allows water withdrawal (de Marsily, 1986, p. 115); an aquitard is a less permeable unit from which water cannot be produced through wells, but where the flow is significant enough to feed adjacent aquifers through vertical leakage; and an aquiclude has very low permeability and cannot give rise to any appreciable leakage (de Marsily, 1986, p. 131). Hydraulic communication between two aquifers may occur across a weak aquitard, in which case there is significant cross-formational flow between the two aquifers. Hydraulic continuity between two aquifers occurs when they are in direct contact. According to Toth (1963), the flow in a local hydrogeological system is from a recharge area at a topographic high to a discharge area at a topographic low that are adjacent to each other, while the flow in a regional system is from a recharge area at the major topographic high to a discharge area at the major topographic low in the basin. Intermediate flow systems are transitional between the two.

The hydrostratigraphic succession in the local-scale study area (Table 2) is relatively complex because of the presence of bitumen-saturated sands and shales in the Cretaceous strata. Sands containing more than 3 mass-percent bitumen are considered to have aquitard-to-aquiclude characteristics. Various stratigraphic units exhibiting similar hydraulic properties are grouped into hydrostratigraphic systems. The hydrostratigraphic succession is shown in dip and strike cross-sections (Figures 6 and 7, respectively). The succession is described in ascending order in the following, together with the hydrogeological regime of formation waters.

Overlying the crystalline Precambrian basement (Appendix, Figure 1), the Basal aquifer, a few meters in thickness, is comprised of the thin-to-absent Granite Wash (also known as La Loche Formation). In the AOSTRA deep well this aquifer has only 2 m in thickness. The Basal aquifer is overlain by the thin Ernestina Lake aquitard, and by the Contact Rapids aquitard up to 40 m thick. Because the often absent Basal aquifer is generally cemented and hard to identify and differentiate, the entire succession from the top of the Precambrian to the top of the Contact Rapids aquitard is grouped into a Basal aquitard system (Appendix, Figure 2).

The Basal aquitard system is overlain by the Winnipegosis aquifer (Appendix, Figure 3), 65 m thick on average. The upper part of this aquifer has very low porosity and permeability because of salt plugging, as seen in the AOSTRA deep well. The lower part of the aquifer has relatively higher porosity and permeability. The formation waters

<table>
<tr><th colspan="2">Group</th><th>Formation</th><th>Hydrostratigraphy</th></tr>
<tr><td colspan="3">Pleistocene deposits</td><td rowspan="2">Upper aquifer system</td></tr>
<tr><td colspan="2" rowspan="4">Mannville</td><td>Grand Rapids</td></tr>
<tr><td rowspan="2">Clearwater</td><td>Clearwater-Wabiskaw aquitard</td></tr>
<tr><td>Wabiskaw aquifer</td></tr>
<tr><td>McMurray</td><td>Wabiskaw-McMurray aquitard</td></tr>
<tr><td colspan="2" rowspan="6">Beaverhill Lake</td><td rowspan="4">Waterways</td><td>Devonian-Cretaceous aquifer system</td></tr>
<tr><td>Christina aquitard</td></tr>
<tr><td>Calumet aquifer</td></tr>
<tr><td>Firebag aquitard</td></tr>
<tr><td>Slave Point</td><td>Slave Point aquifer</td></tr>
<tr><td>Fort Vermilion</td><td rowspan="3">Prairie-Ft. Vermilion aquiclude system</td></tr>
<tr><td rowspan="6">Elk Point</td><td rowspan="3">Upper</td><td>Watt Mountain</td></tr>
<tr><td>Prairie</td></tr>
<tr><td>Winnipegosis (Keg River)</td><td>Winnipegosis aquifer</td></tr>
<tr><td rowspan="3">Lower</td><td>Contact Rapids</td><td rowspan="3">Basal aquitard system</td></tr>
<tr><td>Ernestina Lake</td></tr>
<tr><td>Granite Wash</td></tr>
<tr><td colspan="2"></td><td>Precambrian</td><td>aquiclude</td></tr>
</table>

Table 2. Hydrostratigraphic succession and nomenclature at the UTF site.

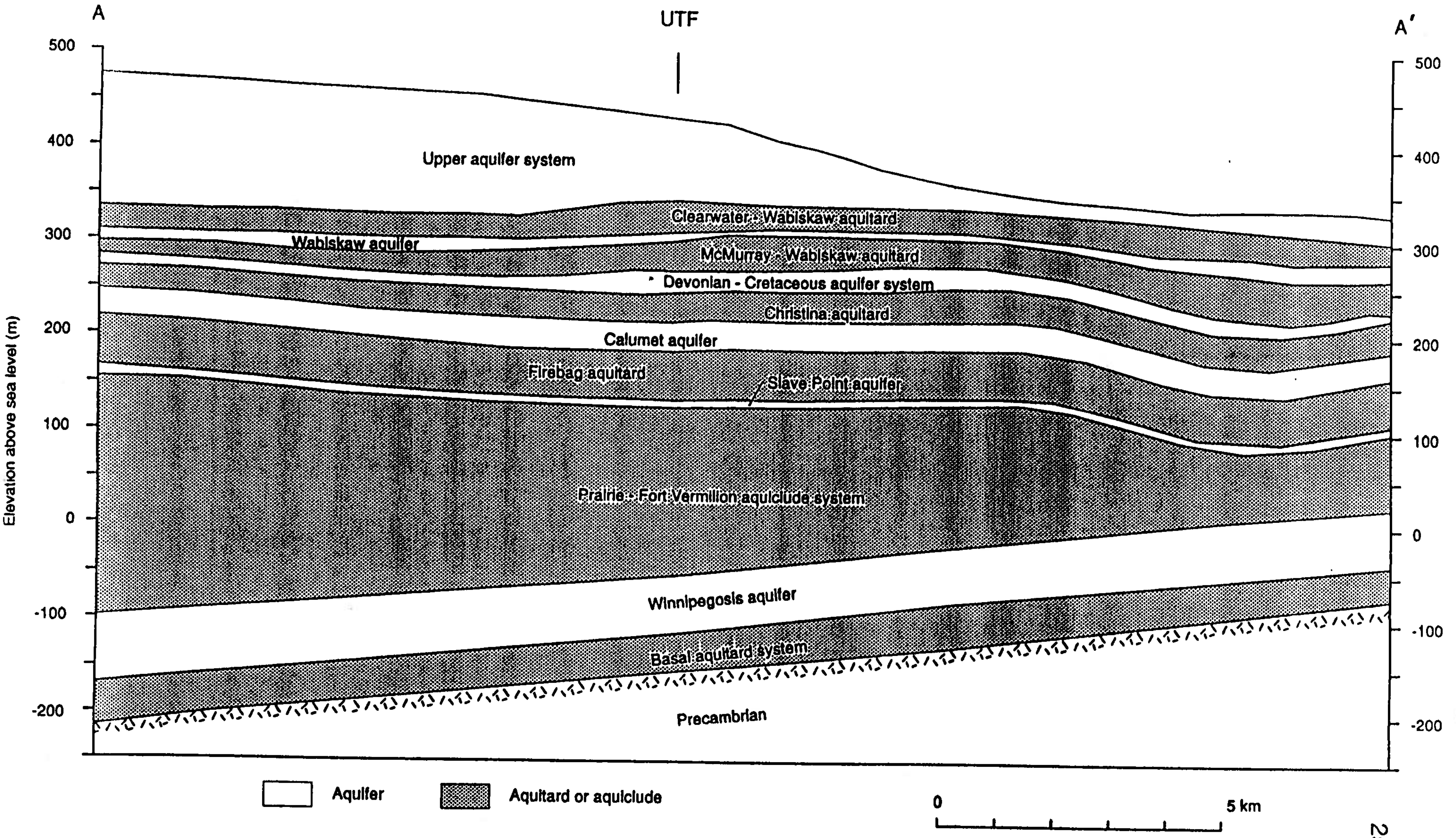


Figure 6. Hydrostratigraphic dip cross-section A-A' of the Phanerozoic succession.

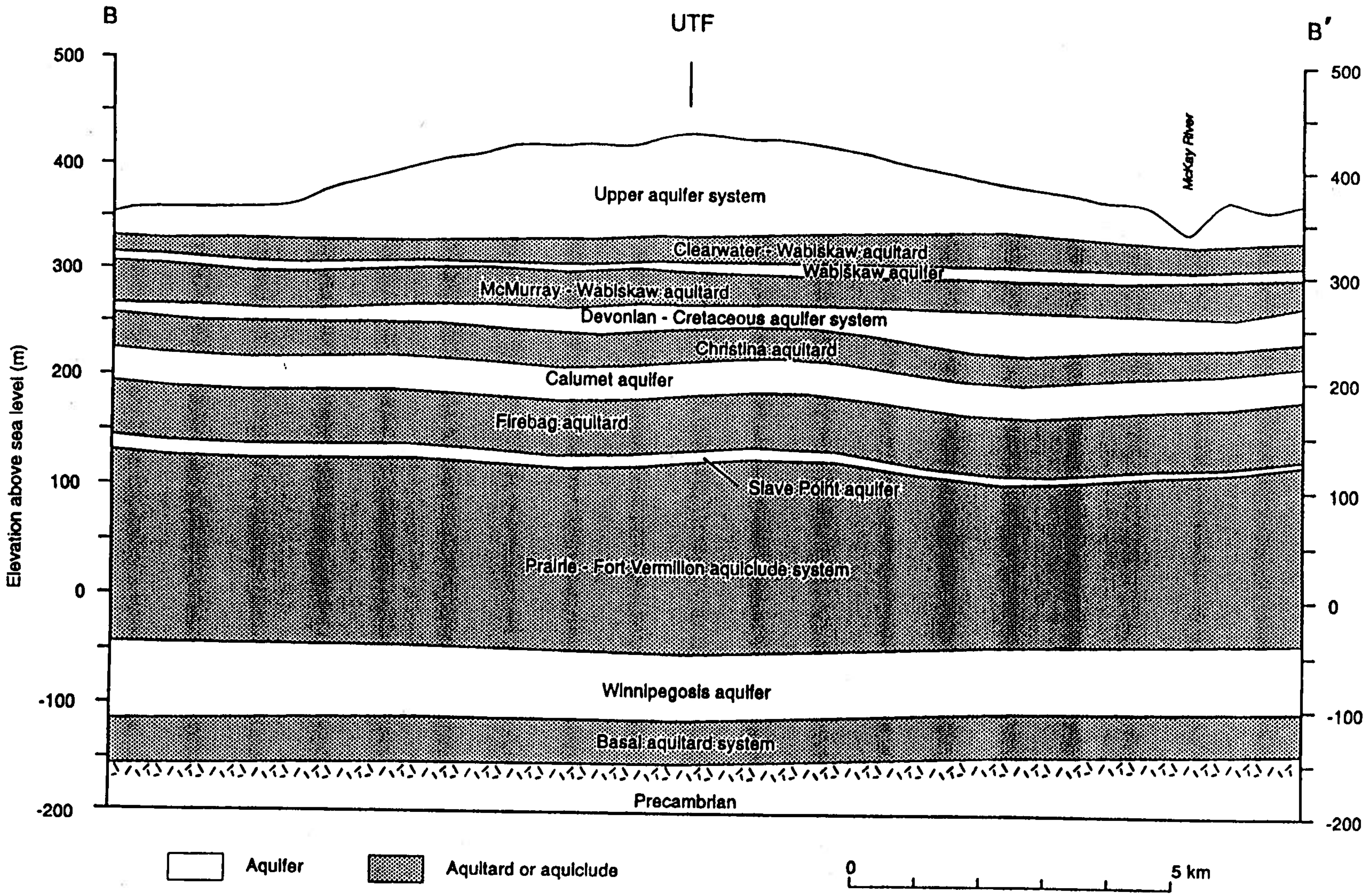


Figure 7. Hydrostratigraphic strike cross-section B-B′ of the Phanerozoic succession.

are very saline (TDS greater than 250,000 mg/l). The distribution of freshwater hydraulic heads suggests flow from the northwest to the southeast in this area (Petroleum Geology and Basin Analysis Group, 1992a, b). However, this is probably misleading because buoyancy effects caused by fluid-density differences are not taken into account.

The Winnipegosis aquifer is confined by the Prairie aquiclude, about 150 m thick on average. The thin Watt Mountain Formation, forming an aquitard approximately 9 m thick, overlies the Prairie aquiclude. The Fort Vermilion Formation of the Beaverhill Lake Group, which is an aquitard-aquiclude on average 9 m thick, overlies the Watt Mountain aquitard. Hydrostratigraphically, the entire Prairie-Fort Vermilion succession is grouped into a single aquiclude system (Appendix, Figure 4).

The remainder of the Beaverhill Lake Group strata is a succession of tight limestone and shales. In absence of any hydrogeological information and based only on lithology, it is assumed that the Slave Point Formation and the Calumet and Moberly members of the Waterways Formation are aquifers, separated by the Firebag and Christina members of the Waterways Formation, which are aquitards. The corresponding isopachs of these hydrostratigraphic units are shown in Appendix, Figures 5-9, respectively. The formation waters could not be characterized for each individual aquifer in the Beaverhill Lake Group because of lack of data. Distributions of salinity and freshwater hydraulic head were obtained at the regional and intermediate scales for the Beaverhill Lake Group aquifer system as a whole (Petroleum Geology and Basin Analysis

Group, 1992a, b). Local-scale salinity and freshwater hydraulic head distributions for the Beaverhill Lake Group (Figures 8 and 9, respectively) were obtained from the intermediate-scale distributions by interpolation, and cannot be associated with any individual aquifer in this succession. Thus, these distributions provide a general understanding of the flow of formation waters, but are not specific enough for any of the aquifers in the Beaverhill Lake Group. The formation water salinity is low (Figure 8), and flow directions are toward northeast (Figure 9) where the Beaverhill Lake Group crops out at the Athabasca River. The regional- and intermediate-scale hydrogeological analyses identified the flow regime in the Beaverhill Lake aquifer system as being intermediate-to-local.

Isolated water sands at the base of the McMurray Formation, (Appendix, Figure 10) overlie the Moberly aquifer below. Although of different lithology and hydraulic properties, these water sands are grouped with the Moberly aquifer in a single Devonian-Cretaceous aquifer system because they are in physical and hydraulic contact. The bitumen-saturated sands of the McMurray Formation and overlying Wabiskaw Member, and the Wabiskaw lower shale wedge form an aquitard with a thickness of more than 20 m throughout the area (Appendix, Figure 11).

The bitumen-free upper Wabiskaw sand is an aquifer approximately 2-3 m thick (Appendix, Figure 12). The distributions of salinity and freshwater hydraulic head for this aquifer (Figures 10 and 11, respectively) were obtained from the corresponding

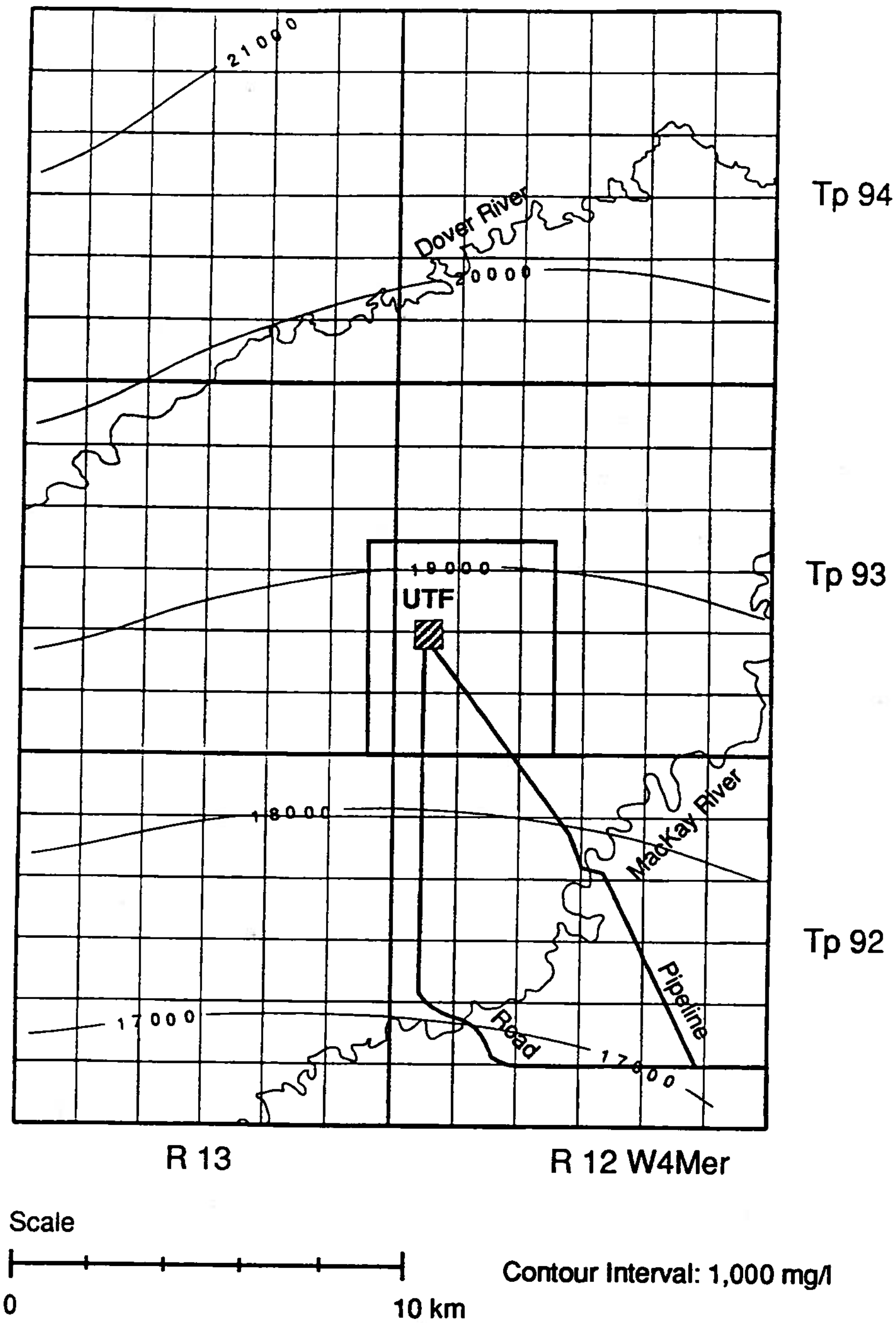


Figure 8. Salinity distribution (mg/l) in the Beaverhill Lake aquifer system.

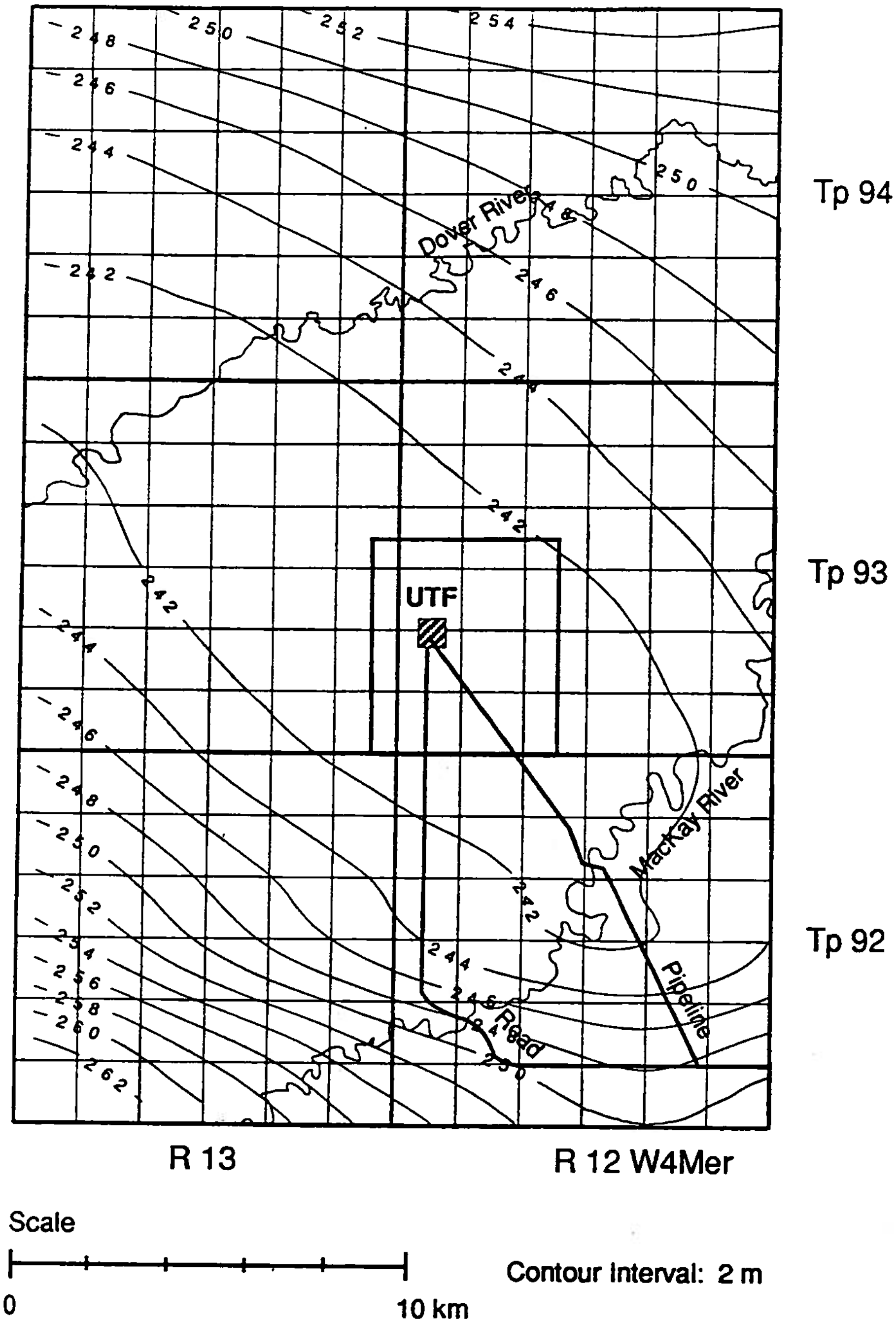


Figure 9. Distribution of freshwater hydraulic head (m) in the Beaverhill Lake aquifer system.

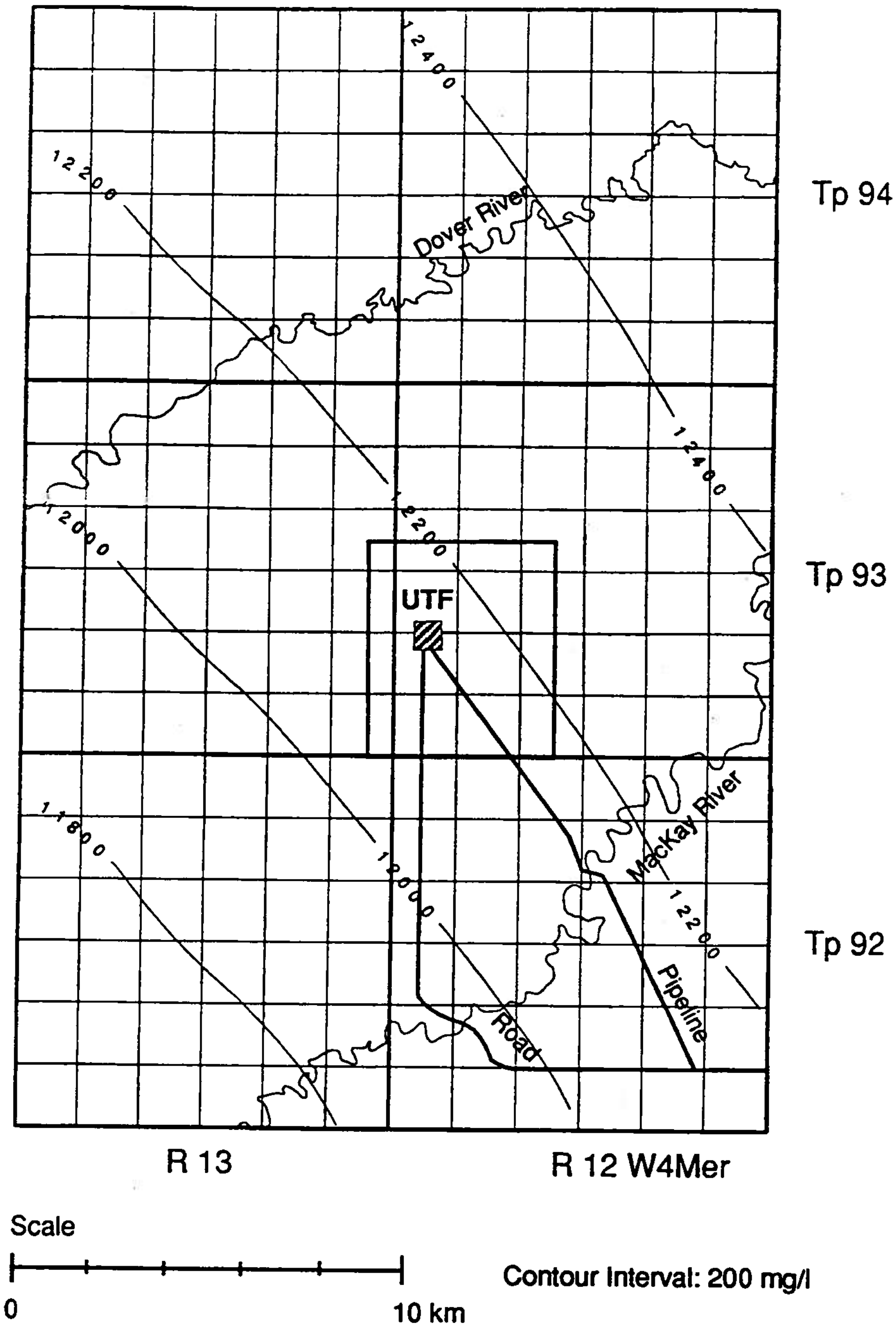


Figure 10. Salinity distribution (mg/l) in the Wabiskaw aquifer.

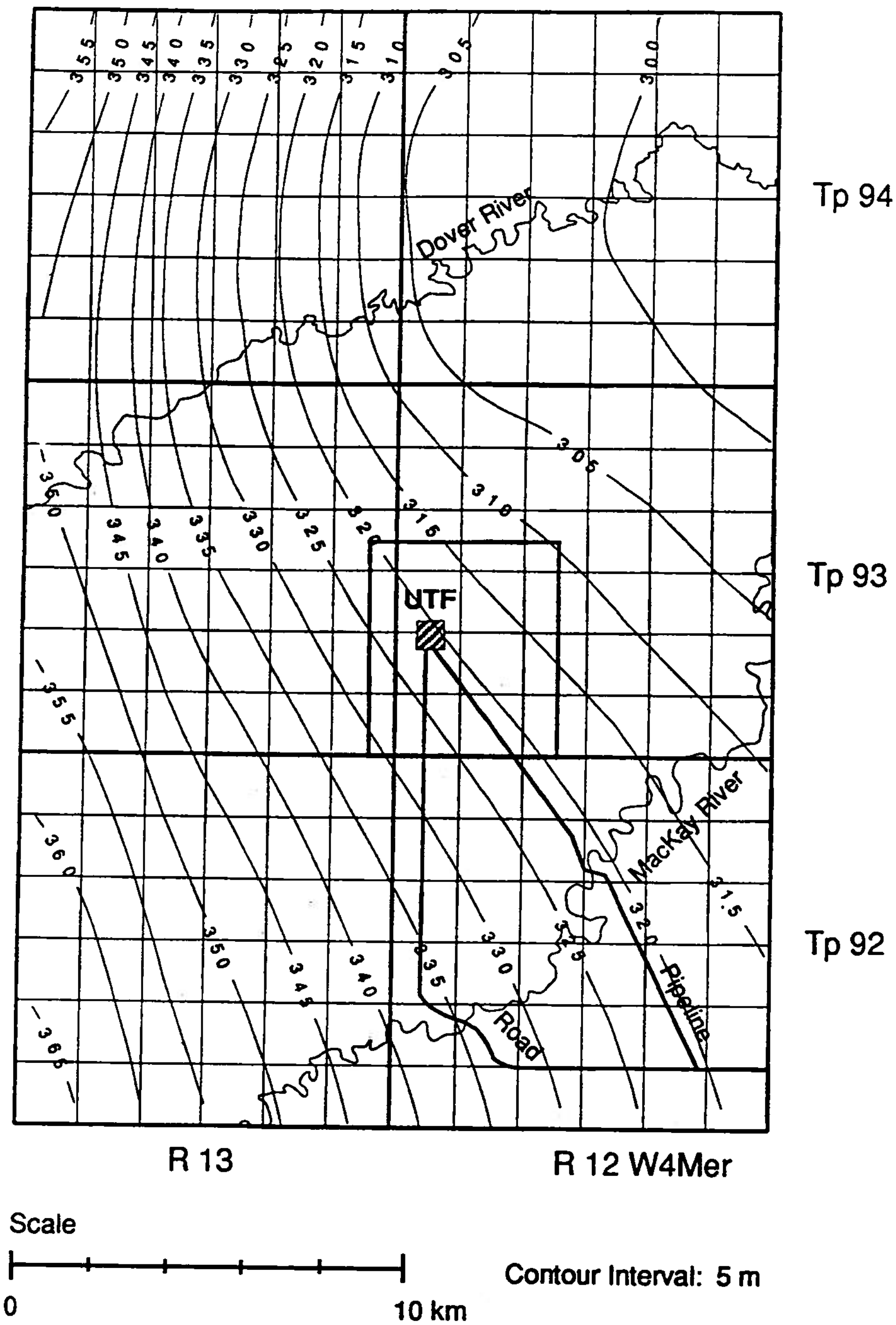


Figure 11. Distribution of freshwater hydraulic head (m) in the Wabiskaw aquifer.

intermediate-scale distributions (Petroleum Geology and Basin Analysis Group, 1992b). The formation water is fresh (Figure 10), flowing in a local system from recharge in areas of high topography to discharge along the topographically low river valleys (Figure 11).

The Wabiskaw upper marine shale and the thick Clearwater Formation shale overlying it form the Wabiskaw-Clearwater aquitard (Appendix, Figure 13). The two coarsening-upward Clearwater cycles above it, where present, are overlain by the sands interspersed with shales of the Grand Rapids Formation, forming together an aquifer at the top of the bedrock. This aquifer is in direct physical and hydraulic contact with the Pleistocene surface aquifer covering the entire area. Although of significantly different lithologies and aquifer properties, these aquifers are grouped into a single, unconfined aquifer system (Appendix, Figure 14), named the Upper aquifer system. Because of lack of data, the actual geometry and internal structure of this aquifer system is poorly defined. The flow in this aquifer system is directly driven by topography.

EFFECTS OF INJECTION

Generally, a suitable disposal aquifer should have adequate porosity and permeability to accept the volume of residual water to be disposed of, and should be confined by aquitards or aquicludes in order to avoid contamination of water, mineral or hydrocarbon resources in the area. Based on hydrostratigraphy, there are theoretically several possible injection units in the Phanerozoic succession at the UTF site. A review of geological data from all the wells drilled to the Precambrian basement in the area defined by Tp. 85-100, R1-18, W4 Mer, and of water disposal practices at the active EOR pilot plants in this area indicated that current disposal horizons in the Athabasca area are the Basal (Granite Wash), Winnipegosis (Keg River or Methy) and McMurray water sands aquifers (AOSTRA, 1992). A deep well drilled by AOSTRA at the UTF site showed the Basal aquifer to be very thin and of very low porosity and permeability caused by sand cementation (AOSTRA, 1992). Because of lack of suitable capacity and hydrodynamic properties, the Basal aquifer was not considered further for deep disposal of residual water at the UTF site. The Winnipegosis aquifer is confined by the overlying salts of the Prairie aquiclude and underlying Contact Rapids aquitard.. The UTF is situated on a Prairie salt scarp whose dissolution edge is immediately east of the local-scale study area. To the east of this salt scarp, which runs through northeast Alberta on a northwest-southeast direction, the Winnipegosis aquifer, where drilled, has been found to be suitable for residual water disposal (Nelson et al., 1991). West of the salt scarp, it appears that this unit is not suitable for injection because of low permeability due to cementing and salt plugging (Nelson et al., 1991). This finding was confirmed by the deep well drilled at the UTF site (AOSTRA, 1992). Higher up in the succession, limestone dominated units in the Beaverhill Lake Group (Slave Point Formation, and Calumet and Moberly members of the Waterways Formation) have low porosity and permeability, making them probably not suitable for injection of residual water. Besides these hydrodynamic considerations, the Moberly Member is excluded as an injection aquifer because of the proximity of the UTF tunnels dug into the Waterways limestone immediately below the McMurray bitumen-saturated sands (Figure 12). Above the Devonian Beaverhill Lake Group, the Cretaceous McMurray Formation is saturated with bitumen except for a few isolated basal water sands in hydraulic contact with the Moberly Member. These sands were deemed by AOSTRA as not having the necessary volume needed for receiving the planned volume of injected residual water (AOSTRA, 1992). Besides this capacity considerent, these sands are not suitable for injection because of flow along the sub-Cretaceous unconformity (Toth, 1978; Bachu and Underschultz, 1993) and because of their contact with the Moberly Member. This leaves the upper sand of the Wabiskaw Member above the McMurray Formation as the only aquifer available in practice for the injection of residual water. This unit is separated from the unconfined Grand Rapids and Pleistocene aquifers above by the shaley Clearwater aquitard.

According to the Alberta Hazardous Chemicals Act, water produced in association with the recovery of oil, bitumen or gas, saline fluids, boiler blowdown water and neutralized caustic or acid water are not defined as hazardous. The regulatory agencies,

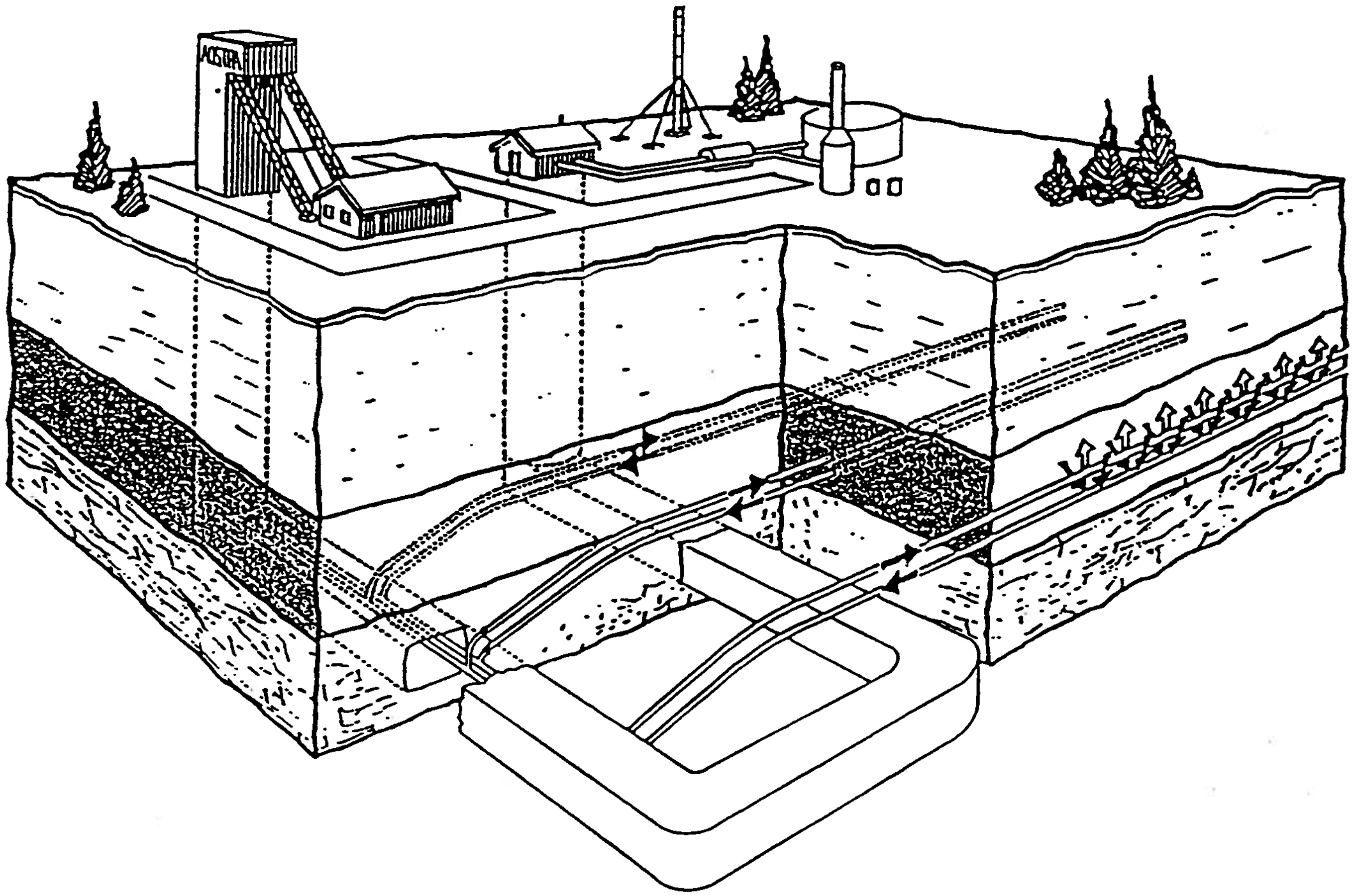


Figure 12. Diagramatic representation of AOSTRA's Underground Test Facility.

Alberta Environment and the Energy Resources Conservation Board, classify the injection/disposal well for such residual water as Class II, subject to various regulations for well completion, injection and monitoring. No restrictions on water quality are imposed for pilot operations in the Athabasca area (Nelson et al., 1991). With respect to injection conditions, the main requirement is that the injection pressure does not exceed 90% of the fracturing pressure.

GEOCHEMICAL EFFECTS

The geochemical effects of deep injection of residual water are important at the well-to-site scale because of the potential for mineral precipitation or dissolution as a result of water-rock interactions between the injected water and the formation water and minerals. The hydraulic characteristics of the rocks around the injection well may be modified because of these geochemical effects, thus influencing the movement of injected water and the pressure buildup at the well. The potential for water-rock interactions can be determined by a variety of techniques. These range from laboratory experiments on representative cores using actual formation and injection waters, to numerical modelling designed to determine individual mineral saturations. In the case of deep injection at the UTF, laboratory experiments are excluded because of the extremely large duration of low-temperature water-rock interactions. Thus, the geochemical effects of injection were evaluated using numerical modelling, for which the composition of formation and injected waters and rock mineralogy are required.

Core samples were collected from the Winnipegosis Formation, Calumet Member in the Beaverhill Lake Group, and Wabiskaw Member upper sand, and analyzed for their mineralogical composition. No core was available for the Slave Point Formation. Dolomite is the dominant mineral in the Winnipegosis Formation strata, with a minor amount of clay minerals and a trace of halite. The dominant mineral in the Calumet Member is calcite, with less than 10% quartz and a very small amount (less than 1%) of halite and clay minerals. The Wabiskaw Member sands are comprised dominantly of quartz, with minor amounts of feldspar in the sandy portions and minor amounts of carbonate and clay minerals in the shaley portion of the unit.

Analyses of formation water chemistry for the Wabiskaw aquifer were supplied by AOSTRA from the UTF site. Water analyses for the Winnipegosis and Calumet aquifers are not available at the UTF, and were obtained at the nearest location from the ERCB data base after checking and culling by the Alberta Geological Survey (Petroleum Geology and Basin Analysis, 1992a, b). All analyses were evaluated for internal consistency and the most representative retained for geochemical modelling. Generally, upon sampling and before analysis, carbon dioxide (CO_2) present in the formation water may be lost because the partial pressure of CO_2 in each formation fluid is greater than atmospheric CO_2 partial pressure. The effect of this loss is a lower total dissolved carbon and a more basic pH in the sample than in the formation. Also, all carbonate minerals (and many other phases) have increased saturation indices (SI). The loss of CO_2 and the resulting shift in SI's were corrected by numerically adding CO_2 back to the fluid until the formation water is in equilibrium with either one of the carbonate minerals, calcite or dolomite. Because at least one and sometimes both minerals are present in the rocks of the respective units, they serve as a constraint on correcting the fluid composition for CO_2 loss. Precipitation of carbonate minerals from the fluid sample may also occur before analysis, but its effect is generally much smaller than that of CO_2 loss. Only one analysis shows the presence of silica (SiO_2) in solution, thus the other analyses were corrected by adding 4 mg/l SiO_2 (a value near quartz equilibrium). Overall, these corrections can be significant. For example, the corrections for the Wabiskaw formation water resulted in a pH shift of over 2 units and an increase in the concentration of total inorganic carbon by more than 1000 mg/l. Table 3 shows the corrected chemical composition of formation waters from the Winnipegosis, Calumet and Wabiskaw aquifers.

When fully operational, it is anticipated that the maximum disposal requirements at the UTF will be up to 1200 m^3/day, for a total projected volume of 900,000 m^3. The injected water consists of an estimated 800 m^3/day of produced water plus approximately 400 m^3/day of boiler blowdown and water softener regeneration fluids (AOSTRA, 1992). The chemical composition of the produced water is the result of geochemical reactions occurring during the recovery process. The steam injected into the McMurray Formation pay zone cools in the reservoir, mixes with any formation water present and, more importantly, reacts with the reservoir minerals. The reservoir mineralogy is comprised mainly of quartz, with minor amounts of clays, feldspars and carbonate, predominantly dolomite. As a result of the geochemical reactions taking place in the reservoir, the

	Winnipegosis	Beaverhill Lake (Calumet)	Wabiskaw
pH	5.2	6.1	7.5
Na	181,170	6,969+	4,413
K	nd	nd	26
Ca	40,850	1,032	67
Mg	6,909	271	75
Cl	181,170	10,947	5,880
SO_4	605	2,944	9
CO_3	0	0	0
HCO_3	220	390	1,991
SiO_2	4*	4*	10
TDS	287,500	22,440	11,104

nd : not determined
+ : determined by difference
* : assumed to be near equilibrum with quartz

Table 3: Composition (mg/l) of formation waters from selected aquifers at the AOSTRA UTF site.

produced fluid, at or near equilibrium with the altered high-temperature mineral assemblage, has high silica and aluminum content and a significantly different pH from the injection steam. Mineral precipitation can take place when the produced water is cooled to disposal temperatures. During production, CO_2 is often lost, modifying the pH of the production water and significantly increasing the potential for calcite precipitation. The chemical composition of the production water to be disposed of is shown in Table 4.

The produced water requires de-oiling prior to injection in order to prevent aquifer plugging. The degree of oil and organic components removal depends also on the characteristics of the disposal aquifer. At the UTF site, the oil or entrained solids content must be reduced to levels of 10 mg/l or less (Nelson et al., 1991).

	Produced Water	Blowdown Water	Treated Blowdown Water	Regeneration Water	Disposal Water
pH	7.8	11.9	7.6	8.0	7.5
Na	1,240	1,620	1,598	19,414	2,521
K	32	27	26	28	30
Ca	19	2.8	2.7	11,310	772
Mg	2	0.4	0.4	9,272	30
Cl	1,875	170	168	29,559	3,380
SO_4	29	1,016	2,297	283	496
CO_3	0	884	0	0	0
HCO_3	217	0	833	766	315
SiO_2	239	27	27	0	180
TDS	4,675	4,135	4,990	69,866	8,320
% of Disposal Water	0.75	-	0.18	0.07	-

Table 4: Composition (mg/l) of residual and disposal waters at the AOSTRA UTF site.

The boiler feedwater, sourced from the shallow Pleistocene unconfined aquifer, is treated by ion exchange to reduce boiler scaling. The resulting boiler blowdown is very basic, with pH values greater than 11 (Table 4). In order to remove its high potential for carbonate precipitation during disposal, the boiler blowdown water is treated by adding acid, thus reducing the pH (Table 4). The ion exchange unit is regenerated using a saline brine, which is also disposed of by injection and whose chemical composition is shown in Table 4. The production, treated boiler blowdown and regeneration waters are mixed at the surface in the proportions shown in Table 4, resulting in a residual water (Table 4) to be disposed of by deep injection.

The geochemical reactions between the injected residual water and formation water and rocks were simulated using the PC version of the geochemical code SOLMINEQ.88 (Kharaka et al., 1988; Perkins et al., 1988) for three possible injection zones (Wabiskaw, Calumet and Winnipegosis aquifers), and for the entire spectrum of mixing between the injected and formation waters. The results are represented in Figures 13, 14 and 15, respectively, as the variation of the saturation index (SI) for various minerals which can form from the water as a function of the degree of mixing. The degree of mixing varies between zero (residual water only) and one (formation water only). A saturation index SI = 0 indicates that the given mineral is in equilibrium at saturation. A SI value greater than zero indicates that the fluid is supersaturated and the mineral has the potential to precipitate. A SI value less than zero indicates that the fluid is undersaturated and the respective mineral will dissolve, if present in the rock matrix. A mineral is more likely to dissolve or precipitate and at a higher rate if the SI value is farther from the equilibrium value. The SI for different minerals cannot be directly

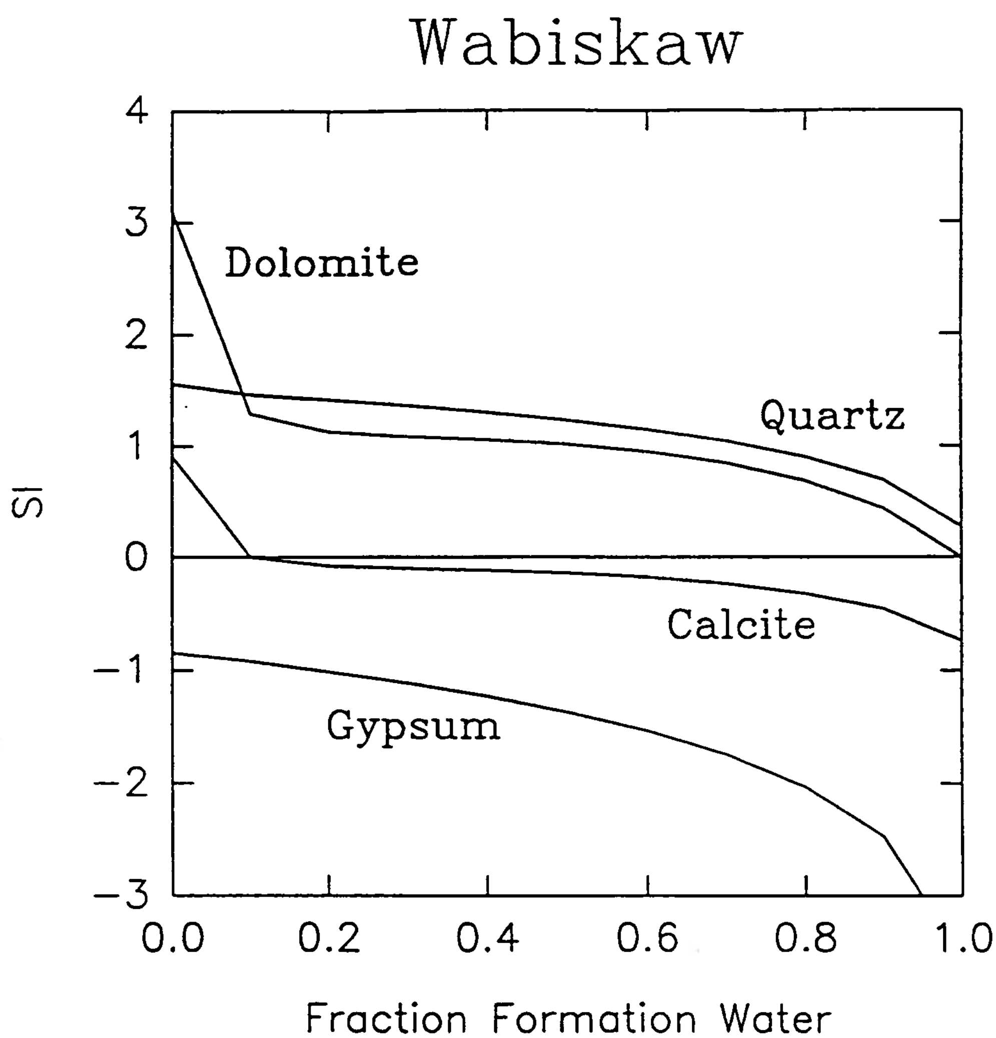


Figure 13. Variation of the saturation index (SI) for calcite, dolomite, gypsum and silica function of the degree of mixing between formation and residual waters, for the case of injection in the Wabiskaw aquifer.

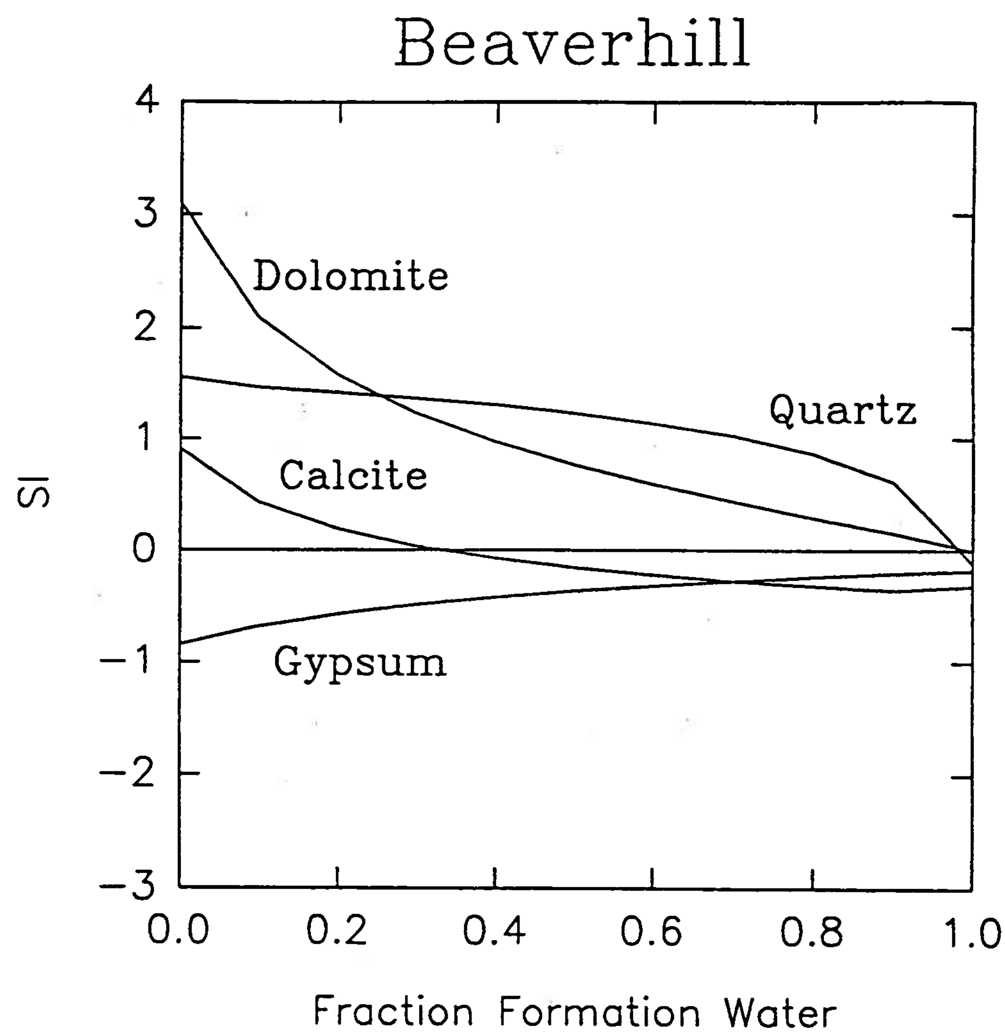


Figure 14. Variation of the saturation index (SI) for calcite, dolomite, gypsum and silica function of the degree of mixing between formation and residual waters, for the case of injection in the Calumet aquifer.

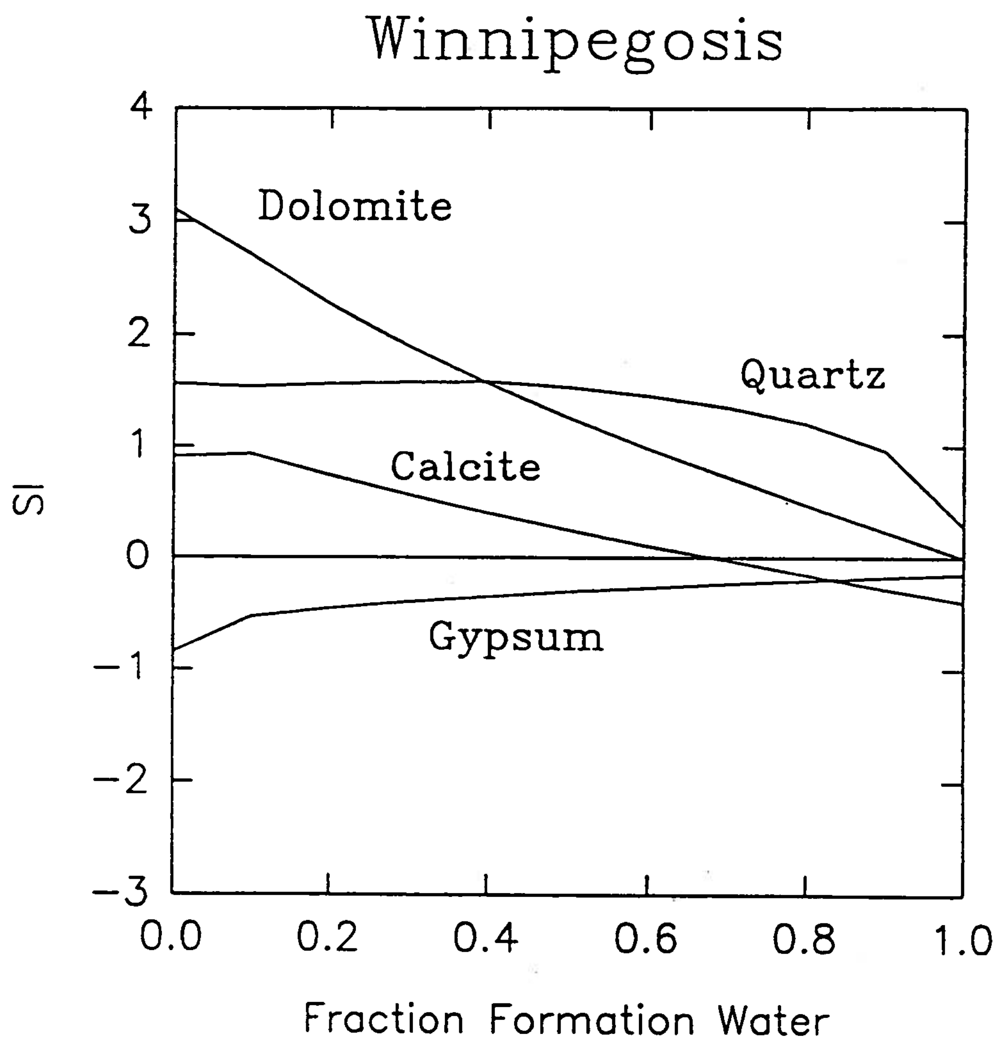


Figure 15. Variation of the saturation index (SI) for calcite, dolomite, gypsum and silica function of the degree of mixing between formation and residual waters, for the case of injection in the Winnipegosis aquifer.

compared with each other, but can serve as a relative guide within a given structural and chemical group.

Figure 13 shows the SI variation for a number of minerals: calcite and dolomite (carbonate), gypsum (sulphate) and silica (quartz); if the residual water was injected into the Wabiskaw aquifer. There is no potential for gypsum precipitation (SI<0), regardless of the degree of mixing. Neither dissolution will take place because this mineral is absent from the rock matrix. The pure residual water has a high potential for carbonate mineral precipitation, largely because of the highly saline regeneration fluid. For calcite, this potential decreases rapidly with increased mixing between residual and formation waters. Since calcite is not present in the Wabiskaw sands, no dissolution can take place. For dolomite, the SI decreases rapidly with increased mixing with formation water, but, nevertheless, remains positive over the entire mixing range, indicating potential precipitation. However, the kinetics of dolomite precipitation at low temperatures is slow. Similarly, there is potential for quartz precipitation over the entire mixing range, most significantly for pure disposal water (over 150 mg/l SiO_2 are available for precipitation because of the high silica content of the produced water). This potential decreases with increased mixing with formation water, which has a slightly positive SI (SI = 0.28), typical for a low temperature formation undergoing minor diagenesis. Because the low temperature kinetics of SiO_2 precipitation is very slow, it is expected that precipitation will take place away from the injection well.

Figure 14 shows the SI variation for the same minerals if the residual water was injected in the Calumet Member of the Beaverhill Lake Group. Similar to the case of injection in the Wabiskaw sands, gypsum has a negative SI over the entire range, with no potential for either precipitation or dissolution (mineral absent in formation). The potential for calcite and dolomite precipitation (SI>0) decreases as mixing increases, but at a slower rate than in the case of Wabiskaw sands. The SI variation for silica (quartz) is almost identical to its variation in the case of injection in Wabiskaw sands. In the absence of specific information and based on lithological similitude, it is assumed that injection in the Slave Point Formation will have similar geochemical effects.

Figure 15 shows the SI variation for gypsum, calcite, dolomite and silica if the residual water were injected in the Winnipegosis Formation. Gypsum is undersaturated (SI<0) but will not dissolve because it is absent in the formation rocks. Calcite has a higher potential for precipitation (SI>0) and over a larger range of mixing compared to injection in either the Wabiskaw or the Calumet units. Dolomite and quartz are supersaturated (SI>0), with a higher potential for precipitation (larger SI) than in the other two cases.

Comparison of the geochemical effects of residual water injection in the Wabiskaw, Calumet and Winnipegosis units clearly indicates that the Winnipegosis aquifer is the least attractive candidate for disposal because of higher potential for formation plugging by precipitation of silica, dolomite and calcite, while Wabiskaw is the best. Also, mineral precipitation will occur faster in the Winnipegosis Formation, therefore closer to the injection well. The geochemical effects of injection are more favourable in the case of the Calumet Member and assumedly of the Slave Point Formation of the Beaverhill Lake Group, because of lower potential and slower rate of precipitation. The conditions are markedly better in the case of Wabiskaw sands because of even lower potential and slower rates of mineral precipitation. The kinetics of silica precipitation are very slow at low temperatures, and it is anticipated that it will take in excess of a hundred years to precipitate half of the silica in solution. The kinetics of dolomite precipitation are also slow, such that dolomite will probably not precipitate in the near-well region. Thus, even if some mineral precipitation will occur, it will not alter significantly the hydraulic properties of the Wabiskaw sands. Possible changes in porosity and permeability will most probably be far from the injection well.

From the above analysis, it follows that, from the point of view of geochemical effects, the Winnipegosis Formation is most probably unsuitable for the injection of residual water, the Calumet Member and Slave Point Formation are uncertain, and the Wabiskaw Member is quite suitable. In terms of solute transport, comparison of the composition of injected and formation waters (Tables 3 and 4) reveals that the salinity (TDS) of injected water is less than that of formation waters. Thus, overall, this would not constitute a case of "pollution". In the case of individual components, only Ca, SO_4 and SiO_2 have higher concentrations in the disposal water than in the Wabiskaw Member waters, and only SiO_2 has higher concentrations in the injected water than in the

Beaverhill Lake Group or Winnipegosis Formation waters. Thus, only with regard to these specific cases, the effects of injection might be cast in terms of "solute transport".

HYDRODYNAMIC EFFECTS

The flow of formation and injected waters in a confined aquifer is described by Darcy's law (de Marsily, 1986, p. 59):

$$\mathbf{v} = -\frac{k}{\mu}(\nabla p + \rho \mathbf{g}) \equiv -\frac{k}{\mu}(\nabla p + \rho g \nabla z) \qquad (1)$$

where **v** is filtration or Darcy velocity, k is aquifer permeability, μ is fluid dynamic viscosity, p is pressure, ρ is fluid density and g is the gravitational constant. In sedimentary media with more or less horizontal stratification, the rock permeability generally is anisotropic. Therefore, permeability has tensorial properties. The horizontal anisotropy is relatively close to unity ($k_{90} \leq k_{max}$), but the vertical anisotropy may be significant ($k_z << k_{max}$).

If the water density is constant, then a potential field driving the flow can be defined using the concept of hydraulic head H defined as:

$$H = \frac{p}{\rho_o g} + z \qquad (2)$$

where ρ_o is the reference density (usually freshwater) and z is elevation. By defining the hydraulic conductivity tensor **K** as:

$$\mathbf{K} = \frac{\rho g \mathbf{k}}{\mu} \tag{3}$$

Darcy's law becomes:

$$\mathbf{v} = -\mathbf{K}\nabla H \tag{4}$$

The fluid mass in the aquifer is conserved according to the continuity equation (de Marsily, 1986, p. 50):

$$\nabla\cdot(\rho\mathbf{v}) + \frac{\partial}{\partial t}(\phi\rho) + \rho q = 0 \tag{5}$$

where ϕ is matrix (aquifer) porosity, t is time and q is the volumetric flow rate of injected or pumped fluid per unit volume. Manipulation of Darcy's law and continuity equation taking into account the compressibility of the fluid, solid rock and porous matrix (de Marsily, 1986, p. 100-109) leads to the diffusion equation for confined aquifers:

$$\nabla \cdot (\mathbf{K}\nabla H) = S_s \frac{\partial H}{\partial t} + q \tag{6}$$

where the specific storage coefficient S_s of the aquifer is defined by:

$$S_s = \rho g\,[\alpha + \phi\,(\beta_f - \beta_s)] \tag{7}$$

In relation (7) α is the compressibility of the porous medium (volume available for water storage) and β_f and β_s are the fluid and solid compressibility, respectively. The diffusion equation (6) is generally used to simulate mathematically water flow in confined aquifers. Usually the aquifer geometry and properties are such that analytical solutions are not available, in which case numerical solutions are sought. This is the case of deep injection of residual water at the UTF site. Thus, evaluation of the hydrodynamic effects of injection at the AOSTRA Underground Test Facility requires a numerical solution to equation (6).

If the fluid does not have constant density like the formation waters in northeast Alberta, then Darcy's law may be written as:

$$\mathbf{v} = -\,\mathbf{K}\,(\nabla H + \frac{\Delta\rho}{\rho_o}\nabla z) \tag{8}$$

where $\Delta\rho$ is the fluid density difference in the aquifer. Relation (8) shows that the flow of a variable-density fluid in an aquifer is driven by external potential forces deriving usually from elevation (topographic) differences and by internal buoyancy forces. For variable-density flow in sloping aquifers, the errors in using freshwater hydraulic heads and Darcy's law in its form (4) could be significant in both flow strength and direction. However, Davies (1987) has shown through numerical experiments for isotropic aquifers that these errors are likely small and buoyancy effects may be neglected if the Driving-Force-Ration (DFR), defined as:

$$DFR = \frac{\Delta\rho}{\rho_o} \frac{|\nabla E|}{|\nabla H|} \tag{9}$$

is less than a threshold value (DFR = 0.5). In relation (9) ∇E is the aquifer slope. In these cases, it is still possible to use the diffusion equation (6) to simulate the flow of formation waters in deep aquifers without significant errors introduced by neglecting density variations.

The hydrostratigraphic and hydrogeological analysis of the sedimentary succession at the AOSTRA UTF site shows that the few aquifers theoretically available for injection of residual waters are individually confined and separated by thick aquiclude and aquitard systems. Thus, as a first approximation and for a preliminary analysis of the hydrodynamic effects of injection, these aquifers can be considered as being isolated, and the various injection scenarios will be examined separately. The aquifers under consideration are Winnipegosis, Slave Point, Calumet and Wabiskaw. The Basal aquifer is too thin, and of uncertain extent and properties to be considered. The Moberly aquifer at the top of the Paleozoic succession and the McMurray aquifer (water sands) at the bottom of the Cretaceous succession are excluded from consideration because the bitumen extraction is operated from tunnels dug into the Moberly limestone. The Upper aquifer system is excluded because it is a protected shallow groundwater resource, used in this particular case as a source of freshwater for steam generation.

Aquifer Properties

Examination of relations (3), (6) and (7) indicates that aquifer parameters such as permeability **k**, porosity ϕ and specific storage coefficient S_s have to be defined, in order to solve numerically equation (6) subject to the given injection rate and initial and boundary conditions. Characteristic values for these parameters were determined previously at the regional, intermediate and local scales around the AOSTRA UTF site. Table 5 presents characteristic values for the hydraulic parameters of interest for the aquifers under consideration. Literature values were used for the cases where no data were available at any scale. In this table, the values of permeability for Winnipegosis, Calumet and Wabiskaw aquifers, vertical anisotropy for Wabiskaw aquifer, porosity for Winnipegosis and Wabiskaw aquifers, and specific storage coefficient for Slave Point, Calumet and Wabiskaw aquifers are based on local-scale data (Petroleum Geoscience Section, 1993). The permeability values for Slave Point aquifer and porosity values for

Aquifer	Horizontal Permeability (m^2)	Hydraulic Conductivity (m/s)	Vertical Anisotropy	Porosity	Specific Storage (m^{-1})
Winnipegosis	1.3×10^{-15}	8.0×10^{-9}	0.2 - 0.5	0.05	n.a.
Slave Point	4.7×10^{-16}	3.2×10^{-9}	0.7	0.24	0.55×10^{-5}
Calumet	1.4×10^{-15}	1.2×10^{-8}	0.7	0.29	0.55×10^{-5}
Wabiskaw	4.1×10^{-12}	2.9×10^{-5}	0.8	0.31	1.00×10^{-5}

Table 5: Characteristic values for hydraulic parameters for selected aquifers at the AOSTRA UTF site.

Slave Point and Calumet aquifers are based on intermediate-scale data (Petroleum Geology and Basin Analysis, 1992b). Literature values were used for vertical anisotropy for the Winnipegosis aquifer (Domenico and Schwartz, 1992) and Slave Point and Calumet aquifers (Bachu and Underschultz, 1992). The hydraulic conductivity was calculated based on permeability and water viscosity data taking into account the temperature and salinity of formation waters (Rowe and Chou, 1970; Kestin et al., 1981).

Because Alberta Environment and ERCB regulations for deep injection of residual water require that the injection pressure be less than 90% of the fracturing pressure P_f of the formation, there is need to calculate or estimate its value for each of the aquifers under consideration. Using various tests and calculation methods, AOSTRA estimates the fracturing pressure in the Wabiskaw aquifer at 126 m depth to be $P_f = 2639$ kPa (AOSTRA, 1992). Unfortunately, no tests or calculations were performed for any other aquifer at the UTF site.

In absence of any other information, the fracturing pressure for the Calumet, Slave Point and Winnipegosis aquifers can be estimated from the weight of the overburden. Generally, the classical theories for evaluating the fracturing pressure assume that: (1) one of the principal stresses is vertical; (2) the horizontal stress field is isotropic; and (3) the stress increases linearly with depth. Making the conservative assumption that the tensile strength of the rocks is nil (like for fractured rock or unconsolidated sediments), then, for a penetrating fluid, the fracturing pressure P_f is equal to the minimum total stress σ_{min}. If the minimum stress is horizontal, it can be calculated from the vertical stress σ_v (Warpinski et al., 1985) according to:

$$\sigma_{min} = \frac{\nu}{1-\nu} (\sigma_v - p) + p \tag{10}$$

where ν is Poisson's ratio and p is pore or fluid pressure in the aquifer. This estimate of the horizontal stress is low for shallow depths (0-150 m) since (σ_{min} - p) is usually greater than (σ_v - p) at these depths. If the minimum stress is vertical, then simply:

$$\sigma_{min} = \sigma_v \tag{11}$$

The vertical stress at the depth D is assumed to be caused only by the weight of the overburden rocks (Warpinski et al., 1985), and is given by:

$$\sigma_v = \int_0^D \rho_b g dz \tag{12}$$

where ρ_b is the bulk density of the rocks. The overburden stress σ_v can be calculated from logs or from the lithostratigraphic column using average porosity and rock density values.

Considering the stratigraphic and lithostratigraphic succession at the AOSTRA UTF deep well WDW #1 6-18-19-12 W4 Mer (AOSTRA, 1992), measured and average porosity values (Table 5; AOSTRA, 1992; Bachu and Underschultz, 1992; Petroleum Geology and Basin Analysis, 1992b), and literature values for bulk and grain rock density (Daly et al., 1966; Johnson and Olhoeft, 1984), the following values for the vertical stress were calculated using relation (12): σ_v = 5100 kPa at 230 m depth, σ_v = 6500 kPa at 300 m depth and σ_v = 11,400 kPa at 520 m depth in the Calumet, Slave Point and Winnipegosis aquifers, respectively. It is generally believed that the minimum stress at shallow depths in the Western Canada and other basins is vertical. In this case, according to relation (11) and the assumption of nil tensile strength, the fracturing pressure P_f for the three aquifers is equal to the estimated vertical stress σ_v. Many fracturing measurements in the USA show that the fracturing gradient for rocks at shallow depths (up to 1000 m) is 23 kPa/m. Using this fracturing gradient value, the fracturing pressure for the Calumet, Slave Point and Winnipegosis aquifers is estimated to be 5300 kPa, 6900 kPa and 12,000 kPa, respectively, close to the values estimated from overburden.

Simulation of Injection

The finite element model FE3DGW (Finite Element 3-Dimensional Groundwater), developed by Pacific Northwest Laboratory (Gupta et al., 1984a, b), was used for the numerical simulation of injection of residual water at the UTF site. The various approximations and assumptions made at each step in data processing, interpretation, mathematical modelling and numerical simulation must be taken into account when assessing the results. A first approximation is made in the DST interpretation leading to pressure and hydraulic head distributions in an aquifer. A second approximation is made when obtaining structure tops and hydraulic heads at regular grid spacing from irregular well data distributions. When representing the regular grid distributions as maps, some errors are introduced caused by the grid resolution and the interpolation method. In mathematical modelling, basic assumptions are being made regarding the flow (e.g. neglect of buoyancy effects), the porous matrix (e.g. material homogeneity within each hydrostratigraphic unit), boundary conditions, etc. In numerical modelling, there are approximations and round-off errors inherent in the numerical method and space and time discretization. Thus, one cannot expect a complete match between observed and computed data.

The grid resolution is also very important for using and interpreting the results. The hydraulic head values obtained at a node representing an injection site are not the actual values at the injection well. They represent the values to be found at an equivalent distance (radius), r_e, from the well. This distance depends on the type and scale of the model, the grid resolution, and the characteristics of the hydrostratigraphic system. In two-dimensional finite difference modelling, there are expressions to compute the equivalent radius, r_e, for a well centred in an isotropic grid block of dimensions Δx and Δy (Peaceman, 1983):

$$r_e = 0.14\ (\Delta x^2 + y^2)^{1/2} \tag{13}$$

There are also expressions which take into account the horizontal anisotropy of the aquifer. Beljin (1987) has shown that the well radius, r_w, and the blocksize Δx, also have an influence on the nodal correction, r_e. Very few attempts have been made to extend these results to multi-aquifer or multi-layered well systems.

In finite element modelling, there are no such expressions to compute the equivalent radius of a node. Charbeneau and Street (1979) used finite element modelling with the discharge assigned to elements rather than nodes, and applied a correction to the hydraulic head around a well. The FE3DGW model used here is a three-dimensional, finite element, multi-layered model, with injection occurring at the grid nodes rather than the block centres. Therefore, it is impossible to compute an equivalent radius of equivalence, r_e, using a formula similar to Eq. 13. However, it may be used as a first approximation.

For modelling purposes it is necessary to define a bounded three-dimensional region with appropriate boundary conditions for fluid flow. Because the present investigation is directed at the effects of deep injection of liquid wastes, the region must be centred approximately around the injection sites and include the prospective injection aquifers and the stratigraphic successions which could be affected. All the aquifers in the hydrostratigraphic succession, except for the Upper and Wabiskaw aquifers have no lateral hydraulic boundaries in the study area. Only geometric boundaries separate the different units, with changes in the values of hydraulic parameters at interfaces. For the Wabiskaw aquifer, the boundary conditions along the outcrop are atmospheric pressure or a hydraulic head equal to outcrop elevation. Everywhere else in the subsurface, the conditions along any boundary are the values of hydraulic head from the respective potentiometric surface.

A finite element grid composed of 313 surface nodes and 291 surface elements was designed to cover an approximately radial area centred at UTF and extending to the MacKay and Dover rivers (Figure 16). The grid is finer around the injection site and coarser toward the edge. For calibration, the potentiometric surface of the Wabiskaw aquifer was calculated using the FE3DGW model. For steady-state fluid flow in an aquifer of constant hydraulic conductivity (permeability), the diffusion equation (6) simply

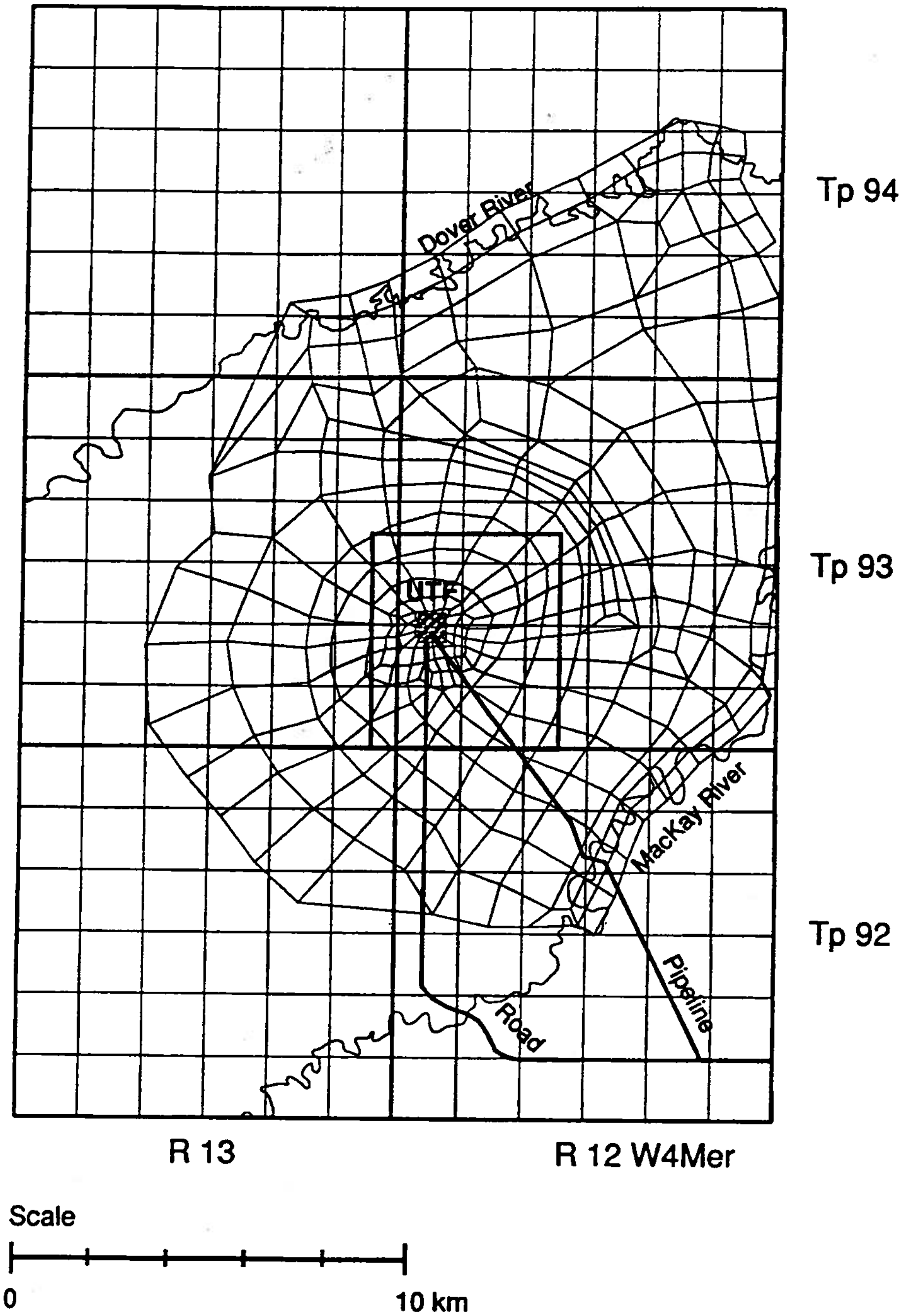
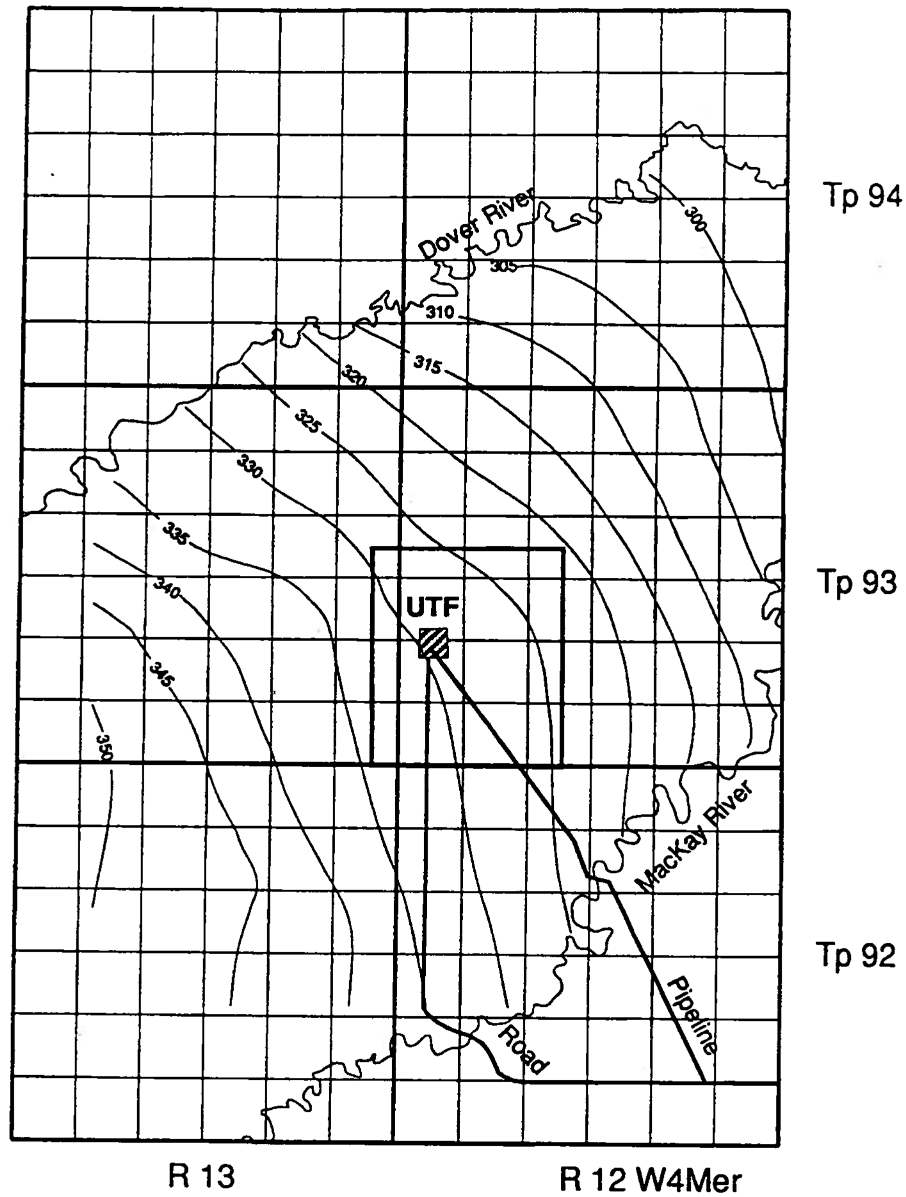


Figure 16. Plan view of the finite element grid used in numerical simulations of injection.

becomes:

$$\nabla^2 H = 0 \tag{14}$$

Its solution depends only on the boundary conditions. Figure 17 shows the computed potentiometric surface of the Wabiskaw aquifer in the area of interest. Comparison of figures 11 and 17 indicates a good match between observed and calculated hydraulic head distributions. Differences, where they exist, are caused most probably by inaccuracies and coarse resolution in obtaining the observed hydraulic head distribution first at the regional scale and then zooming-in at the local scale because of lack of data. Also, differences can be caused by actual variability in hydraulic conductivity (permeability), which was considered constant in the simulation. On the other hand, the mathematical and numerical models inherently conserve fluid mass, adjusting the potentiometric surface accordingly, which may not necessarily be the case for the observed hydraulic head distribution. Overall, the match between the observed and computed hydraulic-head distributions for the Wabiskaw aquifer is considered satisfactory. No steady-state calibration was performed for the Calumet and Slave Point aquifers, because of the lack of potentiometric surfaces associated with these aquifers. Also, no calibration was made for the Winnipegosis aquifer because of strong buoyancy effects present in this aquifer, which are not taken into account by the diffusion equation (6) and its steady-state equivalent (14).



Scale

0 10 km

Contour Interval: 5 m

Figure 17. Calculated (simulated) distribution of freshwater hydraulic head (m) in the Wabiskaw aquifer.

The simulations of injection were performed using the diffusion equation (6) in which the injection rate q was varied according to AOSTRA's forecast (AOSTRA, 1992). The forecasted injection-rate variation was approximated with a function varying in a stepwise fashion (Figure 18) to allow constant injection rates during discrete time steps. The simulations were carried out for a period of injection starting in August, 1992 and ending in March, 1994. In order to check the sensitivity of the results with respect to the size of the time step, two simulations were carried out for injection in the Wabiskaw aquifer, one for $\Delta t = 5$ days and the other for $\Delta t = 10$ days. For the injection node at the end of the injection period, the difference between the computed hydraulic heads using the two time steps is negligible, so all the simulations were subsequently carried out with a time step $\Delta t = 10$ days. For the Wabiskaw aquifer, the computed steady-state hydraulic head distribution (Figure 17) was used as initial conditions rather than the observed hydraulic heads (Figure 11), because of the model's inherent conservation of existing fluid mass. For the other aquifers (Calumet, Slave Point and Winnipegosis), a virtual initial distribution of hydraulic heads was created in each case by imposing an artificial constant hydraulic head along the domain boundary. Because of the linearity of the diffusion equation (6), the choice of initial conditions for these confined aquifers does not affect the simulation results in terms of hydraulic head (pressure) build-up because the latter is additive to the initial distribution.

Figure 19 shows the simulated hydraulic-head buildup at the injection node when

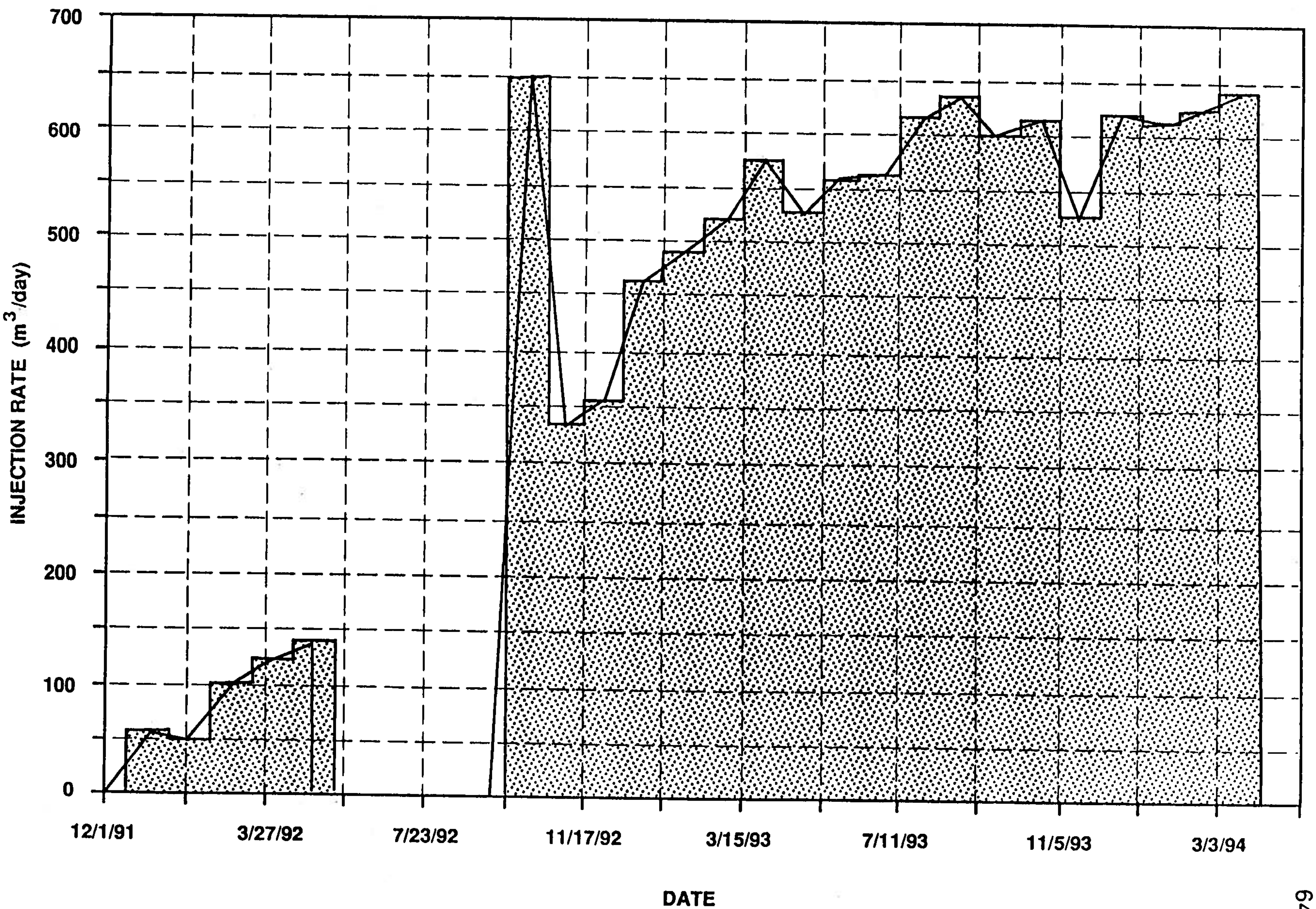


Figure 18. Forecasted injection rate at the UTF site (from AOSTRA, 1992)

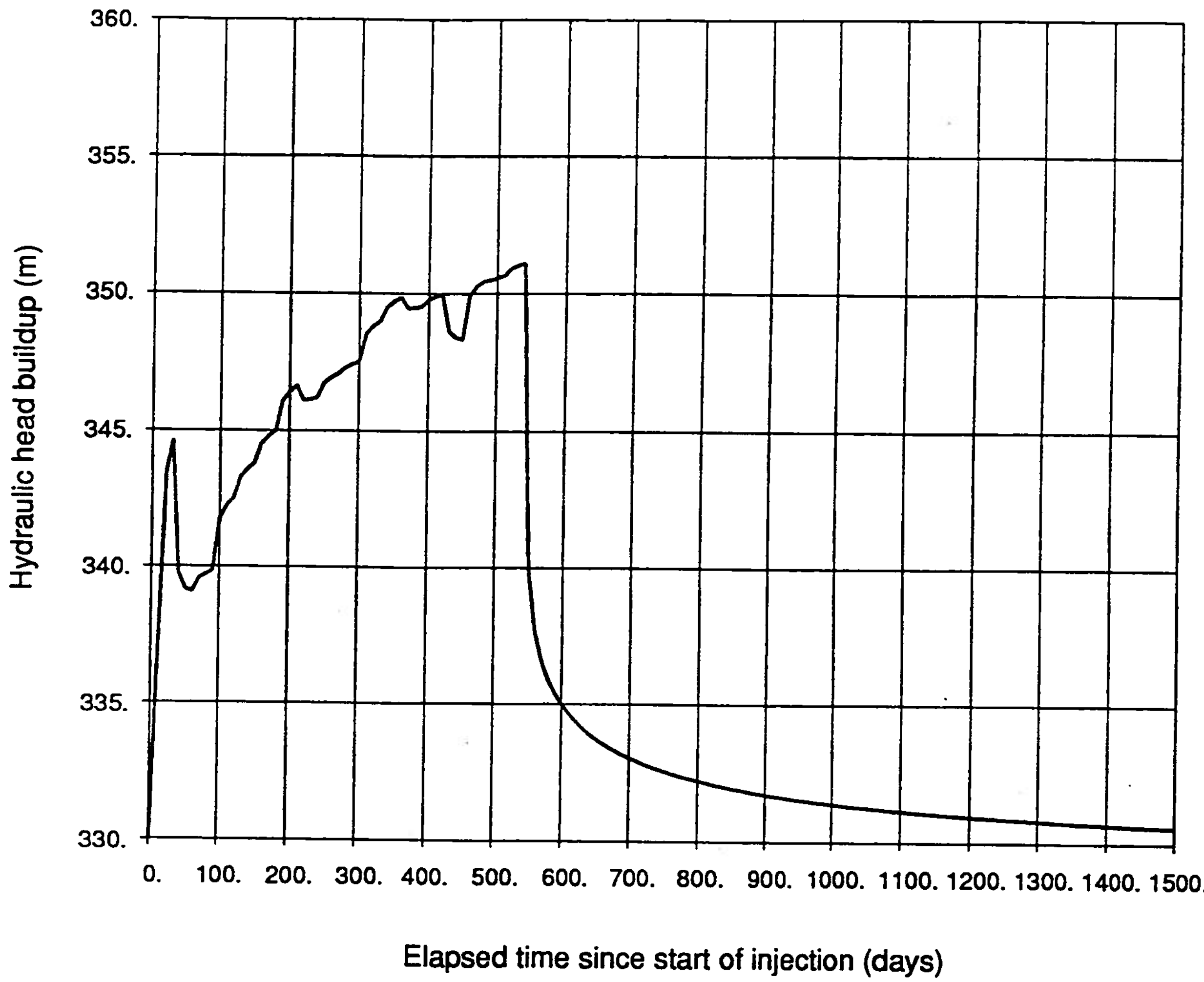


Figure 19. Calculated hydraulic-head buildup in the Wabiskaw aquifer at the injection node assuming a hydraulic conductivity of 2.9×10^{-5} m/s (permeability of 2.5 darcies).

injection takes place in the Wabiskaw aquifer, for the set of hydraulic parameters of Table 5 and injection rate of Figure 18. The variation in hydraulic head buildup closely follows the variation in the injection rate (Figure 18). After the cessation of injection, the hydraulic head (pressure) buildup will rapidly decay assimptotically to the pre-injection conditions (Figure 19). It must be noted that, because of the resolution of the finite element grid, this hydraulic-head buildup is actually not at the injection well itself, but at an approximate distance (radius of equivalence) of $r_e = 200$ m. The hydraulic head buildup at the end of the period is $\Delta H = 52$ m. The hydraulic head equivalent to 90% of the fracturing pressure of $P_f = 2639$ kPa is 550.7 m, corresponding to a buildup of 220.7 m. Thus, the simulation shows that, for the forecasted rates and duration of injection, the pressure in the aquifer, including the injection well, will remain below 90% of the fracturing pressure, as required by Alberta Environment and ERCB regulations. Figure 20 shows the areal spread of the pressure buildup in the Wabiskaw aquifer at the end of the injection period, as indicated by the contour of the hydraulic head increase $\Delta H = 1$ m. The radius of influence is approximately 4 km. The simulations also indicate that the pressure buildup will not reach the boundary of the model area, including the MacKay and Dover rivers. Also, the results show that the choice of the model area was adequate in that the boundaries are sufficiently afar as not to influence the solution. Because the solution is most sensitive to hydraulic conductivity (permeability), an additional simulation was carried out for a hydraulic conductivity ten times lower than indicated by core data. This hydraulic conductivity corresponds to a permeability value of 250 md, and is considered a low limit for the unconsolidated sand Wabiskaw aquifer at the local UTF scale. The pressure

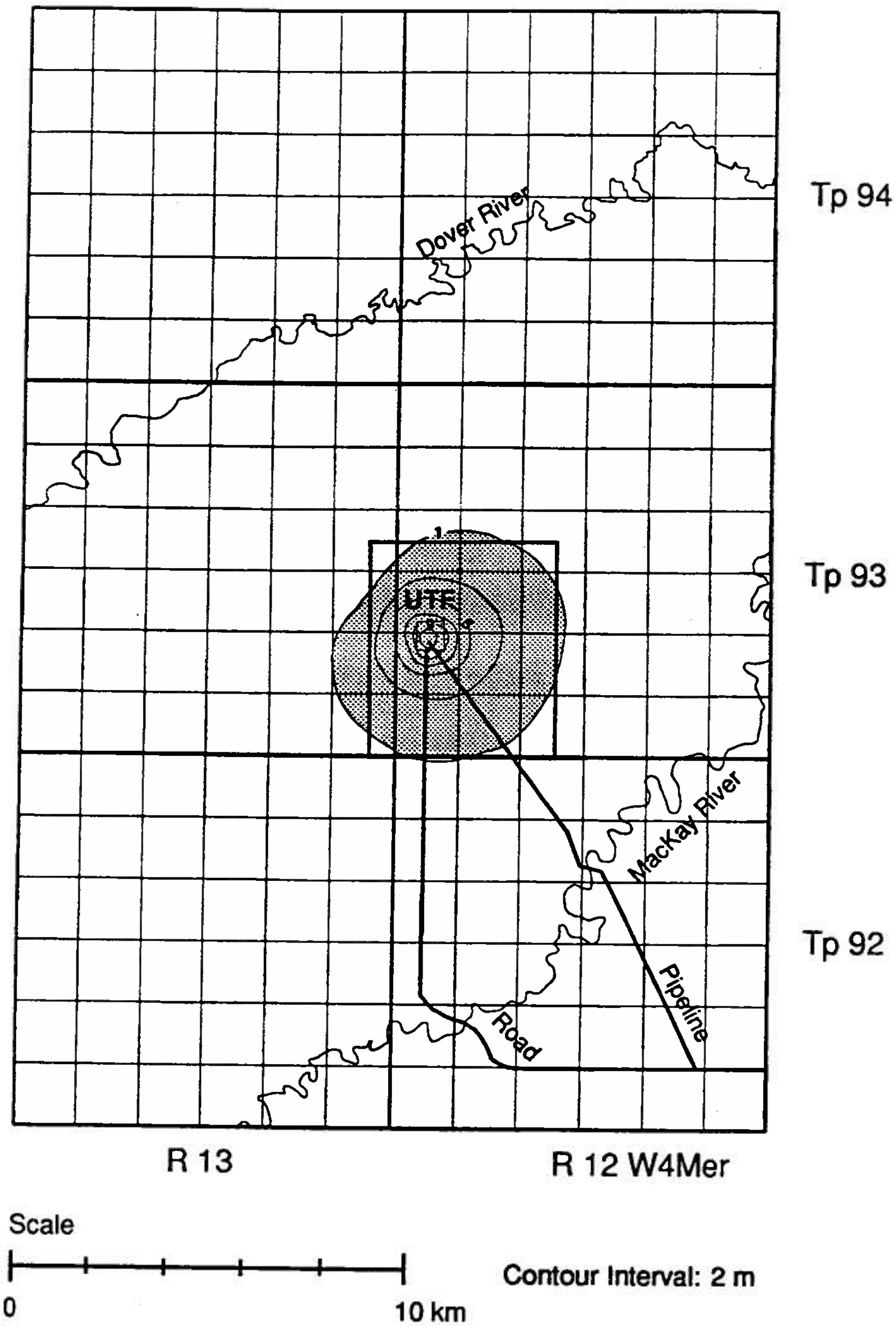


Figure 20. Areal spread of the pressure buildup in the Wabiskaw aquifer at the end of the injection period, for a hydraulic conductivity of 2.9×10^{-5} m/s (permeability of 2.5 darcies).

buildup in this case is ΔH = 160 m at the end of the injection period (Figure 21), equivalent to a hydraulic head of 490 m, still below the limit imposed by regulatory agencies. At the injection well itself the pressure buildup would be higher. The spread of pressure buildup, or radius of influence, is smaller in this case, approximately 2 km (Figure 22), because of reduced hydraulic conductivity (permeability) diffusing away the pressure increase at the injection well. This simulation represents an extreme worst-case scenario because the rock permeability in the Wabiskaw aquifer is generally higher.

Given the linearity of the diffusion equation (6), it was expected that the effect of considerably lower hydraulic conductivity values (Table 5) for the tight limestone and carbonate Devonian aquifers (Calumet, Slave Point and Winnipegosis) will be of significantly higher pressure buildups than for the Wabiskaw aquifer. The numerical simulations confirmed this, with the fracturing pressure being rapidly reached within each aquifer in a matter of weeks. Once fracturing occurs, the hydraulic parameters change and numerical simulations with the values of Table 5 are no longer representative. The simulations results are not shown here for this reason. In order to avoid fracturing, the injection rate (i.e. volume) has to be significantly lower. Given the fact that, by regulation, the injection pressure has to be below the fracturing pressure, it is evident that none of the Devonian aquifers at the UTF site is capable of taking the volume of residual water to be disposed of during the projected period of UTF operations.

The numerical simulations of hydrodynamic effects of injection into either one of

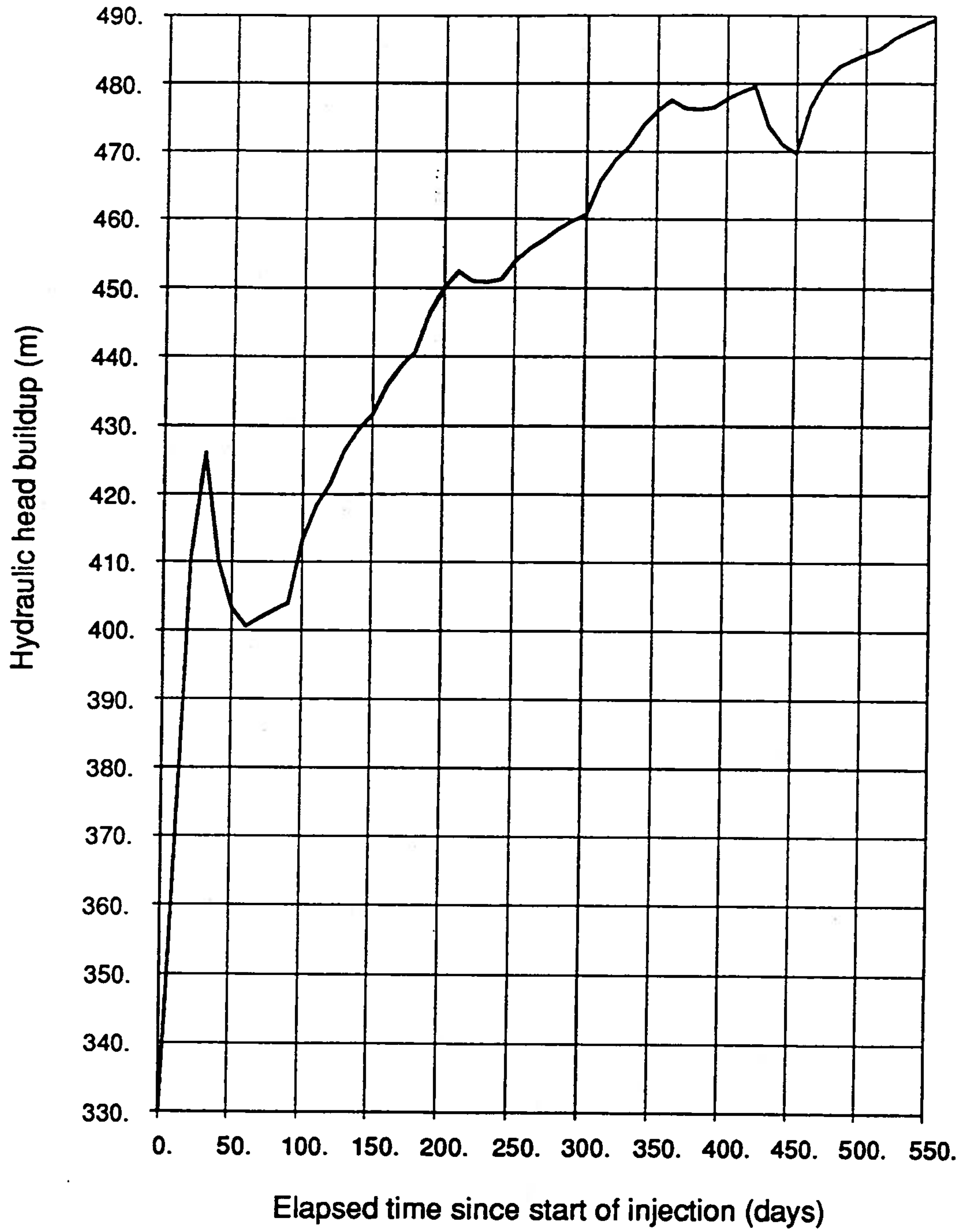


Figure 21. Calculated hydraulic-head buildup in the Wabiskaw aquifer at the injection node assuming a hydraulic conductivity of 2.9×10^{-6} m/s (permeability of 0.25 darcies).

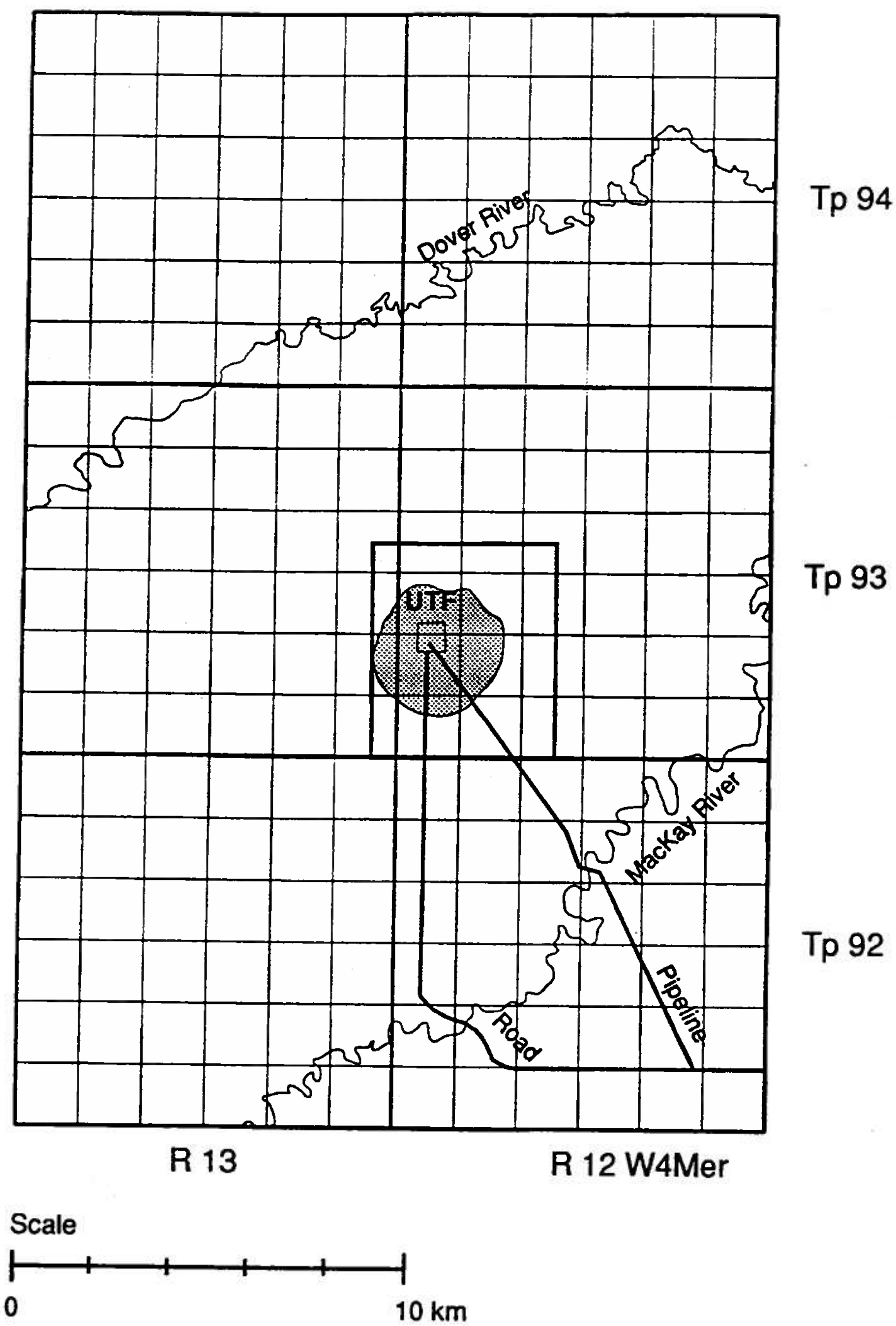


Figure 22. Areal spread of the pressure buildup in the Wabiskaw aquifer at the end of the injection period, for a hydraulic conductivity of 2.9×10^{-6} m/s (permeability of 0.25 darcies).

the Winnipegosis, Slave Point, Calumet and Wabiskaw aquifers at the UTF site indicate that, from a fluid flow point of view, the Wabiskaw aquifer is the only one capable of accepting the projected volumes of residual water to be disposed of. The permeability of the Devonian aquifers (Winnipegosis, Slave Point and Calumet) is too low to allow injecting water at the proposed rate without fracturing the rock. On one hand, fracturing will have the positive effect of increasing aquifer permeability, possibly allowing the injection of the desired volume of residual water. On the other hand, fracturing may have the uncontrolled negative effects of creating vertical conduits for the injected water across confining aquitards and aquicludes. If Alberta Environment and ERCB regulations are to be respected, then the Devonian aquifers at the UTF site are not suitable for injection of residual water.

CONCLUSIONS

Expansion of the AOSTRA Underground Test Facility operations requires disposal of residual water, which is proposed to be achieved by injecting it into a deep formation for a period of 2 years and a total volume of 900,000 m^3, until a long term solution is found. AOSTRA plans and is already testing disposal by injection into the Cretaceous Wabiskaw sands. This is the first aquifer below the Clearwater aquitard, which separates it from the protected shallow groundwater zone above. This study, undertaken jointly by the Alberta Research Council and Environment Canada with data support and cooperation from AOSTRA, examined the geochemical and hydrodynamic effects of injection and assessed the suitability for deep injection of residual water in the Wabiskaw and other deep aquifers at the UTF site.

Regional to local-scale geological and hydrogeological studies previous to this report identified five confined aquifer systems in the sedimentary succession at the UTF site. These are, in ascending order: Winnipegosis, Slave Point, Calumet, Devonian-Cretaceous and Wabiskaw. These aquifer systems are separated, respectively, by: the Prairie-Fort Vermilion aquiclude system, the Firebag and Christina aquitards, and the bitumen-saturated McMurray-Wabiskaw aquitard. The Wabiskaw aquifer is isolated from the unconfined Upper aquifer system by the Clearwater aquitard, which also delineates the lower limit of the protected shallow groundwater zone.

Numerical modelling of both geochemical and hydrodynamic effects of deep injection at the UTF site indicate that the Wabiskaw aquifer is the only aquifer capable of accepting the projected volume of residual water to be disposed of.

The Winnipegosis aquifer has very low porosity and permeability, particularly in the upper portion where the original pore space is plugged with salt originating from the overlying Prairie Formation salt deposits. Because of particularly low permeability, the pressure increase induced by injection will not easily dissipate, leading to a pressure buildup at the injection well which will rapidly reach the rock fracturing threshold estimated at 11,400 kPa. This aquifer also has a high potential for formation plugging by precipitation of silica, dolomite and calcite which would be faster than in any other formation. This will have the effect of reducing the permeability and the pore volume available for injection, leading probably to a more rapid pressure build-up than predicted from hydrodynamic considerents alone.

The dominantly limestone aquifers of the Devonian Beaverhill Lake Group (Slave Point and Calumet) have higher porosity than the Winnipegosis aquifer, but permeability of the same order of magnitude. For these aquifers too the pressure buildup will reach the fracturing threshold (6500 kPa and 5100 kPa, respectively) relatively early in the injection operation. Although the potential and rate of mineral precipitation for these aquifers are lower than for the Winnipegosis aquifer, pore plugging will probably further decrease the porosity and permeability of rocks close to the injection well, again with the expected effect of enhanced pressure build-up.

The Moberly aquifer (Devonian-Cretaceous aquifer system) at the top of the Devonian sedimentary succession probably has hydraulic and geochemical characteristics similar to the Slave Point and Calumet aquifers. Moreover, this unit hosts the tunnels and access shafts for bitumen extractions, thus eliminating it a priori from considering it as a possible injection target. The water sands of the Cretaceous McMurray Formation (Devonian-Cretaceous aquifer system) are also unsuitable for injection because of their limited volume, hydraulic continuity with the Moberly aquifer, and possible flow paths along the sub-Cretaceous unconformity.

The last aquifer in the sequence, the Wabiskaw, is the only one at the UTF site suitable for injecting the projected volume of residual water at the given rates. The porosity of this aquifer is high (around 30%), but, more importantly, the permeability is very high (around 2 darcys), 2-3 order of magnitude higher than for the Devonian aquifers. Thus, the pressure induced by injection will rapidly diffuse away, with the effect that the pressure buildup will most probably remain all the time significantly below the fracturing threshold estimated to be 2370 kPa. The radius of influence (pressure buildup) is estimated to be approximately 4000 m from the injection well at the end of the operation. From a geochemical point of view, the Wabiskaw aquifer is also the most suitable for injection because of the lowest potential and rates of mineral precipitation. Because of very slow low-temperature kinetics of silica and dolomite precipitation, it is expected that any mineral precipitation will occur far from the injection well and will not significantly alter the hydraulic properties of the Wabiskaw aquifer. The possible changes in porosity and permeability, difficult to locate and quantify, will probably be within the range of data uncertainty caused by measurement error, resolution and distribution.

In conclusion, preliminary numerical modelling of geochemical and hydrodynamic effects of injecting residual water at the AOSTRA UTF site shows that only the Wabiskaw aquifer satisfies the requirements imposed by regulatory agencies, namely that the injection pressure remains below the fracturing threshold of rocks for the duration of the projected disposal operation, confirming AOSTRA's choice. The present study addressed only geochemical and hydrodynamic aspects, without considering any other factors. Future, more in depth evaluation of the effects of injecting residual water in the Wabiskaw aquifer should consider additional factors like: 1) spatial variability in rock properties (permeability and porosity) in the Wabiskaw aquifer; 2) higher temperature of injected water than aquifer water; 3) higher concentration of Ca, SO_4 and SiO_2 in the residual water than in the aquifer water; and 4) presence of organic materials in the injected water, if significantly different from the aquifer water. Also, future studies should be performed at a higher spatial resolution now that this preliminary evaluation identified a radius of influence of approximately 4000 m around the injection well. If injection takes place in more than one well, as simulated in the present study, this should also be accounted for. Finally, the start of injection in 1992 and any monitoring performed since then should be used to calibrate the numerical model, particularly with respect to permeability and porosity and any other relevant parameters.

REFERENCES

AOSTRA - Alberta Oil Sands Technology and Research Authority, (1992): Application to develop waste water disposal wells at the Underground Test Facility; Submitted to the Energy Resources Conservation Board.

Bachu, S. and J.R. Underschultz (1992): Regional-scale porosity and permeability variations, Peace River Arch area, Alberta, Canada; American Association of Petroleum Geologists, v. 76, No. 4, pp. 547-562.

Basin Analysis Group (1988): Feasibility study to determine the possible impact on the subsurface environment of future bitumen recovery at AOSTRA Underground Test Facility; Report to Environment Canada, Conservation and Protection, 104 p.

Beljin, M.S. (1987): Representation of individual wells in two-dimensional ground water modelling; *in* Proceedings of the NWWA/IGWMC Conference - Solving ground water problems with models, February 10-12, 1987, Denver, Colorado, National Water Well Association, dublin, Ohio, pp. 340-351.

Charbeneau, R.J. and R.L. Street, 1979: Modeling groundwater flow fields containing point singularities: a technique for singularity removal: Water Resources Research, v. 15, pp. 583-594.

CPA - Canadian Petroleum Association, (1990): Production Waste Management Handbook for the Alberta Petroleum Industry, Calgary, Alberta.

Daly, R.A., Manger, G.E. and Clark Jr., S.P. (1966): Density of Rocks; in Handbook of Physical Constants (S.P. Clark, ed.), The Geological Society of America Memoir 97, New York, pp. 19-26.

Davies, P.B., (1987): Modelling areal, variable density, ground-water flow using equivalent freshwater head-analysis of potentially significant errors; in Proceedings of the NWWA/IGWMC Conference - Solving ground water problems with models, National Water Well Association, Dublin, Ohio, p. 888-903.

Domenico, P.A., and Schwartz, F.W., (1990): Physical and Chemical Hydrogeology; John Wiley & Sons, 824 p.

Glaister, R.P. (1991): Facies description of Keg River (Methy) cores; Technical Report to AOSTRA, 9 p.

Gupta, S.K., C.R. Cole, F.W. Bond and A.M. Monti, (1984a). Finite-element three-dimensional groundwater (FE3DGW) flow model formulation, program listings and users' manual; Pacific Northwest Laboratory, Richland, Washington.

Gupta, S.K., C.R. Cole and G.F. Pinder, (1984b): A finite-element three-dimensional groundwater (FE3DGW) model for a multiaquifer system; Water Resources Research, v. 20, pp. 553-563.

Johnson, G.R. and Olhoeft, G.R. (1984): Density of Rocks and Minerals; in CRC Handbook of Physical Properties of Rocks (R.S. Carmichael, ed.), CRC Press Inc., Boca Raton, v. III, pp. 2-38.

Kestin, J., Khalifa, H.E., and Correia, R.J., (1981): Tables of the dynamic and kinematic viscosity of aqueous NcCl solutions in the temperature range 20-150°C and the pressure range 0.1 - 35 MPa; Journal of Physical and Chemical Reference Data, v. 10(1), p. 71-87.

Kharaka, Y.K., Gunter, W.D., Aggarwal, P.K., Perkins, E.H. and DeBraal, J.D., (1988): SOLMINEQ.88: A computer program for geochemical modelling of water-rock interactions; U.S. Geological Survey Water-Resources Investigations Report 88-4227, 420 p.

de Marsily, G., (1986): Quantitative Hydrogeology; Academic Press, San Diego, 440 p.

Nelson, L.R., Stevens, J.P. and Ksienski, N., (1991): Disposal of produced water at in situ pilot operations in Athabasca; Proceedings of the Environmental Committee Meeting of the Canadian Heavy Oil Association on "Water Management of Heavy Oil Operations", Calgary, November 12, 1991.

Peaceman, D.W., (1983). Interpretation of well-block pressures in numerical reservoir simulation with nonsquare grid blocks and anisotropic permeability; Society of Petroleum Engineers Journal, v. 23, no. 3, pp. 541-543.

Perkins, E.H., Kharaka, Y.K., Gunter, W.D. and DeBraal, J.D., (1988): Geochemical modelling of water-rock interactions using SOLMINEQ.88, in Chemical Modelling of Aqueous Systems II, (D.C. Melchior and R.L. Bassett, eds.).

Petroleum Geology and Basin Analysis Group (1991): Regional geology and hydrostratigraphy in Northeast Alberta; report to Environment Canada, Conservation and Protection, 161 p.

Petroleum Geology and Basin Analysis Group (1992a): Regional subsurface hydrogeology in Northeast Alberta; report to Environment Canada, Conservation and Protection, 150 p.

Petroleum Geology and Basin Analysis Group (1992b): Baseline Hydrogeological regime at the intermediate scale, AOSTRA Underground Test Facility; report to Environment Canada, Conservation and Protection, 134 p.

Petroleum Geoscience Section, (1993): Local-scale baseline subsurface hydrogeology at the AOSTRA Underground Test Facility; Report to Environment Canada, Conservation and Protection, 120 p.

Rowe, A.M., and Chou, J.C.S., (1970): Pressure-volume-temperature-concentration relation of aqueous NcCl solutions; Journal of Chemical Engineering Data, v. 15(1), p. 61-66.

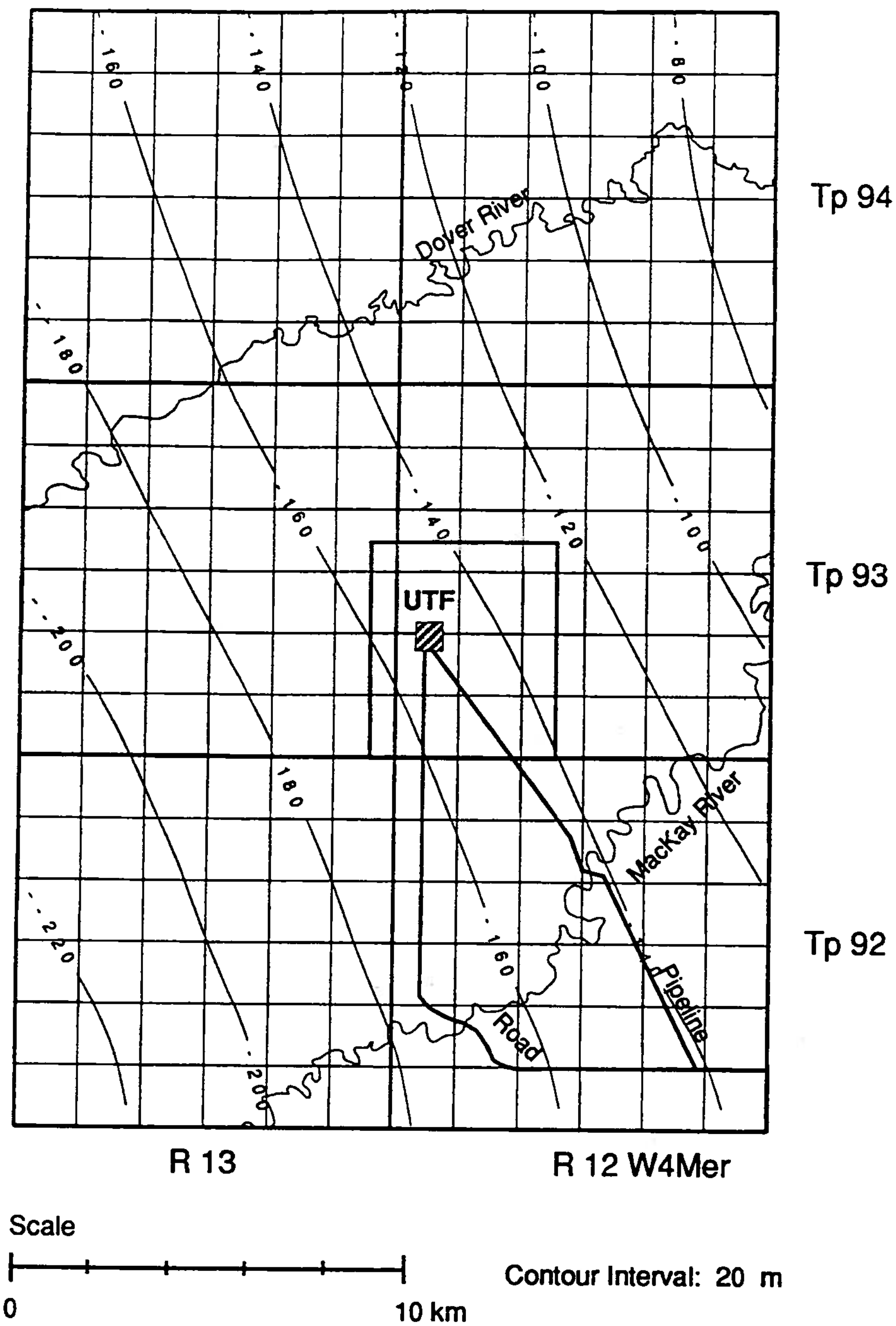
Sadler, K.W., (1991): A regulatory perspective on water management for oil sands operations; Proceedings of the Environmental Committee Meeting of the Canadian Heavy Oil Association on "Water Management of Heavy Oil Operations", Calgary, Nov. 12, 1991.

Toth, J., (1963): A theoretical analysis of groundwater flow in small drainage basins; Journal of Geophysical Research, v. 68, pp. 4795-4812.

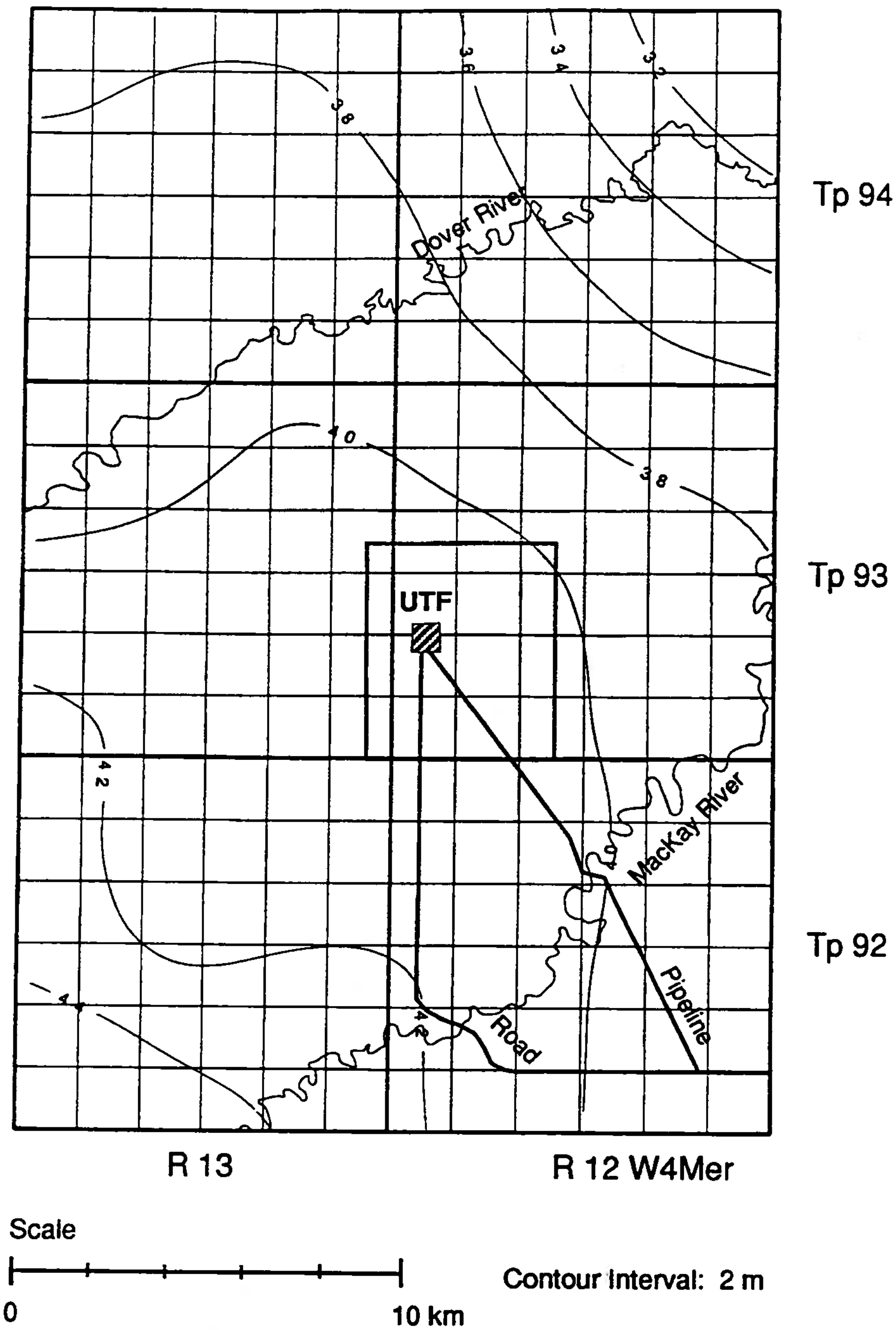
Toth, J., (1978): Gravity-induced cross-formational flow of formation fluids, Red Earth region, Alberta, Canada: Analysis, patterns, and evaluation: Water Resources Research, v. 14, p. 805-843.

Warpinski, N.R., Branagan, P. and Wilmer, R. (1985): In-situ stress measurements at US's DOE's multiwell experiment site, Mesaverde Group, Rifle, Colorado; Journal of Petroleum Technology, v. 37, pp. 517-536.

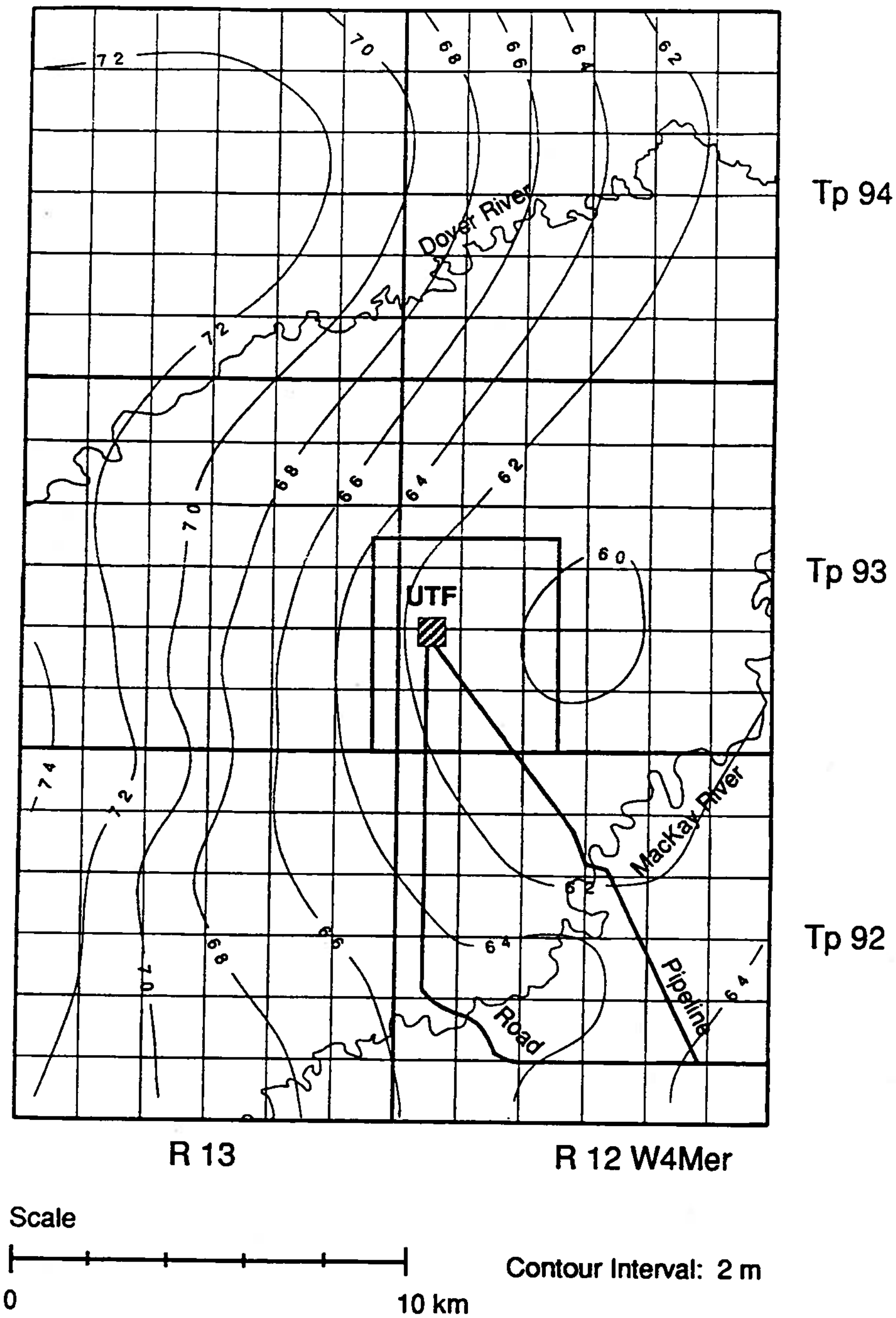
APPENDIX A - ISOPACHS OF THE HYDROSTRATIGRAPHIC UNITS AT THE AOSTRA UTF SITE



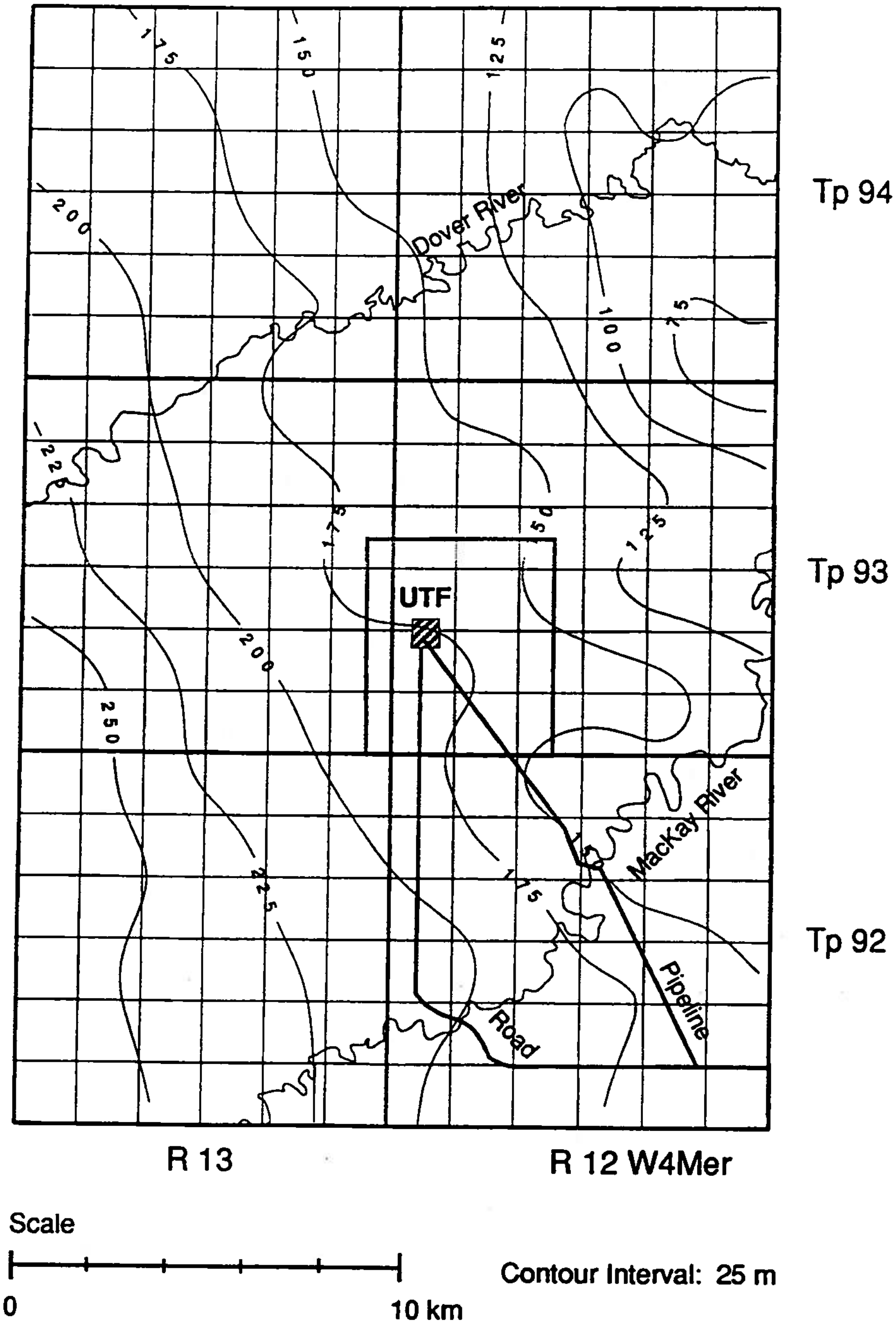
A-1. Structure map of the Precambrian crystalline basement.



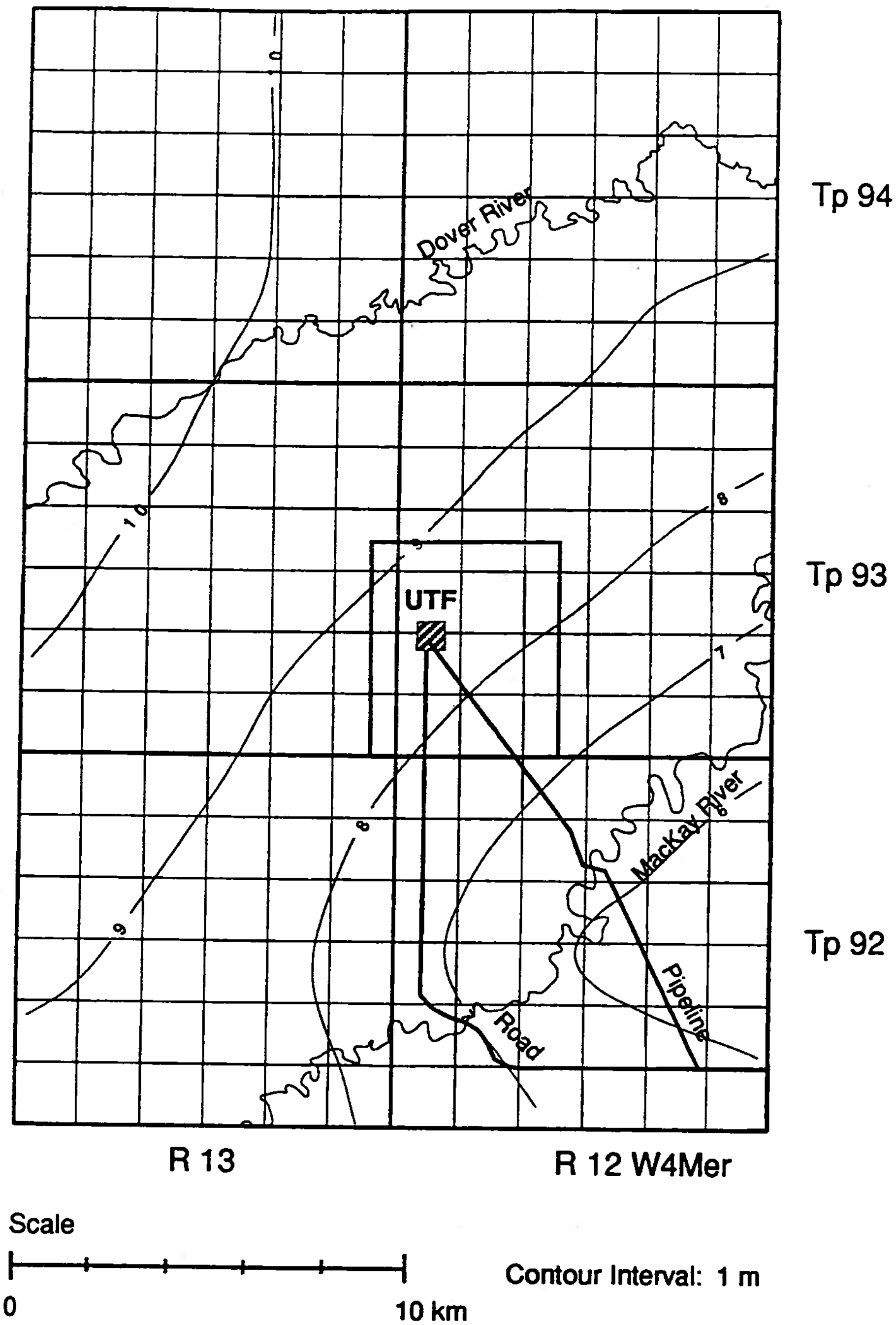
A-2. Isopach of the Basal aquitard system.



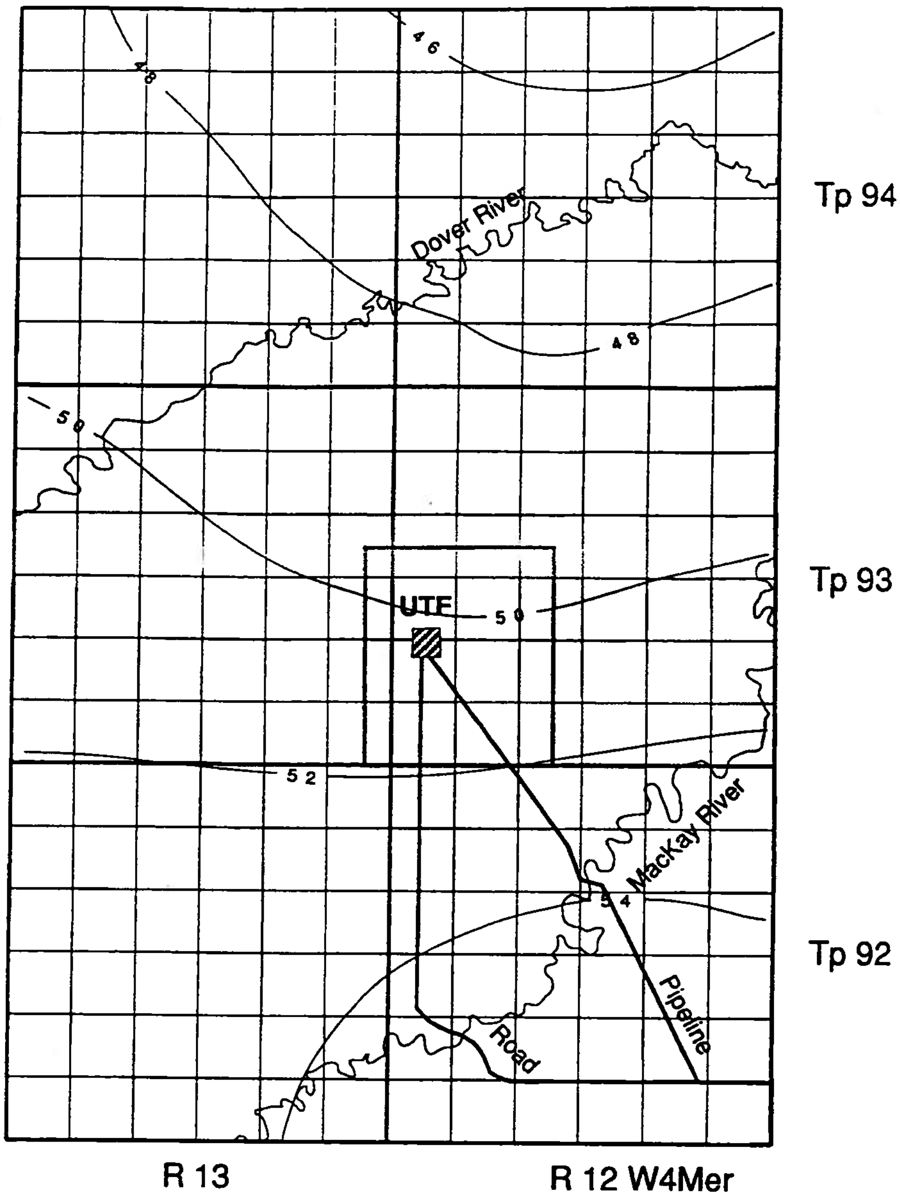
A-3. Isopach of the Winnipegosis aquifer.



A-4. Isopach of the Prairie aquiclude system.



A-5. Isopach of the Slave Point aquifer.

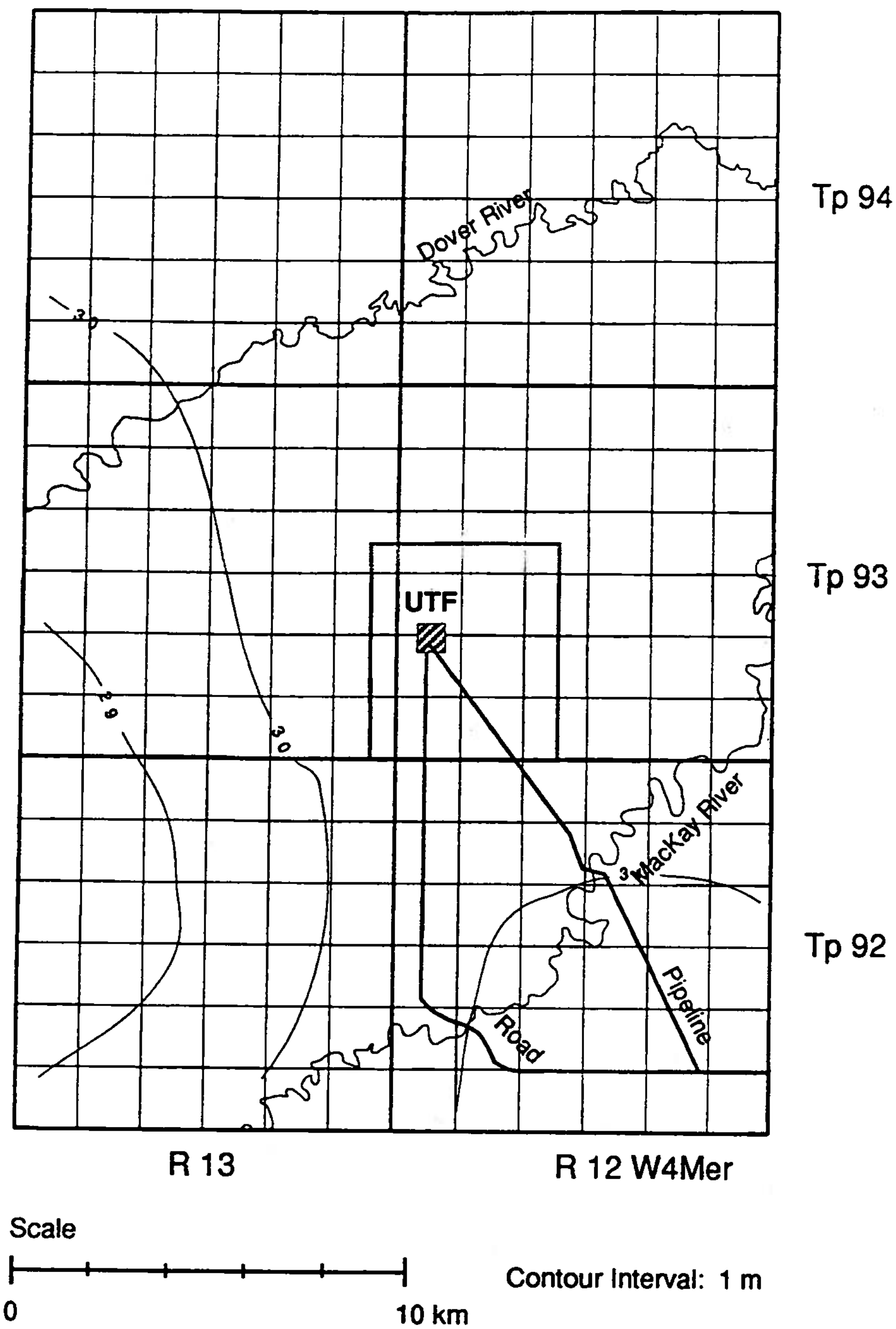


Scale

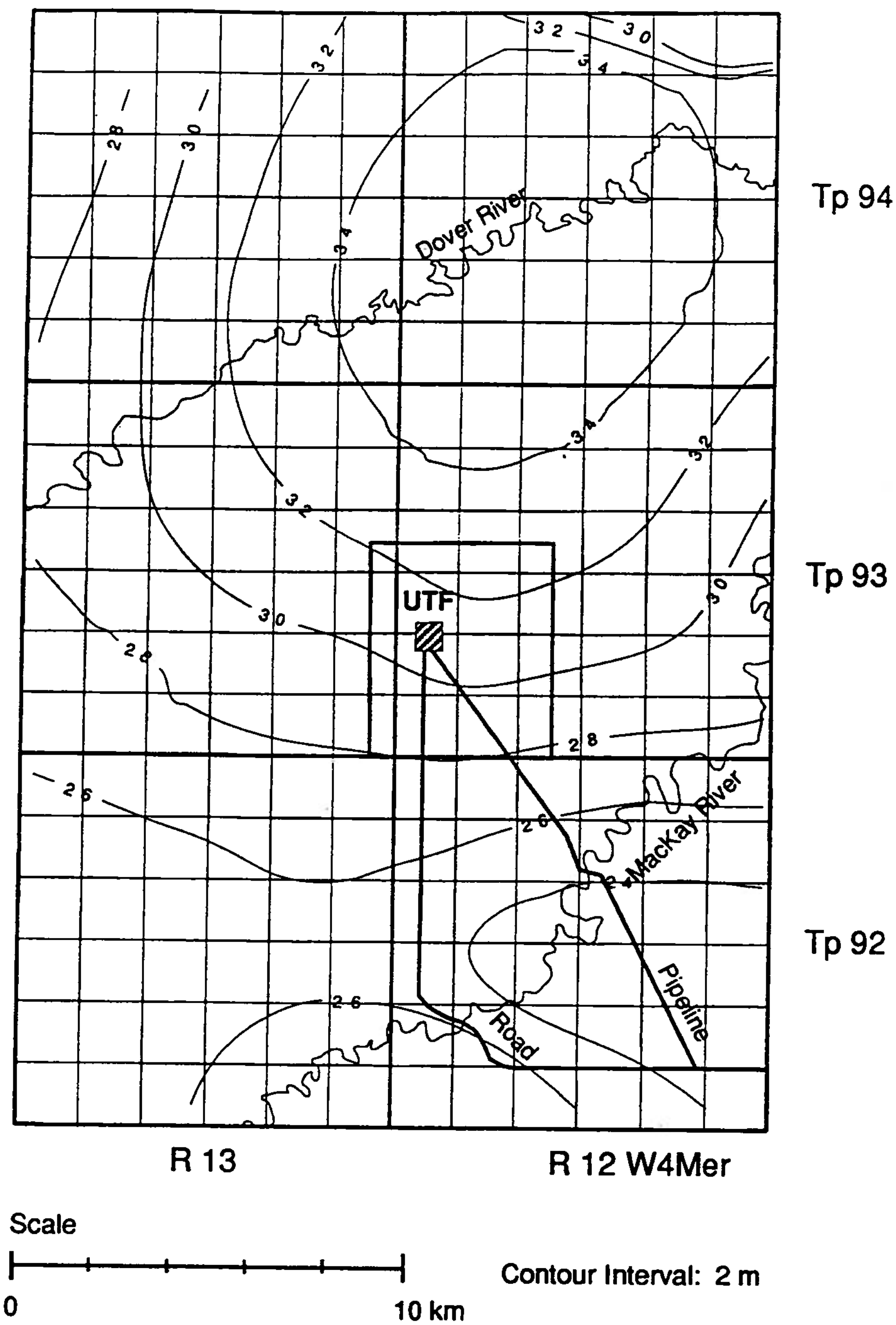
0 10 km

Contour Interval: 2 m

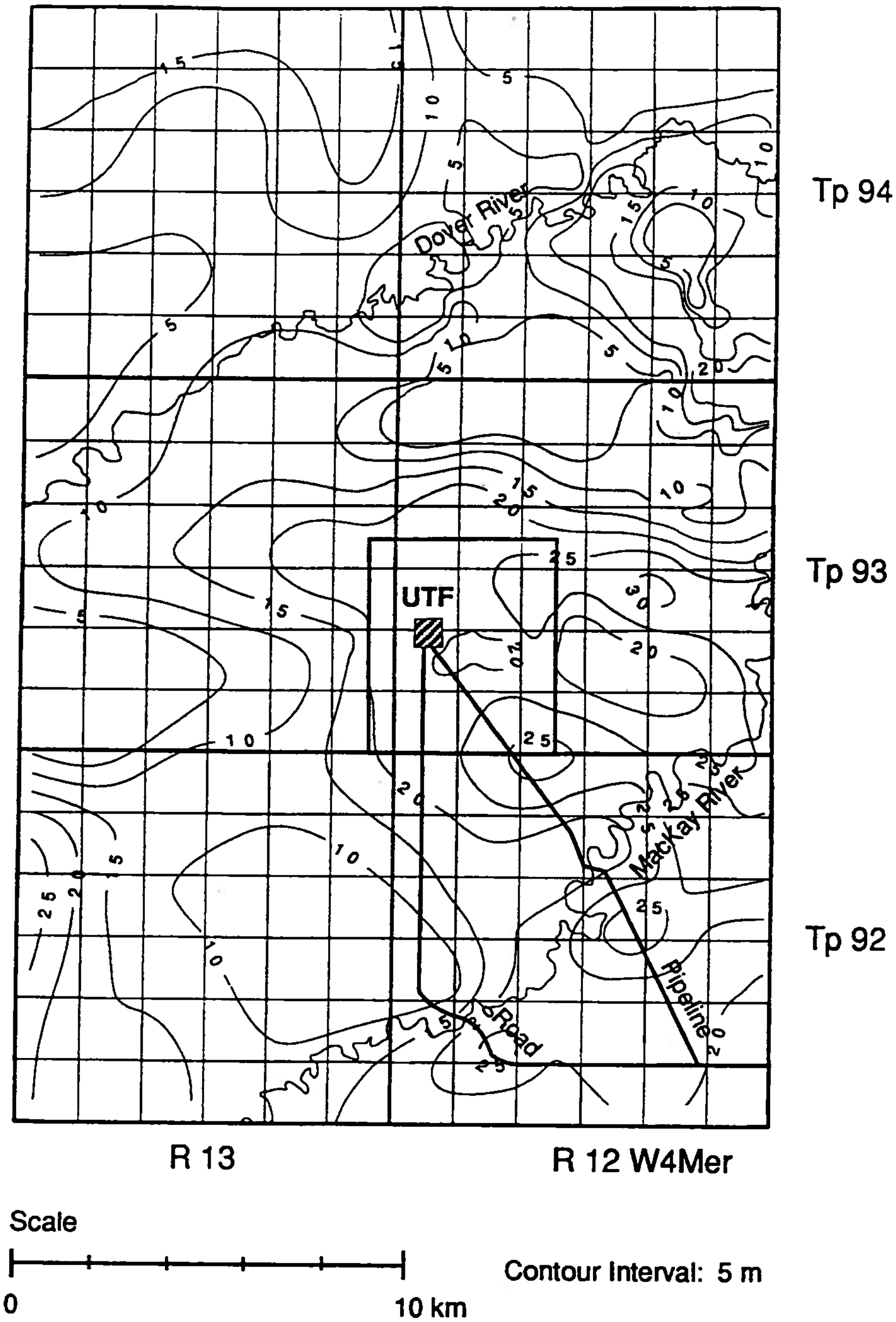
A-6. Isopach of the Firebag aquitard.



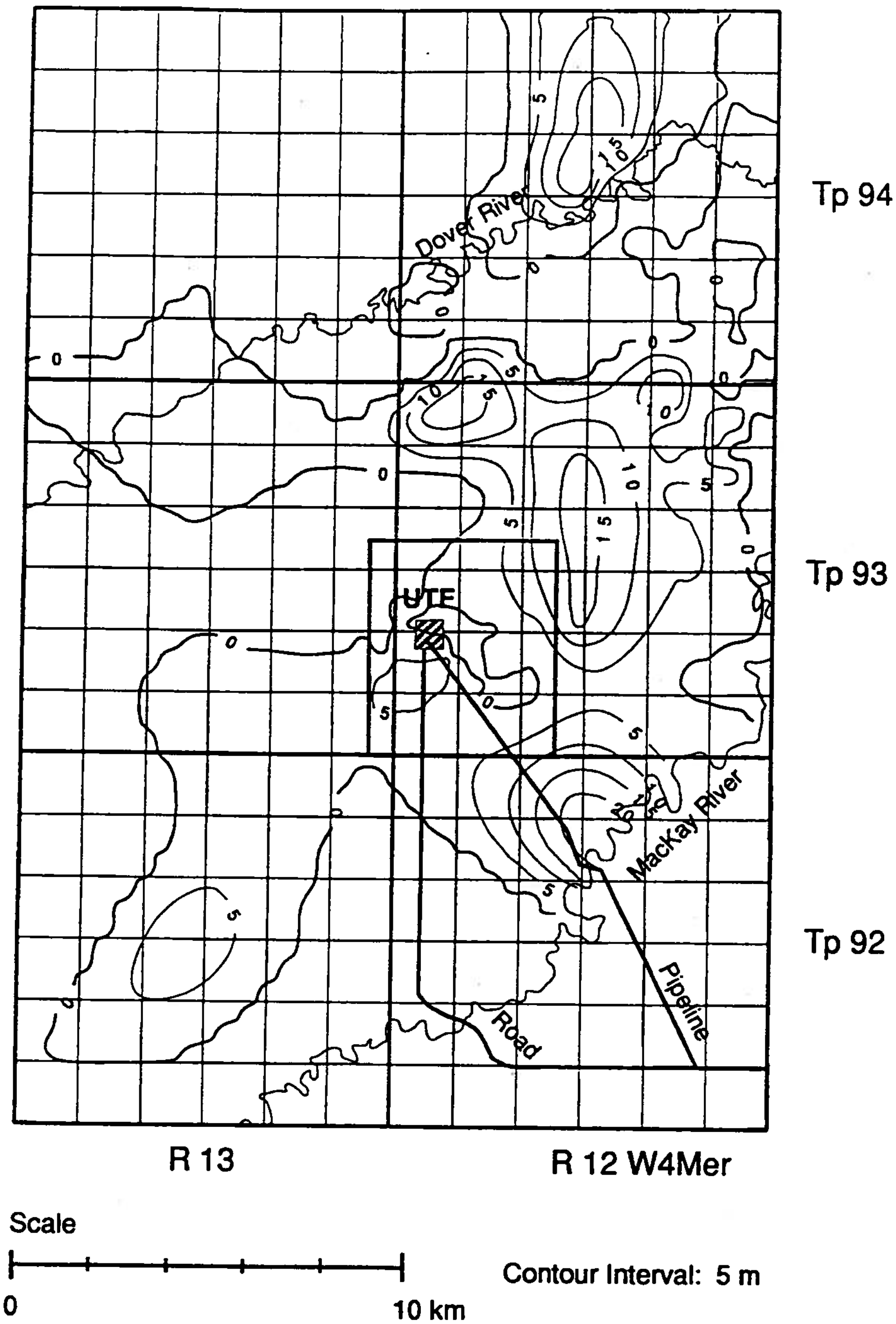
A-7. Isopach of the Calumet aquifer.



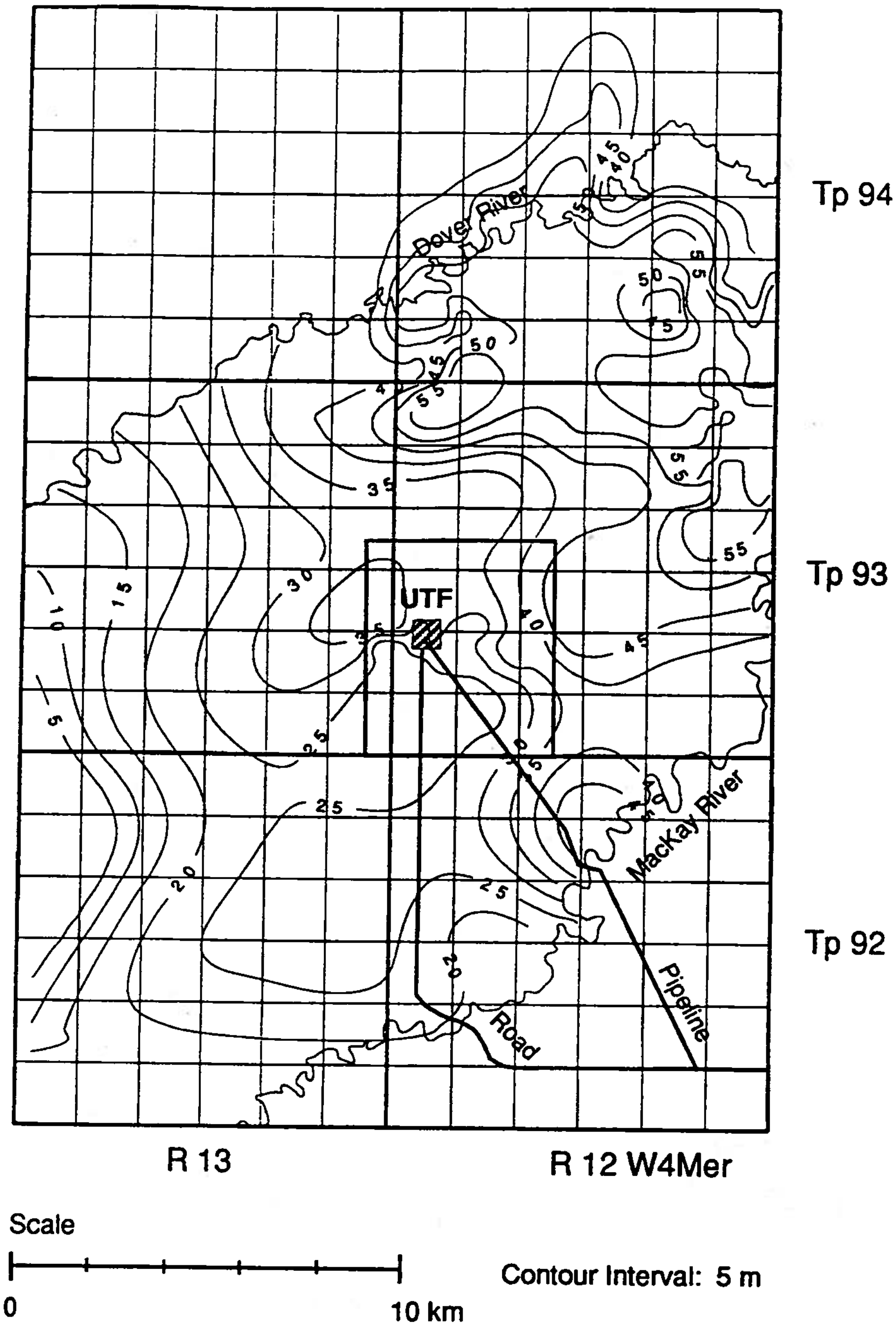
A-8. Isopach of the Christina aquitard.



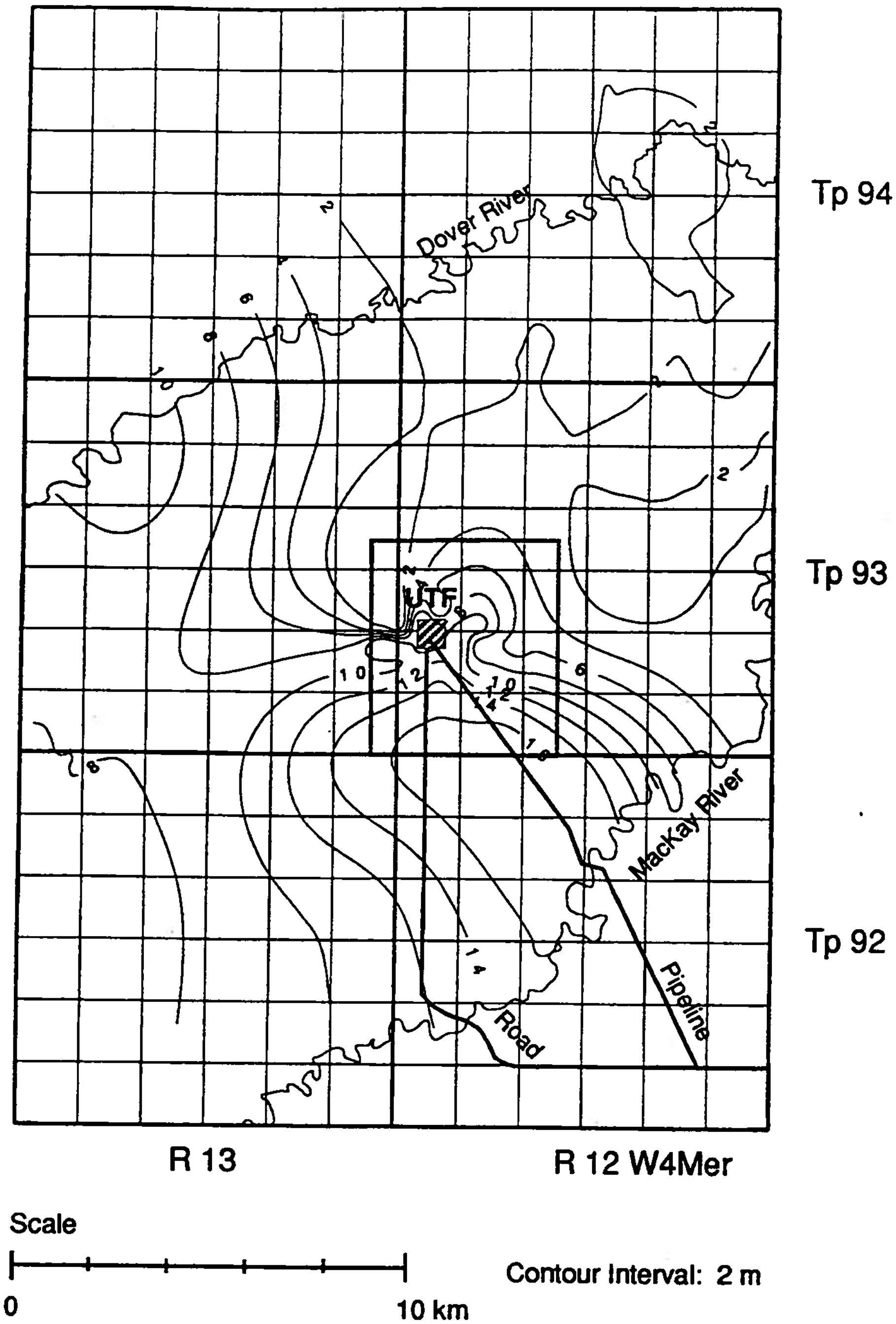
A-9. Isopach of the Moberly aquifer.



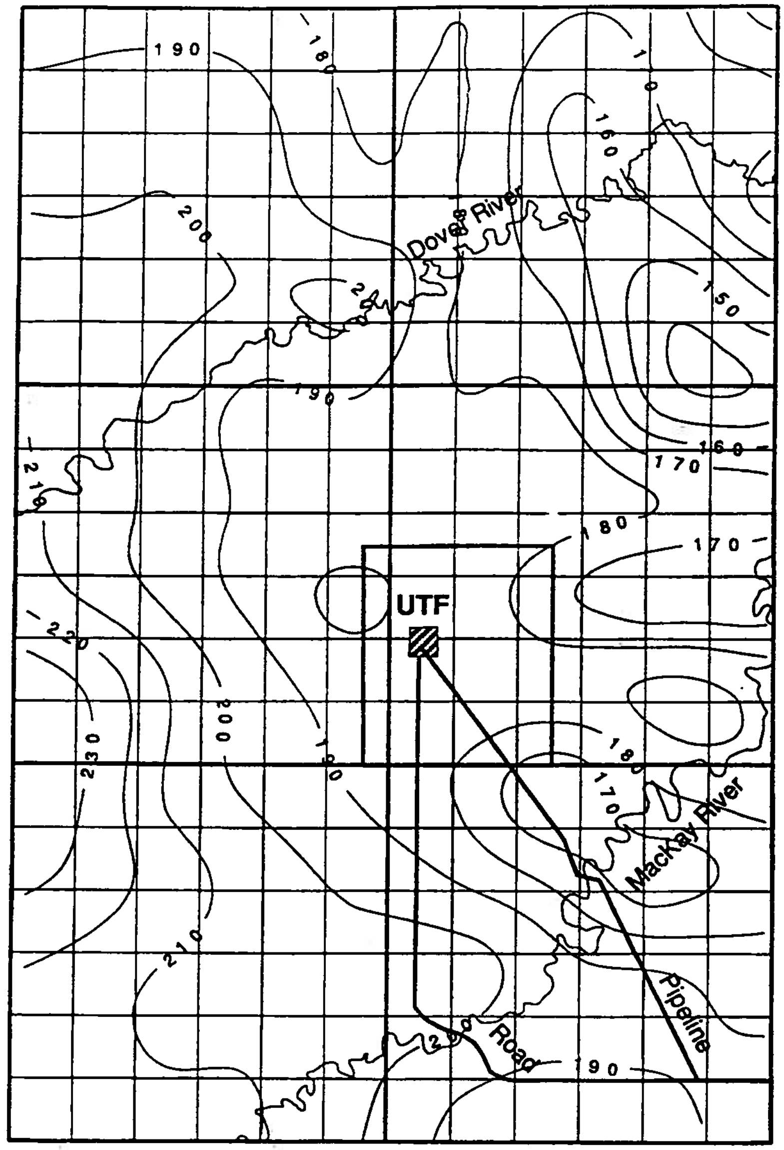
A-10. Isopach of the McMurray water sands aquifer.



A-11. Isopach of the McMurray-Wabiskaw aquitard.



A-12. Isopach of the Wabiskaw upper sand aquifer.



Tp 94

Tp 93

Tp 92

R 13

R 12 W4Mer

Scale

0

10 km

Contour Interval: 10 m

A-13. Isopach of the Wabiskaw-Clearwater aquitard.