GROUNDWATER FLOW MODEL OF THE MERRITT REGION AND POTENTIAL RESPONSE TO COAL SEAM DEWATERING

by

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ABSTRACT

The effects of coal bed methane (CBM) development on the quantity and quality of groundwater in the vicinity of the City of Merritt, British Columbia were assessed through a modeling study.

The impacts of coal seam dewatering for CBM at a pilot scale and at a regional scale are assessed here using a series of groundwater flow models. Two potential pathways were identified that could hydraulically connect a dewatered coal seam and the aquifer: faults within the Tertiary rock and coal seam subcrops.

A pilot scale model included coal seam subcrops along the unconformity between the Tertiary rocks and the Quaternary sediments and examined their potential response to coal seam dewatering. Using estimates of hydraulic conductivity (K) and subcrop exposure, the rate at which groundwater enters the subcrops ranges from approximately 7500 m^3/day for a high hydraulic conductivity scenario to approximately 70 m^3/day for a low hydraulic conductivity scenario. For the medium hydraulic conductivity scenario the groundwater loss was 725 m^3/day. Under a modified scenario where dewatering takes place only in relatively continuous coal seams and relatively far from subcrops, the loss was approximately 45 m^3/day.

The regional scale model assessed the role of a fault that extends from the southwest to the northeast through the region. For a thick, high hydraulic conductivity fault, the estimated loss was approximately 1430 m^3/day whereas for a narrow, medium hydraulic conductivity fault the estimated loss was 83.2 m^3/day.

Based on the results of this study, if coal seam dewatering takes place in areas relatively unaffected by faults, subcrops or other potentially high hydraulic conductivity features, the risk towards the City of Merritt's groundwater supply are likely to be low. However, as the city continues to develop and the groundwater demands increase, there is inherently greater risk to the groundwater supply.

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Finally, I would like to thank my friends in the UBC Hydrogroup for helping to make my time at UBC a very fun and rewarding experience.

DEDICATION

I would like to dedicate this research to my wife Nissa. Thank you for your patience, understanding and support. I could have never done it without you.

1.0 Introduction

Coalbed methane (CBM) resources are currently being assessed by industry and government in British Columbia. CBM is a source of natural gas that is found adsorbed within coal seams. According to a document titled *Coalbed Gas – Energy for Our Future*, the BC Ministry of Energy and Mines estimates that BC's CBM resource is approximately 2.5 trillion cubic metres. CBM is produced by reducing the pressure in a coal seam and allowing the coal bed gas to separate from the coal. The coalbed gas then flows towards a pumping well where it is collected. Typically, in order to reduce the fluid pressure in a coal seam, groundwater must be extracted. The amount of groundwater that is required to be pumped from the coal seam varies depending on the permeability of the coal and the surrounding geologic media. Depending on the quality of the extracted water, it may be re-injected into isolated formations, released to the surface or used for irrigation, habitat, livestock or recreation.

The City of Merritt is located approximately 270 km northeast of Vancouver in British Columbia, Canada. The city is situated near the confluence of the Coldwater River and the Nicola River. The potable drinking water for all of Merritt is currently supplied via groundwater extraction from five pumping wells. The five City of Merritt production wells are named Voght Park #1, Voght Park #2, Fairley Park, May Street, and Collettville. The groundwater that is accessed by the wells is pumped from an unconfined surficial aquifer. The BC Ministry of Environment, Water Stewardship Division classified the Merritt aquifer as one of nine type "IA" aquifers in the province of BC. A type "IA" is considered to be a heavily developed, high vulnerability aquifer. Considering the importance of safe, clean groundwater, municipal and public concern and overall awareness of their groundwater supply is high.

The Merritt Coal Basin comprises several isolated areas of Eocene sedimentary rock. The main area, which covers about 80 square kilometres, is centered on the City of Merritt and includes the mining areas of Coal Gully, Coldwater Hill and Diamond Vale. The Tertiary rocks in the area unconformably overlie the Triassic Nicola Group and Coast Range intrusive rocks. Coal was first mined in the Merritt area in the early 1900's in conjunction with the arrival of the Canadian Pacific rail line. According to JHP Coal-Ex Consulting Ltd (JHP) (2002), the highest coal production period was between 1910 and 1922 where production averaged 143,600 long tons per year. Coal mining operations continued until the 1950's.

In a report issued by the BC Ministry of Energy and Mines titled *Overview of the Coalbed Methane Potential of Tertiary Coalbasins in the Interior of British Columbia,* (2002), the potential CBM resource in the Merritt coalfield is estimated to be approximately 52 billion cubic feet. The areas with the best potential for CBM resources are to the west and beneath the City of Merritt. Forum Developments Corp. (Forum) owns the subsurface rights within a 506 hectare area referred to as Lot 166 to the south of Merritt. The freehold title consists of rights to coal, oil, fireclay and all mines and minerals save gold and silver (JHP, 2002).

Forum is currently assessing the property for potential CBM development. As part of their assessment, Forum has funded this research to better understand the groundwater flow regime in the Merritt area and to assess the potential effects of CMB development.

2.0 OBJECTIVES

This research is intended to investigate the groundwater flow regime in the Merritt area and to assess the potential hydrological effects of coal bed methane development. In order to better understand the groundwater flow regime before and after a CBM development occurs, a conceptual hydrogeological model was formulated based on the available information. The information includes the topography of the Merritt area along with geological descriptions of the various stratigraphic units. The conceptual model also takes into account the surface hydrology including aspects of climate and the various surface water bodies in the Merritt area. The conceptual model was used to formulate a numerical model using Visual MODFLOW version 4.0.0.126. MODFLOW is a finite difference groundwater flow modeling software produced by Waterloo Hydrogeologic Inc. The model was first used to estimate pre-development steady-state condition, then the model was then used to simulate the current groundwater demands from the five City of Merritt pumping wells. Finally, the model was used to simulate coal seam dewatering.

In total, three numerical models have been constructed. The first model is a base case scenario that defines the hydrogeological conditions of the Merritt region. The model takes into account the region's topography, geology, climate, surface hydrology and the City of Merritt production wells. The second model simulates and predicts the hydrogeologic response to pilot scale coal seam dewatering. This pilot scale model is used to assess the feasibility of coal seam dewatering and to estimate the potential groundwater flux from the surficial aquifer material into coal seams and faults in response to dewatering the coal seams. Furthermore, the results of the pilot scale model are used to infer the role of coal seam subcrops and small local scale faults at the regional scale. The third model simulates regional scale CBM development and is used to assess the role of a large regional scale fault on CBM development and regional groundwater flow.

To assess the range of possible responses to coal seam dewatering, a range of plausible parameter values were used to describe the various hydrostratigraphic and structural features in each model.

3.0 PHYSICAL SETTING

Merritt is located 271 km northeast of Vancouver in British Columbia, Canada (Figure 1). The city is in a valley at an elevation of approximately 595 metres above sea level (masl). The highest hills surrounding Merritt reach an elevation close to 1700 masl (Figure 2). Merritt tends to experience mild winters with little snowfall and warm, dry, sunny summers.

Two major rivers converge at Merritt: the Coldwater River, which flows towards Merritt from the southwest, and the Nicola River, which flows towards Merritt from the northeast. After the confluence, the Nicola River continues away from Merritt towards the west. Nicola Lake is situated to the northeast of Merritt and is dammed at its outlet to Nicola River. Several small ephemeral creeks feed the Nicola and Coldwater Rivers.

Figure 1: Location of the City of Merritt

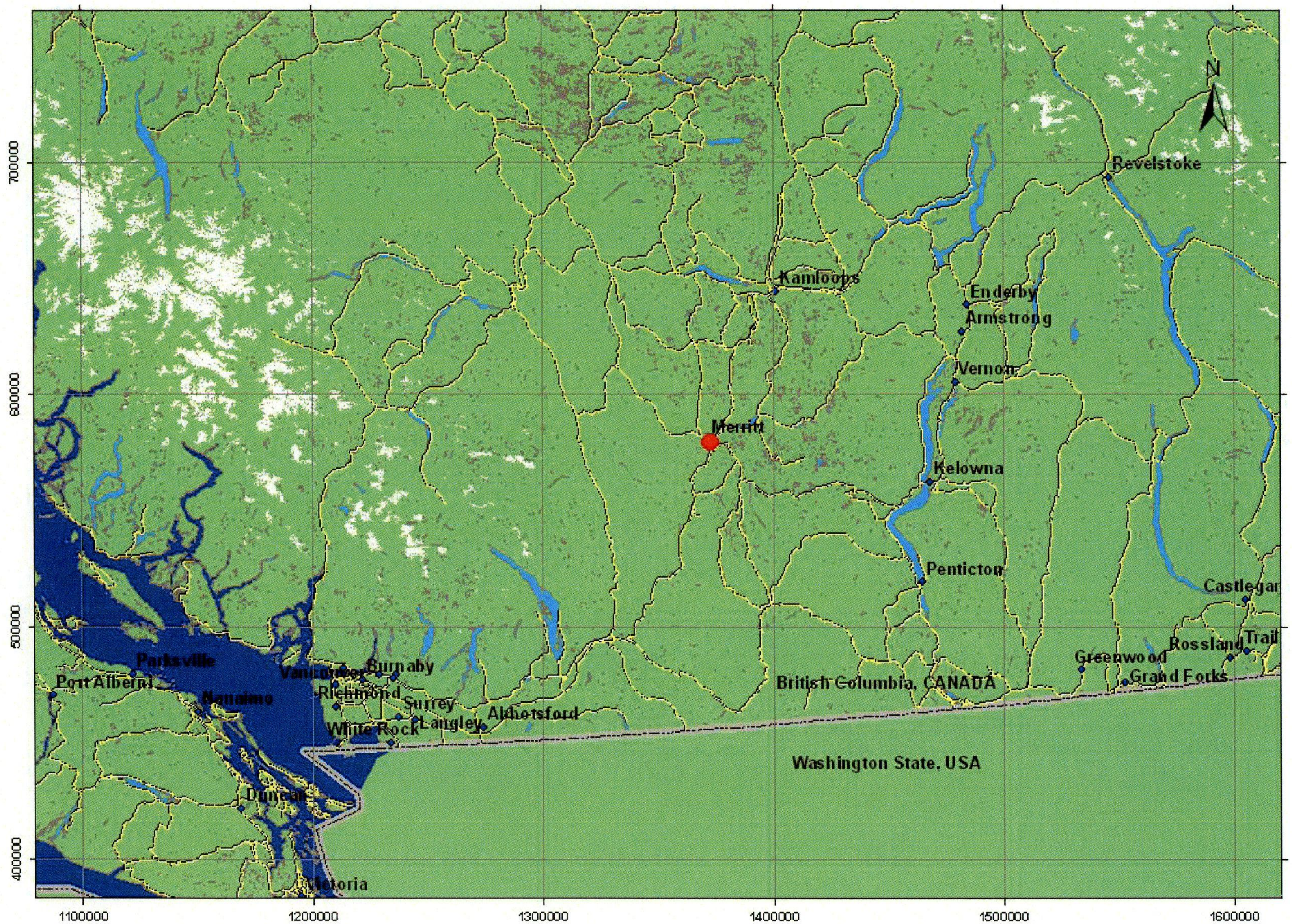

Figure 2: Topography of Merritt

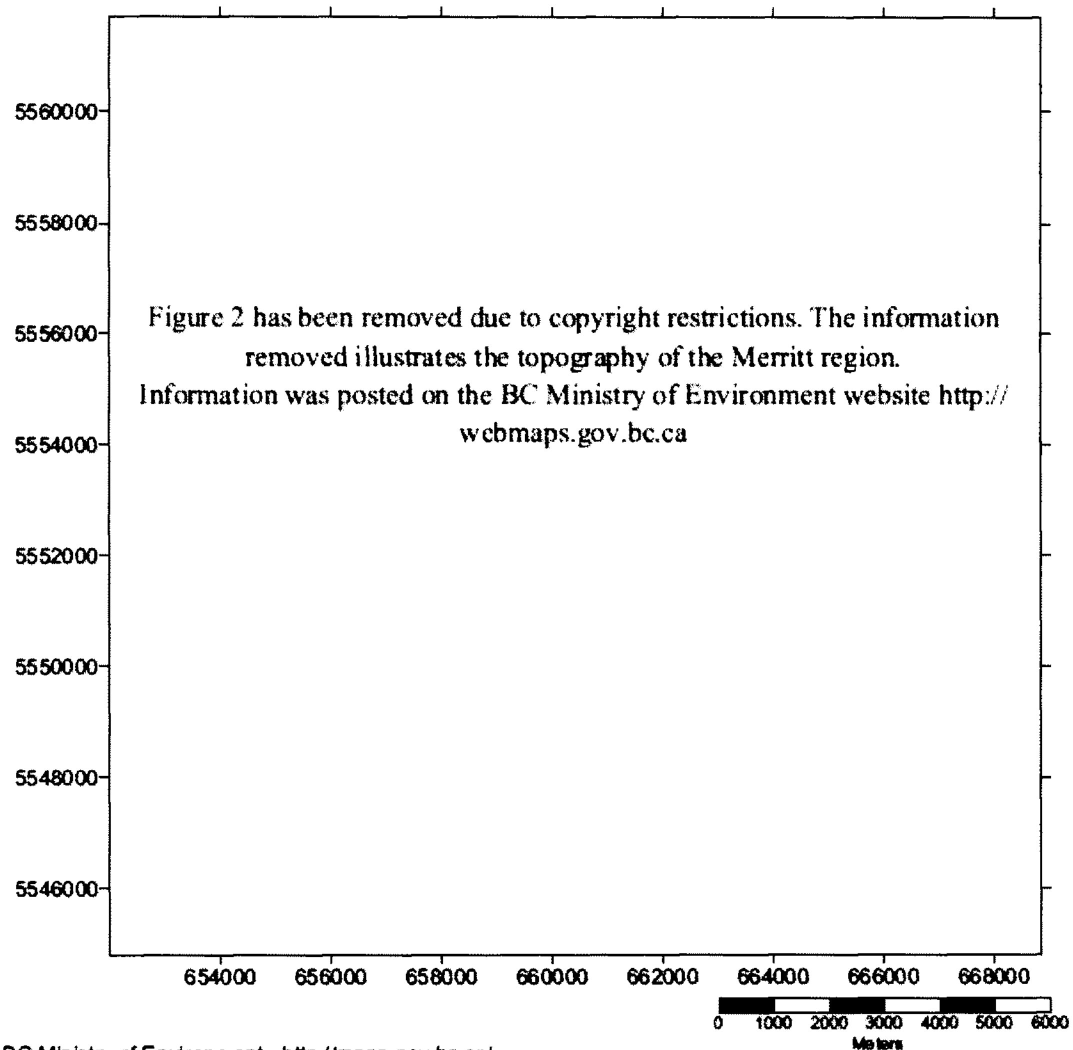

Figure 2 has been removed due to copyright restrictions. The information removed illustrates the topography of the Merritt region. Information was posted on the BC Ministry of Environment website http://webmaps.gov.bc.ca

BC Ministry of Environment - http://maps.gov.bc.ca/

4.0 GEOLOGY

4.1 Regional Geology

The overview of the regional geology presented in this section is based on a summary report by JHP Coal-Ex Consulting Ltd. (JHP) that was prepared for Forum in July of 2002. There are several lithologies in the Merritt area dating from the Triassic period to the Quaternary period (Table 1).

Table 1: Table of Formations - Merritt Coalfield

Period	Epoch	Formation		Lithology
Quaternary	Pleistocene & Recent			Stream Alluvium, Glacial Drift
- - - - -	- - - - -	- - - - -	- - - - -	- - - - -
Tertiary	Miocene of Later	Valley Basalt		Mainly Vesicular Basalt
	Miocene or Earlier	Kamloops Group	Volcanic	Rhyolite, Andesite, Basalt with Associated Tuffs, Breccias, and Agglomerates
			Tranquille Formation	Conglomerate, Sandstone, Shale, and Tuff, Thin Coal Seams
			Coldwater Formation	Conglomerate Sandstone, Shale and Coal
		Copper Creek Intrusions		Granite, Granodiorite, Granite Porphyry
Triassic	Upper Triassic	Nicola Group		Greenstone: Andesite, Basalt; Agglomerate, Breccia, Tuff; Minor Argillite, Limestone, and Conglomerate

\- - - - - - - - - - Unconformity

The latest rocks in the region are the Upper Triassic Nicola Group. This group of rocks consists of predominantly volcanic rocks with minor sedimentary horizons. The volcanics consist mostly of andesite, basalt, agglomerate, breccia and tuff. The sedimentary lithologies in the Nicola Group include argillite, limestone and conglomerate. These rocks host various Tertiary granitic intrusives of the Copper Creek Intrusions. The Nicola Group underlies and surrounds sedimentary lithologies that comprise the Merritt coal field.

The Nicola Group volcanics are unconformably overlain by a Lower Tertiary succession of sedimentary and volcanic units of the Kamloops Group. This Group is made up of three formations: a lower sedimentary sequence, the Coldwater Formation, a middle sedimentary – volcanoclastic sequence, the Tranquille Formation, and an upper sequence of volcanic rocks, the Kamloops Volcanics. Coal seams are present in both the Coldwater and Tranquille Formations, but those of the greatest economic potential are found within the Coldwater Formation. Up to ten coal seams may be present in the Merritt coalfield. Seven seams were measured in the Coldwater Hill area with an aggregate thickness of 23.8 metres contained within a 258 metre section. The coal seam thickness ranged from 0.8 to 8.7 metres (JHP, 2002).

Gilmar and Sharman (1981) described the stratigraphy of the Coldwater Formation as unconformably overlying the Nicola Volcanics and that the lower beds often resemble a breccia. Upwards through the coal measures interstratified sandstone predominates. Variations in thickness and lateral variations of the individual beds suggest deposition in an unstable environment. The lack of uniformity and continuity in nature and rock type greatly hinders stratigraphic correlations. The Coldwater Formation is a non-marine sequence of coal-bearing sedimentary rocks probably accumulated in a restricted inland lake environment. Coal generally grades to shale both horizontally and vertically rather than forming continuous seams.

The Tranquille Formation is composed of conglomerates, sandstone, shales and tuffs with thin coal seams. The Kamloops volcanics are composed of rhyolite, andesite, and basalt with associated tuffs, breccias and agglomerates.

The Merritt coal field is a Tertiary basin that was developed within part of a drowned valley system probably conforming to the present topography during the early stages of lake development (JHP, 2002). The basin is elongated NNE-SSW and measures approximately 19 km in length and 1.5 to 5 km in width. The basin is comprised of two isolated sub basins, the Nicola area, covering an area of approximately 80 km^2, and the Quilchena area covering approximately 25 km^2. A strike-slip fault extends from the south-west to the north-east of Merritt and is interpreted to cut through the sedimentary basin (Figure 3). The basin is overlain unconformably with Quaternary glacial, glaciofluvial, glaciolacustrine and recent fluvial deposits. In a report prepared for Imperial Oil Ltd. by Ron Swaren (1977) a geological map and a series of three cross-sections was prepared that interprets the geology across the Merritt basin and approximates the possible locations of coal seam subcrops.

The report by JHP focused mostly on the area surrounding Coldwater Hill and provides a summary of the structural geology in that area. JHP found that the geological structures trend predominantly northwest-southeast, with the main elements of the structural geology comprised of a series of anticlines and synclines and normal faults. The folded sedimentary sequence is cut by a series of northwest-southeast trending faults. These faults are interpreted as normal faults, but have been referred to as strike slip faults as well.

4.2 Merritt Aquifer

In 1970 Ed Livingston described the depositional history of the Merritt aquifer. According to Livingston, at the time of melting of the last glaciers in the Merritt area the Nicola Valley was dammed, probably by ice both east and northwest of Merritt, forming a lake at least 75 metres deep at Merritt. Sediment filled meltwater from the Coldwater Valley deposited sand, silt and clay as prominently banded clays at the lake bottom. As the dams forming the lake were destroyed the lake level decreased and it finally disappeared in the Merritt area. Once the lake had gone, the Coldwater River, which was probably choked with gravel above the former lake level, cut into the soft lake beds to a level perhaps as much as 30 m below its present level. As the size of the river decreased due to depletion of ice in the mountains to the southwest, the river channel filled with clean gravel forming the gravel fan on which most of the town is built. This gravel is the aquifer supplying the town wells.

According to an *Aquifer Protection Plan* prepared by EBA Engineering Consultants Ltd. for the City of Merritt in December of 2002, the thickness of the Merritt aquifer ranges from 5 to 50 m; however, about 80 percent of the aquifer is interpreted to be less than 10 m thick. The area that is less than 10 m thick occurs mostly on the floodplain between the Coldwater and Nicola Rivers. The deepest part of the aquifer occurs along a trough that runs sub-parallel to the Coldwater River. Most of the city production wells access this deep trough for the city water supply. Appendix A contains figures showing the locations of the City of Merritt production wells and two cross sections of the valley sediments. Figure 4 shows the lateral extent of the Quaternary deposits in the Merritt area.

Currently the City of Merritt and BC Groundwater Consulting Services Ltd. are investigating the potential development of a new groundwater supply well that would operate independently from the existing production wells. The siting of the possible production well is within a deeper aquifer system. The deep aquifer system is thought to be confined by the overlying glaciolacustrine silt (Kala, 2004); however, it remains undetermined if this deep aquifer is hydraulically connected to the surficial aquifer and/or the surface hydrology by relatively permeable materials. For the purpose of this thesis the presence of the deep aquifer is not considered and potential development of a new groundwater supply well within the deep aquifer is not explored.

Figure 3: Bedrock Geology and Fault Locations

Figure 3 has been removed due to copyright restrictions. The information removed illustrates the topography of the bedrock geology and fault locations in the Merritt region. Information was posted on the BC Ministry of Energy, Mines and Petroleum Resources website http://webmap.em.gov.bc.ca/mapplace/minpot/bcgs.cfm

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Geology from BC Ministry of Energy and Mines

Figure 4: Lateral Extent of Quaternary Deposits

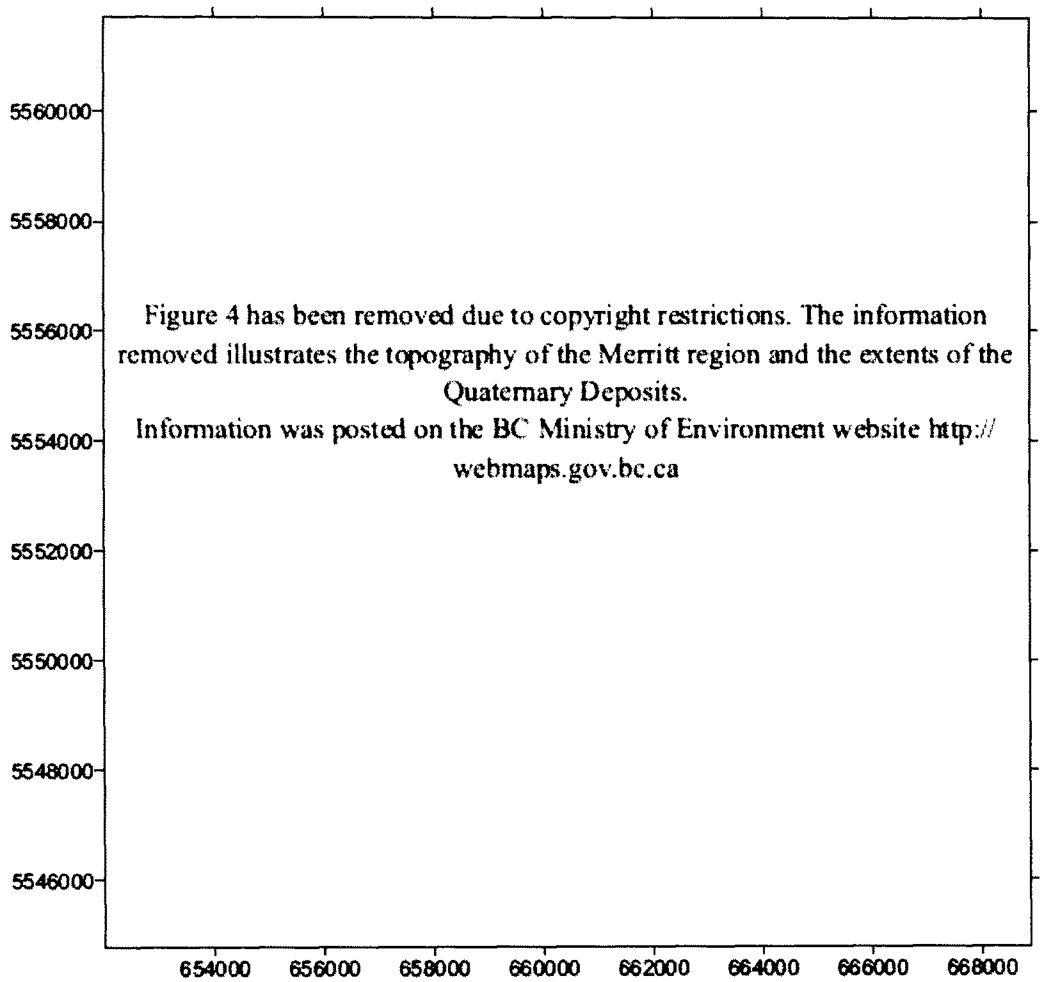


Figure 4 has been removed due to copyright restrictions. The information removed illustrates the topography of the Merritt region and the extents of the Quaternary Deposits.
Information was posted on the BC Ministry of Environment website http://webmaps.gov.bc.ca

0 1000 2000 3000 4000 5000 6000
Meters

Yellow area represents Quaternary geology
Color Hillshade and Quaternary Extent from BC Ministry of Environment - http://maps.gov.bc.ca/

5.0 COALBED METHANE

5.1 Coalbed Methane Overview

The interior of British Columbia contains a number of fault bounded Tertiary basins that contain coal (BC Ministry of Energy and Mines, 2002). Among these Tertiary basins is the Merritt Coal Field. Under the appropriate conditions coal can act as a source, a reservoir and a trap for significant quantities of methane and minor amounts of other gases (Bustin and Clarkson, 1998). CBM is retained in coal in a number of ways including: adsorbed molecules within micropores; trapped gas within matrix porosity; free gas in cleat and fractures; and as a solute in groundwater within coal fractures (Bustin and Clarkson, 1998). CBM is formed in the coal by either biogenic or thermogenic processes. If the coalbed is buried deeply, so that there is sufficient hydrostatic pressure, the methane will remain adsorbed on cleat surfaces and in micropores in coal. The gas is held in place by weak attractive forces between the coal and the gas and by hydrostatic pressure from groundwater in the coal. Gas migration by desorption, diffusion, and free-phase flow takes place when the pressures in the coalbeds are decreased, which can take place either naturally or by human activities (Rice, 1993). Human activities that can reduce the pressure in a coalbed include coal mining or gas production from wells. Because most coals are characterized by high water saturations, depressurization results from dewatering of the coal seam (Rice, 1993). To produce the gas, water is pumped from wells completed in the coal seam, the hydrostatic pressure is reduced, and the gas is desorbed. The gas and water move to the well as a two-phase fluid. The water enters the pump and is discharged through the water line and the gas flows up the well casing to be extracted by a low-pressure compressor.

Natural gas is generated in coalbeds throughout their burial history. The gas can be generated during three stages: (1) early biogenic gas, formed by bacteria in the early stages of coalification; (2) thermogenic gas, formed by thermal processes during the main stages of coalification; and (3) late stage biogenic gas, which can form in coals of any rank if the right conditions are met for methane producing bacteria to flourish (Johnson and Flores, 1998).

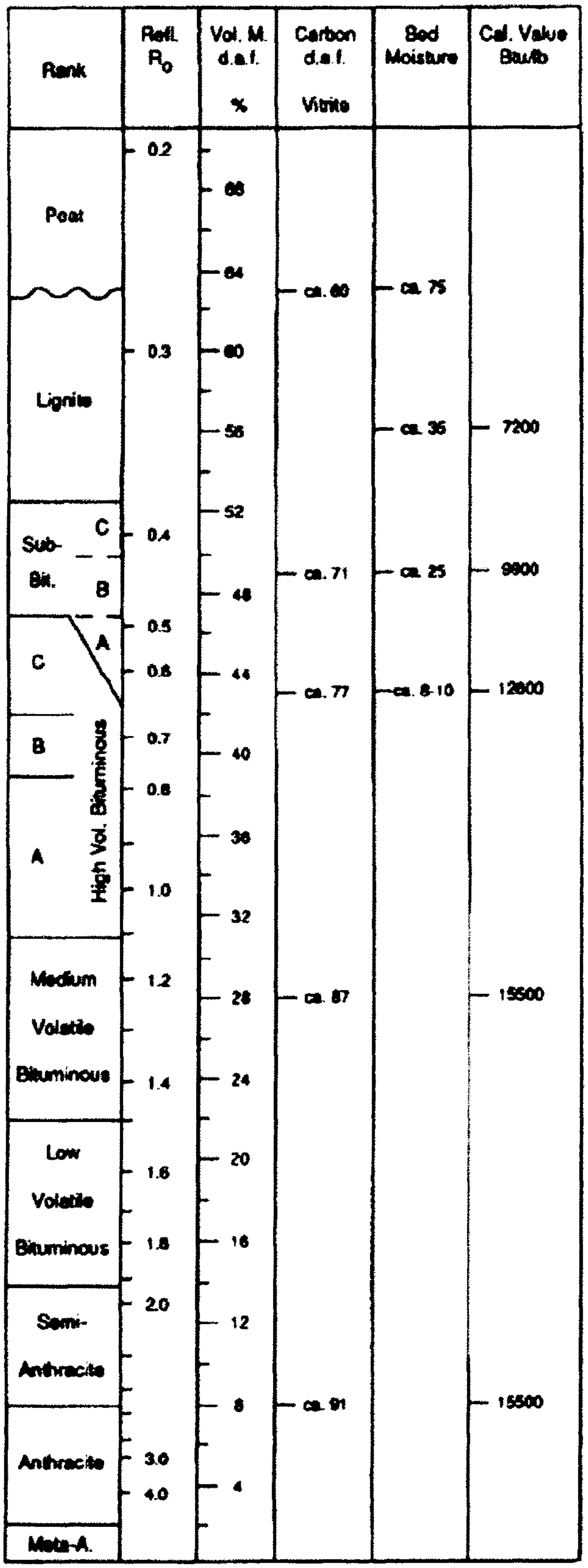
Early biogenic gas is generated by the degradation of the organic matter in coal at shallow depths and low temperatures in rapidly accumulating sediments during early stages of coalification and at low ranks (Rice, 1993). Typically, methane generation occurs if the temperature is less than 75°C, the environment is anoxic with low sulphate concentrations and adequate pore space exists (Johnson and Flores, 1998). Two pathways have been identified for early methane generation in coals: carbon dioxide reduction and methyl-type fermentation (Rice, 1993). Most biogenic methane found today is the result of carbon dioxide reduction (Johnson and Flores, 1998).

With the increased temperatures and pressures that occur during subsidence and burial of a coalbed, coal becomes enriched in carbon as large amounts of volatile matter rich in hydrogen and oxygen are released (Rice, 1993). The onset of thermally generated hydrocarbon gases begins at coal ranks near the high volatile bituminous reflectance of 0.6% (Figure 5) (Johnson and Flores, 1998).

If the coal seams are later uplifted and the temperature and pressure drop, late stage biogenic gas may be produced. Methane generating bacteria can be reintroduced into the coalbed via transport with groundwater. Cleat apertures tend to dilate as the pressure of overburden is reduced, which facilitates the flow of groundwater into the coalbed (Johnson and Flores, 1998). Conversely, flow of groundwater through a coal seam can deplete the coal of methane, as methane desorbs to equilibrate with the water.

Kaiser *et al.* (1994) found that CBM producibility is determined by six controls: coal distribution, coal rank, gas content, permeability, groundwater flow, and depositional and structural setting. Peat accumulation and preservation as coal requires a balanced subsidence rate that maintains optimum water table levels but excludes disruptive clastic sediment influx. The depositional systems define the substrate upon which peat growth is initiated, and ultimately enables prediction of coalbed thickness, geometry, and continuity. Traditionally, thermally generated gas content has been correlated to coal rank, however; gas content cannot be determined by coal rank alone. Greater burial depths raise reservoir pressures and increase the methane adsorption capacity of the coal.

Figure 5: Stages of coalification and common properties of measurement (Rice 1993). d.a.f.=dry and ash free.



Furthermore, Bustin and Clarkson (1998) found that there were no consistent trends in methane adsorption capacity with composition or rank of coals. Gas content of coals can also be enhanced, either locally or regionally, by generation of late stage biogenic gases or by diffusion and long-distance migration of gases to no-flow boundaries such as structural hinge lines or faults for eventual re-adsorption and conventional gas trapping. Gas migration requires laterally extensive, permeable coals and dynamic groundwater flow. Permeability of a coalbed is determined by its fracture (cleat) system, which is in turn largely controlled by the tectonic/structural regime. The cleat system is the primary avenue for gas and water flow during gas production; however, the majority of gas (up to 95%) resides in the coal matrix (Cui *et al*, 2003). Consequently the producibility of a coal seam is not only dependent on the permeability of the coalbed, but also the rate of gas diffusion within the coal matrix.

Coal seams can act as conduits for gas migration, but also commonly act as aquifers with permeabilities that are orders of magnitude larger the surrounding sedimentary strata. Although high permeability can result in high producibility of gas, permeability that is too high can result in high water production. High water production may be detrimental to the economic production of coalbed methane if the water is of poor quality compared to the regulatory standards since it would require treatment and/or disposal according to applicable federal and/or provincial regulations. Furthermore, if a coal seam is developed for CBM, and production of water is high, the surrounding aquifers may be affected. If there is connection between a coal seam and an aquifer via a relatively high permeability pathway, removal of groundwater from the coal seam may result in depletion of the aquifer.

McKee and Bumb (1987) identified that if the hydrostatic pressure in the coal seam is significantly higher than the desorption pressure, gas production may follow three stages from a coal bed methane reservoir. During the first stage, a water-saturated coalbed methane well produced and commonly encounters only single-phase or water saturated flow. During the second stage the reservoir pressure continues to be reduced and methane gas begins to form as the result of desorption from the coal. As methane gas forms, some of the pathways which were originally saturated with water become blocked by gas bubbles. By blocking water flow pathways the relative permeability of the formation to water is reduced. However, during the second stage, the gas does not yet flow because the bubbles are not connected within the porous coal matrix nor in the cleat or natural fracture system of the coalbed. The second stage is characterized by the presence of two phases, gas and water, however only the water phase is mobile. The third stage is reached as the reservoir pressure decreases and additional gas is desorbed. The gas saturation builds until the gas bubbles connect and form a continuous pathway to the producing well. Two-phase flow begins at the point where the relative permeability to gas becomes non-zero. As the reservoir pressure is further reduced and additional gas is desorbed, the relative permeability to gas increases and the relative permeability to water decreases. If the initial water pressure is not higher than the pressure at which gas begins to desorb the water saturated flow stage and possibly the unsaturated flow stage could be absent (McKee and Bumb, 1987).

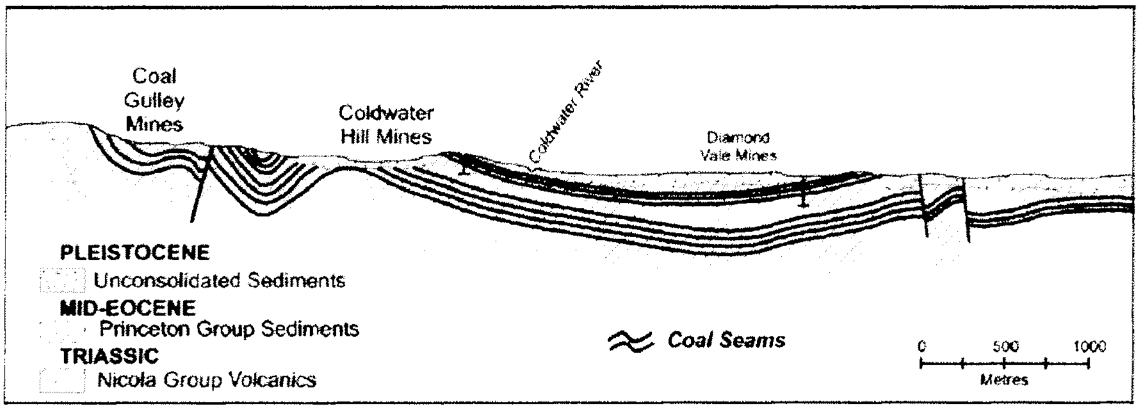
Due to the many factors that determine the producibility of a coal seam, it is very difficult to predict how a coal seam will respond to gas production. There is significant interplay between the factors listed above which taken together determine if CBM production is feasible or not feasible.

5.2 Merritt Coalbed Methane

Based on the regional geology of the Merritt area, and considering the complex interplay between factors that influence CBM producibility, the CBM potential in the Merritt area is difficult to estimate. A description of the depositional history of the sedimentary geology was provided by Gilmar and Sharman (1981) and is included in section 4.1. The rank of the coal spans the range from high-volatile bituminous C to A. No tests for methane content have been conducted (JHP, 2002). The Tertiary units are described to have been deposited in a non-marine sequence that likely accumulated in a restricted inland lake environment. The continuity of the coalbeds is further compromised by the folding and faulting in the area. Figure 6 shows a simplified cross section of the Merritt basin along a plane extending from the southwest to the northeast of Merritt. The folding and faulting in the region is most intense to the southwest, where a series of anticlines and synclines are observed. Moving to the northeast, the sedimentary basin appears to follow a broad shallow syncline. The majority of the anticline structure in the Coldwater Hill area is eroded so that coal seams subcrop along an unconformity near the southwest margins of the sedimentary basin. The coal seam subcrops may allow hydraulic connectivity between the near surface hydrology and the individual coal seams. Hydraulic connectivity has potential to decrease the producibility of CBM if groundwater flow is sufficient to strip the coal of methane. Furthermore, if CBM development were to take place, the Quaternary sediments above the unconformity may provide a constant source of water to the coal seam and dewatering may not be feasible. In this scenario, the permeability provides the greatest source of uncertainty when determining if the coal seam can be dewatered. In general the permeability of the coals and surrounding geological units are poorly understood. Although it is assumed that the units surrounding the coalbeds (mostly sandstone/shale) are of lower permeability than the coals, to date, this assumption has not been verified by field measurements.

The Merritt basin's potential for CBM development is poorly understood. Further investigation in the area would improve the understanding of the continuity of the coal seams, the gas content in the coals and the role of groundwater flow within the system. Of particular relevance to the groundwater flow system is the role of faults and subcrops and better constraints for the permeabilities.

Figure 6: Simplified cross section of Merritt Basin (BC Ministry of Energy and Mines, 2003)



6.0 WATER BALANCE

The hydrologic system at the ground surface represents the sources and sinks for the groundwater flow system. The major source of water to groundwater is recharge from precipitation. Precipitation varies annually, seasonally, and geographically, but for the purpose of this project, the annual rainfall in the Merritt area is assumed to be approximately 322 mm/yr (Table 2). Other sources of water to groundwater include: seepage from streams, rivers and lakes, and discharge from anthropogenic sources. Water can be removed from the surface hydrologic system via discharge from steams and rivers, evapotranspiration, sublimation, removal for anthropogenic uses, and recharge to groundwater.

Table 2: Annual Climate Averages

Month	Evapotranspiration (mm)	Precipitation (mm)	Deficit (mm)
January	15.5	37.2	21.7
February	31.9	23.6	-8.3
March	58.9	16.6	-42.3
April	102.0	14.5	-87.5
May	148.8	26.8	-122.0
June	132.0	34.1	-97.9
July	161.2	25.8	-135.4
August	155.0	22.1	-132.9
September	87.0	23.6	-63.4
October	46.5	23.5	-23.0
November	21.0	34.7	13.7
December	15.5	39.6	24.1
Sum	975.3	322.1	-653.2

ET data collected from Farmwest: http://www.farmwest.com from the Kamloops Airport Station
Precip data collected from www.climate.weatheroffice.ec.gc.ca/climate_normals

Environment Canada operates three hydrometric stations in the Merritt area, one on Coldwater River (station ID 08LG010), one at the outlet of Nicola Lake (station ID 08LG065) and one approximately 6.5 km to the northwest of the confluence of the Coldwater River and the Nicola River (station ID 08LG007). These three hydrometric stations are shown on Figure 7. Six additional hydrometric stations are located in the Merritt area, three to the north of Merritt and three to the south of Merritt. The three stations to the north of Merritt are located outside of the drainage area for this study's region of interest and therefore are not considered for the remainder of this report. The three stations to the south of Merritt lie within the drainage area of the Coldwater River catchment and are ephemeral with low peak flows compared to the peak flows of the Coldwater River. Therefore, the hydrometric stations south of Merritt are not considered for the remainder of this report.

Historical hydrometric data from Canada's HYDAT database for the three hydrometric stations shown in Figure 7 was used to formulate a water balance for the Merritt region. The water balance also uses data collected from the BC Ministry of Environment, Water Stewardship Division for water license permits. Only active permits are considered when calculating the maximum amount of surface water that is permitted for use by the BC Ministry of Environment. There are several uses for the permitted water including irrigation, domestic use, stock watering, and industrial. Historical hydrometric data and details of the water licenses are included in Appendix B. There are several groundwater wells that were identified using the BC Ministry of Environment Water Resources Atlas, mostly located in valleys. Volumes of groundwater extraction from these wells are unknown as groundwater wells in British Columbia are not regulated.

In order to accurately approximate a water balance for the Merritt area, several additional factors must be considered that are not directly addressed as part of this study. A major factor is the contribution of snowmelt to surface runoff during the spring freshet. It is expected that snowmelt during spring contributes the majority of surface runoff in the Merritt basin. The volume of runoff due to snowmelt depends on how much snow accumulated over the winter and the rate of sublimation. Furthermore, the amount of surface runoff during snowmelt and during periods of heavy precipitation depends, in part, on the capacity of the soil to allow infiltration. Other considerations include the volume of water that is able to flow along valley basins as baseflow. The water balance formulated in the following sections use average streamflow values and does not take into account the above factors. It is expected that these fluctuations in the surface hydrology would not affect the groundwater flow system, especially at the depth of coal seam dewatering.

Considering that the above listed factors are dependant on natural processes, it is prudent to measure streamflow on unregulated water courses. Unfortunately, the three hydrometric stations considered in this hydrological summary record flow measurements from regulated water courses. When determining a water balance, streamflows measured from regulated water courses may introduce additional uncertainties. Water may be retained upstream of hydrometric stations on regulated streams. The retained water may be for human uses or for storage. Another result of surface water retention is that there is additional water available for evapotranspiration, especially during the summer months. It is likely that more water is removed from the hydrological system along regulated streams than along unregulated streams.

6.1 Coldwater River

The gross drainage area for the hydrometric station at Coldwater River is approximately 914 km^2 and extends from its origin near the Coquihala toll booth up to the confluence with the Nicola River. According to the Environment Canada Water Survey, at its confluence with the Nicola River, the mean discharge of the Coldwater River is approximately 8.21 m^3/s. Kala (2004) determined average low annual flow in the Coldwater River to be approximately 1 m^3/s; however, flows have been recorded to be as low as 0.1 m^3/s. Using an annual rainfall of 322 mm/yr, the drainage area receives approximately 9.32 m^3/s of recharge to the surface. Based on these calculations approximately 88 percent of surficial recharge in the Coldwater River watershed is discharged as stream flow. In a semi-arid region such as Merritt, a high proportion of stream flow to area and precipitation is not expected. An additional climate station is located near Brookmere, approximately half way between the Coquihala toll boot and Merritt. The average precipitation at this station (climate ID 1121090) is 564 mm/yr. Based on this average precipitation there is a large precipitation gradient with elevation moving towards the headwaters of the Coldwater River. With a precipitation of 564 mm/yr, approximately 50 percent of surface recharge discharges as streamflow.

Figure 7: Locations of Hydrometric Stations Near Merritt

Figure 7 has been removed due to copyright restrictions. The information removed illustrates the river and stream network in the Merritt region and the locations of nearby hydrometric stations.
Information was posted on the BC Ministry of Environment website http://webmaps.gov.bc.ca

0 1000 2000 3000 4000 5000 6000
Meters

Color Hillshade from BC Ministry of Environment - http://maps.gov.bc.ca/

Although there are not any additional climate stations up the Coldwater River valley, it is plausible that precipitation will continue to increase with increasing elevation. Based on observations of the climate regime near Merritt it appears as if the area near the upper Coldwater River receives the most precipitation within the Coldwater River and Nicola River watersheds.

The precipitation that is not accounted for in the streamflow measurements can be explained by water withdrawals and evaporation. Currently there are twenty-six active permits allowing use of water from Coldwater River. From the twenty-six active permits, water is removed from the Coldwater River at a rate of approximately 0.23 m^3/s. The amount of water permitted for human use accounts for 2.5 percent of the water loss in the system. The remaining water is likely removed from the system via evapotranspiration (ET). Table 2 shows the average ET is greater than the average rainfall in nine months of the year. The potential evapotranspiration rates depend upon the temperature, intensity of solar radiation, the vapour pressure, and wind speed as well as the land use type. Actual evaporation rates depend on the factors listed above, but are largely constrained by the amount of water that is available at or near the ground surface. Due to the large difference in precipitation with elevation and location within the Coldwater River watershed, it is difficult to estimate the water loss due to ET; however it is likely greater than 50 percent of the total precipitation.

6.2 Upper Nicola River and Nicola Lake

The gross drainage area for the hydrometric station located at the outlet of Nicola Lake is 2990 km^2 and extends to the northeast from Nicola Lake. Nicola Lake is dammed at its outlet and according to the Environment Canada Water Survey the mean discharge directly after the dam is 5.12 m^3/s. Based on an annual rainfall of 322 mm/yr, the drainage area receives approximately 30.5 m^3/s of recharge to the ground surface. Based on these calculations, approximately 16.8 percent of the surface recharge to the Nicola River watershed is discharged at the outlet of Nicola Lake. According to the BC Ministry of Environment, Water Stewardship Division there are thirty-six active water licenses permitting use of water from the Upper Nicola River and Nicola Lake. From the thirty-six active permits, water is removed from the Nicola River and Nicola Lake at a rate of approximately 0.53 m^3/s. Furthermore, Fisheries and Oceans Canada and Ministry of Environment Water Right Branch own the rights to very large amounts of water from Nicola Lake. The permits are for storage and conservation purposes. The stored water is used only during drought to maintain a healthy water level in the river for aquatic life and is rarely released (per conversation with Fisheries and Oceans Canada). The amount of water permitted for human use accounts for 1.75 percent of the water loss in the system. The majority of surface recharge, approximately 81.5 percent, is likely removed from the system via ET and discharge into the groundwater system.

The difference between the loss from the Nicola drainage area and the Coldwater drainage area may be due to the amount of available water at the ground surface and the residence time of surface water in each drainage area. Surface water for the Coldwater drainage area flows into the Coldwater River from a relatively narrow catchment and is then transported relatively quickly via the Coldwater River. Since the residence time for water in the Coldwater drainage area is relatively short and the water available for ET is relatively low, the effects of water loss are less pronounced. Conversely, surface water for the Nicola drainage area flows into Nicola Lake where there is a large amount of water available for ET for the entire year. For the purpose of this study, the hydrology of the upper Nicola is not considered further, as the limits of the region of interest do not extend beyond Nicola Lake.

6.3 Lower Nicola near Merritt

The gross drainage area for the hydrometric station located approximately 6.5 km to the northwest of the confluence of the Coldwater and Nicola rivers is approximately 4350 km^2. According to the Environment Canada Water Survey, the mean average discharge at this station is 13.9 m^3/s. Kala (2004) determined average low annual flow in the Nicola River to be approximately 5 m^3/s; however, flows as low as 1 m^3/s have been recorded. Based on an annual rainfall of 322 mm/yr, the drainage area receives approximately 44.4 m^3/s of recharge to the ground surface. Based on these calculations, 31.3 percent of the surface recharge to the drainage area is discharged at the location of this station.

The drainage area of the lower Nicola River is approximately 446 km^2, subtracting the area of the upper Nicola River and the Coldwater River. Based on the size of this drainage area, the annual recharge to the ground surface due to precipitation would be 4.55 m^3/s. The sum of the mean discharge at stations 08LG010 and 08LG065 is 13.33 m^3/s. Therefore, the total volume added to the area is 17.88 m^3/s. Another possible source of water added to this area is from the City of Merritt wastewater treatment plant. According to the City of Merritt Public Works and the City of Merritt wastewater plant, wastewater is discharged at a rate of approximately 0.04 m^3/s. The wastewater is discharged to rapid infiltration basins and emergency overflow discharge to the river happens during flood conditions and only twice in the past ten years. The infiltration basins are located along the Coldwater River near the west side of Merritt. Based on this information, it is unlikely that the wastewater plant is a significant source of water to the surface hydrology. Based on a total of 17.88 m^3/s added to the catchment and a total discharge of 13.9 m^3/s at station 08LG007, approximately 77.7 percent of the surface water is discharged. The BC Ministry of Environment, Water Stewardship Division reports that there are thirty active water licenses permitting use of water from the Merritt area of the Nicola River. From the thirty active permits, water is removed from the Nicola River at a rate of approximately 0.14 m^3/s. The amount of water permitted for human use accounts for 0.78 percent of the water removed from the system. The remaining 21.5 percent of the water removed from the system is likely lost due to ET and recharge to the groundwater system. It is important to note that station 08LG007 is located within the basin of Nicola watershed. To the west of Merritt, the valley and likely the aquifer narrows, therefore groundwater likely discharges to surface water at a higher rate near station 08LG007 than at stations 08LG010 and 08LG065 (more explanation in section 7). As such, the discharge rate measured at station 08LG007 may be overestimated if accounting for surface water contributions alone.

An additional loss of surface recharge includes recharge to the groundwater flow system. Groundwater within the drainage area may eventually be discharged to stream flow. As such, if the system is at steady state, any loss of surface water to groundwater may coincide with a gain from groundwater discharging to surface water. The low flow values provided by Kala (2004) for the Coldwater River are approximately 1 m^3/s for the Coldwater River and 5 m^3/s for the Nicola River. It is expected that the streamflow during low flow conditions (typically end of March, prior to snow melt) is largely dependant on groundwater discharge. The values estimated by Kala represent 11.3 percent and 10.7 percent of recharge to the Coldwater and Nicola catchments, respectively. Thus, at steady state, the groundwater recharge from precipitation likely represents approximately 11 percent of the total precipitation.

The total water balance for the Merritt region is difficult to estimate due to the wide range of possible ET values. Nevertheless, perhaps a reasonable estimate would be approximately 70 percent of the precipitation is removed from the catchment via sublimation and evapotranspiration, 20 percent of the precipitation results in surface runoff directly to streamflow (mostly during snowmelt) and 10 percent of the precipitation recharges the groundwater system.

6.4 Water Balance Modeling

Due to the relatively wide range of possible evapotranspiration, runoff and groundwater recharge values VADOSE/W was used to refine the estimate of groundwater recharge. VADOSE/W is a two dimensional finite element modeling software used for analyzing flow from climate inputs, across the ground surface, through the unsaturated vadose zone and into the groundwater system. The modeling software accounts for potential and actual evapotranspiration as a function of soil water pressure, snow accumulation and melt, plant transpiration, surface seepage, runoff and ponding, and groundwater recharge.

The two dimensional model section was interpreted from a series of cross-sections (JHP, 2002) that trend southwest to northeast from Coldwater Hill to Coldwater River. Figure 8 illustrates a cross section of the materials modelled in the VADOSE/W simulation. Several parameters must be entered into a VADOSE/W model including: a hydraulic conductivity function and a volumetric water content function for each material type, a plant moisture limiting function, a root depth function, a leaf area index function, thermal conductivity and volumetric specific heat, and daily precipitation, wind, relative humidity and temperature. Field data regarding each of the functions listed above, aside from climate data, have not been measured. As such, functions were chosen from a series of typical functions provided with the VADOSE/W software. Daily climate data was collected from Environment Canada online climate data at the Merritt STP station (ID 1125079).

In general, the simulated hydraulic head was a subdued reflection of topography. Figure 9 illustrates the head equipotentials simulated in the VADOSE/W model. The surficial layers were modeled as sand and gravel or colluvial material. As such, the majority of groundwater flow was simulated as flow within the surficial layer. Groundwater recharged on the hill slopes and discharged along the valley bottom. However, during summer when evapotranspiration rates are high, the groundwater flow direction reversed from towards Coldwater River to away from Coldwater River.

To estimate groundwater recharge into the surficial layer a series of flux sections were introduced. A flux section is a section of the model that can be specified for model output. Since the highlands and hill slopes make up the majority of the area in the area of interest, the flux sections that were used to collect output recharge values from the VADOSE/W model were specified along a hill slope.

The groundwater recharge varied significantly over the course of a year, where high recharge was observed during spring freshet and late fall and very low recharge was observed during summer when evapotranspiration is high. At some times, the infiltration was calculated as a negative value. This indicates that evapotranspiration exceeds precipitation to the point that negative pressures are simulated in the surficial layer causing a net upwards flux of vapour flow. Using a yearly average for recharge the VADOSE/W model simulated that approximately 6 percent of the annual precipitation infiltrates into the groundwater flow system.

Based on the estimates of recharge presented in this water balance section, the groundwater recharge for the area of interest is approximately 6 to 10 percent.

Figure 8: VADOSE/W Model Cross-section

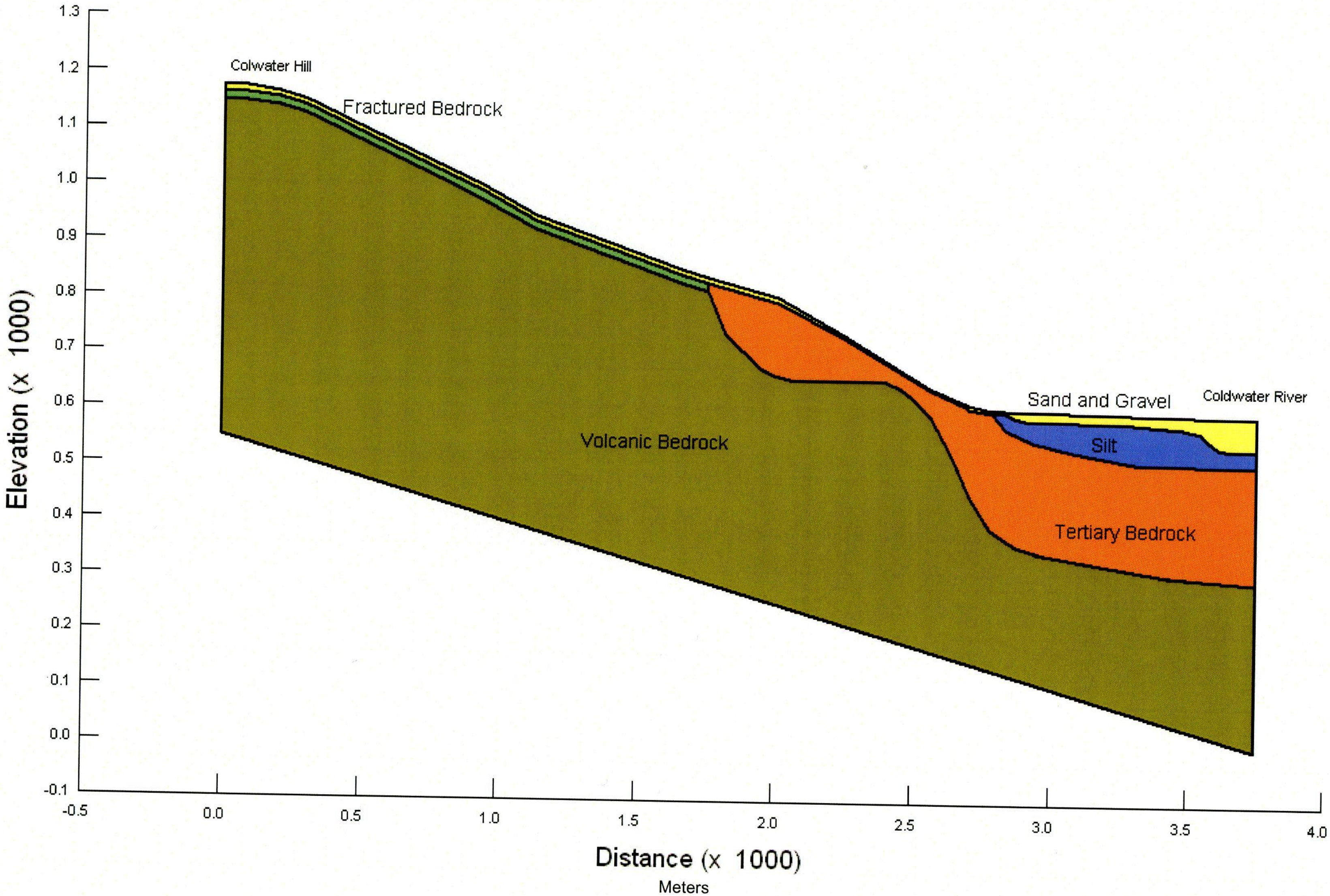
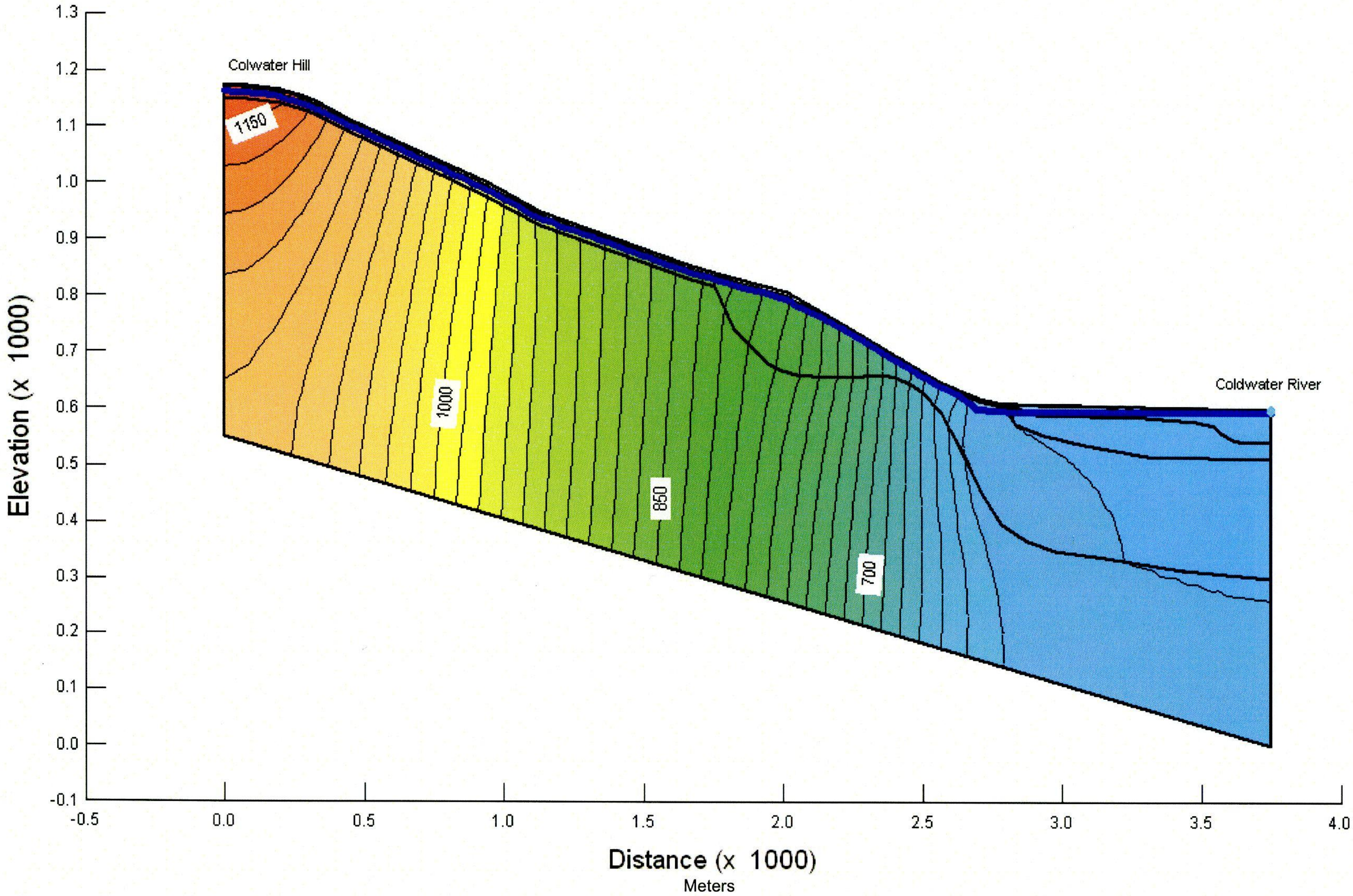


Figure 9: VADOSE/W Simulated Hydraulic Head Equipotentials



6.5 Surface Water/Groundwater Interaction

BC Groundwater Consulting Services Ltd. (BC Groundwater) prepared a Surface Water/Groundwater Interaction Study for the City of Merritt in March, 2006. BC Groundwater concluded that groundwater recharge to the Merritt aquifer originates from the catchment areas to the north, east and south of Merritt and also from precipitation within the city limits. Groundwater from the north and northeast flows beneath and into the Nicola River, while groundwater recharge from the south flows beneath the Coldwater River. The main contributor to the surficial aquifer recharge is leakage from the Nicola River, with limited leakage from the Coldwater River. Coldwater River may be limited to surface water flow and the river may become disconnected from the water table during certain periods of the year.

7.0 CONCEPTUAL MODEL

To better understand the groundwater flow dynamics and create a predictive tool to understand how the flow system near Merritt will behave in the future, a numerical groundwater flow model was constructed. To construct the numerical model for the Merritt region a conceptual model is required to define the most important aspects of the flow characteristics of the system. The conceptual model of a flow system is the foundation upon which the model is constructed. The accuracy of the conceptual model cannot be tested until the numerical model is constructed and the results are compared to field observations of the real system. This allows the modeller to assess the conceptual model and make appropriate changes. It also guides future data collection that can be used to produce a conceptual model that is more consistent with field observations. Thus, formulating a conceptual model is an iterative process where it may be continuously updated.

For the Merritt region, a challenging scenario is presented. Very little information about the hydrogeological conditions for the region is available and there is little information to compare the conceptual model with field observations. Accordingly, the initial conceptual model is simplified and contains several subjective interpretations. Furthermore, the conceptual model cannot be reassessed upon reviewing the numerical model results since relevant field data does not exist to date. This study therefore employs a range of estimates for key parameters to develop the conceptual model and subsequent numerical models.

Although little hydrogeological information was available, several other sources of information were considered when creating the conceptual model. These sources of information included:

- Previous reports published such as Swaren (1977), EBA (2002), JHP (2002), Kala (2004), BC Groundwater Consulting Services (2006) and Westwater Mining (2003);

- Conversations with members of the Merritt community, Urban Systems Ltd., BC Groundwater Consulting Services Ltd., and government representatives; and,

- Several site visits to familiarize with the study area, collect groundwater samples from available wells and springs, and observe some of the surficial sediments.

In order to accomplish the objectives of this study, three different numerical models were created. The first model, a base case scenario, was constructed to represent the topography of the Merritt region, the geometry of the various geological units, aspects of the surface hydrology and the current City of Merritt production wells. A second model was constructed to assess the potential response to coal seam dewatering at a pilot scale. This model is used to investigate the role that faults and coal bed subcrops play on the groundwater flow in response to coal seam dewatering in the area of Coldwater Hill to the south of Merritt. The third model is used to investigate the potential effects on groundwater flow at a regional scale and includes the role of a major fault on the hydrogeologic response to CBM development. Due to a lack of hydrostratigraphic information, for each of the three scenarios a sensitivity analysis was performed to assess the hydrologic response to a wide range of plausible parameter values.

The hydrostratigraphic configurations employed in these conceptual models were very simple. The conceptual models were designed to maintain the essential features of the geology and flow regime of the system, yet allowed for flexibility and numerical stability in the models. This flexibility allowed the models to be conceptually accurate while, given the software limitations, ensured that the numerical models would converge and produce reasonable results.

7.1 Base Case Model

In the Merritt region there are several distinct hydrogeological layers. The main geological formations are Triassic volcanics overlain by Tertiary sedimentary units overlain, in part, by Quaternary sediments. For the base case model the objectives were to reproduce the current groundwater flow system in the Merritt region, and in particular, simulate the City of Merritt production wells at a regional scale. Detailed information about the properties of the Triassic volcanics and the Tertiary sediments are not as pertinent to the base case model as the information regarding the Quaternary sediments since the production wells are completed in the surficial Quaternary aquifer.

The information provided in section 4.2 suggests that the sedimentary units do not extend through the entire region, and they are completely surrounded by the Tertiary volcanics. At some depth below the sedimentary units and/or the surface, the volcanics are likely to have a very low hydraulic conductivity and behave as a barrier to groundwater flow, or a no-flow boundary. To date, there is no physical evidence to support or invalidate this assumption of a no-flow boundary. Between the sedimentary units and/or the surface and the no-flow boundary a relatively gradual change in hydraulic conductivity is assumed as the volcanics grade from relatively weathered and/or fractured rock to stable un-weathered bedrock. The thickness of the weathered material is not known, however, it is considered to be significant since the region has undergone folding, faulting, glacial weathering and post glacial uplift. Conceptually, the weathered volcanic rock appears like a shell beneath the surface and/or sedimentary units with hydraulic conductivity grading from high to low with increasing depth.

Due to limitations in the software, the geometry of the Tertiary sedimentary units was simplified. There are six major coal seams that extend across the sedimentary basin. The configuration of the sedimentary units is complex and there are folds and faults causing the various strata to become laterally discontinuous and, in some cases, outcrop to the surface. Ideally, these six coal seams would be represented in the numerical model; however, due to constraints with the software (discussed in section 8.1), the use of six relatively thin coal seams is not feasible. Consequently, the six coal seams are simplified into two coal bearing units with uniform thickness which still reflect the undulating surfaces of the folded and faulted units.

The Quaternary sediments are made up of glaciolacustrine silts underlying alluvially deposited gravel and sand. The presence of the glaciolacustrine silts was determined from previous drilling; however, the depth and extent of the silts is poorly defined. The depth of the silts is inferred in a pair of cross sections prepared by Kala (2004) (Appendix A) in the area directly beneath Merritt. The silts are assumed to underlie the alluvial gravel and sand throughout the region. However, since the city of Merritt is situated over the pre-historic ice dammed lake described in the section 4.2, the thickness of the silts may decrease with distance from Merritt and the glaciolacustrine basin. The alluvial gravel and sand deposits are relatively well defined. The BC Ministry of Environment Water Resources Atlas displays online information related to the water resources of the Province of British Columbia, such as watersheds, water quantity and quality monitoring sites, aquifers, water wells and flood protection works. Several water wells were found in the Merritt area and borehole logs were available for some of these wells. From the borehole logs the bottom of the alluvium was determined in several locations. Also, the two cross sections prepared by Kala (2004) (Appendix A) were used to determine the bottom of the alluvium beneath the city of Merritt. The extent of the Quaternary deposits is shown on Figure 4. Conceptually, the Quaternary deposits appear like a trough in the Nicola and Coldwater valleys. Furthermore, the alluvial gravel and sand forms a trough within the glaciolacustrine silts.

Harrison (1995) described the idealized flow system in an upland-lowland setting as an: upland to lowland flow component recharged at high altitude and discharged along lower slopes and the valley bottom, and a flow component that is parallel to the valley bottom. This conceptual flow system is illustrated in Figures 10 and 11. This upland-lowland flow results in an upward flow beneath the river valley that is maintained by recharge and infiltration in the upland areas. Upland to lowland flow may also result in seeps or streams near local topographic lows and near the valley bottom. Figure 10 depicts a flow system with homogenous hydrostratigraphy. In reality three-dimensional flow is governed not only by the topography, but also the configuration of the various geologies. For this conceptual model, the flow is likely dominant in the most surficial layers because the hydraulic conductivity is relatively high and the recharge of water to the surface from precipitation.

To identify common flow systems, mixing locations and water quality, several groundwater samples were collected in the Merritt area and analyzed for various geochemical parameters. The results of the chemical analysis were made available for this study by the City of Merritt, Urban Systems Ltd. and BC Groundwater Consulting Services Ltd. Furthermore, five additional groundwater samples were collected as part of this study on July 20th and 21st, 2005. Chemistry results are included in Appendix C.

The major ions in natural water are sodium (Na^+), potassium (K^+), calcium (Ca^{2+}), magnesium (Mg^{2+}), chloride (Cl^-), carbonate (CO_3^{2-}), bicarbonate (HCO_3^-) and sulphate (SO_4^{2-}). The concentration of these major ions can be plotted on a Piper plot to evaluate the changes in groundwater chemistry along a flow path. Groundwater chemistry from nine sampling locations along Coldwater valley are plotted on Figure 12. The samples collected up valley are most consistent with the freshwater chemistry of the Coldwater River. Down valley the chemistry becomes more characteristic of groundwater with higher concentrations of persistent ions such as Na^+ and K^+. The arrows on Figure 12 indicate a groundwater mixing trend with distance along Coldwater valley. The results observed on the Piper plot supports the upland-lowland groundwater flow setting since the groundwater collected from the wells down valley have groundwater chemistry indicative of mixing with upward flowing groundwater. Figure 13 shows a Piper plot for the groundwater samples collected near Merritt. These wells include the city productions wells and a Ministry of Environment monitoring well. According to the Piper plot, the samples collected are similar to the samples collected from Coldwater and Nicola Rivers. This may indicate that groundwater in the surficial aquifer is mostly recharged from the rivers.

The regional hydrology is discussed in detail in section 6. For the purpose of the conceptual model, the Merritt area receives an average of 322 mm/yr of precipitation. The earlier analysis in section 6 indicates that an estimated 70 percent of the precipitation is removed from the system through evapotranspiration or for human use and 20 percent as runoff to streamflow. The remaining 10 percent, or 32 mm/yr, recharges the groundwater flow system. For the purpose of this model the river level remains constant and is not subject to any seasonal or long-term fluctuations in water level or discharge. To simulate the effects of the current groundwater demands for Merritt, the model includes the five City of Merritt production wells.

Figure 10: Conceptual Flow Path

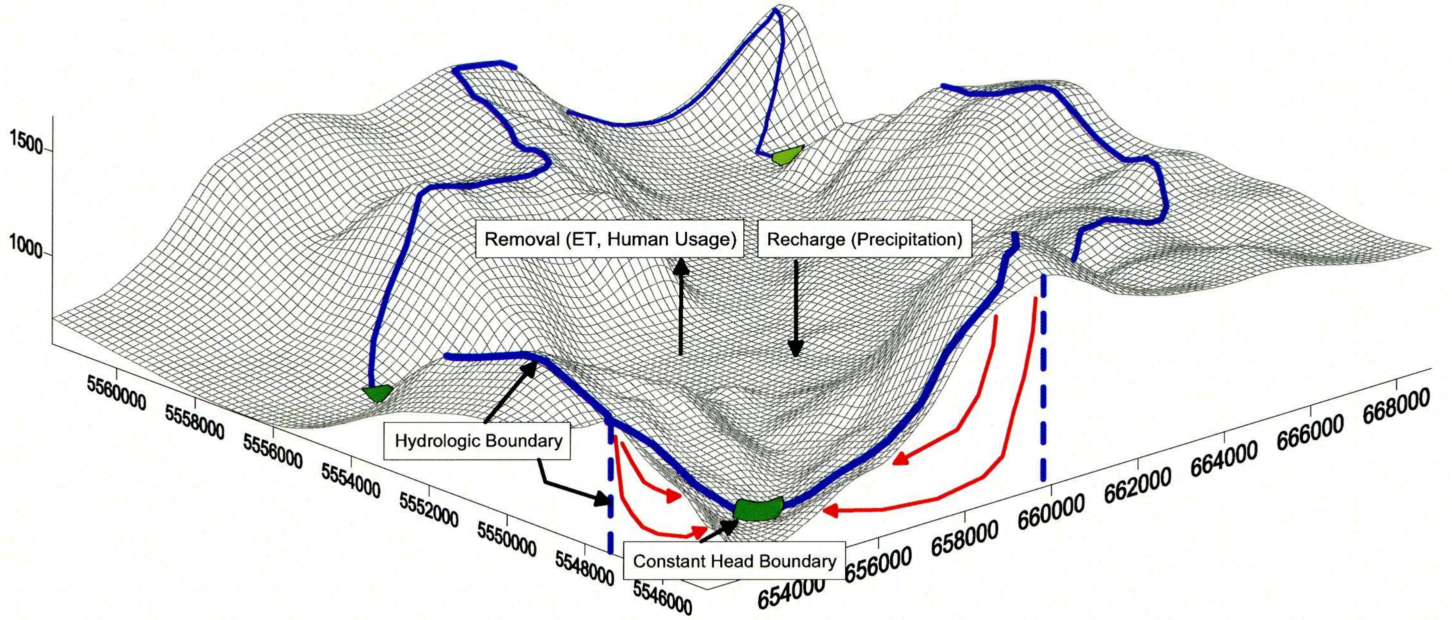
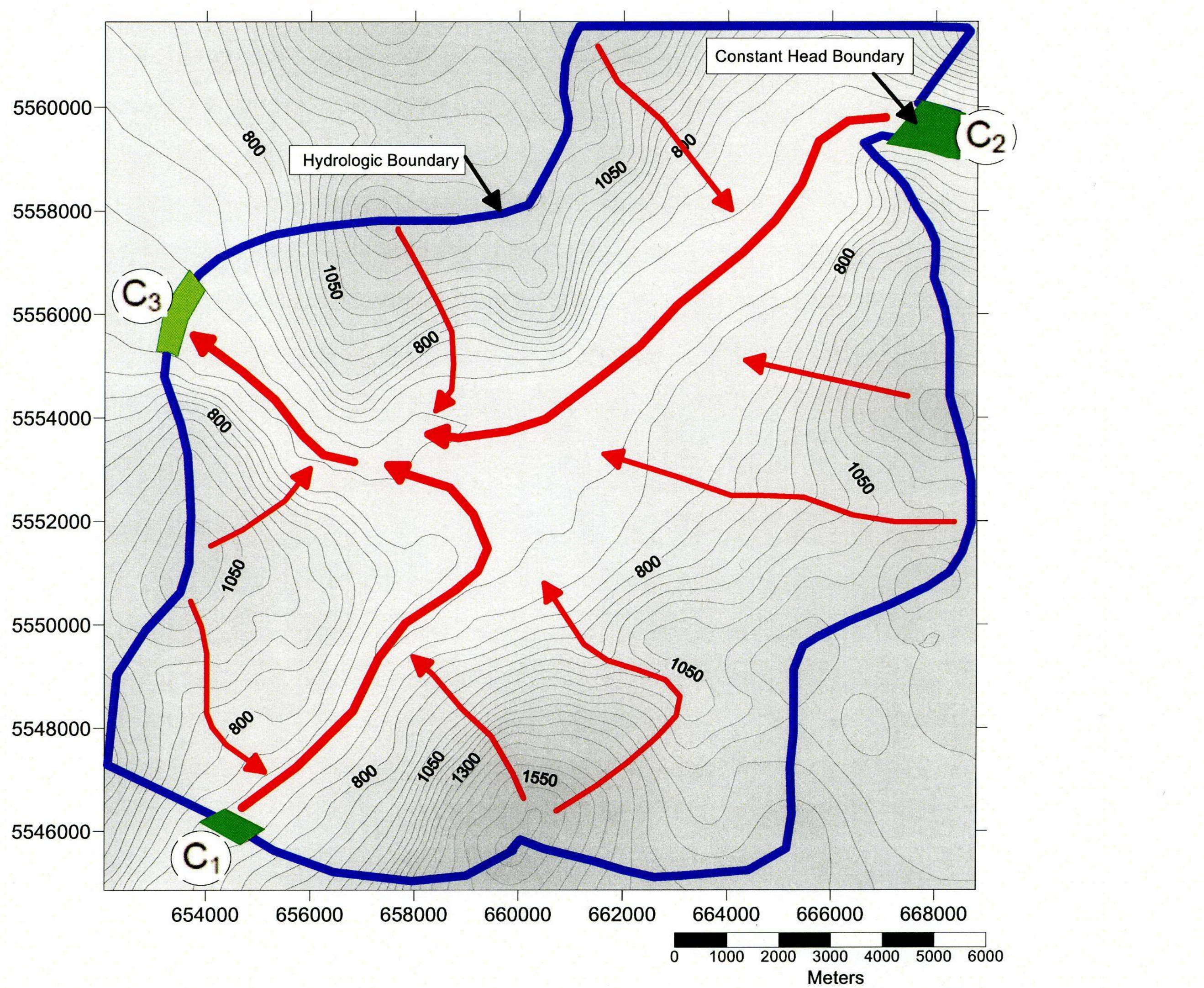


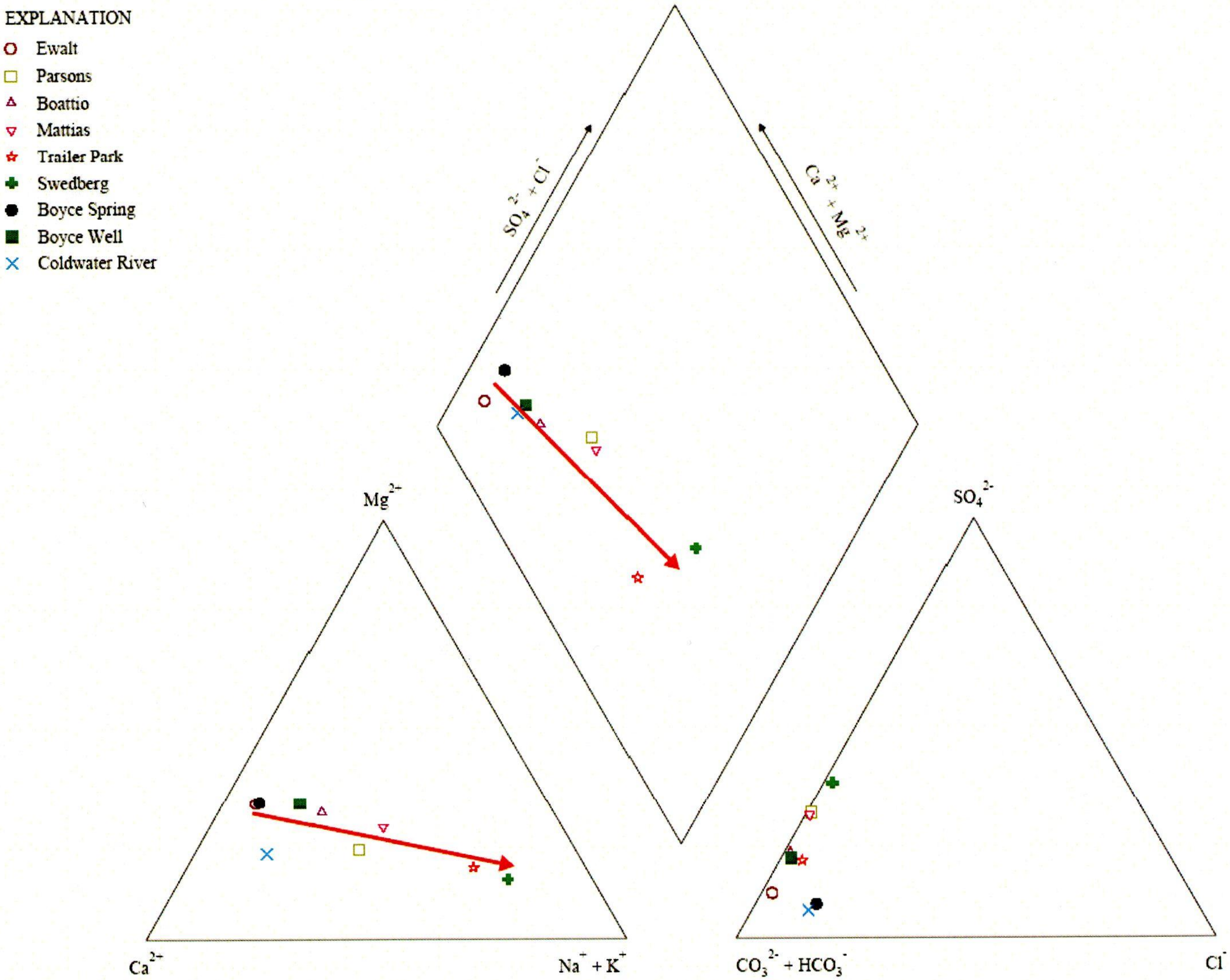
Figure 11: Conceptual Flow Direction



Recharge: R, Constant Head Boundary: $h = c_i$, Hydrologic Boundary: $\delta h/\delta n = 0$

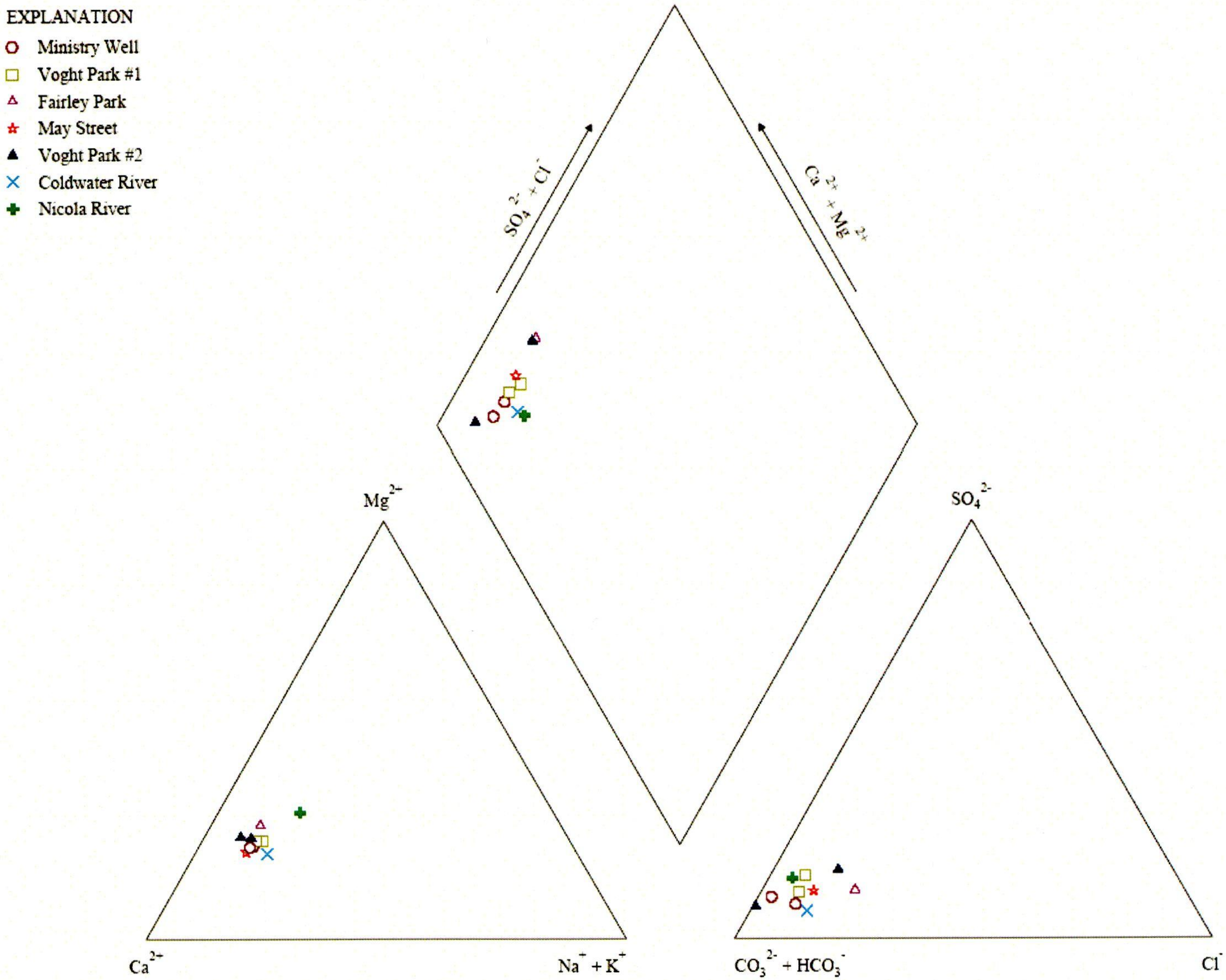
Groundwater Flow Equation: $\delta/\delta x(K_x \delta h/\delta x) + \delta/\delta y(K_y \delta h/\delta y) + \delta/\delta z(K_z \delta h/\delta z) + R = 0$

Figure 12: Piper Plot – Coldwater River Valley



Red Arrow indicates groundwater mixing trend with distance along Coldwater valley

Figure 13Piper Plot – Pi per Plot – Merritt Wells



7.2 Pilot Scale CBM

The objectives of the pilot scale model are to simulate the potential effects of coal seam dewatering in a relatively localized area. If CBM development were to proceed, it would likely begin as a pilot study in a relatively localized area before regional development would begin. The pilot study would be aimed at assessing the feasibility of CBM development on a regional scale. According to the BC Ministry of Energy and Mines the areas with the best potential for CBM resources are to the west and beneath the City of Merritt and Lot 166 (Figure 14) represents a plausible location for a pilot study.

Development of CBM involves dewatering a coal seam using a network of pumping wells to enable methane volatilization. The groundwater flow towards the pumping well is largely dependent on the hydraulic conductivity of the surrounding porous media and the magnitude of the hydraulic gradient. To understand the effects hydraulic conductivity has on the system, the hydraulic conductivity values can be modified for each unit to obtain a variety of possible responses. The geometry of the geology in the Coldwater Hill area is complex and thus difficult to represent accurately using the modeling software. Furthermore, an unconformity occurs between the Tertiary units and the overlying Quaternary sediments. This Tertiary sedimentary sequence was eroded along the unconformity so that several units, including coal seams, subcrop into the Quaternary sediments. Conceptually the model consists of a sequence of layered sedimentary rock with thin coal seams interbedded between units of sandstone/shale. The model must represent the coal seam subcrops and also the series of northwest-southeast trending faults.

To simulate coal seam dewatering, a series of pumping wells were introduced to the coal seam, or coal seams that are interpreted to have methane producing potential. The wells are spaced at 200 metre intervals and the simulation time of the model was five years, as is typical of pilot scale studies. The model results were used to quantify the amount of groundwater that must be pumped from the coal seams to produce CBM. Furthermore, the results were also used to observe the groundwater flux at the interface between the Quaternary sediments and the coal seam subcrops as well as along the series of faults. It was assumed that groundwater flows from the Coldwater Hill area into the Merritt aquifer. If a significant amount of water were removed from the groundwater flow system in the Coldwater Hill area, the result may be a partial depletion of a source to the Merritt aquifer.

7.3 Regional Scale CBM

The objectives of the regional scale CBM model were to simulate the effects of CBM development over a regional scale. Due to the scale of this model, it was not feasible to represent the level of detail that is required to accurately define every feature of the hydrostratigraphy. Instead, results of the pilot scale model were used to infer the role of subcrops and localized faults for the regional system. The main feature of the geology that the regional model was used to evaluate was the strike-slip fault that extends from the southwest to the northeast of Merritt. This fault is interpreted to cut through the sedimentary basin and due to its presence and potential to affect the flow system of the area must be included in the conceptual model. In absence of sufficient hydrogeologic testing, it is difficult to describe a fault in terms of its hydrogeological properties, since there is a broad range of possible hydrogeologic properties for a fault zone. A fault can behave either as a conduit for groundwater flow or a barrier to groundwater flow. As such, the numerical model was used to simulate a broad range of hydrogeological properties for the fault.

The topography of the region and the configuration of the Quaternary units were the same as the base case model; however, the Tertiary geology differed. For a scenario involving coal seam dewatering, the coal seams were represented as thin layers interbedded between units of sandstone and shale.

To simulate coal seam dewatering, a series of pumping wells were introduced to the coal seam, or coal seams, that are interpreted to have methane producing potential. The wells were spaced according to typical well spacing for regional CBM development regulations. The model results were used to examine the groundwater flux at the interface between the Quaternary sediments and the southwest-northeast trending fault.

Figure 14: Approximate Location of Lot 166

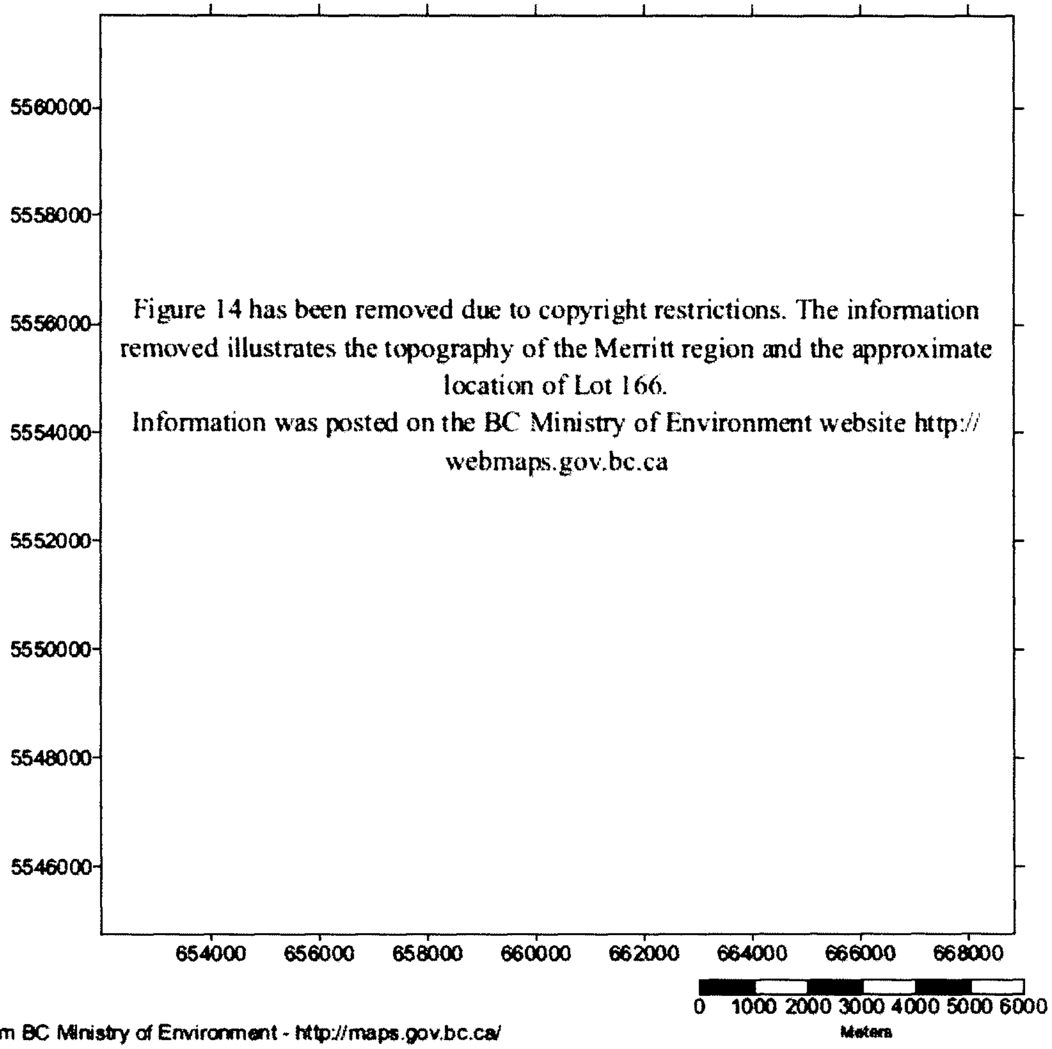


Figure 14 has been removed due to copyright restrictions. The information removed illustrates the topography of the Merritt region and the approximate location of Lot 166.
Information was posted on the BC Ministry of Environment website http://webmaps.gov.bc.ca

Color Hillshade from BC Ministry of Environment - http://maps.gov.bc.ca/

8.0 NUMERICAL MODEL

Using the conceptual models formulated in section 7, a numerical model has been constructed using Visual MODFLOW version 4.0.0.126. MODFLOW is a modular three-dimensional groundwater flow model originally developed by the U.S. Geological Survey and currently by Waterloo Hydrogeologic Inc. The model is based on a block-centered finite difference formulation of the groundwater flow equation requiring all model layers to be continuous across the entire model domain. Each layer is required to have a finite layer thickness in order to assure conservation of mass and, hence, the stability and accuracy of the solution. Input parameters to the model domain include boundary conditions, hydrostratigraphic properties and recharge.

MODFLOW simulates groundwater flow under saturated conditions and can not simulate two-phase flow of gas and water. MODFLOW was used for the pilot scale and regional scale CBM models simulate groundwater flow in response to coal seam dewatering. Using MODFLOW for simulating coal seam dewatering likely introduces some model uncertainties since MODFLOW can not simulate methane desorption as a result of reducing the hydrostatic pressure of the coal seam nor the reduced relative permeability of water during gas desorption. The relative permeability for water for each model is not transient; however, pilot scale and regional scale models simulate groundwater flow under a number of different hydraulic conductivity scenarios.

8.1 Base Case Model

8.1.1 Model Domain

The size of the region to be entered into the base case model was chosen to reflect the hydrologic boundaries of the Merritt Basin (Figure 11). The entire watershed surrounding Merritt (Nicola and Coldwater River Watersheds) was not modeled because most of the watershed falls far outside of the region of interest (see further explanations in section 8.1.3). The size of the regional model is approximately 17 km by 17 km (28,900 hectares); however, the active region is irregular in shape and takes up approximately 20,000 hectares.

Creating a three dimensional model in MODFLOW requires importing surface topography and any other additional boundaries of geologic layers. In order to assure model convergence, the various layers in a MODFLOW model must be laterally continuous. Waterloo Hydrogeologic Inc. specifies that large changes in elevation (especially when the model has thin layers) can cause adjacent cells to become laterally "detached", resulting in a lack of lateral continuity. This disables flow between cells in the same layer. As a rule of thumb, Waterloo Hydrogeologic Inc. specifies that vertical displacement between horizontally adjacent cells in the same layer should not be greater than approximately 50 percent of the cell thickness. Maintaining lateral continuity is particularly difficult to accomplish with thin layers in areas with steep slopes. For constructing the model framework, two methods were used to maintain lateral continuity. The first method was to create a grid with sufficient resolution so that the transition from cell to cell would be smooth and therefore less likely to suffer from discontinuity. Using a sufficiently fine resolution the region was modeled using 200 rows by 200 columns. This results in each grid cell being approximately 85 m by 85 m. The second method was to create fewer layers by combining geologic layers, thereby making the individual layers thick enough to ensure excessive displacement does not occur in areas where the terrain was steep. Although significant simplification of all geologic units must take place, the Tertiary sedimentary units require the greatest degree of modification to maintain lateral continuity. This is because several Tertiary layers, namely the coal seams, are thin and are subject to folding and faulting causing steep changes in elevation. For the purpose of the base case model, combining the Tertiary sedimentary units into composite layers is acceptable because the areas of interest in this model are the surficial layers in proximity to the City of Merritt.

Building the model framework began by collecting data points that included the latitude, longitude and elevation for several locations relating to each geologic layer. These data points were then interpolated to provide a smooth surface that represents the layer surfaces. The surface topography was collected from BC Ministry of Environment Water Resources Atlas. Latitude, longitude and elevation information was collected from a total of 1268 points over the region.

The data points for the surficial aquifer were collected using the BC Water Resource Atlas and also from a report provided by Kala Groundwater Consulting Ltd. (Kala) (2004) (Appendix A). The Water Resource Atlas provides detailed well records for several wells in the Merritt area. Using these well records, the bottom of the aquifer and the lateral extent was interpreted into a series of data points. A total of 1185 data points were used to describe the bottom of the surficial aquifer.

The entire surficial aquifer is confined within the Quaternary deposits including glaciolacustrine silts, tills, etc. The data points for the Quaternary sedimentary deposits were also collected using the BC Water Resource Atlas, including the detailed well records, and the Kala report (2004). The BC Water resource Atlas provides a layer that outlines the Quaternary deposits. This data was used to define the extent of the Quaternary deposits when collecting the data points. A total of 1173 data points were used to describe the bottom the Quaternary deposits.

The sedimentary rock, which includes the coal seams, was relatively poorly defined as compared to the Quaternary geology. A series of cross sections (JHP, 2002), were used to define the bottom of the sedimentary rocks in the area near Coldwater Hill. Additionally, three cross sections (Swaren, 1977) were used to interpret the depth of the various sedimentary layers for the remaining areas of the sedimentary basin. To maintain lateral continuity, the sedimentary layers were simplified into two coal bearing units surrounded by three sedimentary units. Based on the information available regarding the depth and extent of the geologic layers in the Merritt region, a total of nine geologic layers were created. The bottom layer represents the impermeable bedrock and is characterized by a no-flow boundary.

The data points were interpolated with Surfer, a surface mapping software, to create a continuous surface. Because many of the layer surfaces were very steep in areas, especially the sedimentary geology as it is folded and faulted, the layers were smoothed in Surfer. This was another means of maintaining lateral continuity by mitigating the effects of steep slopes.

Once the layer surfaces were created they were imported into MODFLOW. Although the simulated composite layers are thicker than the individual component layers that they represent, this simplified three-dimensional framework provides a reasonably good approximation of the region given the constraints of the modeling software and the limited information available of the subsurface geology. Fortunately, the most important layers in this model, the Quaternary sediments, are likely the most accurately represented in the model.

8.1.2 Hydrostratigraphy

To date, there have been no physical hydrogeological investigations in the Merritt area apart from the surficial aquifer beneath Merritt. EBA Engineering Consultants Ltd. prepared a report titled *Aquifer Protection Plan* for the City of Merritt in 2002 and Kala Groundwater Consulting Ltd. prepared a report titled *Groundwater Potential Evaluation and Test Well Siting Study* for the City of Merritt in 2004. A summary of the hydraulic properties collected from production wells completed in the surficial aquifer is provided in Table 3. The results of the EBA and Kala reports suggest that the hydraulic conductivity of the surficial aquifer ranges from $6x10^{-2}$ to $2x10^{-1}$ cm/s.

Since there is no other measured hydrogeological data from the Merritt region, the remainder of the hydrogeological parameters were estimated based on typical ranges of values for the various geological units. Freeze and Cherry (1979) presented typical hydraulic conductivity values for various geological media (Figure 15). Once the model framework was constructed, the hydraulic conductivity data was entered into MODFLOW. Table 4 presents the horizontal hydraulic conductivities used for each layer in the base case model. For each of the sedimentary units the vertical hydraulic conductivity is assumed to be an order of magnitude less than the horizontal hydraulic conductivity. The hydraulic conductivity for the units composed of volcanic bedrock is assumed to be the same in all directions. To determine the effects that hydraulic conductivity has on the groundwater flow in the surficial layers, three sets of hydraulic conductivity values were used. The three sets of values presented in Table 4 for layers 1 and 2 represent a high, medium and low hydraulic conductivity case within the range

Table 3: Summary of Production Well Completion Data and Hydraulic Properties

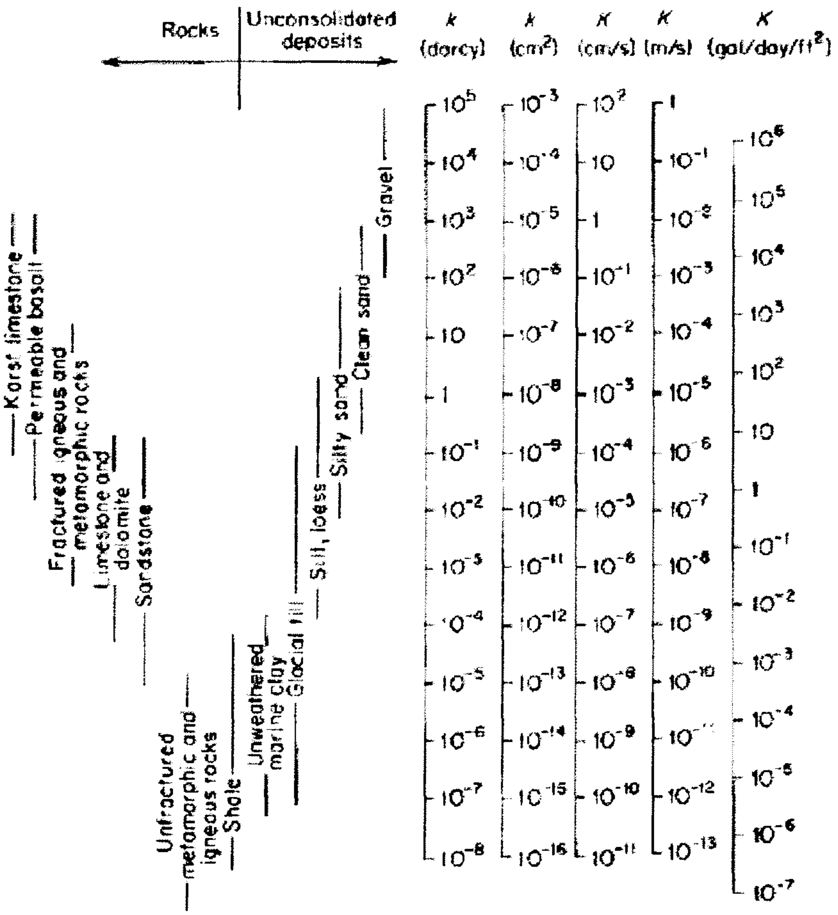
Well	Year of Completion	Diameter	Completion Data		Static Water Level		Hydraulic Properties				Estimated Saturated Thickness (m)	Aquifer Response
			Total Depth (m)	Screen Interval (m)	Depth (m)	Date Measured	Specific Capacity (L/s/m)	Date Measured	Transmissivity (m^2/s)	Hydraulic Conductivity (m/s)		
Colletteville	Jul-78	254 mm	49.1	37.6 0- 45.1	4.1	Aug-78	43	Unknown	8.00E-02	2.00E-03	> 45.3	Leaky-Confined Aquifer
					4.3	Sep-96	23	Unknown				
Fairly Park	Jan-66	305 mm	29.9	19.2 - 25.3	1.86	Feb-71	17	1966	2.00E-02	1.00E-03	23.4	Leaky-Confined Aquifer
							29	Jun-78				
May Street	Oct-70	305 mm	30.5	7.6 - 10.7	2.89	Oct-70	8.8	Unknown	1.00E-02	1.00E-03	7.8	Unconfined Aquifer
					2.9	1972	12	Dec-91				
Voght Park #1	Jul-71	406 mm	29.9	20.7 - 29.9	2.56	1971	8.7	Jul-71	5.00E-02	2.00E-03	26.2	Leaky-Confined Aquifer
					3.48	Sep-76						
Voght Park #2	Sep-76	406 mm	34.8	9.8 - 34.1	3.63	Sep-76	18	Sep-76	2.00E-02	6.00E-04	31.1	Leaky-Confined Aquifer
							8	Jan-90				

Data summarized from EBA *Aquifer Protection Plan*, 2002 measured by EBA (2002), Kala (2004) and BC Groundwater. Hydraulic conductivity values for the remaining geologic units were chosen within their respective ranges presented on Figure 15.

Table 4: Base Case – Range of Values of Hydraulic Conductivity for each Layer

Layer #	Unit Description	Horizontal Hydraulic Conductivity (cm/s)		
		Low	Medium	High
1	Alluvium/Colluvium	5.0E-02	1.0E-01	5.0E-01
1b	Colluvium/Fractured VOLCANICS		5.0E-03	
2	Lacustrine SILT/TILL	5.0E-04	5.0E-03	5.0E-02
2b	Fractured VOLCANICS		1.0E-05	
3	SHALE and SANDSTONE		5.0E-07	
3b	weathered VOLCANICS		1.0E-07	
4	SHALE and SANDSTONE with interbedded COAL seam		1.0E-05	
4b	VOLCANIC bedrock		1.0E-08	
5	SHALE and SANDSTONE		5.0E-07	
5b	VOLCANIC bedrock		1.0E-08	
6	SHALE and SANDSTONE with interbedded COAL seam		1.0E-05	
6b	VOLCANIC bedrock		1.0E-08	
7	SHALE and SANDSTONE		5.0E-07	
7b	VOLCANIC bedrock		1.0E-09	
8	VOLCANIC bedrock		1.0E-09	
9	IMPERMEABLE		-	

Figure 15: Range of Values of Hydraulic Conductivity and Permeability
From Freeze and Cherry (1979)



	Permeability, k*			Hydraulic conductivity, K		
	cm^2	ft^2	darcy	m/s	ft/s	U.S. gal/day/ft^2
cm^2	1	1.08×10^{-3}	1.01×10^{8}	9.80×10^{3}	3.22×10^{3}	1.85×10^{9}
ft^2	9.29×10^{2}	1	9.42×10^{10}	9.11×10^{5}	2.99×10^{6}	1.71×10^{12}
darcy	9.87×10^{-9}	1.06×10^{-11}	1	9.66×10^{-6}	3.17×10^{-5}	1.82×10^{1}
m/s	1.02×10^{-3}	1.10×10^{-6}	1.04×10^{5}	1	3.28	2.12×10^{6}
ft/s	3.11×10^{-4}	3.35×10^{-7}	3.15×10^{4}	3.05×10^{-1}	1	6.46×10^{5}
U.S. gal/day/ft^2	5.42×10^{-10}	5.83×10^{-13}	5.49×10^{-2}	4.72×10^{-7}	1.55×10^{-6}	1

*To obtain k in ft^2, multiply k in cm^2 by 1.08×10^{-3}.

The top two layers consist of alluvial/colluvial sediments and glaciolacustrine silts and till in the valley and colluvium and fractured volcanics in the slopes and hills. The subsequent six layers consist of sedimentary units surrounded by weathered volcanics. The bottom most active layer consists of weathered bedrock. It is assumed that the hydraulic conductivity of the volcanics decrease with increasing depth as the influence of surface processes (i.e. erosion, compressional effects of glaciation, etc.) decreases, thereby reducing the amount of weathering. Furthermore, as the depth increases, so does the weight of the overlying material, which causes more compaction of the geological matrix, thereby decreasing the rock's permeability. Figure 16 shows the configuration of the hydraulic conductivity for each layer.

A fault zone is represented in layers three through eight where there has been displacement of the layers across a fault plane. The fault is assumed to be vertical and the hydraulic conductivity of the fault is poorly constrained. Accordingly, a range of conductivity values between 1×10^{-4} cm/s and 1×10^{-10} cm/s are assigned to the fault plane.

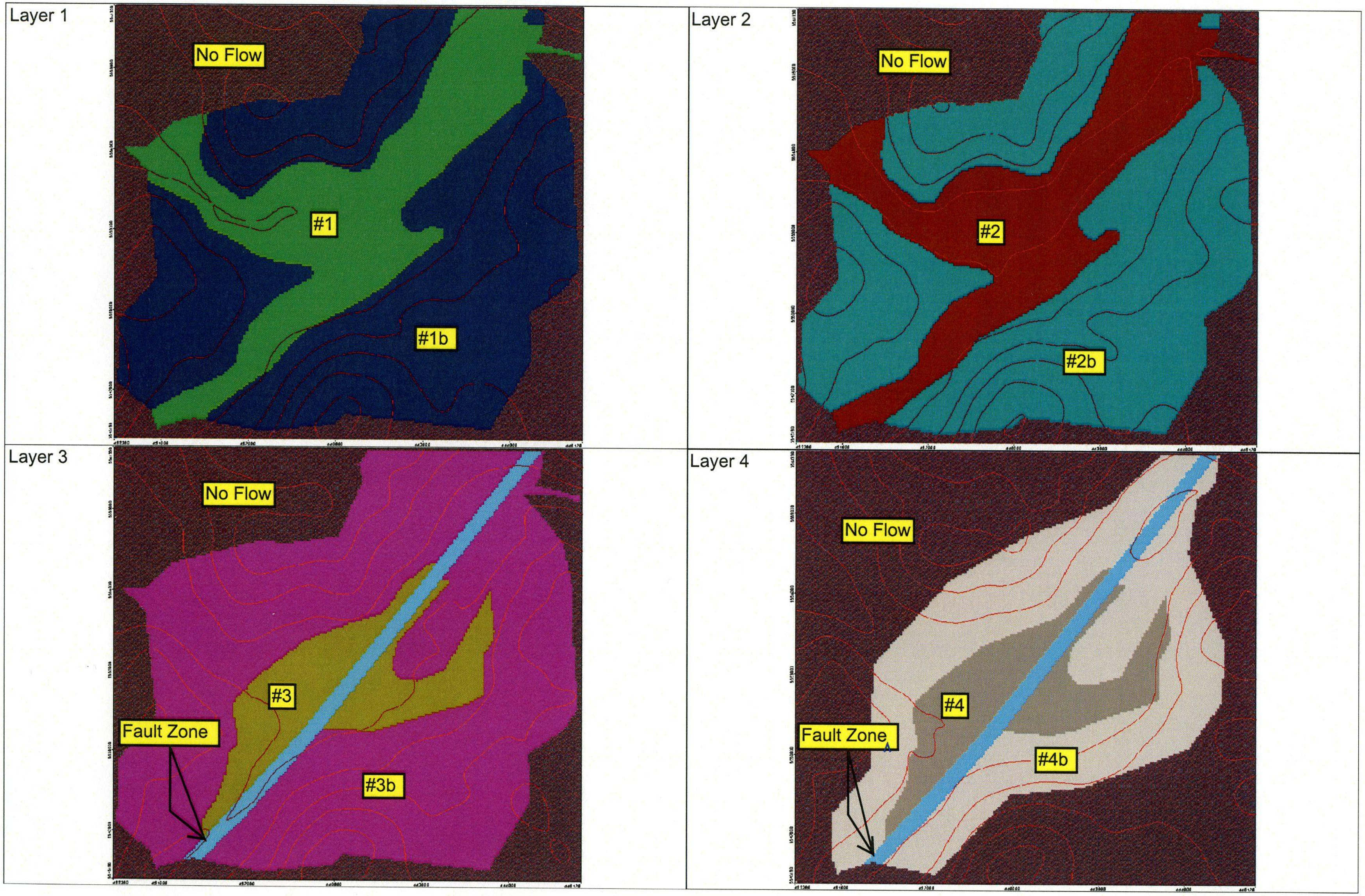
MODFLOW requires values for specific storage, specific yield, effective porosity and total porosity. Storage is not considered crucial since most of the analyses focus on steady-state conditions, which are not affected by storage properties. There have been no hydrogeological investigations that determine the storage values in the Merritt area, and consequently the storage values are estimated based on typical ranges of values for the various geological media. The values for specific yield and porosity were chosen based on typical values provided by Dominico and Schwartz (1998). Specific storage (Ss) was calculated using an equation from Fetter (2001):

$$Ss = \rho_w g(\alpha + n\beta)$$

Where

ρ_w	is the density of water (1000 kg/m^3)
g	is the acceleration due to gravity (9.8 m/s^2)
α	is the compressibility of the aquifer
n	is the total porosity
β	is the compressibility of water (4.6×10^{-10} ms^2/kg)

Figure 16: Hydraulic Conductivity Configuration



It is likely that the compressibility of the aquifers is important when determining the specific storage; however, since α is unknown, the aquifers are assumed to be incompressible. If taking into account aquifer compressibility, the value for specific storage would increase. Thus the equation for specific storage becomes:

$$Ss = \rho_w g n \beta$$

Using the estimated total porosity for each of the geologic units, and assuming g and β are constant, the specific storage can be found using the above equation. The values of specific yield, specific storage and porosity used for each of the geologic units are presented in Table 5. Under steady-state conditions, the storage values are not considered to be of critical importance to the model. Therefore, an assessment of the effects of storage was not undertaken as part of this study.

Table 5: Storage Values for Various Geologic Media

Layer #	Unit Description	Specific Yield	Compressibility (m^2/N)	Specific Storage (1/m)	Porosity
1	Alluvium/Colluvium	0.25	1.00E-07	9.8E-04	0.3
1b	Colluvium/Fractured VOLCANICS	0.2	5.00E-08	4.9E-04	0.35
2	Lacustrine SILT/TILL	0.15	2.00E-08	2.0E-04	0.2
2b	Fractured VOLCANICS	0.1	5.00E-10	5.6E-06	0.15
3	SHALE and SANDSTONE	0.1	1.00E-08	9.9E-05	0.2
3b	weathered VOLCANICS	0.08	3.00E-10	3.4E-06	0.1
4	COAL	0.05	3.00E-08	3.0E-04	0.2
4b	VOLCANIC bedrock	0.08	2.00E-10	2.4E-06	0.1
5	SHALE and SANDSTONE	0.1	1.00E-08	9.9E-05	0.2
5b	VOLCANIC bedrock	0.08	1.00E-10	1.4E-06	0.1
6	COAL	0.05	3.00E-08	3.0E-04	0.2
6b	VOLCANIC bedrock	0.08	1.00E-10	1.4E-06	0.1
7	SHALE and SANDSTONE	0.1	1.00E-08	9.9E-05	0.2
7b	VOLCANIC bedrock	0.08	1.00E-10	1.4E-06	0.1
8	VOLCANIC bedrock	0.08	1.00E-10	1.5E-06	0.1
9	IMPERMEABLE	-	-	-	-

The initial head in the base case model was imported from a steady state simulation of the base case model without the influence of the City of Merritt production wells.

According to Kala (2004), the City of Merritt extracts approximately 100 litres per second (L/s) on an average annual basis from the surficial aquifer via five production wells. Approximately 68 percent of the production is supplied from the Voght Park wells. Table 6 includes the historical and present pumping rates for each of the wells. EBA

(2002) suggested that the City of Merritt would likely require approximately 120 L/s by 2010. EBA (2002) found that extraction rates in excess of 100 L/s may impact the aquifer as a whole and may potentially cause production well interference.

The five production wells used to supply Merritt with their potable water supply are the Voght Park #1, Voght Park #2, Fairley Park, May Street, and Collettville pump stations. The historical information on the pumping rates for each well provided by the City of Merritt is limited to 1993; however, each well has been in operation since before 1993.

Table 6: Yearly pumping rates for City of Merritt Production Wells

	Voght Park #1	Voght Park #2	Fairley Park	May Street	Collettville
1993	43.4	19.7	17.4	5.2	-
1994	6.2	76.8	14.3	4.4	-
1995	5.2	72.7	13.2	4.2	-
1996	15.6	67.7	5.2	1.2	-
1997	4.2	53.5	25.7	0.8	13.4
1998	7.5	67.0	19.5	0.0	14.9
1999	22.8	49.5	23.9	1.6	4.6
2000	20.9	42.0	16.4	1.2	15.4
2001	23.5	48.0	22.8	0.9	9.6
2002	23.2	47.1	23.3	1.8	5.9
2003	13.6	50.6	16.2	1.1	21.9
2004	25.5	43.7	20.4	0.8	12.5
2005	4.1	54.2	32.2	0.7	10.7
2006	1.4	24.2	16.7	0.2	3.5
Total	217.0	716.8	267.3	23.9	112.5
Average (L/s)	15.5	51.2	19.1	1.7	10.2
Average (m^3/d)	1339.5	4423.6	1649.7	147.7	883.6

For the purpose of simulating pumping at these five stations, the average pumping rate at each well is used for each year it was in use.

8.1.3 Boundary Conditions

For the base case model three different boundary conditions were used: an impermeable boundary (*i.e.* no flow), a specified head boundary and a specified flux boundary.

As described above the base case model occupies approximately 20,000 hectares in the Merritt region. The lateral boundaries of the model follow the topographic highs in the area and it is assumed that surface water and groundwater on the outside of these boundaries would flow away from the modeled area. These boundaries are considered hydraulic divides and they are assumed to create a no flow boundary. Geological features such as tilted bedrock and dipping faults may cause errors in the assumed boundaries if water flows into the modeled area from outside the boundaries or vice versa. The entire watershed surrounding Merritt (Nicola and Coldwater River Watersheds) was not modeled because most of the watershed falls far outside of the region of interest. In order to constrain the size of the model, the boundaries of the model do not follow the assumed hydraulic divide in three areas. These three areas are characterized by two rivers flowing into the model (Nicola and Coldwater Rivers) from the east and south and one river flowing out (Nicola River) to the west. The water level in the rivers is assumed to be relatively constant and therefore these three areas are represented with a constant head boundary value at the surface. Furthermore, for the remaining reaches of the rivers, a constant head boundary was applied at an elevation equal to the ground surface.

To constrain the depth of the model, a no flow boundary was assigned to stable bedrock. As discussed above, the volcanic bedrock is assumed to be weathered until some depth below the Tertiary sedimentary units and/or the Quaternary sediments. The thickness of the weathered volcanics is very subjective, however; the hydraulic conductivity of the volcanics is always low compared to the hydraulic conductivity of the surrounding geology. Therefore, groundwater flow within the volcanics is likely to be relatively insignificant.

As discussed in Section 6.0 and simulated by a VADOSE/W model the groundwater recharge in the basin is likely between 6 and 10 percent of the total precipitation. The recharge boundary was applied to the top layer of the model with a value of 30 mm/year.

Figure 17 shows a typical cross section from west to east through the model and Figure 18 shows the plan view of the model with the applicable boundary conditions.

Figure 17: Model Cross-Section through Merritt Basin

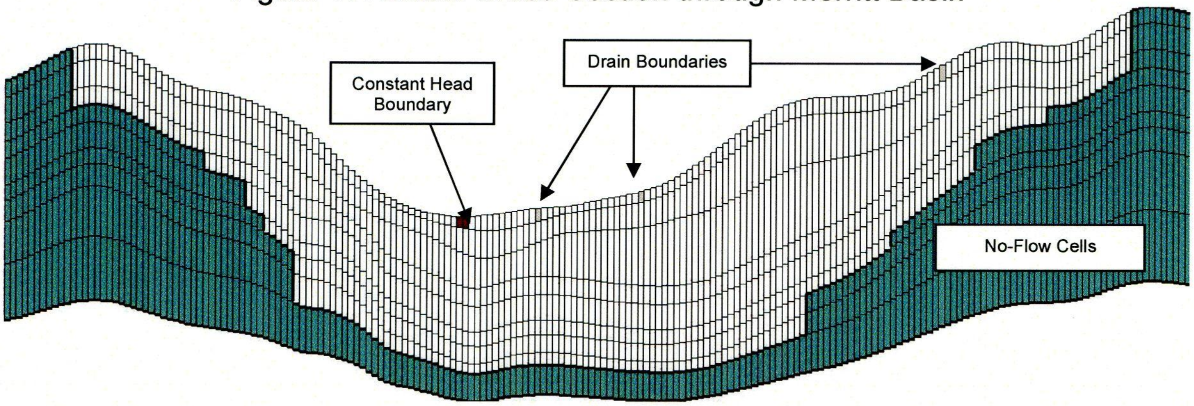
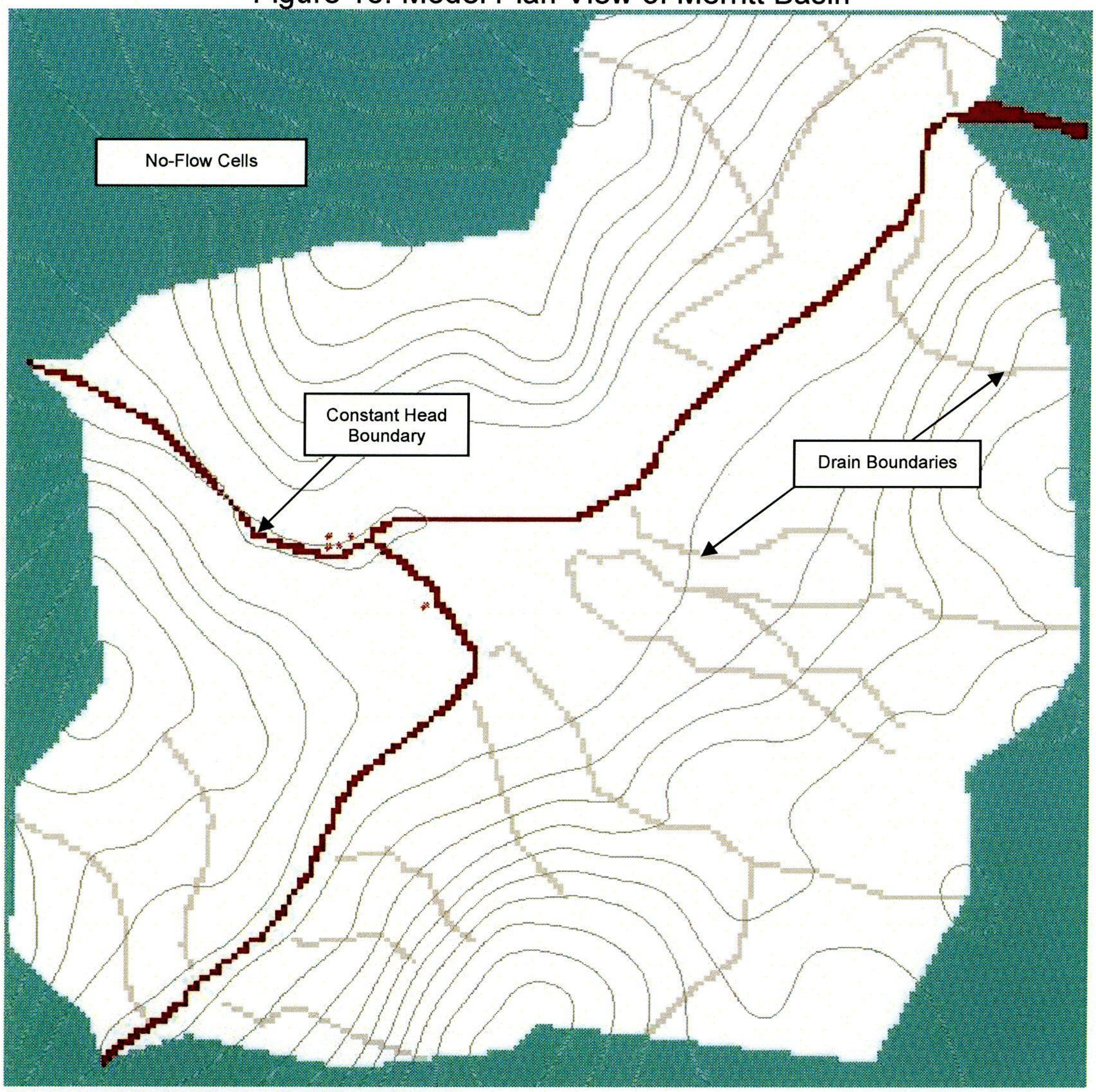


Figure 18: Model Plan View of Merritt Basin



Topographic Contours at 100m intervals

8.2 Pilot Scale Model

8.2.1 Model Domain

The pilot scale model covered an area to the southwest of Merritt in the Coldwater Hill area. The modeled area was near or within the bounds of Lot 166 (Figure 14). The area of the model is approximately 6 km by 6 km (3,600 hectares), however; the active region is irregular in shape and takes up approximately 1,750 hectares. Within this area there is a surface layer that represents the aquifer sediments in the valley and colluvium/weathered bedrock in the hills. Below this layer are the volcanic bedrock and the Tertiary sedimentary units. The grid cells in the area occupied by the Tertiary sedimentary units is approximately 10 m by 10 m, and the grid size in the area occupied by the volcanics is 100 m by 100 m. The reason for the fine grid size in the area of the Tertiary units is that this is the region of interest.

The entire pilot scale model is within the bounds of the base case model and therefore the topography used for the base case model was also used for the pilot scale model. The geology in this area was interpreted through a series of maps and cross-sections prepared by JHP (2002) and Swaren (1977). As discussed above, MODFLOW does not allow laterally detached layers or layers with zero thickness. Because of this it is very difficult to simulate the highly folded and faulted sedimentary units of in the Coldwater Hill area. Furthermore, modeling subcrops is difficult since layers cannot pinch out. To maintain lateral continuity and still adhere to the objectives of the model, the coal seams were modeled as a series of layers with uniform depth and thickness. A total of four coal seams were entered into the model, each with a thickness of 10 m. The depth of each coal seam was assumed as an approximate average of the actual depth. The locations of the subcrops of the coal seams were based on the map prepared by Swaren (1977). The trace of the subcrop was copied vertically downwards until its respective coal seam was encountered. As a result, the subcrop and the coal seam meet at a ninety-degree angle. The thickness of the coal seam and subcrop are uniform at 10 m. In this way, the general shape of the synclinal structure of the coal seams is maintained as well as the lateral continuity. The faults in the area were entered as vertical features that cut through the Tertiary sedimentary units.

8.2.2 Hydrostratigraphy

To date, there has been no hydrogeological investigation in the Coldwater Hill area. Consequently, all of the hydrostratigraphic properties are estimated based on the Freeze and Cherry (1979) values (Figure 15). Since the estimates of the range in hydraulic conductivity are broad, several different scenarios were simulated with varying hydraulic conductivities. Table 7 presents the hydraulic conductivities used for the pilot scale model.

Table 7: Pilot Scale Model – Range of Values of Hydraulic Conductivity for each Layer

Layer #	Unit Description	Horizontal Hydraulic Conductivity (cm/s)		
		Low	Medium	High
1	Merritt Aquifer	5.0E-01		
1b	Colluvium/Fractured VOLCANICS	1.0E-07	5.0E-02	
2	SHALE and SANDSTONE	1.0E-09	5.0E-08	1.0E-07
3	COAL	1.0E-06	1.0E-05	1.0E-04
3b	SHALE and SANDSTONE	1.0E-09	5.0E-08	1.0E-07
4	SHALE and SANDSTONE	1.0E-09	5.0E-08	1.0E-07
5	COAL	1.0E-06	1.0E-05	1.0E-04
5b	SHALE and SANDSTONE	1.0E-09	5.0E-08	1.0E-07
6	SHALE and SANDSTONE	1.0E-09	5.0E-08	1.0E-07
7	COAL	1.0E-06	1.0E-05	1.0E-04
7b	SHALE and SANDSTONE	1.0E-09	5.0E-08	1.0E-07
8	SHALE and SANDSTONE	1.0E-09	5.0E-08	1.0E-07
9	COAL	1.0E-06	1.0E-05	1.0E-04
9b	SHALE and SANDSTONE	1.0E-09	5.0E-08	1.0E-07
10	SHALE and SANDSTONE	1.0E-09	5.0E-08	1.0E-07
11	IMPERMEABLE	-		
-	Faults	5.0E-10	-	5.0E-05

The same storage parameters were used for the pilot scale model as were used in the base case model.

Since the vertical subcrops and faults cannot be represented as layers, they were represented as cells with distinct hydraulic conductivity values. Consequently, the hydraulic conductivity is the same in the subcrops as it is in the coal seams. Figure 19 shows a typical cross-section for the pilot scale model and Figures 20 and 21 show the location of the subcrops and faults in plan view in layer 2 and 7, respectively.

Figure 19: Pilot Scale Model - Typical Cross-section

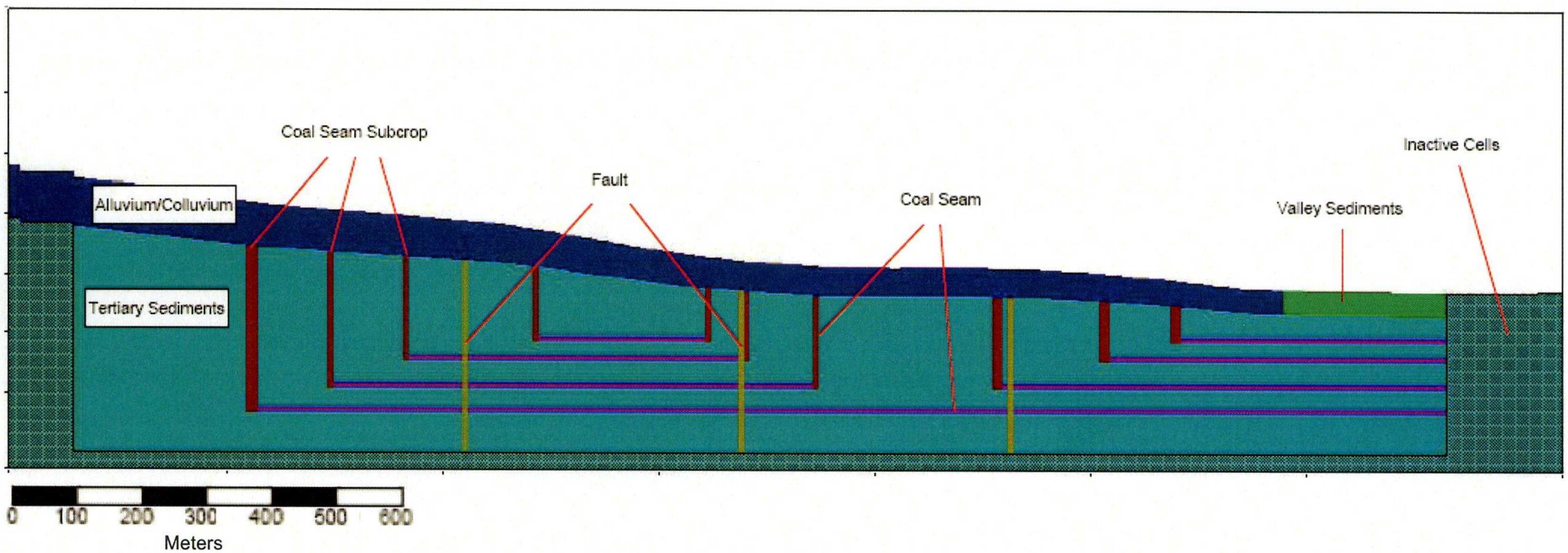


Figure 20: Pilot Scale Model Plan View of Layer 2

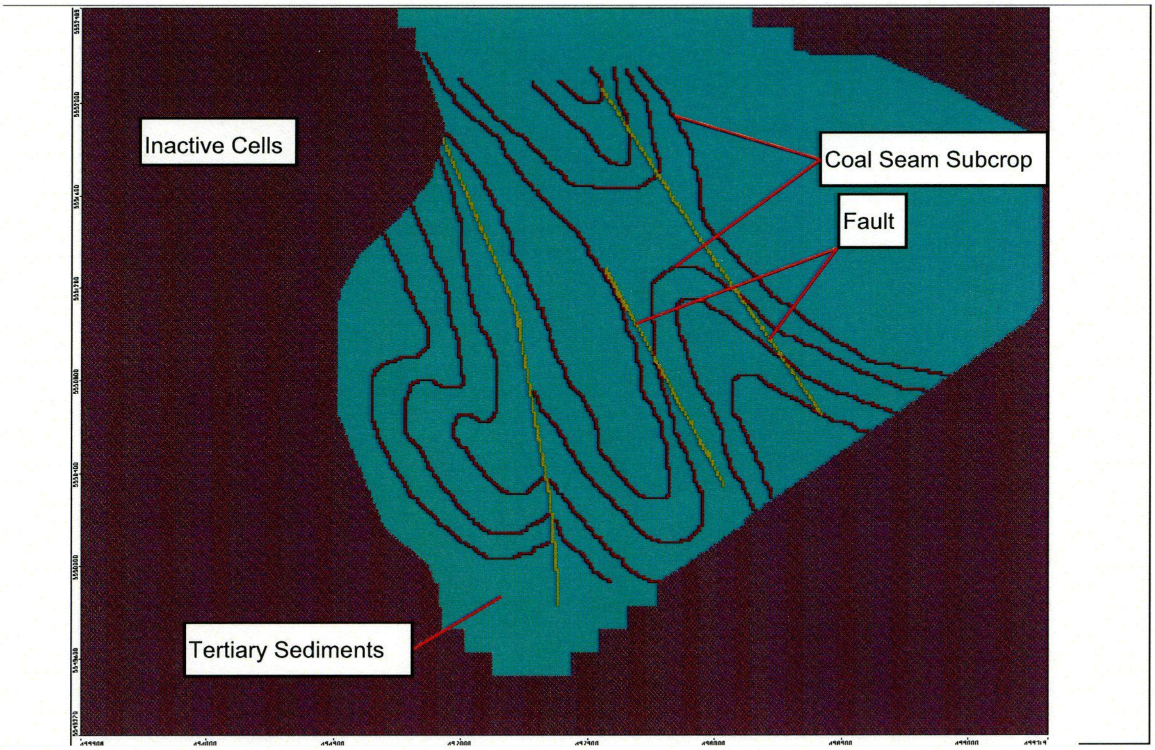
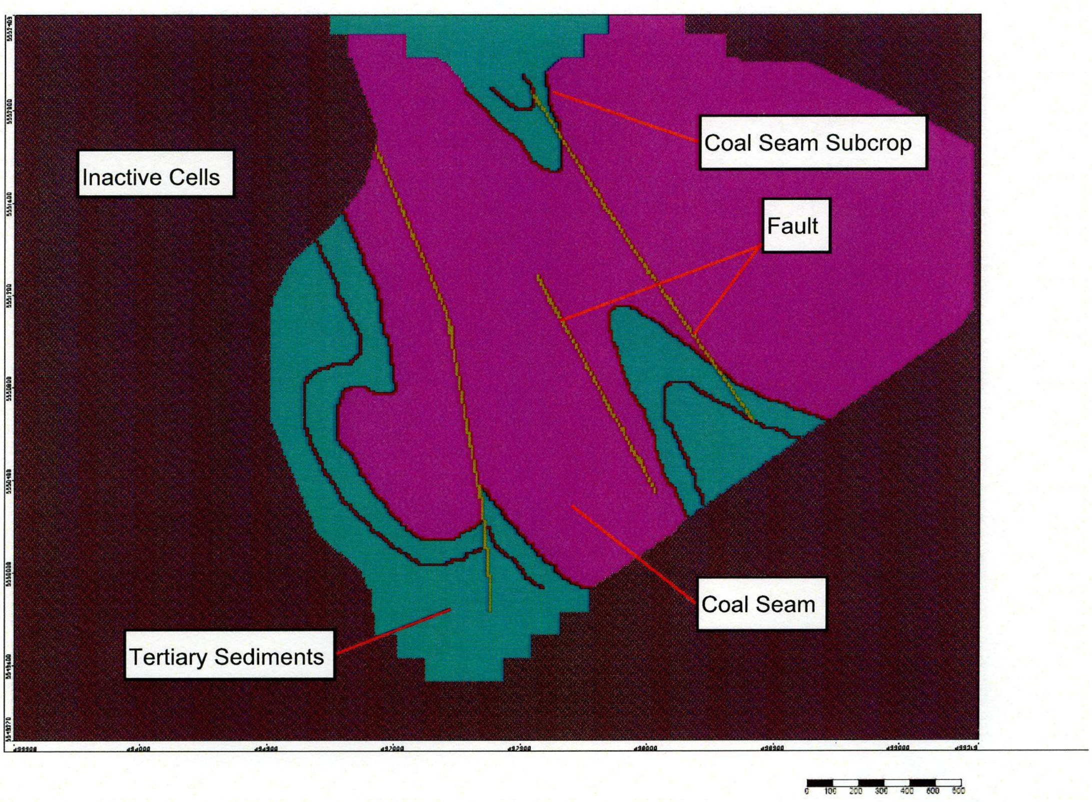


Figure 21: Pilot Scale Model Plan View of Layer 7



8.2.3 Boundary Conditions

In order to limit the size of the model, the boundary conditions were not always aligned with distinct physical boundaries. As with the base case model, the size of the pilot scale model was based on the locations of the hydrologic divides. This assumption is likely valid in the hills to the west and south of the modeled area, however; it may not be valid to the east and north. The boundary chosen for the east and north of the modeled area was Coldwater River. Rivers can act as hydrologic divides, but unfortunately, due to the understanding that the Tertiary sedimentary units dip under and away from the Coldwater River, it is unlikely that this constitutes a hydrologic divide at depth within the Tertiary geology. The coal seam subcrops and the faults, which are the areas of prime interest in the pilot scale model, are located closer to the west and south boundaries and therefore the east boundary has little effect on the results of the model. To test the effect of a no-flow boundary along Coldwater River, the results of the model were compared to using a constant head boundary condition. The constant head boundary was applied beneath Coldwater River and was set to just below the ground surface through the entire depth of the model. Upon reviewing the results of the model, it was determined that applying a constant head boundary beneath the Coldwater River did not change the flux from the surface layer into the subcrops and faults. Applying a constant head boundary did, however, increase the total groundwater flow through the system. Furthermore, the pumping rate for CBM pumping wells close to the constant head boundary also increased. The use of a constant head boundary beneath Coldwater River is likely not a realistic condition since the head most likely changes between the stratigraphic units. If the coal seams are relatively continuous the head is likely higher in the areas of the syncline than represented by the constant head used in the model. If the head is higher in the coal seams there will be less flow through the system and the conditions become closer to the no flow boundary condition case. At this time there are no head measurements in the Tertiary sedimentary rock and therefore, the boundary conditions in this case are only conceptual. Nevertheless, although it is important to note that the pumping rates presented with the modeling results may be higher if a constant head boundary were used, a no flow boundary was used during the simulation of the pilot scale coal seam dewatering.

Unlike the base case model, the contact between the volcanics and the Tertiary sedimentary rock in the pilot scale model is considered a no flow boundary, with exception to the top layer that consists of a composite colluvium/volcanics unit. In the pilot scale model, the attention is placed on the coal seams and the small amount of groundwater flow in the volcanics over the duration of five years is likely not significant.

For the pilot scale model a constant head boundary is applied to the surface of the top layer. One of the objectives of the pilot scale model was to model the flux into the coal seam as a result of dewatering. In MODFLOW, if a cell becomes dry, it becomes inactive. Section 9.2 compares the simulated flux to the estimated recharge to indicate if the boundary condition is valid. Since the hydraulic conductivity (in most cases) is higher in the top layer than in the lower layers, the top layer in the Pilot Scale model acts as a constant water reservoir with a constant head boundary. Consequently, the model is not able to show the occurrence of drawdown in the surficial materials. However, the model is able to qualitatively and quantitatively estimate the groundwater flux from the surface layer into coal seams and faults as coal seam dewatering occurs.

Constant head boundaries were also used to simulate the CBM well field. If the layer is defined as a confined system, a constant head in a cell with a head value at or near the bottom elevation of the cell will simulate dewatering the coal seam without causing the cell, or adjacent cells to become dry. According to a report prepared by Westwater Mining Ltd. (2003), the coal seams with the greatest development potential are the lower coals that are represented in the pilot scale model as layers 7 and 9. The constant head cells, simulating fixed drawdown wells, were placed at 200 m spacing over the entire coal seams represented in layer 7 and layer 9.

8.3 Regional Scale Model

The regional scale model was constructed much like the base case model. The topography is the same, the size and shape of the model area are the same, and the boundary conditions are the same. The major difference is that in the regional scale model the coal seams are represented as flat continuous units similar to the pilot scale model, in contrast to the base case model where the coal seams are represented as thicker composite sedimentary layers. The depth of the coal seams was based on the cross-sections prepared by Swaren (1977).

Table 8 shows the ranges of hydraulic conductivity values that were modeled as part of the regional scale model. For the Regional scale model, the only hydrostratigraphic property that was varied was the hydraulic conductivity of the fault.

Table 8: Regional Scale Model – Range of Values of Hydraulic Conductivity for each Layer

Layer #	Unit Description	Horizontal Hydraulic Conductivity (cm/s)		
		Low	Medium	High
1	Alluvium/Colluvium		5.0E-01	
1b	Colluvium/Fractured VOLCANICS		5.0E-03	
2	Lacustrine SILT/TILL		1.0E-03	
2b	Fractured VOLCANICS		1.0E-05	
3	SHALE and SANDSTONE		5.0E-07	
3b	weathered VOLCANICS		1.0E-07	
4	COAL		1.0E-05	
4b	VOLCANIC bedrock		1.0E-08	
5	SHALE and SANDSTONE		5.0E-07	
5b	VOLCANIC bedrock		1.0E-08	
6	COAL		1.0E-05	
6b	VOLCANIC bedrock		1.0E-08	
7	SHALE and SANDSTONE		5.0E-07	
7b	VOLCANIC bedrock		1.0E-09	
8	VOLCANIC bedrock		1.0E-09	
9	IMPERMEABLE		-	
-	Faults	1.0E-10	5.0E-05	1.0E-04

9.0 MODEL RESULTS

9.1 Base Case Model

The objectives of the base case model were to define the hydrogeological conditions of the Merritt region, simulate the drawdown of the City of Merritt production wells and estimate an overall water balance for the regional system. The simulated time of the base case model was for a duration of 50 years from 1960 to 2010. Each of the five production wells began pumping at its year of completion (Table 3) and continued to pump groundwater at an average rate until 2010.

Figure 22 illustrates the modelled groundwater contours and groundwater flow vectors. Figure 23 illustrates some groundwater flow paths with the addition of modelled particles.

Figures 24 through 26 plot the stream leakage and the groundwater discharge into the stream in response to groundwater pumping from the five City of Merritt pumping wells for three hydraulic conductivity scenarios. For each of the scenarios it is observed that as pumping from the city production wells increases, stream leakage also increases. Furthermore, groundwater that was modelled as discharging into streamflow is reduced during pumping. At conditions close to steady state, the summation of the reduction in groundwater discharge into streamflow and stream leakage accounts for the majority (between 93 and 98 percent) of water that is pumped by the city production wells. In all scenarios, water from stream leakage is the greatest source of recharge to the aquifer accessed by the city production wells. As such, the drawdown created as a result of groundwater extraction is largely controlled by the location of the river.

Based on the results of the simulation, groundwater produced from the Merritt aquifer is largely supplied from stream leakage from Nicola River and/or Coldwater River and to a lesser extent from groundwater flowing into the aquifer from upland areas. The results are supported by the Piper plot of groundwater and surface water chemistry plotted on Figure 13. The chemistry of the surface water and groundwater is of similar type, with little influence from deep groundwater.

The minimum daily streamflow recorded at hydrometric Station 08LG007 (Figure 7) over the period from 1958 to 2006 was 0.552 m^3/s. The value which ten percent of the streamflow values fall below, or the 10 percentile, for the low streamflows at station 08LG007 is 2.61 m^3/s. Modelling simulated approximately 0.095 m^3/s of stream leakage as a result of pumping from the city production wells at 0.1 m^3/s. At the current rate, the pumping wells will not deplete Coldwater and Nicola rivers.

Figure 22: Groundwater Flow Vectors and Head Contours in Layer 1 for Base Case Model

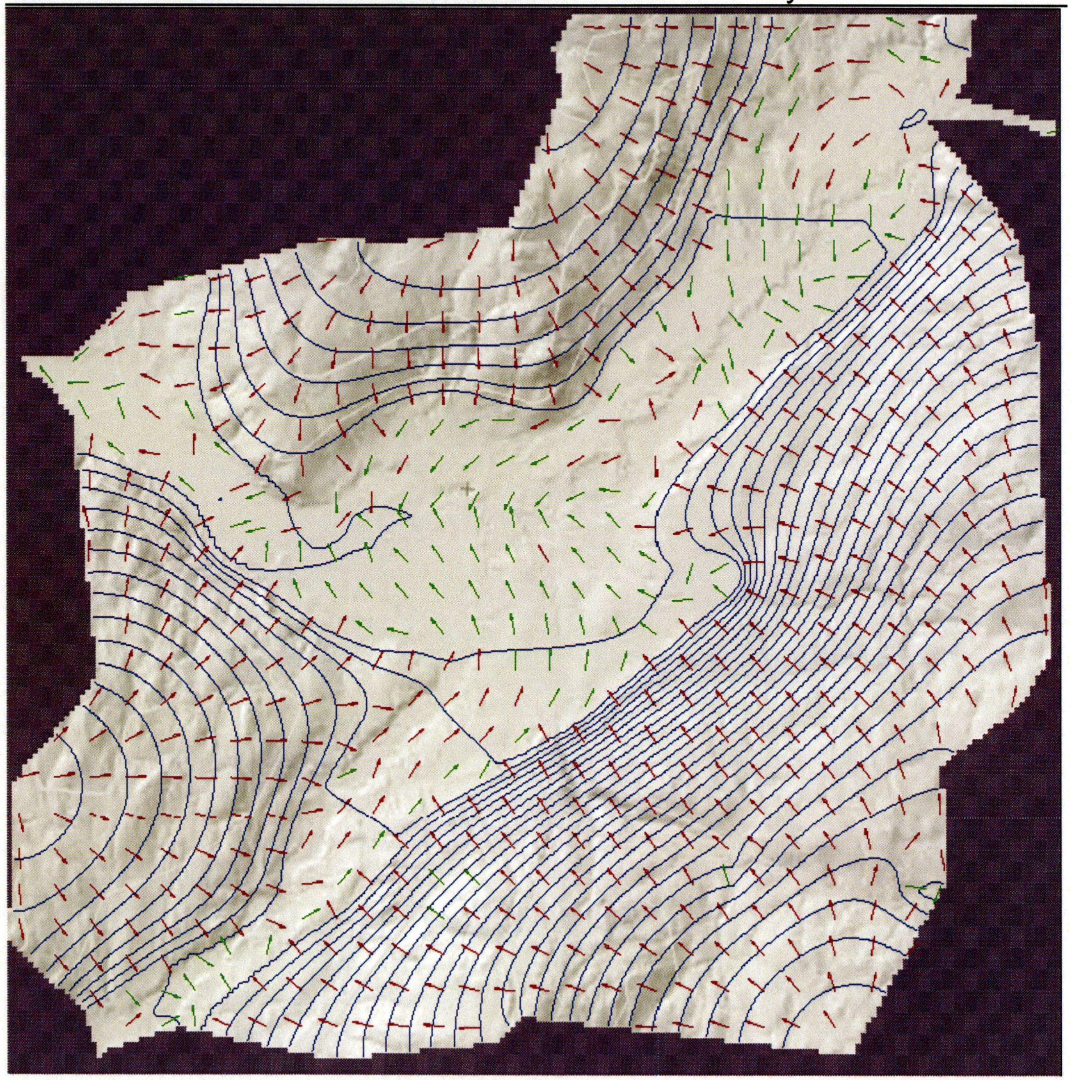
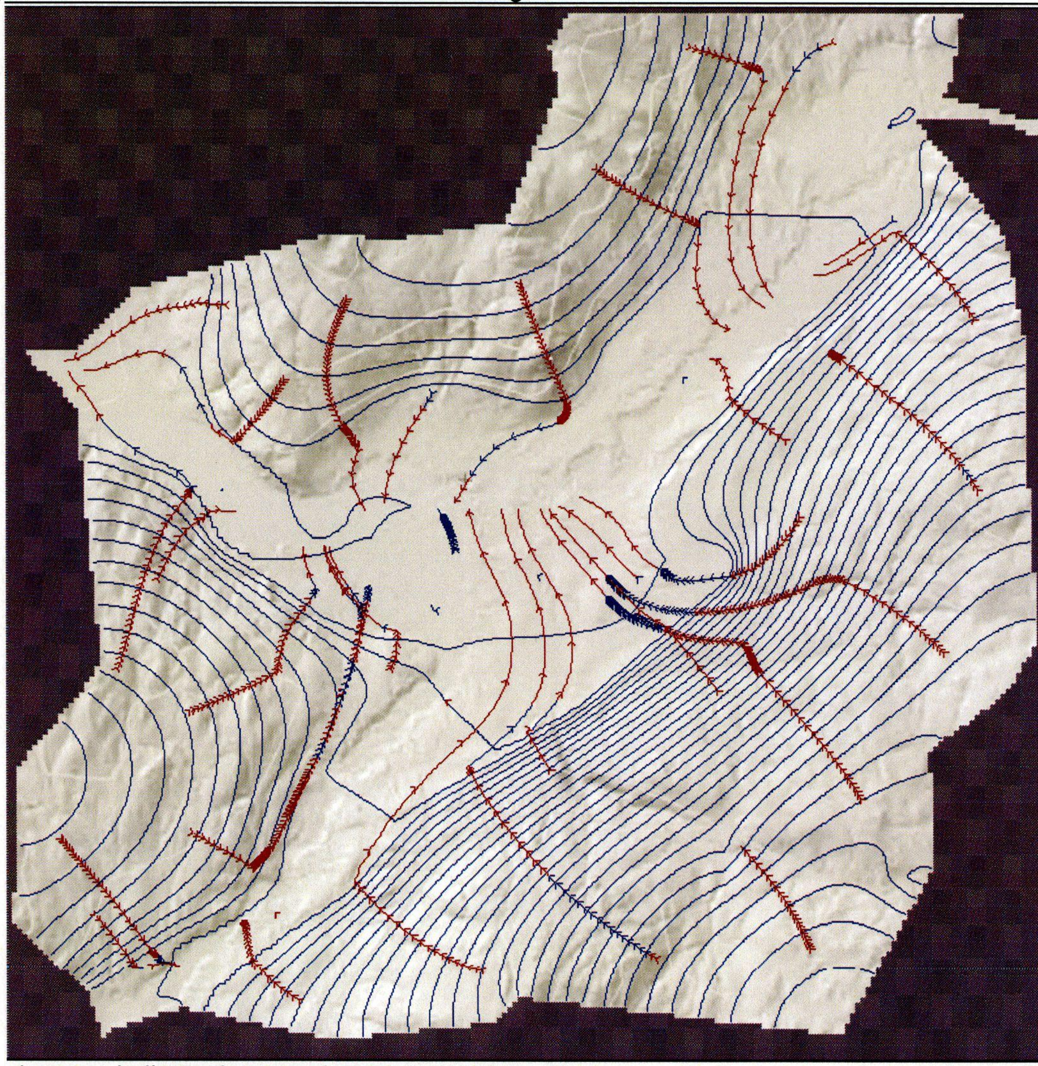


Figure 23: Groundwater Particle Tracking and Head Contours for Base Case Model



Red arrows indicate downward groundwater flow. Blue arrows indicate upward groundwater flow.
Arrows are at 10 year intervals.

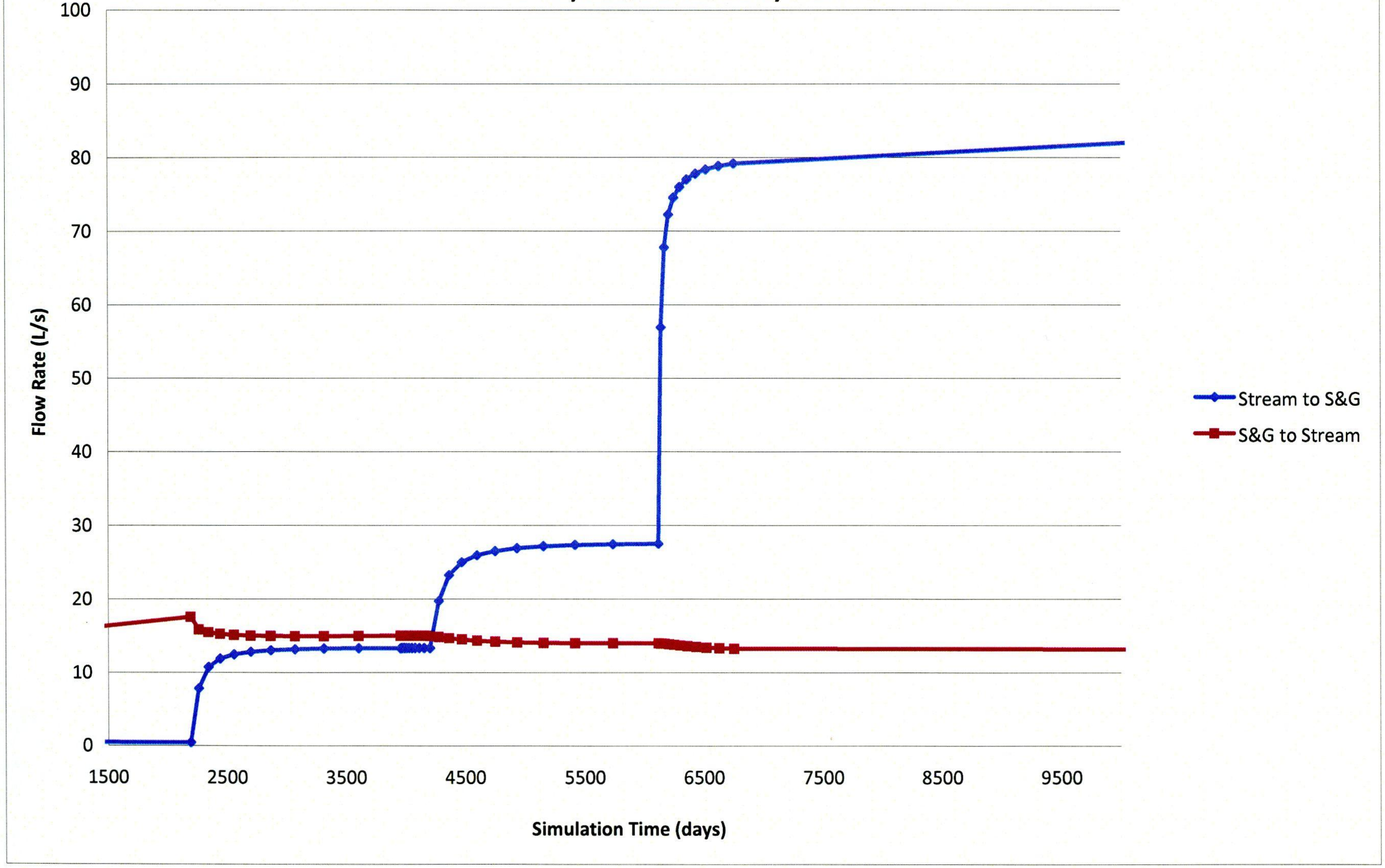


Figure 24: Groundwater Flowing in and out of Nicola River During Production Well Pumping
Low Hydraulic Conductivity Scenario

Figure 25: Groundwater Flowing in and out of Nicola River During Production Well Pumping
Medium Hydraulic Conductivity Scenario

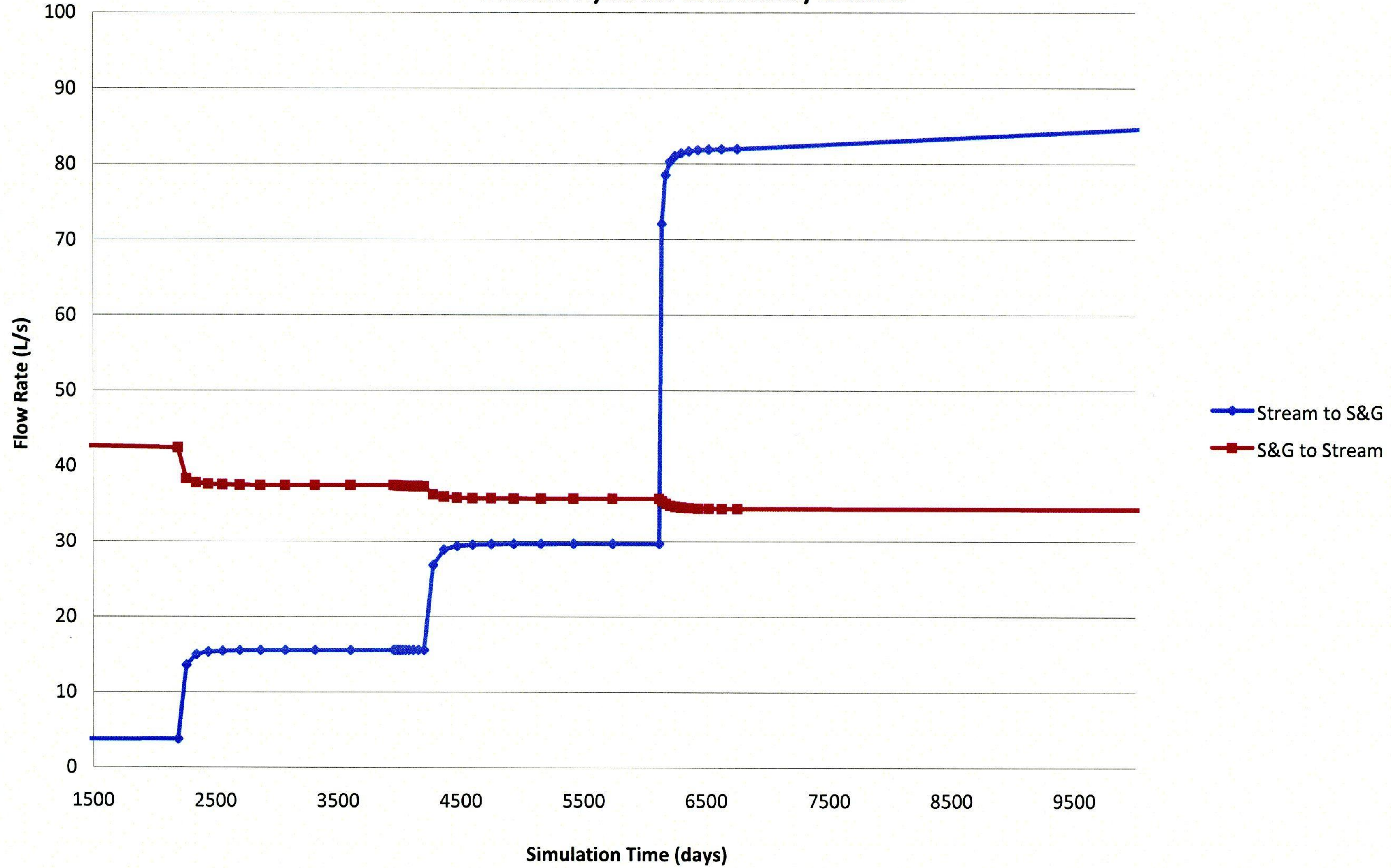
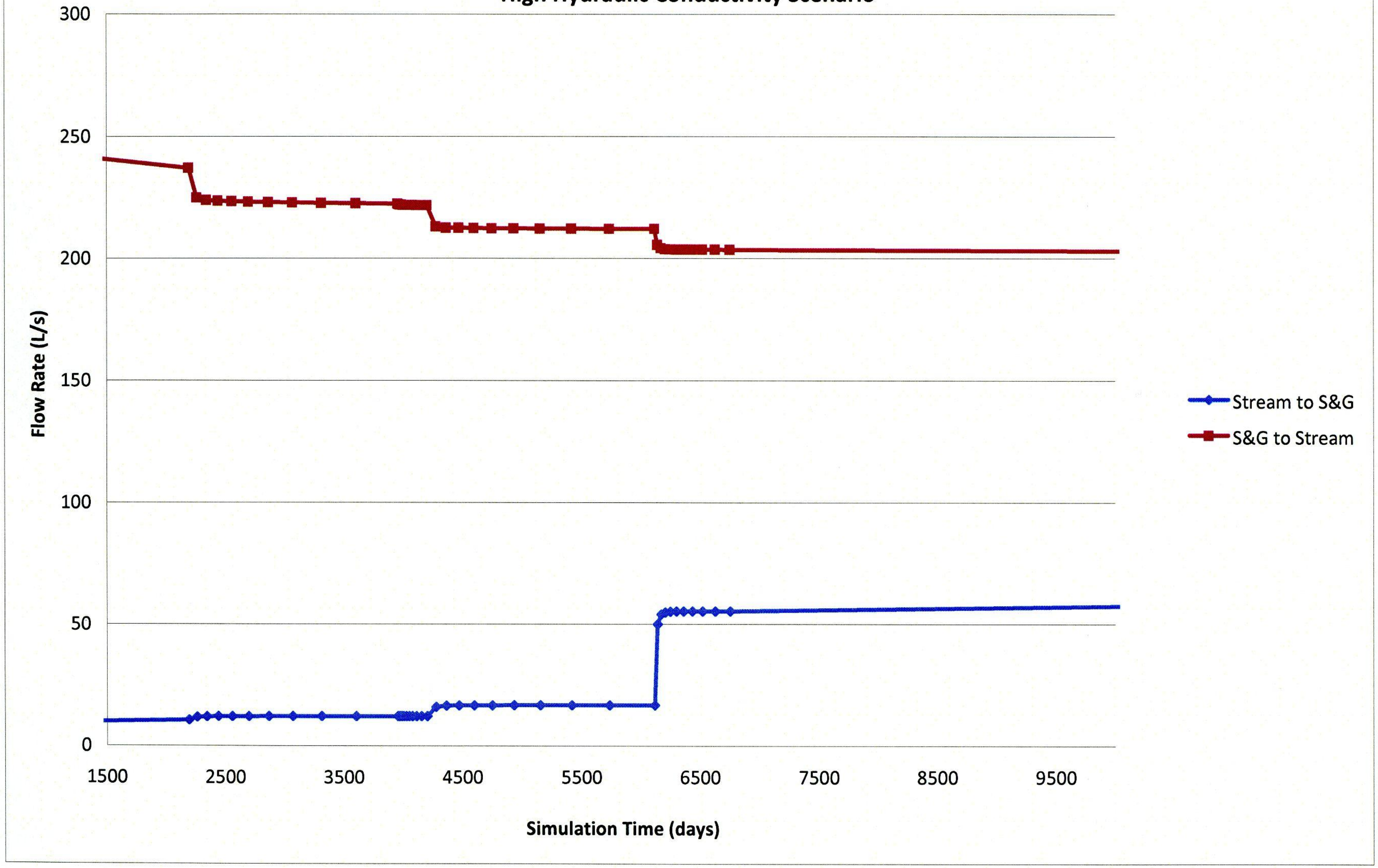


Figure 26: Groundwater Flowing in and out of Nicola River During Production Well Pumping
High Hydraulic Conductivity Scenario



9.2 Pilot Scale Model

A pilot scale study is not meant to operate for a long duration, so the simulated time of the model was a total of 5 years. The objectives of the pilot scale model was to assess the feasibility of coal seam dewatering and estimate the potential groundwater flux from the surficial aquifer material into coal seams and faults in response to dewatering.

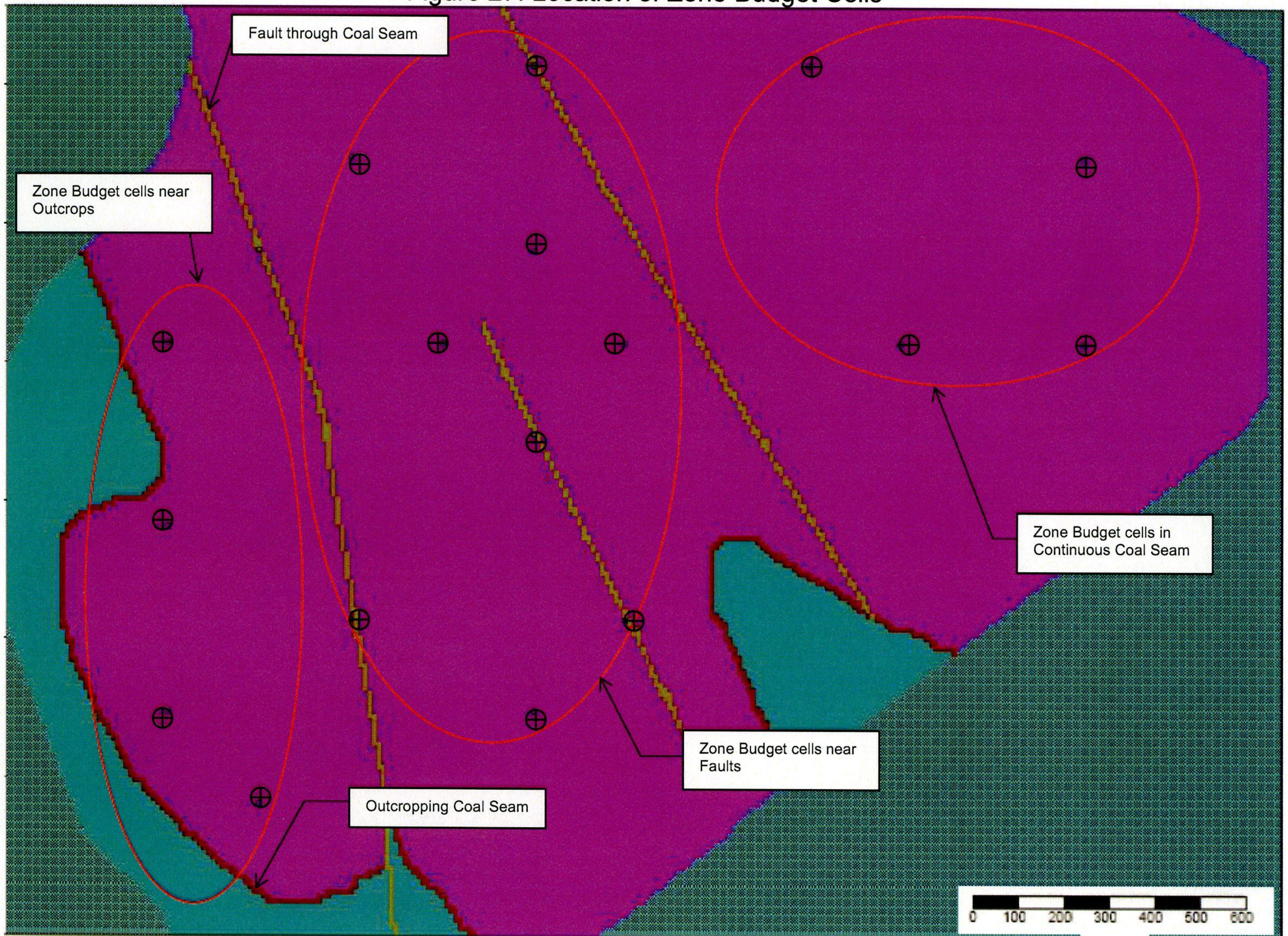
To estimate the response to simulated coal seam dewatering a series of zone budget zones were applied. Zone budget computes subregional water budgets using results from the MODFLOW groundwater flow model. For the pilot scale model several zones were defined, including:

- Cells that represent pumping wells near subcrops,
- Cells that represent pumping wells near faults,
- Cells that represent pumping wells in relatively continuous coal seams,
- Near the unconformity within coal seam subcrops that are being de-watered,
- Near the unconformity within coal seam subcrops that are not being de-watered, and;
- Near the unconformity within faults.

A zone budget within a cell with a pumping well shows the rate at which groundwater is pumped from a well completed in the coal seam. Several cells were defined as zones for each zone budget. The results for the zone budget were then averaged to obtain a budget per cell. As such, the results provided in this section for wells completed in a coal seam represent the pumping rates for one individual well. A zone budget near the unconformity shows the groundwater flux from the surficial material into the coal seam subcrop or fault. Several cells were defined as a zone for each of these zone budgets. The results were averaged per cell, then divided by the area of a grid block (assuming the majority of groundwater flows vertically through the cell) giving a flux value. Figure 27 shows the locations of the zone budget cells. The zone budget results of the model simulation are included in Figures 28 through 32. Each figure consists of four zone budget plots. Three of the plots show the pumping rate for wells in specified areas within two separate coal seams, while one plot shows the groundwater flux in specified areas along the unconformity. For the purpose of this model all CBM production wells were started at the same time. In reality there would be a staged approach as additional wells are completed.

Figures 28, 29 and 31 can be used to assess the role that faults play on the groundwater flow of the system. The results for a medium hydraulic conductivity fault are very similar to the results for a low hydraulic conductivity fault in that there is little to no groundwater flux from the surficial layer when the hydraulic conductivity of the fault is less than its surrounding media. The pumping rate for wells near faults is slightly higher for medium hydraulic conductivity faults than low hydraulic conductivity faults. However, when a high hydraulic conductivity fault is introduced, groundwater flux is much higher as is the pumping rate for wells near faults. Groundwater flux is 0 m^3m^{-2}/day and $1.1x10^{-4}$ m^3m^{-2}/day for low and medium hydraulic conductivity faults, respectively and $3.3x10^{-2}$ m^3m^{-2}/day for a high hydraulic conductivity fault. Although there are no estimates of the thickness of the fault, if the faults are 4.5 km long and 10 m thick the amount of groundwater that is drawn into the faults in response to coal seam dewatering is approximately 1,500 m^3/day. Comparatively, groundwater loss into the faults equates to approximately 18 percent of the amount of groundwater pumped from the City of Merritt production wells. Coal seam dewatering may prove difficult in areas near high hydraulic conductivity faults since approximately 50 m^3/day must be removed from each well as the system approaches steady state. Conversely, approximately 1 to 3 m^3/day must be pumped from each well close to low or medium hydraulic conductivity faults. In areas near subcrops and where the coal seam is continuous, there is little to no difference in the pumping rates despite the range of hydraulic conductivity in the faults.

Figure 27: Location of Zone Budget Cells



⊕ Zone Budget Cells

Figure 28: Pilot Scale Model - Zone Budget
High K Fault

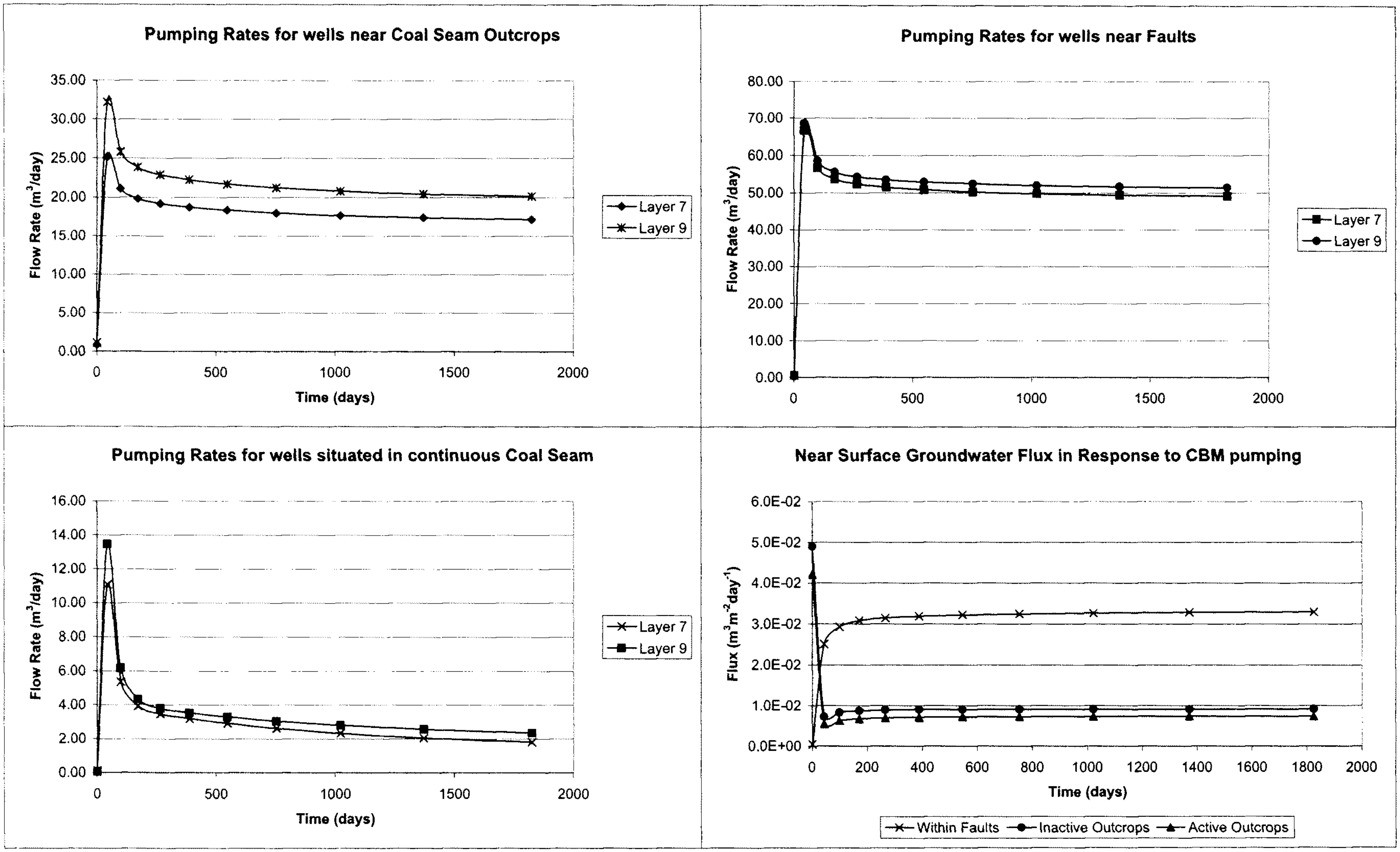


Figure 29: Pilot Scale Model - Zone Budget
Low K Fault

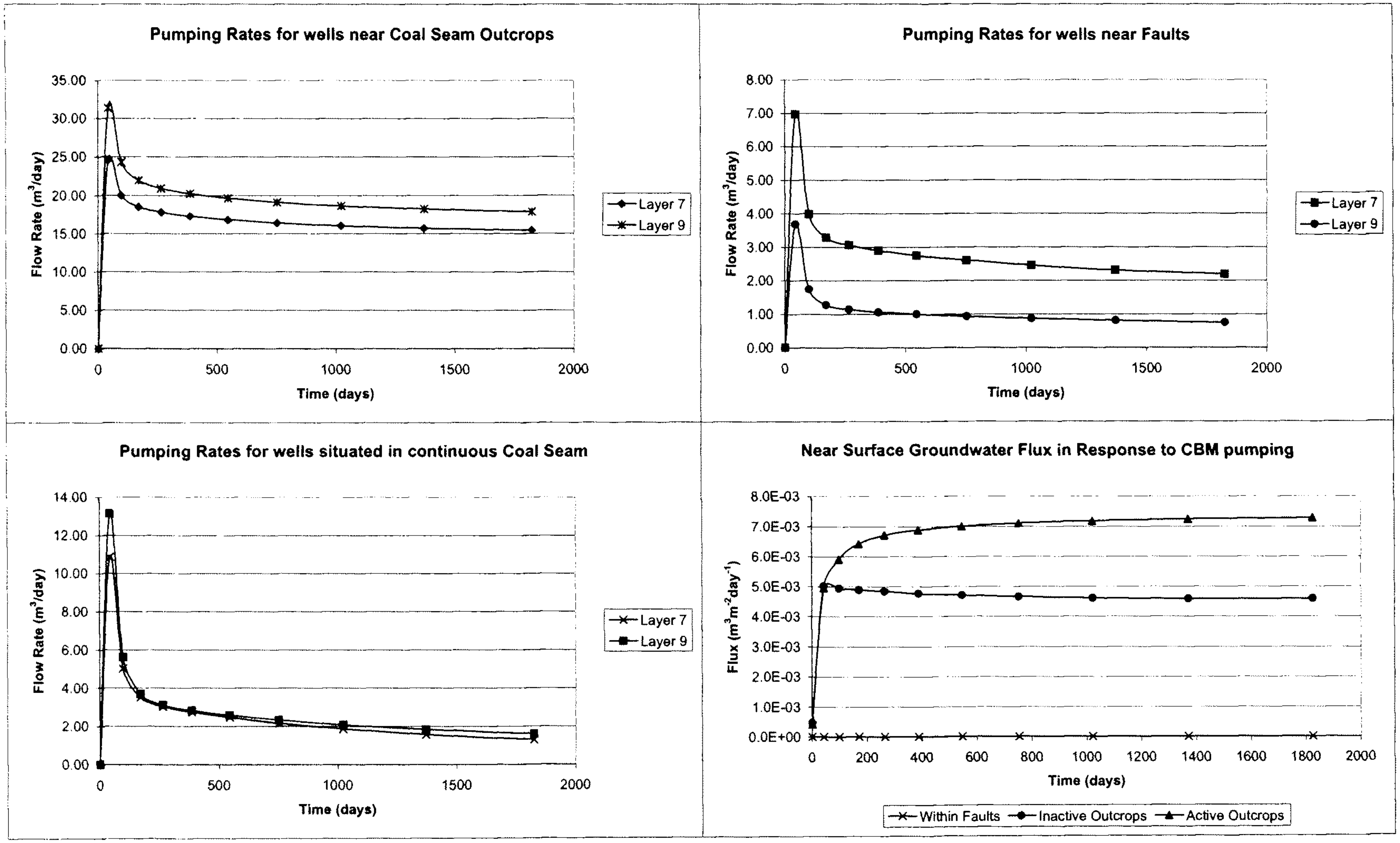


Figure 30: Pilot Scale Model - Zone Budget High K

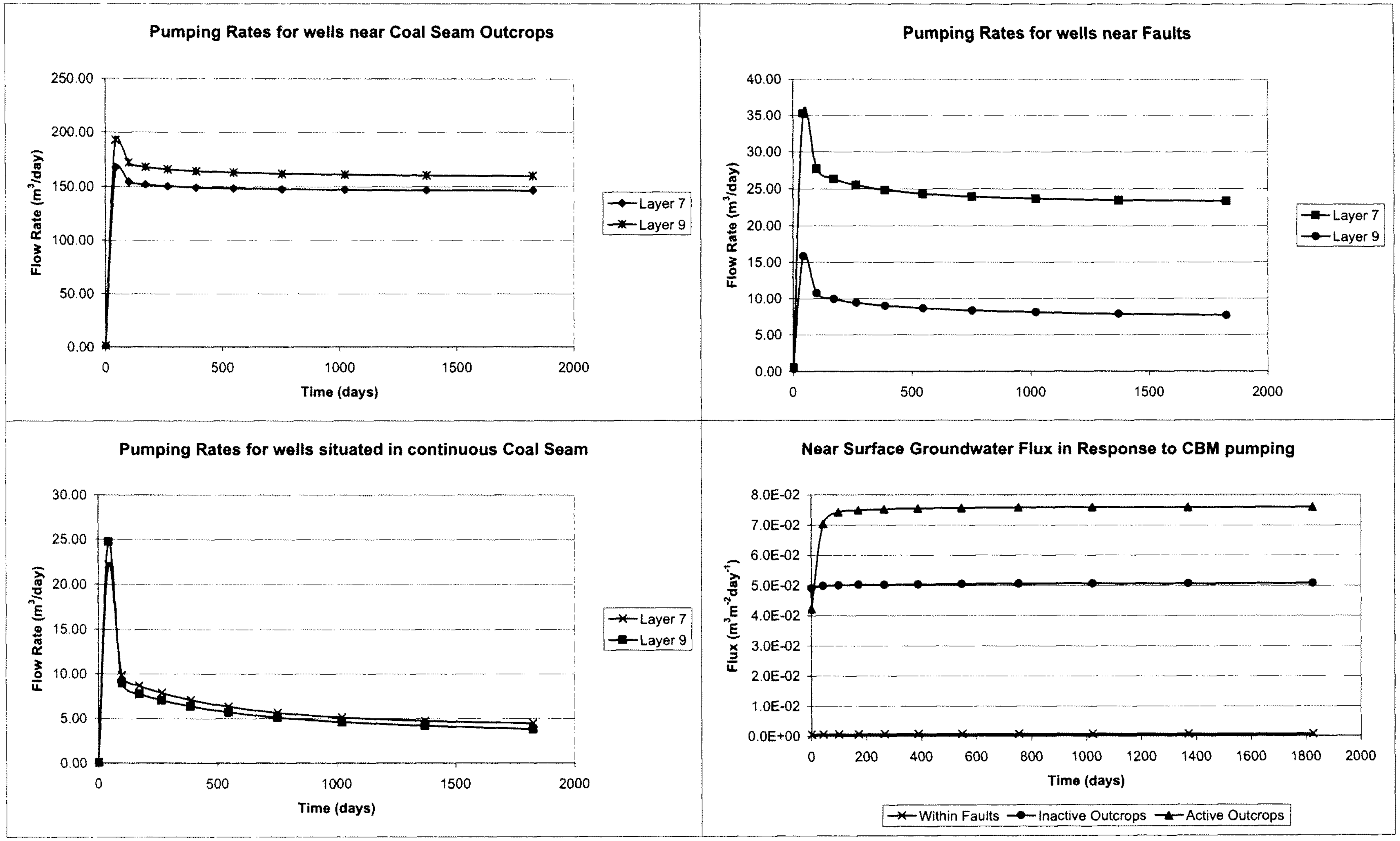


Figure 31: Pilot Scale Model - Zone Budget
Medium K

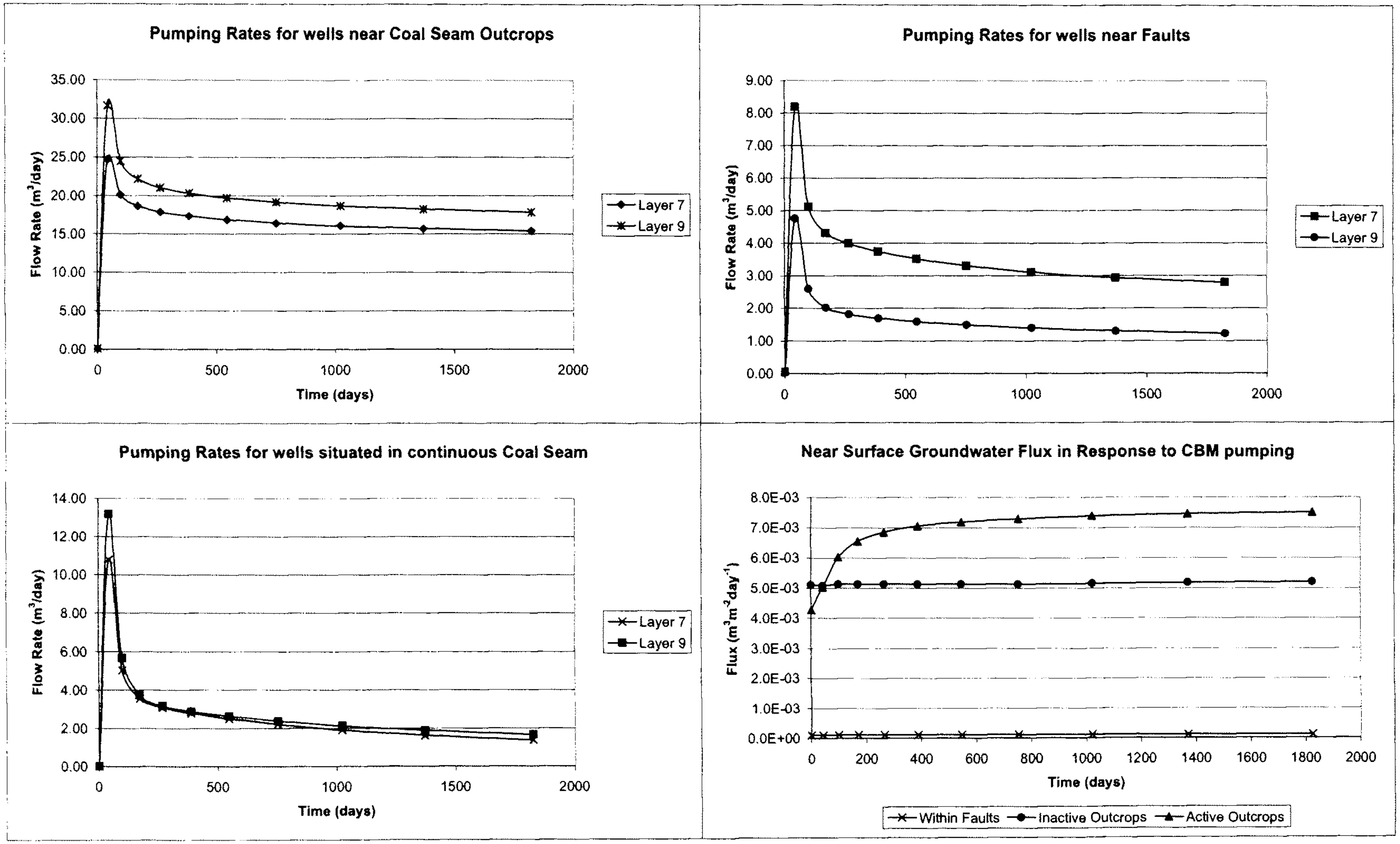
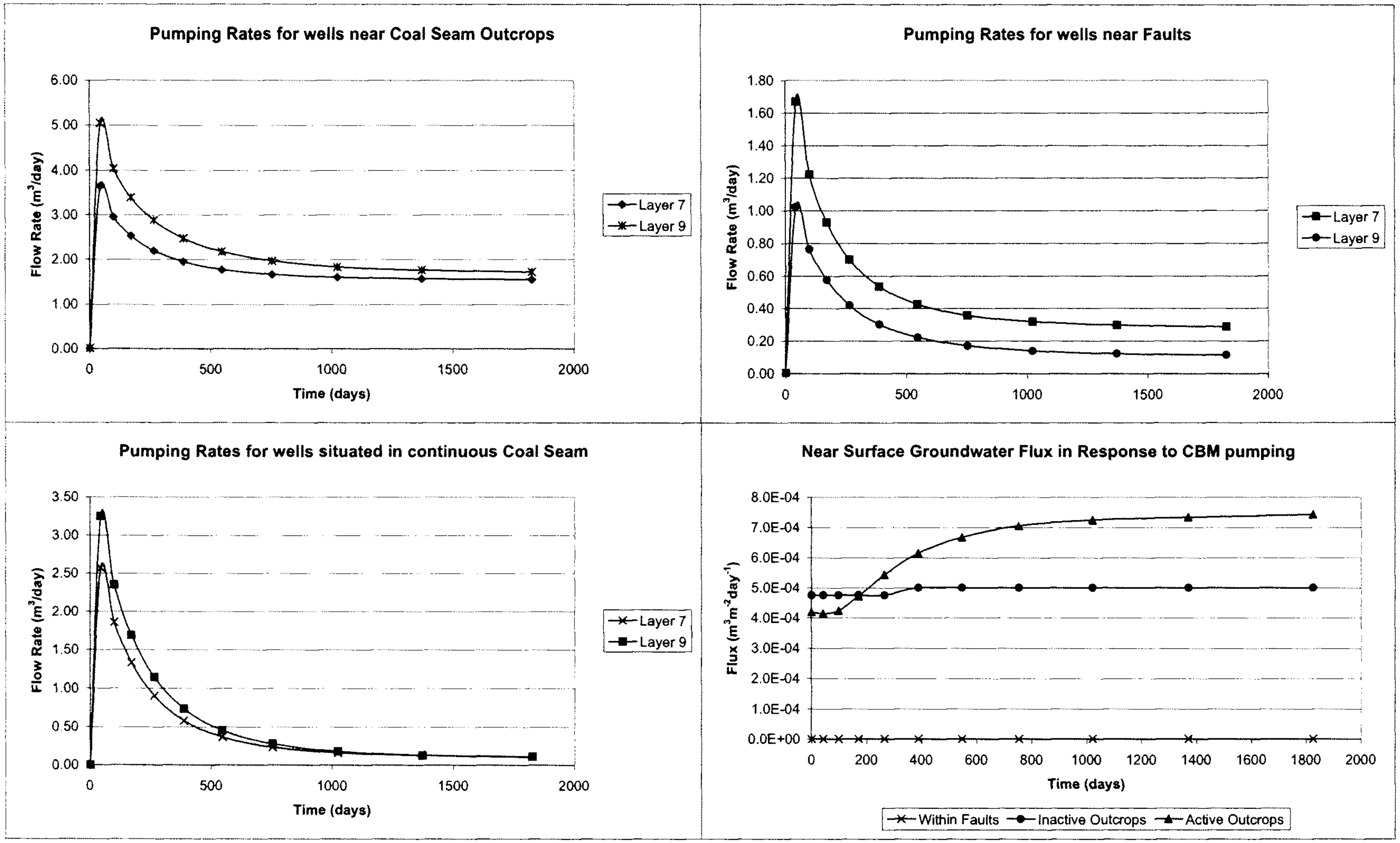


Figure 32: Pilot Scale Model - Zone Budget
Low K



Figures 30 through 32 can be used to assess the role of hydraulic conductivity in the Tertiary sedimentary units as it relates to pumping rate and flux from the surficial layer. The effect of varying hydraulic conductivity is most predominantly observed in wells near coal seam subcrops. The peak groundwater pumping rate in layer 9 near subcrops is approximately 190 m^3/day for the high hydraulic conductivity case as opposed to 32 m^3/day for the medium hydraulic conductivity case and 5 m^3/day for the low hydraulic conductivity case. Furthermore, as the pumping rate approaches steady state, the pumping rate is approximately 155 m^3/day for the high hydraulic conductivity case in layer 9, as opposed to 18 m^3/day for the medium hydraulic conductivity case and 1.7 m^3/day for the low hydraulic conductivity case. The effect of varying hydraulic conductivity is less pronounced in areas near continuous coal seams. For layer 9 peak pumping rates are 25 m^3/day, 13 m^3/day and 3.25 m^3/day for high hydraulic conductivity, medium hydraulic conductivity and low hydraulic conductivity cases, respectively. As pumping rates approach steady state, pumping rates are 5 m^3/day, 1.8 m^3/day and 0.1 m^3/day for high hydraulic conductivity, medium hydraulic conductivity and low hydraulic conductivity cases, respectively. As a comparison, the city of Merritt production wells pump an average of 8,640 m^3/day.

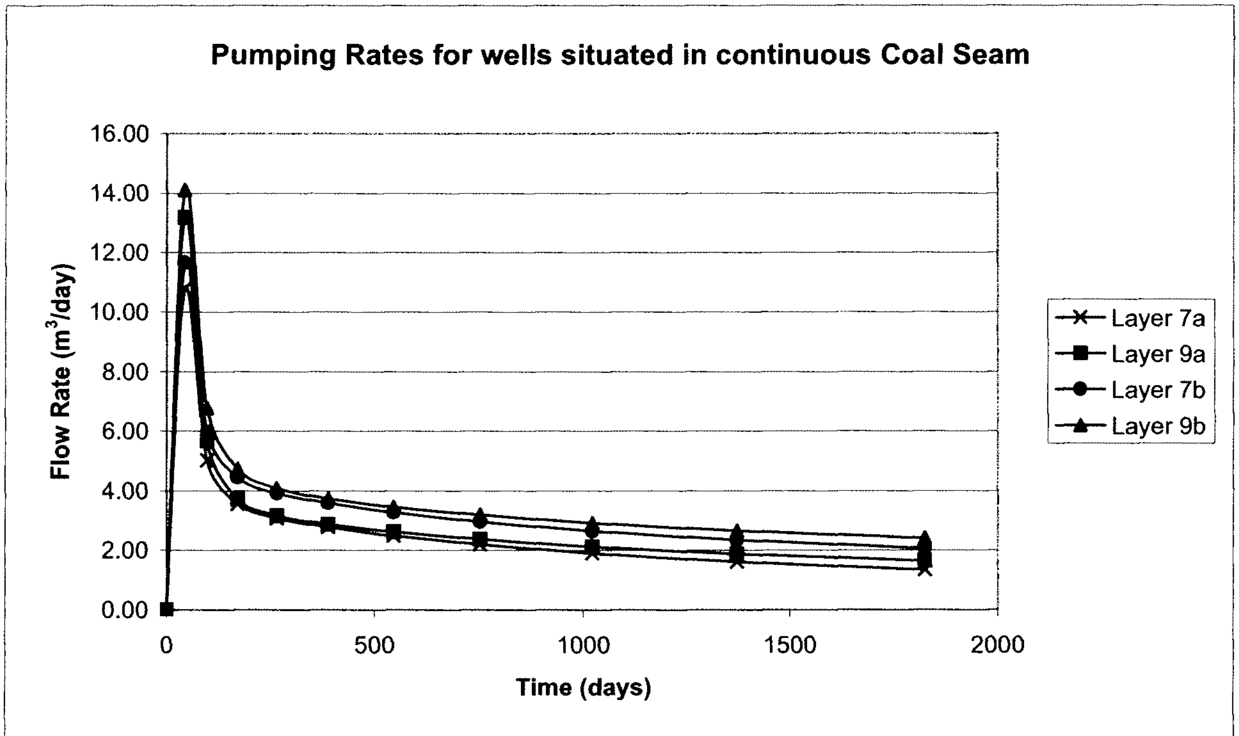
Hydraulic conductivity also has an effect on the duration of peak pumping rates. With decreasing hydraulic conductivity, the duration of peak pumping rate is prolonged. Elevated pumping rates were observed for high hydraulic conductivity, medium hydraulic conductivity and low hydraulic conductivity for a duration of approximately 100 days, 250 days and 500 days, respectively.

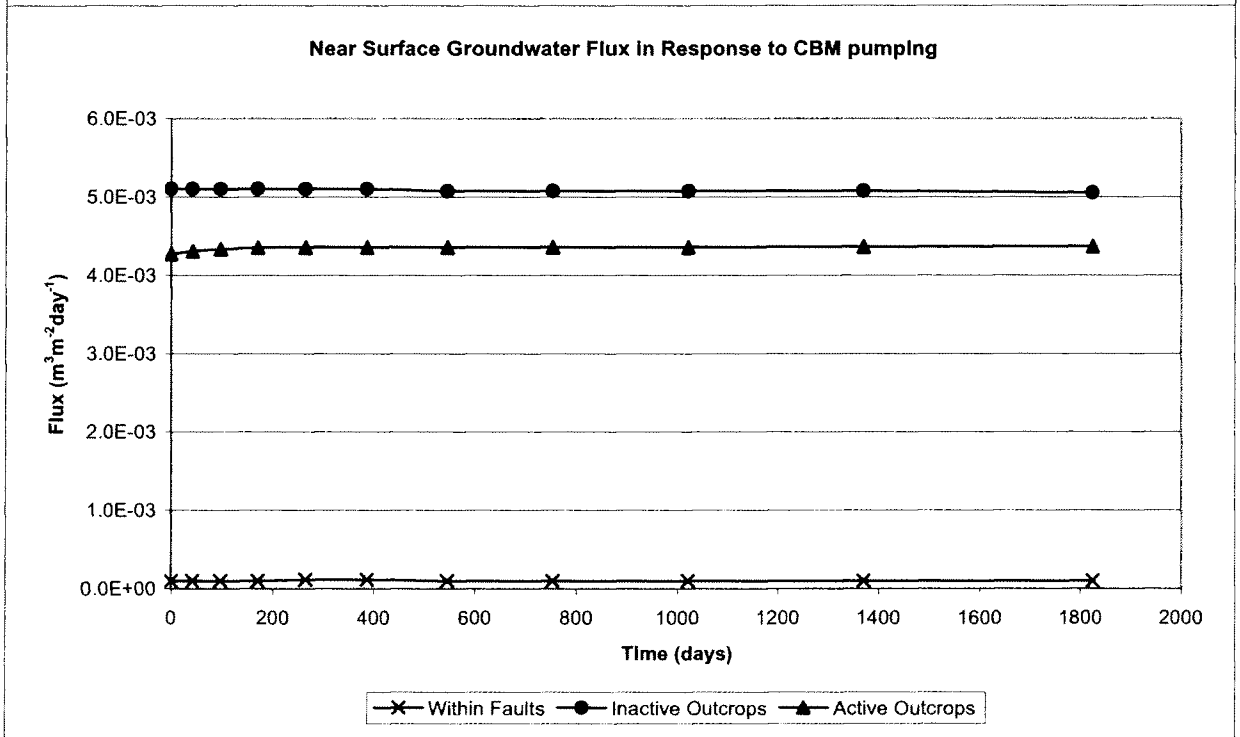
The results of flux from the surficial layer into a coal seam that is being pumped indicate that if hydraulic conductivity changes by an order of magnitude, so does the flux. Groundwater flux into the active coal seam for high hydraulic conductivity, medium hydraulic conductivity and low hydraulic conductivity were $7.6x10^{-2}$ m^3m^{-2}/day, $7.5x10^{-3}$ m^3m^{-2}/day and $7.4x10^{-4}$ m^3m^{-2}/day, respectively. Initially the flux rates were $4.2x10^{-2}$ m^3m^{-2}/day, $4.2x10^{-3}$ m^3m^{-2}/day and $4.2x10^{-4}$ m^3m^{-2}/day for high hydraulic conductivity, medium hydraulic conductivity and low hydraulic conductivity, respectively.

It is important to understand the feasibility of dewatering the coal seam when developing for CBM. Unfortunately the model cannot indicate whether or not the coal seam has been dewatered because of difficulties with dry cells and unsaturated groundwater flow. The model predicts that the hydraulic head throughout the coal seams drops substantially from the initial conditions during CBM production for each of the three hydraulic conductivity scenarios. The amount of head drop depends on the proximity to faults and especially subcrops, the distance from the production wells and the hydraulic conductivity of the coal seam. The smallest head drop occurs near subcrops, further away from the production well and for high hydraulic conductivity coal seams. The highest head drop occurs in relatively continuous coal seams near production wells and with low hydraulic conductivity coal seams. A large head drop indicates that a coal seam has potential for dewatering. Based on the results of the models, perhaps the best way to assess the feasibility of coal seam dewatering is to observe the amount of produced water. Since dealing with the produced water is likely to have financial costs that are dependant on the quality and volume of the produced water, there is likely a point where increased volume will not be financially feasible.

In order to better understand the impact that subcrops and faults have on the groundwater pumping rates and the groundwater flux from the surficial layer, an additional scenario was simulated where coal seam dewatering was only undertaken in the area of the relatively continuous coal seams. This modified scenario was only for a medium hydraulic conductivity case and the zone budget results are provided in Figure 33. The uppermost plot in Figure 33 compares the pumping rates for a scenario where only wells in the continuous coal seam are pumped (series layer 7b and layer 9b) and the medium hydraulic conductivity scenario described above (series layer 7a and layer 9a). As shown on the plot, the pumping rates are slightly higher when pumping only from the areas with continuous coal seams. The lower plot in Figure 33 shows the groundwater flux from the surficial layer into the active coal seam under this modified scenario. The groundwater flux increases slightly from 4.2×10^{-3} m^3m^{-2}/day to 4.4×10^{-3} m^3m^{-2}/day.

Figure 33: Pilot Scale Model - Zone Budget
Medium K Pumping in Continuous Coal Seams Only





Groundwater flux would be a useful expression to estimate the loss of surficial groundwater in response to coal seam dewatering over the entire region if the exposure of the coal seam were known. In the real system, the area of coal seam exposure is unknown so in any case it is difficult to accurately quantify groundwater losses from the surficial layer. Assuming the active coal seam's exposure to the unconformity is continuous across the region and using the geological map prepared by Swaren (1977), the total length of the layer 9 coal seam subcrop in the Merritt region is approximately 12 km. The layer 7 coal seam subcrop is slightly shorter than the layer 9 subcrop, at approximately 10 km. Table 9 provides a summary of the groundwater flux for each scenario and estimates the initial loss (before coal seam dewatering) and the total loss (during coal seam dewatering) from the surficial layer into active coal seams. Furthermore, Table 9 provides a comparison of the total loss during CBM production, to the average pumping rate of the City of Merritt production wells. The values provided for loss from the surficial layer are calculated using a total subcrop length of 22 km and a subcrop thickness of 10 m.

Table 9: Groundwater Flux from Surficial Layer into active Coal Seams

	Initial Flux (m^3m^{-2}/day)	Peak Flux (m^3m^{-2}/day)	Initial Loss (m^3/day)	Peak Loss (m^3/day)	Difference (m^3/day)	% Production Wells
High K	4.20E-02	7.60E-02	9240.0	16720.0	7480.0	88.6
Medium K	4.20E-03	7.50E-03	924.0	1650.0	726.0	8.6
Low K	4.20E-04	7.40E-04	92.4	162.8	70.4	0.83
Modified	4.20E-03	4.40E-03	924.0	968.0	44.0	0.52

It is important to note that the groundwater loss from the surficial layer to coal seam subcrops during CBM production is likely overestimated in Table 9. In the real system coal seams are likely not continuous because of pinch outs and low hydraulic conductivity faults. Also, a coal seam thickness of 10 m is likely an overestimate. Conversely, there are features of the real system that may act to produce an underestimate in Table 9. There could be high hydraulic conductivity faults, which were shown to affect the groundwater flux from surface layers, and jointing of the bedrock during bedrock deformation could introduce high hydraulic conductivity conduits for groundwater flow. Furthermore, past mining activities were not considered as part of this model. Abandoned coal mines act as very high hydraulic conductivity areas. Although it is unlikely that coal mining would influence the coal seams at the depth needed for CBM, abandoned coal mines may still play an important role as conduits for groundwater flow.

To assess the validity of a boundary condition of a constant head boundary in layer 1, the total flux in Table 9 is compared to the estimated recharge. The recharge was estimated as 30 mm/year. Based on an area of 15,000,000 m^2 the total recharge in the area is approximately 1,230 m^3/day. The total flux from the High K and Medium K scenarios are above the total estimated recharge to the area. If this were the case, the total flux provided in Table 9 would represent an overestimate of the actual flux since the flow into the coal seam subcrop would be restricted by the available recharge. For the High K and Medium K scenarios, use of a constant head boundary in layer 1 provides model stability and is useful for simulating the upper bound of total flux, however, likely results in some overestimates of simulated flux into the coal seam subcrops. For the Low K and the modified scenarios, a constant head boundary condition in layer 1 is likely an accurate assumption.

9.3 Regional Scale Model

The objectives of the regional scale model were to simulate regional scale CBM development and assess the role of a large regional scale fault on CBM development and regional groundwater flow. The regional scale CBM development was simulated for a duration of 50 years. The top of layer 3 represents the unconformity between the overlying Quaternary sediments and the Tertiary sedimentary rock. The response to coal seam dewatering was observed using the zone budget option in MODFLOW for several cells in the fault zone in layer 3. The model was used to examine high hydraulic conductivity, medium hydraulic conductivity and low hydraulic conductivity scenarios. Based on the results of the low hydraulic conductivity scenario, if the hydraulic conductivity of the fault is lower than the surrounding geologic media it shows little to no response to CBM production. The low hydraulic conductivity scenario will no longer be considered for the remainder of this section. Figure 34 shows the zone budget results of the regional scale model. As seen on the plots, groundwater flux along the unconformity increases as coal seam dewatering is initiated.

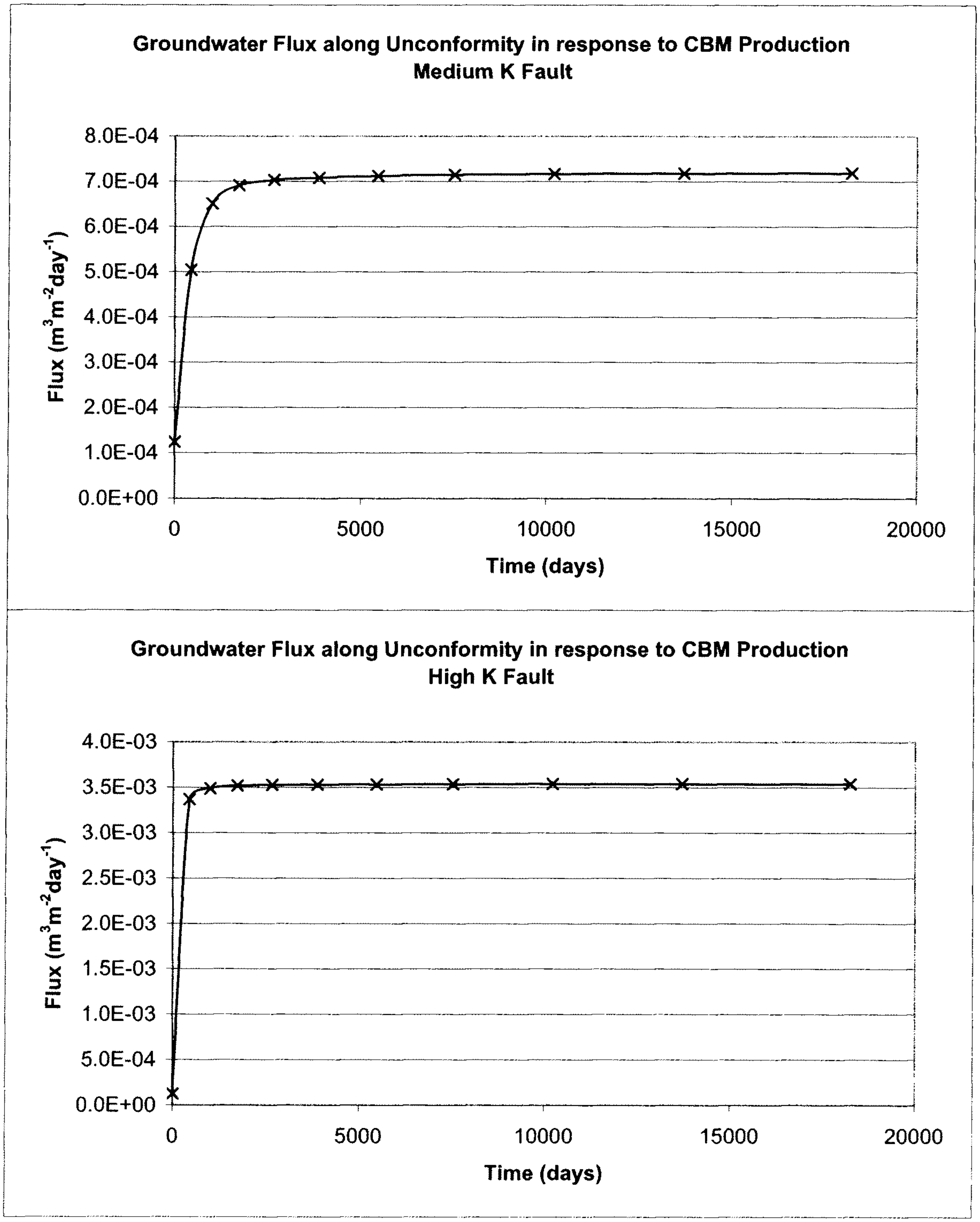
It is not possible to make a reasonable estimate of the groundwater loss from the surficial layer to the fault since the width of the fault is not known. The length of the fault as it passes through the Tertiary sedimentary units is approximately 14 km. Table 10 estimates groundwater loss from the unconformity into a medium hydraulic conductivity and high hydraulic conductivity fault for three fault thicknesses.

Table 10: Groundwater Flux from Unconformity into Fault

	Initial Flux (m^3m^{-2}/day)	Peak Flux (m^3m^{-2}/day)	Initial Loss (m^3/day)	Peak Loss (m^3/day)	Difference (m^3/day)	% Production Wells
Medium K (10m Thick)	1.24E-04	7.18E-04	17.4	100.6	83.2	0.98
Medium K (20m Thick)	1.24E-04	7.18E-04	34.8	201.1	166.4	1.97
Medium K (30m Thick)	1.24E-04	7.18E-04	52.2	301.7	249.5	2.95
High K (10m Thick)	1.24E-04	3.54E-03	17.4	495.3	477.9	5.66
High K (20m Thick)	1.24E-04	3.54E-03	34.8	990.5	955.7	11.31
High K (30m Thick)	1.24E-04	3.54E-03	52.2	1485.8	1433.6	16.97

The values provided in Table 10 only describe the loss along the fault. In the real system there may be additional faults or other low hydraulic conductivity conduits for groundwater flow (i.e. abandoned mines) that would influence the groundwater loss from the surficial layers. Several assumptions were made when constructing the fault in the regional model. As such, the results provided in Table 10 are used only to assess the importance that the fault may play on the regional groundwater flow system.

Figure 34: Groundwater Flux within Fault Zone along Unconformity



10.0 SUMMARY AND CONCLUSIONS

The Merritt region is characterized as having upland to lowland groundwater flow with a flow component parallel to the river valleys. This groundwater flow is directed towards the valley basin where the Merritt aquifer is located. The Merritt aquifer consists primarily of fluvially deposited sand and gravel ranging in thickness from 5 to 50 m; however, about 80 percent of the aquifer is interpreted to be less than 10 m thick. The area that is less than 10 m thick occurs mostly on the floodplain between the Coldwater and Nicola Rivers. The deepest part of the aquifer occurs along a trough that runs sub-parallel to the Coldwater River. The BC Ministry of Environment, Water Stewardship Division classified the Merritt aquifer as one of nine type "IA" aquifers in the province of BC. A type "IA" is considered to be a heavily developed, high vulnerability aquifer. Considering the importance of safe, clean groundwater, municipal and public concern and overall awareness of their groundwater supply is considered to be high.

The main source of water to the surface that recharges to groundwater is precipitation. Precipitation varies both annually and seasonally and the average annual rainfall in the Merritt area is 322 mm/yr. The loss due to evapotranspiration was estimated to be 70 percent of the precipitation, while streamflow runoff accounted for 20 percent of precipitation and groundwater recharge was estimated at 10 percent of the precipitation. Five City of Merritt production wells pump groundwater from the trough area of the aquifer at a rate of approximately 100 L/s. Based on a groundwater flow model of the Merritt region using average pumping rates of the five City of Merritt production wells, the current groundwater demands do not deplete the system. Additional demands, such as increased pumping rates and additional production wells were not explored as part of this project.

In order to better understand the response to coal seam dewatering two groundwater flow models were created. One model was used to simulate pilot scale CBM production for a duration of 5 years, while the second model was used to simulate regional scale CBM production for a duration of 50 years.

The results of the pilot scale model indicates that the effects of faults are not important to the groundwater flow in response to CBM production if the hydraulic conductivity of the fault is lower than that of the surrounding geological media. If the hydraulic conductivity of the fault is higher than the surrounding media, groundwater may be drawn into faults from the surficial material. The amount of water that is drawn into the fault depends not only on the hydraulic conductivity of the fault, but also the extent to which the fault is exposed to the unconformity between the Tertiary rocks and the Quaternary sediments. At this time the extent of the exposure of the fault is not know and therefore it is difficult to meaningfully predict the quantity of groundwater that would be drawn into the fault in response to CBM production.

The pilot scale model also assessed the role that coal seams subcropping along the unconformity between the Tertiary rocks and the Quaternary sediments has on the potential response to coal seam dewatering. Since the hydrostratigraphic properties of the various geological units are poorly understood, the model was used to examine high hydraulic conductivity, medium hydraulic conductivity and low hydraulic conductivity scenarios. In all cases the pumping rates for CBM wells was highest in areas close to subcrops and lowest in areas further away from subcrops and faults in relatively continuous coal seams. It was also found that if CBM production were to only take place in the areas of relatively continuous coal seams, the groundwater flux into the faults and subcrops remains very small. However, under this scenario, the pumping rate in these areas increases slightly. The amount of water that is drawn into the subcrops depends not only on the hydraulic conductivity of the coal seams and the location and extent of the pumping well network, but also the extent to which the subcrop is exposed to the unconformity between the Tertiary rocks and the Quaternary sediments. The extent of the exposure of the subcrops is not know, however, a range of values were utilized to estimate the potential loss of groundwater from the surficial layers for the entire region under a regional scale CBM development scenario. The values range from approximately 7500 m^3/day loss for a high hydraulic conductivity scenario to approximately 70 m^3/day for a low hydraulic conductivity scenario. As a comparison the City of Merritt production well pump approximately 8450 m^3/day from the Merritt aquifer. For the medium hydraulic conductivity scenario the groundwater loss was 725 m^3/day, while in a system with the same parameter values, but under a modified scenario where coal seam dewatering takes place only in relatively continuous coal seams, the loss was approximately 45 m^3/day. Based on the results of the model, it is unlikely that coal seam dewatering would have detrimental effects on the water supply in the area. In all scenarios the volumetric loss of groundwater from the surficial layer was less than the pumping rate of the City of Merritt production wells. Since it was determined that the city production wells are currently not depleting the system of groundwater, it is unlikely that removing a relatively small amount of groundwater from a portion of the catchment area would have any effect on the groundwater supply for the city. Furthermore, if coal seam dewatering were to take place in relatively continuous coal seams, far from subcrops and high hydraulic conductivity faults, the volumetric groundwater loss is very low.

The regional scale model assessed the role of a fault that extends from the southwest to the northeast through the region. The fault is interpreted to cut through the Tertiary rocks and three scenarios were simulated using the model to determine the importance the fault has on the regional groundwater flow in response to coal seam dewatering. The results of the regional scale model indicated that the effect of a low hydraulic conductivity fault is not important to the groundwater flow in response to CBM production. At this time the width and extent of the fault is not known; nevertheless, the groundwater loss into the fault was estimated along the unconformity between the Tertiary rocks and the Quaternary sediments for several different fault widths. For a 30 m wide high hydraulic conductivity fault, the estimated loss was approximately 1430 m^3/day whereas for a 10 m wide medium hydraulic conductivity faults the estimated loss was 83.2 m^3/day.

The results provided as part of this study reflect the large degree of uncertainty incorporated into the various numerical models. In general the hydrostratigraphy of the Merritt region is poorly understood, however, additional investigation in the area would considerably constrain the results of further attempts at modeling the area. Based on the broad results of this study, in a well though out CBM development where CBM production takes place in areas relatively unaffected by faults, subcrops or other potentially high hydraulic conductivity features, the risk towards the City of Merritt's groundwater demands are likely to be low. However, as the city continues to develop and the groundwater demands increase, there is inherently greater risk to the groundwater supply.

11.0 FURTHER WORK

The major shortcomings of this study involve the lack of actual measurements of hydrostratigraphic properties of the various geologies. An exploration program involving drilling boreholes and measuring the hydrostratigraphic properties including hydraulic conductivity and storage would greatly constrain the results of the modeling. In order to predict gas and water production rates, the relative permeabilities of gas and water should be understood. If a drilling program were to take place, geochemical analysis groundwater of samples would be helpful to determine the age of the groundwater and determine possible source locations of the groundwater. Geochemical results could also provide an idea as to the quality of the groundwater and if it would require special treatment and/or disposal in compliance with regulatory standards. Furthermore, a greater understanding of the properties and extent of faults in the region would limit the uncertainty involved in the role of faults on the regional groundwater flow.

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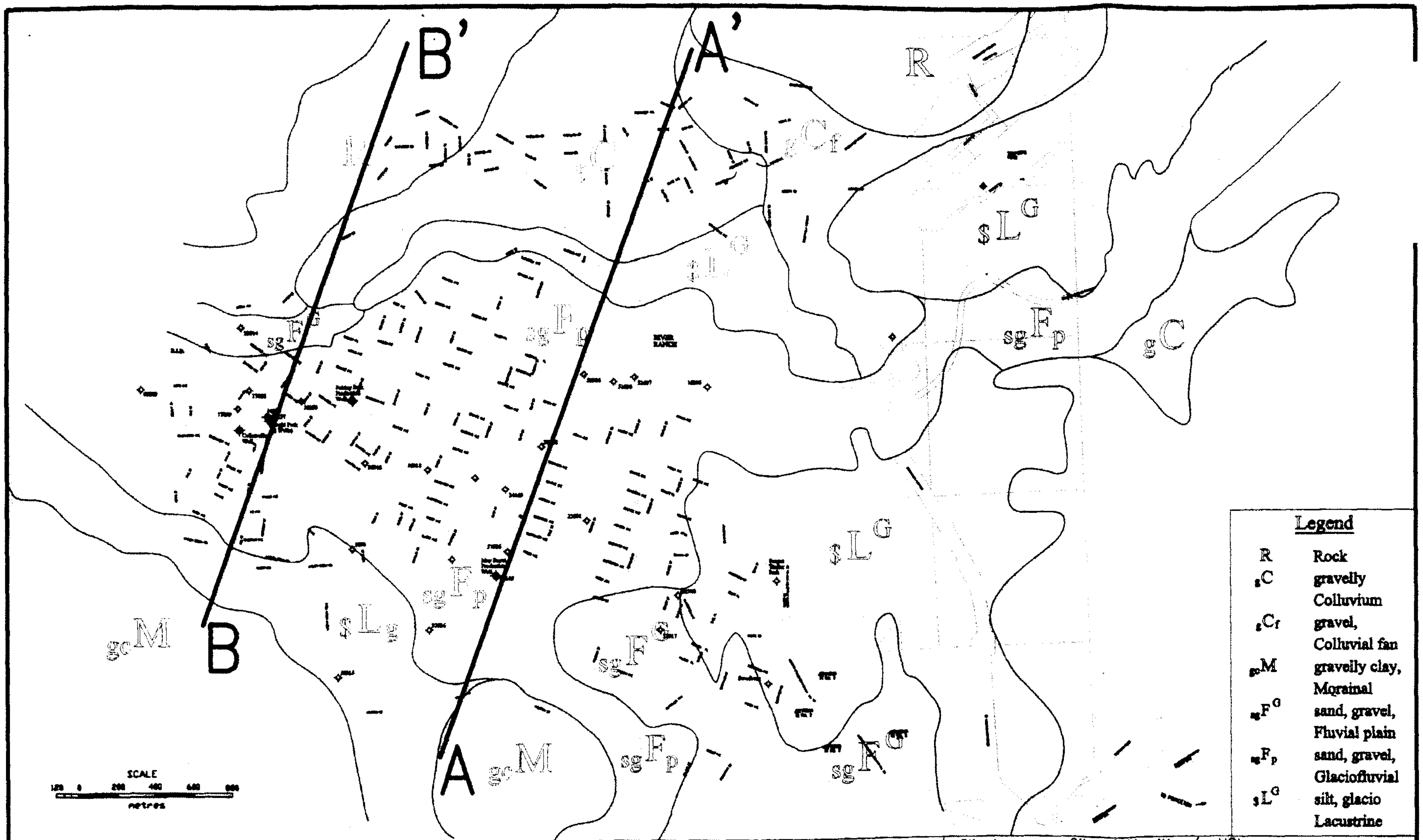
APPENDIX A: KALA FIGS AND CROSS-SECTIONS



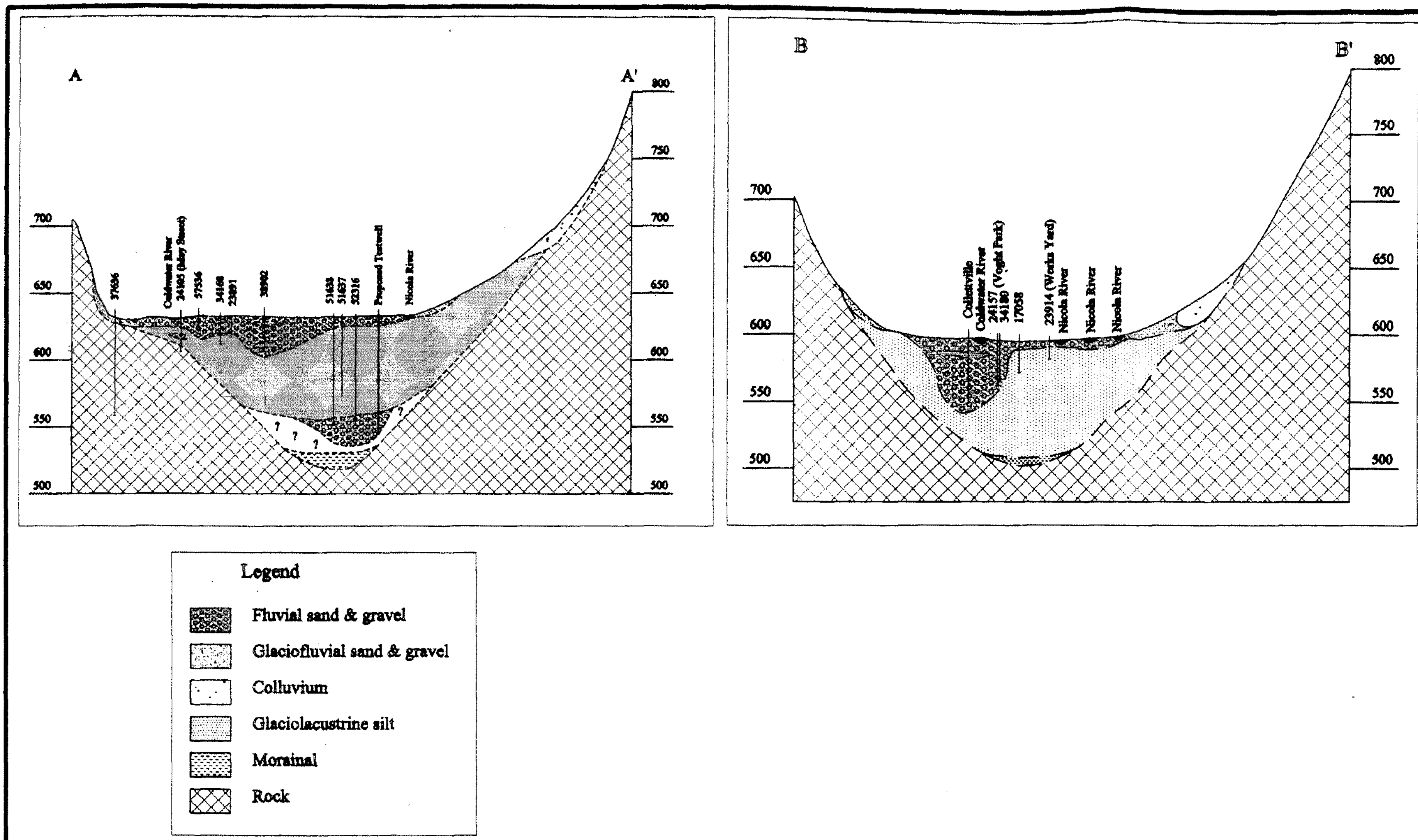
KALA GROUNDWATER CONSULTING LTD.
VERNON KAMLOOPS
1314 McGILL ROAD KAMLOOPS, BC, V2C 6N6
TEL. (250) 372-9194 FAX (250) 372-9398

Notes: This diagram is for conceptual purposes only, locations & configurations are approximate only.

Drawn by: MR
Approved by: TE
Date: Oct. 2004
Scale: As Shown
Ref: 04552

Legend: Production Well
52316 BC MoWLAP Well
A—A' Cross Section Line
File Ref: 04552Fig2.dwg

Client: City of Merritt c/o USL
Project Description: Groundwater Potential Evaluation And Testwell Siting Study
City of Merritt, BC
Diagram: Well Locations And Surficial Geology
Fig: 2



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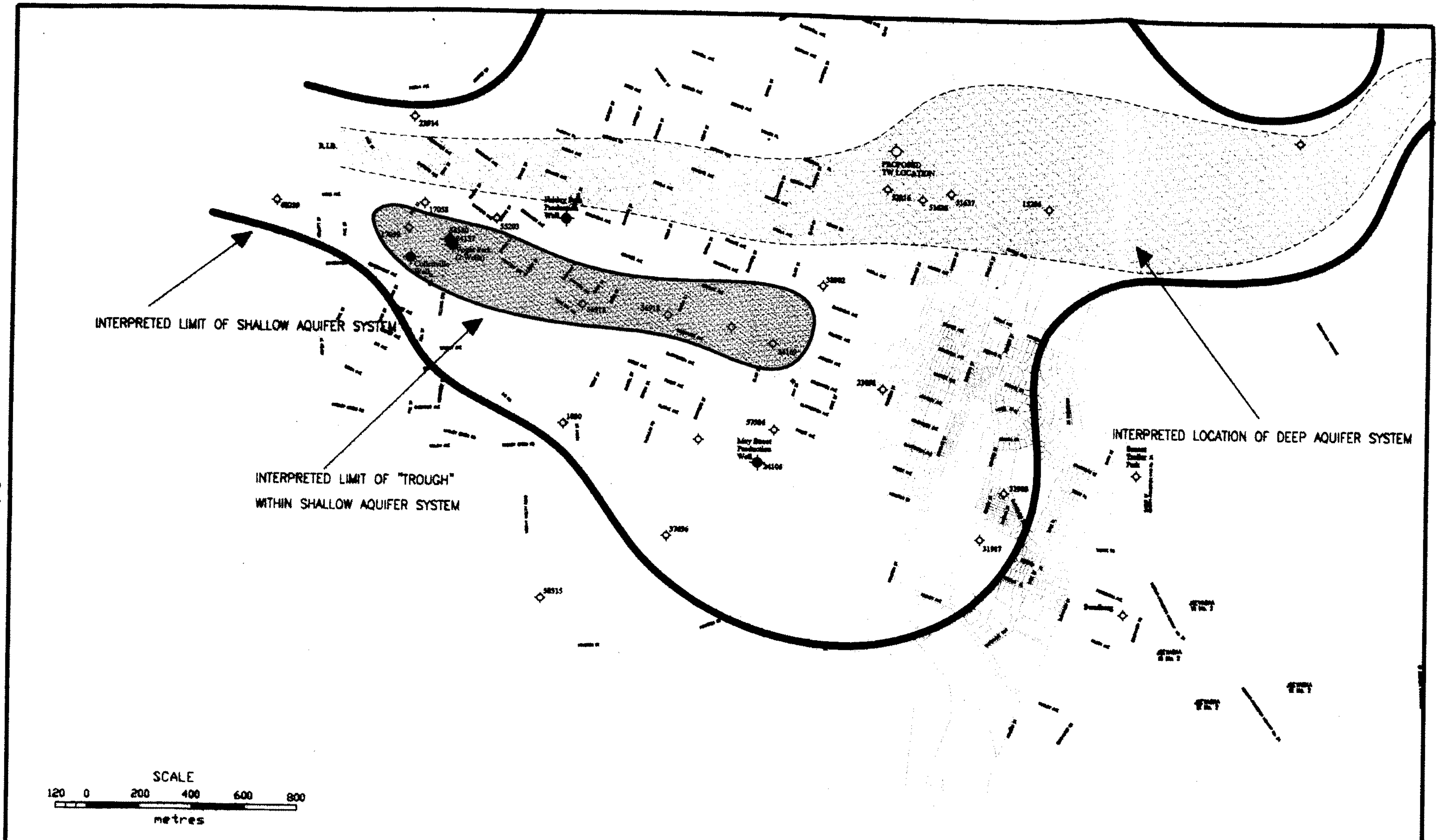
Notes: This diagram is for conceptual purposes only, locations & configurations are approximate only.	Drawn by: MR Approved by: TE Date: Oct. 2004	Legend:	Client: City of Merritt c/o USL Project Description: Groundwater Potential Evaluation And Testwell Siting Study City of Merritt, BC
Scale: As Shown	Ref: 04552	File Ref: 04552fig3.dwg	Diagram: Hydrogeologic Sections — Fig: 3



KALA GROUNDWATER CONSULTING LTD. KAMLOOPS 1314 McGILL ROAD TEL. (250) 372-9194 KAMLOOPS, BC, V2C 6N6 FAX (250) 372-9396	Notes: This diagram is for conceptual purposes only, locations & configurations are approximate only.	Drawn by: MR Approved by: TC Date: Oct. 2004	Legend:
	Scale: As Shown	Ref: 04552	File Ref: 04552 Fig5.dwg

Client: City of Merritt c/o USL

Project Description: Groundwater Potential Evaluation And Testwell Siting Study City of Merritt, BC

Diagram: Interpreted Aquifer Locations

Fig: 5

APPENDIX B: HYDROLOGY DATA

Coldwater River Water Licenses

Data provided by the BC Ministry of Environment, Water Stewardship Division

No	Purpose	Licensee	m^3/s
C025311	Waterworks Local Auth	CITY OF MERRITT	4.38E-02
C026589	Waterworks Local Auth	CITY OF MERRITT	6.57E-04
C030750	Waterworks Local Auth	CITY OF MERRITT	2.03E-02
C030751	Waterworks Local Auth	CITY OF MERRITT	2.03E-02
C053595	Irrigation	WARAWA ALLAN T & MARY E	1.37E-05
C053596	Irrigation	THOMANEK ANJELIKA M	1.56E-05
C053597	Irrigation	MISEK JIRI & ISABELLE H	7.53E-04
C110921	Irrigation	STRANDE WILLIAM C	1.76E-03
C110922	Irrigation	PINE RANCH LTD	1.97E-03
C117033	Conserv.-Use Of Water	FISHERIES & OCEANS CANADA	8.50E-02
C118893	Irrigation	LINDQUIST MICHELE C	3.11E-03
C119905	Irrigation	TAN JENNIFER C & LIM NORMAN C	3.91E-04
C119906	Irrigation	COOKE MARILYN & LOUIS	4.30E-03
C119907	Stock watering	COOKE MARILYN & LOUIS	2.19E-05
C119907	Irrigation	COOKE MARILYN & LOUIS	4.50E-03
F009269	Irrigation	KELLY OLIVER G & PATRICIA M	8.60E-04
F011229	Irrigation	COLDWATER INDIAN BAND	3.91E-04
F011230	Irrigation	COLDWATER INDIAN BAND	8.02E-03
F011230	Irrigation	COLDWATER INDIAN BAND	8.02E-03
F011230	Irrigation	COLDWATER INDIAN BAND	8.02E-03
F011230	Irrigation	COLDWATER INDIAN BAND	8.02E-03
F011230	Irrigation	COLDWATER INDIAN BAND	8.02E-03
F015575	Irrigation	DEVELOPMENT LTD	7.82E-04
F020032	Domestic	TERASEN PIPELINES INC	4.38E-05
		Licensed Quantity (m^3/s)	0.23

Upper Nicola River and Nicola Lake Water Licenses

Data provided by the BC Ministry of Environment, Water Stewardship Division

License No	Purpose	Licensee	m^3/s
C054670	Domestic	SENGER EDWARD & PAULA	2.19E-05
C110654	Irrigation	COQUIHALLA DEVELOPMENTS	1.56E-02
C110654	Irrigation	COQUIHALLA DEVELOPMENTS	1.56E-02
C110654	Irrigation	COQUIHALLA DEVELOPMENTS	1.56E-02
C110654	Irrigation	COQUIHALLA DEVELOPMENTS	1.56E-02
C110654	Irrigation	COQUIHALLA DEVELOPMENTS	1.56E-02
C110655	Irrigation	COQUIHALLA DEVELOPMENTS	5.08E-02
C110655	Irrigation	COQUIHALLA DEVELOPMENTS	5.08E-02
C110655	Irrigation	COQUIHALLA DEVELOPMENTS	5.08E-02
C110655	Irrigation	COQUIHALLA DEVELOPMENTS	5.08E-02
C110655	Irrigation	COQUIHALLA DEVELOPMENTS	5.08E-02
C032982	Waterworks (Other)	UPPER NICOLA INDIAN BAND	4.38E-04
C065616	Irrigation	UPPER NICOLA INDIAN BAND	1.37E-03
C067293	Irrigation	DOUGLAS LAKE CATTLE CO LTD	1.80E-03
C068392	Irrigation	DOUGLAS LAKE CATTLE CO LTD	2.01E-03
C068393	Irrigation	DOUGLAS LAKE CATTLE CO LTD	2.34E-02
C068404	Irrigation	DOUGLAS LAKE CATTLE CO LTD	1.51E-02
C068405	Irrigation	DOUGLAS LAKE CATTLE CO LTD	2.00E-02
C068405	Irrigation	DOUGLAS LAKE CATTLE CO LTD	2.00E-02
C068406	Irrigation	DOUGLAS LAKE CATTLE CO LTD	4.10E-03
C068410	Irrigation	DOUGLAS LAKE CATTLE CO LTD	1.02E-03
C068410	Stock watering	DOUGLAS LAKE CATTLE CO LTD	1.10E-04
F006497	Incidental - Domestic	QUILCHENA CATTLE CO LTD	2.19E-04
F006497	Irrigation	QUILCHENA CATTLE CO LTD	1.78E-02
F006497	Incidental - Domestic	QUILCHENA CATTLE CO LTD	2.19E-04
F006497	Irrigation	QUILCHENA CATTLE CO LTD	1.78E-02
F006498	Incidental - Domestic	QUILCHENA CATTLE CO LTD	2.19E-05
F006498	Irrigation	QUILCHENA CATTLE CO LTD	2.11E-03
F006499	Incidental - Domestic	QUILCHENA CATTLE CO LTD	2.19E-05
F006499	Irrigation	QUILCHENA CATTLE CO LTD	1.90E-03
F009600	Irrigation	QUILCHENA CATTLE CO LTD	7.82E-03
F009600	Irrigation	QUILCHENA CATTLE CO LTD	7.82E-03
F010822	Irrigation	UPPER NICOLA INDIAN BAND	1.86E-02
F010822	Irrigation	UPPER NICOLA INDIAN BAND	1.86E-02
F010822	Irrigation	UPPER NICOLA INDIAN BAND	1.86E-02
F011811	Irrigation	UPPER NICOLA INDIAN BAND	6.84E-04
		Licensed Quantity (m^3/s)	0.53

Nicola River Near Merritt Water Licenses

Data provided by the BC Ministry of Environment, Water Stewardship Division

License No	Purpose	Licensee	m^3/s
C031416	Irrigation	NEALE BROS RANCH	4.69E-03
C037183	Irrigation	SCHOOL DISTRICT NO 58	3.91E-04
C044011	Irrigation	TURCHAK STEPHEN F & KELLY	3.91E-04
C050394	Irrigation	DOUGLAS LAKE CATTLE CO LTD	1.76E-03
C050394	Irrigation	DOUGLAS LAKE CATTLE CO LTD	1.76E-03
C061110	Irrigation	GARTHWAITE GORDON ET AL	3.92E-03
C061111	Irrigation	GARTHWAITE GRETA A	5.08E-03
C063076	Irrigation	BAKER JAMES A	1.76E-04
C068316	Irrigation	TELFORD JAMES	4.89E-03
C068317	Irrigation	VICHERT BRUCE W	9.78E-04
C068656	Irrigation	CHUTTER RANCH LTD	3.71E-02
C068657	Stock watering	CHUTTER RANCH LTD	3.72E-04
C068658	Irrigation	CHUTTER RANCH LTD	1.52E-02
C068659	Irrigation	CHUTTER RANCH LTD	5.18E-03
C068660	Irrigation	CHUTTER RANCH LTD	8.54E-03
C068661	Irrigation	CHUTTER RANCH LTD	1.49E-02
C068663	Stock watering	CHUTTER RANCH LTD	2.19E-05
C068664	Stock watering	CHUTTER RANCH LTD	2.19E-05
C109745	Conserv.-Stored Water	DUCKS UNLIMITED (CANADA)	7.82E-04
C109745	Conserv.-Stored Water	DUCKS UNLIMITED (CANADA)	7.82E-04
C109746	Conserv.-Use Of Water	DUCKS UNLIMITED (CANADA)	7.36E-03
C109746	Storage	DUCKS UNLIMITED (CANADA)	6.26E-04
C118399	Irrigation	BARTLETT CARLENNE & TED	1.70E-03
C118420	Irrigation	BARTLETT CARLENNE & TED	3.05E-03
F005669	Domestic	NEALE BROS RANCH	2.19E-05
F005669	Irrigation	NEALE BROS RANCH	9.38E-04
F008273	Irrigation	GAVELIN WINNIFRED M	6.20E-03
F050528	Irrigation	TORGERSON GLEN & LOIS	2.82E-03
F051490	Irrigation	SENIO TRACY A & KATHLEEN P	1.70E-03
F114234	Irrigation	PEACHEY JON	5.08E-03
		Licensed Quantity (m^3/s)	0.14

Hydrometric Station on Coldwater River (08LG010)
Monthly Mean Discharge (m3/s)

Archived hydrometric data from Canada's HYDAT database.

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Mean
1913	-	-	-	-	31.3	42.8	12.4	1.47	-	-	-	-	-
1914	-	-	-	21.1	41.5	26.8	8.29	0.714	0.947	1.26	-	-	-
1915	-	-	-	17.6	15.6	6.65	2.08	0.685	0.266	3.77	4.12	2.42	-
1916	-	-	-	20.2	-	-	18.2	4.2	1.43	1.02	1.19	0.973	-
1917	0.85	0.85	1.13	2.61	28.2	37.7	15.2	2.34	0.987	1.24	-	-	-
1918	-	-	-	-	-	33.1	7.18	1.8	0.667	4.38	2.47	6.41	-
1919	-	-	11.3	15.5	39.2	36.5	19.4	3.58	1.61	1.44	-	-	-
1920	-	-	-	2.52	16.7	23.7	10.6	1.18	3.48	15.2	4.83	2.77	-
1921	0.85	0.85	6.24	11.9	44.2	45.7	14.8	2.32	4.12	-	-	-	-
1961	-	-	-	-	34.3	34.5	4.82	0.979	1.49	4.2	2.46	1.78	-
1962	4.81	7.5	3.17	11.9	22.5	25.6	4.6	2.28	1.26	2.93	5.89	4.8	8.08
1963	2.19	10.9	5.35	7.01	23.3	17.2	6.99	2.23	1.12	3.13	5.29	7.02	7.62
1964	6.43	3.71	2.49	8.4	26.3	45.1	16.8	2.92	3.35	5.57	2.87	2.77	10.5
1965	2	3.14	3.64	10.8	25.8	23.1	5.23	1.49	0.885	2.59	4.5	3.37	7.21
1966	1.55	1.05	2	12.2	24.5	22.1	9.65	1.34	0.663	2.78	2.38	9.45	7.5
1967	3.31	2.75	2.08	3.44	28.9	43	7.72	1.19	0.306	4.56	6.61	3.1	8.92
1968	22	9.19	11.8	7.85	36.2	36.3	10.8	1.37	1.71	3.09	3.66	3.18	12.3
1969	2.52	2.44	2.14	9.65	39	19.4	3.04	0.651	1.9	3.33	3.5	4.28	7.68
1970	1.12	1.21	2.63	5.24	26.3	28.4	2.2	0.42	0.602	1.09	1.13	0.823	5.94
1971	1.99	5.2	2.88	9.05	57.6	35	14.4	2.23	1.14	1.93	2.19	0.576	11.2
1972	0.725	2.01	11.4	13.3	60.3	55.2	24.4	4.48	1.48	1.51	0.99	0.398	14.7
1973	0.603	0.934	1.67	4.68	23.8	16.3	4.83	0.632	0.38	1.88	2.47	2.45	5.08
1974	2.56	3.03	5.03	18.6	37	55.7	23.1	4.36	0.953	0.959	1.49	1.65	12.9
1975	1.23	1.23	1.39	5.08	33.3	45.9	16.2	1.95	1.12	2.48	9.66	9.36	10.8
1976	5.59	4.14	2.47	7.01	34.9	31.6	22.3	6.9	2.55	1.04	1.87	1.67	10.2
1977	1.88	3.26	2.07	7.94	14.5	14.1	1.93	0.434	0.648	1.12	3.98	3.53	4.6
1978	1.72	1.67	4.58	13.3	27.2	28.7	6.12	1.15	2.36	2.17	4.98	1.55	7.96
1979	1.31	1.25	3.08	6.65	24.3	14.6	2.45	0.526	0.684	0.926	1.32	7.69	5.43
1980	1.86	2.09	2.9	14.7	29.3	18.3	4.06	1.73	2.06	2.14	4.48	18	8.49
1981	8.97	5.73	5.21	10.4	27.1	16.4	8.05	1.4	0.767	2.82	3.87	1.47	7.69
1982	1.4	2.31	2.2	3.95	30.1	43.4	11.8	1.98	0.986	2.07	1.55	1.56	8.62
1983	3.2	2.87	4.87	10.6	32.6	17.8	7.6	1.18	1.31	1.3	5.22	1.47	7.52
1984	10.8	2.74	3.46	5.36	10.2	24.8	8.69	1.6	1.44	2.16	1.69	1.04	6.16
1985	1.08	1.58	1.5	10.1	29.2	23.6	3.49	0.544	0.817	3.34	3.16	0.959	6.62
1986	2.06	4.68	9.74	12.1	28.3	25.5	5.19	1.15	0.806	1.46	3.24	1.93	8.01
1987	2.41	2.16	5.92	16.2	36.9	16.8	3.28	0.634	0.314	0.357	0.52	0.664	7.21
1988	0.485	0.944	1.55	13.7	26.3	19.7	4.76	0.882	0.59	2.32	5.05	2.18	6.53
1989	2.11	2.28	2.26	12.7	31.9	24.2	3.69	2.01	0.981	2.41	9.84	6.68	8.44
1990	2.35	1.43	2.5	17.9	21.3	25.3	7.55	1.07	0.886	7	23.8	6.49	9.78
1991	3.13	15.5	6.97	17.6	36	29.8	14.5	3.05	1.81	1.16	4.22	2.66	11.3
1992	3.06	6.15	10.5	15.8	17.3	8.04	2.92	0.616	0.76	1.76	2.25	1.6	5.88
1993	0.996	1.24	2.86	6.46	25.9	9.01	3.79	2.43	1.07	1	1.2	1.51	4.82
1994	2.09	1.19	5.36	17.9	20.4	9.34	2.66	0.388	0.173	0.616	0.937	2.98	5.35
1995	1.55	6.64	5.1	9.98	35	-	-	-	-	-	-	-	-
Mean	3.13	3.5	4.36	11	29.9	27.5	9.02	1.78	1.26	2.62	3.97	3.51	8.21

Hydrometric Station on Nicola River at outlet of Nicola Lake (08LG065) Monthly Mean Discharge (m^3/s)													
Archived hydrometric data from Canada's HYDAT database.													
Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Mean
1983	2.09	2.09	2.86	3.63	24.6	22.9	6.65	2.64	2.19	1.81	2.09	2.7	6.38
1984	2.89	2.43	2.18	3.01	9.84	33.7	11.1	2.79	1.78	1.23	1.08	0.992	6.07
1985	0.909	0.963	1.21	1.48	9.23	16.9	3.83	1.28	0.884	0.503	0.387	0.334	3.16
1986	-	-	-	-	-	-	5.02	5.46	2.87	1.76	1.38	1.26	-
1987	1.17	1.18	1.22	1.57	13.8	4.3	2.01	1.53	1.71	1.18	1.04	0.528	2.62
1988	0.064	0.321	0.521	0.567	1.48	1.77	1.63	1.44	1.86	1.52	1.43	1.13	1.15
1989	0.905	0.88	1.03	2.69	7.37	11.8	5.37	4.54	3.81	2.73	2.43	2.35	3.84
1990	2.16	2.15	2.11	2.69	11.4	38.1	11.4	2.98	2.39	1.74	1.64	1.56	6.68
1991	1.44	1.51	1.54	2.82	24.9	24.6	12.2	3.99	3.33	2.49	2.36	1.94	6.96
1992	1.36	1.38	1.38	1.81	3.56	2.54	3.65	3.07	1.87	1.64	1.56	1.29	2.1
1993	1.2	1.19	1.22	2.14	19.7	11.8	10.2	16.5	3.55	3.21	3.1	3.08	6.47
1994	2.97	3.67	3.75	9.29	18	4.83	3.59	3.2	2.28	1.76	1.46	1.3	4.68
1995	1.29	1.33	1.37	5.38	19.5	17.8	7.36	3.23	2.95	2.5	2.32	2.37	5.64
1996	2.43	3.12	9.21	12.9	21.8	28.1	7.46	4.65	2.3	1.98	1.95	2	8.15
1997	2.06	3.35	8.5	10.6	42.8	29.4	16	7.62	3.44	3.28	4.38	4.82	11.4
1998	3.79	3.14	3.22	6.71	21.6	8.1	6.79	2.57	1.71	1.47	1.3	1	5.14
1999	0.987	0.916	1.17	6.04	24.8	25	15.2	4.42	2.3	2.4	2.2	2.02	7.32
2000	1.98	1.97	1.93	3.97	19.9	15.4	11.5	5.06	2.55	2.46	2.48	2.08	5.96
2001	1.86	1.78	1.69	1.74	7.25	9.13	3.81	3.24	2.64	1.95	1.74	1.4	3.19
2002	1.36	1.36	1.38	2.03	23.5	33.3	5.98	3.07	2.1	1.65	1.31	0.976	6.5
2003	0.864	0.827	0.835	0.912	1.58	2.17	2.95	2.28	1.78	1.42	1.27	0.894	1.49
2004	0.457	0.62	0.655	0.788	5.76	11.2	3.16	3.01	1.88	1.49	1.74	1.12	2.65
Mean	1.63	1.72	2.33	3.94	15.8	16.8	7.13	4.03	2.37	1.92	1.85	1.69	5.12

Hydrometric Station on Nicola River (08LG007)

Monthly Mean Discharge (m^3/s)

Archived hydrometric data from Canada's HYDAT database.

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Mean
1911	-	-	-	-	-	-	19.2	7.85	5.22	2.64	2.42	2.41	-
1912	3.59	4.78	4.45	10.4	42.5	35.6	14.5	4.68	2.39	1.77	2.7	1.87	10.8
1913	0.923	2.46	2.38	7.26	37.4	49.8	14.3	4.18	3.1	4.27	2.74	1.01	10.8
1914	5.23	2.91	5.12	25.5	66.8	48.1	14.5	2.76	1.9	1.95	-	-	-
1915	-	-	-	20.3	26.4	24	11.1	4.42	1.56	-	-	-	-
1957	-	-	-	-	-	-	-	-	-	-	-	3.18	-
1958	3.5	3.65	4.67	10.5	55.2	33.3	7.75	2.6	2.43	4.29	5.68	10.4	12.1
1959	7.37	4.43	5.81	14.4	55.1	78.3	27.6	6.48	6.33	11.1	12.7	10.9	20.1
1960	5.23	5.18	8.17	23.2	41.3	38.8	8.94	2.72	1.91	3.1	3.02	1.85	11.9
1961	3.46	5.18	4.52	13	52.5	59.1	10.1	2.9	2.04	4.72	3	2.47	13.6
1962	5.58	9.86	4.43	13.9	35.8	53.9	17.1	5.26	3.19	3.47	7.37	7.27	13.9
1963	3.35	13.7	7.44	9.13	28.4	27.3	13.5	6.27	4.19	6.02	7.05	8.49	11.2
1964	7.19	5.71	5.13	10.1	33.6	82.3	35.1	8.78	7.61	8.26	6.03	5.4	17.9
1965	4.71	8.05	7.83	16.2	40	45.6	12.9	6.57	2.5	4.36	6.46	4.6	13.3
1966	4.32	3.46	4.09	15.4	32.2	35.1	15.2	5.08	2.4	4.86	4.43	9	11.3
1967	5.64	4.32	3.63	4.67	38.1	98.4	17.4	3.84	1.76	6.66	11.7	5.74	16.8
1968	10.3	14.2	13.7	8.89	45.6	76.6	24.3	5.12	4.87	5.74	5.83	3.81	18.2
1969	2.35	4.55	4.73	12.2	68	41.6	11.4	5.01	4.31	5.79	4.55	3.55	14.1
1970	2.97	3.12	3.91	5.85	35.2	43.4	8.52	3.62	2.69	2.55	1.61	1.33	9.57
1971	2.62	8.05	4.06	10.1	87.5	90.7	33.3	5.3	2.77	2.98	3.45	2.94	21.2
1972	2.32	2.57	15	23	87.6	95.6	47.1	13.1	5.32	2.9	0.843	1.9	24.8
1974	4.25	4.84	6.36	19.5	62.1	90.8	41.5	10.4	4.14	3.24	3.59	3.57	21.2
1975	2.85	3.26	4.44	8.7	40.5	64.2	22.8	6	3.32	4.29	12.1	9.71	15.2
1976	6.51	5.57	4.35	8.48	41.3	46	25.3	13.4	12.3	5.65	5.25	3.75	14.8
1977	3.54	5.37	4.03	9.26	23.2	20	5.24	2.19	2.04	2.49	4.69	3.89	7.15
1978	2.57	2.42	6.25	15	46.2	50.5	12.4	3.9	5.12	4.8	7.5	3.5	13.4
1979	3.03	3.46	6.24	7.77	37.9	25.3	6.56	2.55	2.38	2.18	1.81	6.85	8.87
1980	2.21	2.56	4.25	14.7	31.1	30.5	8.4	3.8	4.97	4.04	5.98	20.2	11.1
1981	10.6	7.56	7.25	11.1	41.8	38.2	19.9	6.57	4.21	5.76	6.18	4.8	13.7
1982	5.29	5.96	5.61	6.72	46.5	66.1	28.3	10.3	5.01	5.32	4.11	4.47	16.2
1983	5.98	5.82	8.64	15.1	61.2	41.2	14.5	4.3	4.07	3.32	6.68	4.23	14.6
1984	14.4	5.79	5.95	8.57	19.7	61.6	18.7	4.8	3.71	4.17	3.49	2.53	12.8
1985	2.57	3.05	3.34	11.4	36.7	38	7.18	2.04	2.31	4.27	3.61	1.44	9.67
1986	2.75	5.28	13.6	13.5	33.4	41.7	11.3	7.34	4.75	4.6	5.02	3.56	12.2
1987	4.14	3.96	7.82	17.4	47.8	19.6	5.75	2.73	2.52	2.02	2.07	1.54	9.82
1988	0.996	1.66	2.43	13.1	25.2	19	6.88	2.5	2.61	4.4	6.77	3.77	7.45
1989	3.36	3.58	3.99	14.3	36.8	33.2	9.54	7.33	5.53	5.81	12.1	10.4	12.2
1990	5.13	3.48	5.33	19.7	33.1	67.7	20.6	4.63	4.12	9.48	25.9	9.33	17.4
1991	5.24	19.3	9.5	23.1	64.6	59	29.2	7.84	5.61	4.4	7.4	5.5	20
1992	5.18	8.49	13.1	20.1	22.9	11.6	7.63	4.33	3.25	4.06	4.32	3.05	9
1993	2.65	3.12	4.73	9.52	45.9	23.8	17.3	22	5.79	5.39	5.02	5.6	12.7
1994	5.57	5.34	9.28	29.9	40.5	15.8	6.62	3.85	2.83	3.11	3.01	4.55	10.9
1995	3.12	8.12	7.16	16	55	35.1	11.5	5.86	4.12	6.8	22.6	13.4	15.8
1996	10.3	11.1	21.4	39.9	46.1	53	14.8	6.13	3.5	4.7	7.39	3.39	18.4
1997	3.66	9.55	16.7	31.7	95.5	63	28.1	10.1	6.28	9.86	10.6	6.97	24.4
1998	6.78	6.03	7.32	15.8	54.8	23.7	10.7	3.4	2.48	2.67	4.39	4.85	12
1999	5.44	4.26	4.72	17.4	58.6	69.2	41.8	11.4	5.13	5.91	12.8	6.99	20.4
2000	4.88	4.74	4.59	15.7	40.6	37.5	17.7	6.96	4.8	5.57	5.66	3.81	12.7
2001	3.52	2.9	4.06	7.76	25.8	21.2	7.12	4.36	3.35	3.55	6.78	4.03	7.89
2002	7.63	4.21	4.28	13.4	57.7	73.8	19.9	5.21	3.25	3.08	3.93	2.95	16.6
2003	3.27	3.84	4.96	11	21.1	19.2	5.07	2.6	2.23	11.6	4.57	2.98	7.72
2004	2.72	2.79	5.99	15.7	25.8	22.3	4.62	3.22	4.29	3.69	7.82	9.7	9.05
Mean	4.71	5.58	6.67	14.7	44.6	46.8	16.7	5.85	3.89	4.75	6.42	5.27	13.9

APPENDIX C: CHEMISTRY RESULTS

ALS Environmental

CHEMICAL ANALYSIS REPORT

Date:	August 15, 2005
ALS File No.	W1949r
Report On:	Merritt Water Analysis
Report To:	**UBC - Earth & Ocean Sciences** Geophysics 6339 Stores Road Vancouver, BC V6T 1Z4
Attention:	**Mr. Jordin Barclay**
Received:	July 22, 2005

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per:

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1988 Triumph Street, Vancouver, BC Canada V5L 1K5
Phone: 604-253-4188 Fax: 604-253-6700 Website: www.alsenviro.com

REMARKS

This report, ALS file W1949r, supersedes the previous file W1949.
The Dissolved Potassium was re-analyzed for samples previously showing a result of less than 2.0 milligrams per litre.

File No. W1949r

RESULTS OF ANALYSIS - Water

Sample ID			SPRING 1	SPRING 2	DWW 1	DWW 2	DWW 3
Sample Date			05-07-21	05-07-20	05-07-20	05-07-21	05-07-21
Sample Time			16:00	13:00	15:00	17:00	13:00
ALS ID			*1*	*2*	*3*	*4*	*5*
Dissolved Anions							
Alkalinity-Total		$CaCO_3$	301	324	228	289	194
Bromide	Br		<0.050	<0.50	<0.050	<0.050	<0.050
Chloride	Cl		33.7	5.1	0.79	2.21	3.73
Fluoride	F		0.116	<0.20	0.199	0.498	0.089
Sulphate	SO_4		28.6	994	38.2	77.3	44.1
Nutrients							
Nitrate Nitrogen		N	0.269	<0.050	<0.0050	0.0673	0.0269
Nitrite Nitrogen		N	0.0015	<0.010	<0.0010	<0.0010	<0.0010

Remarks regarding the analyses appear at the beginning of this report.
Results are expressed as milligrams per litre except where noted.
< = Less than the detection limit indicated.

File No. W1949r

RESULTS OF ANALYSIS - Water

Sample ID		SPRING 1	SPRING 2	DWW 1	DWW 2	DWW 3
Sample Date		05-07-21	05-07-20	05-07-20	05-07-21	05-07-21
Sample Time		16:00	13:00	15:00	17:00	13:00
ALS ID		*1*	*2*	*3*	*4*	*5*
Dissolved Metals						
Aluminum	D-Al	<0.20	<0.20	<0.20	<0.20	<0.20
Antimony	D-Sb	<0.20	<0.20	<0.20	<0.20	<0.20
Arsenic	D-As	<0.20	<0.20	<0.20	<0.20	<0.20
Barium	D-Ba	0.113	<0.010	0.061	0.038	0.051
Beryllium	D-Be	<0.0050	<0.0050	<0.0050	<0.0050	<0.0050
Bismuth	D-Bi	<0.20	<0.20	<0.20	<0.20	<0.20
Boron	D-B	<0.10	0.14	<0.10	<0.10	<0.10
Cadmium	D-Cd	<0.010	<0.010	<0.010	<0.010	<0.010
Calcium	D-Ca	95.6	301	62.6	84.7	50.9
Chromium	D-Cr	<0.010	<0.010	<0.010	<0.010	<0.010
Cobalt	D-Co	<0.010	<0.010	<0.010	<0.010	<0.010
Copper	D-Cu	<0.010	<0.010	<0.010	<0.010	<0.010
Iron	D-Fe	<0.030	0.604	0.341	0.039	<0.030
Lead	D-Pb	<0.050	<0.050	<0.050	<0.050	<0.050
Lithium	D-Li	<0.010	0.023	<0.010	<0.010	<0.010
Magnesium	D-Mg	31.8	66.5	31.3	34.2	19.5
Manganese	D-Mn	<0.0050	1.09	0.0466	0.0081	<0.0050
Molybdenum	D-Mo	<0.030	<0.030	<0.030	<0.030	<0.030
Nickel	D-Ni	<0.050	<0.050	<0.050	<0.050	<0.050
Phosphorus	D-P	<0.30	<0.30	<0.30	<0.30	<0.30
Potassium	D-K	1.51	2.2	1.99	1.84	1.63
Selenium	D-Se	<0.20	<0.20	<0.20	<0.20	<0.20
Silicon	D-Si	7.57	6.49	15.0	8.16	7.71
Silver	D-Ag	<0.010	<0.010	<0.010	<0.010	<0.010
Sodium	D-Na	13.1	121	22.8	17.9	17.3
Strontium	D-Sr	0.365	6.76	0.466	0.607	0.436
Thallium	D-Tl	<0.20	<0.20	<0.20	<0.20	<0.20
Tin	D-Sn	<0.030	<0.030	<0.030	<0.030	<0.030
Titanium	D-Ti	<0.010	<0.010	<0.010	<0.010	<0.010
Vanadium	D-V	<0.030	<0.030	<0.030	<0.030	<0.030
Zinc	D-Zn	0.0168	<0.0050	<0.0050	0.173	0.0175

Remarks regarding the analyses appear at the beginning of this report.
Results are expressed as milligrams per litre except where noted.
< = Less than the detection limit indicated.

File No. W1949r

Appendix 1 - QUALITY CONTROL - Replicates

Water			DWW 1	DWW 1
			05-07-20 15:00	QC # 453112
Dissolved Anions				
Alkalinity-Total		CaCO3	228	226
Bromide	Br		<0.050	<0.050
Chloride	Cl		0.79	0.80
Fluoride	F		0.199	0.198
Sulphate	SO4		38.2	38.4
Nutrients				
Nitrate Nitrogen		N	<0.0050	<0.0050
Nitrite Nitrogen		N	<0.0010	<0.0010

Remarks regarding the analyses appear at the beginning of this report.
Results are expressed as milligrams per litre except where noted.
< = Less than the detection limit indicated.

Appendix 1 - QUALITY CONTROL - Replicates

Water		DWW 1	DWW 1
		05-07-20 15:00	QC # 453112
Dissolved Metals			
Aluminum	D-Al	<0.20	<0.20
Antimony	D-Sb	<0.20	<0.20
Arsenic	D-As	<0.20	<0.20
Barium	D-Ba	0.061	0.060
Beryllium	D-Be	<0.0050	<0.0050
Bismuth	D-Bi	<0.20	<0.20
Boron	D-B	<0.10	<0.10
Cadmium	D-Cd	<0.010	<0.010
Calcium	D-Ca	62.6	63.0
Chromium	D-Cr	<0.010	<0.010
Cobalt	D-Co	<0.010	<0.010
Copper	D-Cu	<0.010	<0.010
Iron	D-Fe	0.341	0.342
Lead	D-Pb	<0.050	<0.050
Lithium	D-Li	<0.010	<0.010
Magnesium	D-Mg	31.3	31.3
Manganese	D-Mn	0.0466	0.0465
Molybdenum	D-Mo	<0.030	<0.030
Nickel	D-Ni	<0.050	<0.050
Phosphorus	D-P	<0.30	<0.30
Selenium	D-Se	<0.20	<0.20
Silicon	D-Si	15.0	15.1
Silver	D-Ag	<0.010	<0.010
Sodium	D-Na	22.8	22.9
Strontium	D-Sr	0.466	0.464
Thallium	D-Tl	<0.20	<0.20
Tin	D-Sn	<0.030	<0.030
Titanium	D-Ti	<0.010	<0.010
Vanadium	D-V	<0.030	<0.030
Zinc	D-Zn	<0.0050	<0.0050

Remarks regarding the analyses appear at the beginning of this report.
Results are expressed as milligrams per litre except where noted.
< = Less than the detection limit indicated.

Appendix 2 - METHODOLOGY

Outlines of the methodologies utilized for the analysis of the samples submitted are as follows

Alkalinity in Water by Colourimetry

This analysis is carried out using procedures adapted from EPA Method 310.2 "Alkalinity". Total Alkalinity is determined using the methyl orange colourimetric method.

Recommended Holding Time:
Sample: 14 days
Reference: APHA
For more detail see ALS Environmental "Collection & Sampling Guide"

Dissolved Anions in Water by Ion Chromatography

This analysis is carried out using procedures adapted from APHA Method 4110 "Determination of Anions by Ion Chromatography" and EPA Method 300.0 "Determination of Inorganic Anions by Ion Chromatography". Anions are determined by filtering the sample through a 0.45 micron membrane filter and injecting the filtrate onto a Dionex IonPac AG17 anion exchange column with a hydroxide eluent stream. Anions routinely determined by this method include: bromide, chloride, fluoride, nitrate, nitrite and sulphate.

Recommended Holding Time:
Sample: 28 days (bromide, chloride, fluoride, sulphate)
Sample: 2 days (nitrate, nitrite)
Reference: APHA and EPA
For more detail see ALS Environmental "Collection & Sampling Guide"

Metals in Water

This analysis is carried out using procedures adapted from "Standard Methods for the Examination of Water and Wastewater" 20th Edition 1998 published by the American Public Health Association, and with procedures adapted from "Test Methods for Evaluating Solid Waste" SW-846 published by the United States Environmental Protection Agency (EPA). The procedures may involve preliminary sample treatment by acid digestion, using either hotplate or microwave oven, or filtration (EPA Method 3005A). Instrumental analysis is by atomic absorption/emission spectrophotometry (EPA Method 7000 series), inductively coupled plasma - optical emission spectrophotometry (EPA Method 6010B), and/or inductively coupled plasma - mass spectrometry (EPA Method 6020).

Recommended Holding Time:

Sample:	6 months
Reference:	EPA
For more detail see:	ALS "Collection & Sampling Guide"

Results contained within this report relate only to the samples as submitted.

End of Report