EARTH SCIENCES
SIMON FRASER UNIVERSITY

Numerical Groundwater Flow Model of the Abbotsford-Sumas Aquifer, Central Fraser Lowland of BC, Canada, and Washington State, US.

Final Report

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EXECUTIVE SUMMARY

A numerical groundwater flow model was developed for the trans-national Abbotsford-Sumas in southwestern British Columbia, Canada and northwestern Washington State. The aquifer is located in the central Fraser Valley, is bisected by Canada-US boundary, and is located east of Vancouver BC and north of Bellingham, WA, centered around the City of Abbotsford, BC.

The aquifer system area is 160 km^2, and is comprised of heterogeneous glaciofluvial sediments, bounded by glaciomarine sediments that infill steep and variable bedrock topography of buried paleovalleys, bedrock outcrops and mountain ranges. The hydrostratigraphic units were modeled in three-dimensions from standardized, reclassified, and interpreted well borehole lithologs. A three dimensional groundwater flow model of variable spatial resolution (constrained by borehole spacing) was implemented in Visual MODFLOW, and calibrated to historic static water elevations in several thousand wells. The model accounts for large-scale heterogeneity of the sediment fill, in which the hydraulic conductivity and specific yield properties are spatially-distributed in the aquifer layers.

A new methodology was implemented for generating spatially-distributed (and temporally-varying) recharge zonation for the surficial aquifer, using GIS linked to the one-dimensional HELP (USEPA) hydrologic model that calculates aquifer recharge. The recharge model accounts for soil distribution, vadose zone depth and hydraulic conductivity, the extent of impermeable areas, and surficial geology. Recharge is driven by physically-based daily weather inputs generated by a stochastic weather generator that is calibrated to local observed climate.

During the model development and calibration it became apparent that the aquifer is probably very heterogeneous and, at a large scale, the discrete units are not very different from each other. However, there appear to be significant small-scale differences in hydraulic properties. The study also suggests that the groundwater flow patterns are much more complex than originally thought, and any previous simplified well capture models should be re-evaluated. Further improvements to the model may allow for quantifying stream-aquifer interactions in major streams draining the aquifer system; however, detailed local hydrogeologic data will be necessary. Preliminary results suggest that flow rates into the streams and ditches are of the same magnitude as observed streamflows. A model (or sub-model) that is calibrated to local conditions will enable a better mass balance to be achieved, improve our ability to predict baseflow to streams from the aquifer, and link aquifer recharge to streamflow.

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1. INTRODUCTION

1.1. BACKGROUND AND PURPOSE OF RESEARCH

Agricultural land use activities have been identified as the major non-point sources of nitrate contamination of groundwater in many rural aquifers. Numerical models of aquifers can provide valuable management tools for mitigating nitrate contamination. The Abbotsford-Sumas Aquifer (**Map 1**) offers an excellent case study region for developing such a model because although efforts are underway to alleviate the groundwater contamination through possible changes in land use practices, it is still not possible to reliably predict the effect of any land use practices or changes in these practices on the quality of groundwater in the aquifer. This is because the character of groundwater flow in the aquifer (i.e., the rate and direction of groundwater movement) and the region-specific processes controlling the transport and fate of nutrients in the aquifer are complex and not fully understood.

Map 1 Location map of the model area in British Columbia and Washington State.

1.2. PURPOSE OF RESEARCH

The purpose of the proposed research is to develop a regional groundwater flow model of the Abbotsford-Sumas aquifer. This model will provide the first step to better understand these complex processes and their relationships in the aquifer, and subsequently, to predict the potential effects of implementing land use scenarios on the groundwater quality. Not only would this model serve as a tool for tracking and predicting contaminant plume migration over a large scale, but it can also be used to:

- guide future research questions related to nutrient release and movement through the vadose zone as well as in groundwater.

- facilitate investigations of localized groundwater contamination in the aquifer by providing a larger-scale definition of important aquifer properties and boundary conditions that are needed to develop the smaller-scale models needed for these investigations.

1.3. ABBOTSFORD-SUMAS AQUIFER EXTENT AND NUMERICAL MODEL EXTENT

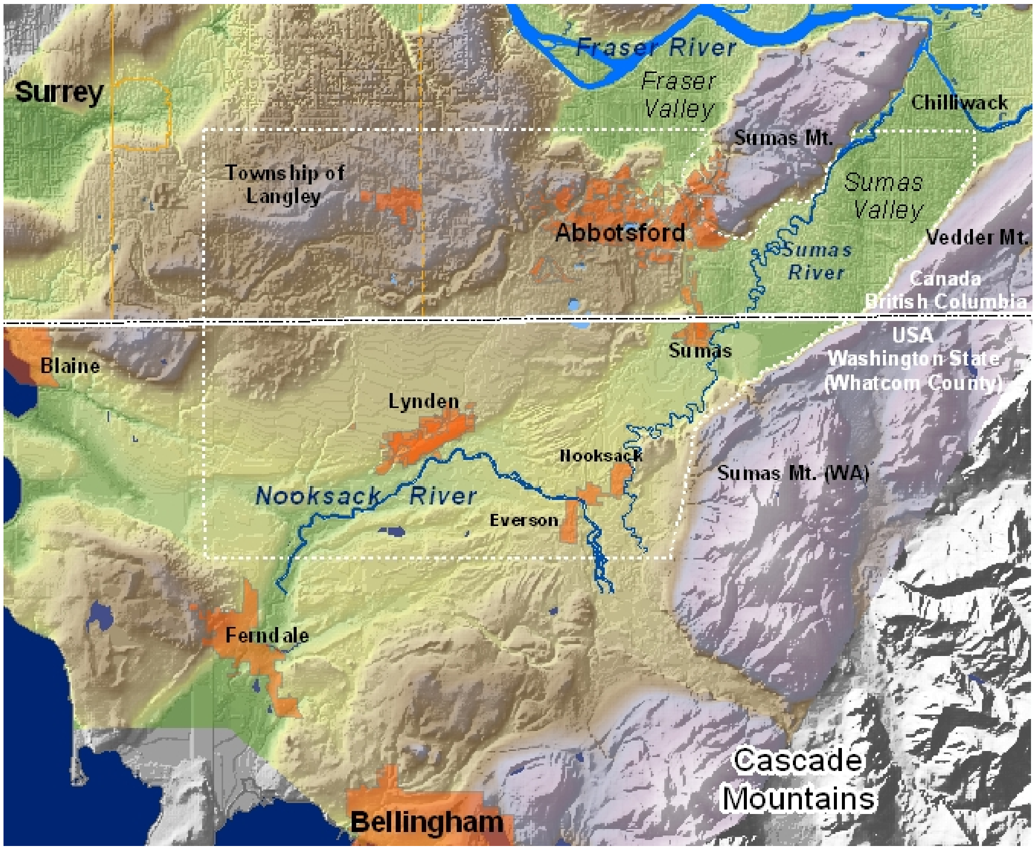
The Abbotsford-Sumas aquifer, which lies within the bounds of the study area (**Map 2**), is located in central Fraser Valley, and consists of several interconnected unconfined and confined aquifers, mostly in coarse grained sediments of glaciofluvial drift origin, and spanning uplands and three river valleys (lowlands or floodplains) on three sides. The uplands are centered on the City of Abbotsford, BC and extend westward through Langley, BC and south to Lynden, WA. The Sumas Valley is a large sediment-filled deep bedrock valley that receives much of the aquifer discharge. To the south is the Nooksack River valley, which receives the largest discharge component from the uplands and the aquifer.

Map 2 Fraser Valley and location of study area.

The aquifer is highly productive, and provides water supply for nearly 10,000 people in the US (towns of Sumas, Lynden, Ferndale, Everson and scattered agricultural establishments) and 100,000 in Canada, mostly in City of Abbotsford, but also in township of Langley (Mitchell et al., 2000). **Map 3** shows the locations of developed areas within the aquifer footprint. Almost half the groundwater is pumped to supply fish hatcheries in Abbotsford, BC. Industrial use is also becoming important (there is a power plant in construction near Sumas, WA). The coastal climate is humid and temperate, with significant rainfall over most of the year. Recharge to the aquifer is primarily from direct precipitation, mostly from October to May. Pumping is also significant, and is on the order of 1/7 to 1/8 of total annual recharge.

Groundwater discharge occurs through springflow, and seepage to small streams and rivers. The Nooksack Valley is in Washington State, whereas the Sumas Valley extends from City of Sumas, WA to Chilliwack, BC. The largest rivers, hydraulically connected to the aquifer system, are the Nooksack River and the Sumas River. These are almost exclusively discharge zones. Small streams on the uplands, and small lakes, have more complex and temporally varying aquifer interactions. To the north is Fraser River floodplain, where a small component of groundwater discharge occurs. On a large scale, the entire valley is called Fraser River Valley, or, more specifically, the central Fraser Valley (also called Fraser Lowland). The aerial extent of the Abbotsford-Sumas aquifer is approximately 161 km^2 (62 sq miles) and is roughly bisected by the Canadian-USA boundary.

Map 3 Central Fraser Valley location map showing model area, cities and towns, topography, international border, and major rivers. White dotted outline shows model boundary, which encompasses the Abbotsford-Sumas aquifer.



The Abbotsford-Sumas aquifer is mostly unconfined in the outwash plains, but there are significant confined pockets. For example, a large part of the aquifer within Sumas Valley is confined, as are smaller aquifers to the west, in the uplands. These aquifers are poorly connected to the Abbotsford-Sumas aquifer. Laterally, the valley sediments are confined by the Tertiary bedrock surface, which outcrops as mountains on both sides of Sumas Valley, and small outcrops south of Nooksack River. The aquifer is underlain by an extensive glaciomarine deposit, which outcrops in the uplands to the west.

The aquifer is composed of uncompacted sands and gravels of the Sumas Drift, a glacial outwash deposit. There is significant heterogeneity of the hydrostratigraphic units, which results in complex groundwater paths. The thickness of Sumas Drift can be up to 65 m, and it is thickest in the northeast where glacial terminal moraine deposits are found. The deepest part of the aquifer system in this region is located along the US-Canada border beneath the City of Abbotsford and toward Lynden, WA, but the most productive areas are near Sumas, WA in south-west end of the Sumas Valley. This report will discuss in great detail the geology, hydrogeology, and other aspects of these aquifers.

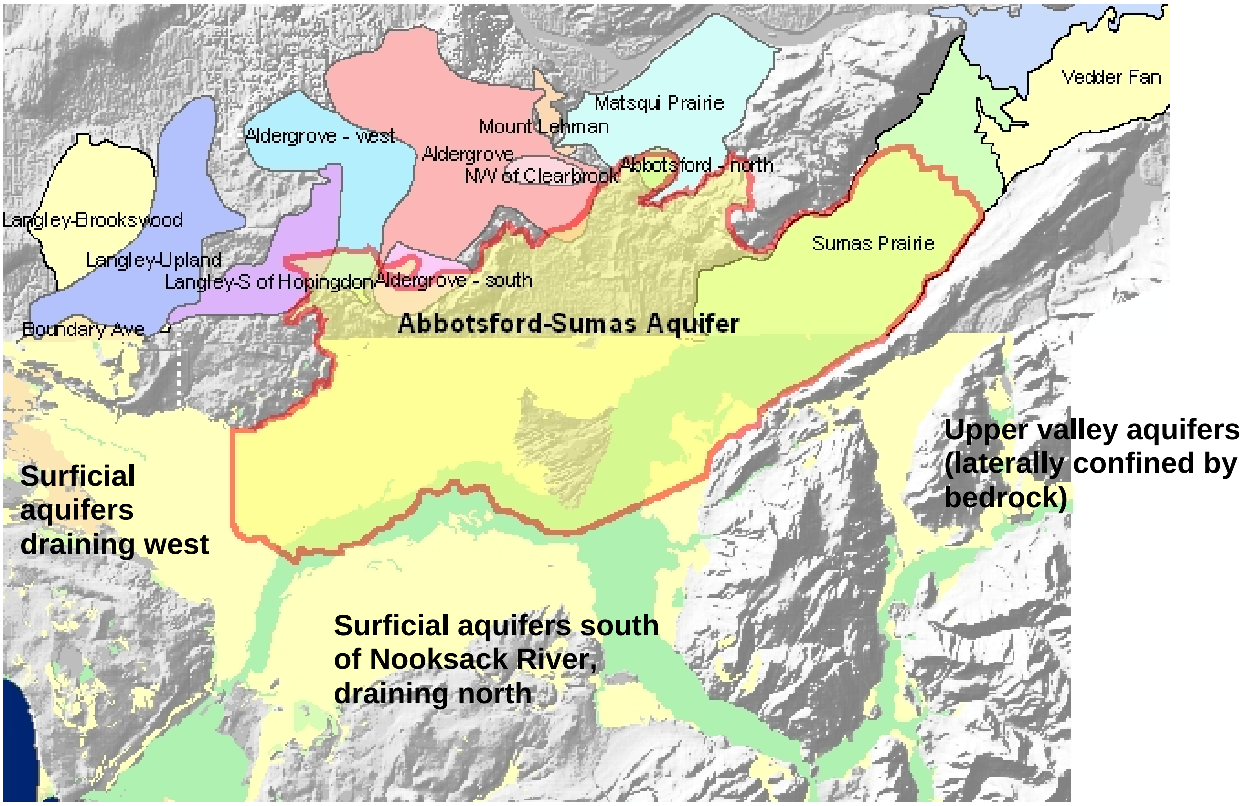
There are numerous smaller aquifers adjacent to the Abbotsford-Sumas aquifer system (**Map 4**), which have been mapped by the BC Ministry of Water, Land and Air Protection (BC WLAP) and the United States Geological Survey (USGS). The most productive of these are the Brookswood aquifer (a delta) and the Vedder Fan aquifer (alluvial fan).

The Aldergrove aquifer is located party in a recharge area of the aquifer system, and is considered part of the Abbotsford-Sumas aquifer. The larger Abbotsford-Sumas aquifer was defined in this study by hydraulic connectiveness, and groundwater flow pathways from recharge areas in the uplands to discharge areas in the lowlands. The uplands south of Nooksack River are composed of similar sediments as the larger aquifer, but they drain a relatively small area and discharge to the Nooksack River, and thus, are not linked to Abbotsford-Sumas aquifer; although they form a continuum of surficial aquifers in these valleys and differ only in groundwater flow directions. The Abbotsford-Sumas aquifer could also be extended to Blaine, WA, to the west, but the recharge areas for that aquifer are in Langley uplands, which have west and south drainages, and are hydraulically distinct from the aquifer draining the Abbotsford uplands.

At northeast end of Sumas Valley, the town of Chilliwack taps into the Vedder Fan aquifer, but the Sumas Prairie area is less permeable, owing to lacustrine deposits and rather thin underlying sands and gravels. However, the aquifer thickens rapidly to the southwest along Sumas Valley, and the southwest portion of Sumas Prairie is highly connected to the Abbotsford aquifer and is very productive along the edge of Abbotsford uplands, below scarps, where major production wells for the City of Abbotsford are located.

The groundwater flow model area was extended to include the unconfined aquifers south of the Nooksack River, in order to better define deeper regional flow patterns. The model also extends to edges of the Vedder Fan aquifer and Brookswood aquifer, although the model has much lower spatial resolution on the edges than in central areas – this model should not be considered as a model of the Brookswood aquifer. The upper valley aquifers were not included in this study because of their confinement by bedrock slopes and disconnection from valley aquifers. Vertically, the model includes all known sediments down to the bedrock surface, although model resolution decreases with depth due to lack of data.

Map 4 Outlines of surficial aquifers of central Fraser Valley, merged with USGS map of surficial aquifers in WA state. The approximate extent of the Abbotsford-Sumas aquifer was defined by groundwater pathways and connection of recharge to discharge areas.



1.4. STUDY OBJECTIVES

The main objective of this study was to develop a three-dimensional groundwater flow model for the Abbotsford-Sumas aquifer. Development of this model would enable more detailed modeling studies to be undertaken by providing 1) a regional context for groundwater flow, 2) establishing boundary conditions at a regional scale that could be used in smaller scale models, 3) the geological framework for nitrate transport modeling, and 4) a base model for climate change impact studies on groundwater in the region. Development of the flow model requires the following:

1. Review and compilation of all available information about Quaternary geology, hydrogeology, hydrology, and climate of the central Fraser Valley.
2. Organization of information into digital databases, and in particular spatial databases using GIS (this includes standardization of borehole lithology datasets, and correcting errors in existing spatial data).
3. Development of 3D hydrostratigraphic model of the area, mostly from 2500 to 4000 water well records that contain borehole lithologs, but also from limited geophysical

studies, previous models and interpretations, and maps.

4. Downscaling of historic (and future) climate predictions from CGCM (Canadian General Circulation Model), and computation of recharge to aquifer on monthly time steps.
5. Preparation of surface water elevation and drainage network datasets, and input of these in the flow model.
6. Construction of a numerical groundwater flow model in MODFLOW and calibration to steady-state conditions using the historical climate predictions.

The study is tied to M.Sc. research by J. Scibek at Simon Fraser University (SFU) in which the Abbotsford-Sumas aquifer is used as a repeat case study "experiment" for linking climate change predictions to groundwater flow models and quantifying the potential impacts on water supply, flow directions, well capture zones. The Abbotsford-Sumas aquifer (described in this report) is the second and larger regional aquifer under study; the other is the Grand Forks aquifer in south-central BC. In association with the climate impacts study (described elsewhere), a transient model was constructed to simulate the impact of future climate change scenarios on groundwater resources. The results of that work are compared to the results of the previous climate change impacts study in Grand Forks.

The model of the Abbotsford-Sumas aquifer will also be used in two ongoing research projects at SFU to examine issues related to nitrate transport in the aquifer. One study centers around defining permeable pathways for nitrate transport at a small scale (using geophysical techniques tied to borehole lithology logs) and making inferences on the role of permeable pathways in nitrate contamination data. The second is a regional study of nitrate transport, which will examine the transport and fate of nitrate from agriculture land use practices at a regional scale.

1.5. OUTLINE OF THE REPORT

- Section 1 Introduction

This section provides background information, and defines the study area and study objectives.

- Section 2: Geologic Setting

This section provides a detailed discussion of Tertiary bedrock surface model, Quaternary geologic history, known stratigraphic units, and a review of our understanding of hydrogeology of this area. Most of the background information presented in this section is derived from a careful review of all published work, perhaps omitting some finer points of Quaternary geology (timing of deglaciations and ages of landforms, which are still under dispute), but does include consideration of depositional environments. Only the Pleistocene sediments above Tertiary bedrock are considered in this study. New and unpublished results include the most complete Tertiary bedrock surface in central Fraser Valley, compiled from all previous published and some unpublished data, valley wall projections, all available borehole lithologs, and a geostatistical surface model.

- Section 3 Hydrostratigraphic Model

This section describes the aquifer architecture and the methodologies used to define the hydrostratigraphy of the aquifer. The hydrostratigrapic model for the aquifer is developed from available litholog data, which have been standardized and mapped at high resolution (from a regional groundwater model perspective).

- Sections 4 Surface Hydrology

The locations of streams, rivers, lakes, and ephemeral streams, as well as the water table elevation and surface water levels are defined in this section.

- Section 5 Numerical Model Description

This section provides a summary of the model design, including layering, boundary conditions (rivers, recharge, and pumping wells), and model run parameters.

- Section 6 Model Calibration

This section describes the calibration methodology and calibration results.

- Section 7 Model Results

The model results are summarized in this section.

- Section 9 Conclusions

This section offers some conclusions of the study.

1.6. ACKNOWLEDGEMENTS

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Thanks to Matt Plotnikoff at SFU for helping with intermittent computer problems, undergraduate student Dejan Milidragovic who helped compile pumping test data and litholog data for Washington State.

The authors also wish to thank Aparna Desphande (M.Sc., SFU) for her contributions to the development of the hydrostratigraphic model, and Dr Nadine Schuurman at SFU who provided interesting discussions about litholog standardization and GIS.

2. GEOLOGIC SETTING

2.1. BEDROCK SURFACE

The lower Fraser Valley and northern Puget Lowland is underlain by sedimentary rocks that were deposited within the Tertiary Georgia Basin. This old basin is flanked by the Coast Mountains and the Cascade Mountains, and is underlain by basement rocks. The Coast Mountains consist largely of granitic plutonic rocks (granodiorite, quartz diorite, diorite, schists and gneisses). The Cascade Mountains are composed of granite, andesite, basalt, quartzite, chert, and graywacke. The deep basement rocks are Jurrasic to Early Cretaceous Coast Belt granitic intrusives and volcaniclastics (Monger, 1990).

The Tertiary sequence of rocks is dominated by sandstones in excess of 1500 m thick. The Paleogene Huntingdon Formation is a succession of fluvial sandstone, pebble conglomerate and mudstone preserved in southwest British Columbia, Canada (Gilley and Mustard, 2003; Mustard and Rouse, 1994). It is correlative with, and continuous in the subsurface to, the Chuckanut Formation in northwest Washington State. The Huntington Formation is exposed at Sumas Mountain north of Abbotsford, BC. The Tertiary surface is buried beneath a thick Pleistocene sediment fill that masks most of the bedrock topography (Clague, 1994). Small grabens and half grabens at high angles to master faults are typical of pull-apart basins, and the Sumas Valley is most likely one such graben structure (Mustard and Rouse, 1994; Mustard, pers comm). The Sumas Valley is bounded by concealed northeast-trending structures, named the Vedder and Sumas faults, between which Paleogene clastic rocks are downdropped to form a graben block (Monger, 1991). These main faults are either projected from surface traces or known from petroleum exploration seismic lines.

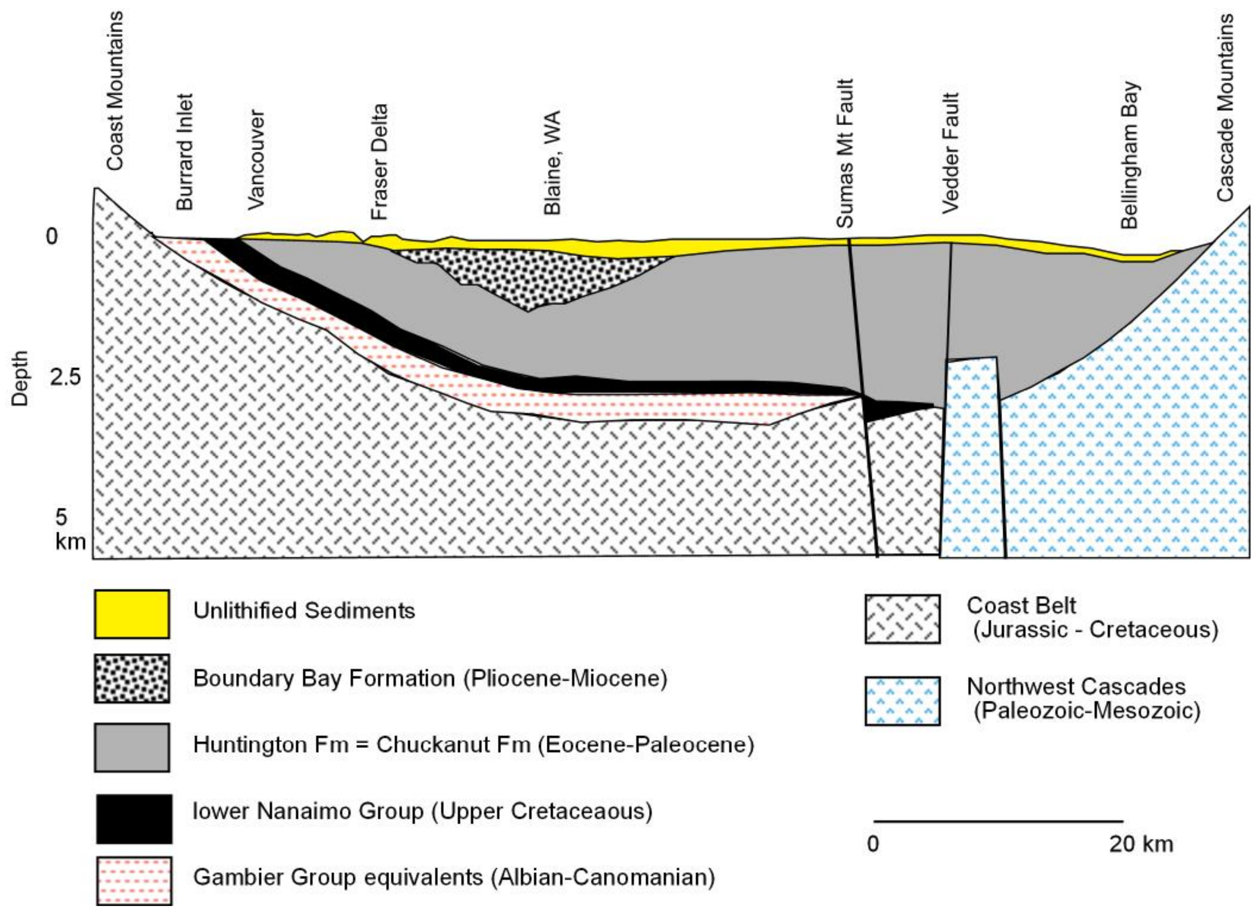
Porosity of the Tertiary bedrock varies from poor to good, and ranges from 7% to 15% (Quigley (1968; Gordy, 1988). The Tertiary sedimentary formations exposed in the foothills of the highlands carry small quantities of fresh ground water in few places where pore space permits (Cox and Kahle, 1999). Consequently, the Tertiary bedrock can be considered an aquitard relative to the overlying Quaternary sediments.

2.1.1. TERTIARY BEDROCK SURFACE MODEL

During Pleistocene time as much as 800 m of Tertiary deposits were eroded on the north side of the Georgia Basin, leaving a highly irregular surface, which has subsequently been covered by up to 610 m of Pleistocene glacial and recent deposits (Easterbrook, 1969). Contact between the Paleogene-Neogene succession and Quaternary deposits is a profound unconformity, manifested as a high relief erosion surface (see Hamilton and Ricketts, 1994; Britton et al., 1995; Ricketts, 1997). The unconformity is exposed well above sea level (e.g., along the north shore of Fraser River), and plunges to depths of 700 m and greater below sea level beneath the Fraser River delta and Lowland. Closely spaced, deep reflection seismic profiles on the Fraser River Delta allow for detailed reconstruction of this surface. Paleoslopes are as high as 10° near Sumas Mountain and Point Roberts areas. Some paleovalleys on the sub-Pleistocene surface trend north-northeast and appear to be extensions of modern valleys in the coast mountains north of Fraser River (e.g., Indian Arm, Pitt Lake, Stave Lake), suggesting that the larger, modern drainage patterns are at least as old as early Pleistocene.

Information on the depth to bedrock is sparse, but available data imply that much of the area south of the North Arm of the Fraser River and west of New Westminster is underlain by 300-500 m of unconsolidated sediments (Hamilton and Ricketts, 1994). Near Abbotsford, BC there is about 300 to 500 m of Pleistocene sediment, which thins out near Sumas Mountain. Near Langley, BC, a bedrock high (elevation close to sea level) is encountered at a depth of approximately 100 m (Conoco-Dynamic Murray Creek borehole, 1993). Near Bellingham, WA, the bedrock protrudes through surrounding unconsolidated valley sediments to 170 m above sea level, but within several kilometers, the bedrock surface drops to over 50 m below sea level and is covered by 30 to 100 m of unconsolidated Pleistocene materials. The bedrock surface is even lower toward the north, lower than 220 m below sea level near Blaine, WA, and at least 170 m below sea level near Ferndale, WA, south of Langley, BC. **Figure 1** shows an east-west cross section through the Georgia Basin (looking south).

Figure 1 Stratigraphic cross-section of Georgia Basin from Burrard Inlet, NW of Vancouver, BC, to Bellingham, WA. From Mustard and Rouse (1994), with permission (modified sketch map and scale approximate with at least 4x vertical exaggeration).



Mustard and Rouse (1994) give locations and descriptions of deep oil and gas exploration wells in the Fraser Lowland. However, Glover (1935) stated "it is difficult to decide from these logs just where the bottom of the Pleistocene deposits lies." Between Bellingham and Ferndale, thicknesses are 99 m, 119 m, 85 m, and 61 m. Northwest of Ferndale, the cover is much thicker (as much as 181 m and 187 m). Near Birch Bay, the overburden is probably less than

61m thick (Glover, 1935).

Ramsay (1973) described the Canadian oil and gas holes in Fraser Valley, and included geophysical surveys in Abbotsford area. Richfield Oil Corporation had a seismic survey run in 1960 from Abbotsford to Point Roberts (Grinsfalder, 1960) and drilled three deep wells. The E-W cross-section runs 2 km north and parallel to the Canada-US border, and shows a 200 to 500 m thick Pleistocene unit with gentle sloping topography, thickening near Abbotsford and pinching out toward Sumas Mountain. The Tertiary rocks thicken to the west and cover the basement, which itself is undulating and slopes down to the west (**Figure 1**). In the Fraser Valley, from Point Roberts to Abbotsford, the great thickness of Pleistocene deposits overlying the Tertiary bedrock presents a problem in seismic interpretations, and the boundary between Pleistocene and Tertiary deposits was not mapped accurately, except for "phantom" horizons within them (Ramsay, 1973).

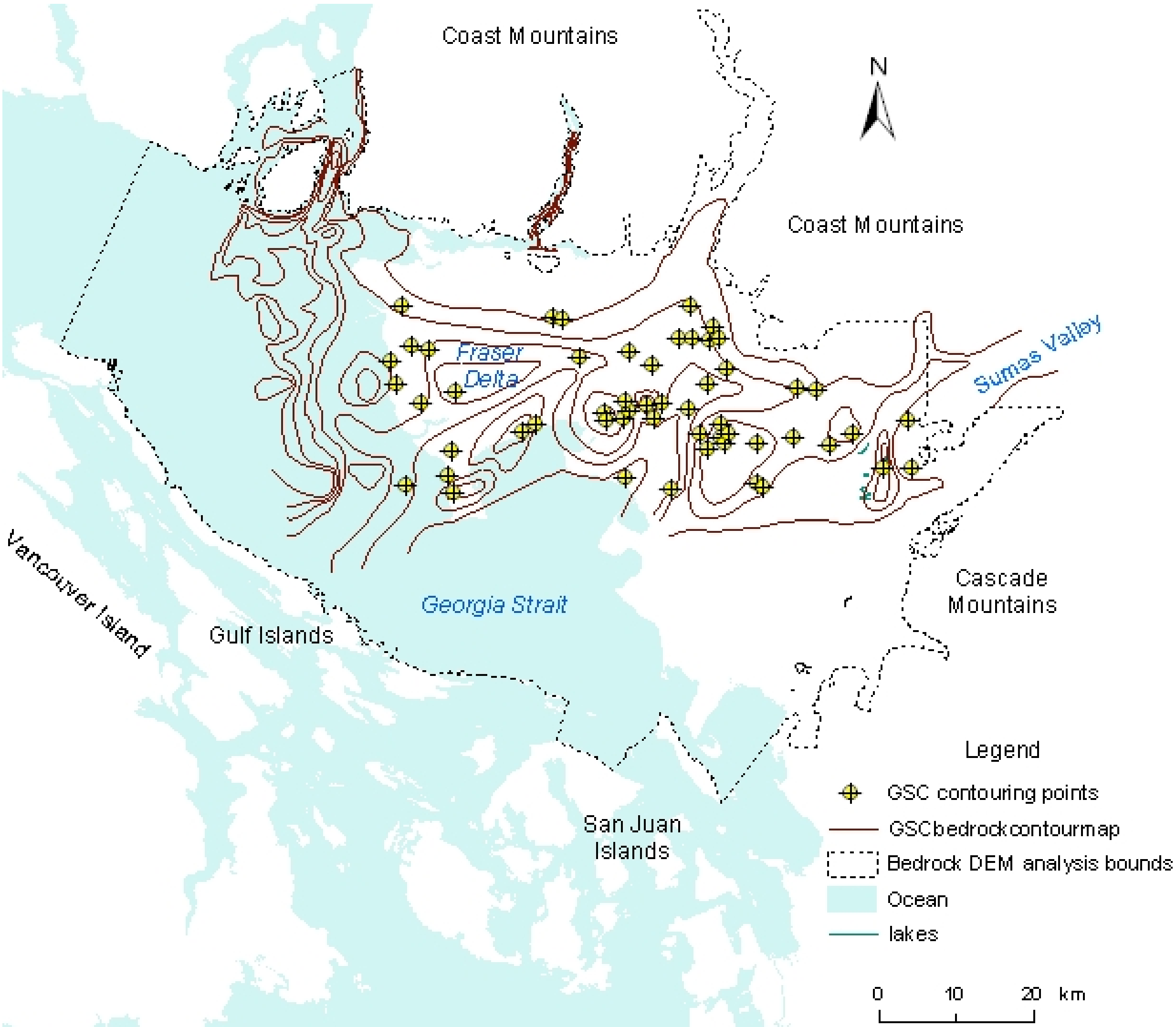
In 1994, Hamilton and Ricketts published a map of Tertiary bedrock surface under the Fraser Valley and Georgia Basin, using data sources from seismic surveys for offshore part of Georgia Basin, and borehole logs for the land areas (**Map 5**). Hamilton and Ricketts (1994) discussed the data sources in detail. The authors commented that seismic data were difficult to obtain (proprietary access) and data were in raw format, with different depths of penetration. The on-shore portion of the map was intended only as a guide to more site-specific studies.

A digital Tertiary bedrock topographic map was generated as part of this study using deep borehole data, existing bedrock contour maps (Hamilton and Ricketts, 1994), valley wall profiles, and extrapolated cross-sections through the study area. Using the Hamilton and Ricketts map as a base, the bedrock surface was further defined by using deep groundwater well lithologs, some of which penetrate the bedrock. **Map 6** shows a contour map of Tertiary bedrock and bedrock control points in Fraser Valley and in Strait of Georgia. The inset map includes bathymetric data off the Gulf and San Juan Islands plus bedrock valley walls at ground surface, all converted to data points for surface interpolation.

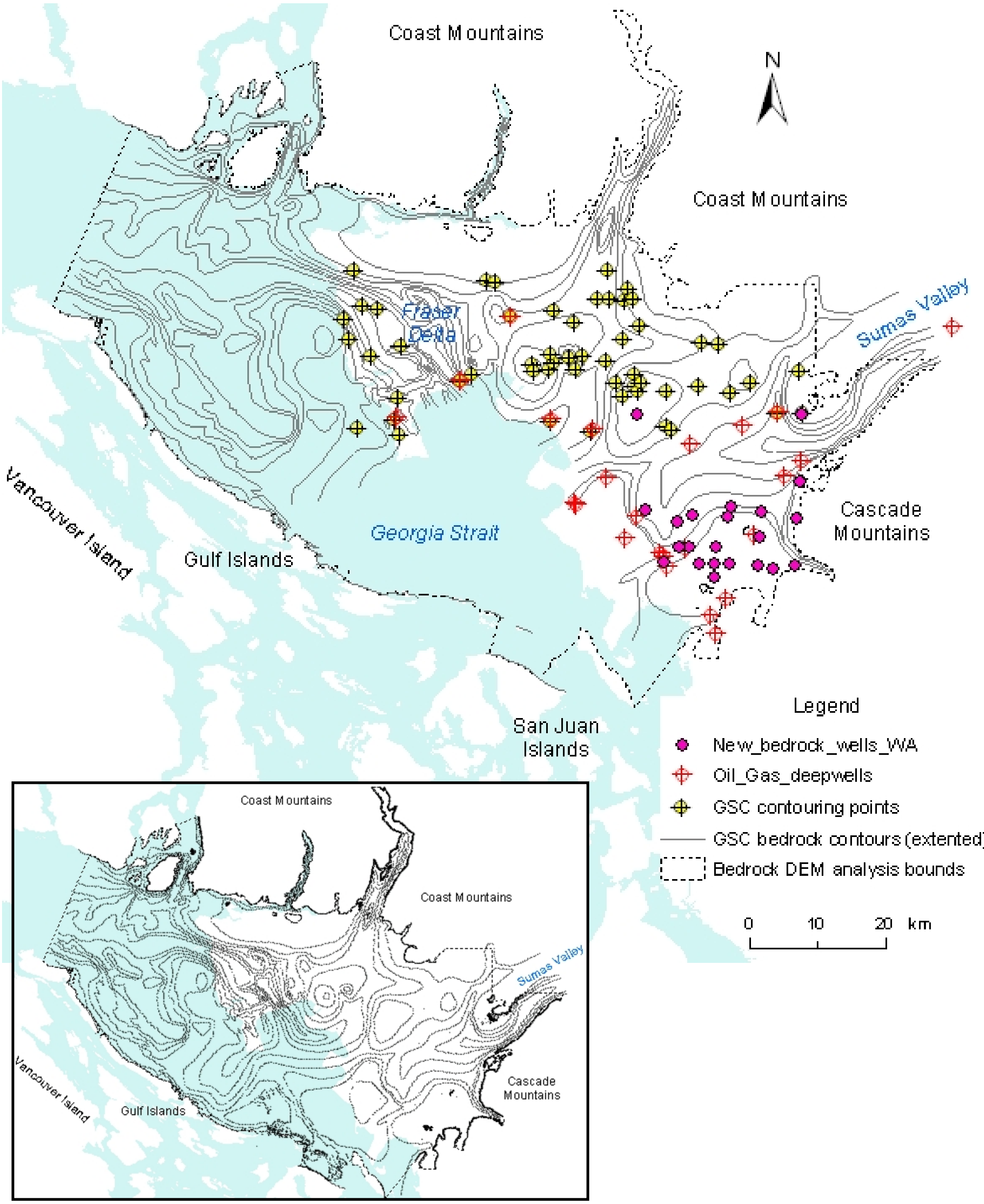
A series of bedrock profiles were then constructed (**Map 7**). Most in-filled valleys in BC have very steep valley walls, have deep sediment fill deposited in glaciofluvial and glaciolacustrine environments during the last glaciation (Clague, 1981; Fulton, 1984; Ryder et al., 1991), and have been modified by glacial erosion. The valley shape, which was carved out by ice flow, can be described by nearly-parabolic curves (Graf, 1970; Wheeler, 1984; Hirano and Aruya, 1988) fitted to valley profiles. The projections of valley walls downward into the Quaternary sediments help in generating a realistic bedrock surface, especially in narrow Sumas Valley (see **Map 7**). Outside of Sumas Valley, bedrock profiles helped in early visualization of the surface, and were used to create additional points for the interpolation of smooth bedrock surface (note: the Kriging method usually requires relatively uniform point density to produce reasonable results. It is not influenced too much by any one side of the valley bedrock outcrops). In the Sumas Valley, the bedrock profiles extrapolated downward from valley walls, intercepting deep wells where possible, and using parabolic shapes for bottom of the valley trough.

Map 8 shows the Interpolated Tertiary bedrock surface in central Fraser Valley and Sumas Valley. **Map 9** shows the Tertiary bedrock surface beneath the Abbotsford-Sumas study area.

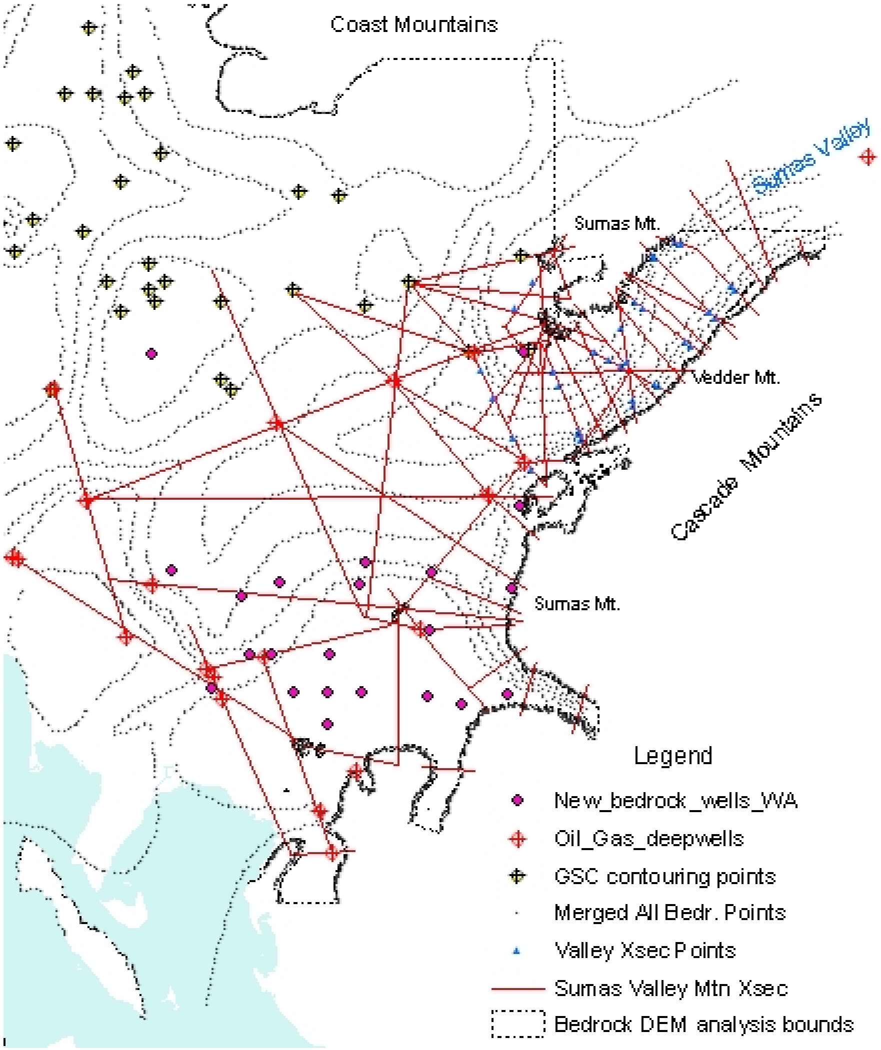
Map 5 Contours of Tertiary bedrock surface and control points used by Hamilton and Ricketts 1994).



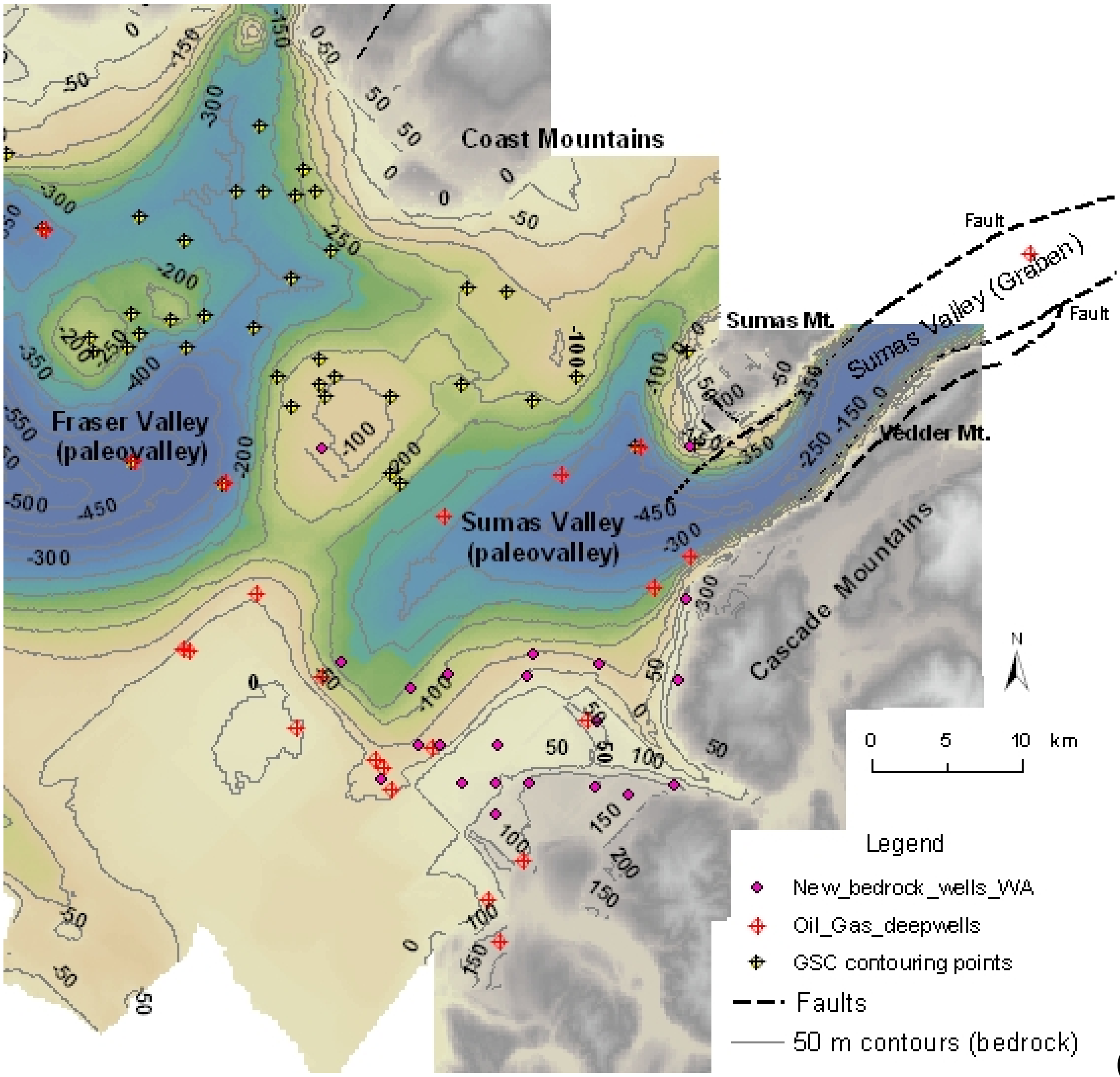
Map 6 Extended contours of Tertiary bedrock and control points in Fraser Valley and in Strait of Georgia; (Inset map) all contours and control points plus bathymetric data off Gulf and San Juan Islands plus bedrock valley walls at ground surface, all converted to data points for surface interpolation.



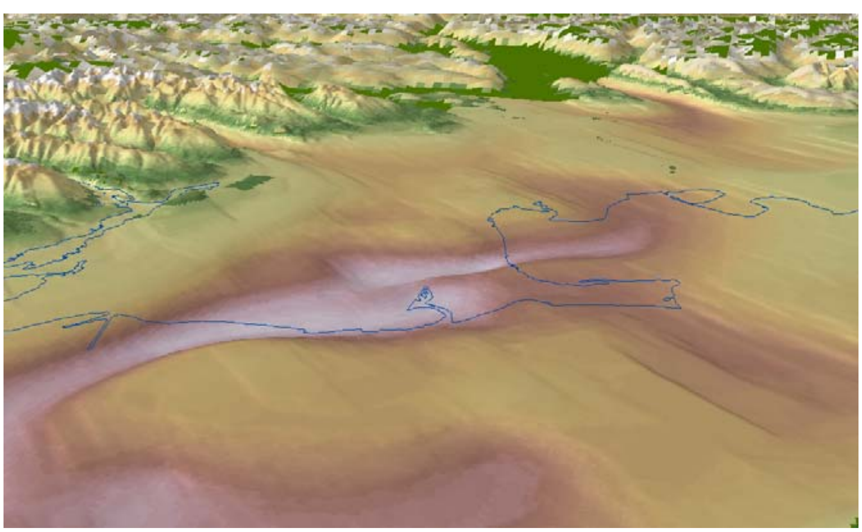
Map 7 Valley profiles (cross-sections) in Sumas Valley and control points for Tertiary bedrock surface.



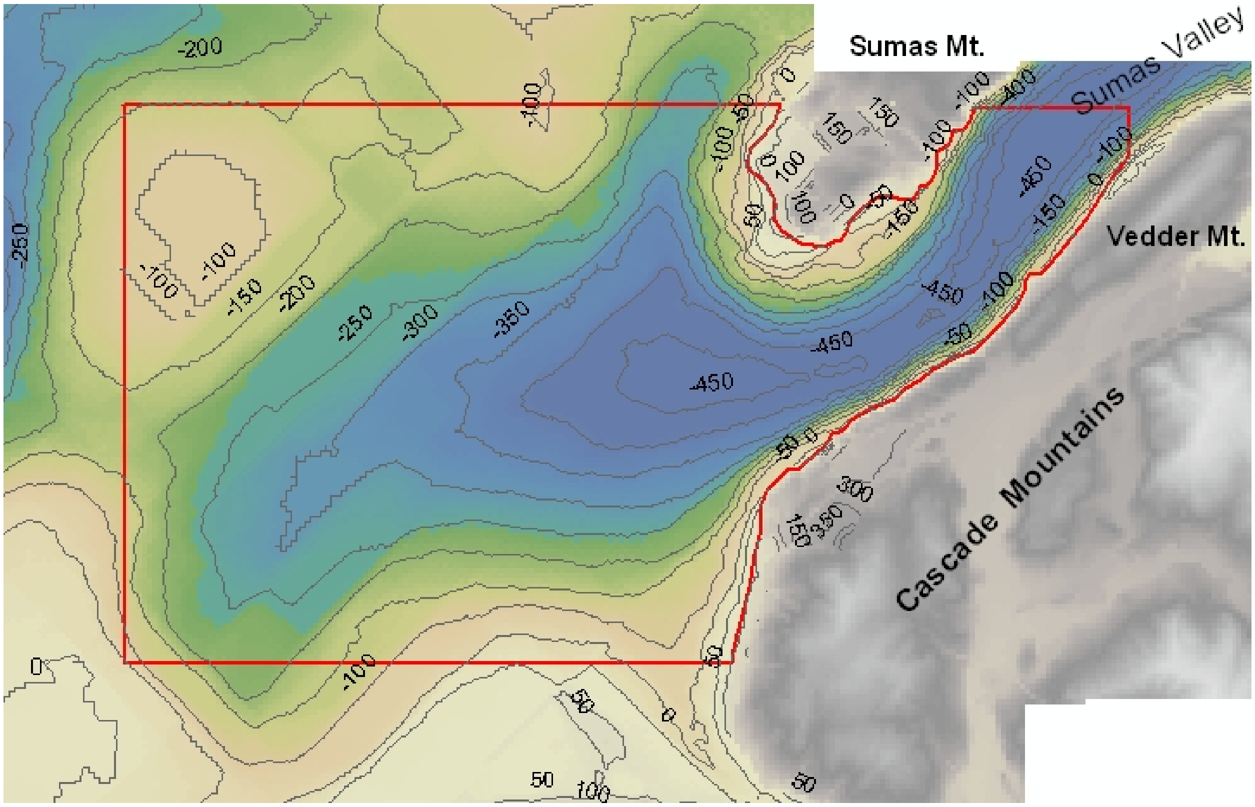
Map 8 Interpolated Tertiary bedrock surface in central Fraser Valley and Sumas Valley: (a) filled contours and control points, (b) overview of paleovalleys in Fraser Valley



(a)


(b)

Map 9 Tertiary bedrock surface under Abbotsford-Sumas model area.



2.2. QUATERNARY SEDIMENTS IN CENTRAL FRASER VALLEY (LOWLAND)

The Fraser Lowland consists of rolling hills of glacial drift, 60 to 120 m above broad valley floors. The floodplains are currently near sea level. There are several prominent bedrock outcrops, such as the Sumas and Vedder Mountains bordering the Sumas Valley. The valley fill consists of complex sequences of diamictons and stratified drift, in various associations with marine and deltaic sediments. The glacial drift deposits in the Fraser and Puget Lowlands were first investigated a century ago by Willis (1989). Easterbrook (1969) provided a history of surficial geologic investigations in this area. In the Fraser Valley, most of the surficial geologic mapping was done by the Geological Survey of Canada (GSC). Armstrong and Brown (1954) described and interpreted the glaciomarine stony clays and other sediments. Between 1957 and 1960 Armstrong produced a series of surficial geologic maps, which are still in use today. A paper by Armstrong (1981) reviewed the Quaternary geology of the Fraser Valley, redefined stratigraphic units, and summarized the chronology of deposition.

In adjacent Whatcom County of Washington State, most of the early and comprehensive Quaternary geologic work was done by Easterbrook (1963; 1965; 1969), who produced a map of surficial geology of the area, and defined the various sediments and glacial events. There have been numerous revisions of terminology and chronology over the years. Matthews et al. (1970) studied sea level changes and crustal movements of the Fraser lowland. In the 1980s, Clague (1980) and Thorson (1980) published more detailed chronology of glacial sediments using carbon dating. The discussion of glacial event chronology has continued until the present, with work by Clague et al. (1997), and Kovanen and Easterbrook (2002).

In the 1990's, continuing the early work of Halstead (1977), the GSC completed numerous hydrogeologic and geotechnical investigations of the Fraser Delta and other parts of the lowland (Ricketts and Liebscher, 1994; Clague et al., 1998; Ricketts, 1998; Hunter et al., 1998), which contributed to high-resolution stratigraphic and hydrogeologic models of the Fraser Valley. Similar work has been carried out in Washington State, notably by Kahle (1991), Jones (1999) at the United States Geological Survey (USGS), Cox and Kahle (1999), and numerous other regional studies or local groundwater investigations (Gibbons and Culhane, 1994; Golder Associates, 1995; Mitchell et al., 2000; Piteau Associates, 1991; 2002).

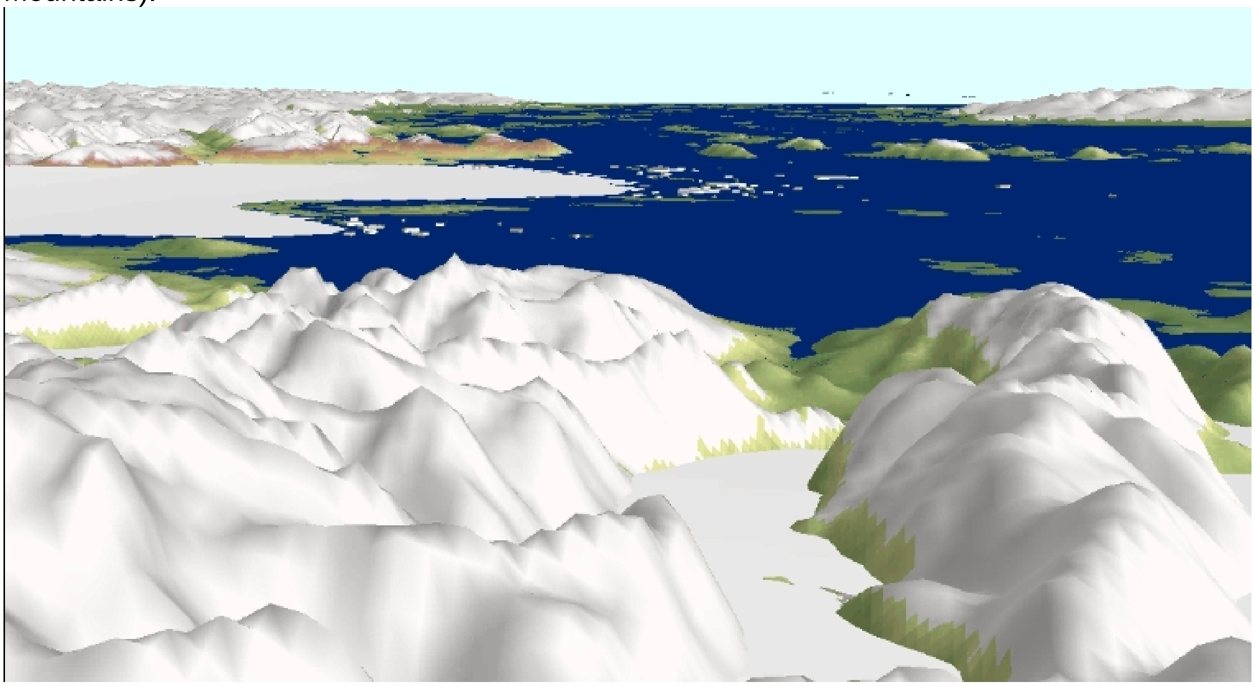
2.2.1. DEPOSITIONAL ENVIRONMENTS AND CHRONOLOGY

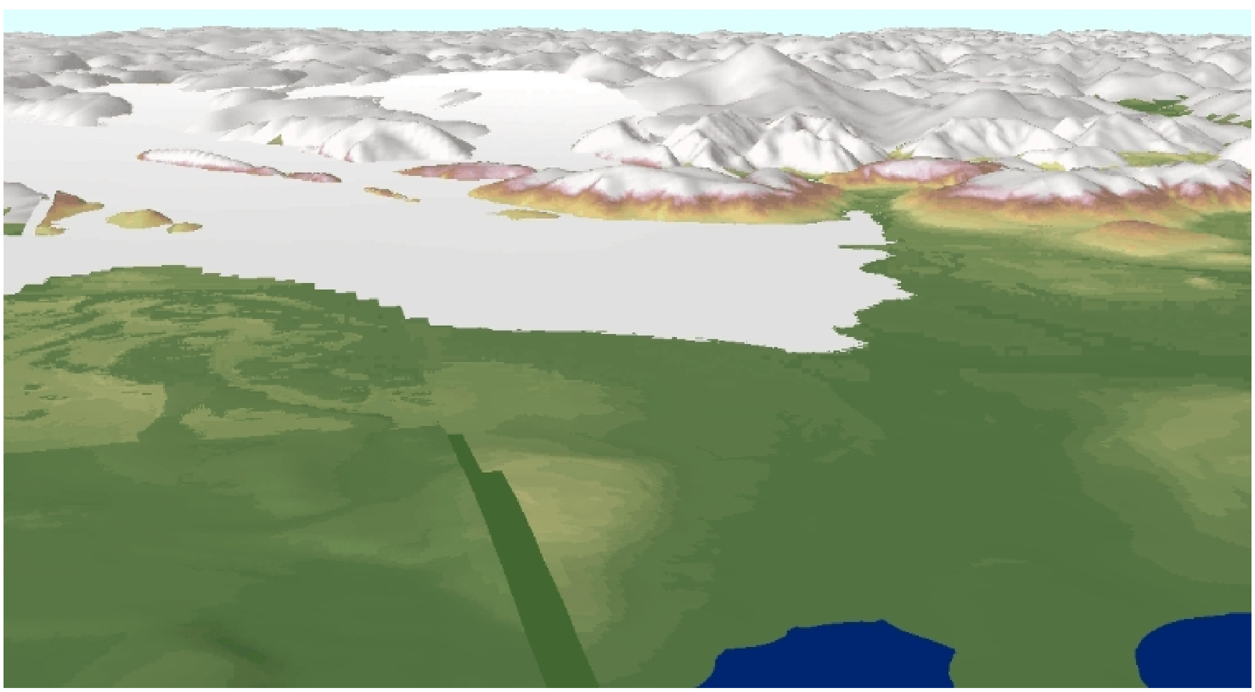
The Quaternary sediments in the Fraser Valley had a complex depositional history during the Wisconsin glaciation of the Pleistocene period, during which the lowland experienced repeated glacial and interglacial events, as described in detail in review papers by Armstrong (1981), Clague (1991; 1994), and others. Between 19 and 30 ka BP, there was a long period of montaine glaciation (Clague, 1981), also named the Olympia Interglaciation (Armstrong et al., 1965), when non-glacial gravels and sands covered the landscape just above the Tertiary bedrock surface. However, most of the glacial valley fill was laid down during the last major glaciation, termed the Fraser Glaciation (Armstrong et al., 1965), which spans from 19 to 10 ka BP. Glacial ice originated from the Cordilleran Ice Sheet, which flowed initially as piedmont glaciers, then coalesced into larger ice sheet (Clague and James, 2002) and a attained maximum thickness of up to 2000 m (Fulton, 1991). Ice covered the Fraser Valley by 18 ka BP and extended as far south into the Puget Lowland as Olympia, WA (Thorson, 1980) by about 15 ka BP. The early radiocarbon dating and chronology of the Fraser Lowland in British Columbia and Whatcom County in WA has been done by Armstrong et al. (1965) and Easterbrook (1969). Further radiocarbon work has been carried out in the Fraser Valley by Clague et al. (1980) and Clague (1981). The maximum glacial ice sheet advance corresponds to the Vashon Stade, which Armstrong et al. (1965) defined as the last major climatic episode during which glacial drift, the Vashon Drift, was deposited by continental ice, until sea transgression at 13 ka BP and deposition of marine and glaciomarine sediments (Armstrong, 1981).

During the rapid deglaciation of the Puget and Fraser Lowlands at the end of Fraser Glaciation, the glacial meltwater sediment flux and glacial ice meltout at the ice margin caused deposition of glaciomarine sediments in isostatically depressed lowlands below 200 m elevation (Armstrong, 1981). Glacier ice did not cover the lowlands, but floating ice and icebergs probably calved off the glacier fronts and carried fine and coarse (e.g., dropstones) debris offshore. The time of retreat of the Vashon ice is called the Everson Interstade (named after the town Everson in Nooksack Valley), as proposed by Easterbrook in Armstrong et al. (1965). These glaciomarine deposits were named Capilano Sediments and Fort Langley Formation (Armstrong, 1981) in the Canadian part of Fraser Lowland. The same sediments were named Everson Glaciomarine Drift, which also include some glaciofluvial sediments, by Easterbrook (1969).

The Everson Interstade ended when the ice re-advanced briefly into parts of the Fraser Lowland. This episode is called the Sumas Stade. The Sumas ice advanced from an unknown position into parts of the central Fraser Lowland, which had been inundated by the pre-Sumas marine submergence (Mathews et al., 1970). Sumas Drift was deposited up to 120 m elevation. Large outwash plains and kame terraces were created by glacial meltwaters (Easterbrook, 1969; Armstrong, 1981).

Map 10 Rendition of depositional environments in central Fraser Valley. (a) raised sea level and receding ice sheet 10 ky BP (view South toward Puget Sound and Gulf Islands – Coast Mountains in the foreground), (b) receding Sumas ice lobe, which blocked Sumas Valley and Abbotsford outwash plain formation (view South-East on Sumas Valley and Cascade Mountains).





3D rendering - the surface DEM has been spliced from various sources and contains "holes", shown by dark uniform shapes on the map

2.2.2. LITHOSTRATIGRAPHIC UNITS (BASED ON CHRONOSTRATIGRAPHIC UNITS) EXPECTED FROM QUATERNARY GEOLOGY

The glacial sediments are very complex in the Fraser Lowland. The lithostratigraphic units are approximately equivalent to the chronostratigraphic units as described in the Quaternary history of the area. The stratigraphic units are (from bottom to top):

1) Bedrock (sandstone, conglomerate, mudstone), Eocene and Miocene, relatively low permeability
2) Early Pleistocene outwash (sands and gravels above bedrock), water bearing: thickness < 5 m
3) Vashon Drift (diamictons and interbedded glaciofluvial deposits): thickness 1 to 15 m
4) Capilano Sediments and Fort Langley / Everson glaciomarine drift (stony clays, thin ice-contact and beach deposits near ground surface): thickness 0 to 150 m
5) Sumas Drift (diamictons, thick glaciofluvial sands and gravels, lenses of till); includes Abbotsford Outwash: thickness up to 60 m
6) Holocene floodplain silts (discontinuous confining unit): thickness usually < 5 m

The stratigraphic units most commonly referred to in this report accumulated during the Late Wisconsinan Fraser Glaciation, although early Pleistocene and possible late Neogene deposits (Clague, 1991) occur deeper within the succession. In fact, most of Fraser Lowland is underlain by the latest Wisconsinan Capilano Formation, Fort Langley Formation and Sumas Drift, and the Fraser River delta by Post Glacial deposits including modern delta and fluvial sediments. Vashon Drift and older units underlie upland areas around Vancouver, Surrey, White Rock and Tsawwassen) and are exposed in cliffs and bluffs (e.g., Quadra Sand - Clague, 1977).

VASHON DRIFT

There are older glacial and interglacial sediments found in several deep borehole records, in addition to pre-Wisconsin glacial tills, clays, outwash sands and gravels, and overlying sediments containing peat and plant remains, which represent the pre-Wisconsin interglacial time (Armstrong and Brown, 1954). During the Wisconsin, glacial tills and stratified drift were deposited to a maximum thickness of 140 m. The tills contain hard, compact mixtures of clay, silt, sand, and stones. The tills originally blanketed the uplands.

The Vashon Drift was deposited during the maximum ice advance of the Fraser Glaciation 14-18 ka (Clague, 1994). The unit is complex, in places including up to three diamictons and interbedded glaciofluvial deposits (Armstrong, 1984). Aprons of thick, well-sorted Quadra Sands were deposited in front of the advancing glaciers during the early stages of the Fraser Glaciation (Clague, 1994). Beneath these sediments lies the Cowichan Head Formation, deposited during the Middle Wisconsinan Olympia nonglacial interval, which is composed of gravel, sand, silt and peat deposited in fluvial, estuarine and marine environments (Armstrong and Clague, 1977).

Information regarding older Pleistocene stratigraphy is limited, but the sediments are interpreted to represent the deposits related to two other glaciations (Semiahmoo and Westlynn Drifts) and an intervening nonglacial period (Highbury Sediments) (Armstrong, 1984; Clague, 1994).

CAPILANO SEDIMENTS

Capilano Sediments consist of glaciomarine sediments deposited beyond the retreating ice margin 10-13 ka (Clague, 1994). In the Nicomekl River valley (west of Langley uplands), these sediments were deposited in what was an arm of the sea during the late Wisconsinan; today the valley is underlain by thick (<300 m) sequences of marine silt, clay and fine sand (Armstrong, 1984). In contrast, the upland areas to the south are covered by thin, discontinuous deposits of sandier Capilano Sediments overlying Vashon Drift.

FORT LANGLEY FORMATION / EVERSON GLACIOMARINE DRIFT

The late Wisconsin marine drift was first described in detail by Armstrong and Brown (1954), who also described the Pleistocene geology of the Fraser Valley. These sediments were deposited following the maximum advance of the last Cordilleran ice sheet (Fraser Glaciation), when isostatically depressed land (about 230 m below present elevations) was inundated by sea water. The original ground surface was covered with sands and gravels (not till) in the central and eastern Fraser Valley. At that time, fossiliferous stony clays, marine clays, minor silts and sands, and minor beach gravels with littoral sands (only few meters thick at most) were deposited (Armstrong and Brown, 1954). These stony silty clays are best exposed in the uplands of Langley area, and thicken eastward to maximum 150 m thickness. The normal marine clays grade into the fossiliferous stony clays. Armstrong and Brown (1954) proposed several mechanisms of deposition, but noted that not one simple process was at work. Most probably the stony clays were formed beneath an ice shelf during retreat stage, but also berg ice and sea ice. As the land rebounded isostatically, the exposed till and marine drift were eroded by waves and currents, and redeposited as turbidites or landslides. These deposits are related to the terraced upland topography. Beach deposits are also common there.

The Fort Langley Formation (approximately time-equivalent to the Capilano Sediments) is a diverse unit composed of interbedded glaciomarine and glacial sediments deposited in an area of fluctuating ice margins (Clague, 1994), and may include diamicton as well as glaciofluvial and ice-contact deposits (Armstrong, 1984). Fort Langley sediments range in thickness from 30 m to >165 m (Armstrong, 1984). The slightly younger till and glaciofluvial gravel of the Sumas Drift (e.g., Brookswood aquifer) were deposited during a minor readvance of the retreating Fraser Glacier in the eastern Fraser Lowland (Clague, 1994).

SUMAS DRIFT

Sumas Drift forms the unconfined Abbotsford-Sumas Aquifer. It is found in northern Whatcom County, around Abbotsford in BC, and less extensively in the central Fraser Valley west of Abbotsford. Sumas Drift consists of diamictons (lodgement and flow tills), thick and well-sorted glaciofluvial outwash sands and gravels (advance and recessional), glaciolacustrine sediments, and ice-contact sediments deposited during the Sumas Stade (Armstrong et al., 1965). It also contains lenses of till. In the Fraser Lowland, the Sumas Drift directly overlies the undulating surface of stony silty clays of the Fort Langley / Everson glaciomarine drift, and underlies the Salish Sediments. The Sumas Drift differs from the glaciomarine deposits in that it is more highly compacted, has a higher pebble and cobble content, a higher sand content, and an absence of shells. It extends a few kilometers south of the Canada-US border and is mostly found near Abbotsford, where it overlies the Fort Langley Formation. The ice contact deposits consist of poorly sorted gravel and sand with large boulders.

Abbotsford outwash is part of Sumas Drift sediments, and forms the thickest and uppermost layer of the Abbotsford-Sumas Aquifer. An outwash terrace, also described as kame terrace

(Mathews et al., 1970), slopes southward across the international boundary from a ridge of ice-contact deposits (Easterbrook, 1969). The terrace ends at Lynden, WA, above the Nooksack River valley and floodplain. The glaciofluvial Abbotsford outwash is composed of stratified sandy gravel, gravel and sand, mostly horizontally bedded with some cross-bedding, scour and fill, and foreset bedding (Easterbrook, 1969). The sediments fine to the south-west, grading from boulder-cobble gravel along international boundary to pebble gravel, then to sand near Lynden. South of the Nooksack River valley, there is much of recent alluvium and the Abbotsford outwash may or may not be present. The Lynden terrace is interrupted by the modern floodplain of the Nooksack River, but continues south of the river for several kilometres and terminates against highlands composed of Everson glaciomarine drift (Easterbrook, 1969). The outwash was deposited sub-aerially. A number of lakes and peat bogs occur in abandoned meltwater channels and kettles on the outwash terrace. The lakes include Abbotsford Lake, Laxton and Judson Lakes, Pangborn Lake and smaller ponds.

HOLOCENE FLUVIAL AND LACUSTRINE SEDIMENTS

To the west lies the Fraser Delta, which is dominated by Holocene delta plain sheet sands up to 216 m thick (Clague, 1983; Monahan et al, 1994). The Sumas Valley and Nooksack Valley are covered by Holocene silts and sands of fluvial origin, some of which form locally important confining units of the underlying aquifers.

2.2.3. SURFICIAL GEOLOGY OF CENTRAL FRASER VALLEY

This section includes surficial geology maps (digital format) compiled from all sources in Canada and US for the Fraser Valley, focusing on the groundwater flow model area of the Abbotsford-Sumas aquifer. Maps are subdivided into sections (**Map 11** to **Map 15**). Several tables list the descriptions of hydrostratigraphic units and surficial geologic units, and their correspondence between Canadian and US maps.

The Canadian surficial geology maps are based on GSC maps; some are in digital format and some were digitized during this project. These GSC (1980) maps are largely for the MISSION area, and mapping was done by Armstrong (1976 and prior investigations). The US surficial geology maps are from Washington State Department of Ecology (WA Ecology, 2004) and are based on Easterbrook (1976). **Map 11** presents the spliced-together surficial geology map of the Fraser Lowland. Note that not all units match exactly as there are more geologic units on Canadian maps than on US maps. **Table 1** lists the corresponding geologic units in the two countries, sorted by hydrostratigraphic unit as identified by Halstead (1986). This table was compiled by Golder (1995) in a site investigation report. The Canadian surficial geologic units and their descriptions are in **Table 2**, and the US surficial geologic units (in this study area here) are in **Table 3**. **Table 4** has all geologic units present in surficial geology maps in this study area.

As a result of different mapping standards, ages of maps, and accuracy of maps, in some areas near the Canada-US border, the geologic units did not overlap or continue across the border, so some generalization of units was required on part of authors of this report.

Sumas Drift and Fort Langley Formation (also known as Everson Glaciomarine Drift or stony clays) are the most extensive geologic units in this study area. Generally, Fort Langley Formation is present in the west and northwest part of the model area, and also underlies the Sumas Drift at depth (see section on hydrostratigraphy in this report). Sumas Drift consists of many sandy and gravelly sediments, which locally include large lenses of flow till and other till types (till being rich in silt and clay, but otherwise similar in sand and gravel content to surrounding drift sediments). The surficial aquifers roughly follow the extent of Sumas Drift. In the Abbotsford area, the Sumas Drift is known as Abbotsford outwash which is most coarse grained and forms major aquifer in that area.

Bedrock outcrops of Tertiary sedimentary and volcanic rocks outcrop in the eastern portions of the study area (e.g., Sumas Mountain in BC). Small pockets of peat are present with association of kettle lakes and stream channels and other depressions in the Sumas Drift.

Map 11 Surficial Geology of selected portion of Fraser Valley, merged from BC and WA geology maps and generalized.

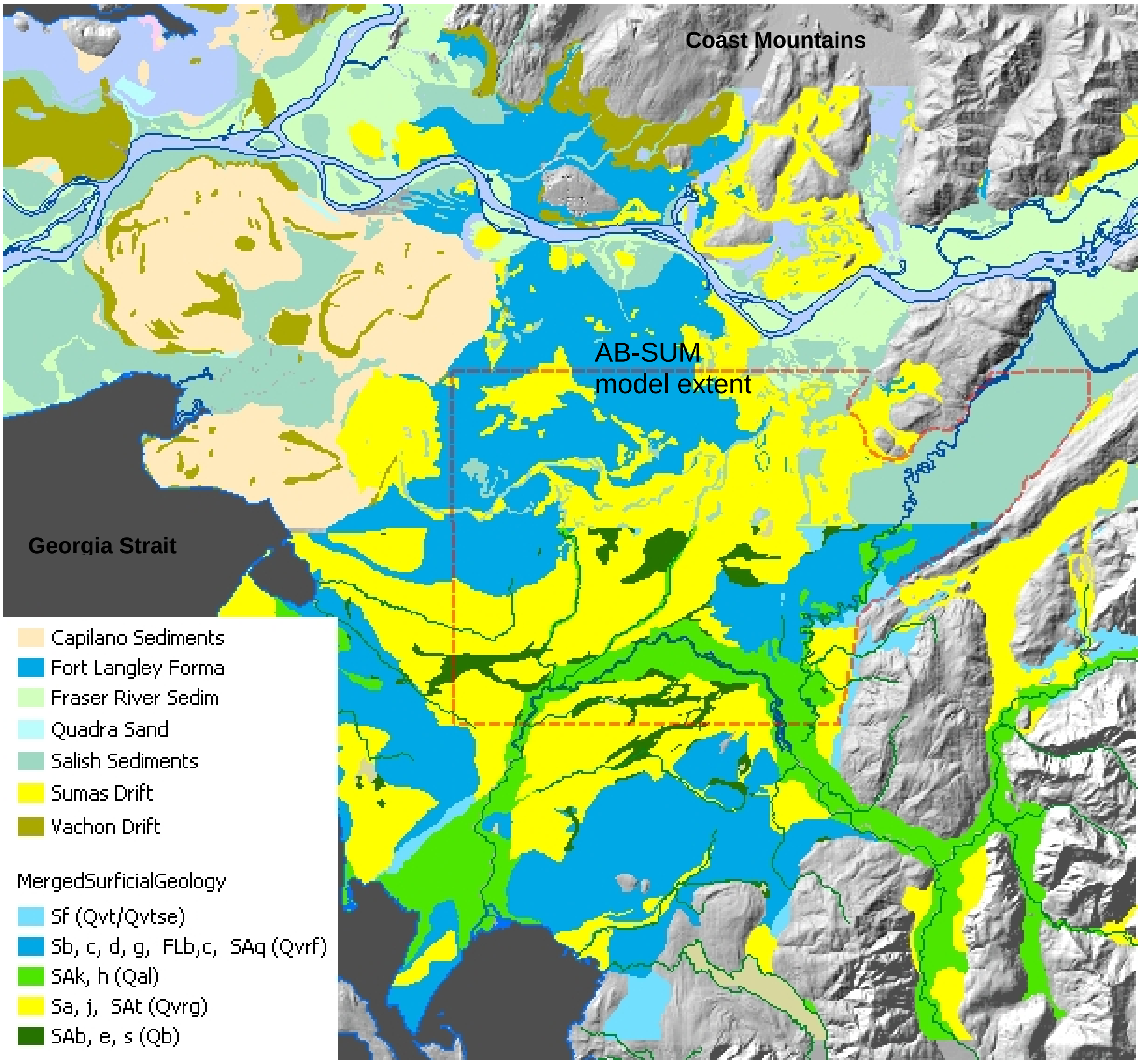


Table 1 Hydrostratigraphic units (Halstead 1986), comparing US and Canadian geologic units (compiled by Golder, 1995).

Hydrostratigarphic Units (Halstead, 1986)	Possible Geologic Equivalents		General Geologic Description
	US Geologic Units (1)	Canadian Geologic Units (2)	
C1	Qt		glaciofluvial sand and gravel deposited by meltwater streams, often occurring as raised deltas
C2	Qal Alluvial Deposits Qp Peat Qs Till and Ice-contact deposits Qsc Silt and Clay Qso Outwash Sand and Gravel	Fraser River and Salish sediments Sumas Drift	fluvial and floodplain deposits of silt, sand, gravel and peat; till, glaciofluvial, and ice-contact deposits; outwash sand and gravel
A/B	Qb Bellingham Drift Qk Kulshan Drift	Fort Langley Formation and Capilano Sediments	glaciomarine deposits consisting of stony clays, and stony silt with marine shells
C3	Qd Deming Sand	Fort Langley Formation and Capilano Sediments	stratified, well sorted sand and gravel with some layers of clay, silt and gravel
D	Qvt Vashon Till Qve Esperance Sand	Vashon Drift Quadra Sand	till and ice-contact deposits of poorly sorted gravel in matrix of silt, clay and sand; and glaciofluvial deposits of sand and gravel
E	Bellingham Drift, Kulshan Drift Pre-Vashon marine deposits	Capilano, Fort Langley, Cowichan Head formations	clay and silt, with interbedded estuarine and fluvial deposits of fine sand and silt
C4	Pre-Vashon sediments	Pre-Vashon sediments	fine to medium sand of fluvial or glaciofluvial origin
F	TKc Tertiary bedrock Th	Tertiary bedrock	Tertiary-aged consolidated sedimentary deposits and interbedded volcanic deposits

(1) after Easterbrook, 1976
(2) after Armstrong, 1981

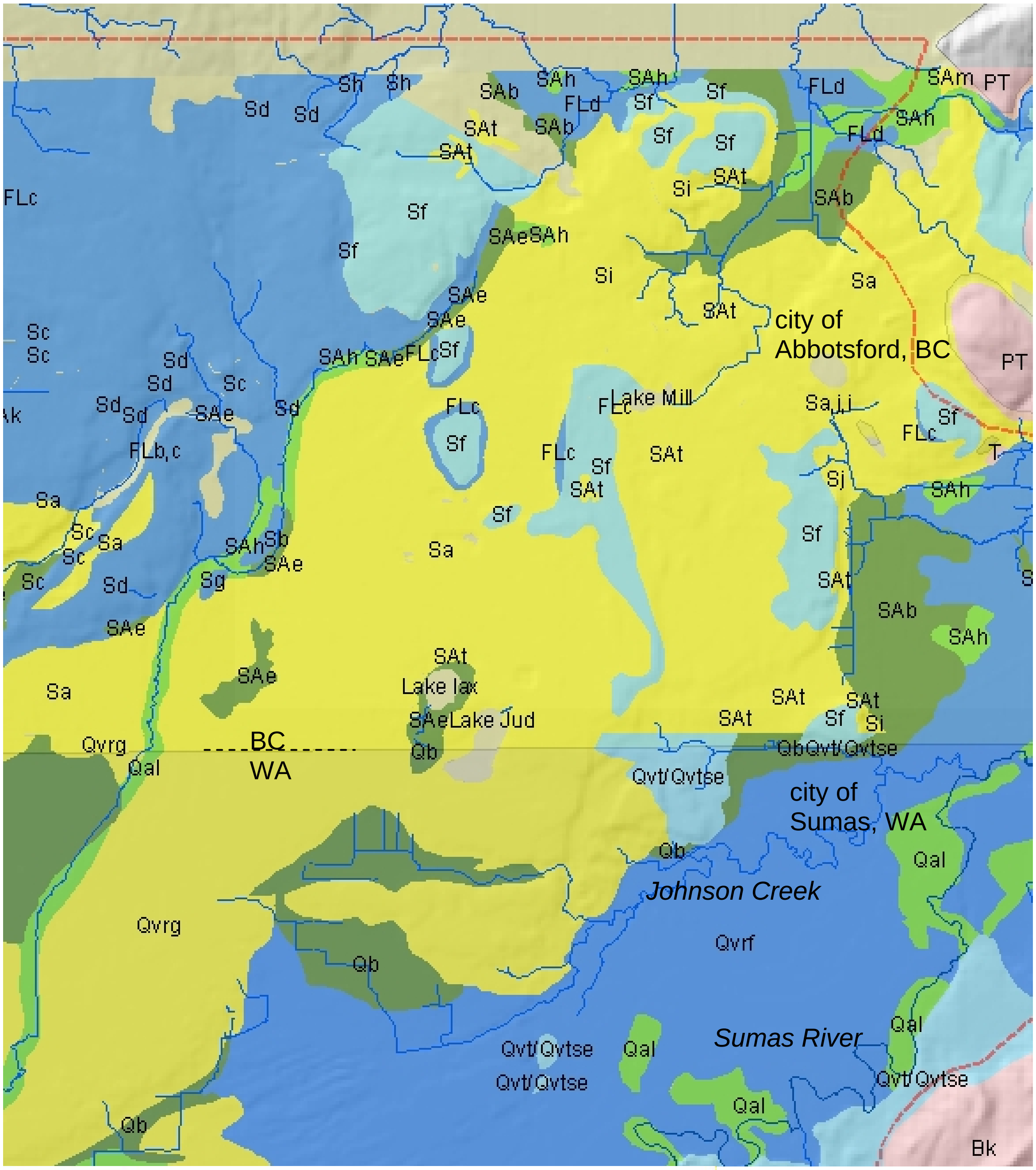
Table 2 Summary of surficial geology map units in Fraser Valley (GSC digital maps of surficial geology in study area).

Map Unit	LITHOLOGY	ENVIRONMENT	DESCRIPTION
Ca, Cb, Cc	Capilano Sediments	marine, shore	sand and gravel
Cd, Ce	Capilano Sediments	glaciomarine	silt / clay
Fa	Fraser River Sediments	fluvial, channel deposits	fine to medium sand
Fa,h, b, c, d, g, h	Fraser River Sediments	fluvial	fine to med. sand, sand
FLa,b	Fort Langley Formation	glacial, glaciofluvial	flow till with sand/gravel
FLa,b,d,e	Fort Langley Formation	glacial, glaciofluvial	flow till, gravel, sand
FLb, c, e	Fort Langley Formation	glaciofluvial, outwash	gravel and sand
FLc, d	Fort Langley Formation	glaciomarine / marine	clayey silt to silty sa
FLe	Fort Langley Formation	glaciofluvial, deltaic	gravel and sand
PVb	Quadra Sand	glaciofluvial, deltaic	gravel and sand
PVc	Quadra Sand	marine, offshore	fine sand to clayey silt
PVf	Semiahmoo Drift	glacial	till
Sa	Sumas Drift	outwash	sand and gravel
Sa,f,j	Sumas Drift	outwash, glacial	sand and gravel, sandy
SA ...	Salish Sediments	fluvial, lacustrine	
Sb, c, d, e	Sumas Drift	glaciofluvial	gravel and sand
Sf, g	Sumas Drift	glacial	sandy till
Sf,h, j	Sumas Drift	glacial, glaciolacustrine	sandy till, silt, silty
Sh	Sumas Drift	glaciolacustrine	silt, clayey silt, silt
Si, j	Sumas Drift	glaciofluvial	gravel and sand
Vb	Vashon Drift	glaciofluvial, outwash	gravel and sand
VCa	Vashon Drift	glacial	lodgement till with sand
T	Tertiary bedrock		sandstone, shale, volcanic
PT	Pre-tertiary bedrock		granite

Table 3 Summary of US and Canadian surficial geology map units in Fraser Lowland and their correspondence.

US Geo Unit	CDN Geo Unit	Lithology	Environment
Qvrg	Sa	Sumas Drift	outwash
Qvt/Qvtse	Sf	Sumas Drift	
Qvrf	Sg	Sumas Drift	sandy till
Qal	SAk	Salish Sediments	fluvial, lowland channel
Qb	SA e b s	Salish Sediments	organic (peat)
Bk	PT	Bedrock	

Map 12 Surficial Geology of Abbotsford area, Abbotsford Outwash



FLc | Qvrf — Ft Langley fm/Everson gm drift (gmstony clays)

Sa | Qvrg — Sumas Drift (sand, gravel, till lenses)

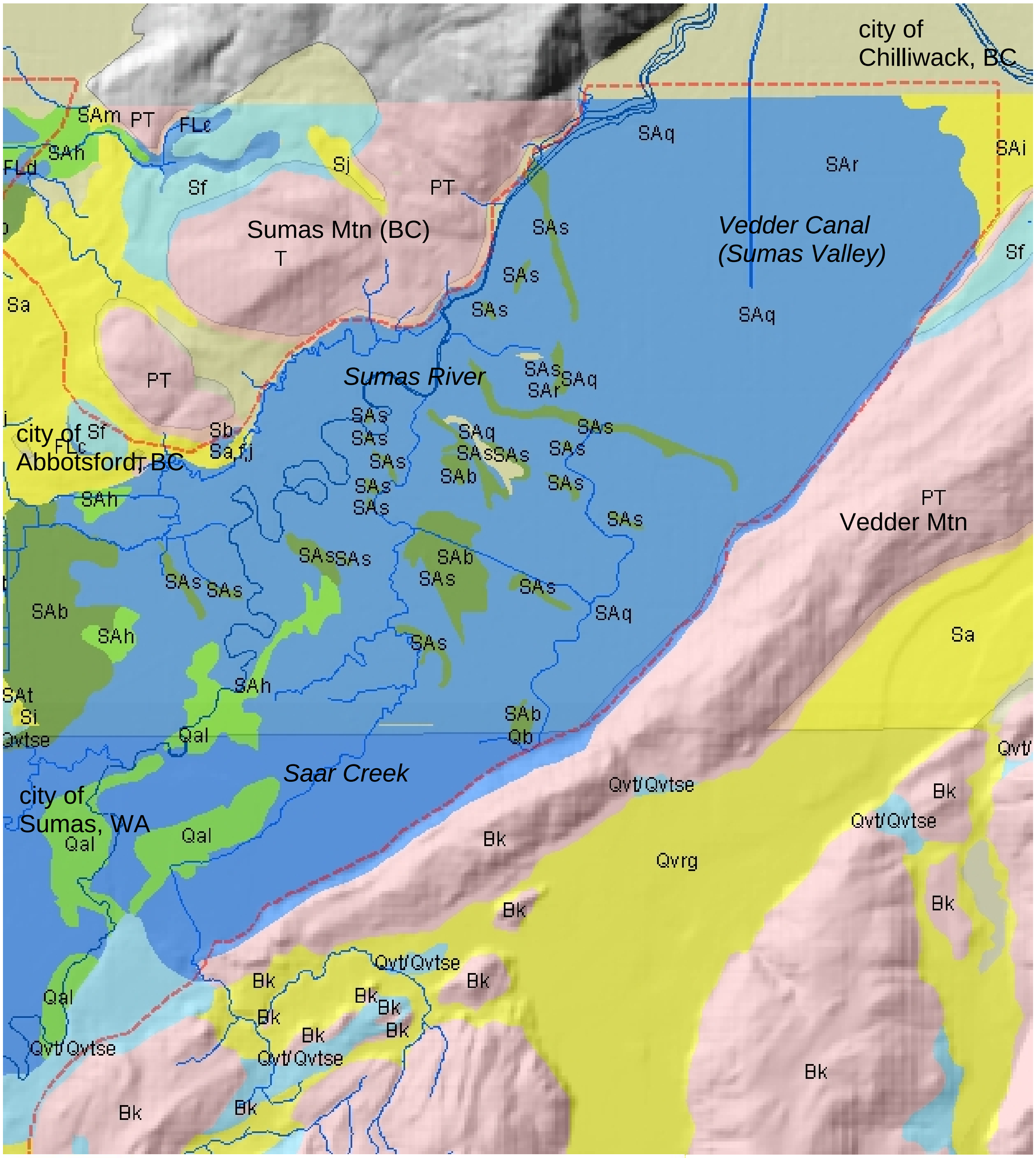
SAb — Salish sediments (peat, glaciolactustrine silt)

Sf — Sumas Drift (till, sandy till)

Qal — Salish sediments (fluvial channel and floodplain silts/sands)

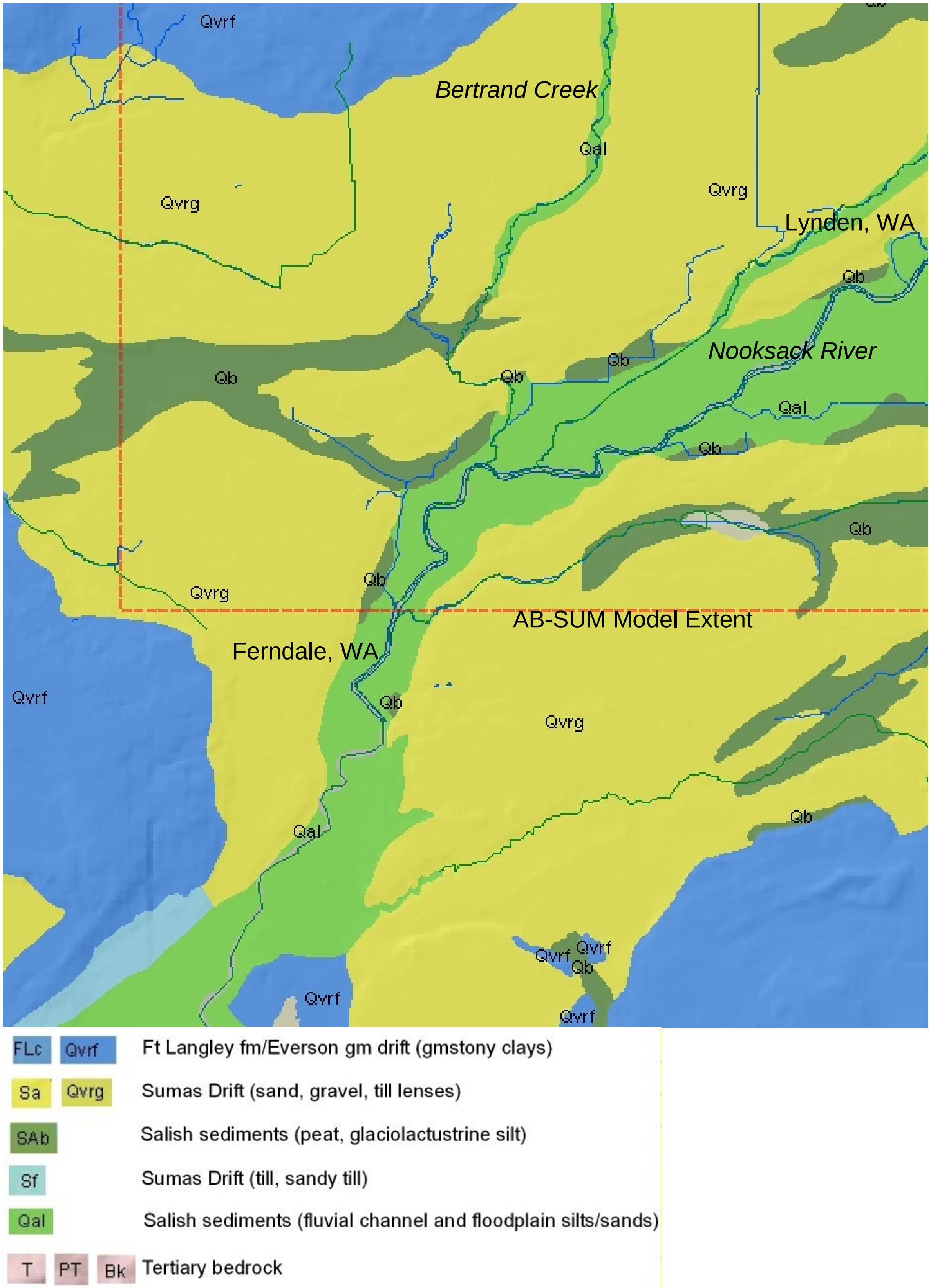
T | PT | Bk — Tertiary bedrock

Map 13 Surficial Geology of Sumas Valley.



FLc Qvrf	Ft Langley fm/Everson gm drift (gmstony clays)
Sa Qvrg	Sumas Drift (sand, gravel, till lenses)
SAb	Salish sediments (peat, glaciolactustrine silt)
Sf	Sumas Drift (till, sandy till)
Qal	Salish sediments (fluvial channel and floodplain silts/sands)
T PT Bk	Tertiary bedrock

Map 14 Surficial Geology of Ferndale, WA, area: Lynden terrace, Nooksack Valley towards Bellingham.



Map 15 Surficial Geology of Everson, WA, area and Nooksack Valley.

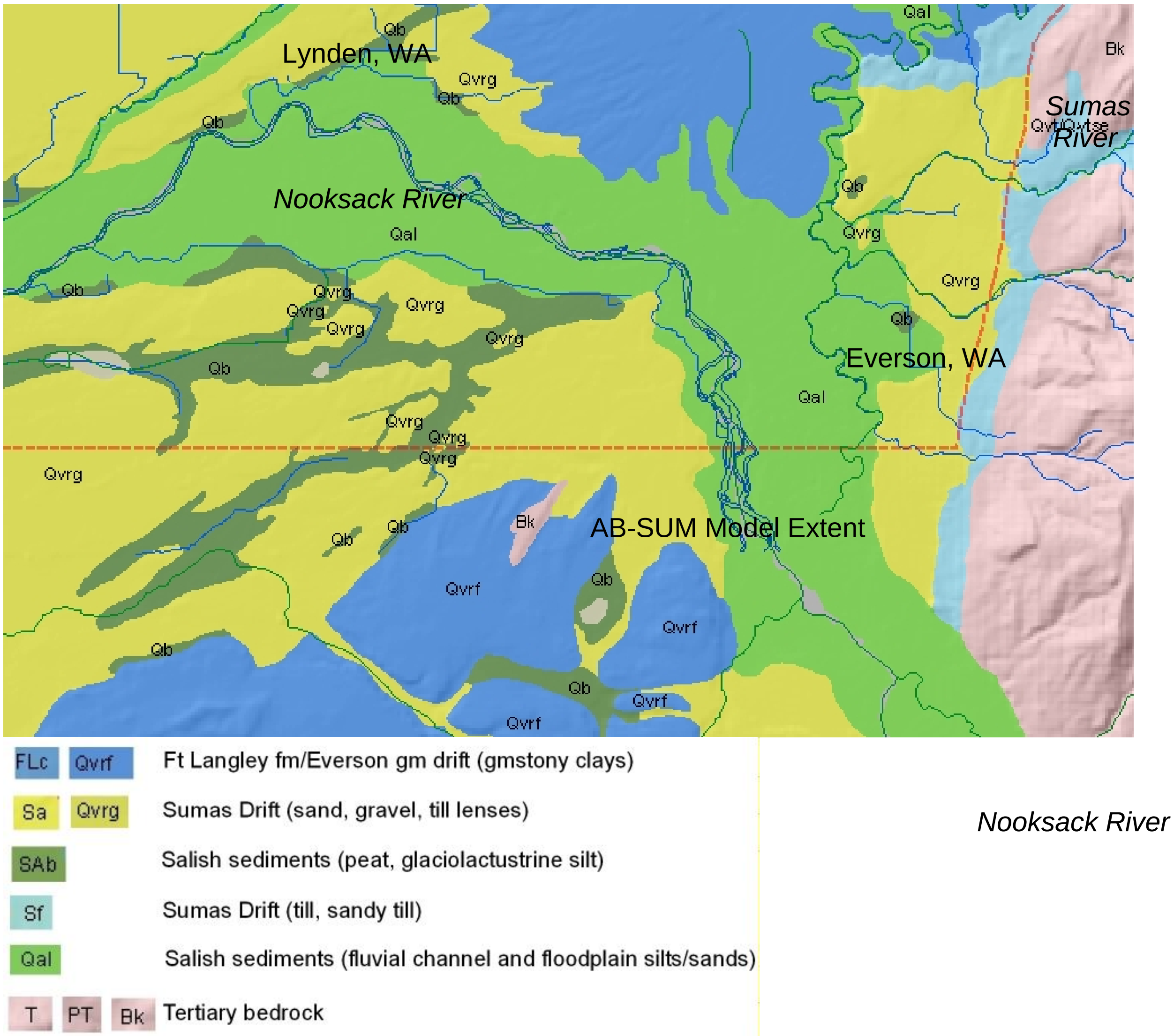


Table 4 Surficial geology map units in Fraser Valley (GSC digital maps of surficial geology in study area).

Map Unit	LITHOLOGY	ENVIRONMENT	DESCRIPTION	THICKNESS
Ca	Capilano Sediments	marine, shore	sand and gravel	up to 8 m
Cb	Capilano Sediments	marine, shore	medium to coarse sand	up to 5 m
Cc	Capilano Sediments	fluvial, deltaic	medium sand to coarse g	up to 15 m
Cd	Capilano Sediments	glaciomarine	silty loam to clay loam	up to 3 m
Ce	Capilano Sediments	glaciomarine	silty loam to clay loam	up to 60 m
Fa	Fraser River Sediments	fluvial, channel deposits	fine to medium sand	10 - 15 m
Fa,h	Fraser River Sediments	fluvial	fine to med. sand, sand	
Fb	Fraser River Sediments	fluvial, overbank dep.	sandy to silty loam	up to 2 m
Fc	Fraser River Sediments	fluvial, overbank dep.	silty to clayey loam	up to 2 m
Fc,d	Fraser River Sediments	fluvial	silty/clayey lm, sandy/	
Fd	Fraser River Sediments	fluvial, deltaic	sandy to silty loam	10 - 40 m
Fg	Fraser River Sediments	fluvial	silty clay loam, silt l	up to 10 m
Fh	Fraser River Sediments	fluvial	sandy loam	
FLa,b	Fort Langley Formation	glacial, glaciofluvial	flow till w sandy lm, g	
FLa,b,d,e	Fort Langley Formation	glacial, glaciofluvial	flow till, gravel, sand	
FLb	Fort Langley Formation	glaciofluvial, outwash	gravel and sand	5 - 10 m
FLb,c	Fort Langley Formation	glaciofluvial, glaciolacustrine	gravel,sand,clayey silt	
FLb,e	Fort Langley Formation	glaciofluvial	gravel and sand	
FLc	Fort Langley Formation	glaciomarine	clayey silt to silty sa	8 - 90 m
FLd	Fort Langley Formation	marine	silty clay to fine sand	5 - 10 m
FLe	Fort Langley Formation	glaciofluvial, deltaic	gravel and sand	10 - 30 m
PT	Pre-tertiary bedrock		granite	
PVb	Quadra Sand	glaciofluvial, deltaic	gravel and sand	5 - 25 m
PVc	Quadra Sand	marine, offshore	fine sand to clayey sil	
PVf	Semiahmoo Drift	glacial	till	2 - 25 m
Sa	Sumas Drift	outwash	sand and gravel	up to 30 m
Sa,f,j	Sumas Drift	outwash, glacial	sand and gravel, sandy	
SAa	Salish Sediments	landfill	sand, gravel, crushed s	
SAb	Salish Sediments	organic	lowland peat	up to 14 m
SAc	Salish Sediments	organic	lowland peat	up to 1 m
SAd	Salish Sediments	organic	lowland sandy loam to c	up to 0.5
SAe	Salish Sediments	organic	upland peat	up to 8m
SAf	Salish Sediments	marine, shore	sand to sandy loam	up to 2 m

Map Unit	LITHOLOGY	ENVIRONMENT	DESCRIPTION	THICKNESS
SAf,j	Salish Sediments	marine, shore, fluvial	sand to sandy loam, gra	
SAg	Salish Sediments	marine, shore	sand to gravel	up to 8 m
SAh	Salish Sediments	fluvial, lowland channel	sandy loam to clay loam	up to 8 m
SAh,k	Salish Sediments	fluvial, lowland channel	sandy/clay loam, sand,	
SAi	Salish Sediments	fluvial, deltaic	gravel and sand	up to 15 m
SAj	Salish Sediments	fluvial, mountain channel	sand to gravel	up to 8 m
SAj,i	Salish Sediments	fluvial, mtn channel	sand to gravel	
SAk	Salish Sediments	fluvial, lowland channel	sand to gravel	up to 5 m
SAm	Salish Sediments	slope	slopewash sand	up to 4 m
SAn	Salish Sediments	slope	slopewash clayey silt,	up to 2 m
SAo	Salish Sediments	slope	gravel, sand	up to 15 +
SAp	Salish Sediments	slope	gravel, sand	up to 10 m
SAq	Salish Sediments	lacustrine	silt to clay	less than
SAr	Salish Sediments	lacustrine	sand to sandy loam	up to 5 m
SAs	Salish Sediments	lacustrine	fine sand	up to 8 m
SAt	Salish Sediments	eolian	fine sand	up to 15 m
Sb	Sumas Drift	glaciofluvial	gravel and sand	2 - 5 m
Sc	Sumas Drift	glaciofluvial	gravel and sand	2 - 5 m
Sd	Sumas Drift	glaciofluvial	gravel and sand	more than
Se	Sumas Drift	glacial, deltaic	gravel and sand	up to 40 m
Sf	Sumas Drift	glacial	sandy till	
Sf,h	Sumas Drift	glacial, glaciolacustrine	sandy till, silt, silty	
Sf,j	Sumas Drift	glacial, glaciofluvial	sandy till, gravel and	
Sg	Sumas Drift	glacial	sandy till	
Sh	Sumas Drift	glaciolacustrine	silt, clayey silt, silt	
Si	Sumas Drift	glaciofluvial		
Sj	Sumas Drift	glaciofluvial	gravel and sand	
T	Tertiary bedrock		sandstone, shale, volca	
Vb	Vashon Drift	glaciofluvial, outwash	gravel and sand	3 - 8 m
VC	Vachon Drift			
VCa	Vashon Drift	glacial	lodgement till with sand	1 - 5 m
VCb	Vachon Drift			

2.2.4. GLACIAL AND GLACIOFLUVIAL LANDFORMS

To large extent, groundwater flow in the surficial aquifers is strongly controlled by topography. The ground surface has been shaped by geomorphic processes since deglaciation. There has been much erosion of portions of the Abbotsford outwash along Sumas Valley, around Sumas Mountain north east of Abbotsford City centre, and south of Lynden, WA, along Nooksack River valley. There are also prominent scarps of eroded material.

Deposition of Holocene floodplain sediments occurred in Sumas Valley along the Sumas River, and lacustrine deposits are found in north-east valley, south of Vedder Fan, in what was known as Sumas Lake. The Sumas River flows across the "Sumas Prairie", which was at one time the bed of a shallow lake (Stevens and Eriksson: 1997). The lake and surrounding wetlands were drained, dredged and dyked in 1925 to create fertile agricultural land (Stevens and Eriksson: 1997).

2.3. HYDROGEOLOGICAL INVESTIGATIONS IN ABBOTSFORD-SUMAS AREA

2.3.1. HALSTEAD (1986)

The most comprehensive summaries to date of subsurface stratigraphy have been compiled by Armstrong (1984) and Halstead (1986). The stratigraphic complexity has resulted from interactions between sedimentation and erosion during advance and retreat of the ice sheets, the concomitant retreat and advance of the seas, and the isostatic effects of ice loading (subsidence) and unloading (uplift). Therefore, there are many units of sufficiently high porosity and hydraulic conductivity to qualify as aquifers, particularly those that accumulated in close proximity to ice. Mapping has identified more than 200 aquifers in the region (Liebscher et al., 1992), where more than 30 have been identified in southeast Surrey - southwest Langley alone (Makepeace and Ricketts, 2000).

Halstead (1986) defined hydrostratigraphic units on the basis of lithology, permeability and porosity, and subordinate factors, such as origin (marine, fluvial), stratigraphic position, and to some extent aquifer type (e.g., water table aquifers); they are different from the formal lithostratigraphic units, which are defined primarily on mappability and degree of homogeneity. Halstead's scheme is useful from a regional perspective, although detailed mapping in the south Surrey-Langley area reveals some ambiguities. Halstead's Unit C, for example, corresponds to the easily mapped, unconfined Sumas Drift aquifers. However, other hydrostratigraphic units, such as units A and B, correspond to the more heterogeneous Fort Langley and Capilano Formations, and not specifically to aquifers within these formations. For example, several aquifers mapped in this project are confined by finer grained Fort Langley-Capilano deposits - some of the confined aquifers appear very similar in general sedimentological characteristics and map extent to the unconfined Unit C aquifers.

Halstead (1986) grouped the sediments into six units of significance to groundwater, either acting as barriers to flow or as units that readily transmit ground water. Piteau Associates summarized the hydrostratigraphic units in Halstead's (1986) report for the BCWLAP groundwater section website as follows (edited excerpts):

Hydrostratigraphic Unit A

Hydrostratigraphic Unit A includes Capilano sediments and the Fort Langley Formation, typically less than 30 m thick. It is composed of clay, stoney clay and silty clays, with varying stone content, as well as silty lenses, sandy silts and in some places marine shells. Thin layers of low permeability, postglacial materials, such as peat and floodplain deposits, which typically overlie the stony clays are included in this unit. It is present at or near ground surface, throughout the central part of the Lower Fraser Valley, with the exception of areas where it is overlain by Unit C. Typically, at or near its base, there is a sand layer with thin lenses of till, which often is sufficiently permeable to yield water sufficient only for domestic use.

Hydrostratigraphic Unit B

This unit is of glaciomarine origin and consists of stony clay with shells. Based on a review of driller's logs, the stone content as well as the clay content appears to be greater than in Unit A. It is a unit of low permeability, generally forming an aquiclude, and is found in the Langley Upland east of Abbotsford, as well as in the valley of the Nicomekl and Serpentine Rivers. In a deep test hole near Aldergrove, about 56 m of Unit B was penetrated (Halstead, 1964), while deep test holes in the Milner and Fort Langley areas penetrated as much as 90 m of this material. Well yields from Unit B are generally less than 0.2 L/s and water quality is poor.

Hydrostratigraphic Unit C

Hydrostratigraphic Unit C consists of permeable, glaciofluvial ice-contact deposits, glaciofluvial deltas and occasional thin patches of till. Where the streams emptied into the sea, deltas were built up (currently near the Township of Langley). This unit generally overlies Unit B, and occasionally Unit A. All major aquifers are located in this unit. For example, a large raised delta, located south of Langley, forms the Langley Aquifer, and former meltwater streams that issued from stagnant melting ice masses in the vicinity of Sumas Mountain have built up a plain of very permeable sand and gravel south of Abbotsford (the “Abbotsford Aquifer”). Discharge of ground water by springs is commonly observed along the edges of the deltas and is responsible for maintaining perennial flows in many streams, such as Anderson, Fishtrap and Chilliwack Creeks. Yields from wells developed in these aquifers range up to 153 L/s.

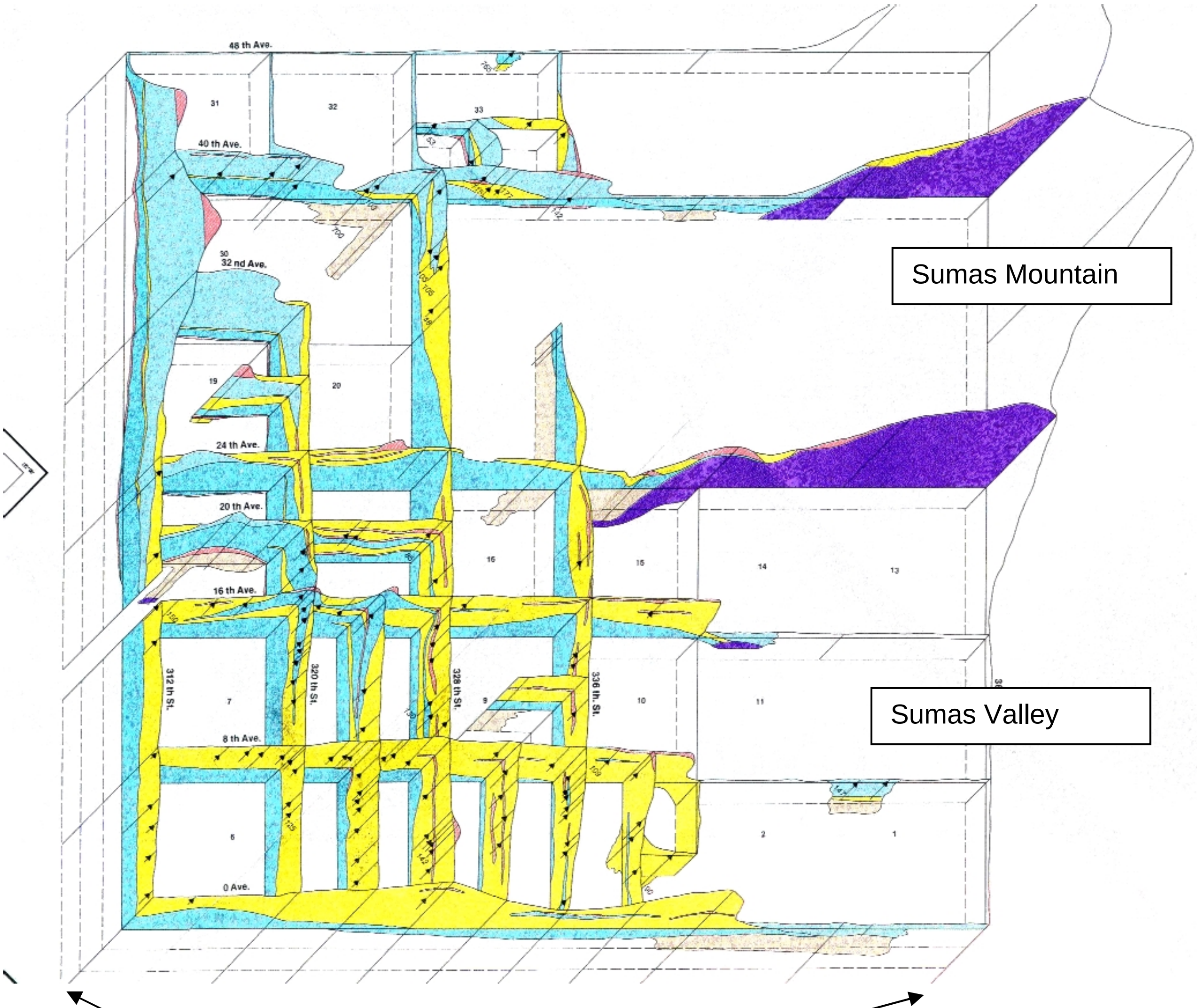
Hydrostratigraphic Unit D

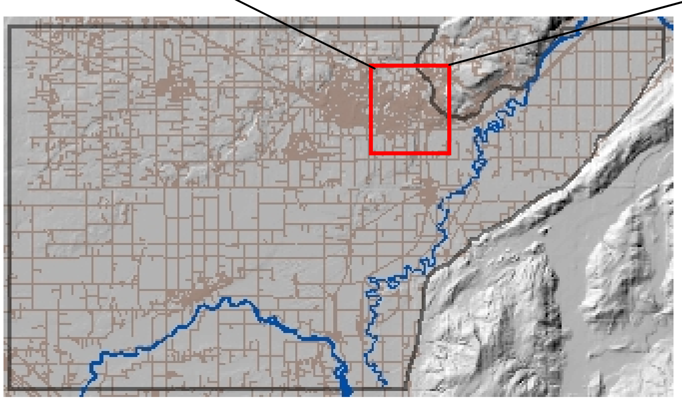
Hydrostratigraphic Unit D includes a range of coarse to fine sediments, commonly referred to as till or diamictons, the components of which are brought together by a wide variety of glacial processes. Till has been found as deep as 90 m below sea level in the Nicomekl and Serpentine Valleys. These tills are not continuous across the valleys in the Fraser Lowland, but do underlie the uplands at an elevation of between plus and minus 15 m relative to present sea level. A multi-till sequence of till-outwash-till underlies the front of the Langley Upland, and is interpreted as the deposits of a single glacier rather than an evidence of multiple glaciations. This unit forms confining units of deeper aquifers in this area.

Hydrostratigraphic Unit E

Unit E comprises older materials, mostly marine sediments interbedded with estuarine and fluvial deposits consisting of fine sand, silt and clayey silts. All drillholes that penetrate to depths of more than 90 m have encountered these materials. Typically, groundwater flow in this unit has a long residence time and hence water quality is poor.

Figure 2 Hydrostratigraphic units in Abbotsford area interpreted by Halstead (1986). Modified from Halstead (1986).





location of box fence diagram by Halstead (1986) shown on shaded relief and Abbotsford-Sumas aquifer model extent

Hydrostratigraphic Unit F

Unit F consists of bedrock. Fractured bedrock is the source of ground water for areas north of the Fraser River as well as in upland areas such as Chilliwack, Sumas and Vedder Mountains. Individual well yields rarely exceed 1 L/s. The bedrock unit is a regional aquiclude, compared to the much more productive overlying sediments.

2.3.2. GEOLOGICAL SURVEY OF CANADA (1993 – 1995)

In 1993 the Geological Survey of Canada (GSC) began a series of hydrogeologic investigations and analyses in the Fraser Valley, with the main objective being the analysis of regional stratigraphic framework of aquifers, groundwater flow, discharge and recharge dynamics (Ricketts and Jackson, 1994). A digital database of over 4300 groundwater wells and associated lithologs, and other information was organized (Woodsworth and Ricketts, 1994; Ricketts and Dunn, 1995), which is currently accessible from the BC Government data sources.

Ricketts and Liebscher (1994) described the regional groundwater in the Fraser Valley as flowing through:

(1) unconsolidated or semi-consolidated Pleistocene and younger sediments (glaciomarine, glaciolacustrine, glaciofluvial, deltaic, fluvial)

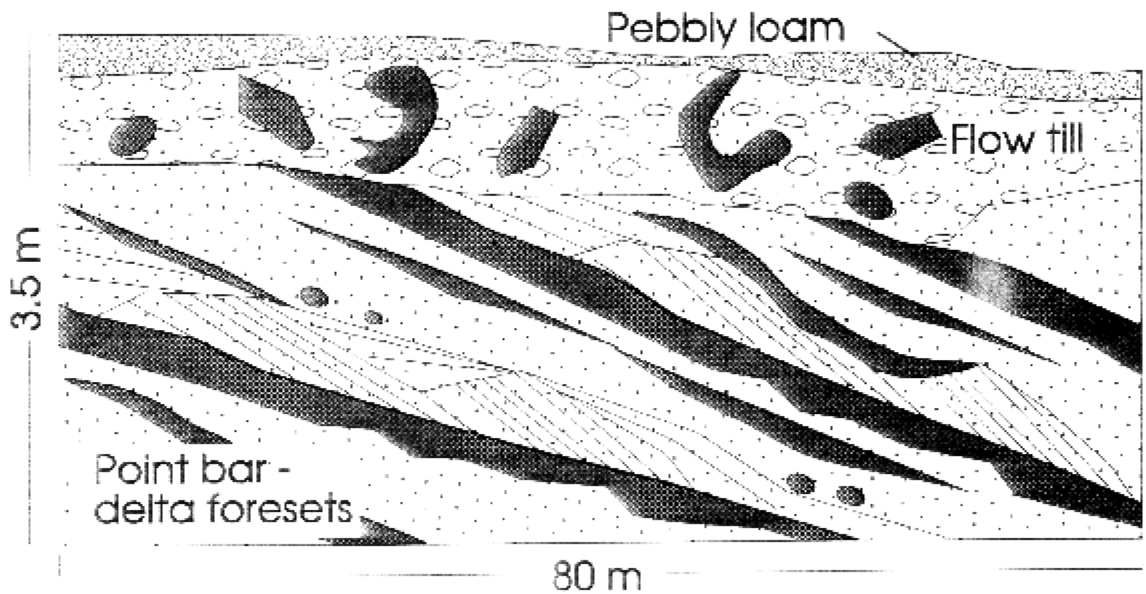
(2) lithified Cretaceous and Tertiary sedimentary rocks of the Georgia Basin (sandstones, conglomerates, shales)

(3) fractured granitic and metamorphosed sedimentary and volcanic rocks mostly greater than 90 million years old in the Coast and Cascade mountains.

The flow is fastest in the sand and gravel aquifers, which generally have high porosity (up to 40%) and high hydraulic conductivity (Ricketts and Liebscher, 1994), and much slower in the Tertiary rocks, which have low intergranular porosity (<15%) and some fracture porosity. The flow component in the basement bedrock is expected to be very low due to very small porosities.

In two unconfined aquifers, previously mapped from surficial geology and well data by Ricketts et al. (1993), ground penetrating radar (GPR) was used to determine the architecture of the topmost part of the Brookswood unconfined aquifer in Surrey and Langley townships (Rea et al., 1994). This aquifer lies immediately west of the present day Abbotsford-Sumas aquifer (see **Map 4**)Error! Reference source not found., and is also composed of Sumas Drift outwash sand and gravel, with interfingering tills or glaciolacustrine clays, up to 40 m thick and overlying the Fort Langley Formation (Armstrong, 1981; 1984). A total of 12 km of GPR data were collected and calibrated with lithological and static water levels from nearby wells. However, the depth of penetration was only between 12 and 20 m, and high clay content in some areas precluded detailed resolution of stratigraphy. Clay lenses within coarser sediments are important for predicting groundwater flow directions, and can be imaged by GPR. The work by Rea et al. (1994) revealed that strong reflections of GPR signal were correlated to transitions from gravel to clay (or till), but could not see through or below clay lenses. The aquifer was observed to pinch out, where a clay-rich unit approached ground surface. In coarser sediments, channel structures were detected. The groundwater table was also easily observed using GPR. The GPR field surveys demonstrated that there is large degree of heterogeneity within the coarse grained unconsolidated deposits, with variable dips of layers, and small-scale changes in aquifer thickness above less permeable layers. However, the technique is limited to shallow depths and was not used again in subsequent hydrogeologic investigations by the GSC. Time domain electromagnetic (TDEM) surveys and approximately 100 electromagnetic (EM) soundings were collected at 9 sites within the lower Fraser Valley and Fraser Delta (Best et al., 1995). The geophysical methods were able to map the stratigraphy and water table to depths up to 200 m. Cone penetrometer tests (CPT) were used extensively in Fraser Delta studies (Campanella et al., 1983; Monahan et al., 1991) in an attempt to image gravelly Sumas Drift deposits near Abbotsford.

Figure 3 Sketch of a large scale sand-clay foreset couplets exposed in gravel pit in north end of Brookswood Aquifer (north-west of Abbotsford-Sumas aquifer area). (Ricketts and Jackson, 1994).



2.3.3. US GEOLOGICAL SURVEY AND WASHINGTON STATE DEPARTMENT OF ECOLOGY

Similar work has been carried out in Washington State, notably by Kahle (1991), Jones (1999), and Cox and Kahle (1999), at the United States Geological Survey (USGS), and Tooley and Erickson (1996) at Washington State Department of Ecology (WA Ecology). The USGS studies are known either as the LENS (Lynden-Everson-Nooksack-Sumas) hydrogeologic study and have been published as WRIA (Water Resources Investigations Area) 1 report – USGS publishes regional hydrogeologic studies as various WRIA area reports. The high quality borehole locations used by Cox and Kahle are shown on **Map 17**. In these studies, the principal surficial aquifers in central Fraser Lowland, consist mostly of the Sumas-Blaine Surficial Aquifer, Discontinuous Surficial Aquifers, and Non-Surficial Aquifers.

<u>The Sumas-Blaine Surficial Aquifer</u>

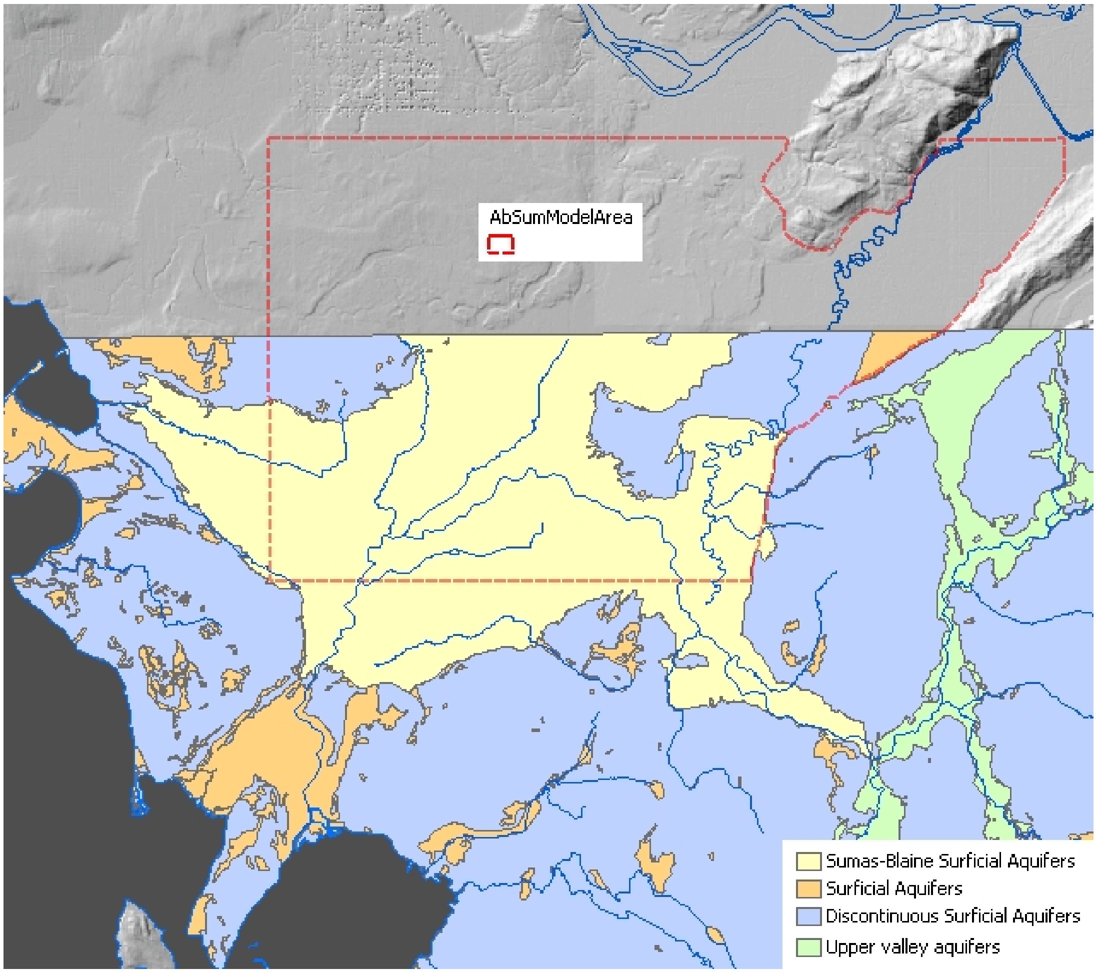
The principal aquifer in the Nooksack watershed is the Sumas-Blaine Aquifer. It underlies the flat glacial outwash plain between the towns of Sumas, Blaine, Ferndale, and the Nooksack

River and occupies about 150 square miles. It consists of mostly sand and gravel glacial outwash deposits and alluvial gravel, sand, silt and clay deposits of the Nooksack and Sumas Rivers (Tooley and Erickson, 1996). The water table is typically less than 10 ft below ground surface (Morgan, 1999). The vertical extent of the Sumas-Blaine Aquifer ranges from less than 25 feet near Blaine (western edge) to more than 75 feet thick near Sumas (eastern edge). At the northeastern edge, the aquifer depth can be more than 200 feet thick (Cox and Kahle, 1999).

<u>Discontinuous Surficial Aquifers</u>

There are many Discontinuous Surficial Aquifers spread throughout the WRIA (Water Resources Investigations) 1 study area. Many of these are located to the west and southwest of the Sumas-Blaine Aquifer, but there are also several of smaller sizes around Lake Whatcom and in the upper valleys. These are found in many geologic deposits such as beach, glacio-fluvial terrace deposits, modern alluvial and floodplain deposits, isolated outwash terraces, and marine terrace deposits (Tooley and Erickson, 1996) – see **Map 16**. The largest of these aquifers are located south of Ferndale, east of Blaine, across the bay southwest of Blaine, and east of Sumas. These aquifers are usually thin and not a major source of water. The definition of their lateral boundaries is based solely on surface soil properties, due to lack of sufficient well data (Morgan, 1999).

Map 16 Surficial aquifers in WA State mapped by Tooley and Erickson (1996) at Washington State Department of Ecology.



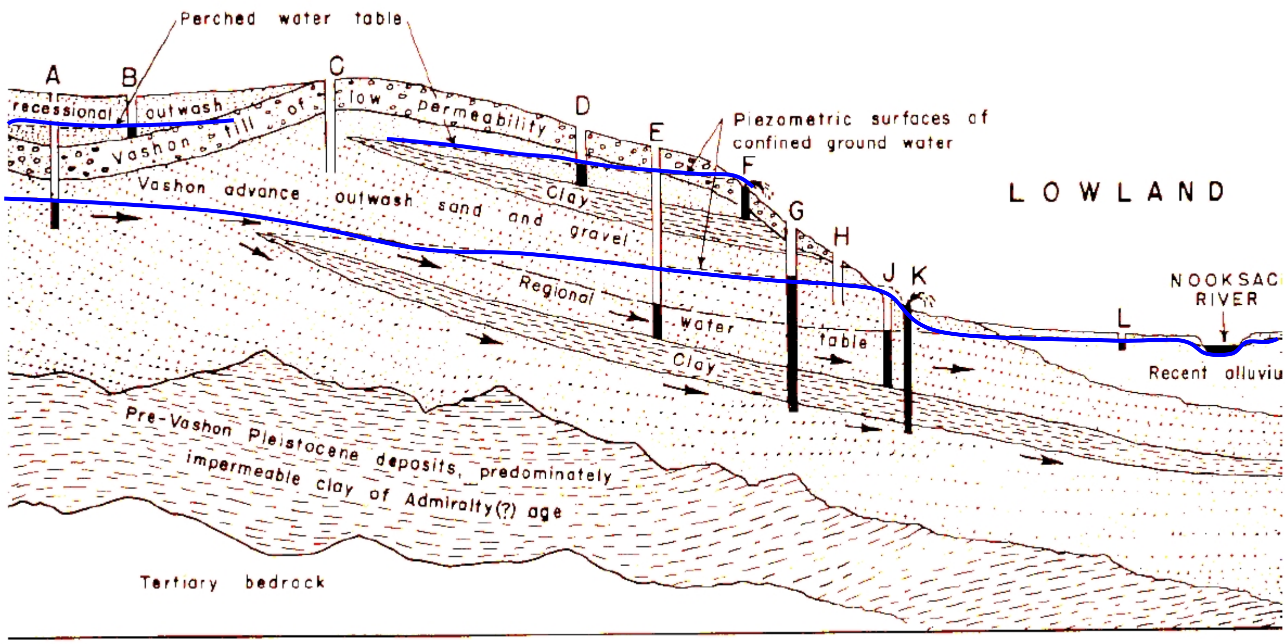
Non-Surficial Aquifers

Tooley and Erickson (1996) found "surficial aquifer not present" mainly south of Nooksack River valley (except small areas around Lake Whatcom), the eastern uplands (except along the river valleys of the North, Middle & South Fork Nooksack), and the western coastal areas (except for the Nooksack delta area and pockets of land around Blaine).

Perched Aquifers

The presence of perched water tables in the Abbotsford area may create problems during numerical flow model calibration. In the Abbotsford and Langley uplands, there are many areas with perched water tables, and it is difficult to distinguish elevated regional water table caused by presence of fine grained sediments, and perched water tables above lenses of fine grained sediments overlying coarse grained aquifers.

Figure 4 Cross-section through Abbotsford outwash plain and Nooksack Lowland along one N-S line, showing water table elvation and flow directions, and perched water tables – part of LENS study (Cox and Kahle, 1999).



2.3.4. OTHER STUDIES

Numerous other regional studies or local groundwater investigations have been undertaken (Gibbons and Culhane, 1994; Golder Associates, 1995; Mitchell et al., 2000; Piteau Associates, 1991; 2002), as well as the development of a numerical model of Sumas area by Earth Science Associates Inc., 1996). Surface-groundwater interactions and water balance have been estimated from streamflow and seepage analyses linked to aquifer water balances (Kohut, 1987; Culhane, 1993; Connely et al., 2002).

2.3.5. AQUIFER VULNERABILITY MAPPING IN BC

Previous aquifer vulnerability studies showed that there are multiple aquifer-aquitard complexes in the valley. Typically, surficial geology was used to define surficial aquifer extent. An aquifer classification scheme has been designed for groundwater management by Kreye and Wei (1994). Aquifers are ranked according to two main criteria: 1) the level of demand with respect to productivity; and 2) the vulnerability of the aquifer to contamination from surface source. In general, unconfined aquifers are the most vulnerable, and in the Fraser Lowland the most utilized aquifers, namely the Brookswood and Abbotsford-Sumas aquifers, are ranked in the top three in the province. Most of the confined aquifers mapped by Makepeace and Ricketts (2000) would probably rank in the middle or lower levels of this scheme, although in most cases an assessment of demand versus productivity and recharge is unknown. The aquifer maps developed for the south Langley-Surrey area provide a basis for quantifying some of these variables.

Aquifer vulnerability zones are represented as polygons for the whole aquifer extent (see **Map 4)**. In a sense, these maps defined the extent of aquifers using vulnerability criteria. Currently it is more common to map vulnerability of aquifers at much finer spatial scales, either by polygons or by raster maps (raster algebra is easier to implement for vulnerability classes). The previous extent of the “Abbotsford aquifer” was one such large polygon. It did not include Sumas Valley, which is hydraulically connected to the uplands, because surficial materials were fine grained and the vulnerability category was lower, and except for USGS studies, City of Sumas wellhead protection study (Assoc. Earth Sci., 1994), and a study by Cameron (1989) on the Sumas Valley there, was no mention in published work about the true extent of this surficial aquifer system. Therefore, the extent of the aquifer based on our work has been determined to be much larger than previous ones.

2.4. WELL LITHOLOG DATABASE AND BOREHOLE DISTRIBUTION

The hydrostratigraphic model of the Abbotsford-Sumas aquifer was constructed mainly from water well borehole lithology information (**Map 18**). In the central Fraser Valley, there are unique challenges in acquiring and integrating Canadian and US datasets. The greatest difficulty is in making use of low quality lithology information.

Sources of lithology data include:

Washington State
- Department of Ecology (WRIA 1 – Water Resources Investigations Area 1 – of USGS regional groundwater study database)
- NWIFC (Northwest Indian Fisheries Commission)

British Columbia
- BC WLAP (Ministry of Water Land and Air Protection)
- BC Ministry of Energy and Mines (several deep exploration boreholes)
- GSC (Geological Survey of Canada) reports and papers
- BC Ministry of Transportation (bridge construction sites)
- SFU (Simon Fraser University) – one MSc thesis with lithologs of Sumas Valley

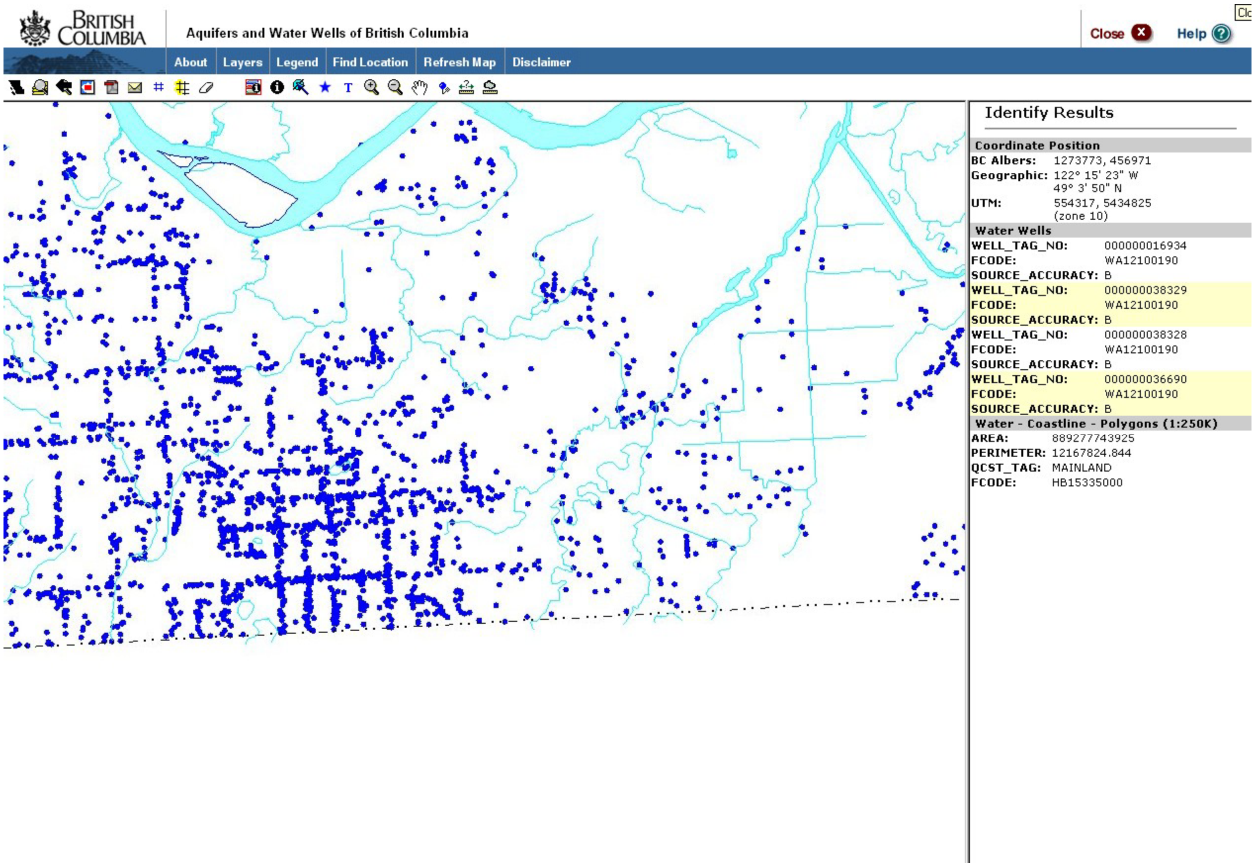
2.4.1. DATA QUALITY

The British Columbia Ministry of Water Land and Air Protection (BC WLAP) has a very extensive well drill record digital database. In BC, submission of well drilling reports is currently not mandatory, and there is no training of drillers in the preparation of well lithologs. As a result, the lithology information and location of wells contain many errors. Typically, litholog quality depends on driller's experience and/or education in geology, the amount of detail recorded in database, transcription errors, method of drilling, geologic setting, misplaced well records, and incorrect location of a well. Location coordinates were not available for many wells. In many instances, the given coordinates were not accurate, and the error was not known. For some of the wells, the coordinates were taken from address information and matched to addresses in Street Network files (Desphande, pers comm). In the lithologic records, the problems included incorrectly formatted text output, truncated lithologs (e.g., maximum 24 layers per litholog), lack of ground elevation of top of well (very common), missing uppermost unit which was assumed to be soil where thin, and problems with conversion of unit top and bottom depths to elevations above sea level (need top of well elevation at least).

Washington State Department of Ecology (WA Ecology) maintains a large and detailed digital database of well drill records, including lithologs. The lithologs are mostly in .tif image format, from scanned images of paper forms (**Figure 5**). In some areas, local governments and organizations have entered the information from paper forms to database records and these can be queried directly. In northern Whatcom County, the south part of our study area along the Nooksack River and on Lynden terrace, the database has only images of litholog paper forms, which had to be entered into text and numeric digital format – this was done by A. Deshpande and D. Milidragovic at SFU. In the WA Ecology logs the values are in feet and locations are in lat/long. All were converted to metres and the UTM coordinate system.

Map 17 shows the borehole locations from the respective provincial and state databases for the study area. Boreholes are clustered in the most productive aquifer areas and in the most populated areas, usually located along roads (see linear patterns in borehole distributions). **Map 18** shows the locations of boreholes from the USGS, the USGS LENS study (Cox and Kahle, 1999), Sumas Valley wells (Cameron, 1989), and Chilliwack geotechnical boreholes. **Map 20** shows the location of the LENS study cross-sections (Cox and Kahle, 1999). This map was created from source data and cross-section traces were digitized in GIS. The cross-sections were constructed from "quality" wells (see LENS wells in database). **Map 21** shows all borehole locations and their depths in central Fraser valley (all data sets). **Map 21a** shows the shallow wells (0.6 to 32 m depth), and **Map 21b** shows the deep wells (32 m to > 200 m depth).

Map 17 Web-based database queries in BC and WA state.



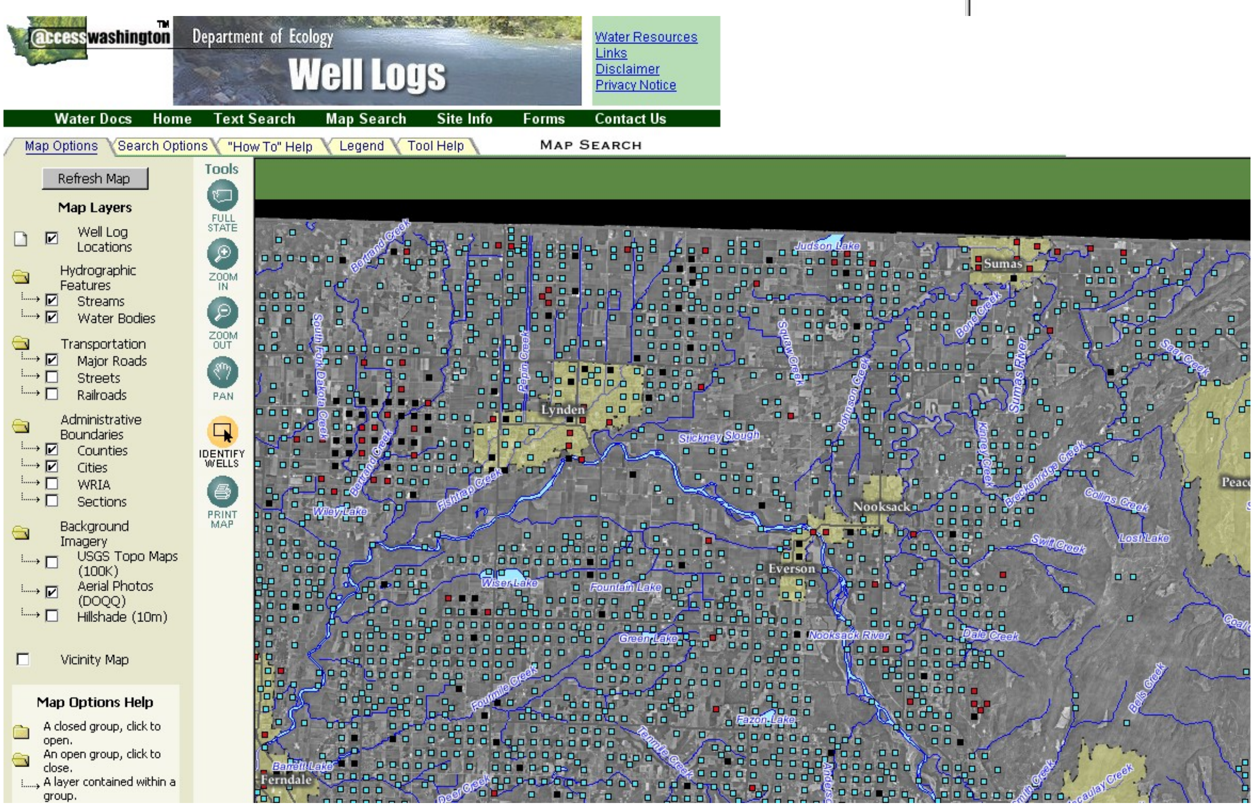
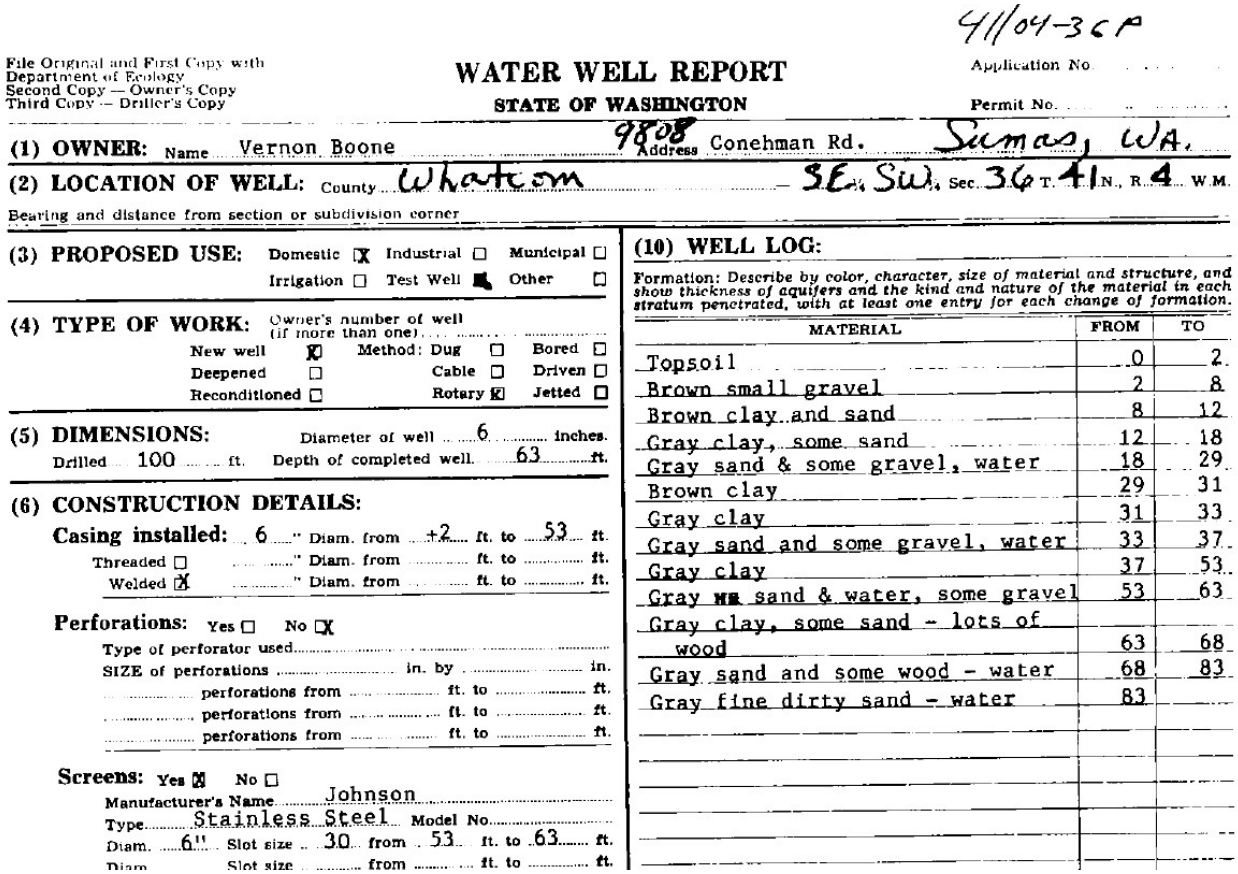


Figure 5 Example of well litholog from WA state.



4/1/04-3CP

File Original and First Copy with Department of Ecology
Second Copy — Owner's Copy
Third Copy — Driller's Copy

WATER WELL REPORT
STATE OF WASHINGTON

Application No.
Permit No.

(1) OWNER: Name Vernon Boone Address 9808 Conehman Rd. Sumas, WA.

(2) LOCATION OF WELL: County Whatcom — SE 1/4 SW 1/4 Sec. 36 T. 41 N., R. 4 W.M.

Bearing and distance from section or subdivision corner

(3) PROPOSED USE: Domestic [X] Industrial [ ] Municipal [ ] Irrigation [ ] Test Well [■] Other [ ]

(4) TYPE OF WORK: Owner's number of well (if more than one)
New well [X] Method: Dug [ ] Bored [ ]
Deepened [ ] Cable [ ] Driven [ ]
Reconditioned [ ] Rotary [X] Jetted [ ]

(5) DIMENSIONS: Diameter of well 6 inches.
Drilled 100 ft. Depth of completed well 63 ft.

(6) CONSTRUCTION DETAILS:

Casing installed: 6 " Diam. from +2 ft. to 53 ft.
Threaded [ ] " Diam. from ft. to ft.
Welded [X] " Diam. from ft. to ft.

Perforations: Yes [ ] No [X]
Type of perforator used
SIZE of perforations in. by in.
perforations from ft. to ft.
perforations from ft. to ft.
perforations from ft. to ft.

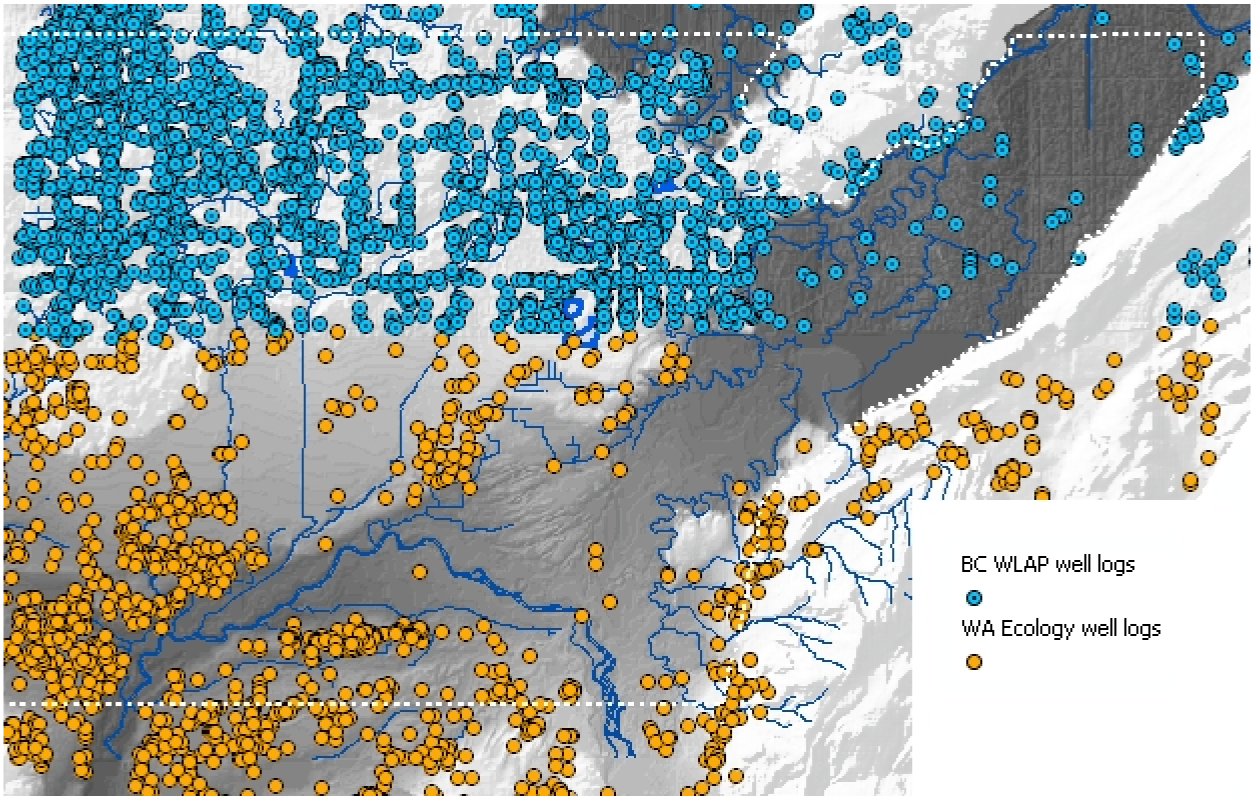
Screens: Yes [X] No [ ]
Manufacturer's Name Johnson
Type Stainless Steel Model No.
Diam. 6" Slot size 30 from 53 ft. to 63 ft.
Diam. Slot size from ft. to ft.

(10) WELL LOG:

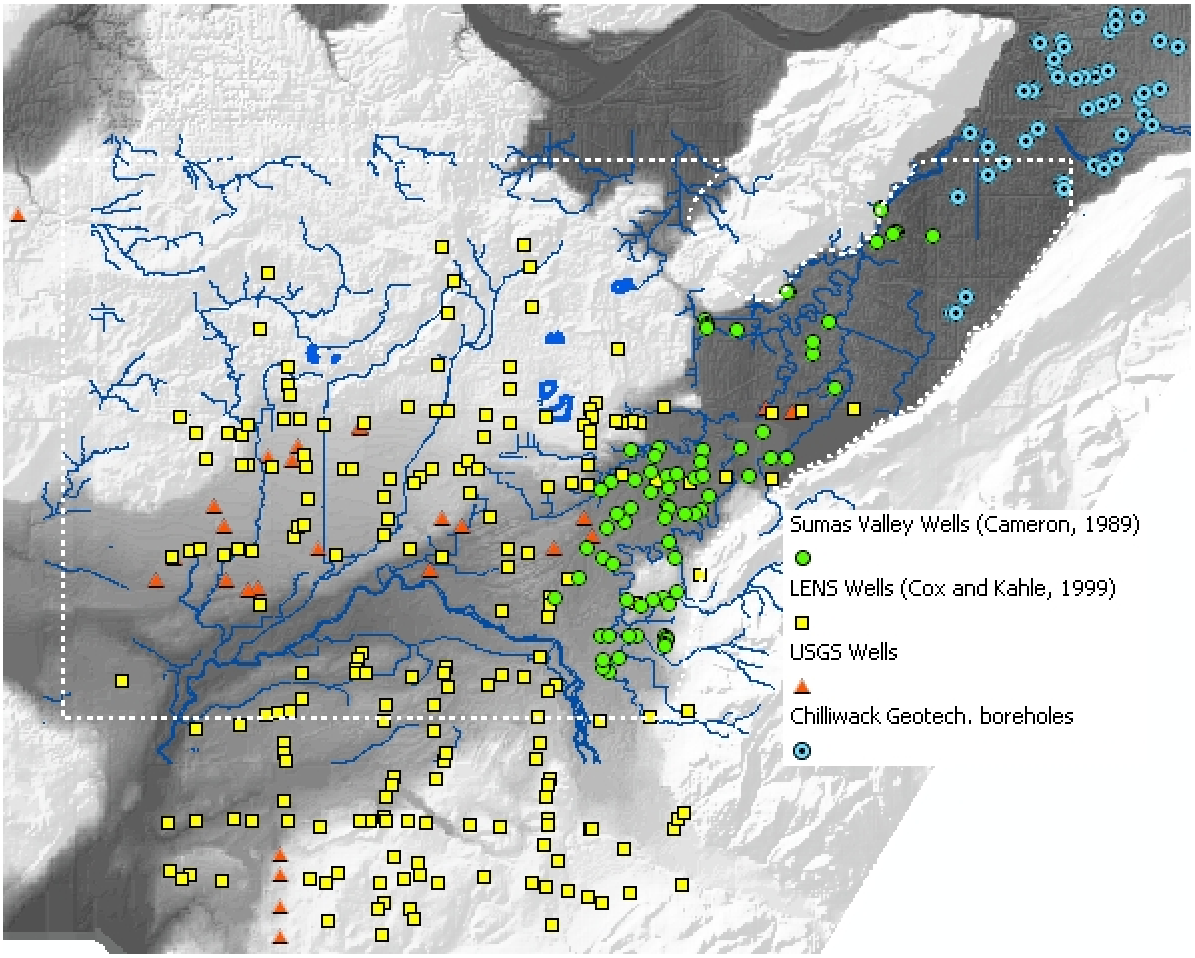
Formation: Describe by color, character, size of material and structure, and show thickness of aquifers and the kind and nature of the material in each stratum penetrated, with at least one entry for each change of formation.

MATERIAL	FROM	TO
Topsoil	0	2
Brown small gravel	2	8
Brown clay and sand	8	12
Gray clay, some sand	12	18
Gray sand & some gravel, water	18	29
Brown clay	29	31
Gray clay	31	33
Gray sand and some gravel, water	33	37
Gray clay	37	53
Gray ~~ws~~ sand & water, some gravel	53	63
Gray clay, some sand - lots of wood	63	68
Gray sand and some wood - water	68	83
Gray fine dirty sand - water	83	

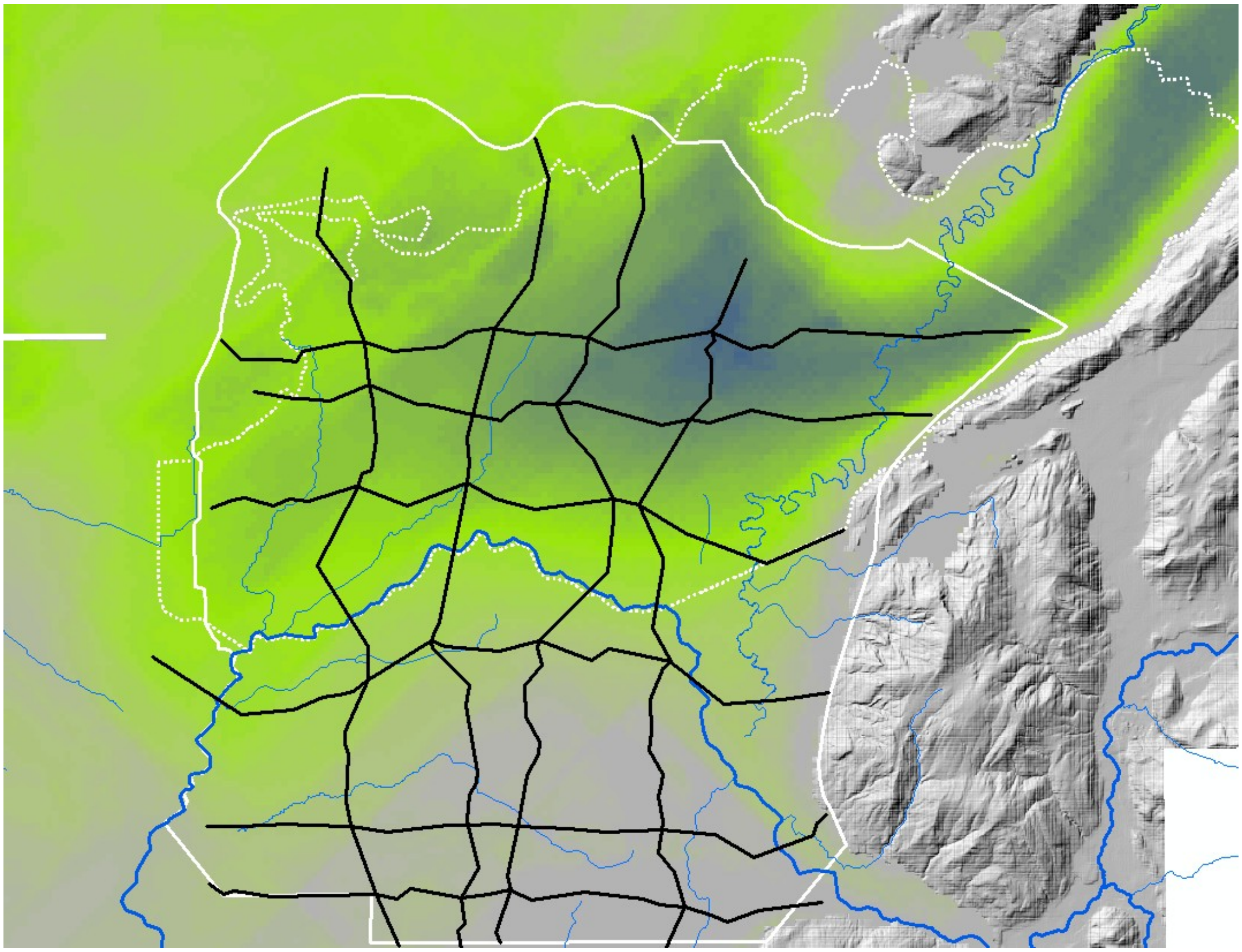
Map 18 Locations of boreholes with lithologs (used in this study) from BC WLAP and WA Ecology databases.



Map 19 Locations of boreholes with lithologs (used in this study) from USGS, the USGS LENS study (Cox and Kahle, 1999), Sumas Valley wells (Cameron, 1989), and Chilliwack geotechnical boreholes.



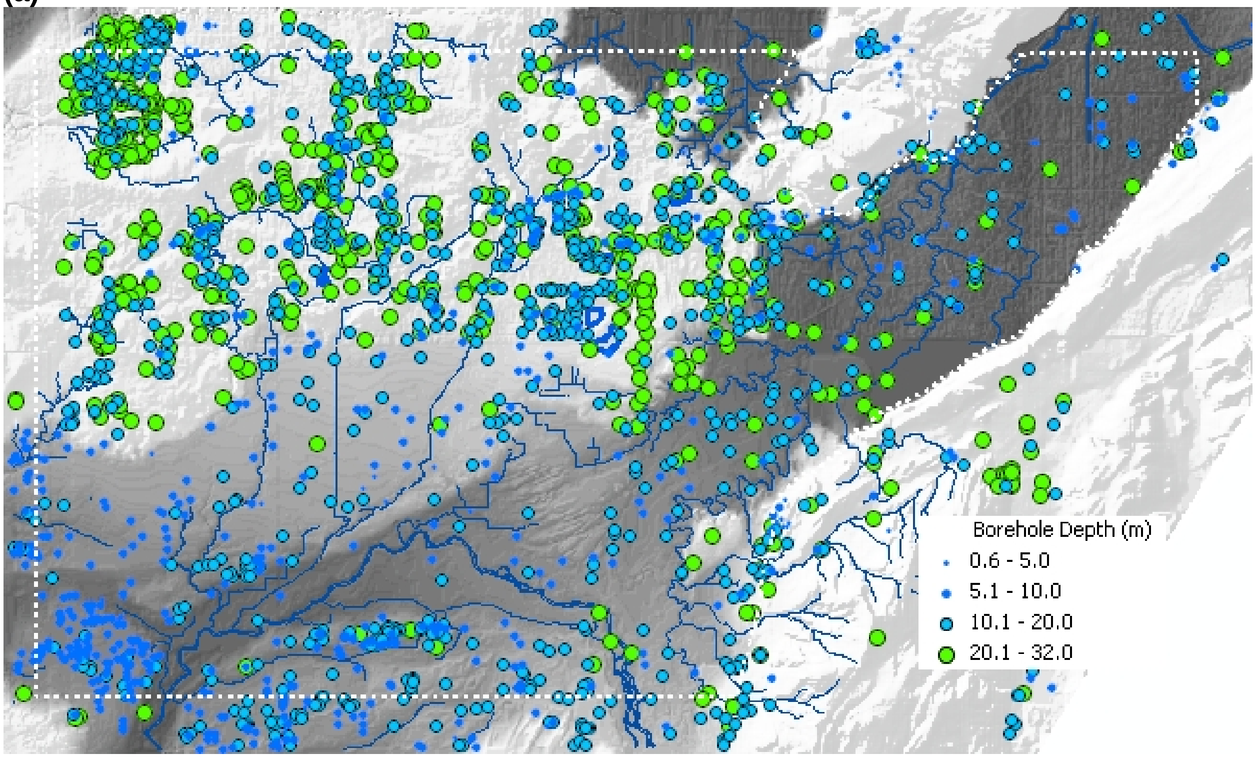
Map 20 LENS study cross-sections (Cox and Kahle, 1999). This map was created from source data and cross-section traces were digitized in GIS.



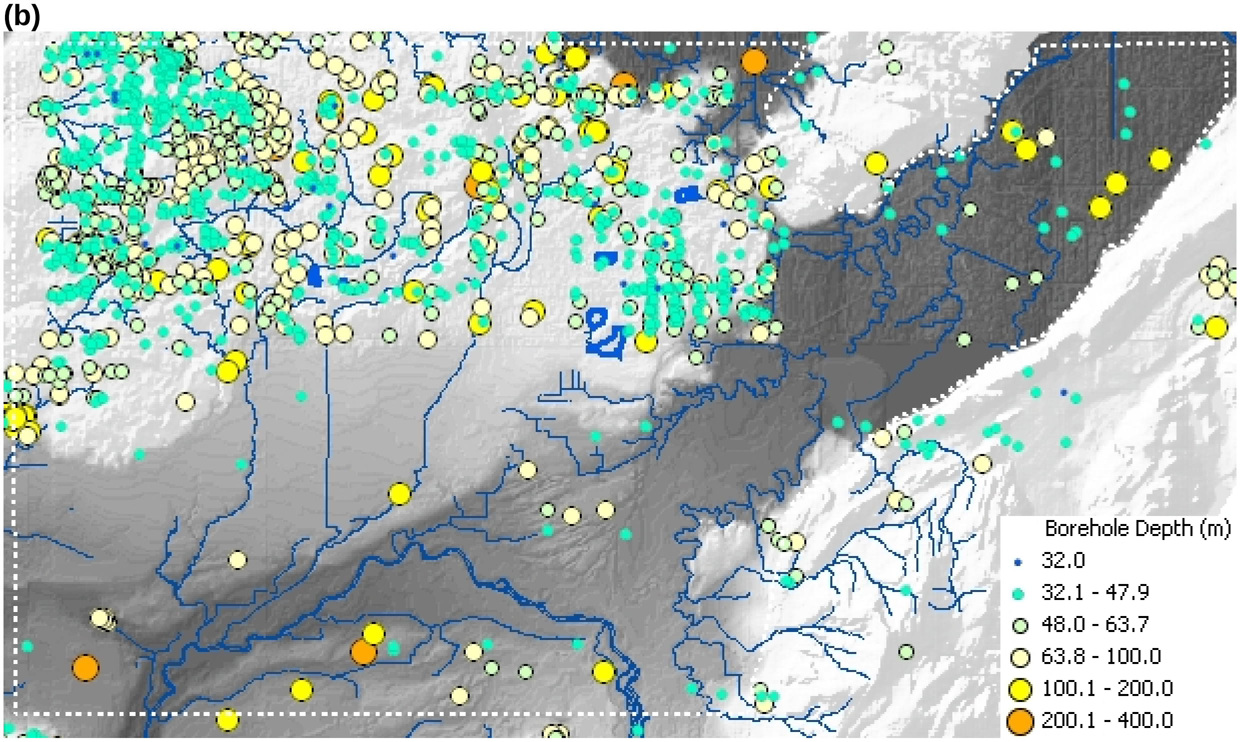
In the background is bedrock surface – coloured below ground, and shaded relief of bedrock outcrops. Nooksack River and Sumas Rivers are shown.

Map 21 Borehole locations and depths in central Fraser valley (all data sets): (a) shallow wells (0.6 to 32 m depth), (b) deep wells (32 m to > 200 m depth).

(a)



(b)



2.5. LITHOLOGIC DATA STANDARDIZATION

2.5.1. OBJECTIVES OF STANDARDIZATION OF BC WELL (BOREHOLE) LITHOLOGS

The primary objectives for standardizing well lithologs are:

1. to present litholog data in a standard format to enhance data value (allow queries, inter-comparisons, and spatial analysis);
2. to retain all the information from the existing lithology database;
3. too correct spelling mistakes, and translate all geologic descriptions into standard descriptors.

2.5.2. PROBLEM DESCRIPTION

A borehole litholog is a record of geologic materials encountered at different depths during the drilling process. The level of precision in such records varies between wells, and probably within each well. Numerous contractors and hydrogeologists have worked on groundwater wells in BC. The variables are quality of expertise, field conditions, drilling purpose, cost of drilling, well depth and size, litholog translation into the database, and database management. All lithologs follow a format that identifies the top and bottom depth of each layer, and give a description of lithology encountered at each depth interval. The choice of words varies slightly to significantly between different lithologs, even those that describe the same material type.

For example, consider a layer of unconsolidated deposits consisting of sand (60% by volume) and gravel (30% by volume) with properties of fine to medium grain size in each, brown in colour, and containing some silt (5% by volume). This lithology description could be worded according to i = 1 to n different sentences as shown in **Table 5**.

Table 5 Varieties of descriptions for potentially the same lithology

1	*brown fine to medium sand and gravel, and some silt*
2	*silty sand & gravel, fine-medium, brown*
3	*sand, fine to medium, brown & silty, gravel, fine to medium*
4	*brn. fn./med. sand & gravel with silt*
5	*silty sand and gravel*
6	*sand with gravel*
7	*sand*
...	
n	

Each of these descriptions is unique, ambiguous to some extent, and typical of lithologs in the BC database. Some authors describe more lithological details than others, and the degree of generalization varies as well. Furthermore, the complexity is increased by frequent non-standard abbreviations and word misspellings, grammatical ambiguities, and variable delimiters (comma, slash, space).

When using these data some assumptions apply:

1) The descriptions can be taken literally and describe the actual lithology of the site where the borehole was drilled. Wells can be assigned litholog quality designations that can be used for weighing the data in further analysis. These are subjective criteria and may be based on the amount of detail written in a litholog; date of drilling, well size, depth, and purpose, noting that larger hydrogeologic studies usually involve professional hydrogeologists.

2) Each litholog can be successfully interpreted as the authors meant it to be. Therefore, lithologs that are too ambiguous cannot be used.

3) The data are output correctly from the database. In each litholog, the data have to be matched to the right well identifier (Well Tag Number – WTN), the sequence of layers has to be correct, and the depths of layers must be in the correct order.

2.5.3. PRE-PROCESSING OF TEXT FILES

Lithology data are stored in BC government's database, which is publicly accessible via a website. Well lithologs can be downloaded one well at a time, or for whole BCGS mapsheets. A typical text file output for one mapsheet from that database is provided in **Table 6** (2 lines shown):

Table 6 Portion of a typical text file output for a mapsheet in the BC Water Well Database

```
BCGS 082E008421 # 1 wtn 000000076552 UTM Zone 11 Easting Northing UTM Code From 6 To 7 Ft. BROKEN
ROCK MOIST CLAY Seq# 2 Water Depth 3.4 Yield 30 Gallons per Hour (U.S./Imperial) Screen from to
PT
BCGS 082E008421 # 1 wtn 000000076552 UTM Zone 11 Easting Northing UTM Code From 0 To 6 Ft. BROWN
SAND & GRAVEL COBBLES Seq# 1 Water Depth 3.4 Yield 30 Gallons per Hour (U.S./Imperial) Screen
from to PT
```

This information can be parsed by a computer program or manually on a spreadsheet to separate the data fields. An in house code was developed as part of this study to undertake these manipulations. The resulting parsed dataset contain various fields: BCGS mapsheet number, a sequential well number for that mapsheet, a well tag number (WTN) that is unique to BC, UTM coordinates, layer top and bottom depths, layer lithology description, sequence number, and additional well information, such as yield and screen depth.

This pre-processing of text is followed by sorting the input lines by mapsheet, then by well tag number, and finally by litholog line sequence number within each litholog. The data are stored in the program in arrays for further processing (**Table 7**).

Table 7 Data storage format for well litholog data

```
From 0   To 20  Ft. silty sand and coarse gravel           # 1
From 20  To 22  Ft. sand and coarse gravel                 # 2
From 22  To 28  Ft. grey/brn med. sand  few pebbles        # 3
From 28  To 48  Ft. grey/brn med. sand-coarse gravel  few  # 4
From 0   To 0   Ft. pebbles up to 2''                      # 5
From 48  To 84  Ft. grey/brn med coarse sand some gravel   # 6
From 0   To 0   Ft. few pebbles.                           # 7
From 84  To 136 Ft. gry/brn med coarse sand  trace med     # 8
From 0   To 0   Ft. gravel at 117'.                        # 9
From 136 To 156 Ft. gry/brn fn-med sand  trace silt        # 10
```

One technical difficulty with the format for the BC database is the coding of depth values. A set of rules was implemented to recognize when litholog descriptions for a single layer with given depth were stored on multiple sequence lines (the depths were repeated or were 0 and 0) as in sequence 4 and 5 in the above example. The program combines the text from multiple lines for one litholog layer, and in the processed text each sequence number corresponds to a unique layer in each litholog. In some wells, the first sequence line contains information about the bedrock or a summary of the entire litholog. These lines are recognized by comparing the depth order to all the other depths in other layers. Lines in the wrong sequence order, which are not a continuation of another line, were moved to the proper spot in the litholog sequence. A more serious problem was encountered where depths had logically incorrect values when compared to the rest of the sequence. These wells were flagged for visual inspection and not processed further.

A multi-dimensional array of mapsheets, wells, and their lithologs was then processed further. At this stage a litholog layer is the smallest unit of data aggregation. An array of litholog data for one well is shown in **Table 8**.

Table 8 Example of a litholog array for a single well

```
1   0  20 silty sand and coarse gravel
2  20  22 sand and coarse gravel
3  22  28 grey/brn med. sand few pebbles
4  28  48 grey/brn med. sand-coarse gravel few pebbles up to 2''
5  48  84 grey/brn med coarse sand some gravel few pebbles.
6  84 136 gry/brn med coarse sand, trace med gravel at 117'
7 136 156 gry/brn fn-med sand trace silt
```

2.5.4. WORD RECOGNITION PROCESS

For each litholog layer in each well in each mapsheet, the text is broken up into word groups as delineated by word separators in the original text. These can be commas, slashes, or other characters. Periods after words are removed from the text because they are used in abbreviations, but decimal points in numbers are preserved. The word groups preserve the grammatical structure of the source text.

In the word recognition process, each word is read separately (words are considered to be space delimited within a word group) and compared to a custom dictionary of geological terms.

This dictionary consists of lists of words and their alternative spellings for different categories of words, based on grammatical meaning. These lists were developed for words describing rock and unconsolidated sediment materials (e.g., “granite”, “sand”), words specifying grain size, colour, sedimentological structure or rock structure (e.g., “interlayered”), modifying words such as “sandy” or “wet”, hydrogeologic terms, words describing technical aspects of well design and drilling process, and special words used to recognized grammatical relationships between words (e.g., “and”, “to”). One list also links some modifying words to material types such as “sandy” to “sand”.

For each word in the dictionary there may be many alternative spellings, abbreviations, and synonyms. For example, the colour “brown” is often written in lithologs as “brn” or “brwn”. In extreme cases, a commonly used word “gravel” is spelled in all of the following forms in the database: “gravel”, ”grav”, “grv”, “gravels”, “grvl” in a combination of lower and upper case letters. Therefore, each word is also converted to lower case as a default.

Word recognition reaches practical limits where words are badly misspelled, joined together (missing separator), or totally ambiguous. The program also outputs a list of unrecognized words, which are checked by the user who then updates the appropriate word lists. The program is re-run for the entire database until all important words are recognized by the program. This process may take a long time. For example, the text “*fn. to med. gry. sand & grav. with coarse gravels*” is recognized as “*fine-medium grey sand and gravel and coarse gravel*."

2.5.5. MATERIAL PROPERTY ASSIGNMENT

The largest challenge in this program concerns grammatical structures of litholog text. In that text there are descriptions of different materials (rock or unconsolidated deposit) and their properties. The materials are also arranged in order of importance, where usually the most abundant material is specified first, and all other subsequent materials are present in smaller amounts. There are exceptions, identified by such as words as “and”, which relate two materials as being equally abundant in a layer. For grain size ranges, the word “to” links “size” descriptors such as “fine” or “coarse”, and “-“ dash character may also be used instead of “to”. The modifying terms such as “silty”, when combined with a material such as “sand” have a special meaning, from which two separate materials “sand” and “silt”, the silt being the lesser amount, must be extracted to standardize this text. The complexities grow exponentially with poorly constructed sentences and ambiguous sentences.

The goal is to extract all the materials and all separate properties, in standard form, from all lines in all lithologs. This task involves an iterative process of test-and-run to verify the results and modify the program. The practical limit is in cost of program development to correctly standardize the largest possible number of lithologs in the database. It is most economical to train the program on about 5% of the cases, let the program handle about 80% of the cases, and verify the remaining 15% cases by visual inspection without further modifications to attempt to improve the program. Software that would successfully recognize > 95% of the lithologs with proper grammatical relationships would be able to almost mimic a human being, and is thus impractical to develop because of complexity.

2.5.6. STANDARDIZED LITHOLOGS

The output of standardized lithologs is a text file with special fields for WTN, layer number, layer class, depth to top of layer, depth to bottom of layer, thickness, material 1, modifier word, grain size, color, structure, material 2 ... (all the properties) ... material n ... (all the properties), hydrogeology terms, drilling terms, and original source text. The original source text must be retained until the database is completely standardized, but should be kept for process verification indefinitely. The number of materials is unlimited in each layer, but it is most practical to have less than 4 materials for unconsolidated sediments. Bedrock wells usually identify a single rock type for each depth interval unless a more detailed mineralogy analysis has been done.

Table 9 shows an example of a non-standardized litholog for one well. The standardized litholog for the same well is shown in **Table 10**. The standard forms can also be formatted to show the relative thickness of each unit to improve depth perception and litholog interpretation. Standard forms can be queried in a database environment using SQL statements or other methods, and layers can be generalized for spatial and structural analysis.

Table 9 Example of a non-standardized litholog

```
coarse gravel and silt
 clean coarse sand and small w b  gravel
 very coarse sand/ coarse gravel and fine silt
 coarse sand and med  sand
 med  sand/ thin clay layers and some boulders
 med  and coarse sand/ fine sand and silt
 coarse gravel with clay layers
 coarse sand and some gravel
 medium sand with pebbles
 gravel/ some sand
 very coarse gravel/ very little sand
```

Table 10 Standardized litholog output from in house standardization code

[WTN]	[layer num]	[layer class]	[depth (top of layer)]	[depth (bottom of layer)]	[thickness]	**[material(1)]**	[modifier]	[size]	[color]	[structure]	**[material(2)]**	[modifier]	[size]	[color]	[structure]
22427	1		0	24	24	gravel		coarse			silt				
22427	2		24	50	26	sand	clean	coarse			gravel		fine		
22427	3		50	57	7	sand		very-coarse			gravel		coarse		
22427	4		57	69	12	sand		coarse			sand		medium		
22427	5		69	75	6	sand		medium			clay	thin			layered
22427	6		75	86	11	sand		fine-coarse			silt				
22427	7		86	87	1	gravel		coarse			clay				layered
22427	8		87	90	3	sand		coarse			gravel	some			
22427	9		90	95	5	sand		medium			pebbles				
22427	10		95	102	7	gravel					sand	some			
22427	11		102	116	14	gravel		very-coarse			sand	some			

2.6. LITHOLOG DATA CLASSIFICATION AND INTERPRETATION

Rules were developed for litholog classification, which were used as guides for constructing the original cross-sections. Computer code was written to apply the rules and produce representative (interpreted) material types for all intervals in all lithologs. The classification is simple when only one material type is present because the classified material is the same as the constituent material. For mixtures, the following rules were applied. These rules are not ideal, may be modified, and attempt to capture the important hydrogeologic properties of the subsurface materials. The presence of clays and silts with, or interbedded with, other materials is more significant than the opposite. Not all borehole lithologs have the same quality. Quality here refers to the amount of detail recorded and accuracy of descriptions.

Gravel

Gravel is the most common grain size present in material 1 to 3 in water well lithologs in this model area. The question is then to distinguish relative importance of other materials as opposed to just gravel. For example, in the Abbotsford uplands, the main recharge area of the Abbotsford-Sumas aquifer, gravel is the dominant material, followed by sand and larger boulders, and locally clay and silt. The clays occur in lenses associated with tills, and silt content may vary in the sand matrix of those gravels. Small silt lenses may be present, but silt is more common as lacustrine deposits in the Sumas Valley, which experienced more lacustrine flooding and deposition, while the Abbotsford uplands were the location of Abbotsford outwash plain. Therefore, a detailed knowledge (in 3 dimensions) of the depositional environments would be required to properly interpret borehole lithologs from water well records, in all intervals containing gravel and other materials. Even the presence of only gravel as the recorded material does not guarantee that only highly permeable clean gravel was drilled through. Clean gravels are rare except in lenses of fluvial or glaciofluvial deposits. The main source of error in distribution of hydraulic conductivity for the groundwater flow model in this area comes from our inability to adequately map highly conductive gravels and sand, and less conductive "dirty" gravel and sand mixtures that contain some finer grained materials, which lower the hydraulic conductivity. Typically, the difference can be as much as one order of magnitude. For example, 300 m/d for clean gravels and sands, and 20 m/d for dirty gravel. From most of the well lithology information, it is impossible to distinguish these high and low zones. Model calibration helps to indicate areas where less or more hydraulically conductive sediments are located, as compared to those originally mapped. Here, the flow model calibration process, the spatially-distributed residuals and clusters of residuals, provide a feedback to the hydrostratigraphic model, and thus, to our understanding of Quaternary geology of the area.

If the only materials are gravel or cobbles then classify as gravel.

- *gravel + cobbles (or boulders) = gravel*
- *sand + gravel = gravel (if gravel is the dominant material)*
- *gravel + clay or silt = NOT gravel (see clay or silt classification)*

Sand

Sand material type usually occurs with other materials, and most commonly with gravel. If the driller's logs were all consistent and recorded the materials in the correct proportions, the occurrence of sand and gravel in material 1 and 2 in the log sheets could be interpreted as sandy gravel, or sand with some gravel, or sand with gravel lenses, or vice versa if sand was the secondary material and gravel first. For the purpose of this aquifer model, the occurrence of sand alone in the litholog was interpreted (due to lack of other information) as pure sand (fine to coarse – unknown grain size distribution). Sands are associated with deltaic deposits, beach deposits (here these are usually marine, but could be lacustrine in Sumas Valley, or even aeolian).

The rules used in litholog classification for sand as primary material were:

- *sand + gravel = sand*

Clay

In the central Fraser Valley, clays are present in most deep lithologs at some intervals, and are present in most of boreholes in Langley uplands where Fort Langley Formation glaciomarine stony clays outcrop at ground surface or lie beneath thin sands or gravels of Sumas drift or other coarse grained sediments. Clay is almost exclusively associated with clay-rich tills, as it is know from Quaternary geologic history of glacial retreats and small re-advances at the margin of the ocean, complicated by changing sea levels. Near ground surface, there are relatively small clay-rich till lenses embedded in the gravels and sands of Sumas Drift in the Abbotsford uplands. It would be tempting to use “till” classification here instead of clay, but till is a genetic term, of depositional environment, and there are many till types, so it would only complicate matters and create potential confusion. The simplest method of using primary materials in the borehole lithologs was selected, and the intervals containing predominantly clay, or at least clay as secondary material (which suggests some type of till), were classified as clay material. Therefore, most “clay” intervals inherently contain mixture of sand, gravel, boulders, or silt.

We expect that many lithologs confuse silt with clay, but that is beyond the scope of this project to check those source data. From groundwater flow point of view, clay and silt both have lower hydraulic conductivity than sands and gravels of the aquifer units, thus the error is expected to have small effect on modeled flow patterns. Therefore, if clay contains silt, or is interbedded with silt, classify as clay, then the following rules are applied:

- *clay + silt = clay*

If clay is present as a minor constituent or trace amount, and it is a thin layer, then ignore clay.

- other material + trace clay or thin clay layer = other material

If clay is present as a major constituent, then classify as clay.

- *other material + clay = clay*

Silt

Small silt lenses may be present, but silt is more common as a lacustrine deposit in the Sumas Valley, which experienced more lacustrine flooding and deposition. Small silt lenses are often recorded as “hardpan” in well lithologs. These are thin and have small aerial extent.

If silt is present as a minor constituent or a trace amount, and is a thin layer, then ignore silt.

- *other material + trace silt or thin silt layer = other material*

If silt is present as a major constituent, then classify as silt.

- *other material + silt = silt*

Bedrock

Bedrock should be present as the only material, but sometimes bedrock fragments can be mixed with other materials near the bedrock surface. In that case, classify as the other dominant material. For the purpose of this study, the mineralogies of bedrock were not differentiated.

Soil and surficial fill

Soil and fill were ignored. These are very local in extent and are usually in the unsaturated zone, so do not play a major part in groundwater flow. The types of surficial materials determine infiltration rates, but this component of the study focused on subsurface stratigraphy. Soil is considered in recharge modelling (Scibek and Allen, in prep).

Thin layers

Some thin layers represent local lenses of materials, while others are part of larger, but thinning, continuous layers. For interpolation purposes, some layers were aggregated into larger more generalized layers, some thin layers were preserved, and others were ignored. During interpolation, these decisions may be changed to provide better fit to data. However, the borehole density is insufficient in some locations to resolve the detailed stratigraphy.

- preserve all clay layers as these are important for groundwater flow (retard it)
- preserve silt layers if the thickness is significant (the threshold can be adjusted)
- if clay is interbedded with thinner layers of other materials, then generalize this group of layers as clay
- (same as above for silt)

Interlayering

All intervals were preserved. The hydrostratigraphic units were mapped by visual examination in three dimensions of all borehole lithologies together. The geology was filled in and re-interpreted through many "passes" and was interpreted again after initial model calibration indicated incorrect initial geologic interpretation in selected areas.

2.6.1. CLASSIFICATION RESULTS

The actual implementation of rules was done in VB code and run on an Excel spreadsheet with the litholog database. This method provided a quick and visual environment for data manipulation. In the "big picture" the frequency of occurrence of each material class and average thickness is very helpful in selecting appropriate aggregation rules and selecting appropriate material classes - graphed in **Figure 6**. The upper graphs with the blue bars show mean thickness of litholog units (intervals of unique material class) and standard deviation (variability) in thickness, respectively. The bottom bar graphs have frequency histograms of material class occurrence in these litholog intervals. The results of the second classification pass are on the left side, and results of third classification (with fever classes due to aggregation) are on the right.

1st classification

Hundreds of combinations of different materials within lithologic intervals were simplified into 39 classes of materials, usually by binary pairings of materials (e.g., silt / sand, gravel / sand) – see **Table 11**.

2nd classification

The 39 classes of materials were aggregated into only 14 classes. The most abundant sediment types, according to this classification scheme, were "gravel / sand" and "sand". This is because of bias toward shallow wells in the valley sediments (aquifer is productive even at shallow depths). Other common materials were “gravel”, “gravel or coarser” (boulders etc.), “silt” and “unknown” sediments. Unknown refers to missing intervals in lithologs (but these were usually thin as shown in thickness histogram). The other common materials were relatively thick (6 to 10 m) when they occurred. Material thickness statistics are shown in **Figure 7** as an example.

Clay and related (“clay and coarser”, “till”, “silt and clay”) were much less common in lithologs, but tended to be thick (especially “clay” having 10 m mean thickness). “Silt” as the only material was rare and moderately thick. Surficial “fill” was very insignificant and thin – see Figure 6.

3rd classification

In the 3rd classification pass, the fine grained materials were grouped together (e.g. “clay” and “clay and coarser” and “silt and clay” ---> “clay”, “silt” and “silt and clay” -----> “silt”). The coarse grained materials were also grouped (“gravel” and “gravel and coarser” ----> “gravel”). Some categories such as “gravel / sand” were not changed as these represent large number of intervals in lithologs and are relatively thick.

Figure 8 shows a digital orthophoto from below (inverted view), looking west on Tertiary bedrock topography (shaded relief and colour fill), and colour-coded borehole lithology intervals protruding downward from ground surface. The pink long borehole is an old exploration borehole that only recorded depth to bedrock and other bedrock mineralogies. Most of the water well holes are relatively shallow compared to total overburden thickness in this area.

Figure 6 AB-SUM aquifer litholog classification histograms of material occurrence and thickness: material classes in lithologs after 2nd and 3rd aggregation-reclassification pass using computer code written to follow the classification rules.

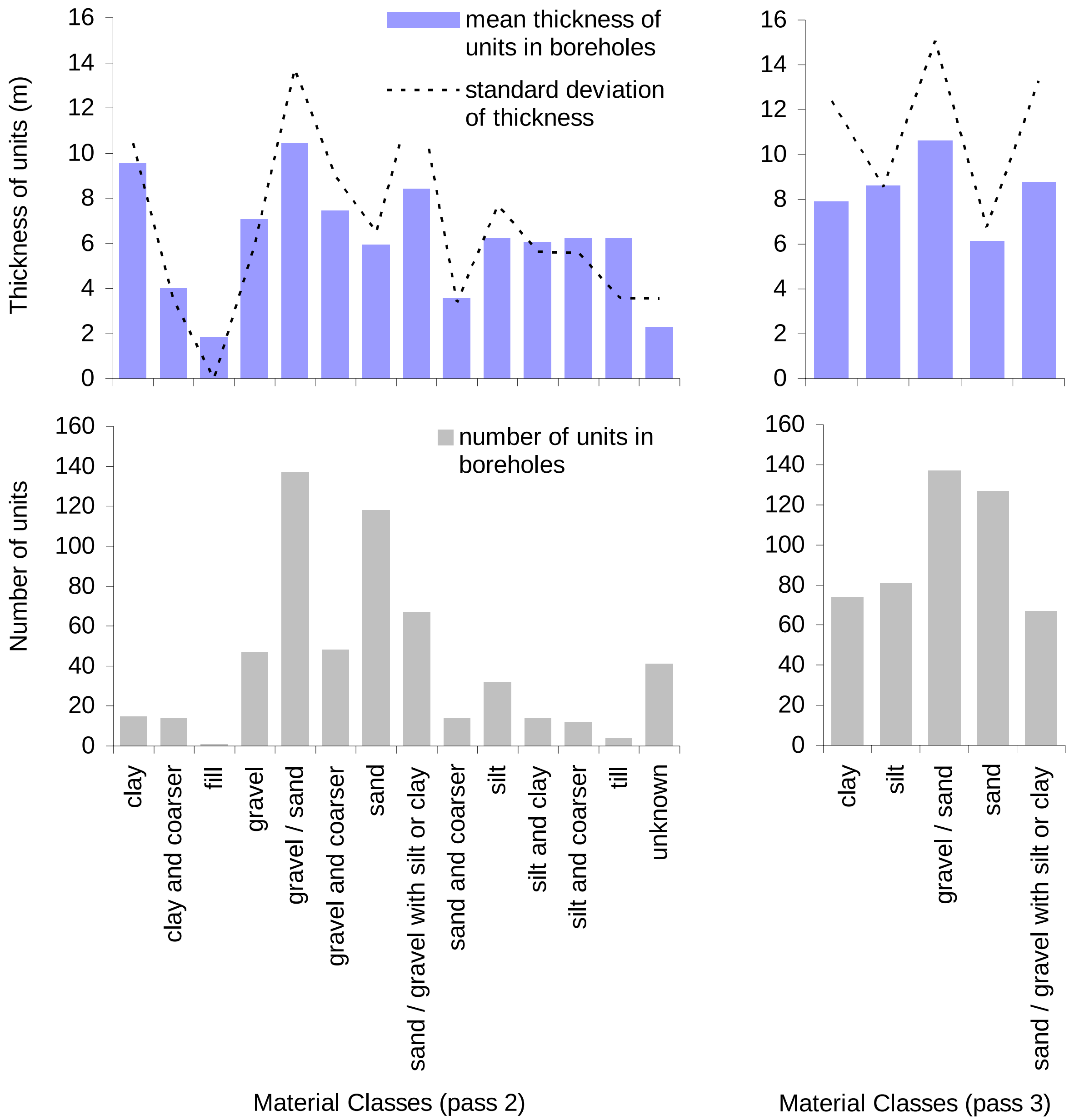


Figure 7 Material unit thickness for 10 material classes (after 1st reclassification).

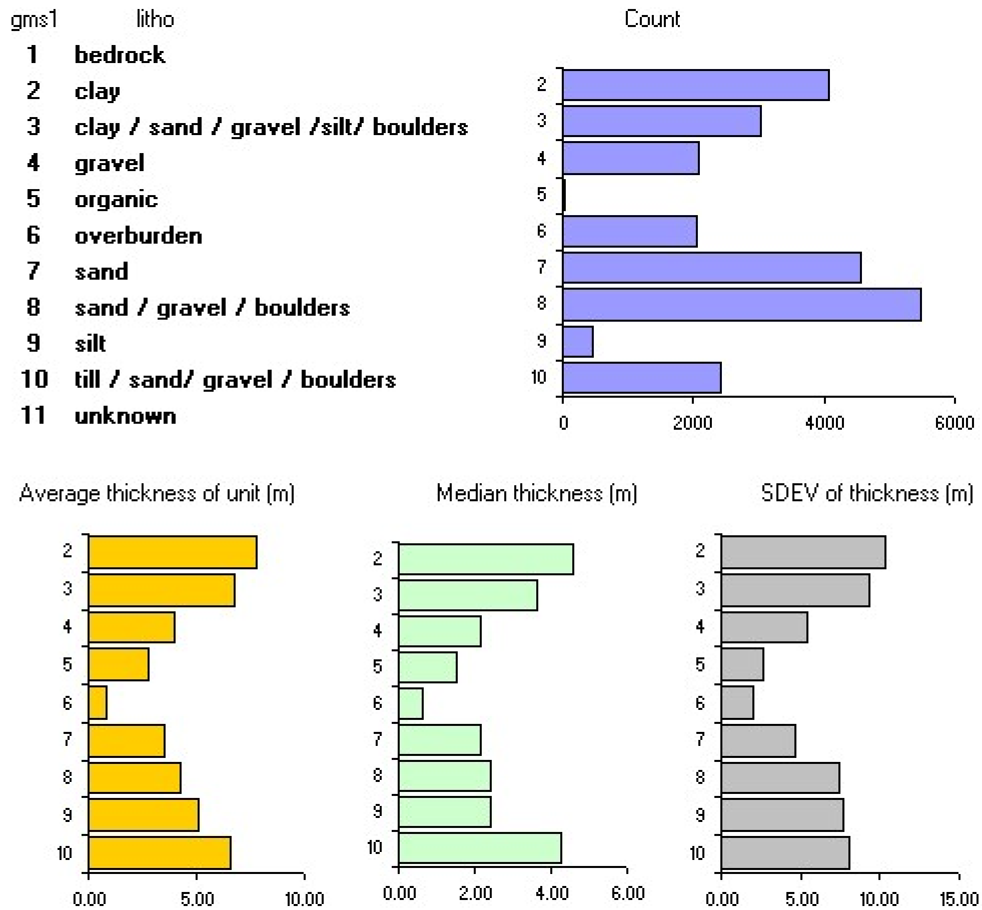
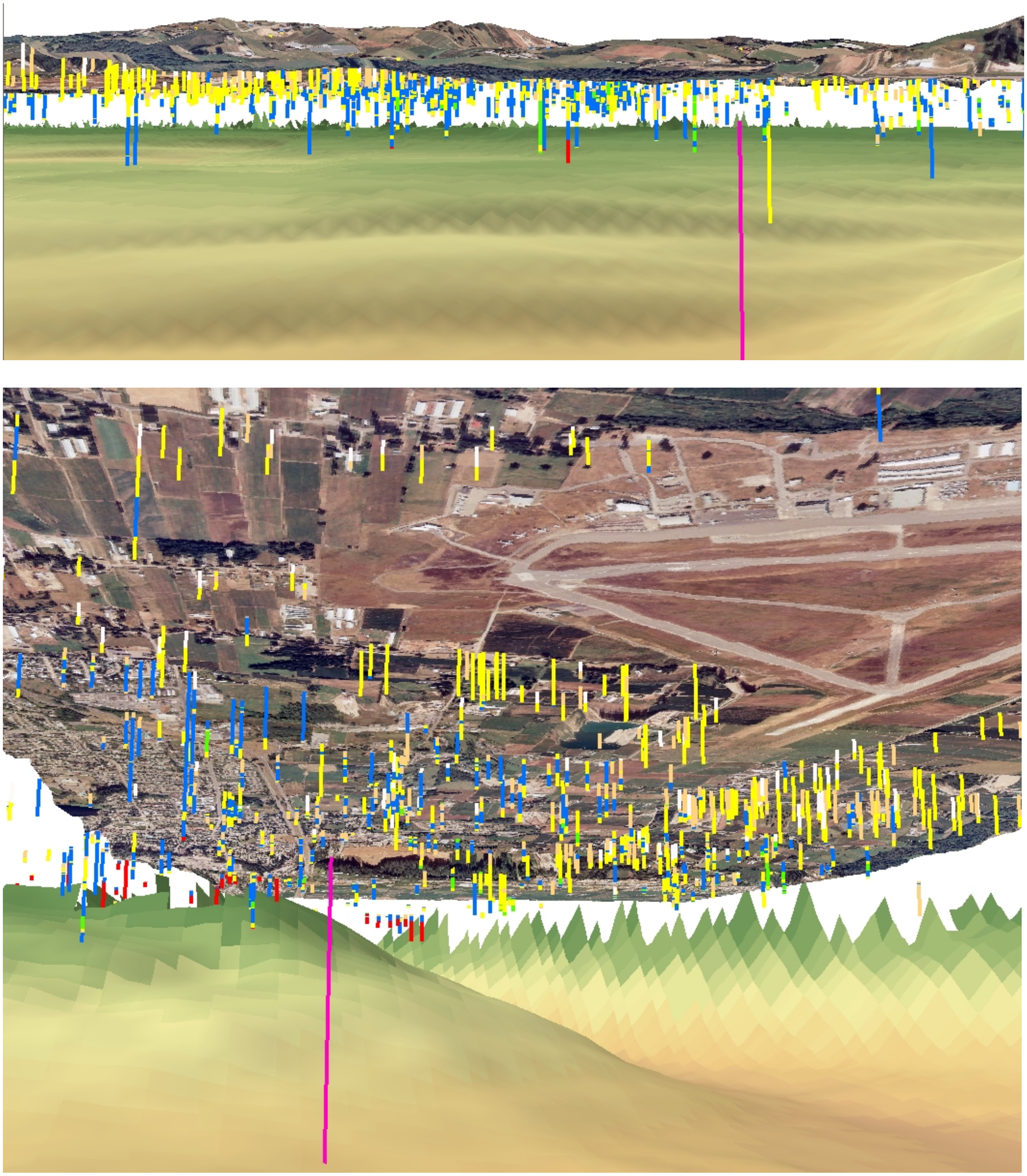


Table 11 Rules used in 1st reclassification.

delete		**replace**		**reason**	
1	bedrock	delete all below		not needed	will use bedrock surface
5	organic	below unit		thin and rare	
11	unknown	above or below unit		must fill space	assumption
6	overburden	below unit		thin and not needed	usually similar to what is below
preserve		**reclassify**		**reason**	
2	clay	4	clay	common and thick	
7	sand	2	sand	very common and med thickness	important for aquifers
9	silt	5	silt	rare but thick	
join		**reclassify**		**reason**	
3	10	3	till	similar mixture of materials (cannot determine which more important)	
4	8	1	gravel / sand	gravel is often a misture of sand / gravel / larger clasts	

Figure 8 Perspective view of borehole lithologs above bedrock surface in central Fraser valley.



3. HYDROSTRATIGRAPHIC MODEL – CONCEPTUAL HYDROGEOLOGIC MODEL OF SUBSURFACE

3.1. PREVIOUS ATTEMPTS AT 3D MAPPING OF THE ABBOTSFORD-SUMAS AQUIFER FOR THE DEVELOPMENT OF A NUMERICAL FLOW MODEL

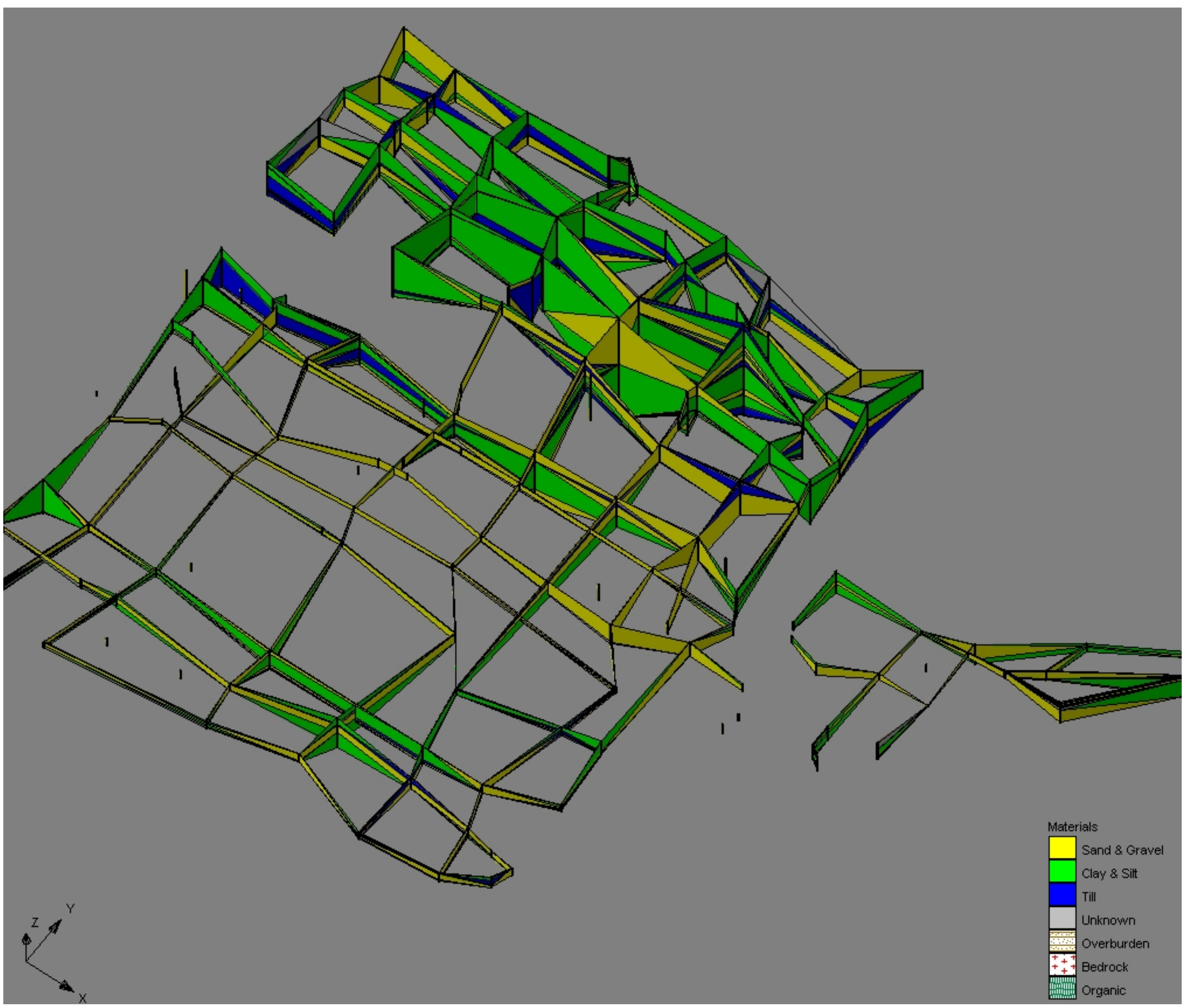
The original 3D mapping of the Abbotsford aquifer (only extent in BC north of US-Canada boundary) must be credited to Halstead (1986), who produced series of detailed fence diagrams and maps showing interpreted aquifer units and depths of water wells (**Figure 2**). Halstead's work preceded numerical flow modeling, and the products were paper maps and not digital database or CAD drawings. In mid 1990's, the GSC (Ricketts, 1994) produced the first digital databases and numerical flow models of the Fraser Delta area, but the program was cancelled in late 1990's and the Abbotsford aquifer was never modelled or studied in detail. The Fraser Delta projects were linked to liquefaction hazard studies in that area. The GSC did attempt to use GPR (Ground Penetrating Radar) in the Brookswood Aquifer (west Langley area). The GPR produced some insights into shallow (down to 10-20 m) aquifer heterogeneity. However, no layers or cross-sections were formally published for the Abbotsford area. For the purpose of this study, the GSC projects produced very important information on the surface of Tertiary bedrock surface (discussed earlier), and a general framework of the hydrogeology of the Fraser Valley (Ricketts and Liebscher, 1994).

In Washington State, the USGS did a major water resources investigations study (WRIA I) and produced maps and cross-sections from selected high quality boreholes, including overburden thickness (Cox and Kahle, 1999). One of the authors worked on MSc project in the Sumas area and produced cross-sections in paper format (Kahle, 1991). In the Nooskack River valley area, the surficial aquifers were studied by Tooley and Erickson (1996) at WA Ecology, resulting in more cross-sections and maps. The USGS project (1999) also produced, now the most up to date and extensive – and useful, cross-sections and maps, but finally digital GIS databases were created, and these were used in this study, combined with Canadian and other US data sources. There were also small hydrogeologic projects carried out by consultants near various landfill sites, water supply well locations, proposed power plant sites (CH2M HILL, 1985; Golder, 1995; and others). The Sumas well head protection study (Associated Earth Sciences, 1996) by consulting firms reporting to City of Sumas, WA, produced a numerical flow model of the Sumas area. This model was relatively crude compared to one developed here, but it was the first report to indicate the hydrologic link between the Abbotsford uplands and the Sumas Valley, and the presence of low and high hydraulic conductivity zones in otherwise identical materials: outwash gravels.

When SFU began looking at the Abbotsford aquifer in 2002, the study area was extended south of the border, to include the Sumas aquifer in Sumas Valley, and also the Nooksack Valley and surficial aquifers there. The Abbotsford Aquifer International Task Force meetings and meetings with hydrogeology researchers in Bellingham, helped to delineate the study area. At SFU, Aparna Deshpande (MSc student) and Dr. Nadine Schuurman (Geography Dept.) and Dr. Diana Allen (Earth Sciences Dept.) worked on methods of borehole lithology standardization in geospatial databases, and specifically in BC water well database. That research resulted in standardized lithology database for the Abbotsford-Sumas aquifer, although it is less complete than final database used in the groundwater modelling of these aquifers. **Figure 9** is an attempt at hydrostratigraphic model of the Abbotsford aquifer by A. Deshpande, created from selected deepest boreholes. The image is a fence diagram from GMS (Groundwater Modelling System) and shows units "sand and gravel" (aquifer), "silt and clay", "till". "Till" was used as a material wherever it occurred in the lithology database. The geology shows thick underlying fine grained (if till is included in that category) units and shallow aquifer layers on top. There are localized thick aquifer units. Deshpande worked under the assumption of layered hydrostratigraphy in the study area – or at least the goal was to produce "surfaces" of various units after some "generalization" of the database. However, after much effort, Deshpande (pers comm. and M.Sc. thesis, 2004) reported that it was practically impossible to fit any "surfaces" to the very heterogeneous Quaternary sediments in that area. The authors of this report also evaluated that possibility, and rejected the layered approach of representing local geology as unworkable due to heterogeneity. In this aquifer, the heterogeneity of sediments is such that its impossible to fit any regional "geologic layers" or "hydrostratigraphic layered units", without reducing model resolution so greatly as to make it not possible to calibrate at a regional scale, and definitely not possible to calibrate to local conditions.

Deshpande's lithology database was later modified by more extensive error-checking (using VB code as opposed to Access queries), and about 20% more lithologs were added – by authors of this report. Most notably, the WRIA I (Cox and Kahle, 1999) high quality boreholes were added.

Figure 9 Hydrostratigraphic model by Deshpande (2004) after initial lithology database standardization.



3.2. HYDROSTRATIGRAPHIC MODEL OF THE ABBOTSFORD-SUMAS AQUIFER SYSTEM (THIS STUDY)

3.2.1. REPRESENTATION OF HYDROSTRATIGRAPHIC UNITS AND AQUIFER HETEROGENEITY IN THE MODFLOW MODEL

The approach here was to use the HUV package in MODFLOW 2000 (Waterloo Hydrogeologic Inc., 2000) to represent geology in a 3D grid, rather than assigning geologic layers (if any) to MODFLOW layer surfaces. The primary reason for standardizing the lithology database was to allow 3D (here 3D refers to perspective 2D view) computer representation and manipulation in geospatial databases and flow modeling software of the borehole logs. At first, the GMS 5.0 software was used to examine the information, but the very large quantity of data (> 2000 boreholes) slowed down the software so much as to make it not practical to use (**Figure 10**). The second solution involved use of ArcGIS 8.3 (ESRI, 2004) to display the boreholes in 3D, together with pre-defined MODFLOW surfaces (slices of the aquifer area without regard for geology, but thinning toward ground surface to increase resolution of mapping), ground and bedrock surfaces, and surficial geology polygons. One example of such view is shown in **Figure 11** (the view spans area of City of Abbotsford, east of the airport, and into Sumas Valley). The software (ArcScene module in ArcGIS 8.3) allows rotation, zooming in and out, in 3D, and proved to be very fast and easy to use. Lithologic materials were colour-coded for quick reference. In this report, the following colours are used to represent different lithologies: clay (blue), silt (green), gravel (orange), sand (yellow). Surficial fill or soil units were not displayed to simplify the materials to only 4 general types.

The mapping process took 3 months, and an additional month for local reinterpretation during model calibration. The goal was to fill the 3D space of the model domain with geologic materials, classed into lithostratigraphic units, based on borehole lithologs. The lithostratigraphic units were also used as hydrostratigraphic units by assigning hydraulic conductivity, porosity, and storativity values, such that some lithostratigrahic units could be joined with others by assigning identical K, n, and S values. Since the borehole records, after standardization processing, are very crude in most cases, the lithostratigraphic unit distributions were almost directly converted to hydrostratigraphic unit distributions (there were only 4 based on dominant materials). Locally, some refinement is possible (refinement is encouraged by the authors of this model – the model can be refined with new or existing data by simply defining new aquifer property zones as needed.

The MODFLOW grid was defined after initial examination of all information. Layers were created as slices (flat where possible), and thickening downward. Near ground surface, the layers were thin (3 m first layer, 5 to 10 m second in the uplands, 1 to 3 m in lowlands). MODFLOW requires continuous layers and some judgment was required to create appropriate slice elevations. This was done through GIS, where elevation zones were created for each slice surface, then imported to MODFLOW as xyz surface elevation points. The surfaces were displayed in GIS during the mapping process (see **Figure 12**). For example, to map geology in layer 4, the surface of bottom of layer 4 would be displayed, effectively truncating all deeper lithologs in the view, and surface of bottom of layer 3 could be switched on and off, to constrain the mapped litholog intervals. Mapping was done city block by city block (street network and drainage network were used as orientation guides), small area by small area, directly into Visual MODFLOW sotfware (WHI, 2004), by "painting" zones of geologic materials on the MODFLOW grid in each layer. In each small area, all boreholes were examined from many views, through all layers, checking with surficial geology, and also viewing row and column cross sections of

MODFLOW grid with defined (colour-coded) material zones.

To restate the objective, the goal was to map lithostratigraphy into as many zones as required. In MODFLOW, the zones represent hydraulic conductivity zones. Therefore, this method of mapping geology bypassed many difficult steps of mapping 3D solid regions of geology onto MODFLOW cells and defining hydraulic conductivity zones. In this project, the standardized lithology database contained only one type of sand, and one type of gravel (just the primary materials as dominant), but if there were more subtypes, those could be mapped in the same process, creating more different zones in MODFLOW, that could be later merged by assigning identical properties.

After initial model calibration attempts, there were areas with large residuals that did not respond to changes in hydraulic conductivity within reasonable range for each mapped K-zone (hydrostratigraphic unit zone). In those areas, the geology was re-interpreted again from borehole lithologs, this time with much more attention to possible interpretations and keeping in mind the model residuals, surficial geology, and looking at individual borehole records to verify standardized lithologic units. In many areas, there are many possible interpretations of local geology due to poor distribution of boreholes. The interpretation favouring diminishing of the model residuals was selected and the geology re-mapped in that area. Therefore, the groundwater flow model was used as another piece in the puzzle of the subsurface geology in this area – the attempt to explain groundwater levels, flows, existence of lakes and other features, gives additional information to help interpolate the geology from poorly distributed boreholes.

Figure 10 Lithology log database used for construction of hydrostratigraphy.

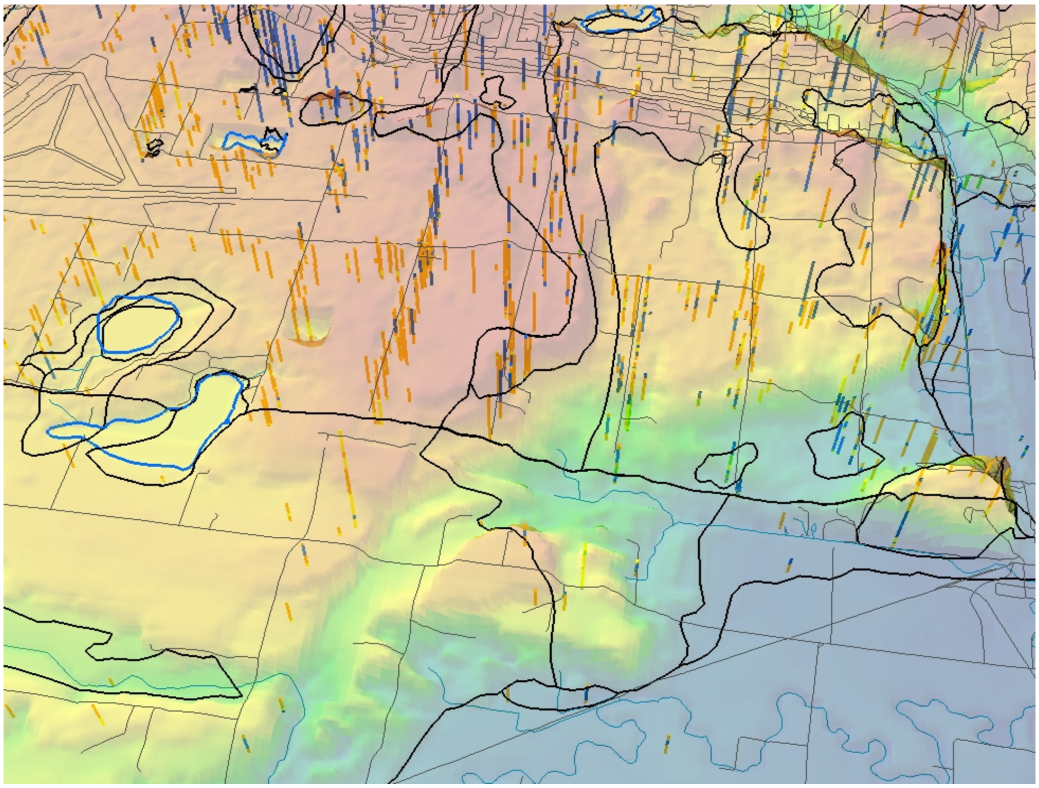


Figure 11 Litholog database in 3D view intersected by MODFLOW surfaces, (b) Viewing lithologs in ArcScene, mapping onto MODFLOW cells in Visual MODFLOW.

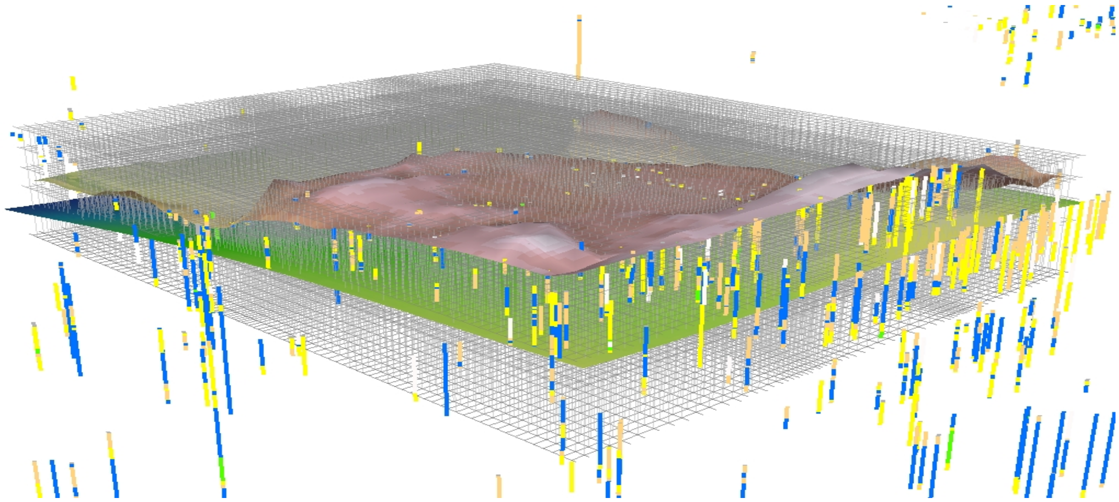
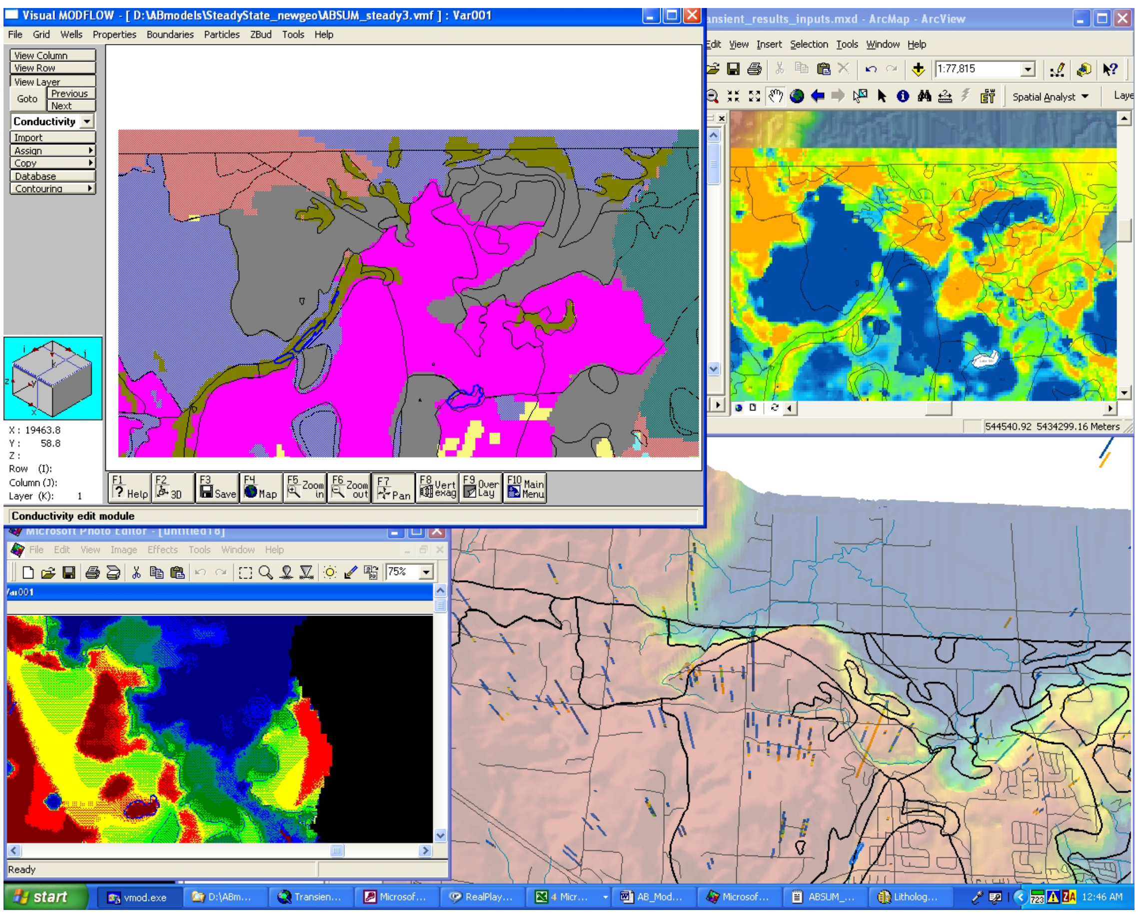


Figure 12 Example of digital GIS-assisted mapping process of hydrostratigraphic units from borehole lithologs and surficial geology, onto MODFLOW model cells.

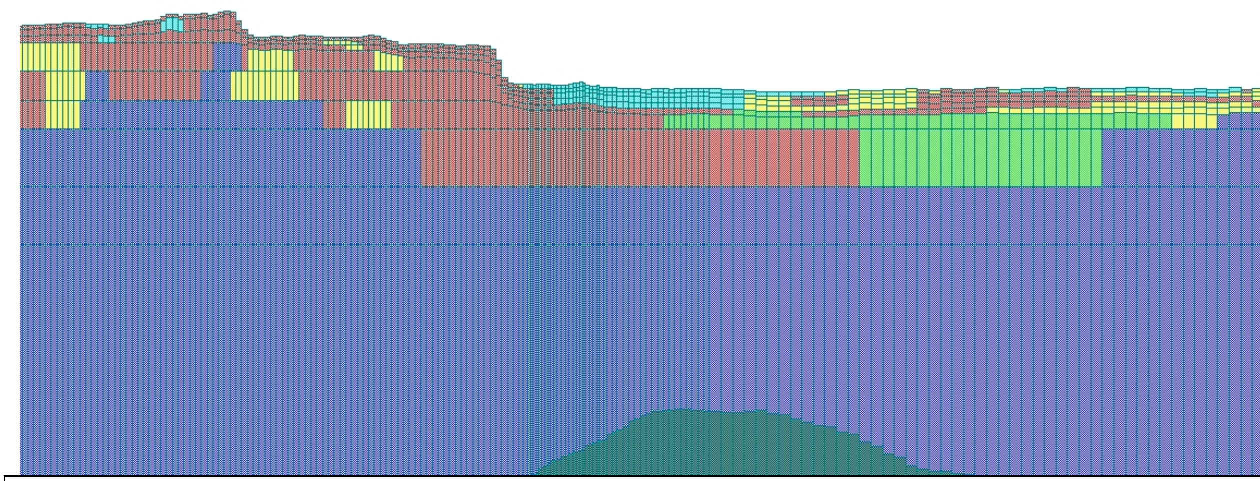


3.3. MODEL CROSS-SECTIONS AND MAPS OF HYDROSTRATIGRAPHIC UNITS

Geologic cross-sections mapped in this project, look similar to those of USGS LENS study in the Sumas Valley area. **Figure 13** and **Figure 14** have a 10x vertical exaggeration, but look similar to cross sections drawn by Kahle (1990) and Cox and Kahle (1999), and in Sumas well field numerical model (Associated Earth Sciences, 1994). Sand and gravel units are interlayered or present in lenses. Clay (glacioimarine clay – Fort Langley formation / Everson glaciomarine drift) underlies the coarse grained sediments. Silt is present in Sumas valley, also agreeing with interpretations by Kahle (1990). **Map 22** through **Map 26** show slices through the MODFLOW model, representing each model layer (1 through 9).

Figure 13 Cross-section through the model along US-Canada border, showing hydraulic conductivity zones in MODFLOW.

Abbotsford uplands ***Sumas Valley***

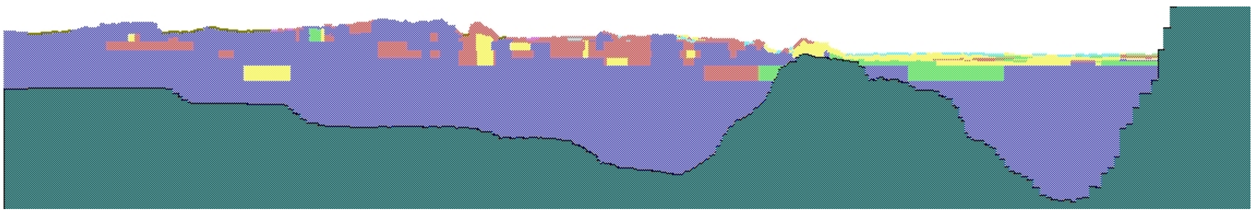


red = gravel dominant
yellow = sand dominant
green = silt (or silty sand)
blue = clay (till, clay or silt, with other materials)
light blue = fine grained lenses (silt, clay, or various tills) at or near ground surface

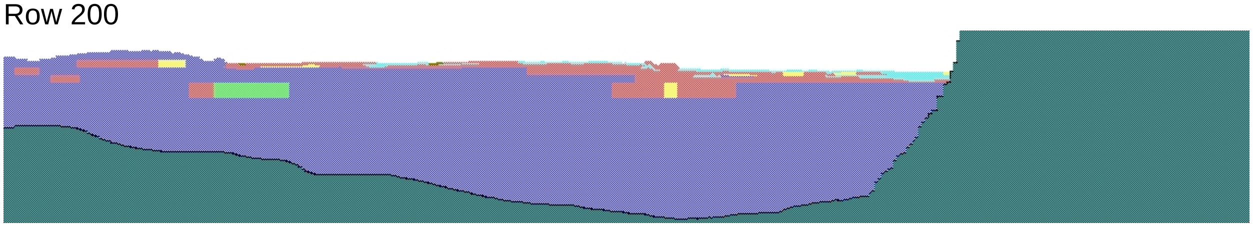
Figure 14 Cross-sections through MODFLOW model domain, hydraulic conductivity zones, and bedrock surface.

Cross sections

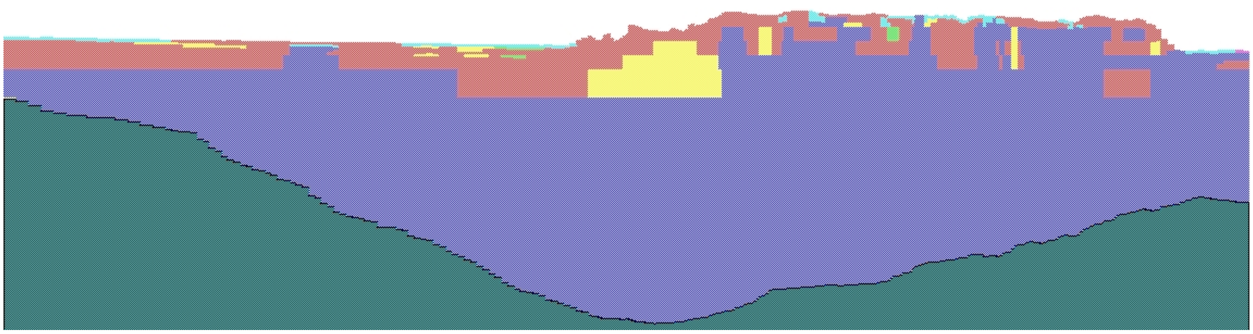
Row 90 (W to E, ve = 10x)

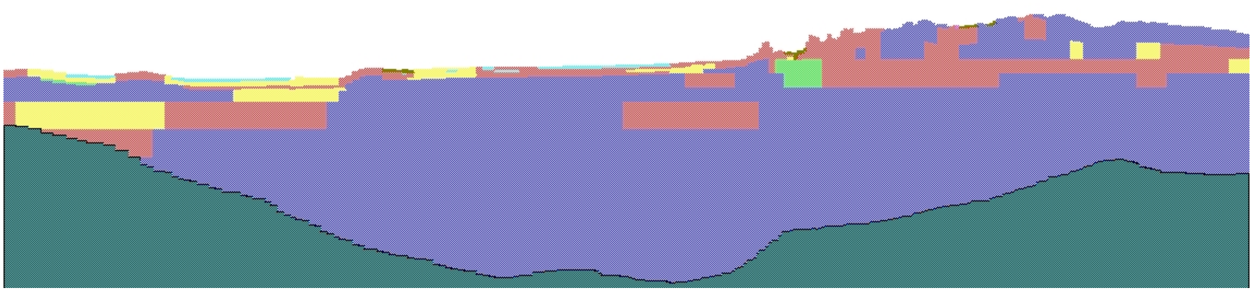


Row 200



Col 300 (S to N, ve = 10x)

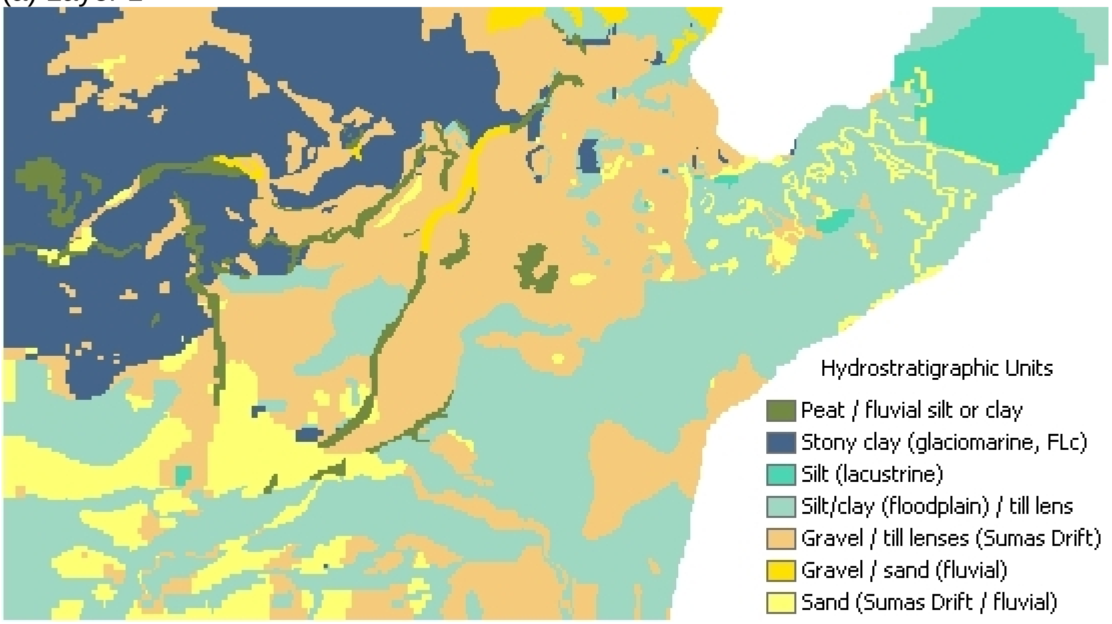




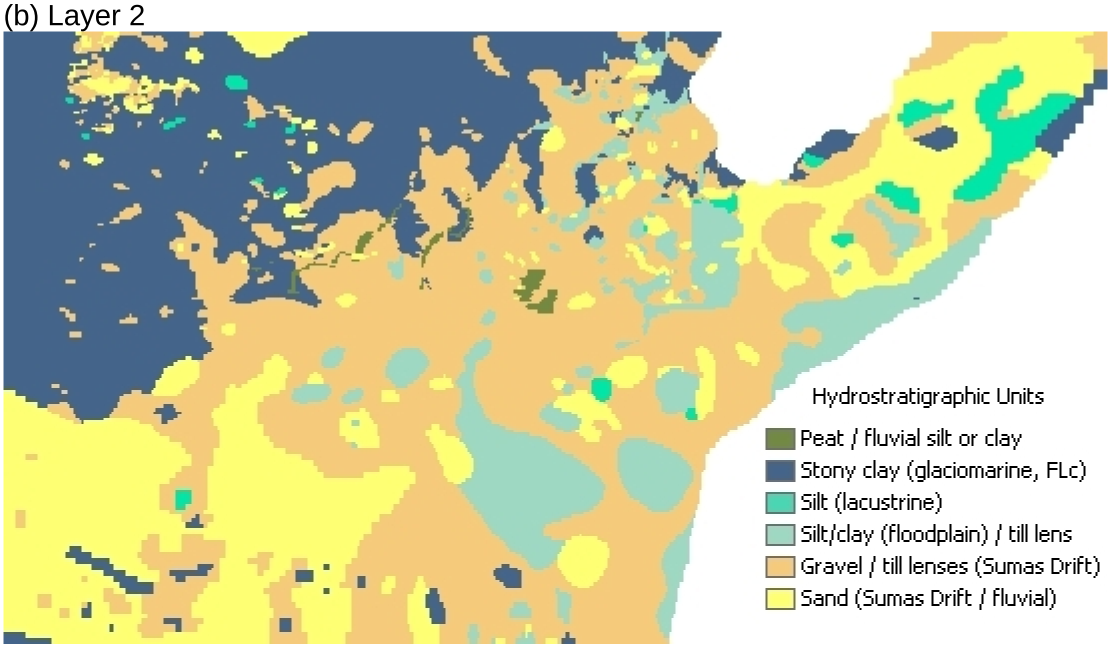
Row 135 (W to E, ve = 10x) Sumas Valley near Sumas, WA, with model grid

Map 22 Hydrostratigraphic model of central Fraser valley fill by MODFLOW layer (nearly-horizontal slices of valley).

(a) Layer 1

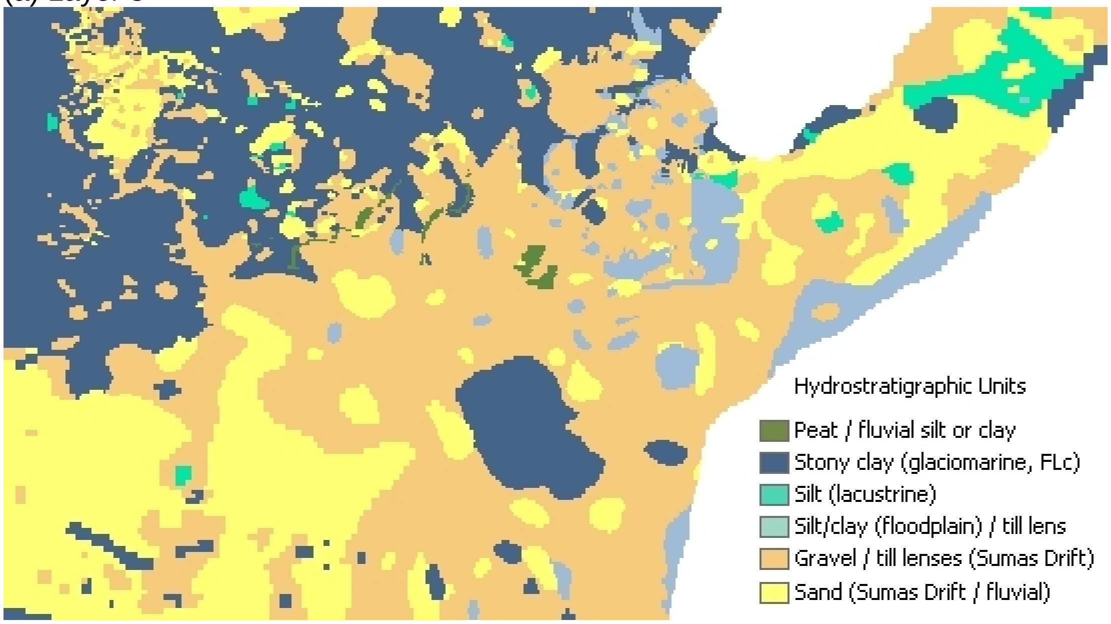


(b) Layer 2

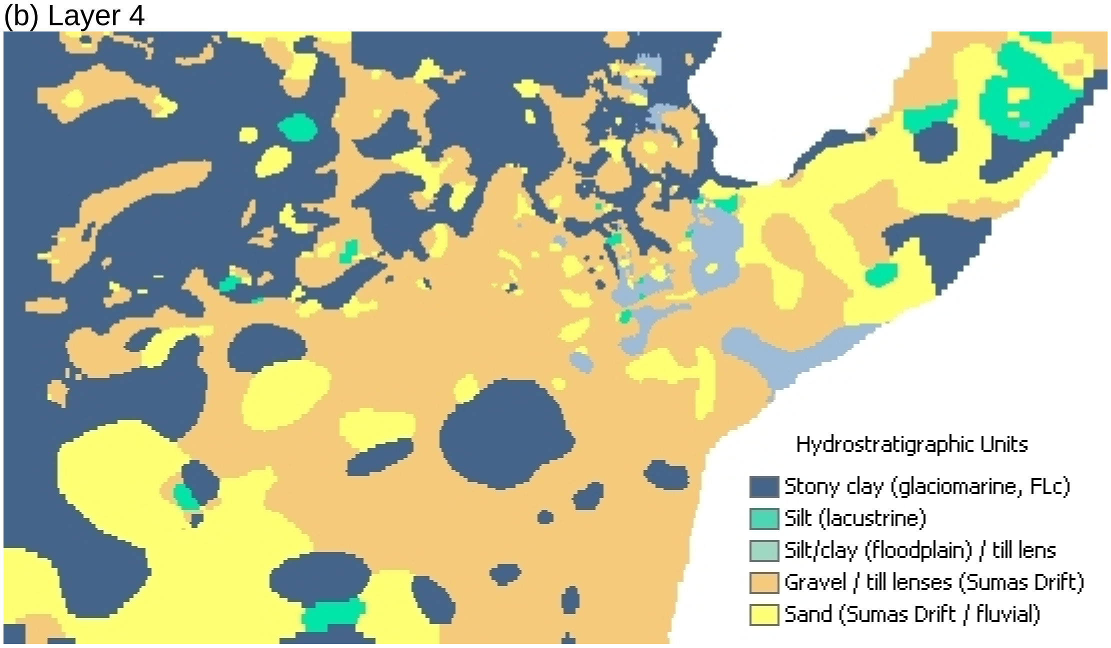


Map 23 Hydrostratigraphic model of central Fraser valley fill by MODFLOW layer (nearly-horizontal slices of valley).

(a) Layer 3

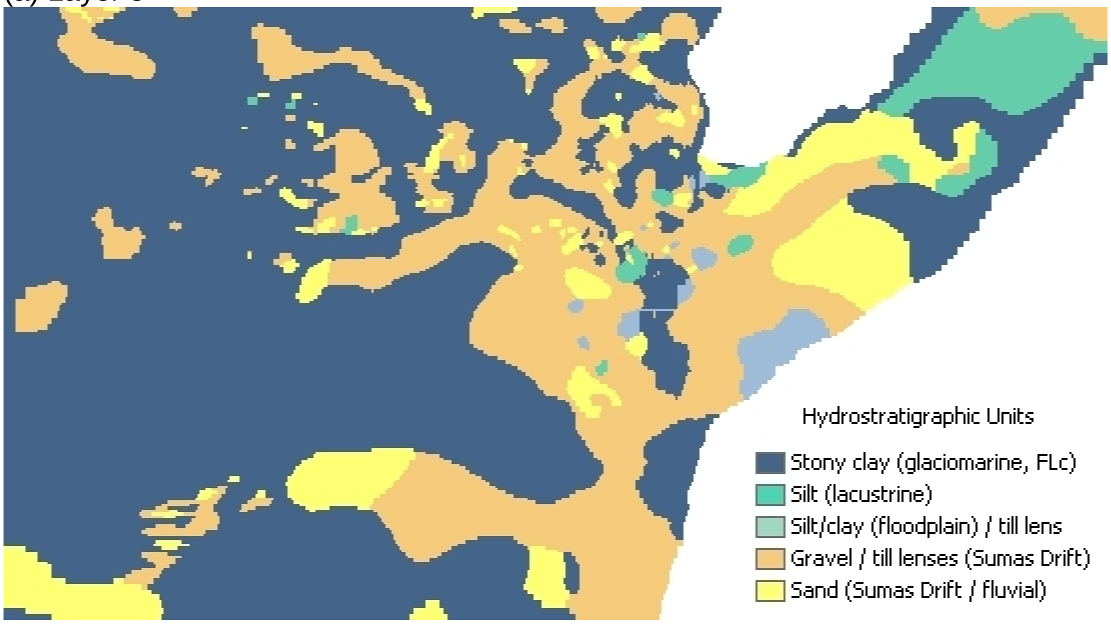


(b) Layer 4

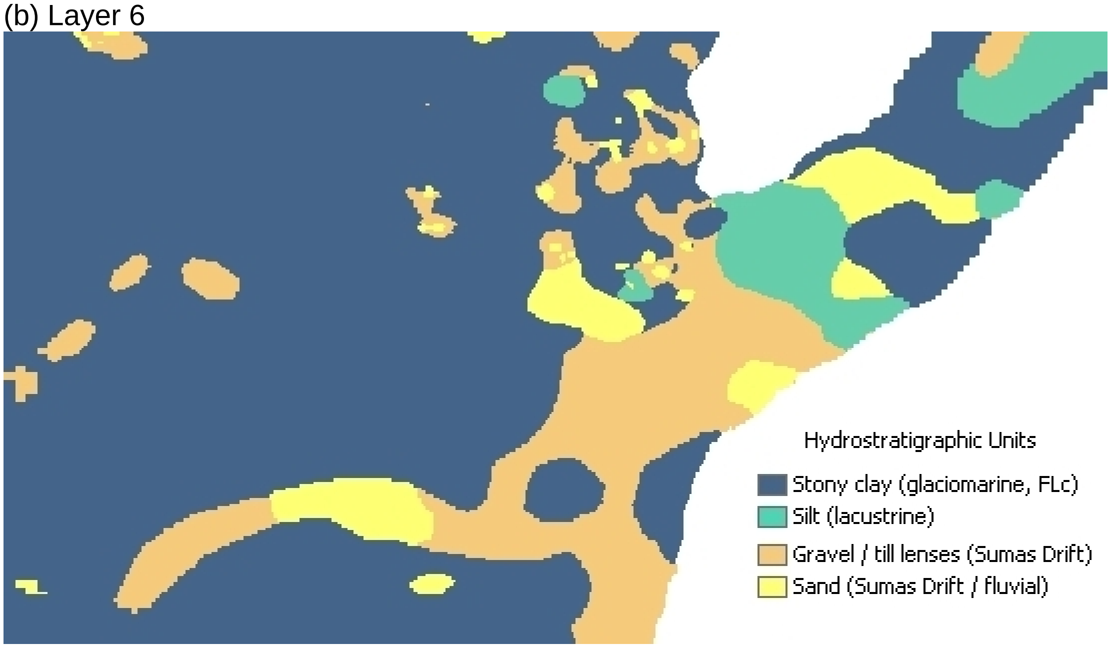


Map 24 Hydrostratigraphic model of central Fraser valley fill by MODFLOW layer (nearly-horizontal slices of valley).

(a) Layer 5

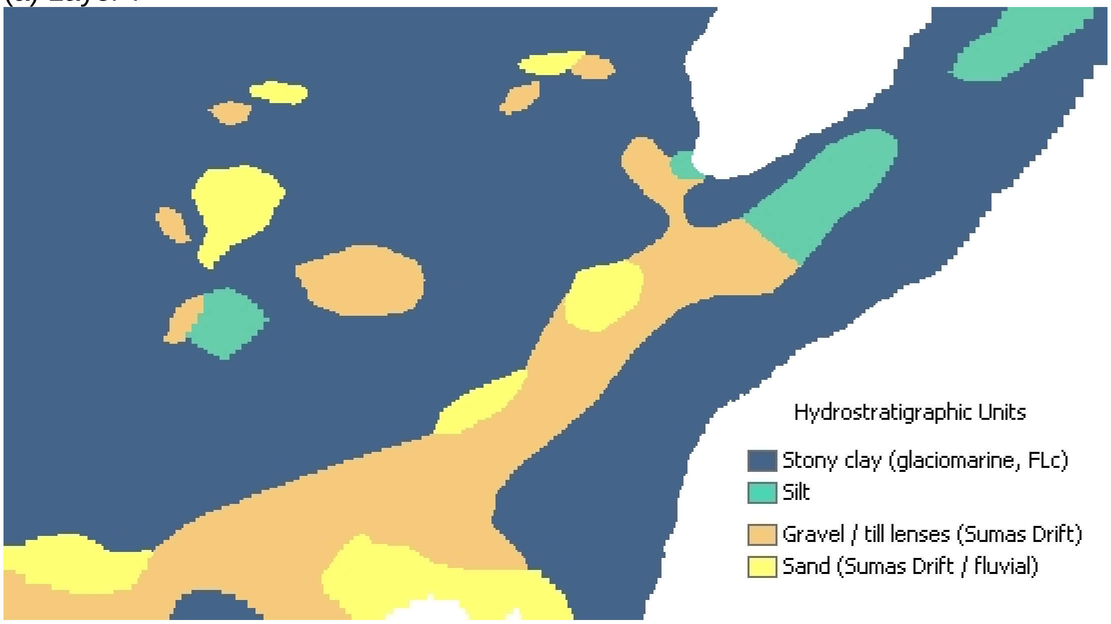


(b) Layer 6

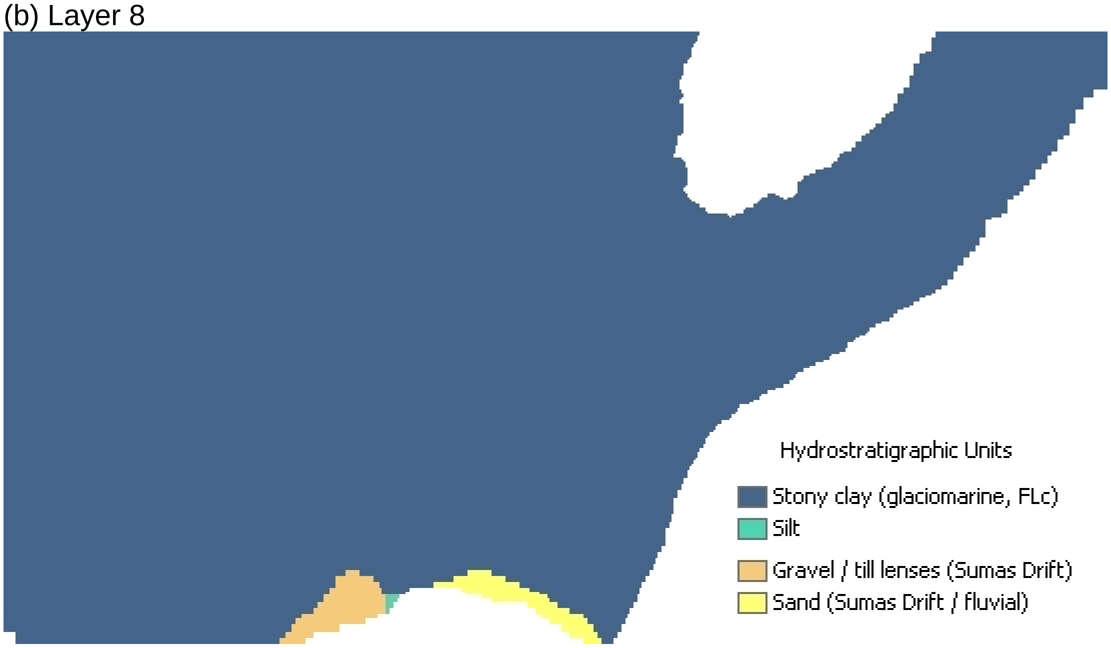


Map 25 Hydrostratigraphic model of central Fraser valley fill by MODFLOW layer (nearly-horizontal slices of valley).

(a) Layer 7

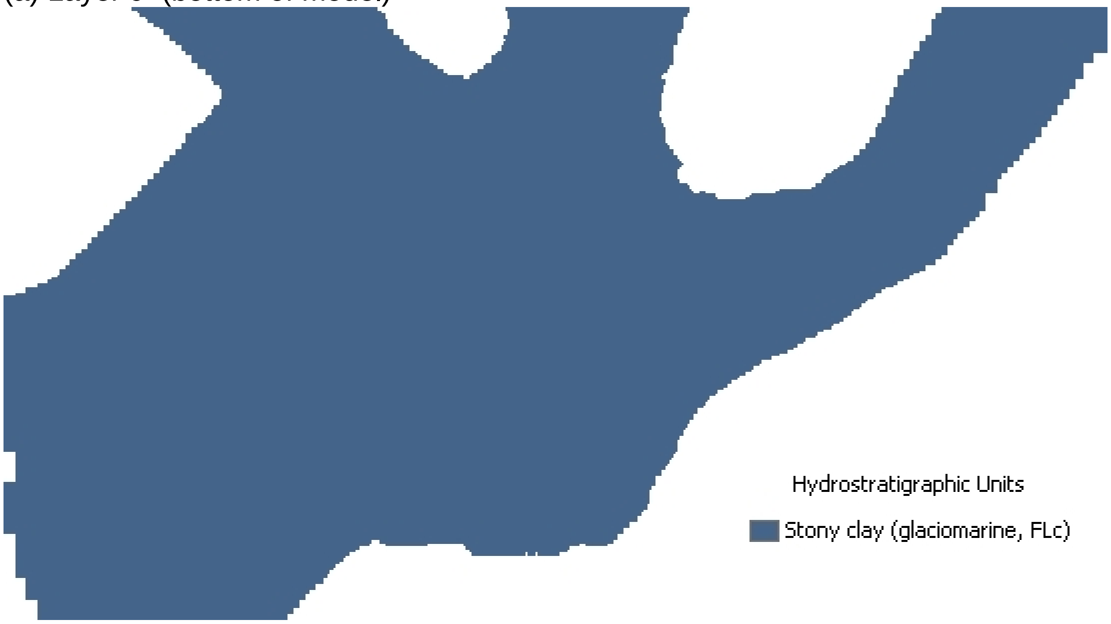


(b) Layer 8



Map 26 Hydrostratigraphic model of central Fraser valley fill by MODFLOW layer (nearly-horizontal slices of valley).

(a) Layer 9 (bottom of model)



3.4. STOCHASTIC HYDROSTRATIGRAPHIC MODEL – AN ALTERNATIVE TO REPRESENT AQUIFER PERMEABILITY

The alternative conceptual model is that of heterogeneous media as interpolated using geostatistical methods from well lithologs. In the discrete-interpolated model, all lithologic information is obtained from quality-controlled, standardized well logs. Although ultimately not used for this study, a brief summary of the methodology employed for creating the realizations of aquifer heterogeneity is presented.

In depositional environments, the hydrofacies represent hydrostratigraphic units, and these can be modelled from borehole lithologs and other geologic information. Modeling such sediment distributions in 3D, involves transition probability-Markov approaches (Carle et al., 1998). The same method can be applied to multi-scale systems, such as alluvial fans or whole basins (Weissmann et al., 1999a), or smaller sites with shallow sediments and soils only (Weissmann et al., 1999b). The alluvial aquifers can be considered as interconnected networks of high conductivity sediments (e.g., gravel channel beds), and lower hydraulic conductivity sediments, which can be represented in 3D by stochastic methods (Fogg et al., 2000; Ritzi et al., 1996; 1994; Sminchak et al., 1996; Weissmann and Fogg, 1999). Other geostatistical methods involve Kriging as the most common approach (Ritzi et al., 1994). This method interpolates surfaces and trends in hydrofacies, but does not involve random generation of “realizations” of subsurface, as does the stochastic approach. The stochastic method is also easier to implement in 3D grids, which are compatible with finite difference groundwater modeling codes such as MODFLOW. For interest purposes, aquifer heterogeneity was represented using a stochastic method using T-PROGS software in Groundwater Modeling System (GMS) (**Figure 15**).

Transition Probability Geostatistical Software (T-PROGS) is included in GMS 4.0 modeling package. T-PROGS was developed by Carle (1999) and its purpose is to enable implementation of a transition probability/Markov approach to geostatistical simulation of categorical variables. In comparison to traditional variogram-based geostatistical methods, the transition probability/Markov approach improves consideration of spatial cross-correlations and facilitates the integration of geologic interpretation of facies architecture into the model development process (Carle, 1999).

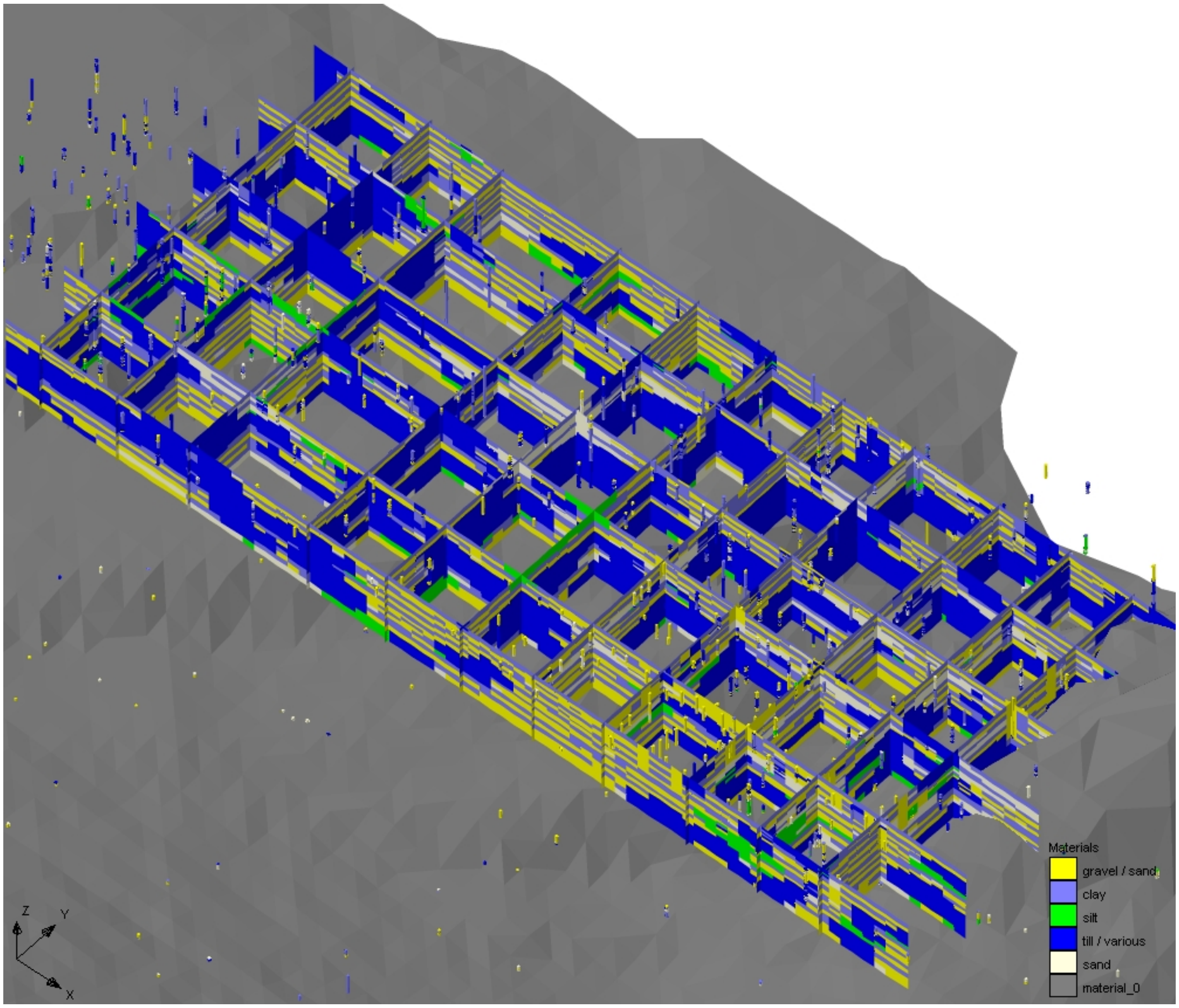
The abstract by Carle (1999) best summarizes the problem:

> "The unknown heterogeneity of the subsurface remains a major obstacle to reliable simulation of subsurface flow and transport processes. Characterization of spatial patterns in properties with typically sparse data requires knowledge of the geologic processes that created the patterns. A geostatistical approach based on transition probability theory provides a means for quantitative modeling of three-dimensional hydrostratigraphy through the use of commonly available field data as well as geologic fundamentals and knowledge of the depositional processes. By modeling inter-facies transition probabilities with Markov chains, an intuitive method for building three-dimensional models from basic geologic principles is developed, extending qualitative geologic characterization into the quantitative realm necessary for flow and transport simulation. This geologic/geostatistical technique, implemented with the software TProGS, uses the hard data together with interpretive input on proportions, average lengths, and juxtapositioning of geologic facies to create multiple realizations of heterogeneity. The resulting characterizations honor fundamental probability laws while preserving observed or inferred facies proportions, continuity, asymmetries (e.g., fining upward sequences), and facies relations (e.g., levee adjacent to channel facies). Lateral facies relations, which are typically undersampled, can be modelled based on the observed vertical patterns in facies through the use of Walther's Law. Furthermore, the approach can incorporate nonstationarities such as spatially varying dip angles, or more severe nonstationarity, such as unconformities and transitions between different depositional environments."

The embedded transition probabilities can be edited. It is conducive to sites with data because the embedded transition probabilities can be determined from the borehole data. When a simulation is initialized, and if borehole data exist, default embedded transition probabilities are computed from the borehole data. If borehole data do not exist, the embedded transition probabilities can be estimated with some basic geologic knowledge including the average mean lengths of each material for each direction and depositional trends.

A prerequisite for building T-PROGS data is a three-dimensional grid. The grid was generated in GMS for central Fraser valley. The indicator arrays generated by the T-PROGS algorithm are interpolated to a grid, and therefore, a grid must exist. The T-PROGS algorithm is compatible with two types of grid. If the option to generate material sets for a multi-layer grid is selected, the grid must be orthogonal with uniform row, column, and layer dimensions. The row dimensions can be different from the column dimensions, but the row dimensions must be the same throughout the grid. The same conditions exist for the columns and layers. If the option to generate HUF arrays or material sets for a one-layer grid is selected, the grid must have uniform row and column widths, but cells can have varying Z dimensions and a curvilinear geometry.

Figure 15 One realization of stochastic hydrostratigraphic model of Abbotsford-Sumas aquifer/aquitard system. Modelled with T-PROGS in GMS: (a) fence diagram for area north of US-Canada border from Abbotsford BC to Langley BC.



4. SURFACE HYDROLOGY

4.1. SURFACE WATER FEATURES

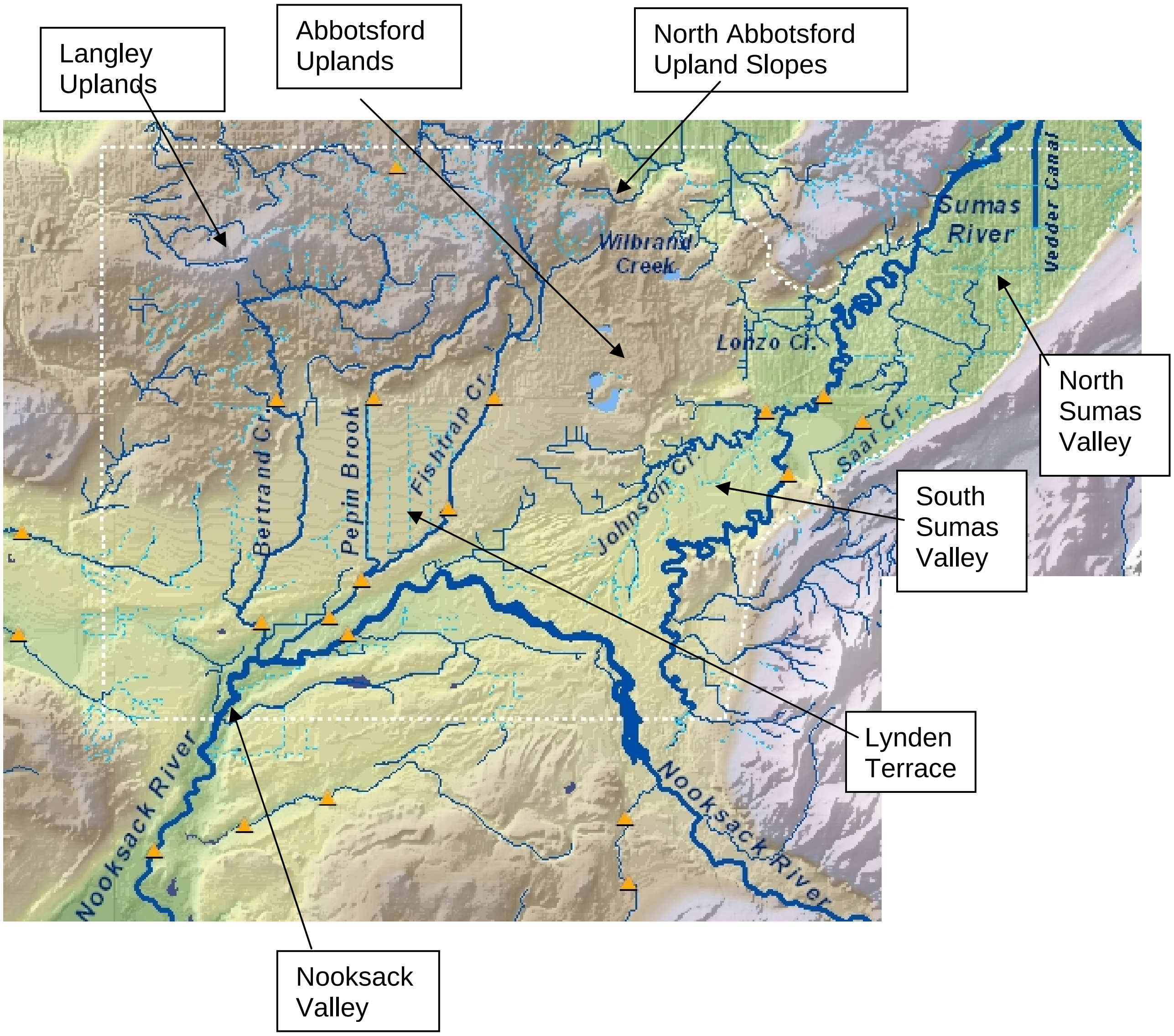
The model area includes portions of three distinct river valleys and associated floodplain areas, all bounded by steep valley walls composed of bedrock (**Map 27**). The largest valley in this area is the Sumas Valley, which runs north-east to south-west and contains the lower drainage of the Sumas River. Sumas River flows to the north-east and picks up significant baseflow component from aquifer discharge on its eastern side. To the south is the Nooksack River, flowing to the west and then south, and draining most of southern drainage. It has baseflow contributions from the Abbotsford-Sumas aquifer, as well as from the aquifers to the south. Nooksack River is incised into the floodplain, and is well below the Lynden Terrace. Most of the surface and groundwater flow from the Abbotsford-Sumas aquifer ends up in the Nooksack River. To the north, the model area includes a portion of the Fraser River floodplain. Several sizable creeks drain to the north, but the quantity of groundwater traveling north is considerably less than that flowing south and west. The western boundary of the aquifer system is formed by groundwater divides in the highlands over Langley township, but some of the flow occurs west through small interconnections between confined aquifers (inferred), and also west toward Birch Bay (near Blaine, WA), but that is small from the defined model area in this study.

4.2. SUMAS VALLEY HYDROLOGY

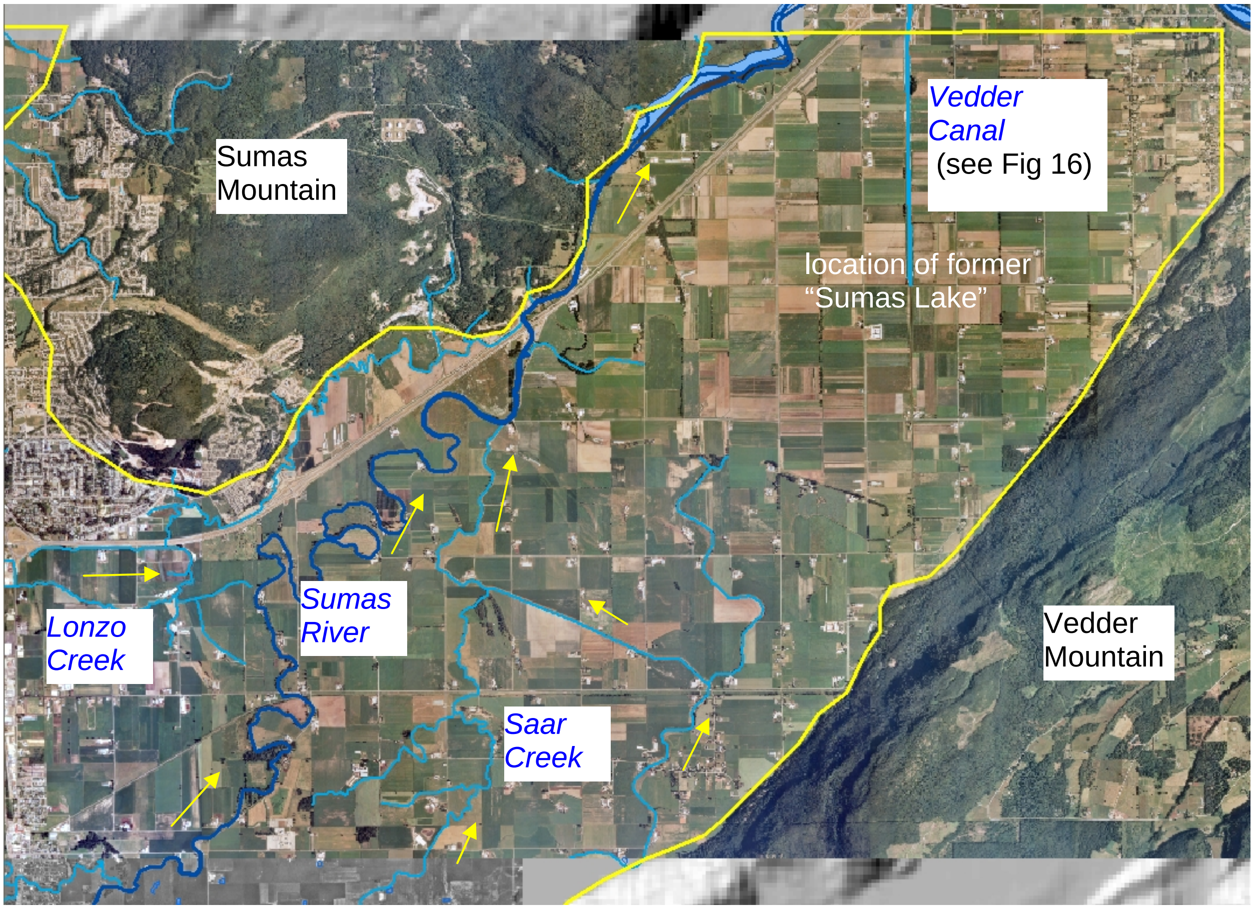
Sumas Valley (also called Sumas Prairie) is located between Sumas Mountain and Vedder Mountain. As shown in **Map 27**, in this report this area of the valley will be referred to as Sumas Valley North. It runs from south-west to north-east from the international boundary of Canada and USA. The Sumas Prairie has an area of about 10,000 hectares. Drainage from the prairie flows to the Fraser River just east of Sumas Mountain. The basin is characterized by small gradients in the drainage system with resultant small velocities in the creeks and drainage canals (IRC, 1994). Sumas Valley South in this report is the area near town of Sumas, WA, along the scarps of Abbotsford uplands, and south to groundwater divide with Nooksack Valley and its drainage.

The Sumas River watershed consists of the Sumas River and Sumas Drainage canal, Arnold and Stewart Sloughs, and Marshall (Lonzo) and Saar Creeks (**Map 28**). Sumas River, Arnold Slough and Saar Creek flow North from their head waters in the U.S.A. into B.C. A large portion of the Sumas River, from No. 2 Road to Hougen Park, is dyked (91%) and passes through agricultural land. Peak discharges at the International border occur in December/January and minimums in August/September. The north side of Arnold Slough is dyked from Vye Road to the Saar Creek junction. From Saar Creek junction the North side of Saar Creek is dyked until it meets the Sumas River.

Map 27 Streams and rivers of central Fraser Valley, draining the Abbotsford-Sumas aquifer system, and locations of streamflow gauges.



Map 28 Surface waters of North Sumas Valley. Flow directions are shown with arrows.



In 1924, a shallow lake occupying part of Sumas Prairie was artificially drained after construction of the Sumas Drainage Canal (or Sumas Lake Canal) and exposed terraced beached sands around its perimeter (Halstead, 1986) (**Figure 16**). The lake left a thin (3 to 10 m) layer of silt deposit, which has been mapped on surficial geology maps.

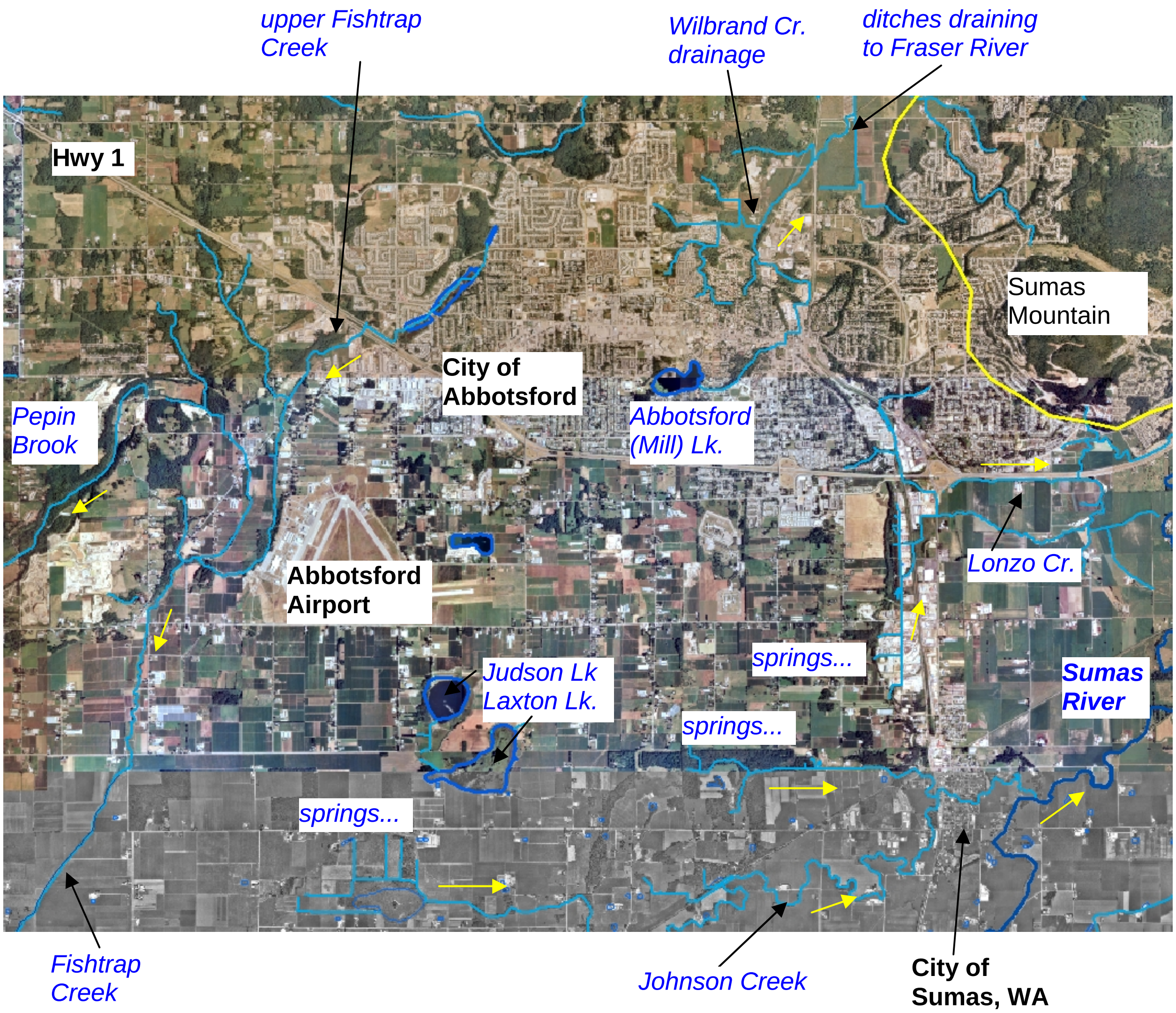
The level in the Sumas River is controlled by gravity drain floodgates for irrigation purposes at Barrowtown pump station (Hutton, 1987). Considerable seepage from the Vedder Canal into the Sumas watershed and land base around the Sumas Drainage Canal occurs. Much of the Prairie is 1 or 2 meters below the Sumas Drainage Canal elevation.

Figure 16 Sumas Lake Canal in Sumas Valley (looking North) – photo from IREL website at UBC.

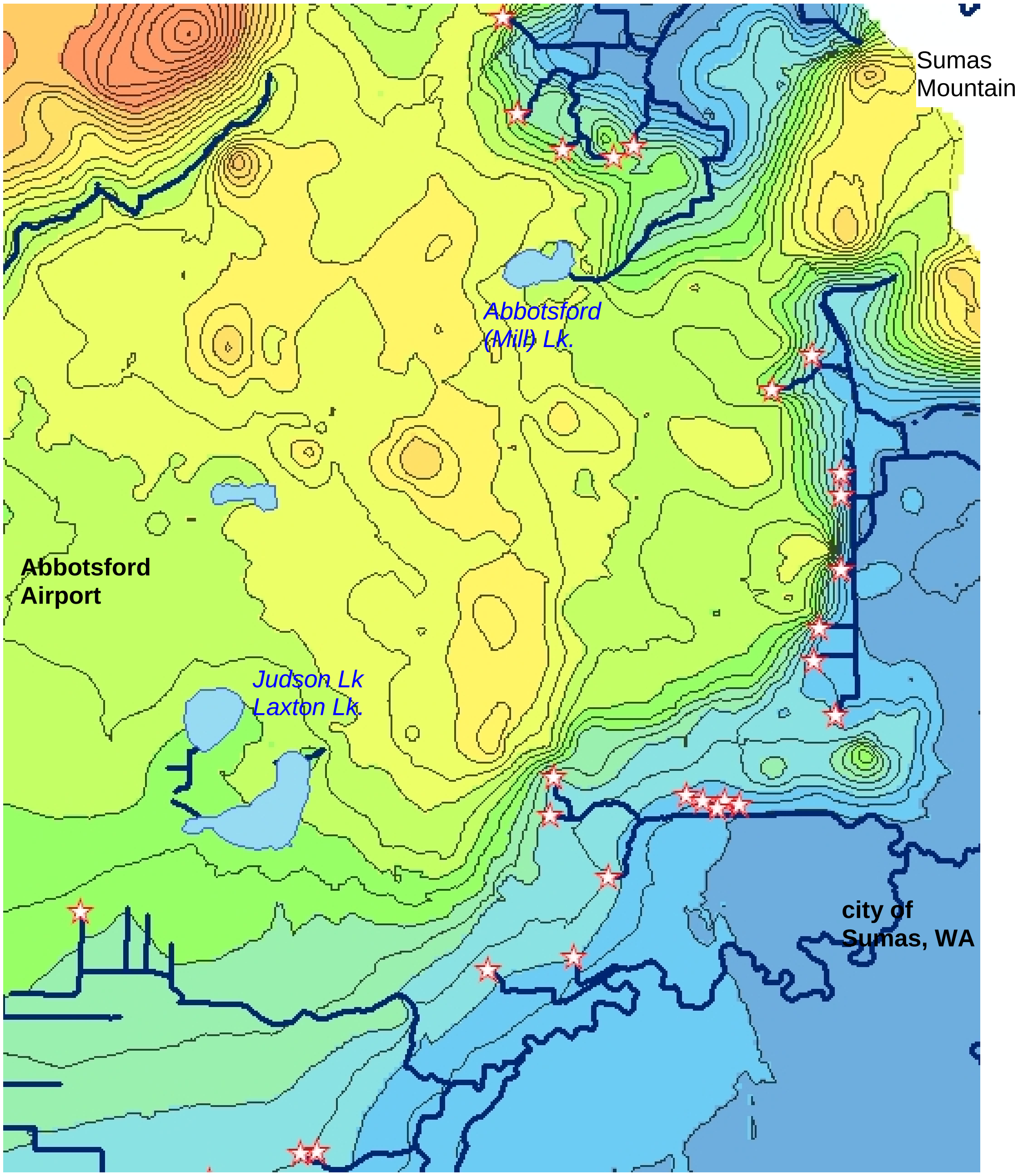
4.3. UPLANDS HYDROLOGY

A number of lakes and peat bogs occur in abandoned meltwater channels and kettles on the outwash terrace. The lakes include Abbotsford Lake, Laxton and Judson Lakes, Pangborn Lake and smaller ponds (**Map 29**). **Map 30** shows locations of major springs along scarps of the Abbotsford Uplands and Sumas Valley. **Map 31** shows surface waters between Langley uplands and the south end of Lynden Terrace.

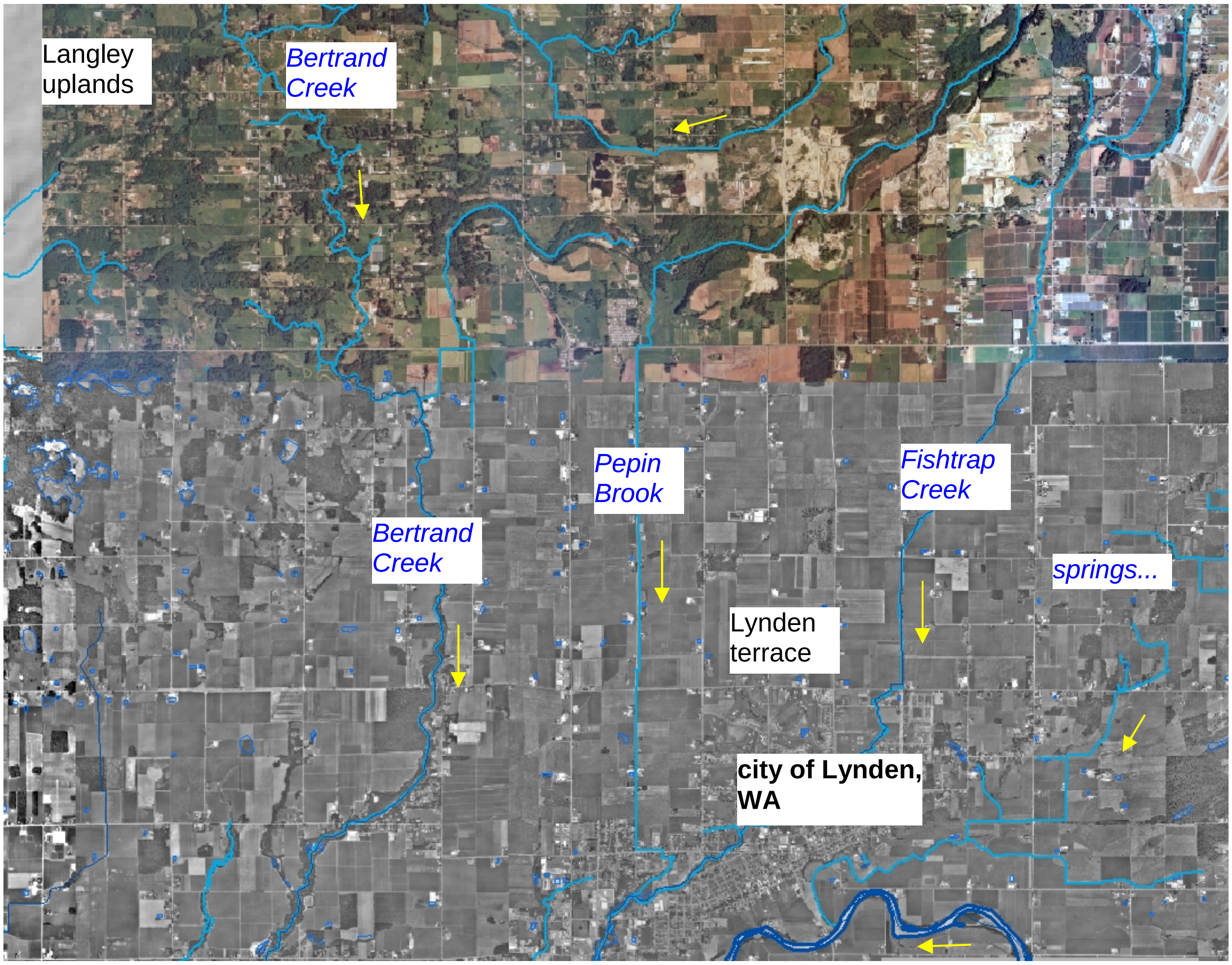
Map 29 Surface waters of Abbotsford Uplands.



Map 30 Locations of major springs along scarps of Abbotsford Uplands and Sumas Valley, shown with potentiometric surface map (here it is mostly water table) and major streams and flowing ditches.



Map 31 Surface waters between Langley uplands and south end of Lynden Terrace.



Nooksack River

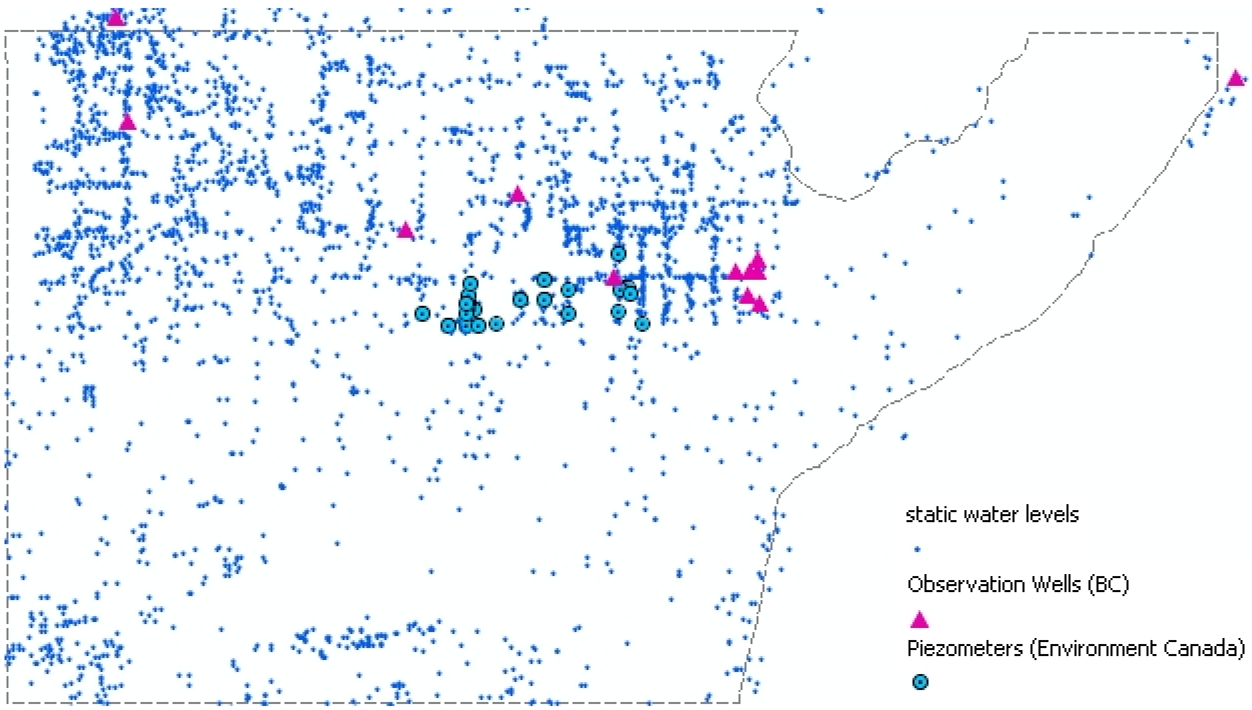
4.4. GROUNDWATER PIEZOMETRIC SURFACE FROM STATIC WATER LEVELS

4.4.1. WATER LEVEL DATA DESCRIPTION

Water level records number in thousands in the Fraser Valley. The datasets that were selected include all static water levels in BC WLAP groundwater well database, all available USGS and WA Ecology well records, transient water observations from piezometers and observation wells monitored by Environment Canada (south of Abbotsford Airport), USGS, WA Ecology, and others. 2958 wells with static water levels were selected and used for calibration of the steady-state model. These well include all of the domestic water wells, of varying depth, in addition to the production wells, that have been drilled in the area. The wells are well-distributed spatially throughout the aquifer (**Map 32**), and thus, provide an excellent means for steady-state and model calibration. It is important to recognize, however, that the water elevations used for model calibration were determined at the time of drilling, and therefore, may not be representative of current groundwater conditions. In this respect, the ability of the model to accurately represent local detail is lower that it would be had the calibration data and stream elevation data been collected at the same instant in time.

In the MODFLOW model, the ground surface was imported from 20 m digital elevation model grid (BC province DEM, USGS DEM). As a quality assurance step, the reported well elevations were compared to the available ground DEM surface. In **Figure 17** the histogram of differences between well elevation and DEM elevation has an approximately normal distribution. Although the histogram alone would suggest that random measurement errors could account for differences between well elevations and the DEM, the spatial distribution of such differences (**Map 33**) reveals trends and clusters.

Map 32 Wells with static groundwater levels used as observed heads for steady state model calibration.



The model residuals were computed for original well elevations (observation wells in MODFLOW), from which static groundwater levels were derived by subtracting depth to static water level from well top elevation. There is small error in this analysis because there is no information on whether the depths to water table were corrected for height of well casing or not. The same observation wells were also corrected in a separate calibration run to correspond to ground surface DEM to test whether the model would agree more closely or not with such modified static water levels. The calibrated model was better calibrated to original well elevations than to modified ones, and given the evidence of poor DEM quality and good correspondence of reported well elevations to floodplain maps, the original well elevations were kept for model calibration.

Map 33 Difference between top of well elevation and ground DEM elevation at wells with water level observations (all databases).

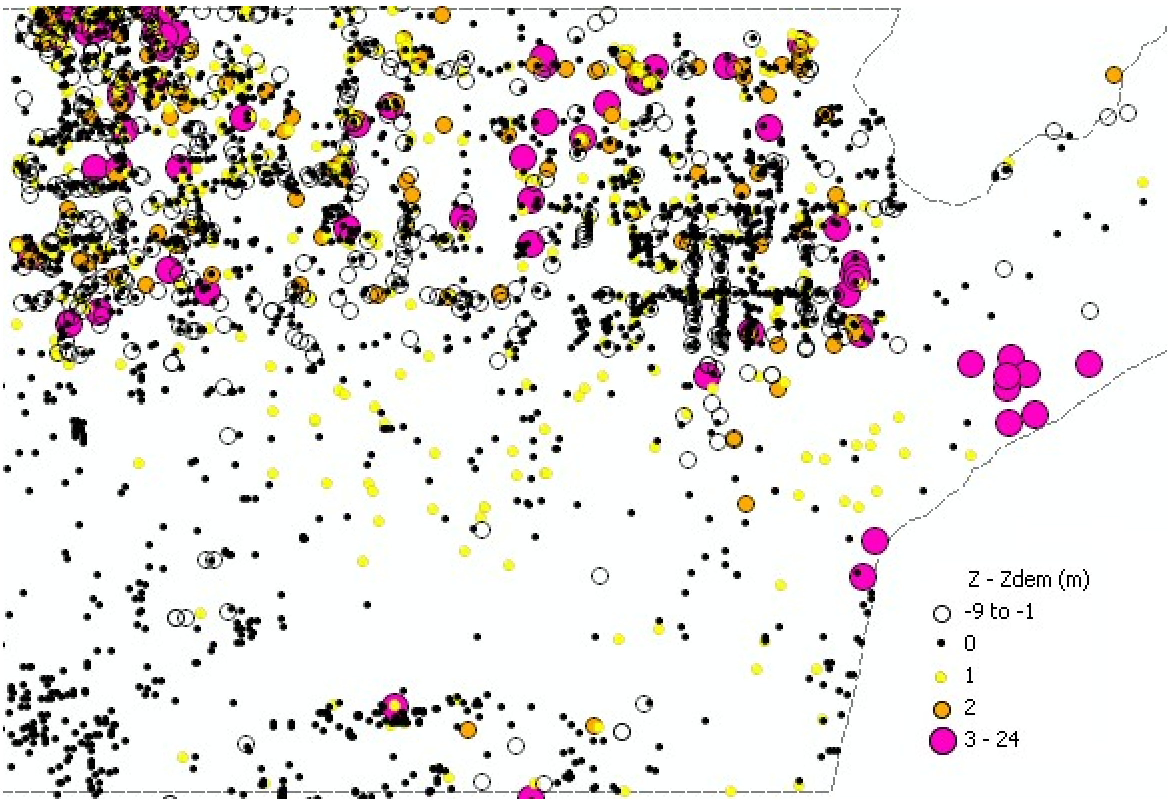
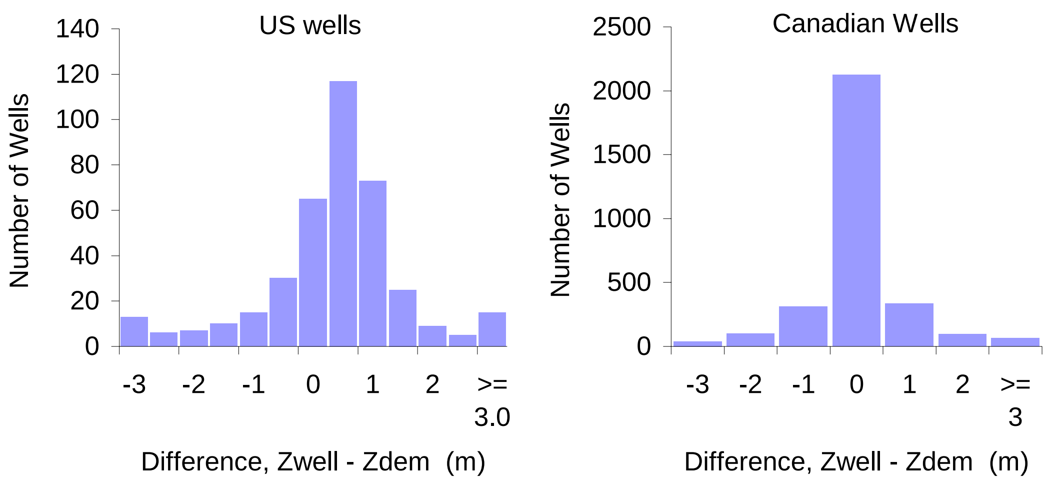


Figure 17 Histogram of inconsistencies in well elevations as compared to DEM elevation at Abbotsford-Sumas aquifer.



4.4.2. STATIC WATER TABLE MAP

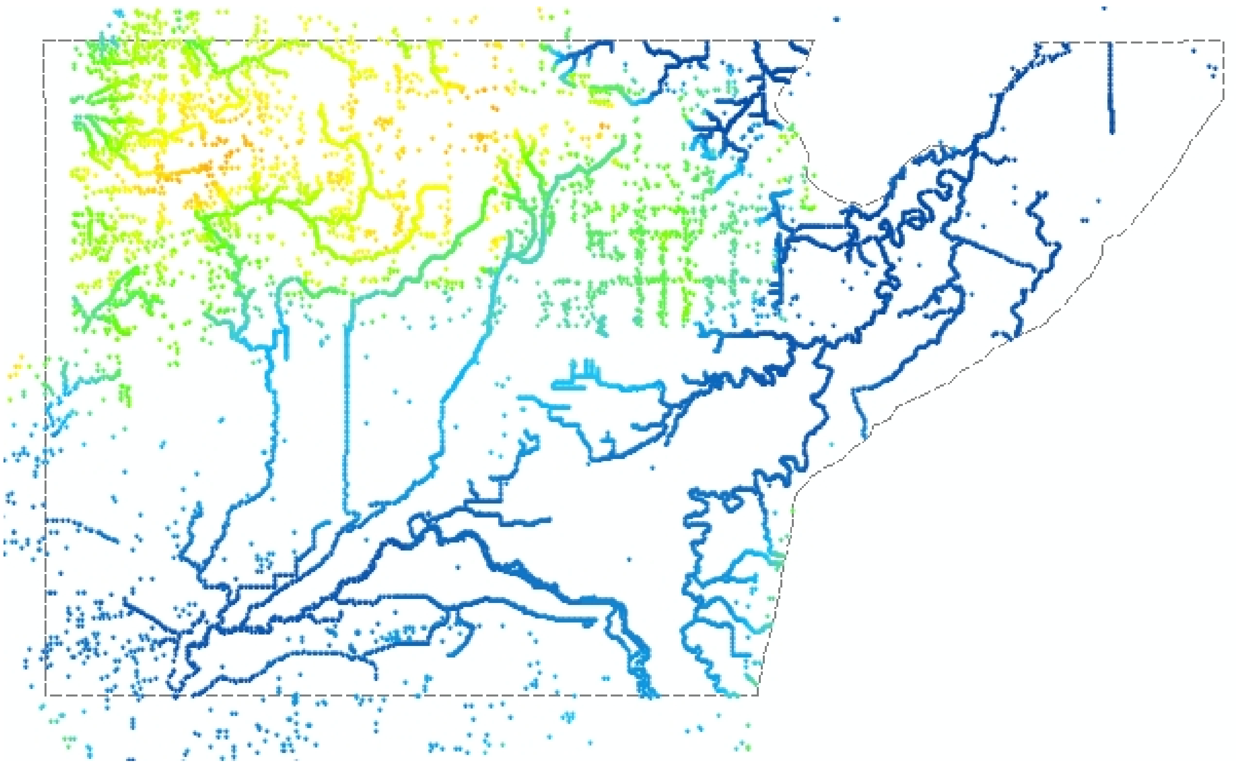
The source data for interpolation of static groundwater levels was the combined dataset of static water levels and the dataset created from sampling of surface water elevations (along streams and lakes, flowing ditches, springs, and rivers) - **Map 34** - the assumed potentiometric surface of unconfined aquifer. Surface water bodies help to pin down the water table to more realistic shape. The static water level map (**Map 35**) was interpolated using both Kriging and inverse distance methods, with similar results in central valley, but different results near valley edges. High density contours suggest high hydraulic gradients, which tend to occur along slope breaks in ground surface where groundwater seeps into the river from higher terraces, setting up large gradients in water table surface. This map was the first estimate of hydraulic heads in the aquifer for the purpose of model calibration; however, modeled heads were used in subsequent initial head inputs to consecutive calibration runs. This type of map can be considered accurate where static level observation point density is high, and is very inaccurate away from static points toward valley walls or in any other extrapolated direction.

In the Abbotsford uplands (**Map 36**) there is high density of water level data points, but the water level varies greatly at some locations – indicating either poor observation or data conversion quality or high temporal variability in water table elevation, or even locally perched water tables. The lower map (**Map 36**) shows areas where interpolated water table is above DEM ground surface model. In such locations, the water table elevation must be reshaped to at least fall below the ground surface. The process of final reshaping of the water table surface is demonstrated in **Map 37**. The water table surface corrected for ground surface elevation in selected areas where original interpolation exceeded ground surface. Two locations are shown: Wilbrand Creek area north of Abbotsford and part of Fraser River floodplain and Sumas Valley near Sumas, WA. The water table surface can then be shifted down using raster algebra on pixel by pixel basis, or through re-interpolation of original surface, but using co-kriging interpolation where the second variable is ground surface elevation at selected locations – resulting surface is drawn on **Map 38**. The two water table surfaces (before and after correction for ground surface) are too similar to observe differences at regional scale – the differences are only in the identified problem areas (**Map 40**). This is the best interpretation of water table elevation thus far and it was used as initial heads to the flow model.

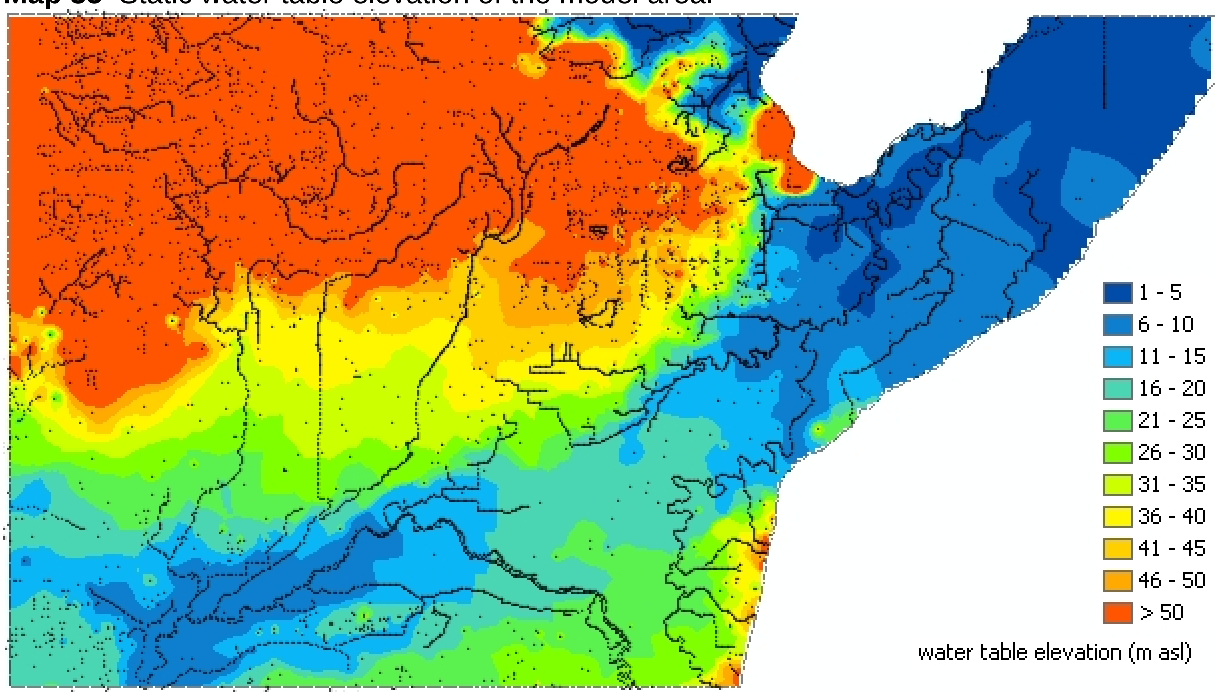
The groundwater elevation in the unconfined aquifer is highest in the Abbotsford uplands, although some areas may be confined (any "peaks" in water table elevation) or perched. The valleys have low and relatively flat water table elevation. There are transition zones of high hydraulic gradients, particularly along the scarps of uplands and Sumas Valley north of Sumas, WA. Depth to water table was computed as the difference between ground surface and modeled water table surface (**Map 39**). Many upland areas have high unsaturated thickness of the aquifer, where as the valleys have very shallow unsaturated thickness.

Water table elevation and its slope was highly correlated to occurrence of springs and discharge areas. After much experimentation, the potential seepage areas were identified by slope of water table > 1.0 deg and depth to water table < 4.0 m. These locations are shown with surface drainage and springs in **Map 41**.

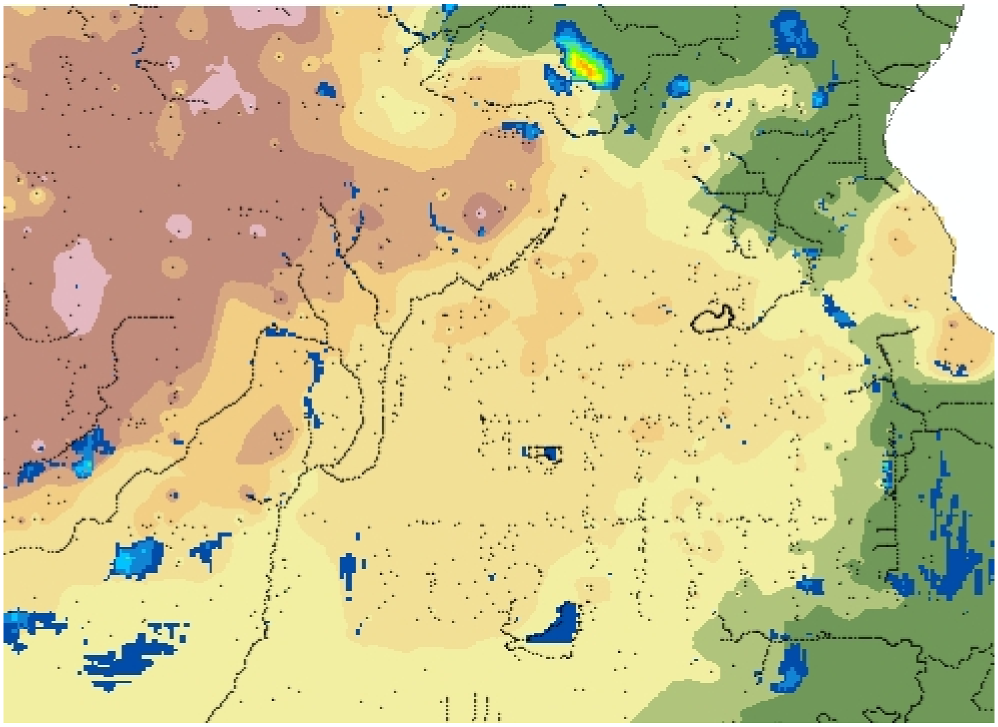
Map 34 Merged static groundwater levels and surface water elevations used in interpolation of groundwater table elevation.

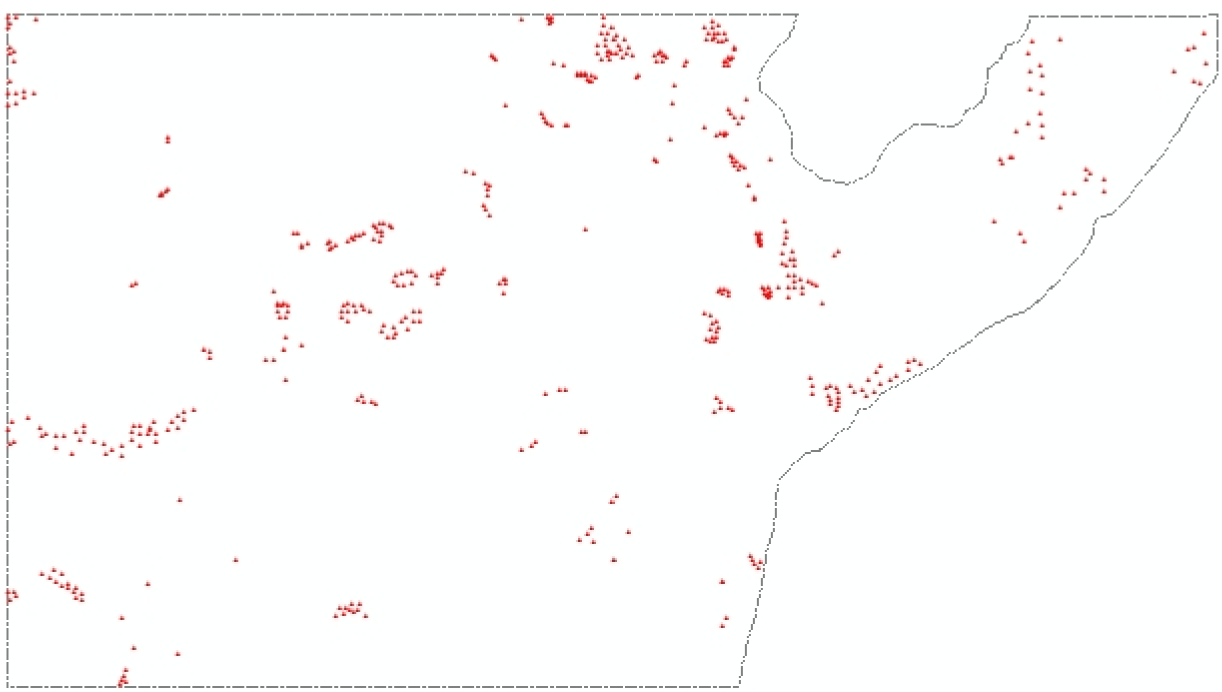


Map 35 Static water table elevation of the model area.

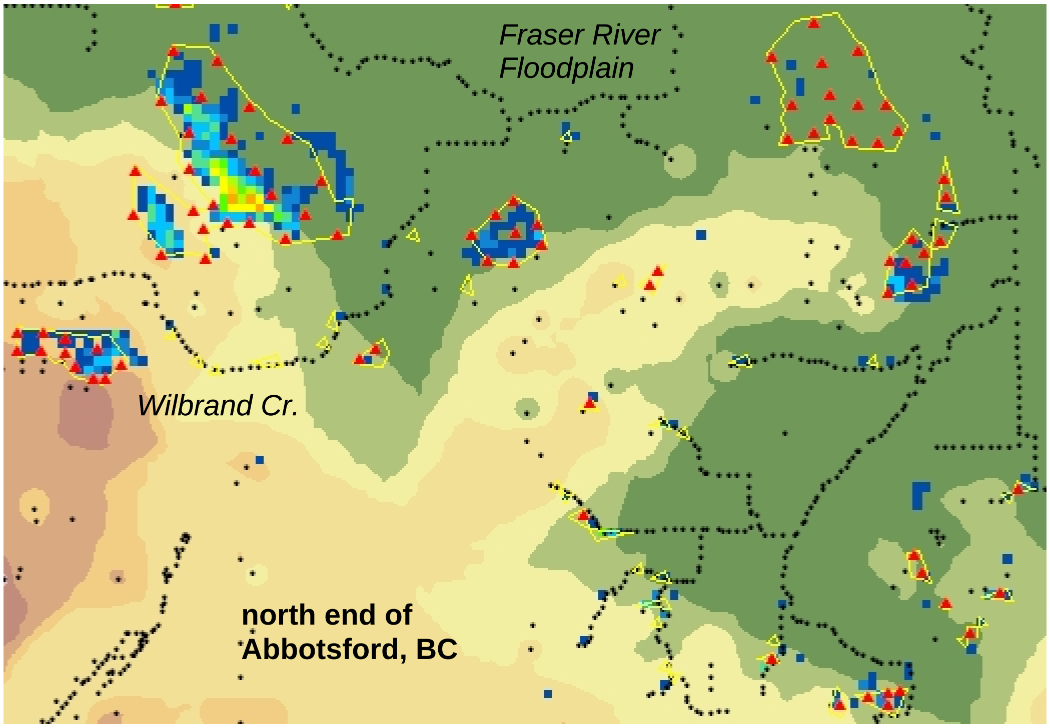


Map 36 Map of water table interpolated using inverse distance method from all static water level measurements, stream channel elevations, and lakes. Lower map shows areas where interpolated water table is above DEM ground surface.

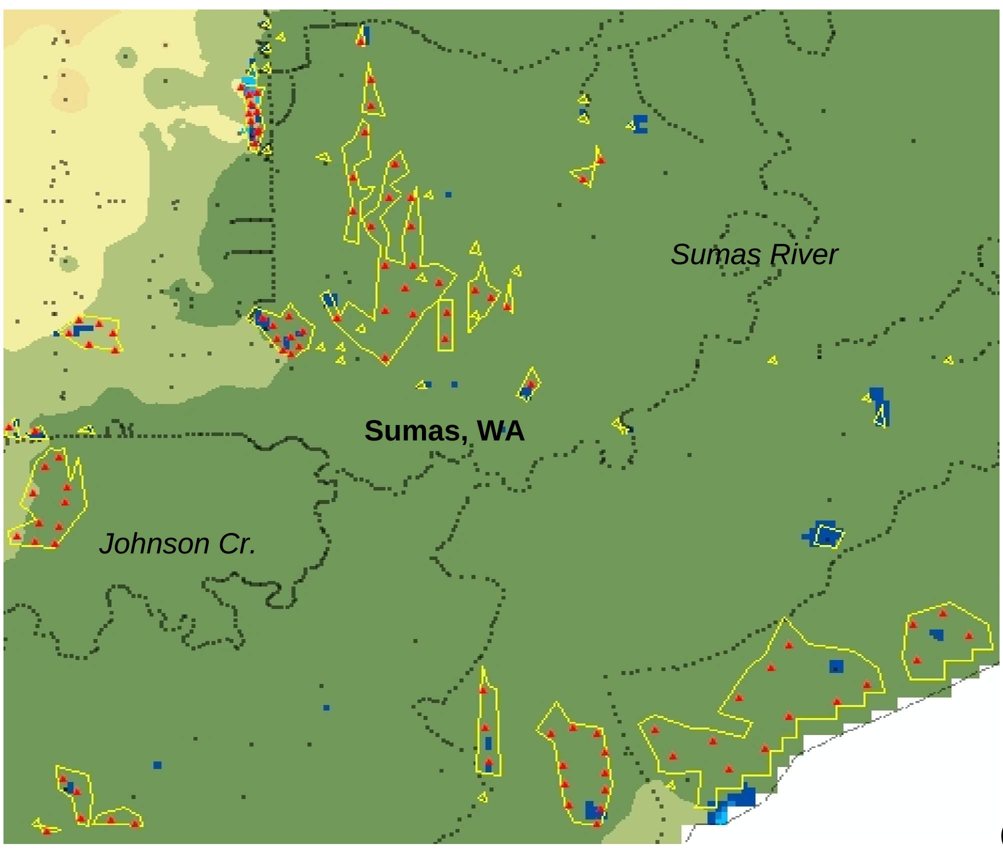




Map 37 Water table surface corrected for ground surface elevation in selected areas where original interpolation exceeded ground surface. (a) Wilbrand Creek area north of Abbotsford and part of Fraser River floodplain, (b) Sumas Valley near Sumas, WA.

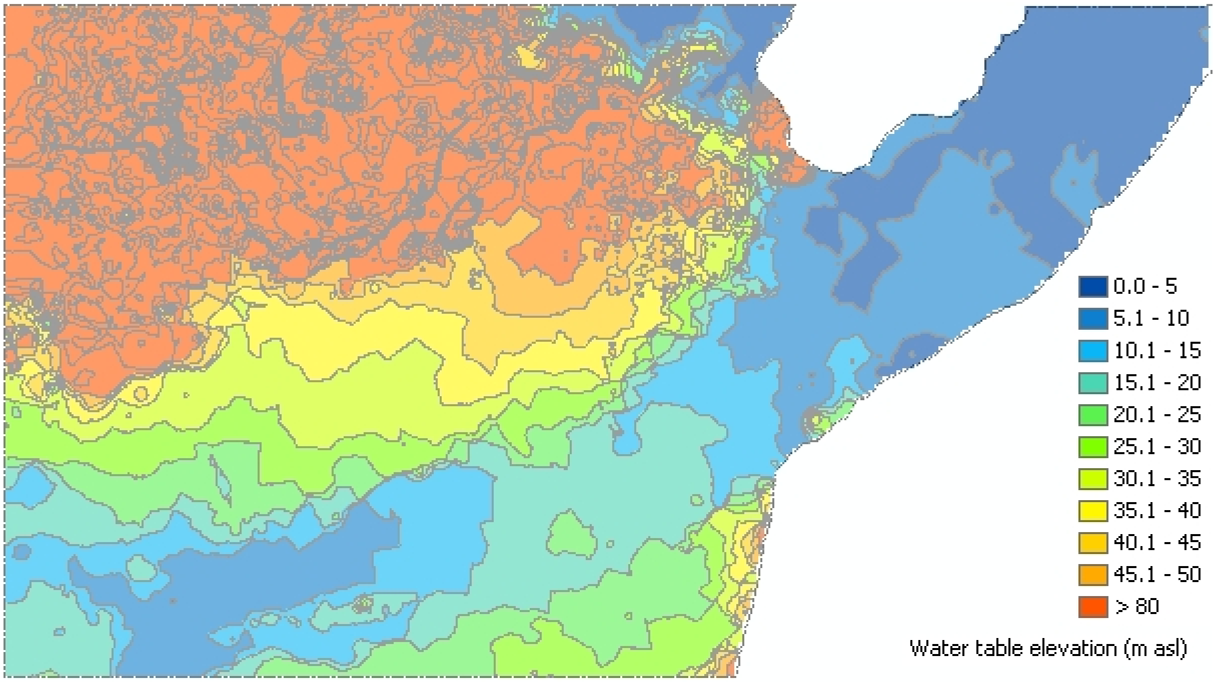


(a)

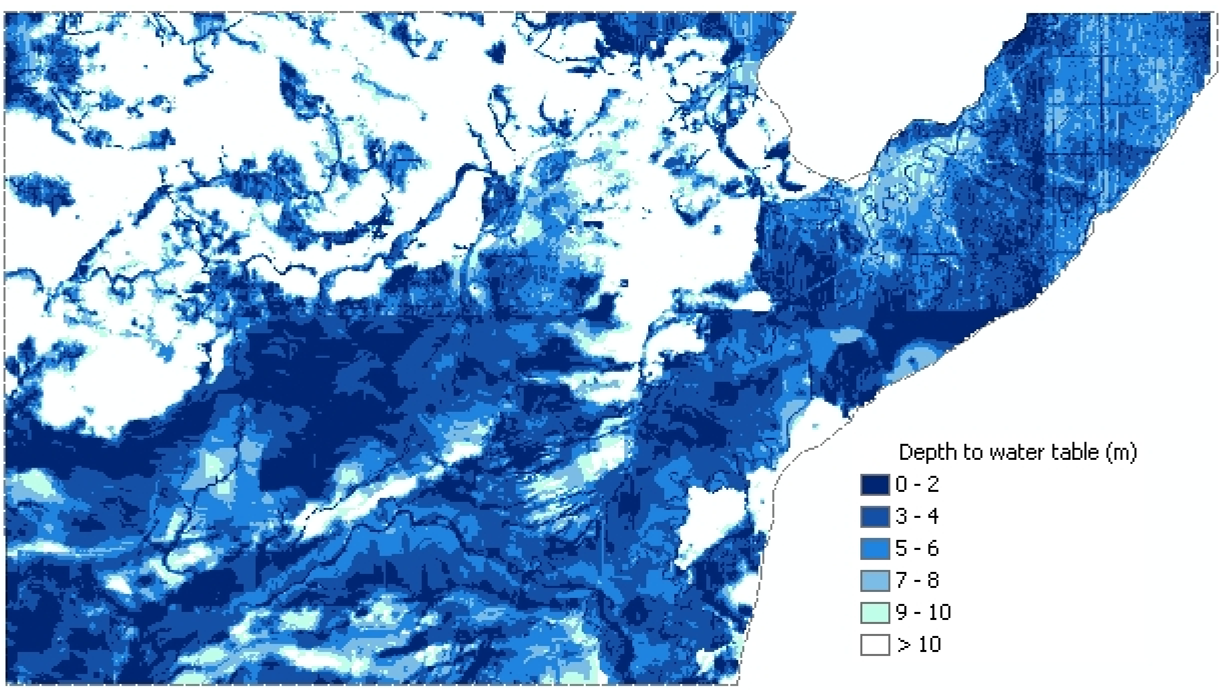


(b)

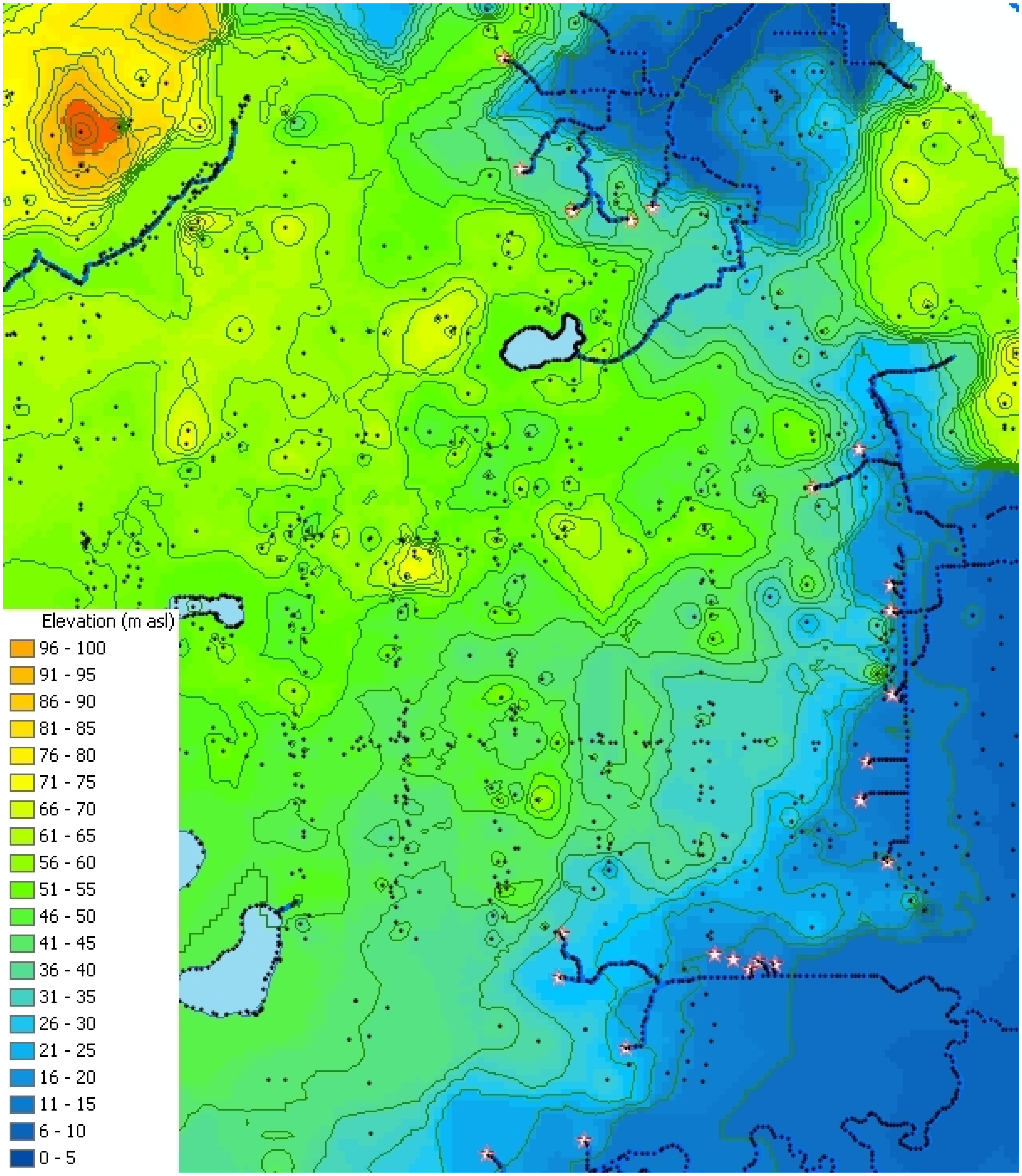
Map 38 Water table elevation modeled with co-kriging of water levels and selected ground surface points, with 5 m contours.



Map 39 Depth to water table (difference between ground surface and modeled water table surface).



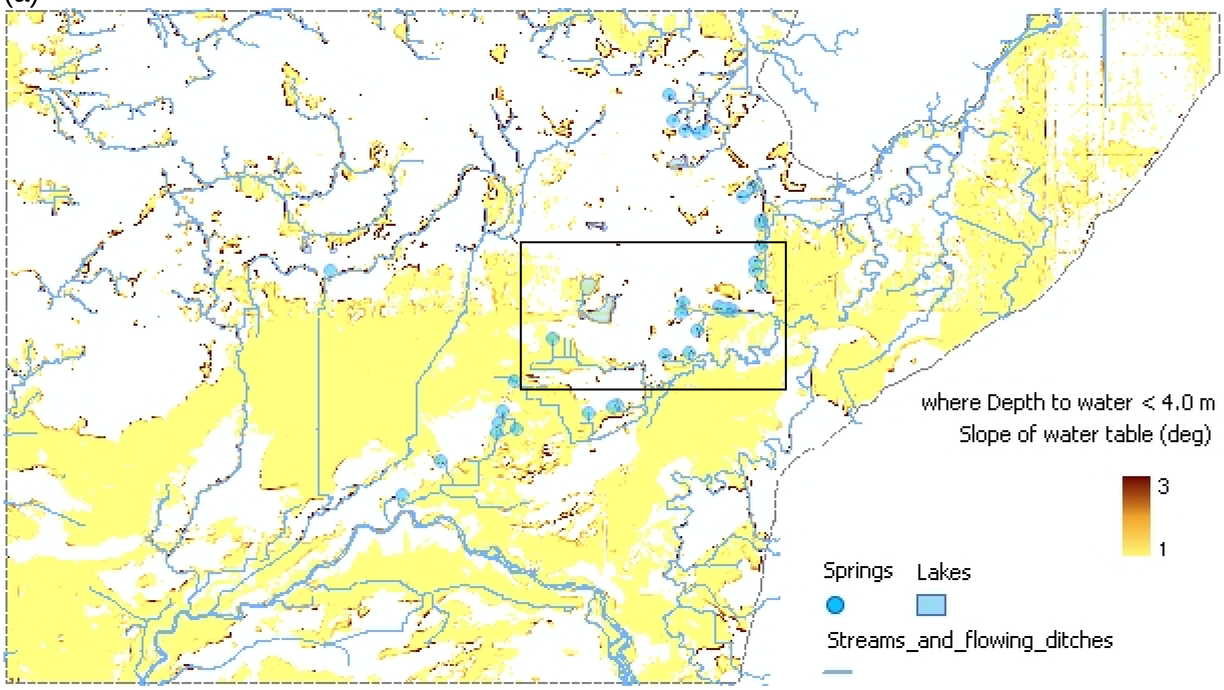
Map 40 Water table elevation (modeled with co-kriging of water levels and selected ground surface points) showing surface water drainage and springs where greatest groundwater seepage occurs.



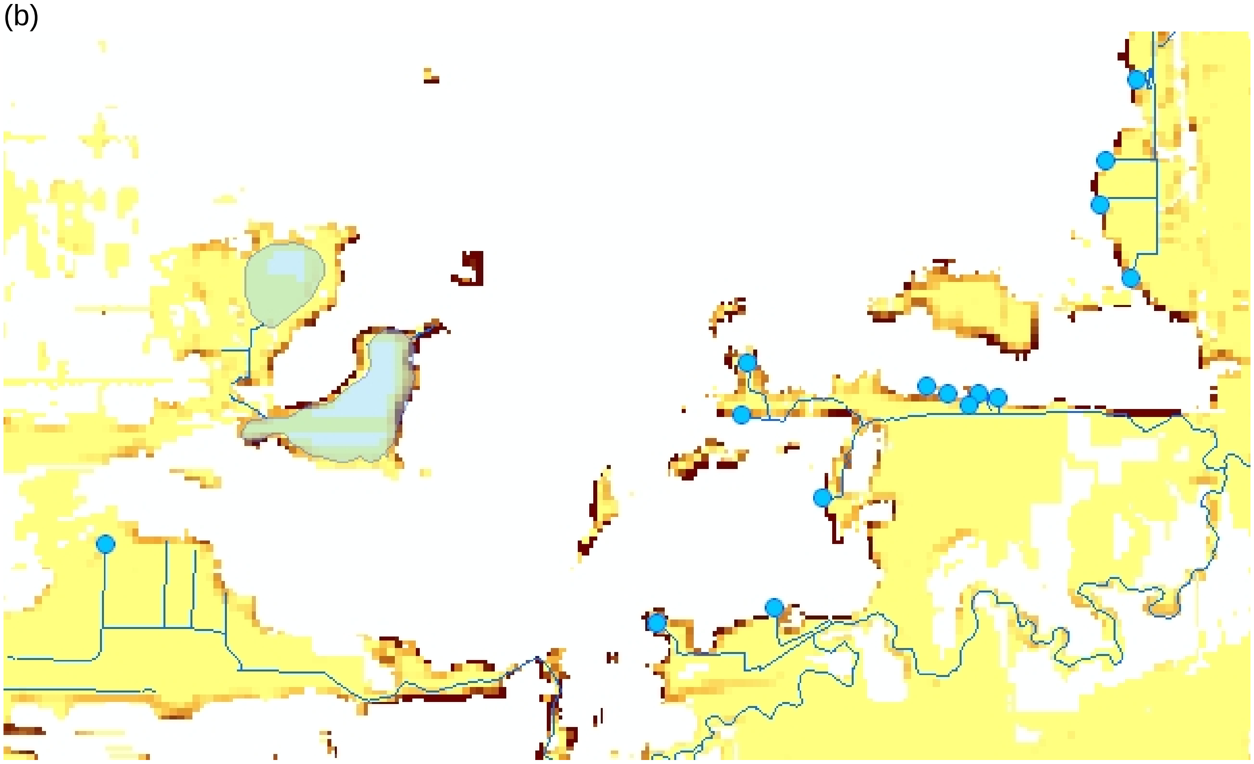
Note: this is the best interpretation of water table elevation (considering all data) thus far. It should be compared to modeled water table elevation to evaluate model performance.

Map 41 Potential seepage areas that were identified by slope of water table > 1.0 deg and depth to water table < 4.0 m, shown with surface drainage and springs: (a) model area, (b) inset area south of Abbotsford Airport and west of Sumas, WA.

(a)



(b)



5. NUMERICAL MODEL DESCRIPTION

5.1. MODELING SOFTWARE

Visual MODFLOW v3.1.83 (Waterloo Hydrogeologic Inc.) was the modeling software environment for running MODFLOW 2000 and other packages, such as ZBUD (Zone Budget), and MODPATH (particle tracking). MODFLOW is a 3D block-centered finite-difference code (McDonald and Harbaugh, 1988) used for solving flow through porous media. The advantage of MODFLOW is that is it widely used and its performance has been verified in numerous modeling studies. The regular grid design involves rectangular arrays for each layer, which are easy to modify using computer code, and are very easy to link with GIS (raster based) systems.

All recharge modeling was done outside of MODFLOW. The recharge and river inputs were modeled external to MODFLOW and are described in boundary condition section of this report. All hydrostratigraphic modeling was aided by ArcGIS for spatial database and spatial interpolation and all other spatial analyses, as well as Visual MODFLOW (WHI, 2004) as the hydrostratigraphic (3D raster of MODFLOW cells) model depository. Automated parameter estimation was not used here.

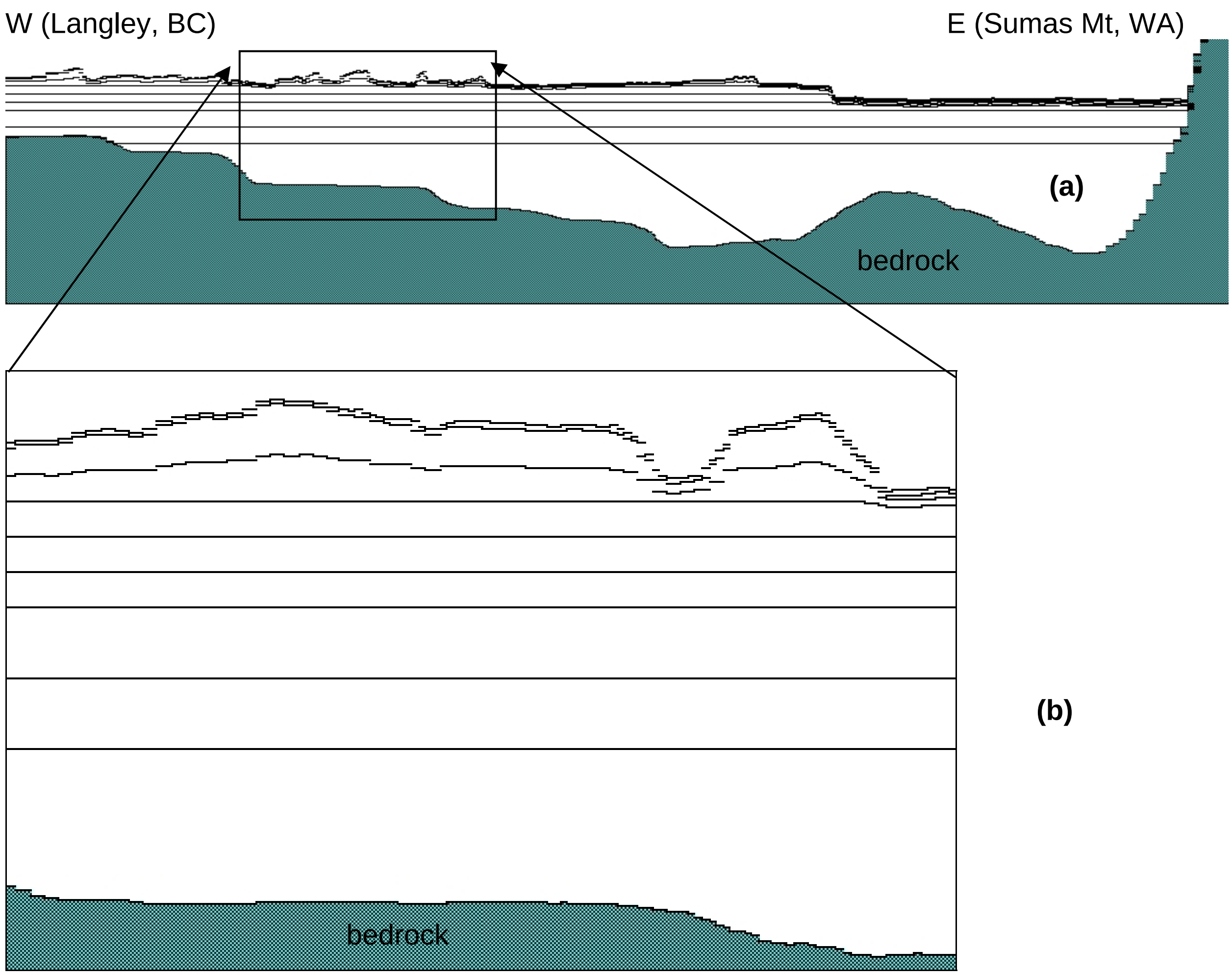
The finite difference grid has many limitations, one being the “layered” approach and difficulty in representing lenses of materials. The new version of MODFLOW 2000 uses the HUV package, which allows for representation of heterogeneities with hydraulic property arrays (the grid is uniformly or variably layered, but material types are represented by flow-properties alone – hydraulic conductivity and storage). The model then creates transition of properties where the solid model of materials shows transition between two different materials. Another alternative is to use a finite-element solution method as implemented in the FEFLOW modeling system. A mesh is more flexible in representing complex surfaces than a 3D grid. The boundaries are more exact. Nonetheless, given the requirements of this project, including input of spatially-distributed recharge and mapping the results in GIS, the finite difference model type was selected.

5.2. MODEL DOMAIN, MODFLOW LAYERS AND GRID

A finite difference grid was constructed in three dimensions following standard grid-construction rules (Anderson and Woessner, 1992). The grid was refined in areas where significant changes in the hydraulic heads were anticipated over short distances (e.g., near rivers and production wells), using standard telescopic mesh-refinement techniques. The horizontal grid spacing is customized in telescopic grid refinement to increase grid density near production wells and rivers.

The MODFLOW model of the central Fraser Valley, and the overlying Abbotsford-Sumas aquifer was implemented in 9 layers (plus bedrock as layer 10) as seen in profile view of the model domain cross-section in **Figure 18**. Each layer represents a dominant sediment type, as was determined from borehole lithologs. Due to MODFLOW layer representation, the layered hydrostratigraphic units are assumed continuous in aerial extent. Where sediments of any type are absent, the layer was represented as thin. Near valley walls, the layers drape the bedrock slopes. Bedrock forms the bottom surface of the model domain.

Figure 18 MODFLOW grid spacing in model domain: (a) grid layer boundaries in W-E cross-section along US-Canada boundary (10 x vertical exaggeration) (b) enlarged section showing ground surface topography and MODFLOW layer boundaries.



5.2.1. BEDROCK WALLS AS NO-FLOW BOUNDARIES

In the groundwater flow model, the active cells are limited to valley sediments. All cells corresponding to valley walls (bedrock) were deactivated and are assumed to be a no-flow boundary condition, relative to the groundwater flow in the much more permeable unconsolidated sediments that overlie the bedrock.

5.3. HYDRAULIC CONDUCTIVITY DISTRIBUTIONS

5.3.1. USGS DATA (WRIS 1 STUDY AREA)

The USGS data first appeared in a report by Gibbons and Culhane (1994). Kahle (1991) identified two aquifer systems in the Sumas Drift deposits: the upland unconfined aquifer (Abbotsford outwash plain, City of Abbotsford BC area) and the Sumas Valley confined aquifer. The hydraulic properties of these two aquifers change with surficial geology, and are transitional from unconfined to confined in various areas. The two aquifers are hydraulically connected (Culhane, 1993; 1994) and on regional scale, form one aquifer system; one part unconfined, and other parts confined (but not totally).

Based on an analysis of aquifer test data from 8 wells, the hydraulic conductivity of the Sumas outwash sand and gravel ranged from 1.07 ft/d to 298 ft/d (0.326 m/d to 90.8 m/d) according to Culhane (1993). Culhane also estimated K for other ice contact deposits and moraine (till) deposits using tables in Freeze and Cherry (1979) for different sediment types (**Table 12**).

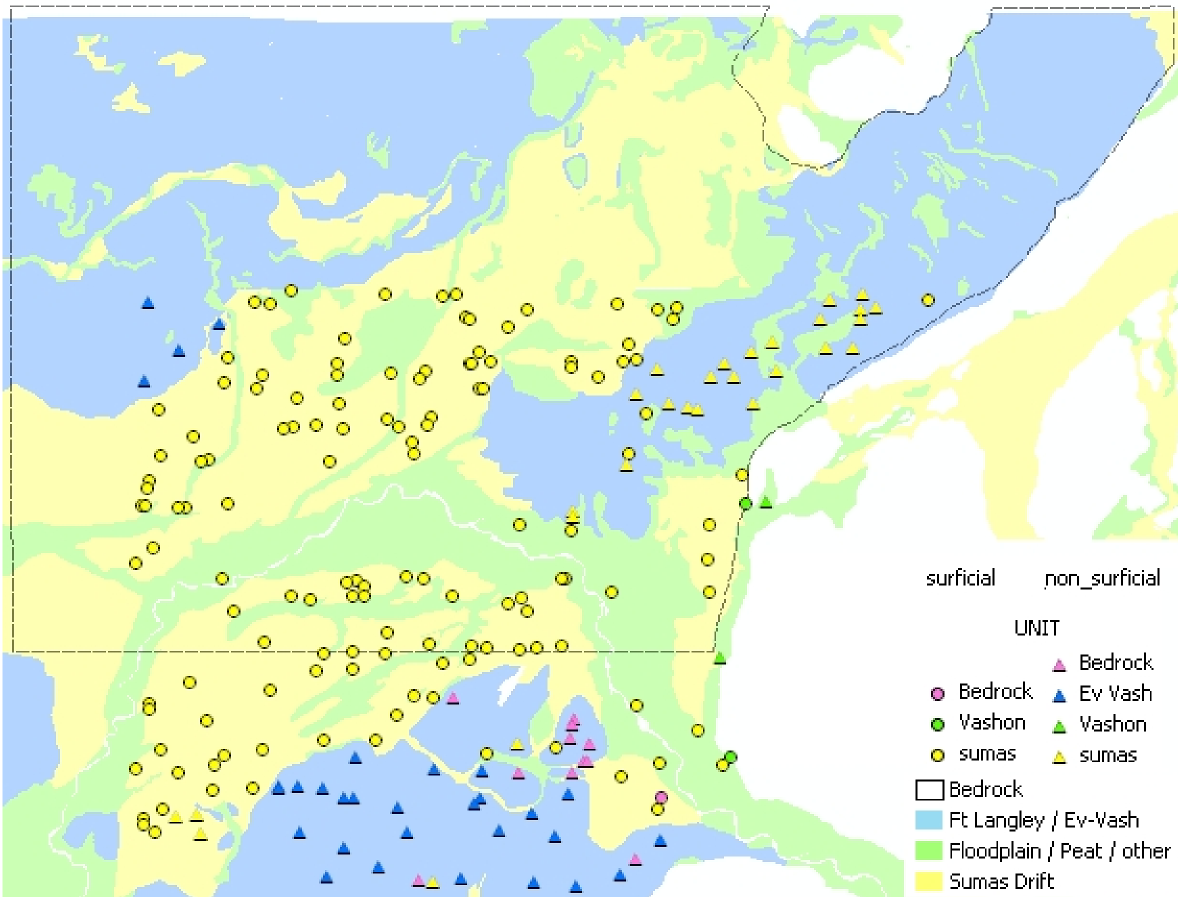
Table 12 K values from Freeze and Cherry (1979), as used by Gibbons and Culhane (1994)

UNIT	UNIT	min K	max K
(Easterbrook, 1976; Kahle, 1990)	*(Armstrong 1984; Clague 1994)*	(m/d)	(m/d)
Bellingham Drift	Fort Langley Fm (stony clays)	4.1E-07	4.1E-04
moraine (till) and ice contact deposits		4.1E-07	4.1E-01
Sumas Valley sandy silty clay		4.1E-05	4.1E-02
Nooksack River alluvium		4.1E-01	4.1E+02

The hydraulic conductivity data are log-normally distributed, after log-transformation, which allows a geometric mean of the data to be calculated. The water resource investigations of Culhane (1993) covered an area from Bertrand Creek and Nooksack River, to the international boundary and eastern edge of the valley. This is the southern half of this Abbotsford-Sumas aquifer model area and corresponds to transmissivity data distribution used in LENS study as shown in **Map 42**. For the Culhane (1993) study, the mean transmissivity was 12593 gpd/ft ± 9574 gpd/ft (47.7 m^3/d ± 36.2 m^3/d). Note that the standard deviation was almost as large as the mean value, which indicates very large spread in data, suggesting very large aquifer heterogeneity in this area (Culhane, 1993). The report contains a contour map of transmissivity, suggesting presence of large scale trends, perhaps explained by buried outwash stream channels in southern Sumas Valley, according to speculation by Gibbons and Culhane (1994).

In 1999, Cox and Kahle authored the USGS report, which included all high quality hydraulic conductivity, storativity, and transmissivity data. This report focused on the hydrogeology and groundwater quality of lowland aquifers of Whatcom County, WA and part of BC (central Fraser Lowland). The data are in print format in one volume. Digital data were obtained for this study from USGS through downloading from an ftp site. There are hundreds of pump tests, summarizing information for each well (casing diameter, screen length, discharge, drawdown, time, and hydraulic conductivity). The database also contains comprehensive reference list for many obscure and hard to find data sources of various hydrogeologic investigations. Cox and Kahle (1999) is one of the best sources of information on hydrogeology of this area.

Map 42 Pump test data (pump tests and SC tests) published by Cox and Kahle (1999) in USGS report on groundwater resources in northern Whatcom County, WA. Data points are classified by aquifer types used by Cox and Kahle (1999), and overlain on the surficial geology map.



Of 608 wells with Specific Capacity (SC) data, 219 were selected where there was complete and reliable information (discharge rate, drawdown, long term test, well construction data, and a geologic log). Two different sets of equations were used to compute transmissivity (T) and hydraulic conductivity (K).

<u>Method 1 (K1)</u>

For wells that had a screened, perforated, or open hole interval, the modified Theis equation was used:

$$T = (Q / 4 \pi s) * \ln (2.25 T t / r^2 S)$$

where S = storage coefficient, Q = pumping rate (discharge), T = transmissivity of hydrogeologic unit, t = length of time of pumping (days), r = radius of well, s = drawdown in well. The equation was solved for T using Newton's iterative method. Horizontal hydraulic conductivity could then be calculated using:

$$K1 = Kxy = T / b$$

where b = length of open interval of well to approximate hydrogeologic unit thickness assuming that a well is open to the entire thickness of the unit, which was almost never the case (Cox and Kahle, 1999).

Method 2 (K2)

For wells that had only open ends (no screen interval), the authors computed Kxy using Bear's (1979) equation for hemispherical flow to an open ended well just penetrating aquifer.

K2 = Kxy = Q / 4 pi s * 1/ r

Transmissivities were rounded to the nearest 1,000 gallons per day per foot. Only aquifer tests with both observation and pumping wells or single-well tests of at least one hour were included in that study. For sites for which no latitude and longitude were provided, the description of the site in the original data source was used to plot the approximate site location on a topographic map. The latitude and longitude of the plotted sites were determined by digitizing the locations. The locations of all miscellaneous measurement sites were identified as "approximate locations" in the WRIA 1 study area.

Cox and Kahle (1999) defined four hydrostratigraphic units, much more generalized than the present Abbotsford-Sumas model project. Nevertheless, the summaries of hydraulic properties (**Table 13**) are valuable. The main aquifer units are Sumas Drift, which is subdivided into Abbotsford outwash and Sumas Valley (semi-confined). Sumas Drift corresponds to a mixture of units 1 and 2 (sandy and gravelly Sumas Drift) in this report, and Everson-Vashon Drift consists of glaciomarine sediments described as stony clays and other sand and gravel lenses, which form local aquifers – this unit corresponds to Fort Langley Formation and Capilano Sediments, which are usually aquitards. The means were derived from log K values, then converted to normal units (here all units are m/d for K, m^2/d for T, and dimensionless for S). We prepared the histograms of K and T values (**Figure 19**) for the Sumas Drift and Everson-Vashon (Fort Langley Formation or stony clays) hydrostratigraphic units (Cox and Kahle, 1999).

Table 13 Hydraulic properties of hydrostratigraphic units from Cox and Kahle (1999), summarized from spatial database of pump test data summaries. K was determined using two methods (K1, K2).

Hydraulic Conductivity (m/d)

	Mean log K				Standard Deviation			
UNIT	K	K2	n	n2	sdev K	sdev K2	min K	max K
Sumas Drift (surficial - Abb. Outwash)	58.2	93.8	136	42	4.0	3.3	2.1	2377
Sumas Drift (Sumas Valley)	184.3	474.1	28	22	3.9	4.1	12.2	2347
Ev-Vash (stony clays)	19.3	21.5	30	10	4.0	4.2	0.9	125
Bedrock	1.6	0.7	6	9	7.1	6.0	0.09	23.5

Transmissivity (m^2/d)

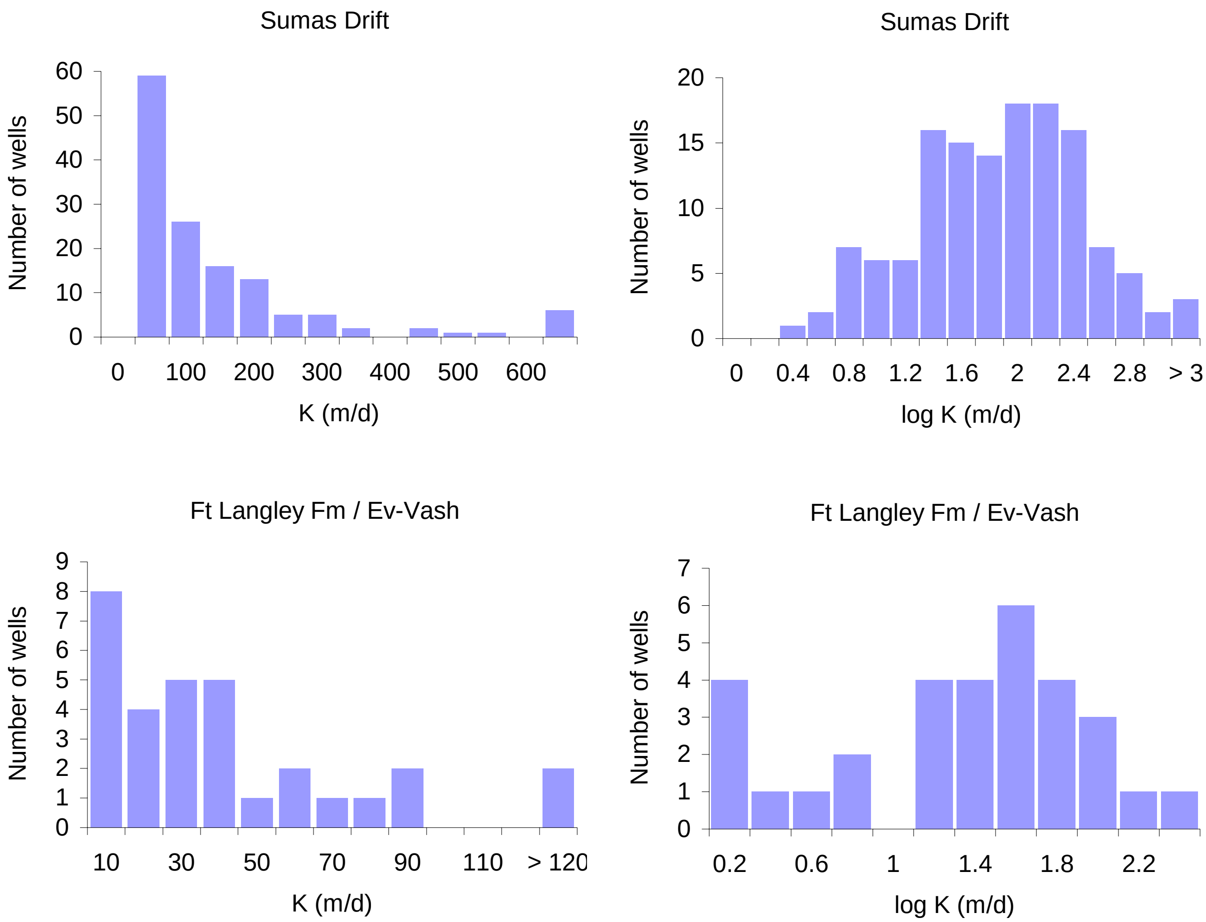
UNIT	Mean log T	n	sdev T	min T	max T
Sumas Drift (surficial - Abb. Outwash)	108.6	110	4.3	3.2	1812
Sumas Drift (Sumas Valley)	652.4	27	4.6	22.3	11446
Ev-Vash (stony clays)	26.8	22	4.3	0.9	159
Bedrock	1.1	8	21.3	0.01	142

Storativity

UNIT	Mean log S	n	min S	max S
Sumas Drift (surficial - Abb. Outwash)	1.1E-01	110	8.5E-05	5.9E+02
Sumas Drift (Sumas Valley)	4.0E-04	27	1.6E-05	1.1E-01
Ev-Vash (stony clays)	9.9E-05	22	1.0E-05	1.9E-04
Bedrock	7.0E-04	8	9.0E-05	7.5E-02

The Abbotsford outwash (Sumas Drift in uplands near City of Abbotsford) has hydraulic conductivity mean value of 58.2 to 93.8 m/d (depending on K calculation method) based on a maximum 136 observations with 4 m/d standard deviation of log-normally distributed values (see **Table 13**). The actual data ranged from 2.1 to 2377 m/d. The highest values represent highly permeable portions of the aquifer and are not typical of most locations. The Sumas Valley aquifer (Sumas Drift) encompasses the transition zone from the uplands to the valley, where large production wells are located (e.g., Fraser Valley Fish Hatchery, Sumas City water supply, Abbotsford City water supply). The mean hydraulic conductivity was 184.3 m/d to 474.1 m/d (depending on K calculation method) with 4 m/d standard deviation, based on maximum 28 observations. Actual values ranged from 12.2 to 2347 m/d.

Figure 19 Histograms of hydraulic conductivity values from Cox and Kahle (1999) report: (a) Sumas Drift hydrostratigraphic unit (aquifer), (b) Fort Langley Formation / Everson-Vashon Glaciomarine Drift (aquifer).



5.3.2. SPATIAL DISTRIBUTION OF HYDRAULIC CONDUCTIVITY, TRANSMISSIVITY AND STORATIVITY

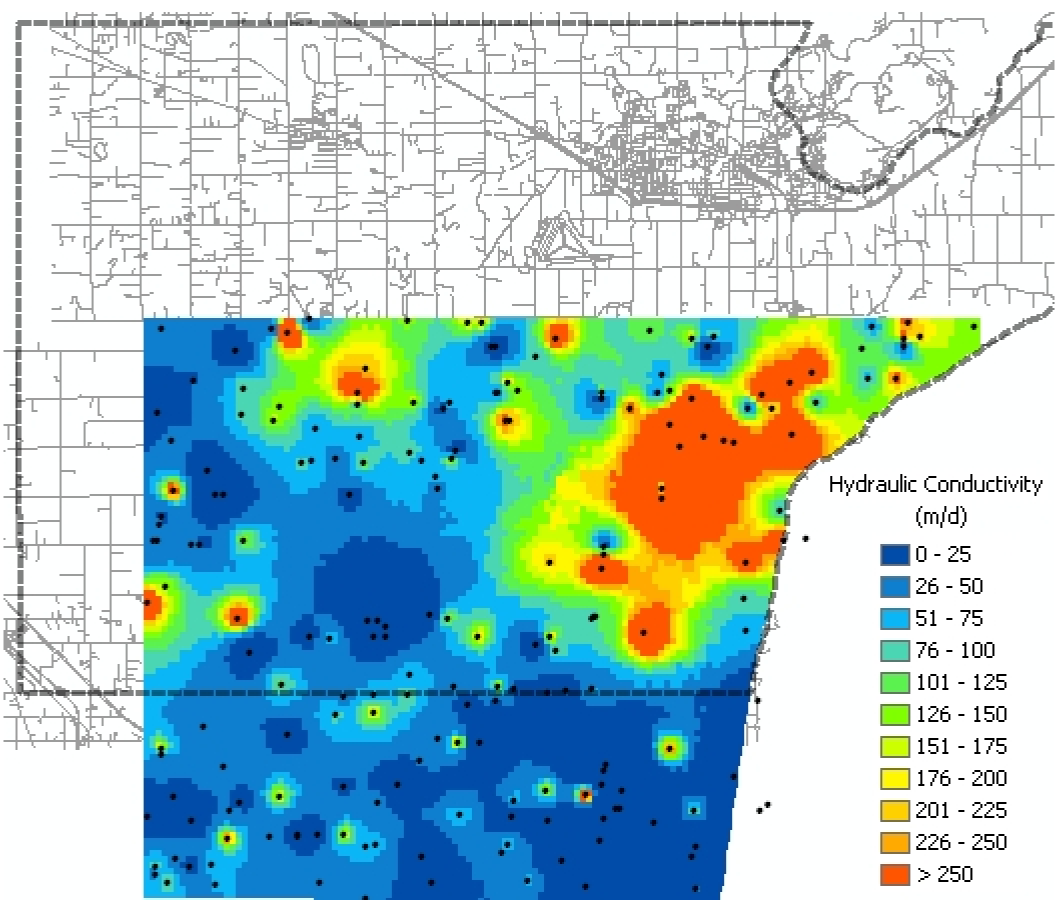
Spatial trends in hydraulic conductivity (**Map 43**), transmissivity (**Map 44**), and storativity (**Map 45**) were interpolated using an inverse distance method in ArcGIS 8.3, from source data in Cox and Kahle (1999). All spatial maps in this report were generated as part of this study from source tabular data. Patterns show strong zonation on regional scale, and also aquifer heterogeneity at more local scale.

There is a high T (and K) zone that runs along the Sumas Valley, which is bounded by Abbotsford outwash plain and Lynden Terrace to the west, and Nooksack River floodplain to the south. Interestingly, this area coincides to a low S zone. The northern extent of this highly conductive zone is not known due to lack of pump test data east of the City of Abbotsford and in Sumas Valley, BC. High values are also locally found south of Abbotsford Airport and perhaps to the east. West of Sumas Valley, the aquifer is either very heterogeneous, or the pump tests have large variation in quality of hydraulic conductivity estimates. Hydraulic conductivity is greater than 400 m/d in this zone, and some values approach 1000 m/d. These are extremely high numbers, but it is not obvious if these numbers are consistently in error, or if the aquifer is extremely conductive there. The most productive high capacity pumping wells are all located in this zone. These values may be lower than 400-1000 m/d if the aquifer is assumed to be of greater thickness than assumed by Cox and Kahle (1999). The sand and gravel units extend to a depth of over 50 m below ground surface under center of this zone, which would mean lower K values than estimated using screen length as aquifer thickness. The high values would then range from 80 to 300 m/d, which are more reasonable. In the model, a high K zone was calibrated to be between 150 and 300 m/d, and the lower 150 m/d value was eventually used.

A low K zone extends through the entire Nooksack River valley.

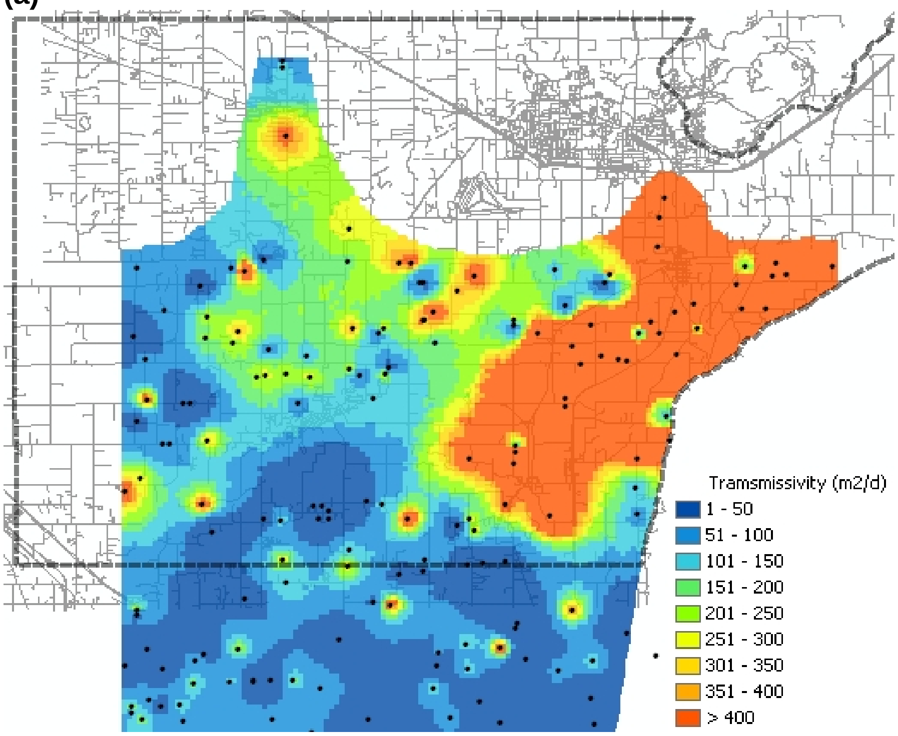
A table of pump tests was found in the WRIA 1 (USGS) study (Cox and Kahle, 1999), on a website associated with the report. **Map 46** has the pump test locations, compiled in that report, other than the pump test data used in interpolation of K zones.

Map 43 Hydraulic conductivity field interpolated from USGS and other pump test results (Cox and Kahle, 1999). Inverse distance interpolation over part of model area of log K values. Hydraulic Conductivity calculated from transmissivity using screen interval as aquifer thickness in m/day.

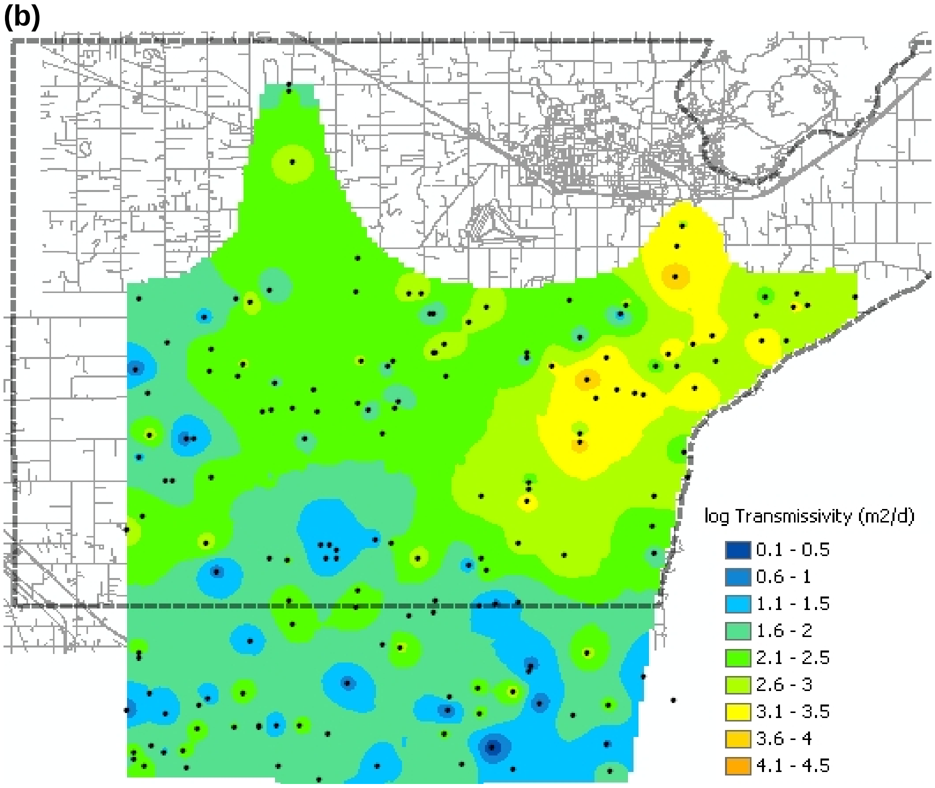


Map 44 Transmissivity field interpolated from USGS and other pump test results (Cox and Kahle, 1999). Inverse distance interpolation over part of model area of log T values. (a) Transmissivity in m^2/day, (b) log Transmissivity values.

(a)



(b)



Map 45 Storativity field interpolated from USGS and other pump test results (Cox and Kahle, 1999). Inverse distance interpolation over part of model area of log S values. (a) Storativity, dimensionless, (b) log Storativity values.

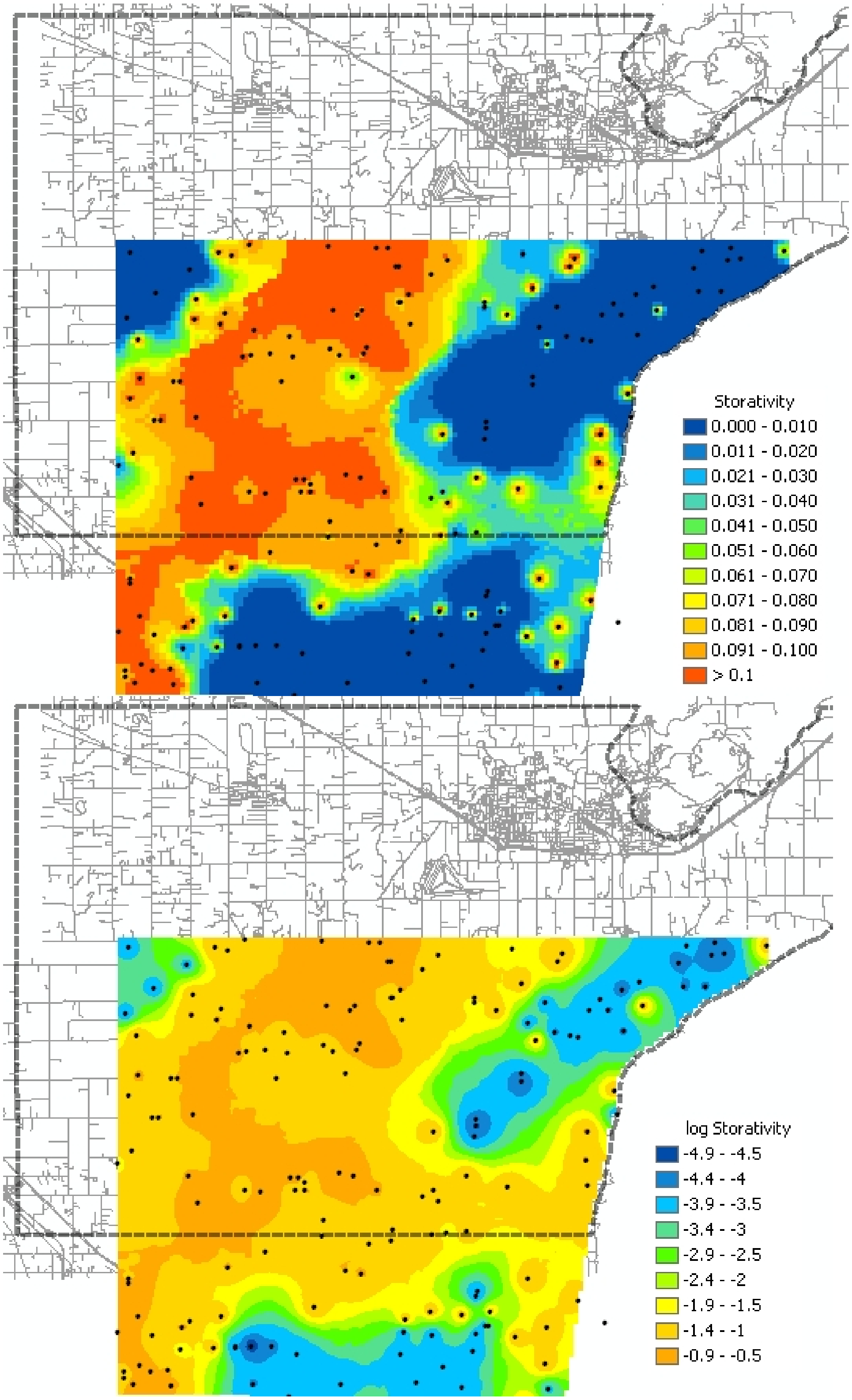
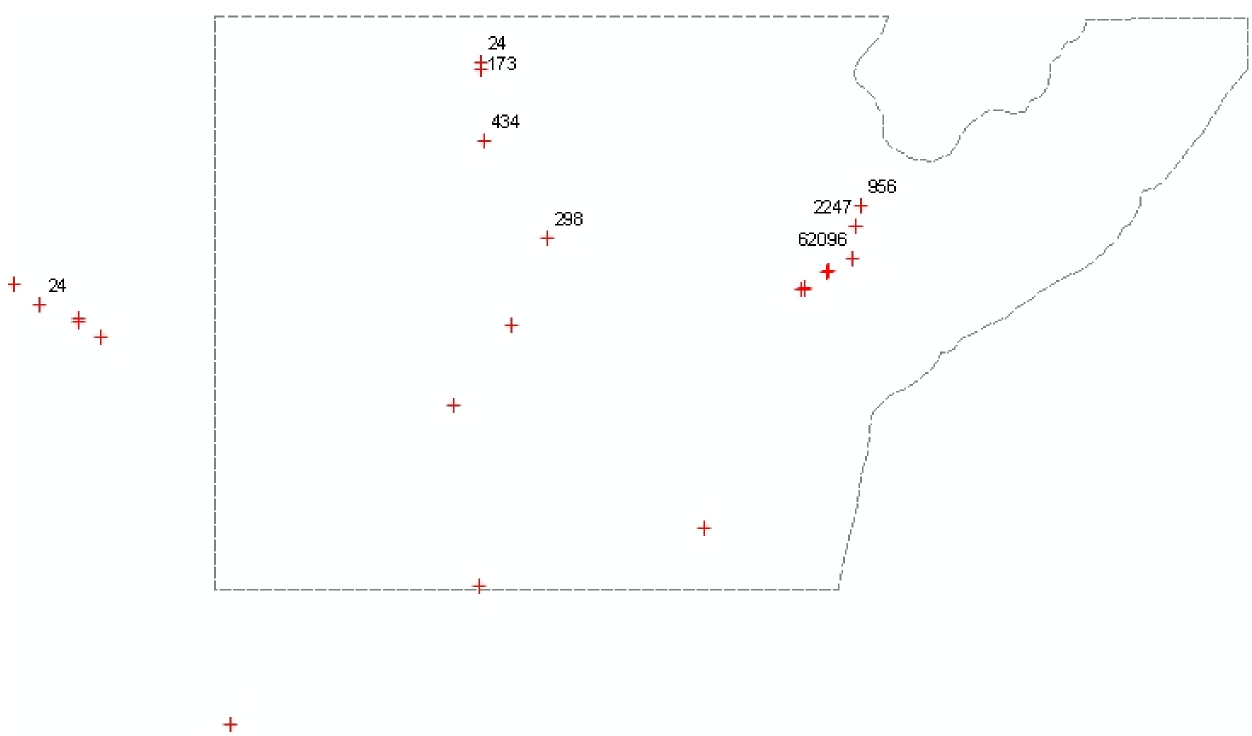


Table 14 Pump test results listed in WRIA1 report (Cox and Kahle, 1999).

WRIA1 Catalogue Number	Geographical Area	Storativity: S min	Storativity: S max	Transmissivity: T min (m^2/d)	Transmissivity: T max (m^2/d)	Aquifer Thickness (m)	Hydraulic Conductivity: K max from K = T/d (m/d)	Hydraulic Conductivity: K min (m/d)	Hydraulic Conductivity: K max (m/d)
GW-001	Everson	0.0300	0.4200	633	2447	10	245		
GW-003	Lynden							2	108
GW-006	Blaine	0.0002	0.0050	25	1304	90	14		
GW-017	Sumas				1590				
GW-018	Sumas				497				
GW-019	Sumas	0.0070			1490				
GW-022	Sumas	0.0004	0.0040	522	3477				
GW-041	Edaleen Dairy							17	228
GW-061	Sumas	0.0002			3415	8	417		
GW-066	Ferndale	0.0050			559	6	92		38
GW-068	Lummi Nation			50	224	2	149		
GW-069	Point Roberts	0.0270			62				
GW-070	Pole Road, south of Lynden				273				19
GW-094	Fraser Valley Trout Hatchery	0.1000		1242	1863				
GW-37	Canada			7452	62096				
GW-37	Canada				2248				
GW-37	Canada				956				
GW-37	Canada				174				
GW-37	Canada				298				
GW-37	Canada				435				
GW-37	Canada				25				

Map 46 Pump test results from WRIA1 report, mapped onto model area and showing maximum transmissivity values.



5.3.3. OTHER HYDROGEOLOGIC INVESTIGATIONS

Aldergrove Aquifer (Piteau, 1991):

In 1991, Piteau Associates carried out hydrogeologic assessment of the Aldergrove aquifer, west of Abbotsford and located in township of Langley, BC. A simple 5 layer finite difference model was run. The transmissivity of the aquifer layer was assigned as $5x10^{-3}$ m^2/s (432 m^2/d), based on results of pump testing by Pacific Hydrology Ltd. (1984). Storativity ranged from 0.0004 to 0.0010 in the calibrated model. Transient model simulations of one pumping well (pump test) gave best fit for storativity of 0.0006. Mean annual recharge was estimated from water balance and reported as 12.6% to 16.1% of mean annual precipitation of 1650 mm.

An older report by Piteau (1984), for the Township of Langley, investigated the Brookswood-Fernridge area, south of Langley, BC and just west of the western model boundary in this study. **Table 15** provides a summary of municipal wells and pump test results.

Table 15 Table of pump test results from Brookswood-Ferndale area (Piteau Associates, 1984). One value or range of values provided.

Transmissivity (m^2/d)		**Hydraulic Conductivity (m/d)**		**Storativity**
389	1728	17	78	
605		26		
181				
173	1382	8	35	
3974		173		
138	4838	173		
86	173	4	8	0.01 – 0.09
3110		121		
Ave.	**1305**	**Ave.**	**55**	

Sumas Aquifer (City of Sumas wellhead protection plan and flow modelling study)

Associated Earth Sciences Ltd. (1996) did a project for the City of Sumas, in which a MODFLOW model was designed (100 x 100, with 50 to 150 m spacing) and run in steady-state. The approach involved delineating zones of hydraulic conductivities from USGS data and the same data as used by Gibbons and Culhane (1994).

The model assumed lateral isotropy (Kx = Ky), but Kz was two orders of magnitude less. The following summarizes the parameters used in that model.

a) Sumas Valley (silt and clay confining layer) = 0.64 ft/d (0.195 m/d)

b) Sumas Valley (aquifer, from scarp edge) = 2000 ft/d (610 m/d) with Kz = 0.01of Kxy

Zonation was also incorporated into the model. It consisted of:

a) a transition zone (ice marginal/till deposits) between upland and Sumas Valley = 10 ft/d (3.048 m/d)

b) upland areas zone (Abbotsford Airport area) = 400 ft/d (121.92 m/d) with Kz = 4 ft/d (or 0.01 of Kxy)

A similar zonation was observed in this study, although here zonation was spatially more refined to account for lake elevations and flow directions, and observed water levels from hundreds of wells.

Chilliwack (north-east Sumas Valley)

The Sardis-Vedder aquifer lies immediately north of the Vedder River in Sardis and extends north to the No. 1 Highway. It is bounded on the west by the City of Chilliwack's border with Abbotsford. Several pump tests have been completed on wells constructed in the Sardis-Vedder aquifer, ranging in duration from a few hours to 48 hours (District of Chilliwack, 1998). Results of pump test analyses (**Table 16**) give an average transmissivity of 11232 m^2/d, and storativities ranging from 7.5 x 10^{-5} to 0.02. The results are fairly consistent, which confirms the uniformity of the aquifer over a distance of approximately one kilometre.

Table 16 Table of pump test results from Sardis-Vedder aquifer (District of Chilliwack, 1998).

Pumped	Well Duration	Transmissivity (m^2/d)	Storativity
Well 2	48 hours	10368	0.02
Well 3	Unknown	6912	0.02
TW95-1	24 hours	12960	7.5 x 10-5
TW97-2	48 hours	8640	NA
TW98-1	8 hours	17280	NA

Cherry Point power plant site investigation (Golder Assoc., 2004)

The hydraulic conductivities of the weathered and unweathered portions of the Bellingham Drift (corresponding to Fort Langley Formation and Capilano sediments) were estimated using slug tests and laboratory falling head tests. Hydraulic conductivities ranged from .45 m/d to 1.0x10^{-5} m/d (in the weathered Bellingham Drift) and 6.6x10^{-3} to 1.5x10^{-5} m/d in the unweathered Bellingham Drift. Only a few hydraulic tests were conducted in wells connected to the Deming Sand aquifer (Fort Langley Formation and Capilano sediments) and the results indicate hydraulic conductivities from .05 to 3x10^{-5} m/d. The results for the Deming Sand aquifer may be low because the wells partially penetrated this unit only a few feet. An earlier estimate of hydraulic conductivity for the Deming Sand aquifer was 4.3 to 0.43 m/d based on grain size descriptions (CH2M HILL, 1983). **Table 17** summarizes the results of this study.

Table 17 Hydraulic conductivity and porosity range estimated for Fort Langley Formation sediments (Golder Associates, 2004).

Bellingham Drift (Fort Langley fm. and Capilano sediments)

	K (m/d) min	max	porosity
weathered	4.49E-01	1.04E-05	0.33 to 0.50
unweathered	6.65E-03	1.47E-05	

Deming Sand (Fort Langley fm. and Capilano Sediments)

	K (m/d) min	max	porosity
pump tests	4.92E-02	3.28E-05	0.25 to 0.35
grain size	4.32E+00	4.32E-01	

5.3.4. MAPPING HYDRAULIC PROPERTIES WITHIN THE MODEL

After the hydrostratigraphic units were mapped, for wells where transmissivity values were known or estimated, the well screens were located in the model layers (**Map 47**). At each well, the transmissivity values (from pump tests) were assigned to appropriate hydrostratigraphic unit (category) and then summarized as descriptive statistics (mean transmissivity and others). Model layers with hydrostratigraphic units and locations of wells with transmissivity values are on **Map 48** and **Map 49**. If the hydrostratigraphic units have (on average) differences in transmissivity values, then there should be differences between the mean transmissivity as counted here by well screen locations.

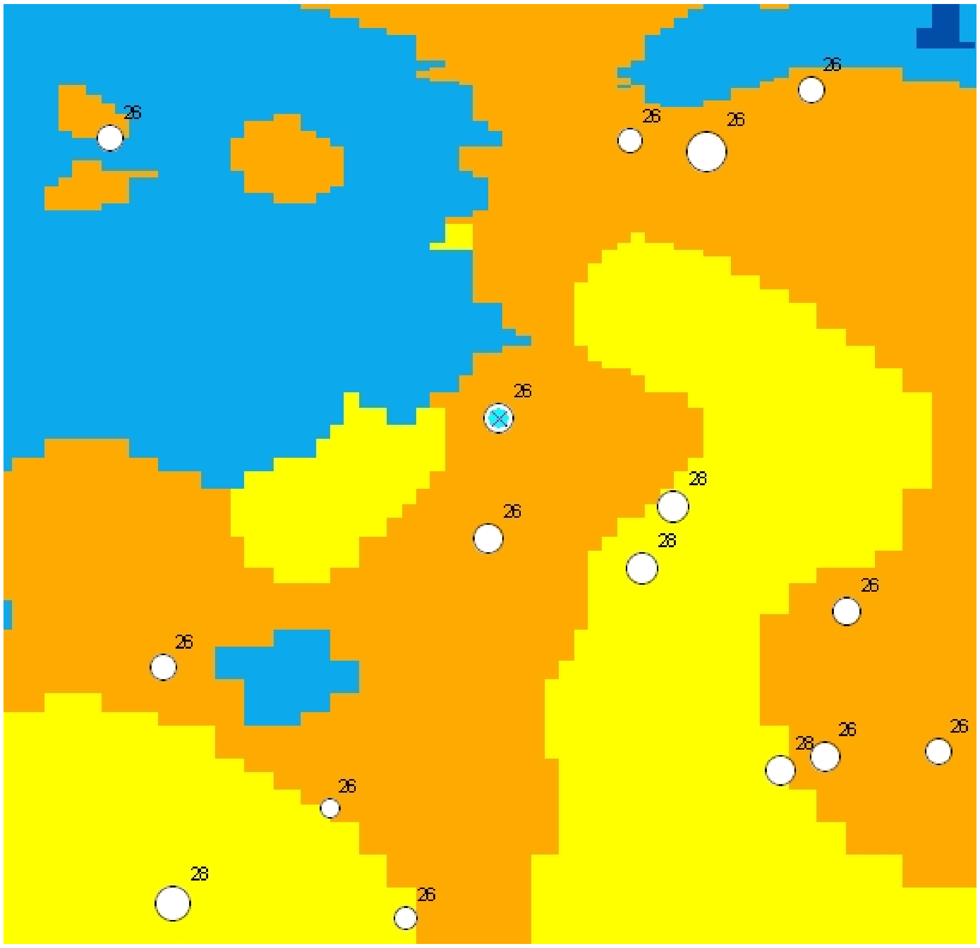
Results are in **Table 18** and graphed in **Figure 20**. Aquifer hydraulic properties from pump tests (Cox and Cahle, 1999), summarized by hydrostratigraphic unit where well screen is located, were assigned to the new hydrostratigraphic model of Abbotsford-Sumas aquifer. Four hydrostratigraphic units were considered: Sumas Drift (sandy), Sumas Drift (gravelly), silt (mostly silt), and clay or till (mostly Ft Langley formation and similar). The mean hydraulic conductivity was the highest in Sumas Drift (gravelly) unit at 105 m/d, as expected, but it was surprisingly high in both Sumas Drift (sandy) and silty units. One conclusion is that silty units contain sand lenses and should not be considered as having typically low hydraulic conductivity of silt. The average K value for clay/till unit was also surprisingly high, compared to expected values for this type of material. The conclusion is that the aquifer is probably very heterogeneous and discrete units are not that different from each other, but there may be strong local differences.

Transmissivities were largest for the silt unit, probably due to error estimates of saturated thickness. If the silt unit is ignored in results for transmissivity, the other units make sense: gravel has higher T value than sand and clay/till is the lowest. Storativity was calculated to be the highest in Sumas Drift (sandy) unit and lowest in silt unit. This does not make sense, so the results for storativity are not useful in further analysis. Overall, only the hydraulic conductivity results (statistics per hydrostratigraphic unit) are useful.

We know that there is a “high” and “low” zone of these values (as contoured from USGS data). The problem arises where these statistics (**Table 18** and **Figure 20**) lump together two different populations of K, T, and S values. The other problem is lack of data on the Canadian side. Here, the mean values can be used to assign K, T, and S to hydrostratigraphic units and use geology distribution as substitute for K or S distribution. In other words, the K and S distribution can be generated from hydrostratigraphic units. However, within each hydrostratigraphic unit there is some heterogeneity, and sometimes a strong one, of each parameter. During model calibration, additional zones may have to be created to account for local “problems” with calibration, on the Canadian side.

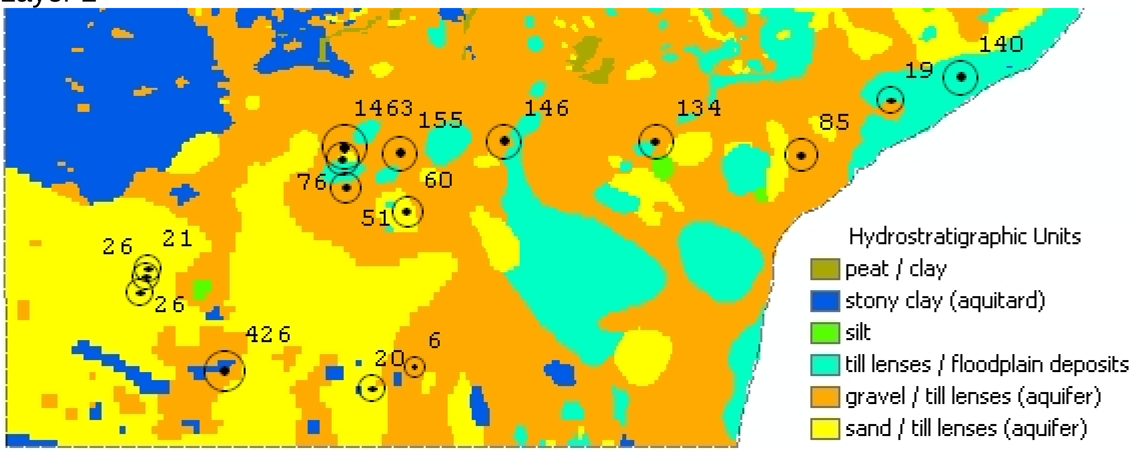
As a first approximation of actual average hydraulic conductivities of hydrostratigraphic units in this flow model, the average values as calculated here were assigned to the model K property zones (hydrostratigraphic units). We acknowledge that issues of aquifer heterogeneity are very important and will continue to create challenges in flow model calibration.

Map 47 Mapping K onto hydrostratigrahic units using GIS.

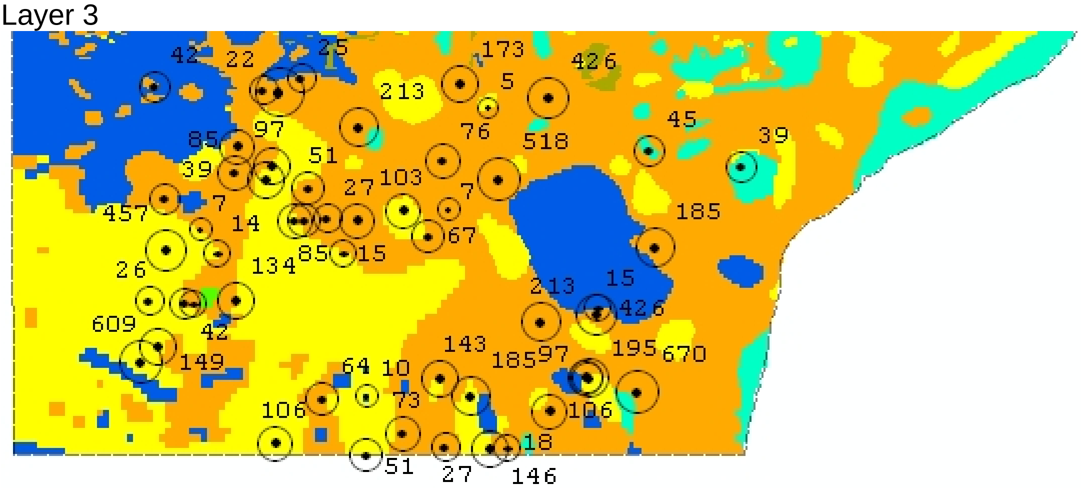


Map 48 Hydraulic conductivity by model layer and hydrostratigraphic units as mapped from borehole lithologs: model layers 2 to 4.

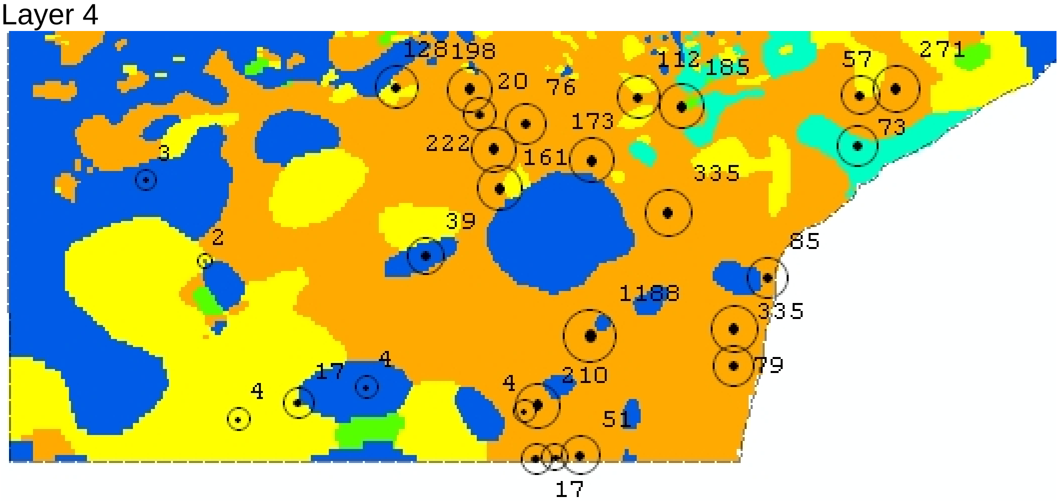
Layer 2



Layer 3

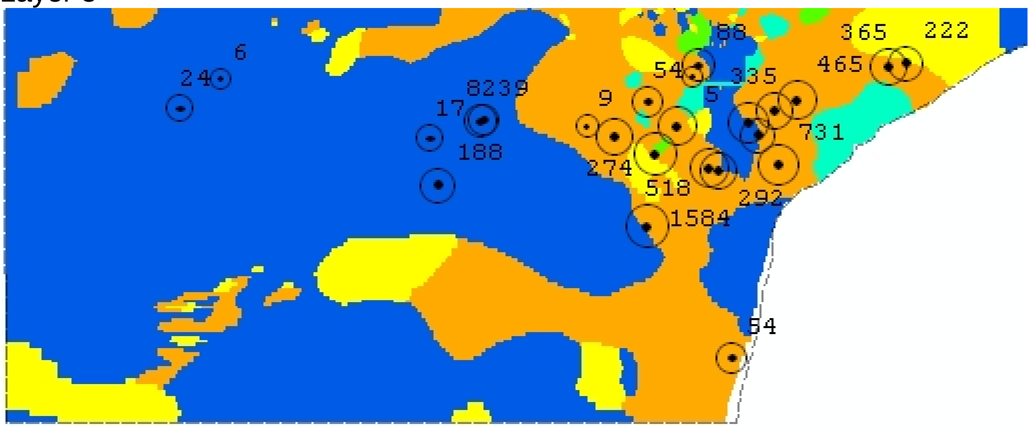


Layer 4

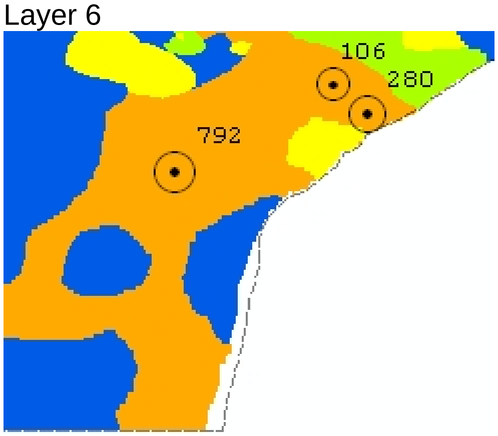


Map 49 Hydraulic conductivity by model layer and hydrostratigraphic units as mapped from borehole lithologs: model layers 5, 6, and 1.

Layer 5



Layer 6



Layer 1 (ground surface)

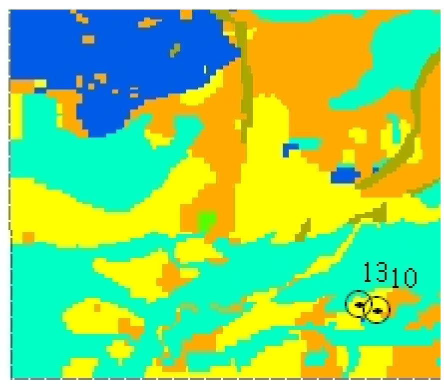


Table 18 Aquifer hydraulic properties from pump tests (Cox and Cahle, 1999), summarized by hydrostratigraphic unit where well screen is located in the new hydrostratigraphic model of Abbotsford-Sumas aquifer.

Hydraulic Conductivity (m/d)

HydrStrat		mean log K	mean K	Stdev log K	Stdev K	median K	n
1	Sumas Drift (sandy)	1.75	56.6	0.64	4.34	94.0	26
2	Sumas Drift (gravel	2.02	105.4	0.62	4.21	106.7	85
3	silt	1.71	51.5	0.32	2.08	45.7	5
4	cley/till	1.30	19.8	0.53	3.35	17.1	11

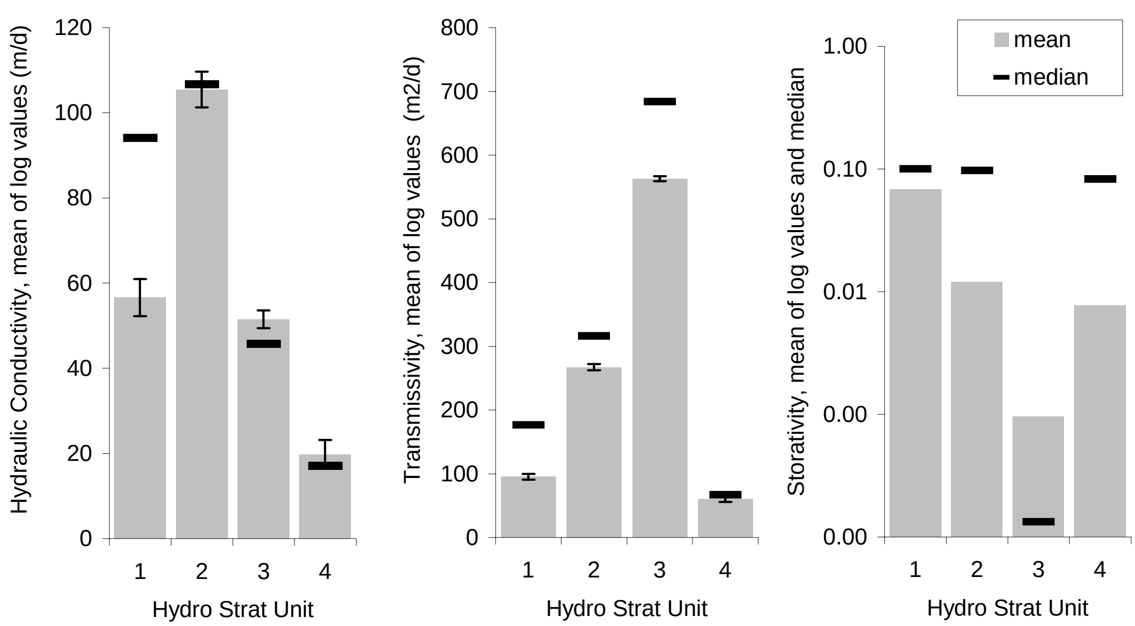
Transmissivity (m2/d)

HydrStrat		mean log T	mean T	Stdev log T	Stdev T	median T	n
1	Sumas Drift (sandy)	1.98	95.4	0.66	4.59	176.5	21
2	Sumas Drift (gravel	2.43	267.2	0.69	4.93	316.3	72
3	silt	2.75	562.8	0.59	3.88	683.8	3
4	cley/till	1.78	60.1	0.66	4.52	66.9	11

Storativity

HydrStrat		mean log S	mean S	Stdev S	Stdev log S	median S	n
1	Sumas Drift (sandy)	-1.17	0.0682	0.029	0.66	0.1004	21
2	Sumas Drift (gravel	-1.92	0.0120	0.052	1.42	0.0970	68
3	silt	-3.02	0.0010	0.042	1.62	0.0001	3
4	cley/till	-2.11	0.0077	0.047	1.46	0.0826	11

Figure 20 Hydraulic conductivity, transmissivity, and storativity from pump tests summarized by hydrostratigraphic unit for all layers of model. Hydro Strat Units: 1= Sumas Drift (sandy), 2 = Sumas Drift (gravel), 3 = silt, 4 = clay/till



5.3.5. VADOSE ZONE HYDRAULIC CONDUCTIVITY

The HELP model, which was used for recharge estimation, requires estimates of K_{sat} (or K_z) in the vadose zone. There was large quantity of spatially distributed K, T, and S data available. This modeling report describes all K and T fields (distributions) and sources of data. For all hydrostratigraphic units in all layers, representative values of K were assigned, and representative vertical hydraulic conductivity was computed for each raster cell 50x50 m over the aquifer area. According to Leonards (1962), an equivalent vertical hydraulic conductivity (Kz), which is at right angles to stratification of assumed homogeneous and isotropic units, is given by formula:

$$Kz = \frac{\sum m_i}{\sum\left(\frac{m_i}{K_i}\right)}$$

where m_i is the thickness of layer i having equivalent hydraulic conductivity K_i. Although other methods of averaging are available (Domenico and Schwartz, 1998), the K_i values for the layered media in standardized lithologs are not as reliable and numerous as to be able to perform more complex statistical analyses, thus the simple averaging method presented here was used. The averaged units m_i are, by default, homogeneous and isotropic as represented by equivalent K_i. There are no data for the aquifer on microscale isotropy.

The thickness of the saturated zone depends on the position of the water table elevation (estimated from all data sources). The MODFLOW model layering intercepted the water table in different model layers (**Map 50**). This map should be similar to map of depth-to-water-table. MODFLOW layers that intercept the water table are from 1 to 5 (top of model downward, decreasing in elevation). The spatial variability in both model layers and water table elevations required small raster cells to be the analysis "window", typically 20x20 m cells, to capture the spatial variability and to estimate Kz.

Map 50 Map of MODFLOW layer (numbers) that contain the water table surface.

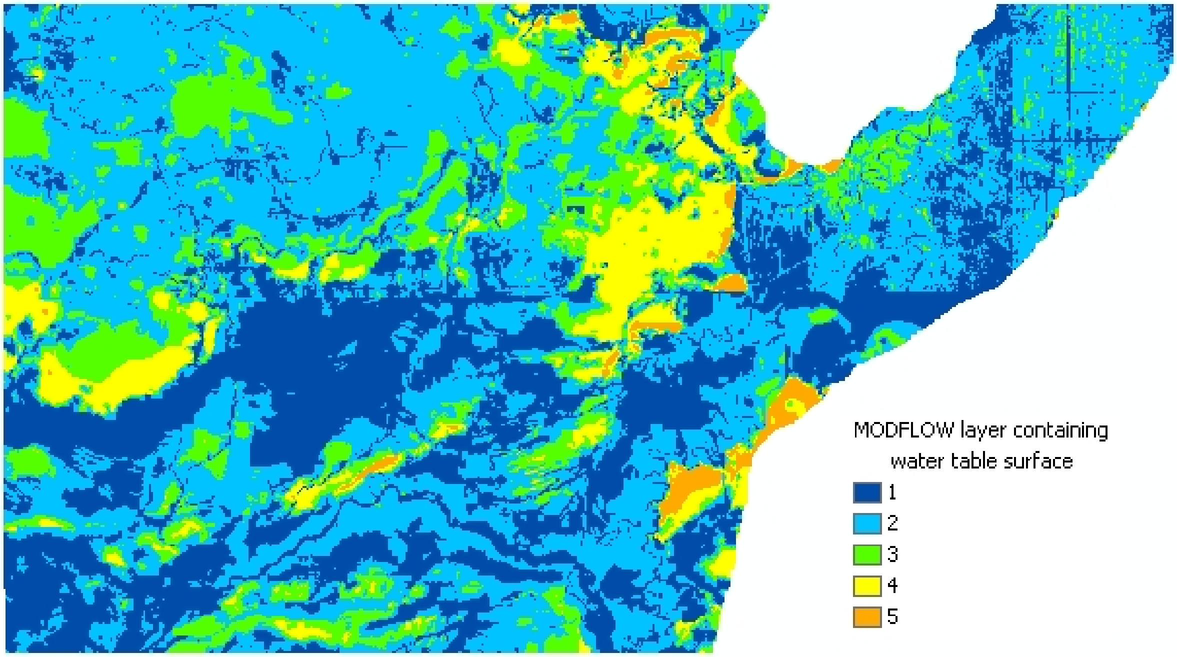
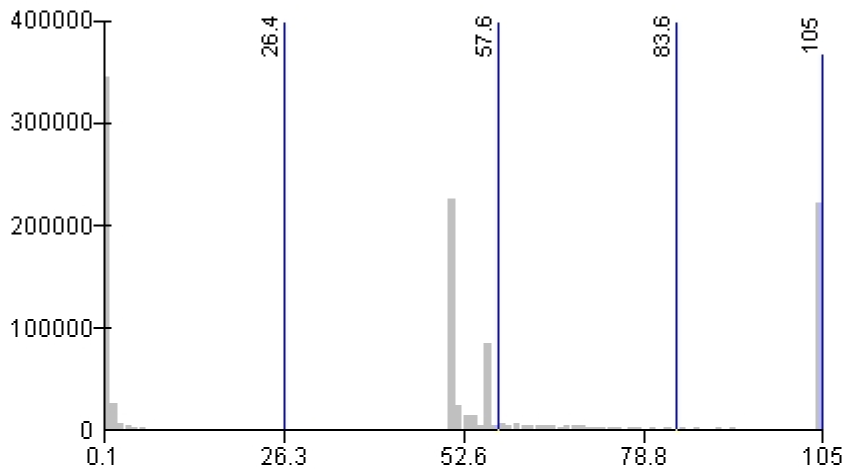


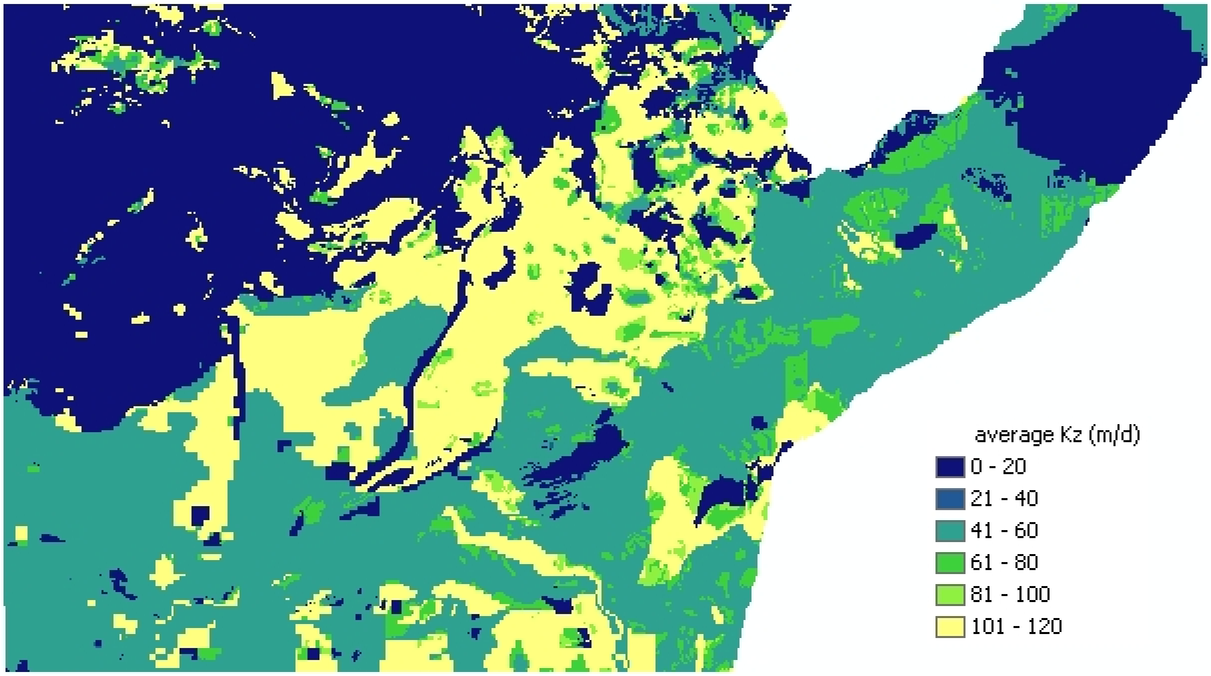
Figure 21 shows a histogram of K_z values for all 50x50m grid locations over the aquifer area. K_z values over a million pixels ranged from 0.1 to 105 m/d, median of 50.91 m/d, mean 46.3 m/d, and quartile values of 0.51 and 89.84 m/d. The K_{sat} in the vadose zone were interpolated using Inverse Distance Weighed interpolator (power 2, number of points = 5, output cell size 100 m), and computed on representative vertically averaged Log K_{sat} values at all available point locations where lithologs exist. After interpolation, 10^(Log K_{sat}) of the interpolated raster was computed. K_{sat} values were then converted to units of m/d. Five K_z classes were chosen as $1x10^{-6}$ to 20 m/d, 21 to 40 m/d, 41 to 60 m/d, 61 to 80 m/d, and 81 to 120 m/d (**Map 51**). The higher values mean that water will percolate more easily through the vadose zone during recharge events. Representative material K_{sat} in HELP soil columns will be 315, 40, 1.4, and 0.015 m/d (mid value in each class).

Figure 21 Histogram of averaged vertical Kz (above water table) for all 50x50m pixels over Abbotsford-Sumas aquifer**.**



Overall, the K_z distribution is very heterogeneous. Low K_z values occur over Fort Langley Formation (stony clays) sediments in the western part of model area, and in Sumas Valley in the former location of a lake (lacustrine silts). There are also low K_z values along river channels where there are mapped silts and other low-K deposits (slack water deposits). Moderate K_z values occur in Sumas Valley, due to floodplain silty sands cover, and over southern parts of the aquifer system. High K_z values are found in Abbotsford area, in the uplands associated with highly permeable Sumas Drift consisting of gravels and sands, interspersed with till deposits.

Map 51 Average computed vertical hydraulic conductivity in the unsaturated zone, based on material types in 20 m grid cells, mapped hydrostratigraphic units, assignment of average K values (assuming) Kz = Kxy within each unit, and vertical averaging to approximate Kz.



5.4. RECHARGE BOUNDARY CONDITION

This section provides a brief overview of recharge mapping and definition of the recharge boundary condition. A full discussion of recharge mapping and methodology is provided in a separate document (Scibek and Allen, in prep).

Recharge shows a strong North-South gradient with mean annual precipitation (see **Map 54** at the end of this section). The flow model was assigned recharge based on the spatial distribution of two factors:

1) Precipitation zonation
2) Type of soil cover, slope and vegetation.

Irrigation return flow, stream-aquifer interactions, and other sources of recharge were not accounted for directly in the model.

Temporal variations in recharge were calculated using HELP (US Environmental Protection Agency), input to the groundwater model as summarized below. The program WHI UnSat Suite (Waterloo Hydrogeologic Inc.), which includes the sub-code Visual HELP (US EPA Hydrologic Evaluation of Landfill Performance model), was used to estimate recharge to the Abbotsford-Sumas aquifer.

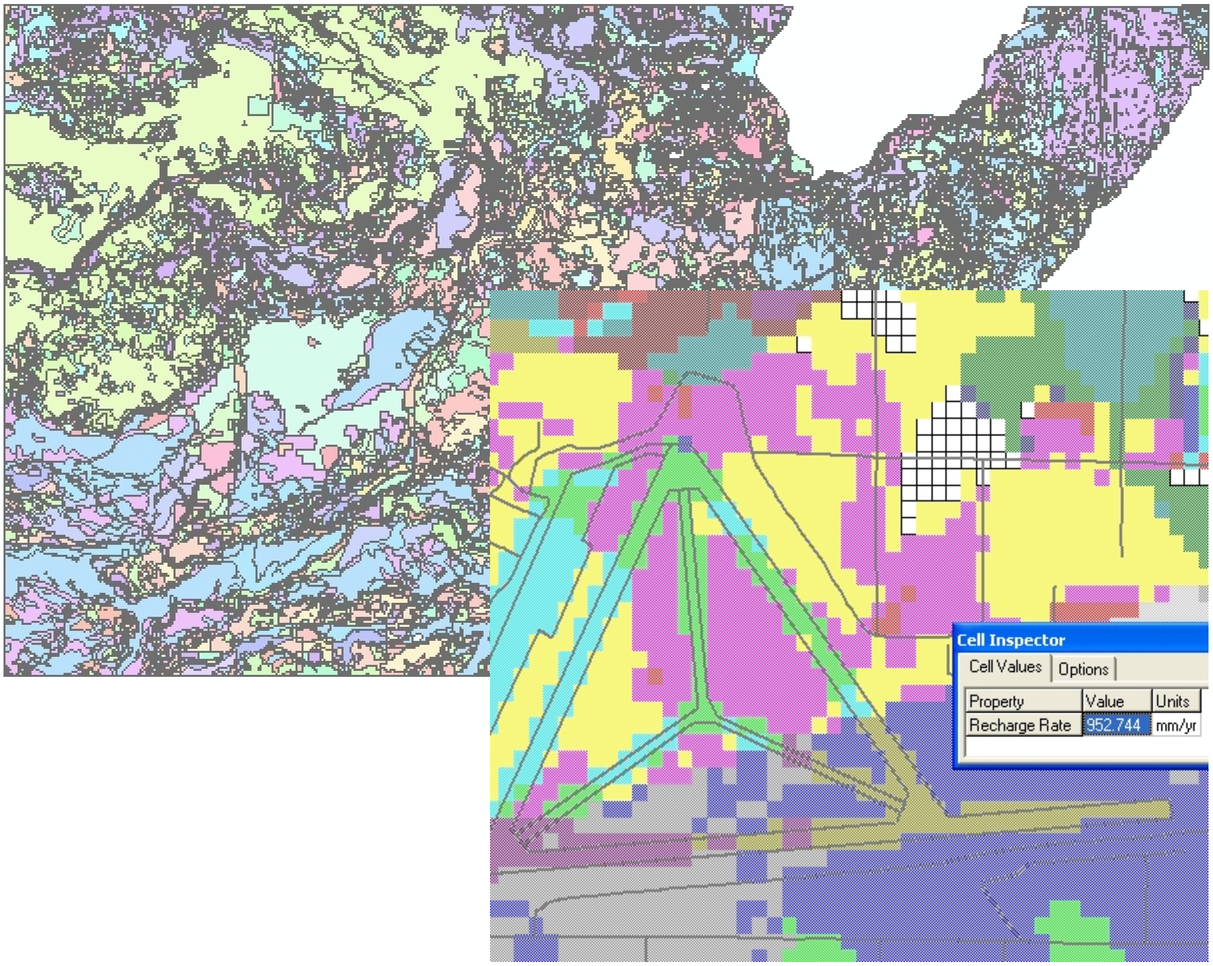
HELP is a versatile quasi-two-dimensional US EPA model for predicting hydrologic processes at landfills and testing the effectiveness of landfill designs, enabling the prediction of landfill design feasibility. HELP is also effective in estimating groundwater recharge rates. Inputs consist of modeled sediment column with defined soil and sediment properties, engineering design features, surface slope, meteorological conditions, and evaporation rates. HELP uses numerical solution techniques that account for the effects of surface storage, snowmelt, runoff, infiltration, evapotranspiration, vegetative growth, soil moisture storage, and various engineering parameters (e.g., lateral subsurface drainage). The natural water balance components that the program simulate include precipitation, interception of rainwater by leaves, evaporation by leaves, surface runoff, evaporation from soil, plant transpiration, snow accumulation and melting, and percolation of water through the profile.

Recharge scenarios were generated for all combinations of defined classes (4 categories each) of vertical aquifer permeability (Kz), depth of vadose zone, and soil type. The four Kz classes were “very high”, “high”, “moderate”, and “low” hydraulic conductivity of aquifer media. Depth classes included: 3, 8, 11, and 25 meters (coded as d3, d8, …). Soil classes were coded in terms of permeability, as “low”, “moderate”, “high”, and “very high." Note that there are only 4 discernible soil types over most of the area of the valley. Using ArcGIS, the aquifer was reclassified into percolation column scenario polygons, based on cross-referencing of 3 raster images for the 3 variables (classed maps). The conditional statement for raster calculation had 64 conditions specified, and was constructed on a spreadsheet before use in ArcGIS. There is relatively high spatial variability in the three variables of aquifer media, resulting in many small recharge zone polygons (**Map 52**). In most parts of the valley the resulting recharge zones are small, except the eastern section where Kz had low variability due to low number of interpolated points (smother Kz distribution), and where depth to water table was small throughout. The higher the variability in these scenarios over space, the more accurate the recharge distribution will be.

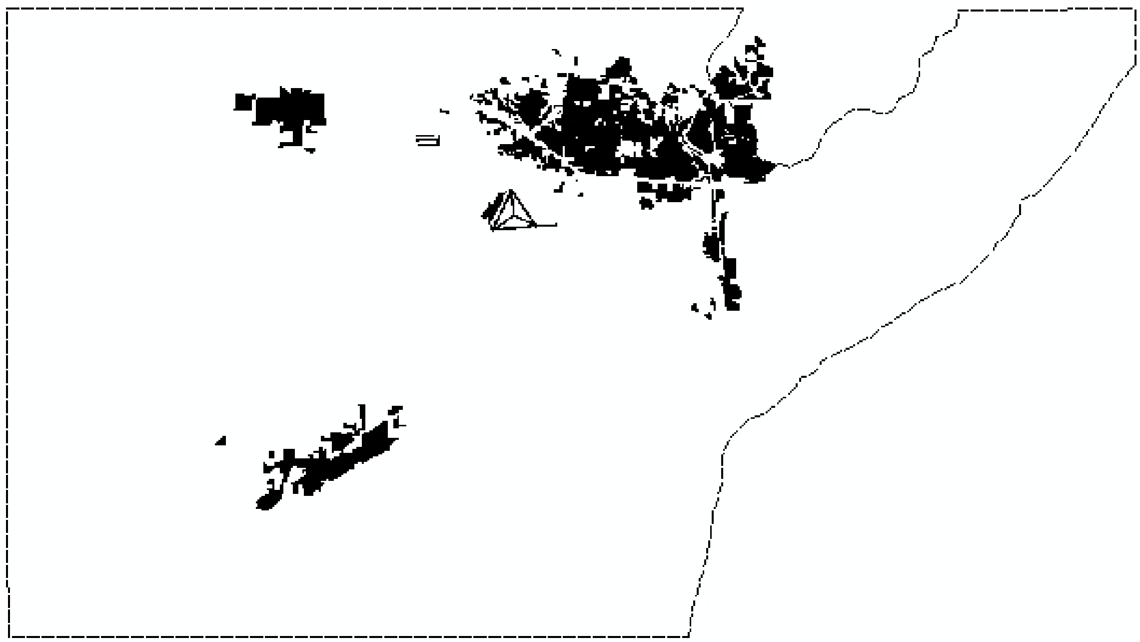
More categories of Kz and depth could be added, but that would result in many more percolation columns in HELP model, thus more data analysis requirements. Kz is interpolated, and larger number of Kz classes would represent the interpolated Kz distribution more smoothly, but it would not improve the accuracy of the model because Kz distribution is not that well known; in itself, it is heavily averaged and has many assumptions. Depth to water table is relatively well known, probably the best of these 3 parameters, but in areas where depth has low variation, the addition of more depth classes would not improve the resolution (the scenario map would look almost identical to present one). Over paved areas, recharge was reduced by 50%, to simulate storm runoff into drains (**Map 53**).

The actual process of extracting spatial information from a GIS system and mapping that onto MODFLOW cells required development of custom code for reading and writing to/from MODFLOW grid files and boundary value files. In the top layer, mid cell-locations were read, then matched by location to mid-points of MODFLOW cells mapped in GIS as polygons. Each MODFLOW cell was assigned a unique ID number. A simple table join was performed in GIS, linking recharge polygons to MODFLOW cell midpoints, which picked up the recharge zone number and that was imported into recharge zone array in MODFLOW. The recharge zone definitions contained the recharge schedules (total annual for steady state model) for each recharge zone.

Map 52 Spatial distribution of aquifer media categories (recharge scenarios)



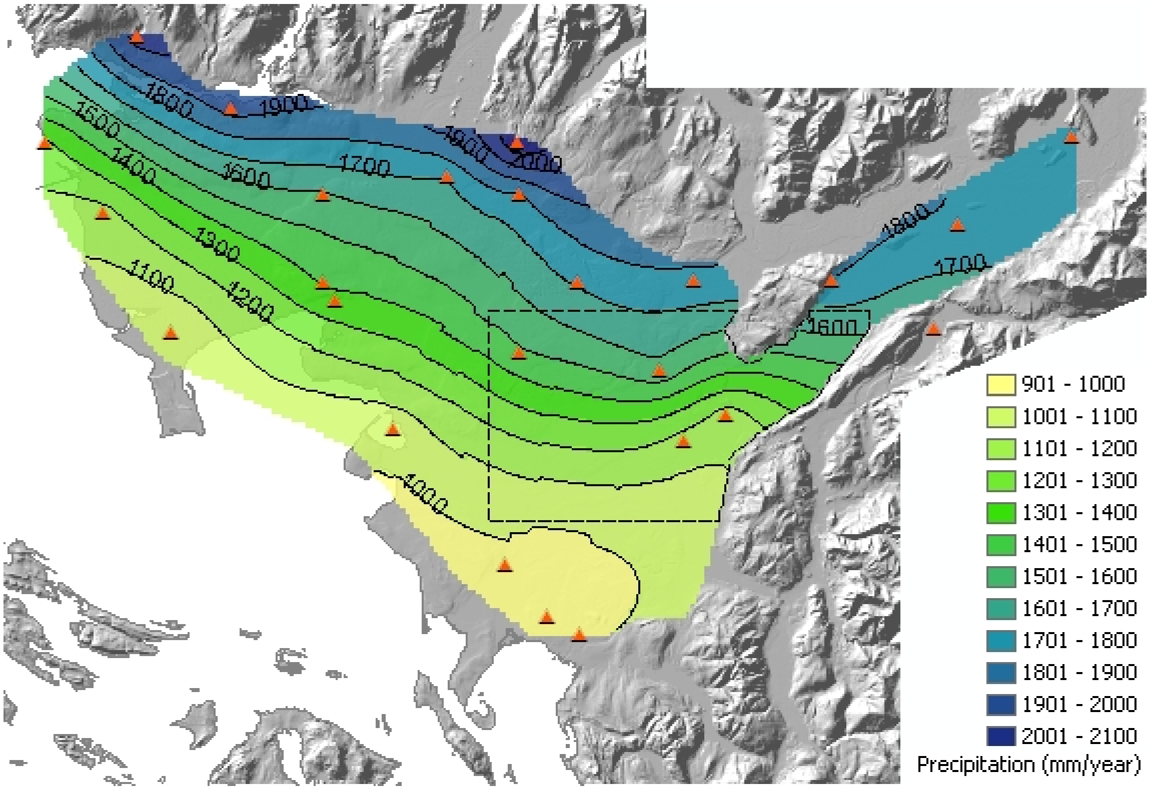
Map 53 Urbanized areas that are paved to large extent.



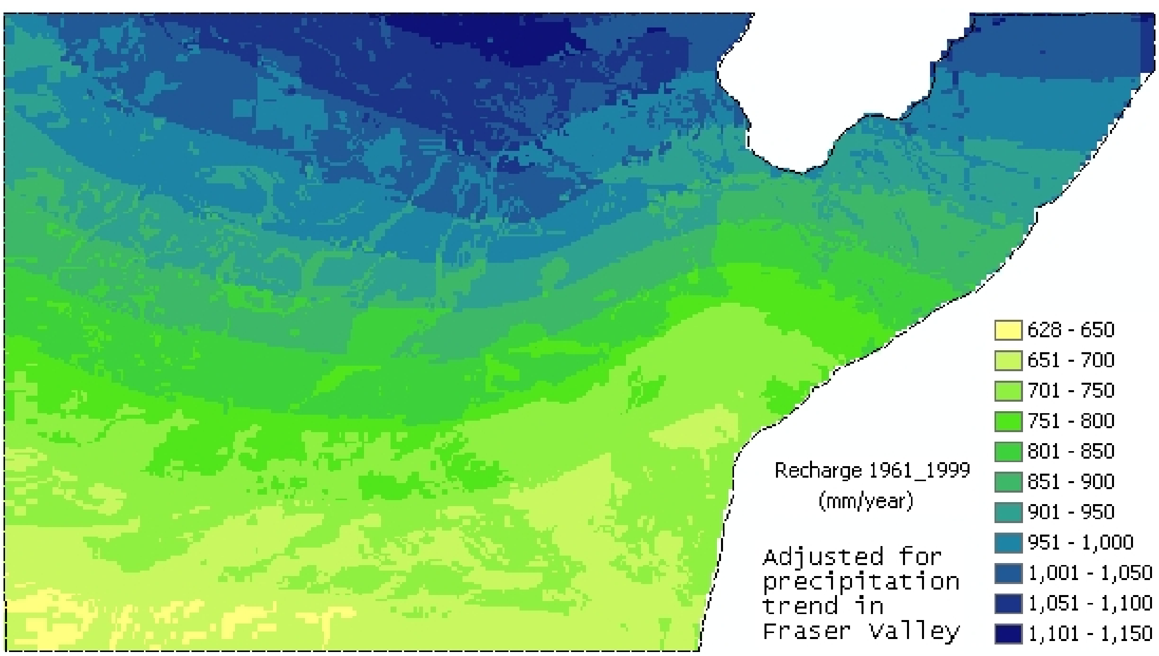
Recharge estimates based only on soil type, vadose zone properties, and mean annual rainfall, were subsequently adjusted for the precipitation gradient (**Map 54**). The precipitation map was computed as percent difference in mean annual precipitation to that recorded at Abbotsford Airport, which was used as the index station for weather generation in HELP. Thus, all recharge estimates were adjusted proportionally by the same percent difference, assuming that recharge is directly proportional to precipitation for any given recharge zone. This is the simplest method of such calculation, otherwise the inputs to HELP model would have to be estimated for all locations of the model prior to determination of recharge zones by the HELP model output. The other assumption is that the precipitation gradient is similar throughout the "typical" year. The gradient magnitudes are different in the 12 months, but gradient direction should be similar to mean annual precipitation gradient. The final recharge map for the Abbotsford-Sumas aquifer region is shown in **Map 55**.

The LENS study area, which covers most of the central Sumas–Blaine aquifer (note this is terminology used by Cox and Kahle, 1999), has recharge values in six classified ranges within the study area ranging from 11 to 50 in/year (280 to 1270 mm/year), increasing roughly from south / south-west to east / north-east (Cox and Kahle, 1999). Our HELP recharge estimates show 650 to 1000 mm/year recharge in the vicinity of this area. The aquifers near the City of Sumas have annual ground water recharge ranging from 30 in/year (760 mm/year) in the Upland area and 6 in/year (152 mm/year) in the Sumas Valley (City of Sumas Wellhead Protection program/Plan Report). The recharge to lowland areas might be smaller than estimated by HELP model, but the flow model is not sensitive to recharge in those lowland areas, but it is in upland areas. According to Cox and Kahle (1999), (estimates are based on Vaccaro et al., 1996, and Kohut, 1989), most of the Fishtrap watershed has a recharge of 660 – 762 mm/year. A point estimate at Abbotsford Airport, just outside of Fishtrap water shed has 965 mm/year (Washington State Department of Ecology, 2001). Assuming the recharge to be the unknown in the mass balance equation, an inverse estimation for recharge can be performed using the other components of the water balance, resulting in 416 mm/year or about 1/3 of mean annual precipitation. Overall, our new recharge estimates seem acceptable in light of previous estimates.

Map 54 Mean annual total precipitation in Fraser Valley interpolated from a selection of weather stations with long records, showing trend over Abbotsford-Sumas aquifer model extent.



Map 55 Spatial distribution of mean annual recharge to Abbotsford-Sumas aquifer model, showing strong South-North precipitation gradient, superimposed on smaller but more detailed variation of recharge depending on aquifer media and surface properties as computed in HELP model.



5.5. SURFACE WATERS AS MODEL BOUNDARY CONDITIONS

Steady-state flow models are useful in evaluating long term-average groundwater flow conditions, and for sensitivity analysis of the model to various parameters (e.g., river stage, pumping rates, and evaporation rates). In steady-state simulations, the boundaries largely determine the flow pattern. The correct selection of boundary conditions is a critical step in model design (Anderson and Woessner, 1992).

The MODFLOW model contains two packages that account for leakage to and from rivers. The River package allows rivers to be represented with a stage fixed during a stress period with leakage to and from the aquifer (McDonald and Harbaugh, 1988). It requires an input value for streambed conductance to account for the length and width of river channel, the thickness of riverbed sediments, and their vertical hydraulic conductivity. New versions of MODFLOW (2000 or later) also include the Streamflow-Routing Package, which allows leakage to and from the stream, but it also maintains mass balance between the river and the aquifer. The Streamflow package assumes very simplified uniform rectangular geometry of river channel.

Another boundary condition type that may be used to represent a stream is a ditch. In this case, the ditch nodes are only activated when the level of the water in the aquifer exceeds the ditch bottom. Ditches may also be assigned a conductance value.

The purpose of this section is to justify choices of types of boundary conditions in the groundwater flow model.

5.5.1. SURFACE WATER INVESTIGATIONS: FISHTRAP CREEK EXAMPLE

The previous investigations in Washington State on streams draining the Abbotsford uplands established that baseflow component is very high, between 70 and 95% of stream flow in large creeks such as Fishtrap Creek as listed in **Table 19** (Sinclair and Pitz, 1999). These streamflow statistics provide evidence for strong link of groundwater and streamflow in the creeks draining the Abbotsford-Sumas aquifer system. Most of these creeks flow southward from BC to WA and are gauged at various locations, usually at south end of Lynden terrace or near their confluences with the Nooksack River (**Map 56**).

There have been attempts at estimating water balances for entire watersheds (WA Ecology and presented in a report by Connely et al. (2002)). Runoff is roughly one third of estimated precipitation over the catchment area. At least 6% error in water balance is expected for Fishtrap Creek (**Table 20**), mostly due to errors in precipitation estimates, but the accuracy of all three components of the water balance in the lowlands is reflected in the near closure of the water balance in many watersheds (including the Sumas River near Sumas).

In Canada, most the tributaries to Fishtrap Creek flow in natural channels, but in the US the drainage network has been highly modified to form a system of north/south ditches at half-mile interval adjacent to the roads. Fishtrap Creek lies within a part of the Sumas aquifer that is predominantly outwash sand and gravel, generally unconfined, and overlain by the Everson-Vashon (Ft. Langley Fm.) semi-confining unit (Cox and Kahle, 1999). There are five stream gauge points in Fishtrap Watershed. Three stations are in a close range and are within the US. Data for 1997-1998 for station #1221200 (above Lynden) are shown in **Figure 22**. This station has 23 (1948–1971) water years of data.

There are three seepage measurement sites on Fishtrap Creek. The data were collected by Washington Department of Ecology (WDOE), Whatcom County Conservation District, Cascade Environmental Service (WRCD/CES), and Water Survey of Canada. The measurement stations are denoted by M-60, M-303 and M-62, from North to South. There are five tributaries on these sections. Four of them are unnamed channels and the fifth one is called Pepin Creek. The flow per unit length of for the river has been found by assuming a linear stream flow production. The average stream flow gain for 9/14/00 measurement is 0.0256 m3/s/km. This is comparable with 0.0228 m3/s/km measured on 9/20/93. As shown in **Table 21**, the flow per unit km increases during the wintertime. This is also partly because the tributaries delivered higher flows during these times (Washington State Department of Ecology, 2001).

Map 56 Locations of streamflow gauges on streams and rivers (selected) in the Abbotsford-Sumas aquifer model area and locations of water elevation surveys done in 2002 (Environment Canada, 2002).

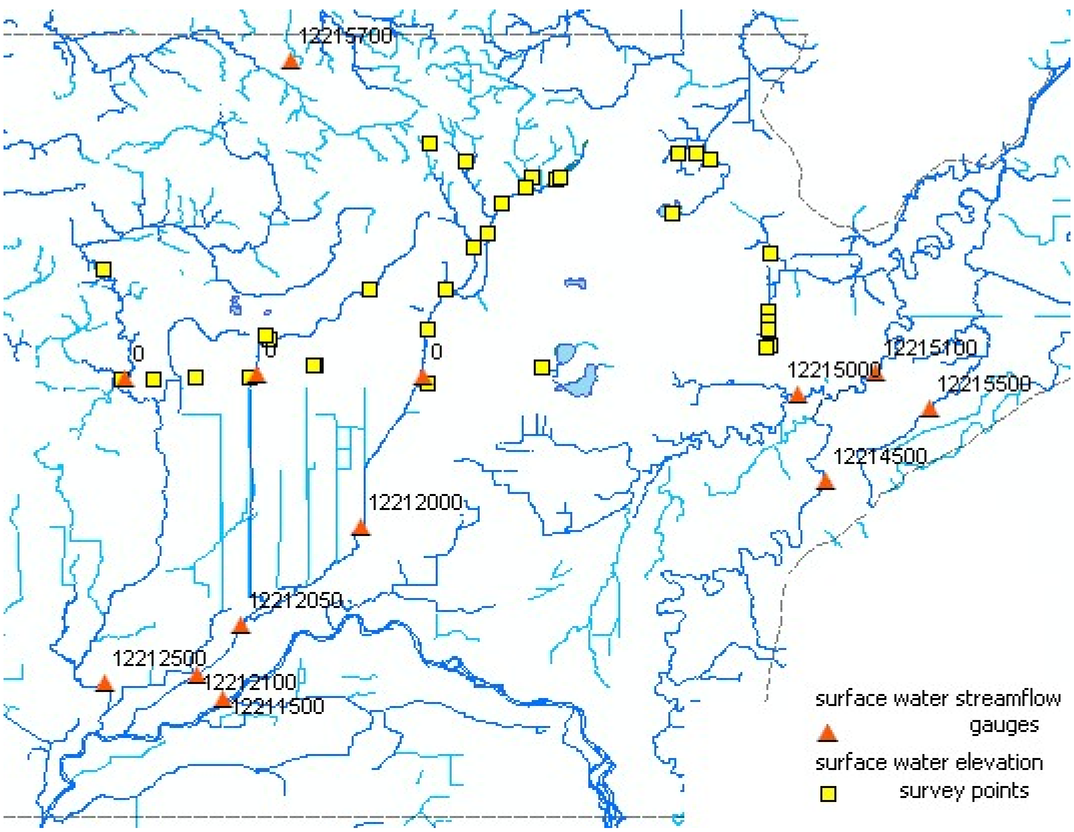


Table 19 Baseflow statistics for Fishtrap Creek at Lynden, WA (Sinclair and Pitz, 1999).

	Mean base flow	Mean surface runoff	Mean stream flow	Mean base flow	Mean surface runoff	Mean stream flow	Mean BF as % of stream flow	Mean base flow
		(mm)			(m^3/sec)		%	(m^3/s/km^2)
October	17	5	22	0.4	0.1	0.5	76	0.006
November	38	16	53	0.8	0.3	1.2	71	0.014
December	61	27	88	1.3	0.6	1.9	69	0.023
January	72	31	102	1.6	0.7	2.2	70	0.027
February	71	26	98	1.7	0.6	2.3	73	0.030
March	65	14	79	1.4	0.3	1.7	82	0.024
April	47	9	56	1.0	0.2	1.2	84	0.019
May	31	5	35	0.7	0.1	0.8	87	0.011
June	18	2	20	0.4	0.0	0.5	89	0.007
July	12	1	13	0.3	0.0	0.3	95	0.005
August	9	1	9	0.2	0.0	0.2	94	0.003
September	8	1	10	0.2	0.0	0.2	87	0.003

Table 20 Comparison of annual water balance components for selected primary and inter-gauge watershed areas (Connely et al., 2002).

Name	PRISM P	Estim. Runoff Qp	Estim. Evapotraspir. Ep	Water balance error	% error relative to P	Comments
			(mm)		%	
Dakota Creek near Blaine	1389	564	790	36	3.0%	Good
Sumas River near Sumas	1631	747	815	69	4.0%	Good
Fishtrap Creek at Lynden	1506	597	831	97	6.0%	Qp underestim.

Figure 22 Base flow and stream flow for station #12212100, 1997–1998, Fishtrap Creek (Washington State Department of Ecology, 2001)

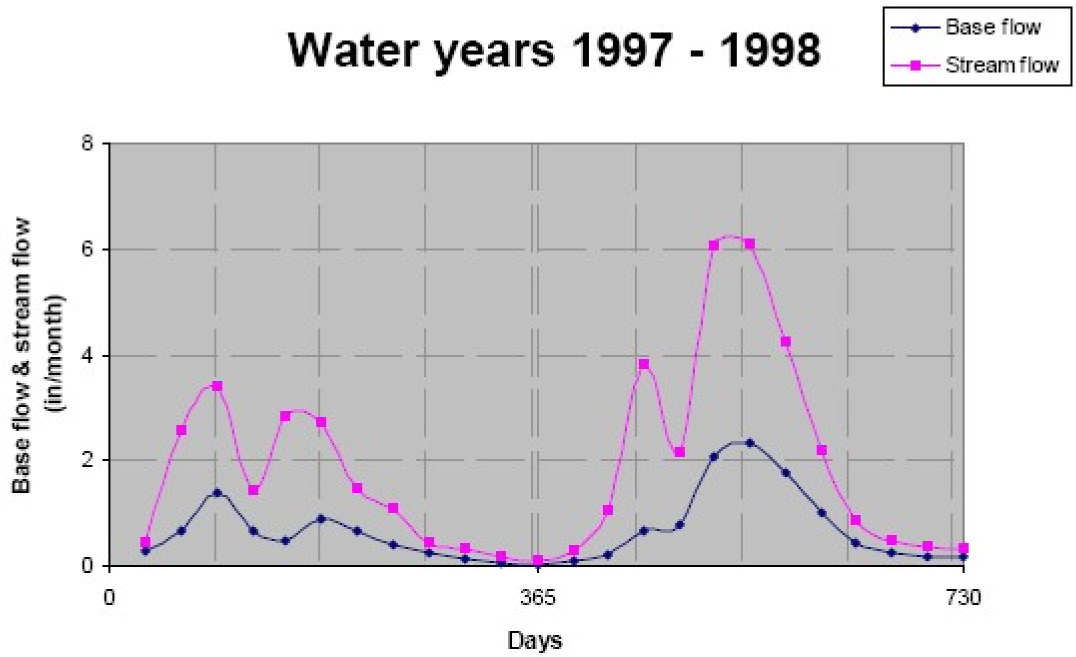


Table 21 Flow per unit distance along Fishtrap Creek (Washington State Department of Ecology, 2001)

Date	**Stream Recharge**
	m^3/s/km
13-Sep-93	0.017
20-Sep-93	0.023
8-Nov-93	0.023
14-Dec-93	0.271
12-Jan-94	0.310
25-Jan-94	0.108
Average	0.125

5.5.2. RIVERS AND LARGE STREAMS (CONSTANT HEAD BOUNDARIES)

Knowing from previous investigations that the creeks draining the Abbotsford-Sumas aquifer receive a large component of streamflow from groundwater recharge (baseflow), and that the stream channels are strongly hydraulically linked with the aquifer, the question arises as to what boundary condition is most appropriate for the groundwater flow model along these streams.

The constant head nodes do not have any conductance coefficients, and thus, assume perfect hydraulic connection between the river and the aquifer. The river can leak and receive water to and from the aquifer, but the river stage will not change as a result of such interaction. In other words, the river will act as an inexhaustible supply of water and will influence the aquifer water levels, but the aquifer will not have any effect on river discharge and stage, thus the term constant head.

In the upper reaches of the streams such as Fishtrap Creek, the stream bed is often perched above the regional water table. In the lower reaches, the stream receives large inflow from groundwater. The groundwater elevations change by 2 to 4 m seasonally, away from the streams according to observation well hydrographs (Environment Canada, 2003). However, stream water elevations vary much less, although streamflow does change seasonally. It is unlikely that changes in streamflow in a creek such as Fishtrap Creek would affect groundwater elevations in the adjacent aquifer. Over most of the stream distance, the stream gains baseflow from the aquifer. Therefore, the streams can be represented as specified head boundaries, such that the head schedules will represent the modeled river stage in transient aquifer model. **Map 57** shows the specified head boundaries used in the model, and **Map 58** shows a zoom-in of cells assigned specified head boundary conditions. The term “constant head” and “specified head” are equivalent here because the head is “constant” for the duration of a time step, but then is specified to change to different value with time.

Larger rivers such as Sumas and Nooksack Rivers have seasonally changing discharge and stage hydrographs (**Figure 23**). However, most of the hydraulic heads in the aquifer above the river floodplains are not affected by changes in river stage, only the adjacent areas to the river are affected. It is a simplification in the model to represent the larger valley rivers as constant head boundary conditions, without temporally varying stage hydrograph, but because the groundwater flow model covers mostly aquifer area above the valley floodplains and the larger rivers (e.g., Abbotsford uplands and Lynden terrace), the assumption of constant head in the larger rivers will not affect model results in those upland areas, even in a transient model.

However, where there is suspicion of potential changes in streamflow caused by stream-aquifer interactions and feedbacks from climate change, the streamflow should be investigated by transient model that includes seasonal variation of streamflow and stream stage in the channels affected and full stream-aquifer interactions, as these may be two-way locally (although mostly one-way in this aquifer system: groundwater recharging the streamflow in creeks).

Figure 23 Streamflow discharge hydrograph for Sumas River (1985-1990) at gauging station near Huntington, BC (12215100).

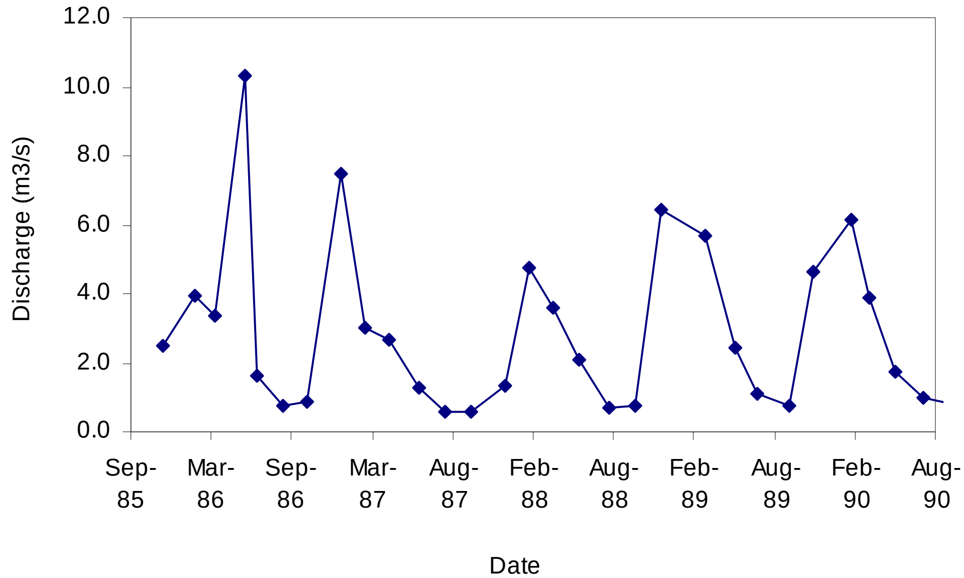


Table 22 Current and historical streamflow gauging-station records in the WRIA 1 study area (US Geological Survey, Environment Canada) – source: Greenberg et al (1996).

Station number	Station name	Period of record	Years of record	Source of data
12211500	Nooksack River near Lynden	1945-67	23	USGS
12212000	Fishtrap Creek at Lynden	1948-71	24	USGS
12212050	Fishtrap Creek at Front Road, at Lynden	1999-present	1	USGS
12212100	Fishtrap Creek at Flynn Road, at Lynden	1997-98	2	USGS
12213100	Nooksack River at Ferndale	1967-present	33	USGS
12215000	Johnson Creek at Sumas	1954*	<1	USGS
12215100	Sumas River near Huntington, BC	1952-59 (EC); 1960-78 (USGS); 1979-present (EC)	19	USGS, EC
12215500	Saar Creek near Sumas	1948*;1954*	<1	USGS
08MH152	Bertrand Creek at International Boundary, BC	1984-86*;1987-present	13	EC
08MH153	Fishtrap Creek at International Boundary, BC	1984-86*;1987-present	13	EC
08MH156	Pepin Creek at International Boundary, BC	1985-present*	15	EC

Table 23 Streamflow discharge in Bertrand Creek (SW-085, M-23 station) in 1997. Source WRIA1 report USGS 1999.

Date	Discharge (m3/s)
4-Aug-97	0.512535
27-Aug-97	0.399268
22-Sep-97	0.614476
24-Sep-97	0.529525
18-Nov-97	1.868912

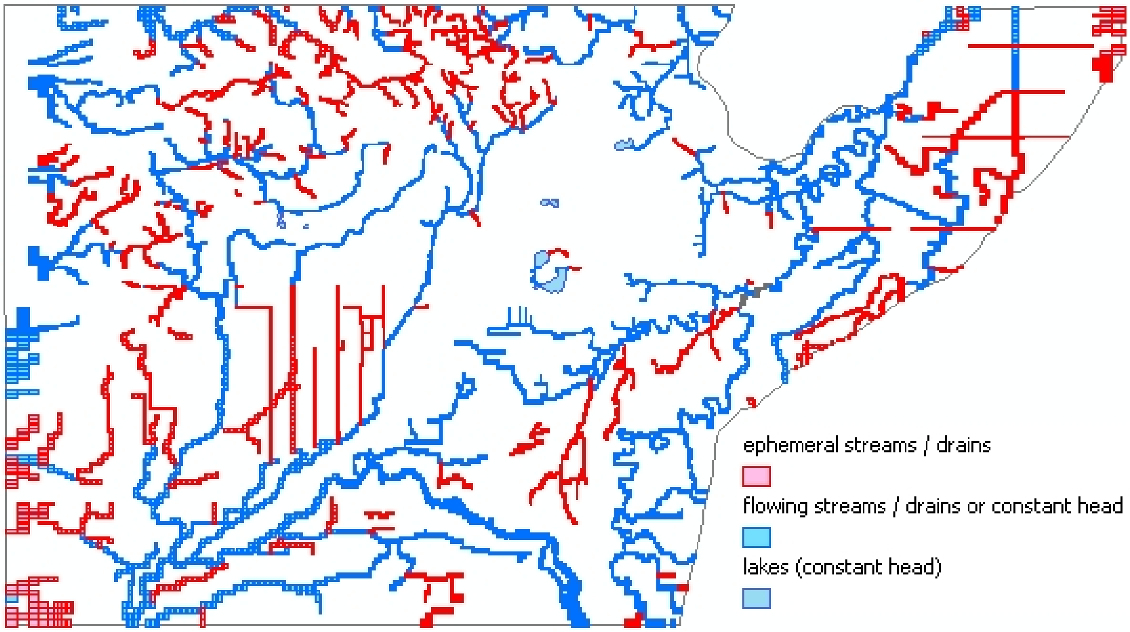
5.5.3. EPHEMERAL STREAMS AND DITCHES (DRAIN BOUNDARY CONDITIONS) AND LAKES

Drain boundary conditions were used for small lakes and large drains or swamps (**Map 57** and **Map 58**). Lake and drain elevations were taken from floodplain maps. Drains were used only in areas where the flow model calculated heads were too high above ground (or lake) surface, and drains were used to tie-in the water table elevations to lake and drain elevations. Default drain conductance was specified as 100 m/d for all drains. The purpose of drain boundary condition is to force groundwater levels in groundwater flow model to not exceed the drain elevation (if given high enough drain conductance to drain all excess water).

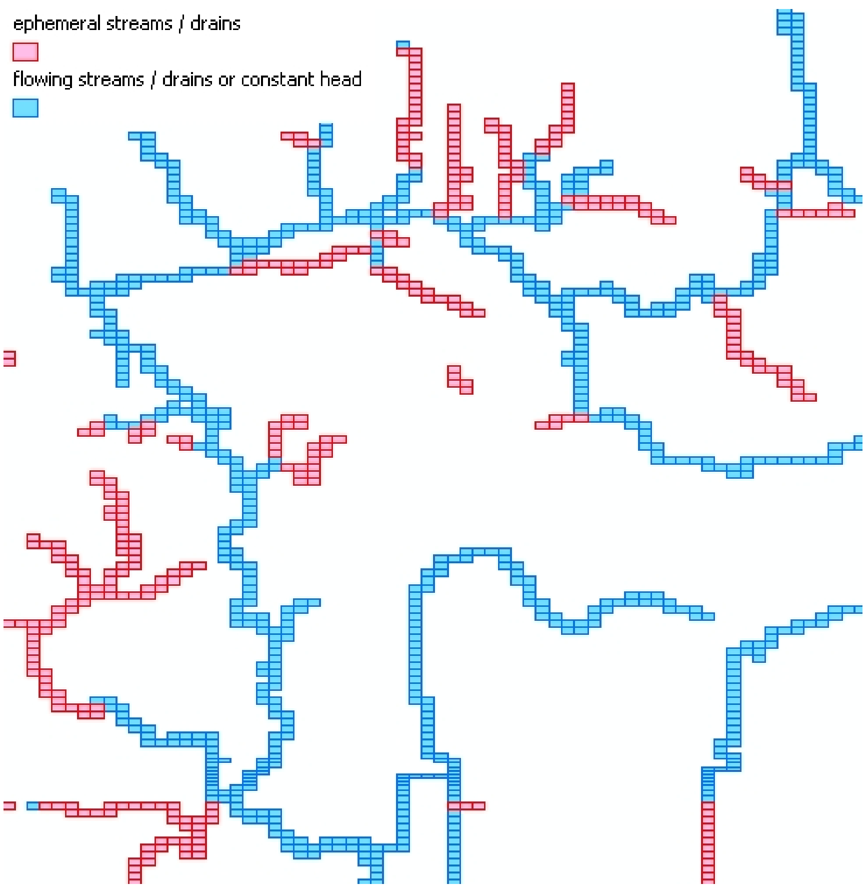
In this model, the drains are not assumed to be in contact all year with saturated zone of the aquifer and many are probably perched above mean annual water table elevation. There is simply a lack of data to verify which of these drains are linked to the aquifer and to what extent. In this simplified methodology, all ephemeral streams (as mapped from orthophotos and checked with DEM elevations) were assigned as drains in the flow model. Drains only affect the flow model when water table rises to or above the drain elevation, and the drains then take groundwater out of the aquifer to simulated seepage and baseflow. In effect, the model can be calibrated to simulate filling of drains during high water table levels (high recharge months) and dry drains during low water table levels (low recharge months). Any transient model of this aquifer should be checked for this behaviour.

Those lakes that have gauges were modeled as constant (specified) head boundary condition in both steady state and transient models, although limited gauging information exists for few lakes and these could be used in transient models as time-varying specified heads. To simplify the model and noting lack of temporal water level data for most lakes, all lakes were assigned as constant head values for average surface water elevation. **Map 57** shows Judson and Laxton lakes as represented by constant head boundary conditions.

Map 57 Drains boundaries and specified head boundaries in Abbotsford-Sumas aquifer model.



Map 58 Zoom-in of drains boundaries and specified head boundaries in Abbotsford-Sumas aquifer model.



5.5.4. LINKING STREAM WATER ELEVATIONS TO MODFLOW SPECIFIED HEAD CELLS

In all flowing streams, the main channel reaches were mapped using GIS onto MODFLOW grid cells (also represented as polygons in GIS after exporting from MODFLOW model environment in Visual MODFLOW software) – see **Map 59a**. Uppermost reaches of streams were avoided as these plot well above the water table elevation and indicate a perched stream channel above the regional water table. It is well known that upper sections of stream networks in this area originate in uplands (Langley and Abbotsford) that are dominated by glaciomarine clays (Ft. Langley Fm), where small perched ponds are present. Thus, initially, the headwaters of streams represent mostly surface runoff and are not in direct contact with deep underlying aquifers (Abbotsford-Sumas aquifer under the uplands where present). All the main stream channels in middle and lower reaches are assumed to be in direct contact with the aquifers (mostly true as these are gravel-bed streams flowing over gravel/sand aquifers).

For each MODFLOW cell (polygon with MODFLOW row/column ID), the ground elevation of nearest DEM elevation (in 20x20 m grid) was initially taken as the stream bed elevation, and distance along channel recorded (also using GIS) – **Map 59b**. All stream segments were numbered separately and their downstream distances tabulated separately.

5.5.5. ELEVATIONS OF STREAM BEDS

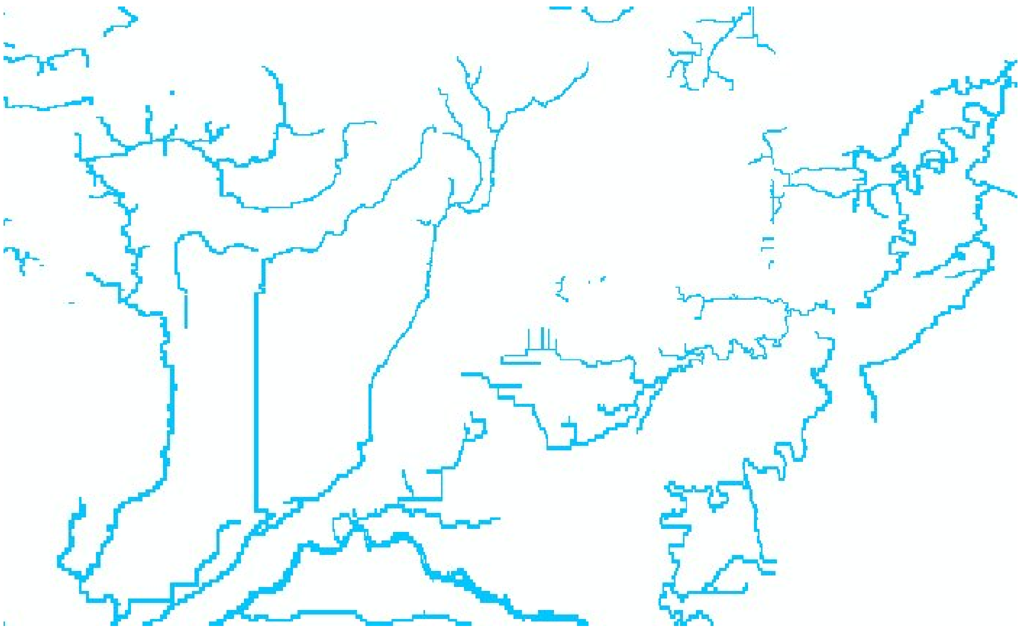
It would be a simple task of mapping stream channels onto the DEM and picking elevations, but the channel location accuracy and DEM elevation accuracy is simply not good enough at 20x20 m grid spacing to represent stream channels for the purpose of boundary condition mapping of water elevations for flow models. Caution should be exercised in using the DEM products in groundwater modeling in this area as other such problem areas may exist elsewhere. For example (**Map 60**), note that the US maps were not as detailed as the Canadian ones, despite the misleading fact that US DEM's have 10 m grid and Canadian DEM's have 25 m grid in this area. The 10 m grid is a smooth version of less accurate data! There is lack of contour data in part of Sumas Valley, just south of the border, and as a result the DEM is completely wrong in that section as can be seen from comparing Canadian DEM elevations and US DEM elevations **Map 61a**). The actual elevation should be between 8 and 12 m, but in US DEM in that section it is 1 m, a difference of almost 10 m. To correct for this large error, the DEM elevation on US side of that problem section was assigned value of 8 m wherever it was below 8 m asl, to match better with Canadian DEM (**Map 61b**).

Initially, there was no choice but to use the digital elevation model (DEM) at 20 m grid resolution to approximate channel profiles, but a program was written to pick only minimum DEM elevations along the river channels. The profile was shaped to pass along low points in the ground surface, minus 1 to 2 m downshift to allow for channel depression compared to river banks, which are sampled in the DEM rather than the channel. All stream channel profiles for all segments separately were plotted and used to adjust the channel profile (**Figure 24** to **Figure 27**). It is assumed that channel bottom elevation decreases with distance downstream along the channel.

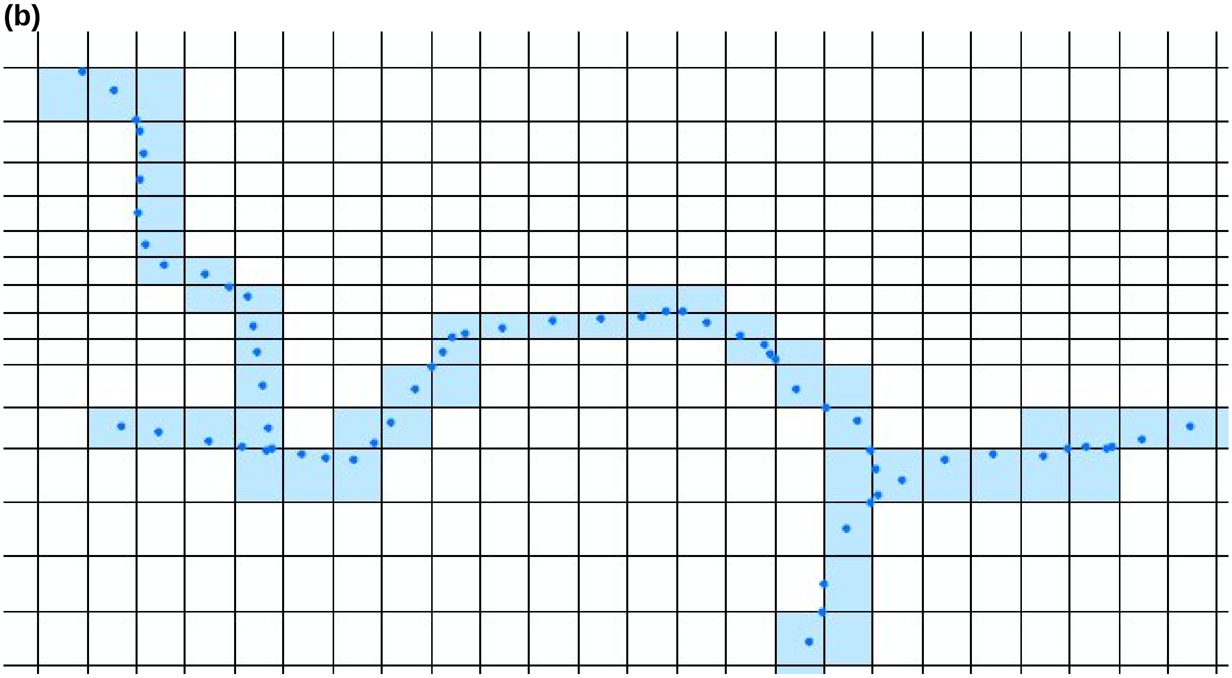
In the upland areas, creeks flow in deep gullies, which are 5 to 10 m below gully banks, and the DEM elevation seriously overestimates channel elevations. Survey points along creek channels in the uplands demonstrate that problem (**Figure 25**). Custom software was written to map the stream channel elevations (fitted and shaped on graphs) directly to MODFLOW cells and to boundary condition files (e.g., constant head boundary conditions). Therefore, smoothly decreasing stream elevations in the downstream direction were enforced on the model boundary conditions, avoiding serious errors in water elevations in the model that could cause non-convergence of the flow model. This was done for drain elevations also.

Map 59 Constant head boundary conditions mapped onto MODFLOW cells (a) from surface waters in GIS (b) constant head boundaries in model domain (from streams and rivers).

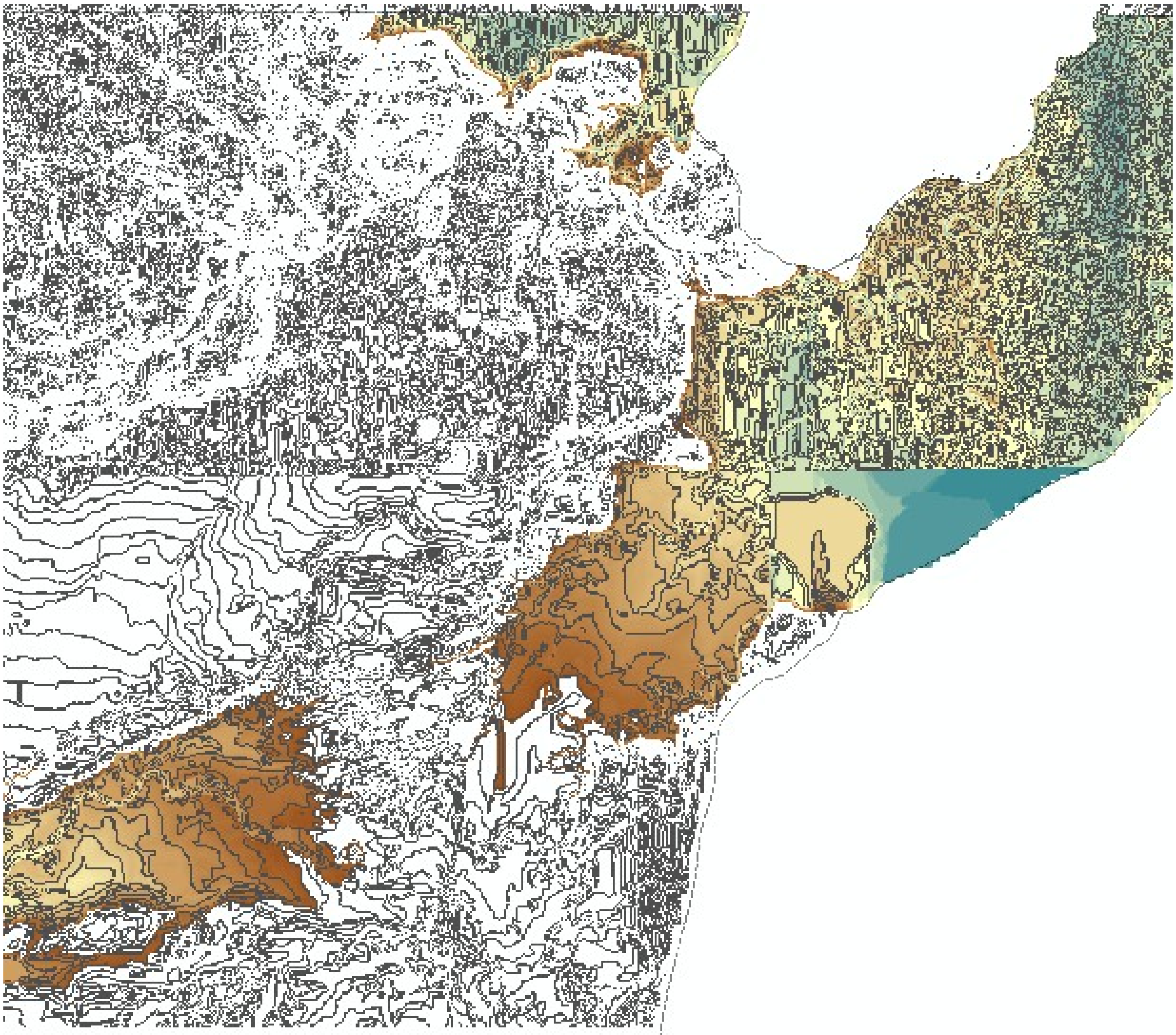
(a)



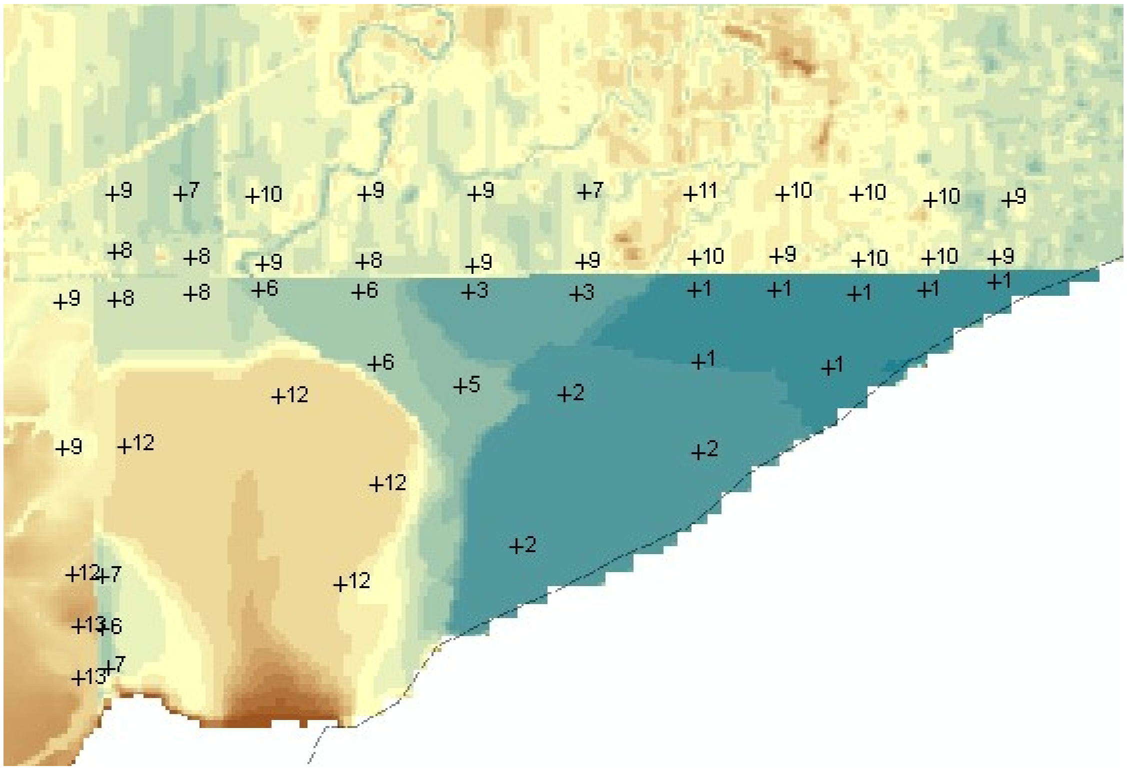
(b)



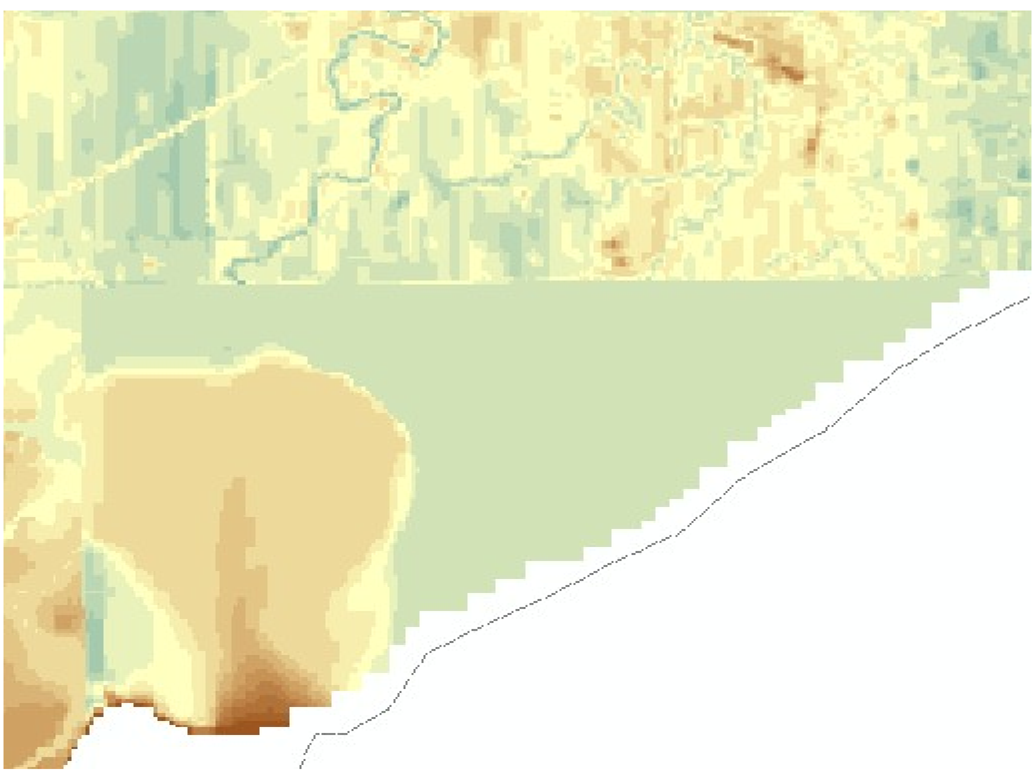
Map 60 Valley topography from DEM model (coloured between 0 and 20 m asl elevation) and map contour lines that were used to originally construct the DEM, as inferred from detailed slope analysis (digitized lines leave small residual slope break from 0.57 to 1.2 degrees slope, where as other values correspond to actual slope.



Map 61 Ground surface DEM in part of Sumas Valley along US-Canada border, east of Sumas, WA. (a) original DEM with erroneous surface on US side and point elevations shown, (b) adjusted DEM surface for MODFLOW.



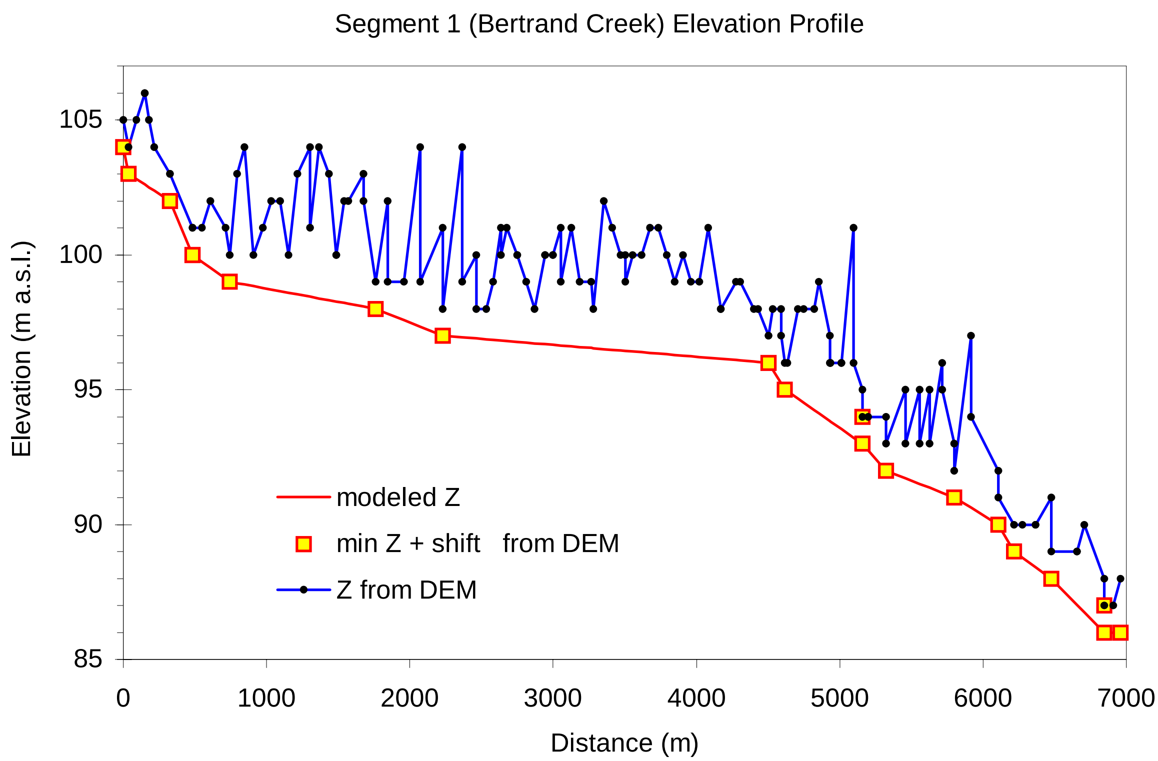
(a)



(b)

Figure 24 Channel bottom profiles for Bertrand Creek, modeled to be below minimum ground surface elevation and fitted to survey points. (a) upper segment of main channel, (b) entire elevation profile over longitudinal distance along channel.

(a)



(b)

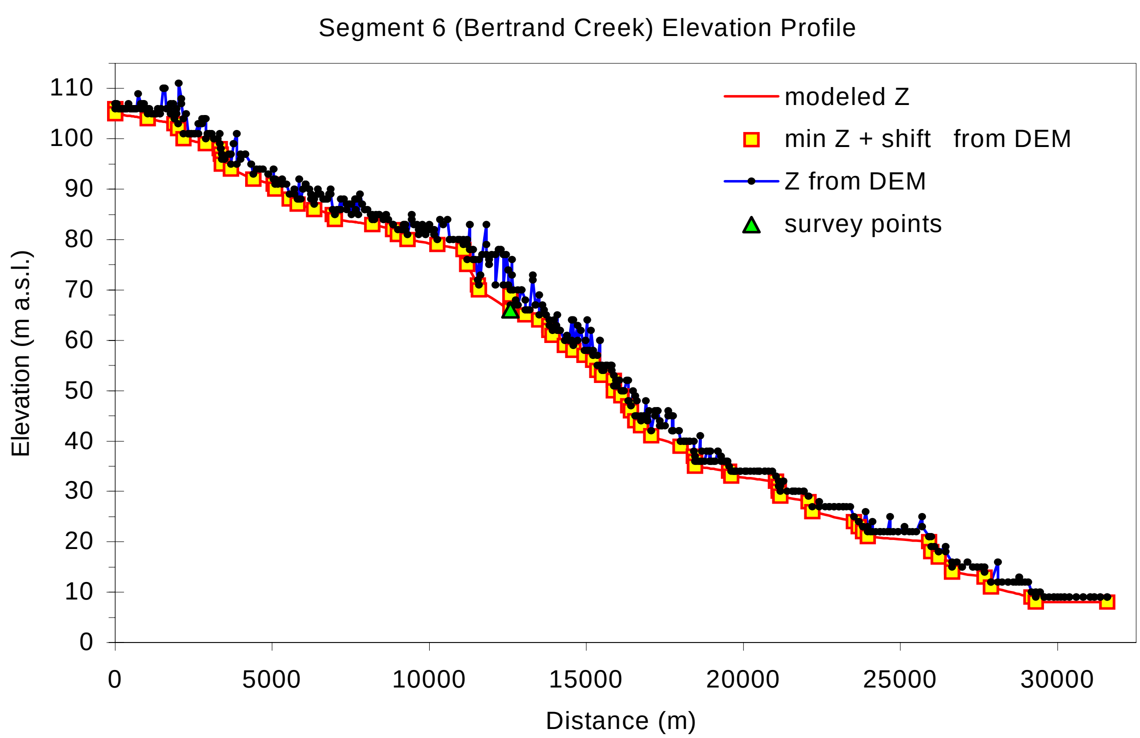
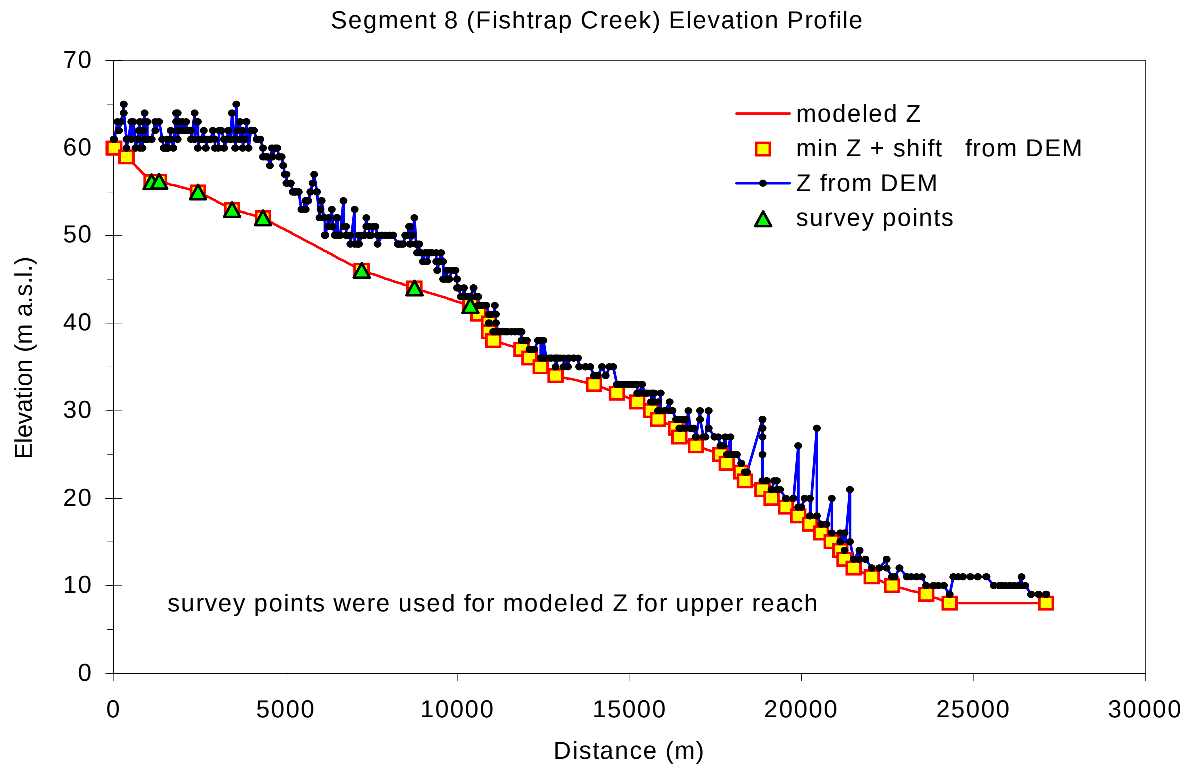


Figure 25 Channel bottom elevation profiles for (a) Fishtrap Creek and (b) Pepin Brook, modeled to be below minimum ground surface elevation and fitted to survey points.



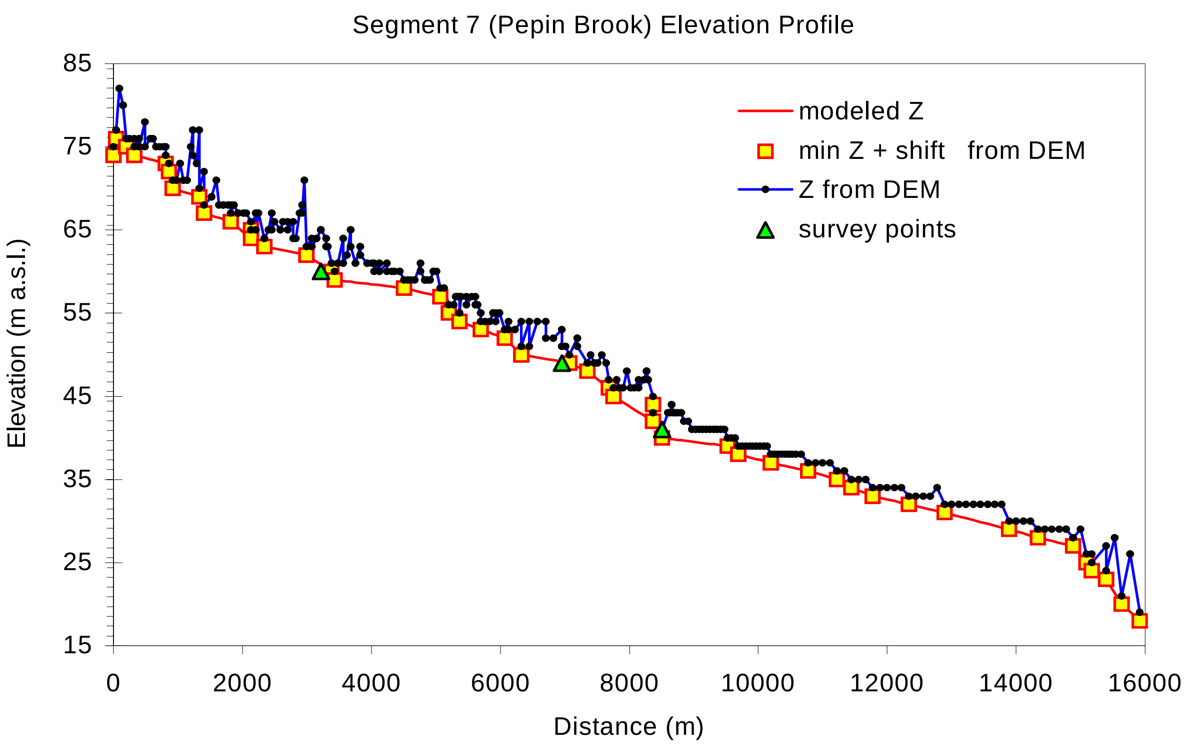
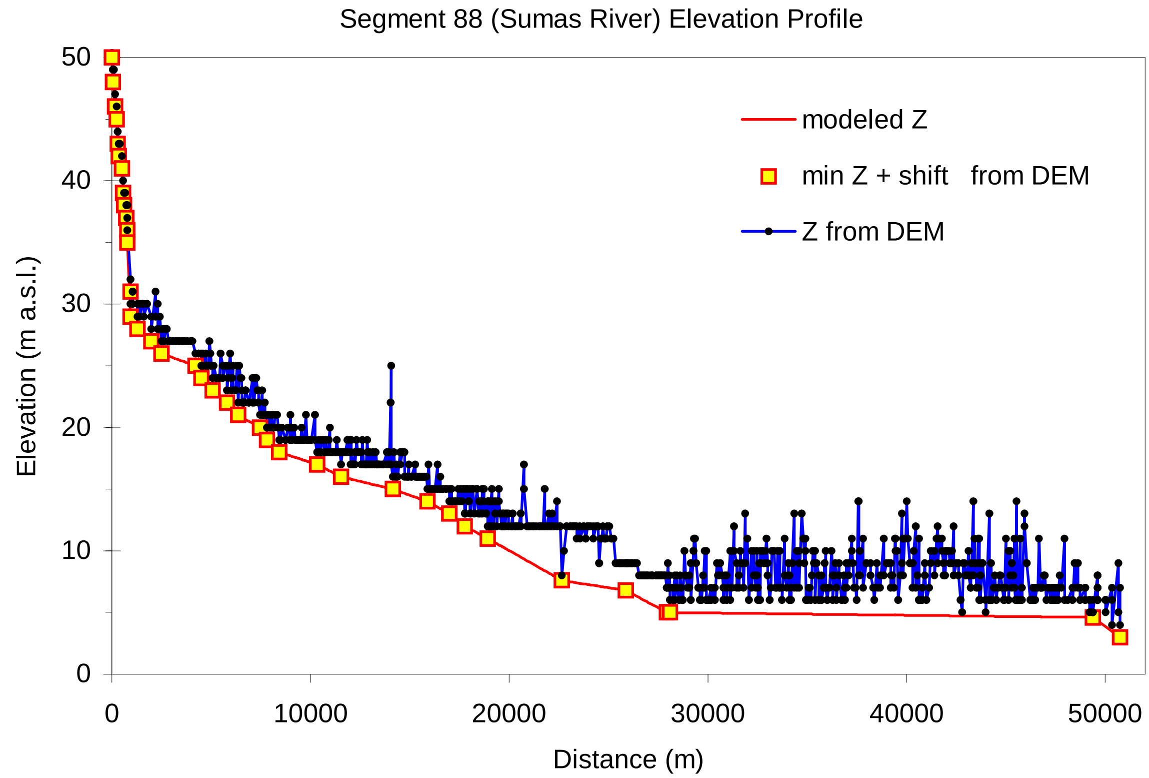


Figure 26 Channel bottom elevation profiles for (a) Sumas River and (b) Nooksack River, modeled to be below minimum ground surface elevation and fitted to survey points.



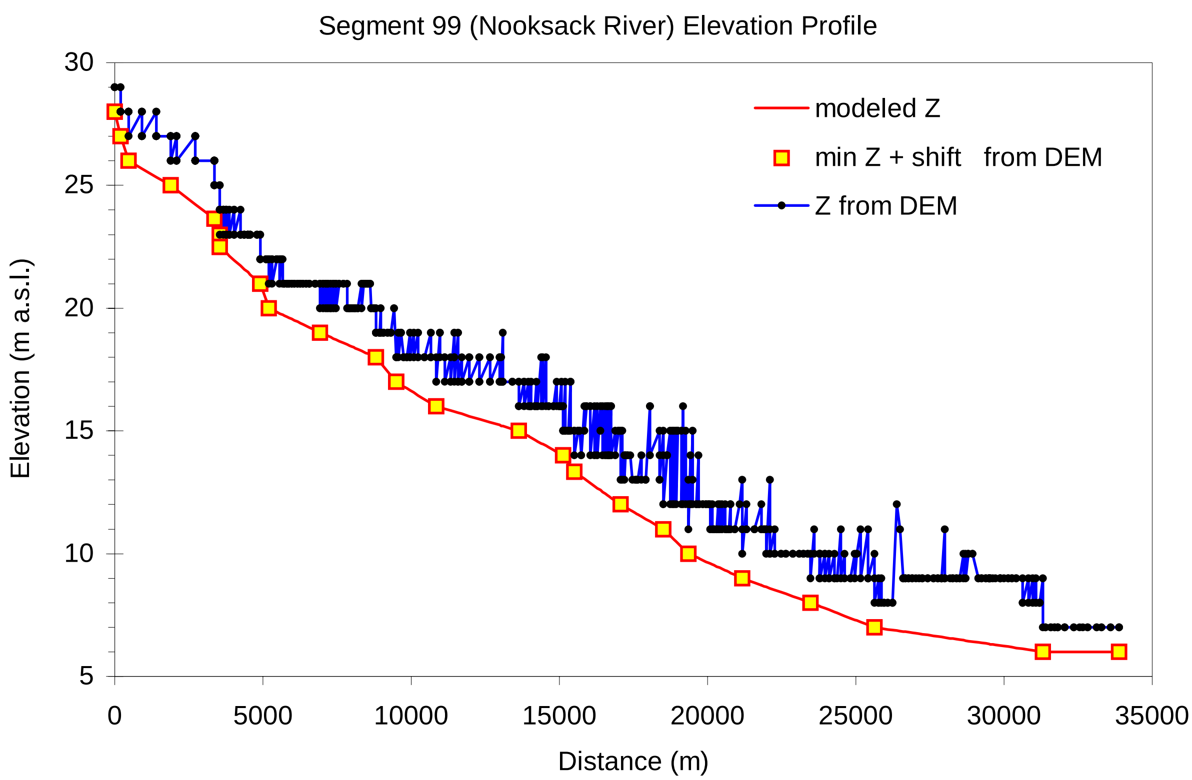
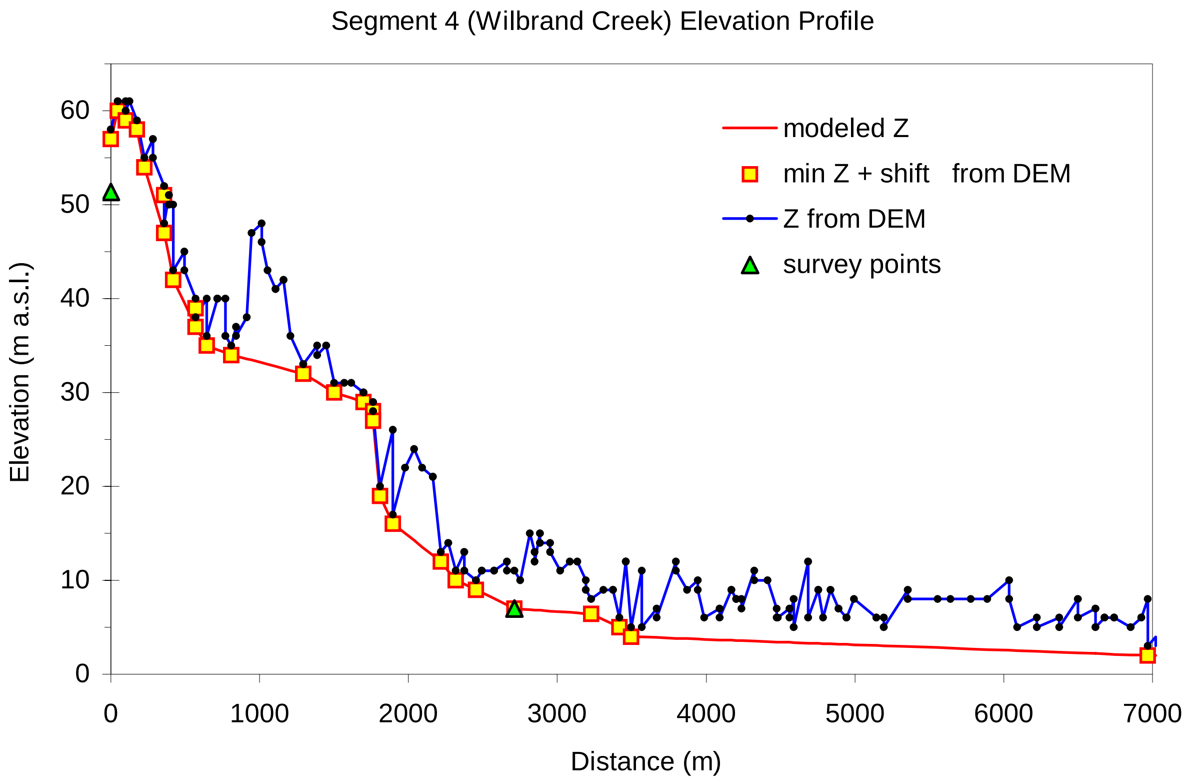
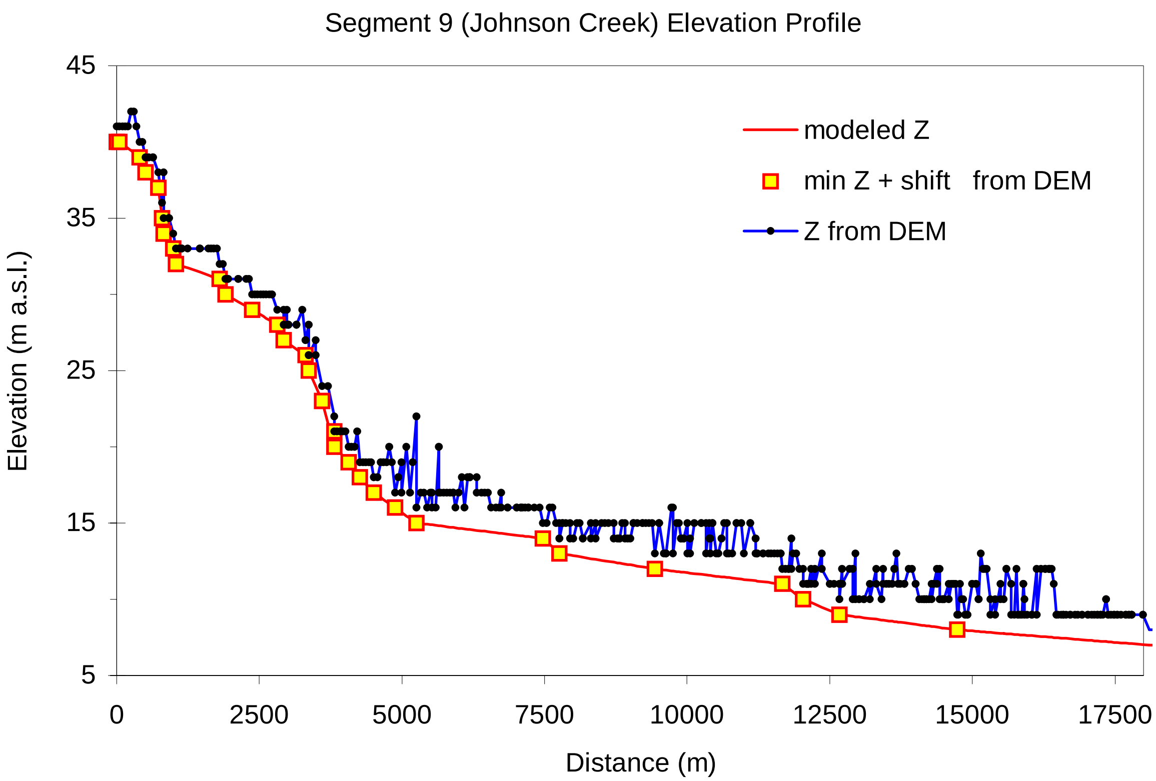


Figure 27 Channel bottom elevation profiles for (a) Wilbrand Creek and (b) Johnson Creek, modeled to be below minimum ground surface elevation and fitted to survey points.





5.6. PUMPING WELLS

5.6.1. GROUNDWATER USAGE

The Abbotsford-Sumas aquifer is highly productive, is bisected by the international boundary, and provides water supply for nearly 10,000 people in the US (towns of Sumas, Lynden, and farmlands) and 100,000 in Canada, mostly in City of Abbotsford, but also in township of Langley (Mitchell et al., 2000). The coastal climate is humid and temperate, with large rainfall over most of the year.

The total quantity of water in 1985 from all wells tapping the aquifer was estimated at 12M m^3/yr (Kohut, 1987). An approximate breakdown is industrial (41%), municipal (34%), irrigation (21%) and domestic (4%).

Municipal

There are four organizations supplying large quantities of groundwater through municipal water distribution systems. These are District of Chilliwack, Town of Hope, Corporation of the Township of Langley, and White Rock Utilities Ltd. The Dewdney/Alouette Regional District and District of Matsqui have a number of high capacity wells, but use them only as a backup source for a surface water supply coming from Norrish Creek.

Estimated annual municipal consumption in 1987 was 15.2M m^3. This compares with an estimated 16.6M m^3 consumed in 1981 (Halstead, 1986). This small decrease is mainly due to the Districts of Abbotsford and Mission switching to a surface water source.

Fish Hatcheries

There are five major fish hatcheries located in the valley using an estimated 14.3M m^3 of ground water. The Fraser Valley Trout Hatchery has four wells. In addition, there are a dozen or more small private hatcheries and small trout rearing operations that use warm ground water during the late winter for fish rearing.

Domestic

There are an estimated 10,000 domestic wells in the valley and, assuming an average per well consumption of 1.4 m^3/day throughout the year, the total annual domestic usage is estimated at about 5.1M m^3.

Irrigation

A number of berry farmers use high capacity wells for irrigation during the summer months. There are no accurate records for this water usage, but it is not expected to exceed 5M m^3/yr (Halstead, 1981).

Industrial

Industrial usage includes forest nurseries, dairies, gravel pit operations and industries located in isolated areas away from municipal water sources. The estimated annual consumption is 1.6M m^3.

Other aquifers in this area are the Fort Langley aquifer (as named in BC aquifer classification) and the Aldergrove aquifer.

The Township of Langley operates a 20 m deep well, which penetrates sediments of a backfilled former channel of the Fraser River. This unconfined aquifer is located south of Fort Langley and has an arcuate shape. The well yields about 126 L/s, and is in a zone that is well flushed by exfiltration from the Salmon River, and hence has good quality water. In contrast to this, a well in a less flushed portion of the same aquifer had the same potential yield but, because of a high dissolved iron concentration, the water was undrinkable (Dakin and Holmes, 1987).

In the Aldergrove area, just west of the City of Abbotsford, there are four production wells in the aquifer that pump an average of about 4 M m^3/yr. The aquifer is mostly confined, and is positioned between the Salmon River and Abbotsford Aquifers. The degree of hydraulic connection between all three aquifers is not well known, but is likely well connected to the Abbotsford Aquifer.

5.6.2. PUMPING WELL LOCATIONS

Well locations are positioned on **Map 62**, categorized by estimated pumping discharge. The largest production wells have yields greater than 5000 m^3/day and there are only 17 of those in the model area. Most large wells pump between 500 and 5000 m^3/day. These include the fish hatchery wells and most water supply wells in Abbotsford area. Vast majority of wells (**Figure 28**) pump between 50 and 200 m^3/day. The wells were also plotted as a graph of cumulative discharge from wells, sorted by well discharge rate (**Figure 29**). Over the model area, most of the pumping discharge, in terms of total volume pumped, occurs through small wells, although large production wells may have locally large drawdowns.

The discharge rates in wells were assigned revised pumping rates in MODFLOW based on values reported by the various operators for summer peak operating conditions. Productions wells often have capacities that are higher than the rates the wells are operated at. There is also a large range in well productivity. Drawdown associated with pumping will vary depending on well location and aquifer properties. In this model, pumping rates were taken as equal to maximum well capacity. Actual pumping rates are much smaller than maximum well capacity.

Not all pumping wells in the various databases had screen interval information. **Map 63a** shows the location of pumping wells in the Abbotsford-Sumas aquifer, where both the maximum well yields (capacities) are known (or estimated) and where well screen depths are also known. In many shallow wells, only well depth was available and the screened interval was assumed to be 5 m above well bottom.

Map 62 Distribution of pumping wells over model area, classed into major production wells (>5000 m^3/day), and smaller wells (each of 500-5000 m^3/day and <500 m^3/day).

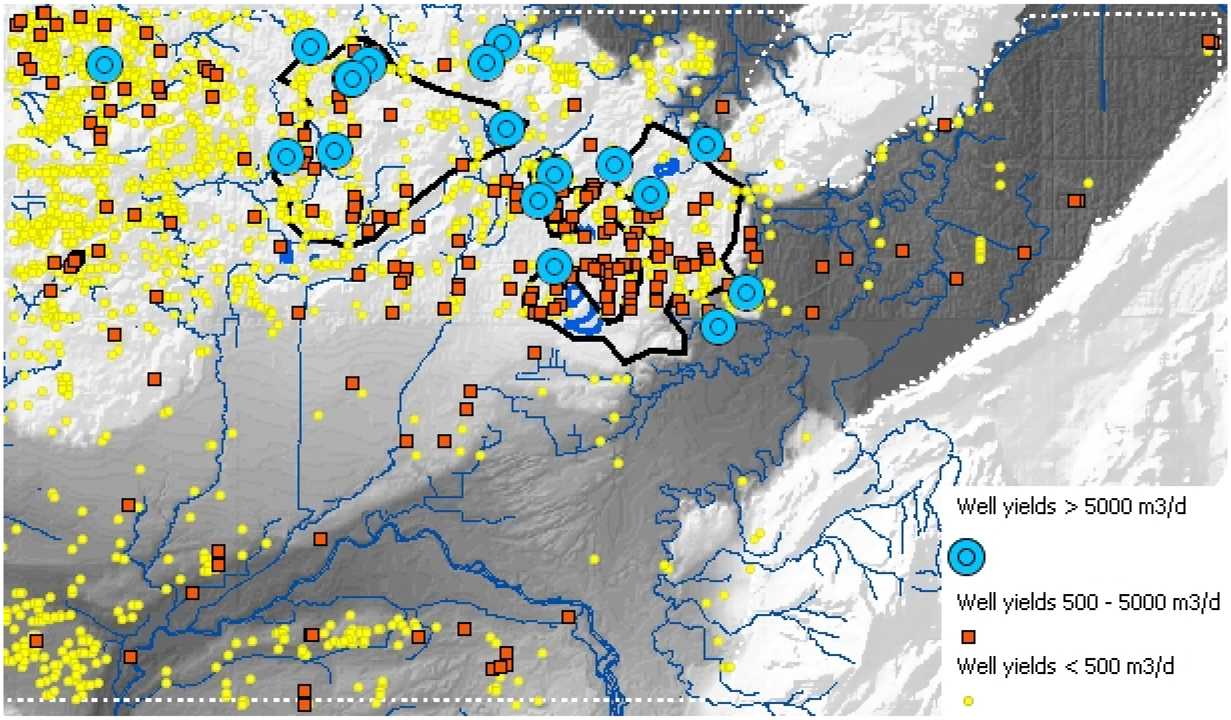


Figure 28 Histogram of pumping discharge in all wells over the model area.

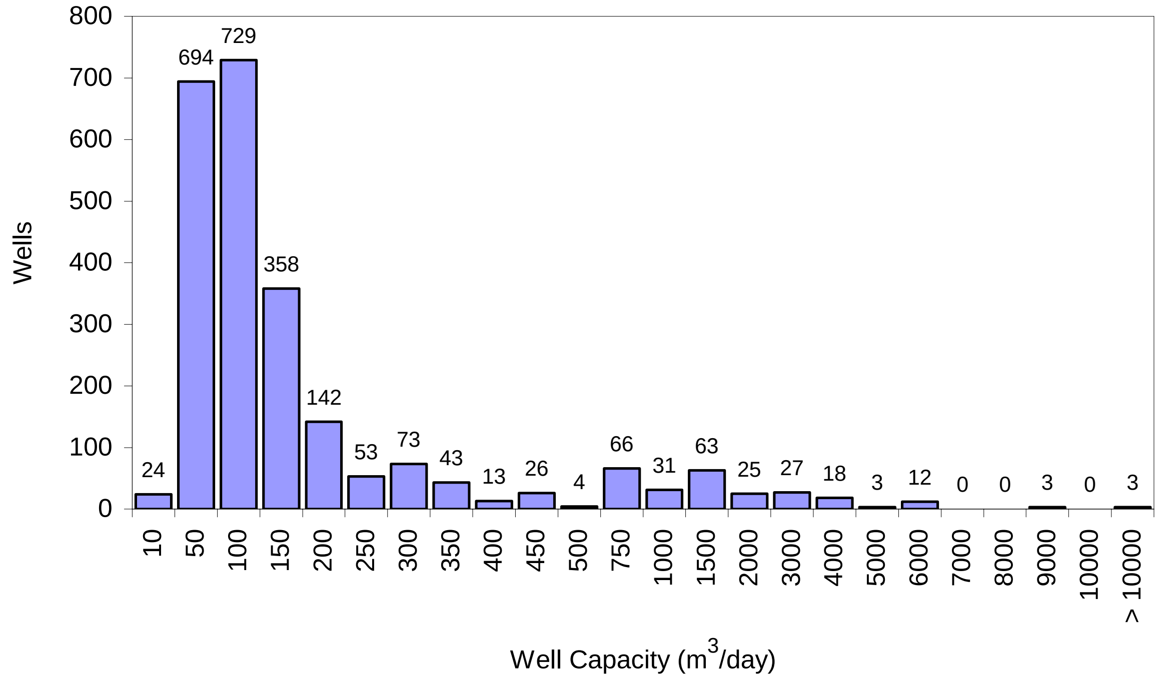
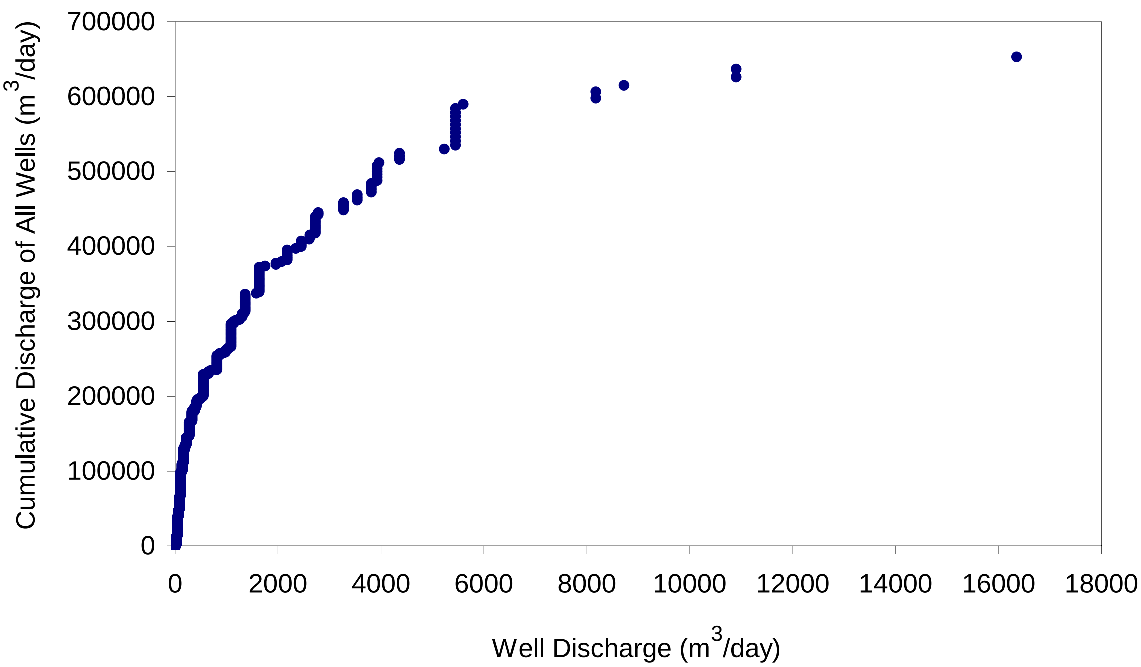
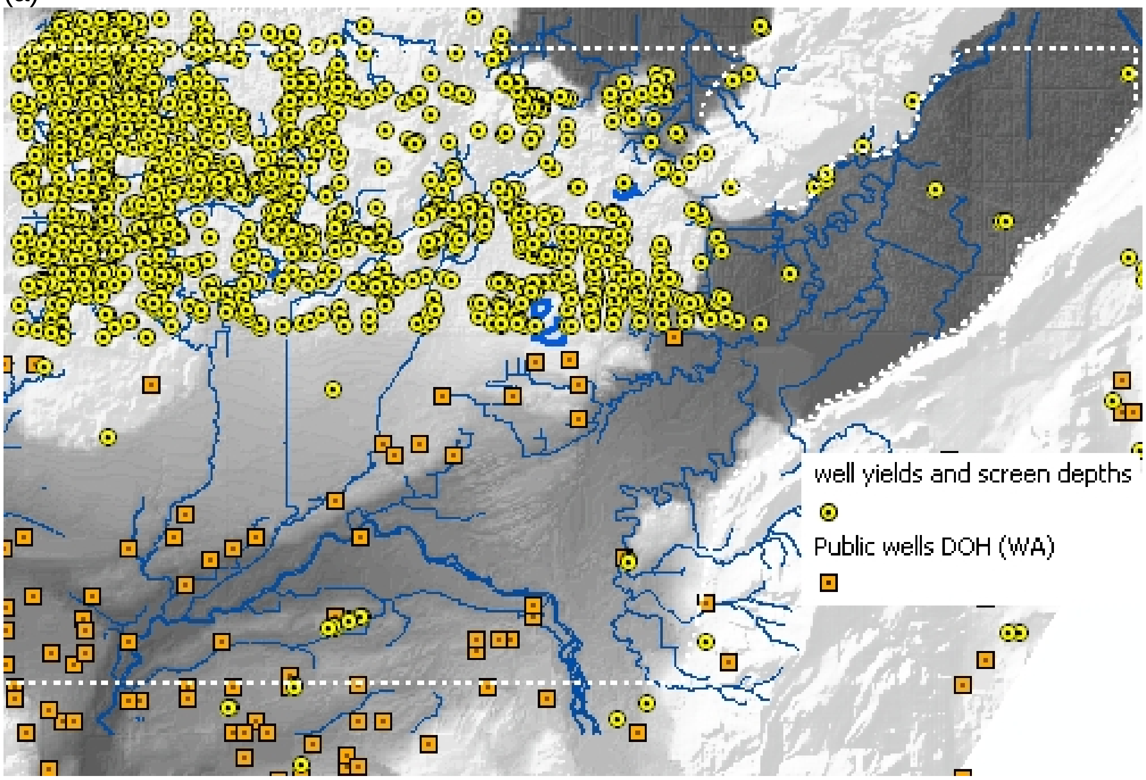


Figure 29 Relative contribution of wells of increasing capacity (graph of cumulative discharge from all wells versus well discharge).

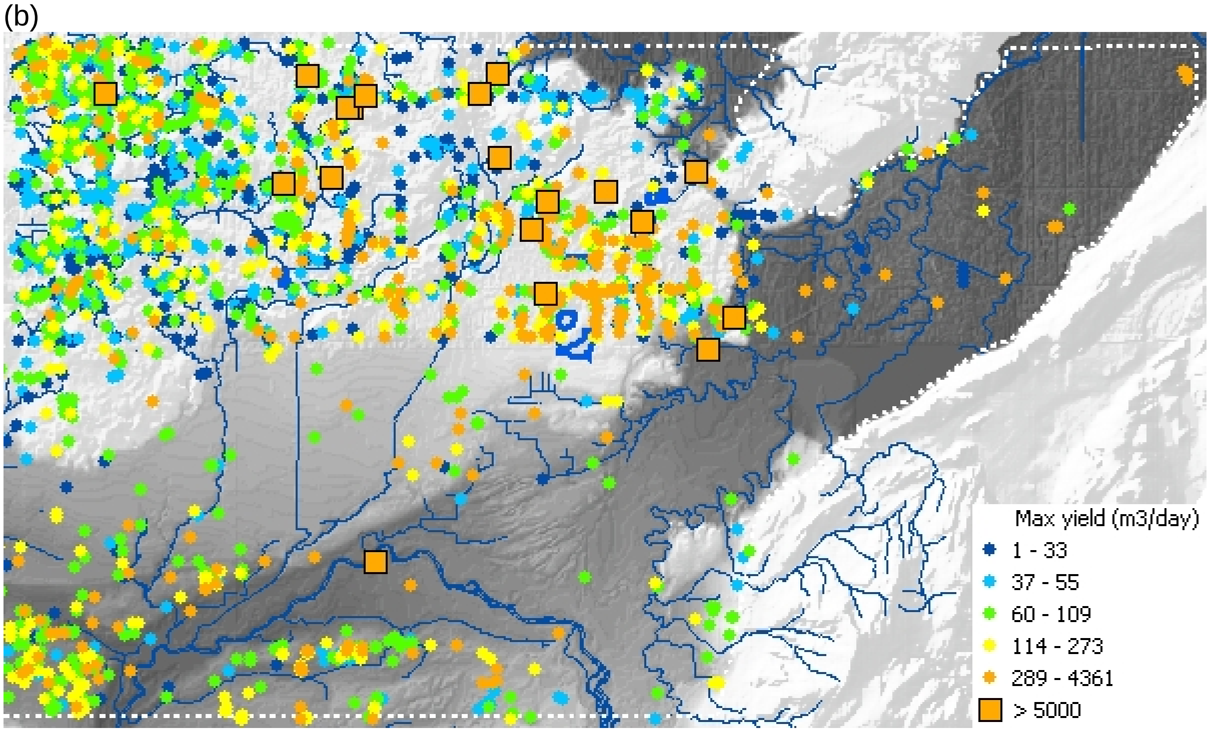


Map 63 Production wells in Abbotsford-Sumas aquifer, where maximum well yields (capacities) are known or estimated and where well screen depths or well depths are also known: (a) well locations and data source, (b) approximate well yield (capacity) classes.

(a)



(b)



5.7. MODEL SETTINGS

5.7.1. INITIAL HEADS

Initial head distribution is required for both steady-state and transient models, because solution methods are iterative, based on an initial guess of the distribution of heads. The solver is very sensitive to initial head distribution, and the initial estimate of heads may cause non-convergence if specified improperly. As a first attempt, initial heads were imported form the interpolated water table map constructed from static water elevations in all wells, with added stream channel bottom elevations.

The initial head distribution was changed during model calibration, which proved to be sensitive to initial head distribution. There were several “test” transient models developed and tested and calibrated.

5.7.2. STRESS PERIODS AND TIME STEPS

Stress period start and end times were selected at equal intervals 1 month, using the actual Julian days for month breaks, where first interval is from initial head at time 0 to day 1.

Each stress-period is divided into a user-defined number of Time Steps at which the model computes the head solution using the solver. The time step Multiplier is the factor used to increment the time step size within each stress period (ratio of length of time step to preceding time step). During early model development, there were 10 time steps and multiplier of 1.2 (for time step expansion), but these were changed to 5 time steps and multiplier of 1.3 due to technical difficulties with saving files when MODPATH was run, and excessive run times, with no apparent difference in results. For example, Visual MODFLOW exceeded 2.1 GB composite budget data file .BCF when MODPATH was run, because MODPATH forced output of flow terms and heads at all time steps and all stress-periods. The .BCF file is required for MODPATH in transient simulations only.

5.7.3. SOLVER SETTINGS

The new MODFLOW 2000 includes the Link-Algebraic Multigrid Solver (LMG), Mehl and Hill (2001). For the flow simulations, the following settings were used for both steady state and transient models.

Max outer iterations (MXITER)	= 100
Max inner iterations (ITER)	= 60
Residual criterion (RC)	= 0.1 m
Head change criterion (HC)	= 100
Damping factor (DAMP)	= 1.0
Upper bound of estimate (NPBOL)	= 1 (calculate estimate)

The RC value is used to judge the overall solver convergence in any time step. A typical value is 0.01 m. The HC value is unit-dependent and is typically 100 or greater if the unit of time is days and unit of length is metres, and it is used to judge convergence of inner iterations.

The initial model mass balance at residual criterion 0.1 m and head change criterion of 100 m^3/d were found to produce up to 2% mass balance discrepancies, although all outputs looked plausible.

The damping factor (DAMP) is used to restrict head change from one iteration to the next, and is useful in solving non-linear problems, because at DAMP < 1, the solution changes slowly (called under-relaxation).

In addition, the Recharge setting was selected to apply recharge to the highest active (non-dry) cell in each vertical column. This approach must be used if dry cells are present and recharge can percolate through unsaturated zone.

All model layers were assigned as type 3 (in Visual MODFLOW) Confined/Unconfined, variable T, variable S - both the transmissivity of the layer and the storage coefficients may alternate between confined and unconfined values.

Anisotropy settings were all assigned “by layer”, and the ratio was always Ty/Tx = 1 for all layers, due to lack of any data about layer horizontal anisotropy in Grand Forks. The borehole data are too sparse and of too poor quality to give indication of y/x anisotropy.

5.7.4. RE-WETTING SETTINGS

For accurate modeling of water table in aquifers, the re-wetting option must be turned on. However, this option also causes the solution to be much more unstable. The re-wetting options were set as follows:

Wetting threshold = 0.1 m
Wetting interval = 10 iterations
Wetting method = from sides and below
Wetting head = calculated from threshold
Wetting factor = 1
Head value in dry cells = 0.1 m
Minimum saturated thickness for bottom layer = 0.1 m

The wetting method (from all sides and below) was selected because this option is useful where a dry cell is located above a no-flow cell, which is the case near valley walls on steep slopes in this model. Wetted head was calculated from the wetting threshold:

Head = Zbot + Wetting factor * (Wetting threshold)

which is less reasonable than computing it from neighbouring cells (less accurate), but much more stable and as it causes less non-convergence. It had to be used to allow the solver to solve during cell re-wetting in this model. The head value in dry cells was assigned to just above cell bottom (instead of large negative value by default) to avoid large residuals during re-wetting and improve convergence of model. Different solvers may require different re-wetting intervals to converge, although re-wetting every 1 interval is the ideal case.

6. MODEL CALIBRATION

The primary objective of model calibration is to verify the model by comparing observed known values against model derived values. In hydrogeologic models, this procedure typically involves calibrating against known water levels, either under steady state conditions or transient conditions.

Model calibration is undertaken normally by varying model input parameters; aquifer properties, recharge, etc. within acceptable ranges in order to determine the best combination of these parameters that reproduce the observed data. Because recharge parameters had been established following a rigorous methodology (Scibek and Allen, in prep), only the aquifer properties (hydraulic conductivity, specific storage, and specific yield) were varied during calibration. It is also important to note that specific storage and specific yield are not required for steady state model calibration as these two parameters only appear in the relevant transient groundwater flow equation.

6.1. PRELIMINARY CALIBRATION TO STEADY STATE AND STATIC GROUNDWATER ELEVATIONS

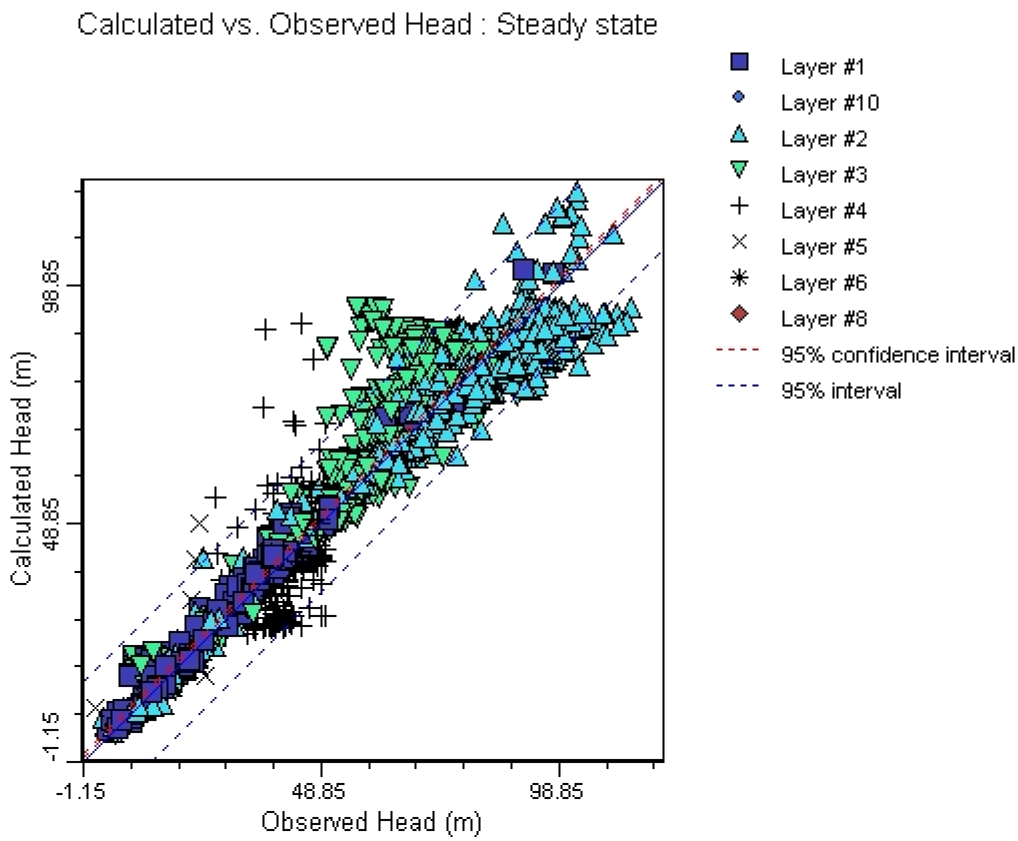
6.1.1. CALIBRATION STATISTICS (WHOLE MODEL AND BY LAYERS)

The calibration of the steady state model was done to all static water levels over the entire study area. Calibration goal was to minimize the RMS (Root Mean Square Error) of the residuals between calculated and observed head values (water table elevations in unconfined areas). The best achieved RMS was 8 m with normalized RMS of 7.1 % (see **Figure 30**), both acceptable values in modeling such large regional aquifer and given the number of observations. The residual mean is positive 1.2 m, suggesting over-prediction of water table elevation over the regional area. However, further model runs could not reduce the residual mean closer to 0 without worsening the RMS value. The calibration residuals were normally distributed (**Figure 31**).

A breakdown of calibration statistics and model residuals for model layers 1 to 5 are given in **Figure 32** to **Figure 35**. Most observations were in layer 2 (839 obs), then in layer 3 (381 obs points), layer 1 (231 obs), and layer 4 to 5 (244 obs). The shallowest wells and shallowest depths to water table have the best model fit to observed. These are the lowland valleys and river floodplains where there is very small variation in water table elevation and excellent model performance of 3.7 % normalized RMS.

The model is also reasonably well calibrated in upland areas and transitional areas where the water table is near ground surface (most wells in Layer 2) with normalized RMS of 5.7% (very good fit). In areas where uplands have large unsaturated thickness, there might be many perched water tables or other explanations of the more mediocre model calibration of 13% normalized RMS. In areas in the uplands where depth to water table is the greatest (i.e., where wells screen is in Layer 4 or 5, typically in the City of Abbotsford area or near Langley township), the model calibration suffers at 20% normalized RMS. Therefore, further efforts at model calibration improvement should be focused on upland areas where there is great unsaturated thickness.

Figure 30 Calculated versus observed heads from steady-state model of Abbotsford-Sumas aquifer – best achieved calibration in all layers together and all observation wells.



Num. of Data Points : 1695
Max. Residual: 52.308 (m) at 51262/1
Min. Residual: 0.003 (m) at 33293/1
Residual Mean : 1.285 (m)
Abs. Residual Mean : 5.525 (m)

Standard Error of the Estimate : 0.193 (m)
Root Mean Squared : 8.052 (m)
Normalized RMS : 7.145 (%)
Correlation Coefficient : 0.953

Figure 31 Calibration residuals histogram.

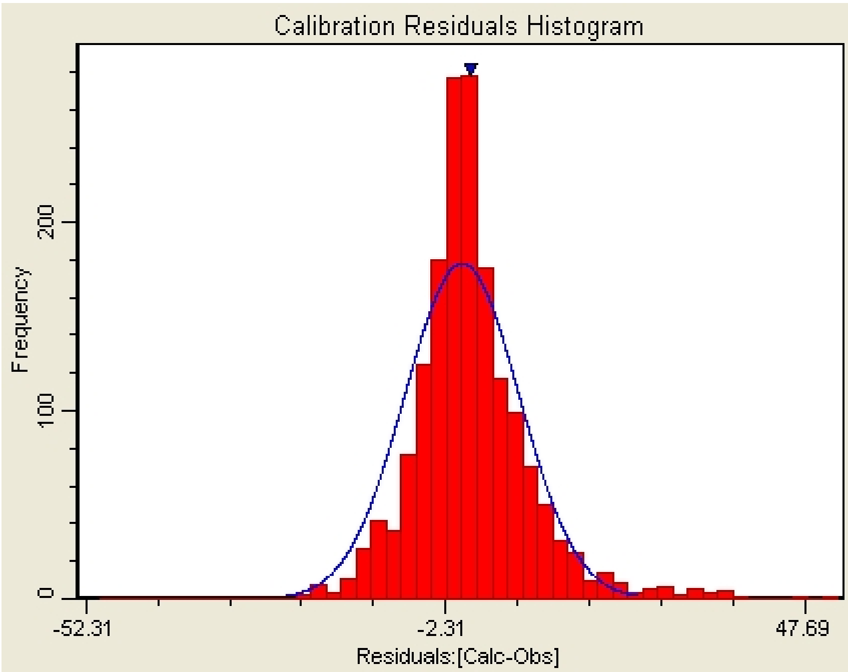
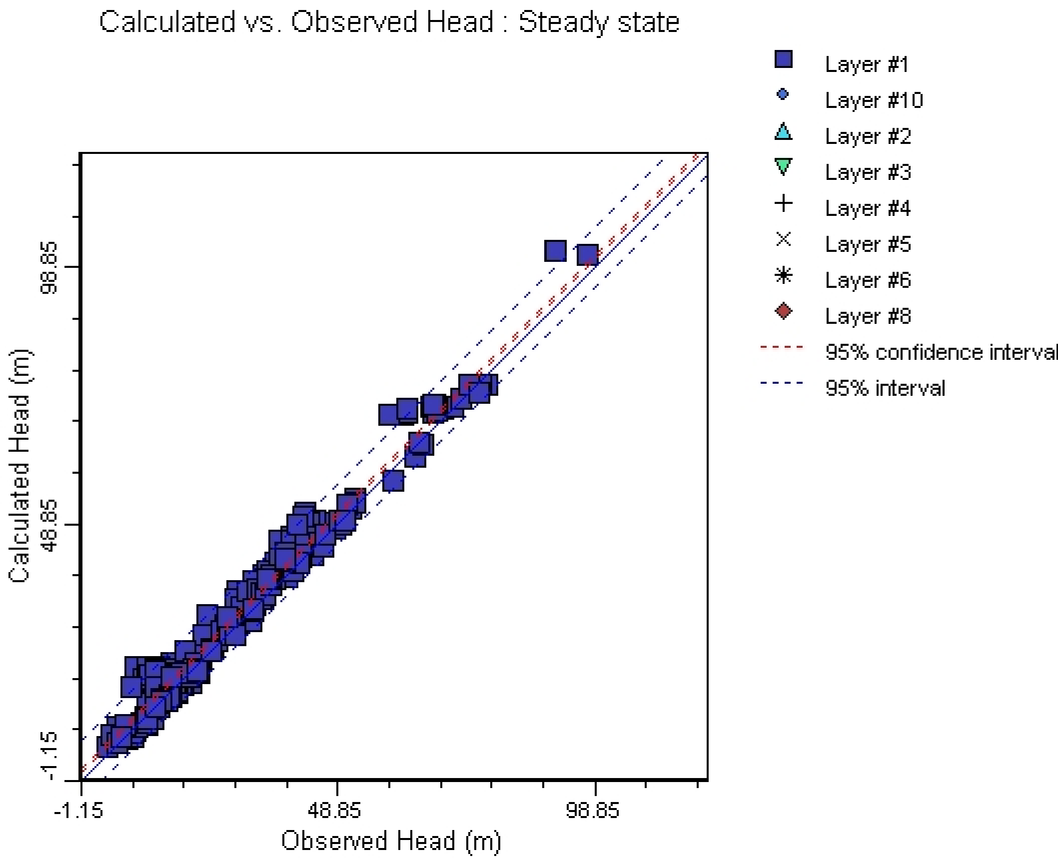


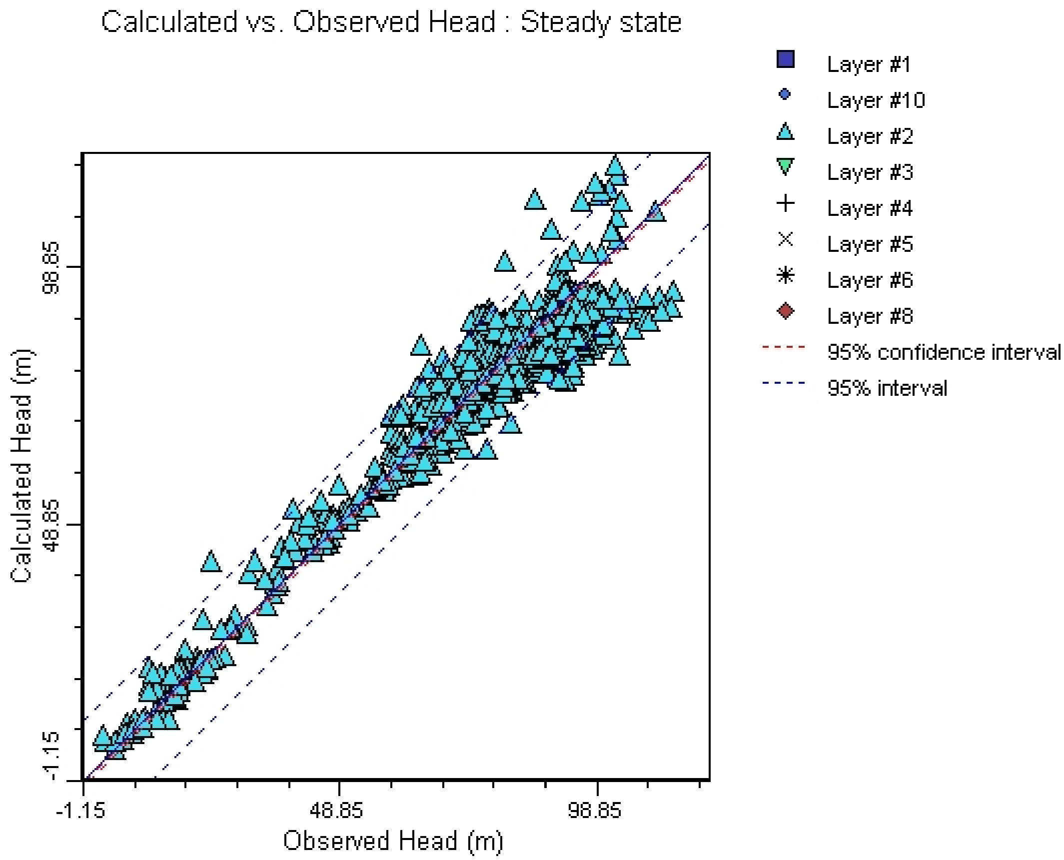
Figure 32 Calculated versus observed heads from steady-state model of Abbotsford-Sumas aquifer – best achieved calibration in model layer 1.



Num. of Data Points : 231
Max. Residual: 11.666 (m) at 136/1
Min. Residual: -0.003 (m) at 483/1
Residual Mean : 1.968 (m)
Abs. Residual Mean : 2.488 (m)

Standard Error of the Estimate : 0.195 (m)
Root Mean Squared : 3.556 (m)
Normalized RMS : 3.791 (%)
Correlation Coefficient : 0.988

Figure 33 Calculated versus observed heads from steady-state model of Abbotsford-Sumas aquifer – best achieved calibration in model layer 2.



Num. of Data Points : 839
Max. Residual: 25.056 (m) at 42911/1
Min. Residual: 0.003 (m) at 33293/1
Residual Mean : -0.78 (m)
Abs. Residual Mean : 4.754 (m)

Standard Error of the Estimate : 0.219 (m)
Root Mean Squared : 6.397 (m)
Normalized RMS : 5.763 (%)
Correlation Coefficient : 0.961

Figure 34 Calculated versus observed heads from steady-state model of Abbotsford-Sumas aquifer – best achieved calibration in model layer 3.

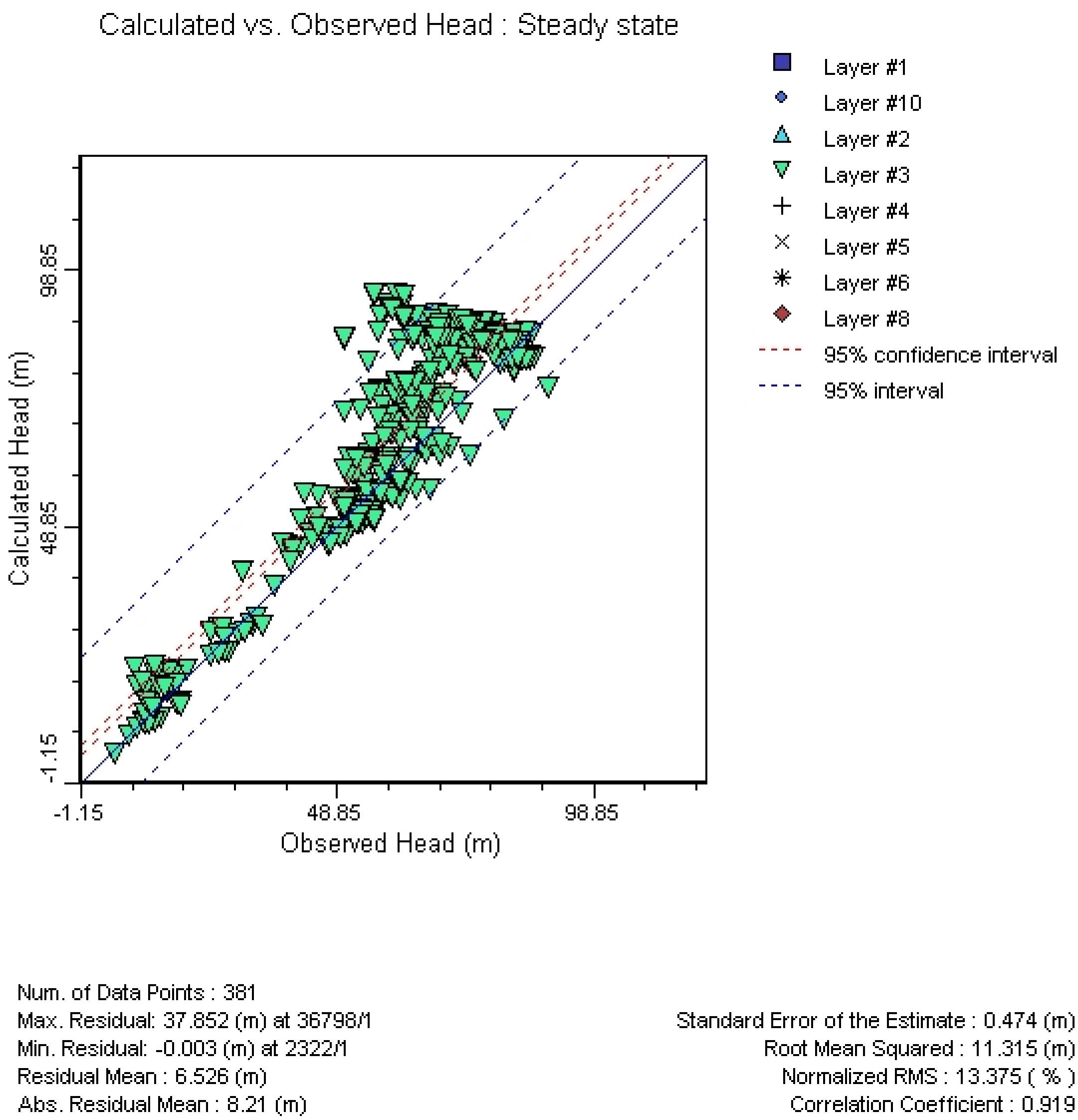
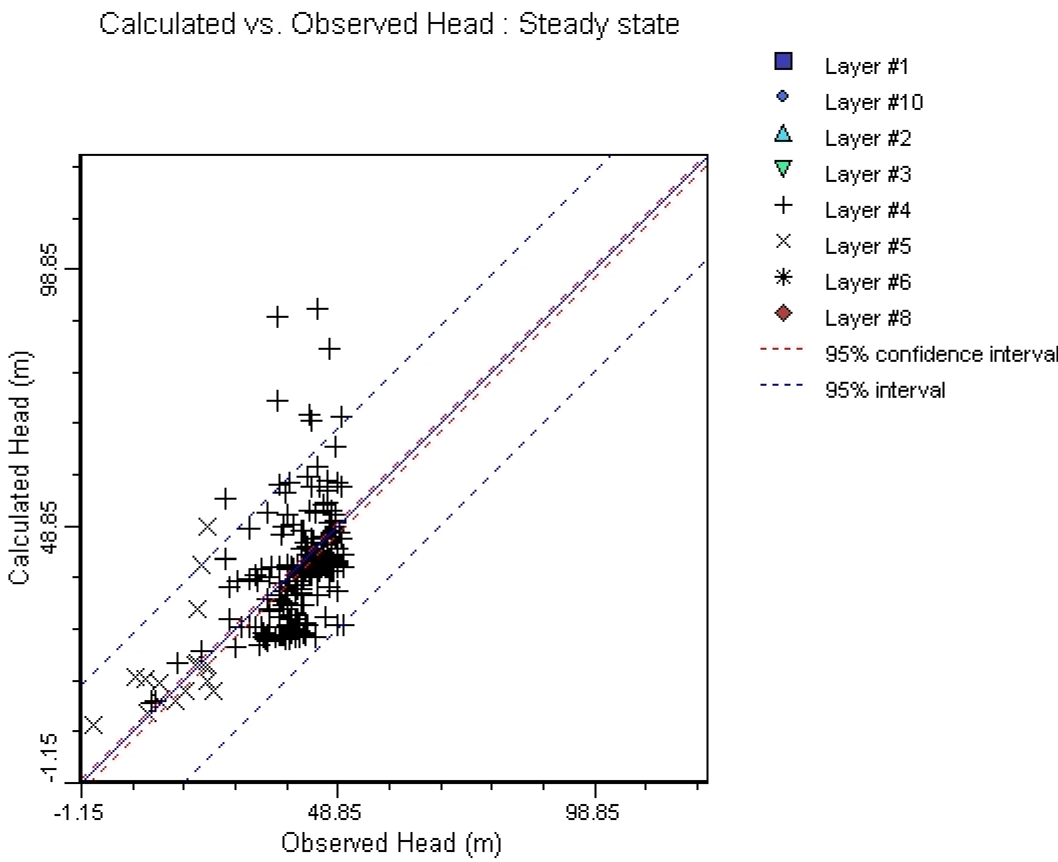


Figure 35 Calculated versus observed heads from steady-state model of Abbotsford-Sumas aquifer – best achieved calibration in deep model layers 4 and 5.



Num. of Data Points : 244
Max. Residual: 52.308 (m) at 51262/1
Min. Residual: -0.06 (m) at 41863/1
Residual Mean : -0.441 (m)
Abs. Residual Mean : 6.857 (m)

Standard Error of the Estimate : 0.634 (m)
Root Mean Squared : 9.89 (m)
Normalized RMS : 20.309 (%)
Correlation Coefficient : 0.579

6.1.2. SPATIAL DISTRIBUTION OF RESIDUALS (CALIBRATIONS TO LOCAL AREAS)

Comparing modeled to observed water table elevation

Static groundwater levels were represented as an interpolated surface (**Map 64a**), and compared to modeled water table elevation (**Map 64b**). The static water levels include some wells penetrating confined aquifers. The resulting surface has localized peaks and depressions, which result from mixing confined and unconfined piezometric levels. The modeled surface is also much smoother than the static one, because the modeled surface is the water table elevation, which is more consistent temporally than the static piezometric surface (static levels were taken in different months and years, including high and low aquifer water levels), and is smoother due to less heterogeneity in the model than in reality.

In the uplands, the highs are predicted by within few metres (on average) by the model. The very localized mounds of groundwater indicated by static levels, are most likely confined areas, but some are also perched water tables in hilly areas composed of drift and till lenses, and also in areas that were assigned hydraulic conductivity values that are too high relative to the values expected for the tills that are present (much lower K values locally). The till areas will be shown later. The model was ultimately adjusted to include those areas as lower K zones.

In the transition areas, from uplands to lowlands, the modeled hydraulic gradients approximately equal those represented in the static piezometric surface. The resulting model output in **Map 64b** was the initial calibration result, and in the City of Abbotsford area, it severely under-predicted groundwater elevations, especially in proximity to escarpments and near small lakes (e.g., Judson Lake). This problem was corrected in a subsequent calibration.

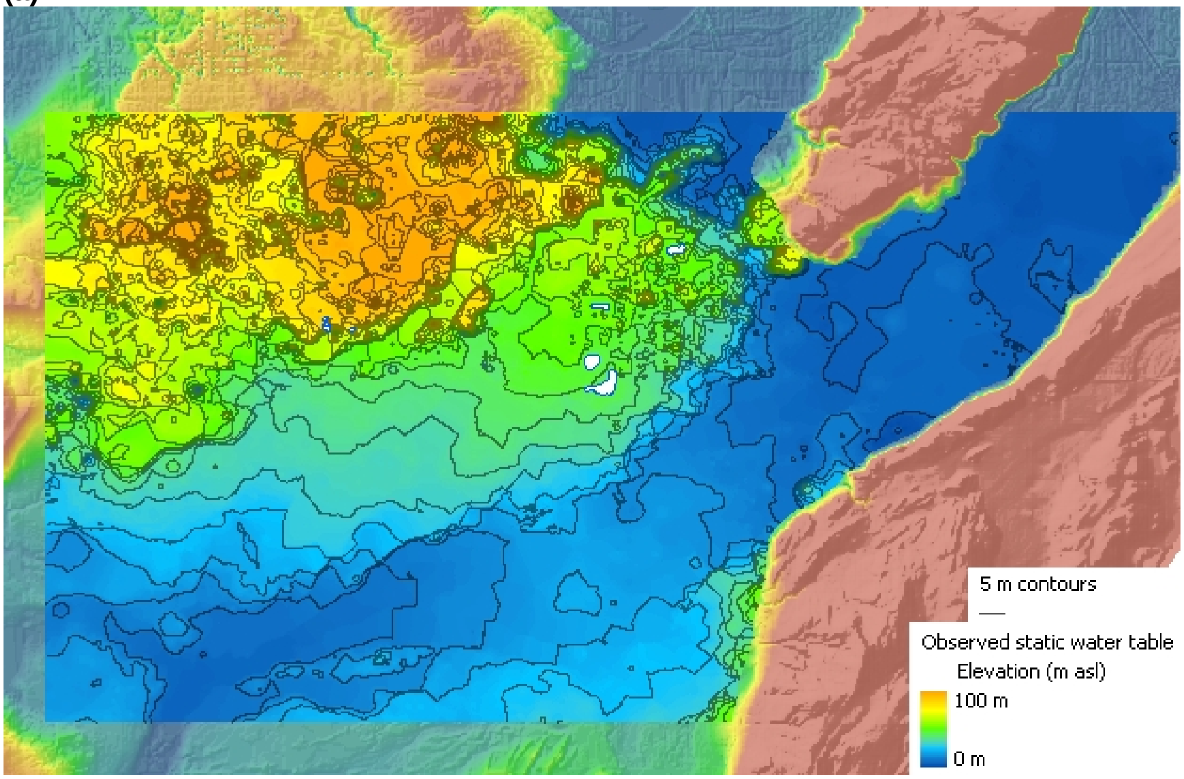
The lowland groundwater levels are very well represented in the model, partly as a result of being constrained by many boundary conditions (constant head along rivers), and partly by the fact that there are small hydraulic gradients and a shallow depth to water table - the model has less freedom to calculate different hydraulic heads. On regional scale, the model seems to perform reasonably well, but on local scale, there are serious problems with this initial calibration, particularly in City of Abbotsford area.

City of Abbotsford area

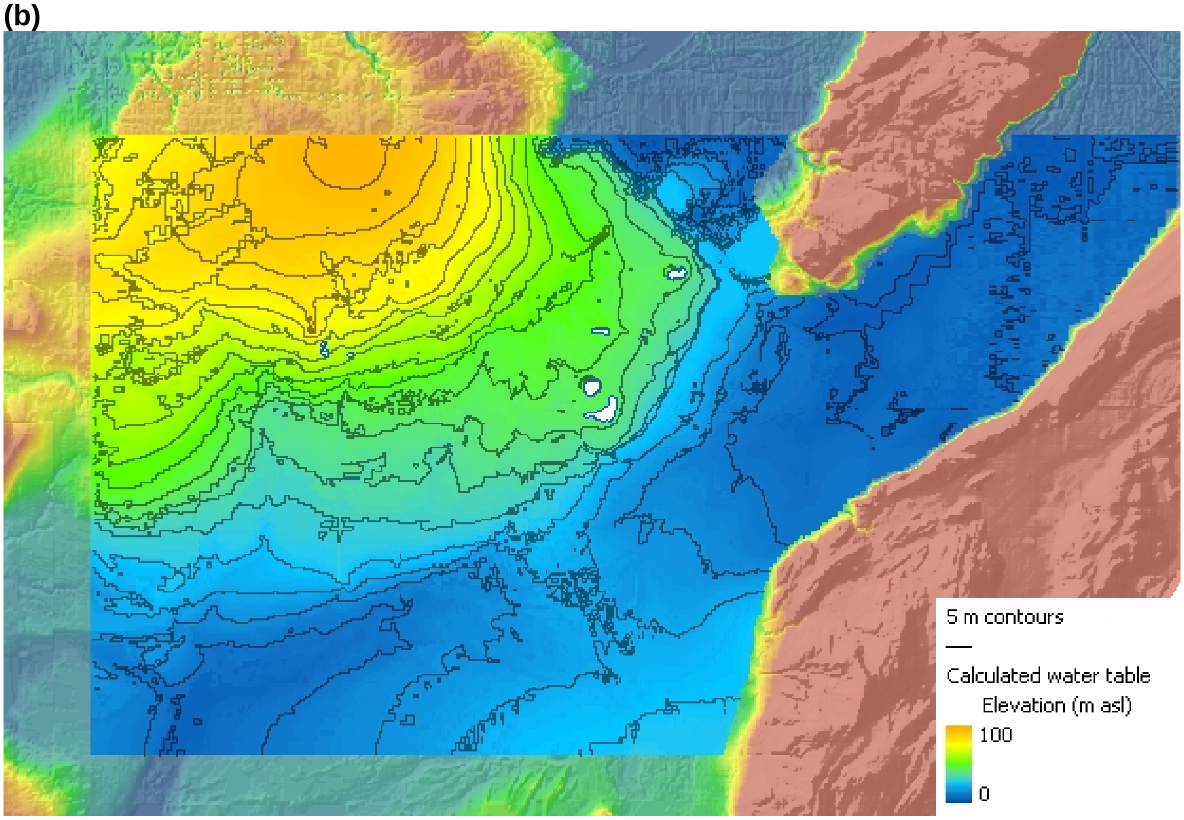
Calibration residuals are represented in **Map 65** as raster image, calculated from difference between modeled and observed water table elevations (static elevation in observed - interpolated between points to create raster image). The differences were reclassified to between values -10 and +10 m. In some areas the differences are larger than 10 meters. This results from a combination of confined conditions (when comparing static to modeled water table, the static was assumed to be for unconfined conditions), poor conceptual model and model performance locally - wrong K and recharge, seasonal variation in groundwater levels in static surface, and errors in observed water levels.

Map 64 Water table elevations (a) observed static water table, interpolated between all measurements and contoured, with ground surface DEM as background, (b) calculated steady-state water table elevations in one calibration run.

(a)

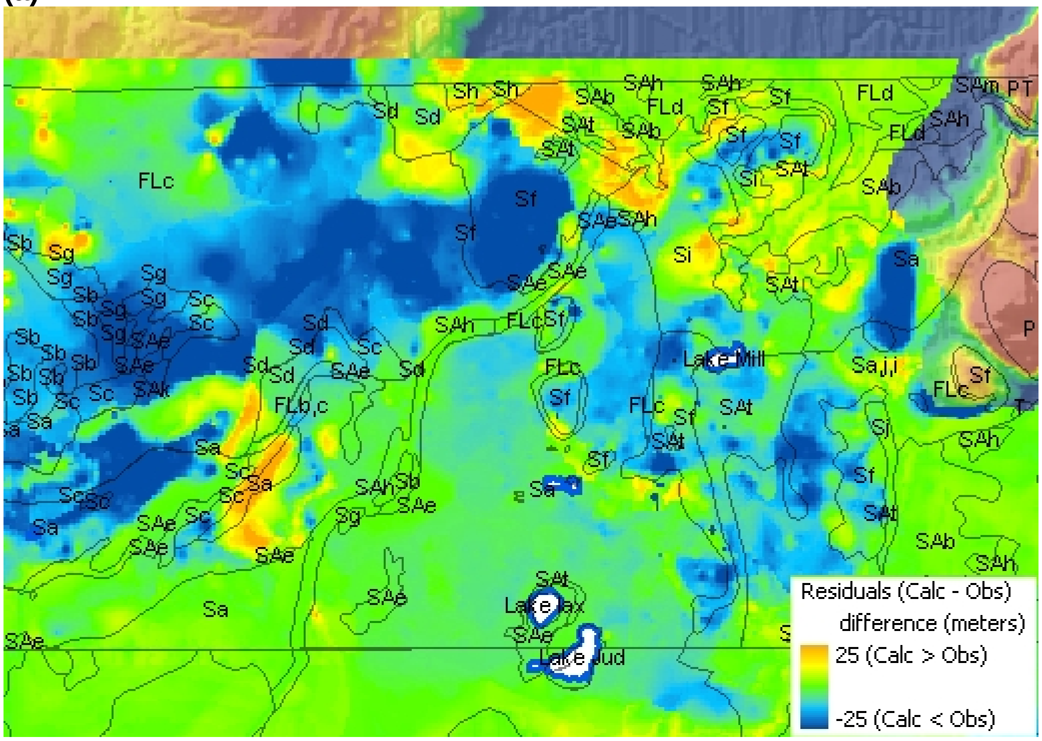


(b)

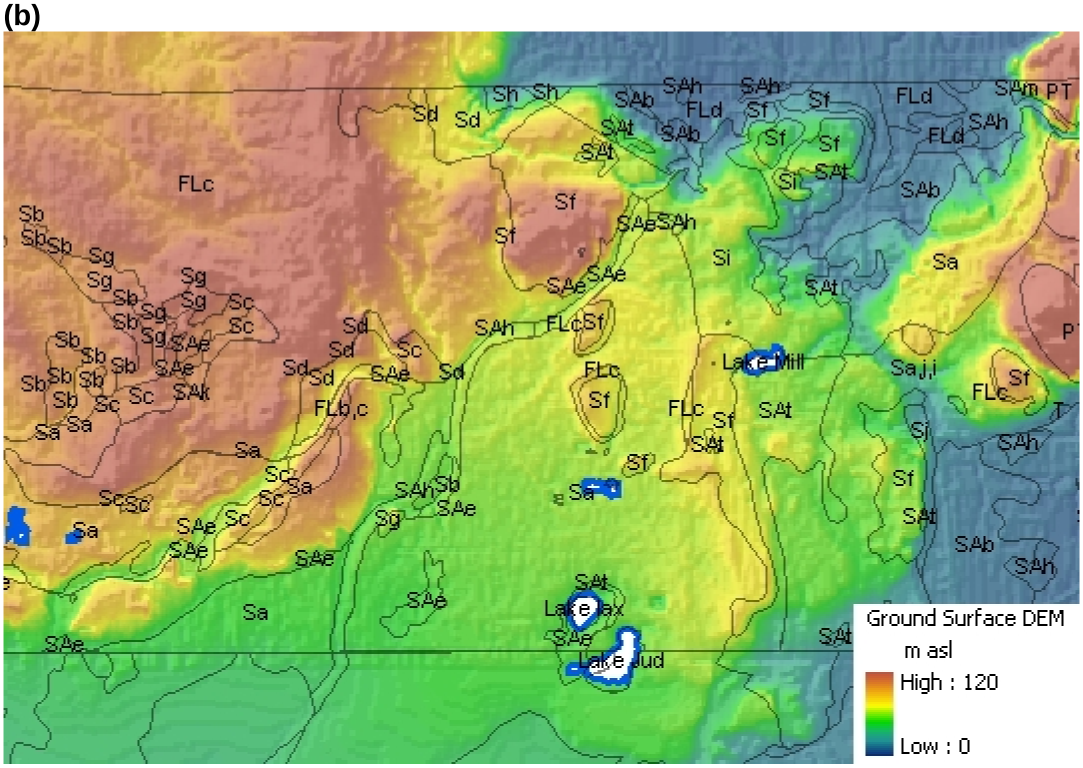


Map 65 Differences between calculated and observed water table elevations from the initial steady-state model run, which had large errors, even after many improvements (a) water level difference, (b) ground surface.

(a)



(b)



6.1.3. AREAS WITH POOR INITIAL MODEL CALIBRATION

The results of each steady-state model were examined for all areas of the aquifer system. The most useful information were the differences between calculated and observed water table elevation, flow velocity vectors, elevation of water table, hydraulic conductivity distributions, and composite 3D map of borehole lithologs superimposed on the ground surface DEM, surficial geology, and drainage maps. Note that hydraulic head could have been used, but due to dry cells in layers 1 to 4, only layers beneath layer 5 could be used. However, there are confined conditions in many parts of the aquifer within and beneath layer 5. The observed water level maps also contain information on confined conditions, as static water levels in some wells have elevated hydraulic heads due to confining layers below.

The model was initially calibrated only to RMS and other "whole-model" calibration statistics, but the only method to calibrate this model to site specific conditions was to re-examine the hydraulic conductivity distribution, and also to re-examine lithology data, and make appropriate adjustments in specific areas. The problem with lithology data was uneven distribution of deep boreholes, thus some areas have only interpolated hydrostratigraphic units, which could be interpreted differently by different hydrogeologists. In those uncertain areas, the lithologs could be interpolated differently, depending on local lack of model calibration – but only for major problem areas. In particular, lakes that were assigned specified heads, resulted in heads well above the calculated water table. These were observed to drain too fast, resulting in grossly incorrect hydraulic connections that resulted in very high flow gradients locally. Thus, incorrect water levels were produced, which disagreed strongly with observed conditions.

Calibration of the model to local conditions ultimately determines the flow paths, and any future usefulness of this flow model. Thus, as much care as possible was given to locally calibrate this model, and to repeatedly review the hydrostratigraphic unit distribution, and to adjust the hydraulic conductivity values.

6.2. TEMPORAL VARIATION IN WATER LEVELS

Groundwater level measurements are collected monthly by Environment Canada on the BC side of the Abbotsford-Sumas aquifer. We obtained records for the period 1990 to 2002, from numerous piezometers and observation wells. The period of record varied between piezometers, as some were installed in different years. In the early 1990's there had been an effort on the part of Environment Canada to monitor water levels, contaminant concentrations, and an attempt to correlate and explain the trends in both. Two USGS piezometers were also included in data set we received. **Table 24** contains monthly summaries for these selected piezometers for period of record listed below for each piezometer.

Period of Record:

1990-2002	ABB1, ABB2, ABB3, ABB4, ABB5, ABB6
1992-2002	91-4, 91-5, 91-7, 91-8. 91-10, 91-13
1994-2002	P-A-35, P-B-35, P-C-35
1995-2002	94-Sh29, 94-Q-27
1999-2002	USGS5, USGS4

Table 24 Long term mean water levels, monthly averaged for period of record, in piezometers and observation wells in Abbotsford-Sumas aquifer near Abbotsford airport (Environment Canada source).

Month	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
Julian Day	30	60	90	120	150	180	210	240	270	300	330	360
Monthly averages for period of record												
ABB1	44.2	44.1	44.0	43.9	43.8	43.7	43.5	43.3	43.3	43.4	43.9	44.2
ABB2	47.7	48.0	48.0	47.9	47.7	47.4	47.0	46.6	46.3	46.0	46.3	47.0
ABB3	43.7	44.4	44.8	45.0	44.9	44.6	44.3	43.8	43.3	43.0	42.8	42.9
ABB4	41.9	42.6	42.9	43.1	43.0	42.8	42.5	42.1	41.6	41.4	41.1	41.2
ABB5	45.2	45.3	45.1	45.0	44.7	44.4	44.1	43.7	43.6	43.5	44.2	44.9
ABB6	48.2	48.6	48.7	48.6	48.4	48.1	47.6	47.2	46.8	46.5	46.7	47.5
91-4	43.5	44.3	44.7	44.9	44.8	44.6	44.2	43.8	43.3	43.0	42.7	42.7
91-5	43.4	44.2	44.6	44.8	44.7	44.5	44.2	43.7	43.2	42.9	42.6	42.7
91-7	43.5	44.3	44.7	44.8	44.8	44.6	44.2	43.8	43.3	42.9	42.7	42.7
91-8	47.1	47.8	48.1	48.1	48.0	47.7	47.2	46.7	46.2	45.8	45.7	46.3
91-10	48.4	48.9	49.0	48.9	48.6	48.3	47.9	47.4	47.0	46.7	46.6	47.5
91-13	43.8	43.8	43.7	43.5	43.2	42.8	42.4	42.1	41.9	41.8	42.4	43.3
P-A-35	48.4	48.3	48.2	48.7	48.5	48.2	47.7	47.2	46.9	46.7	46.5	47.7
P-B-35	47.2	47.5	47.4	47.1	46.9	46.6	46.2	45.9	45.7	45.6	46.0	46.8
P-C-35	47.7	47.9	47.9	47.9	47.7	47.4	46.9	46.5	46.1	46.0	46.2	47.0
94-Sh29	25.0	31.4	29.2	26.4	26.2	25.8	25.6	25.2	24.9	24.7	24.5	24.6
94-Q-27	51.1	47.8	48.3	51.4	51.0	50.7	50.3	49.7	49.3	49.0	49.2	50.1
USGS5	45.9	47.0	46.5	46.9	46.6	46.3	45.9	45.4	44.9	44.6	44.5	45.3
USGS4	46.2	46.6	46.5	46.3	46.0	45.8	45.4	45.0	44.8	44.5	44.4	45.0

The USGS also monitors groundwater levels at many locations, and there have been various consulting companies, WA Dept of Ecology, and others collecting groundwater level observations. However, only some of these data were used because most could not be located. A preliminary transient model was run using only the Canadian transient records (with the two USGS wells) to calibrate the model calibration – or, at least, attempt to calibrate the model.

At one of the piezometers, ABB4, in the unconfined Abbotsford-Sumas aquifer near Abbotsford airport, the monthly water levels are plotted in **Figure 36**. Measured monthly precipitation was also plotted for the period of water level measurements from July 1989 to March 2003 (water levels are also measured monthly at the present time). The water levels are assumed to represent the water table elevation as there is no evidence of a confining layer. The groundwater levels varied monthly (within each year) by approximately 2 m. The largest annual variation was about 3 m and the smallest about 1 m. Precipitation was correlated to water levels, indicating direct link between amount of recharge and groundwater levels. There are decadal-scale trends in this time series, where groundwater elevations fluctuate at that time scale by about 1 m (see marked decline from 1989 to 1995, then leveling out).

Mean monthly water levels were calculated and plotted by month for all piezometers (**Figure 37**) to explore the seasonal variation. Most of the piezometers had very similar temporal variation in groundwater levels. The water table elevation is highest in from February to April, then declines in elevation at a non-linear rate until August, when the rate of decline becomes smaller. The minimum groundwater levels occur between September and November. In December, or as early as November, the increased precipitation (in wet years) causes a rise in the water table again. The piezometers differ obviously in local elevation, but there are also differences in peak water elevations and rate of change over the year. Piezometers ABB1 and ABB5 have less water level variation than most other piezometers (1 m or less from low to high). At most locations sampled, the amplitude of these groundwater level hydrographs is between 2 and 3 m. This behaviour can be seen more clearly in **Figure 38**, where water levels were subtracted from Month 1 water levels at all piezometers separately, to bring all observations to the same elevation datum.

Figure 36 Average monthly water table elevations and measured monthly precipitation in an unconfined portion of the Abbotsford aquifer (BC side) measured by Environment Canada in piezometer ABB4. Data from 1989 to 2003 showing monthly variation and decadal trends.

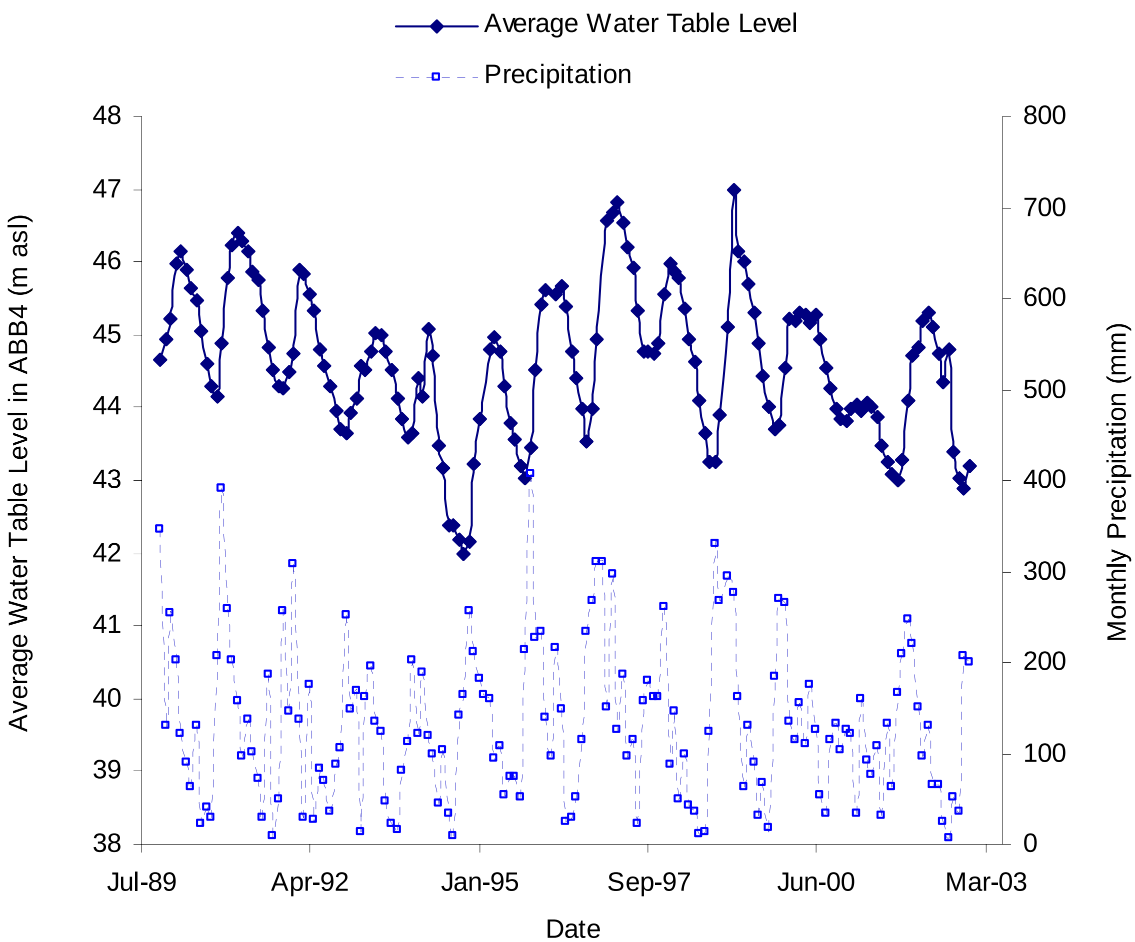


Figure 37 Mean monthly groundwater levels in observation piezometers near Abbotsford Airport, in Abbotsford-Sumas aquifer (period of record varies from 1990 to 2002 between piezometers).

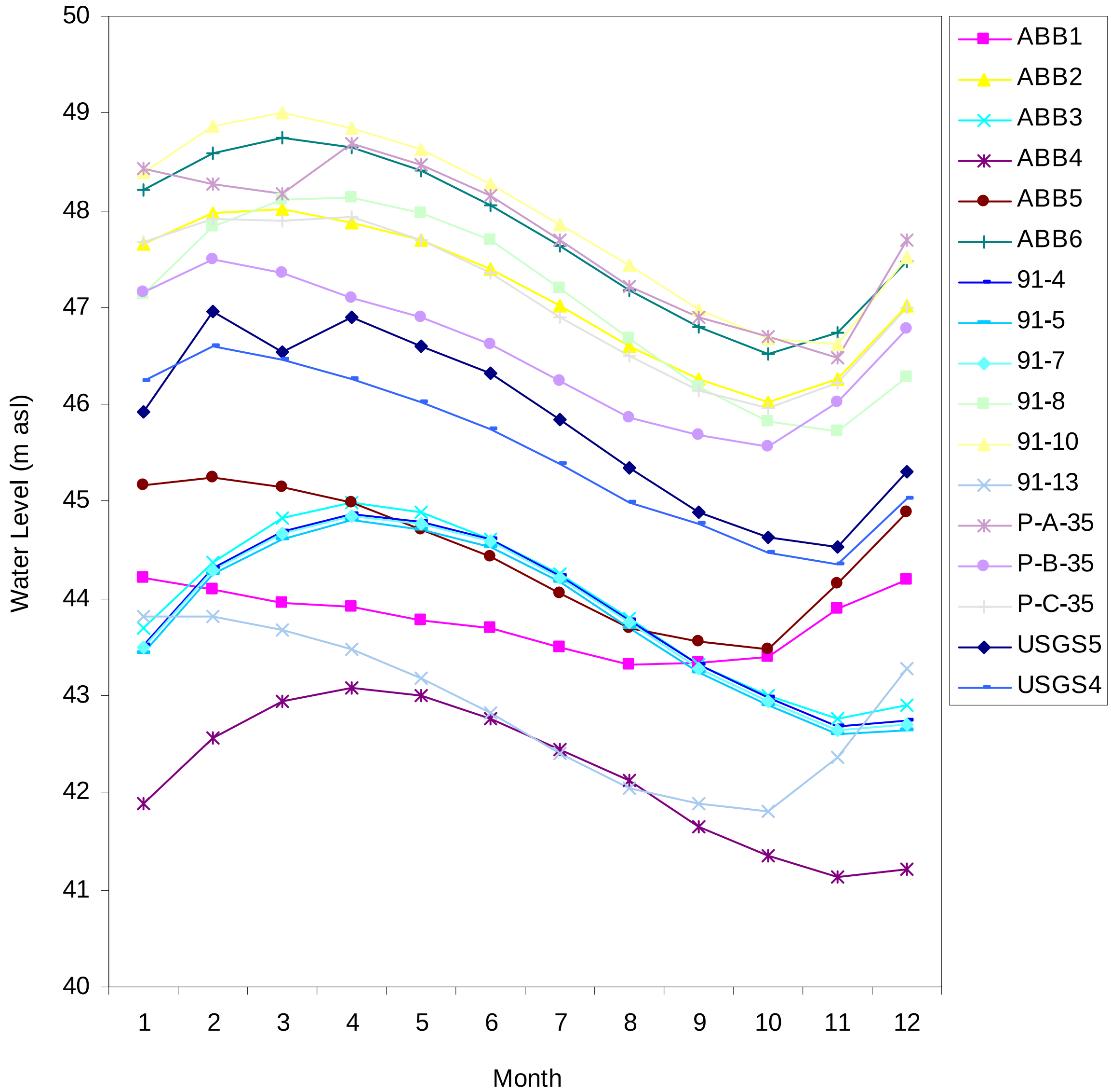
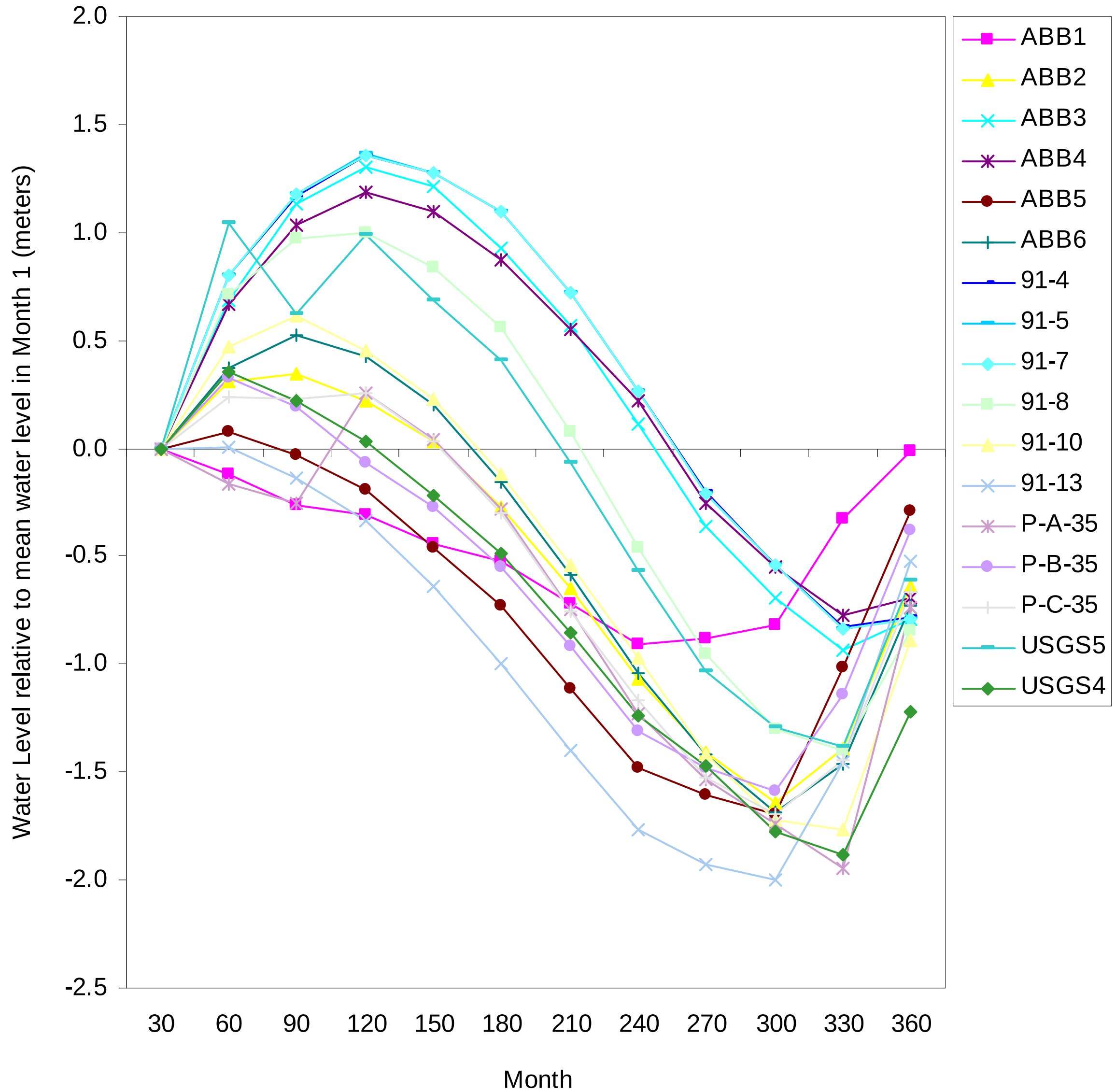


Figure 38 Mean monthly groundwater levels as deviation from water level in Month 1 in observation piezometers near Abbotsford Airport, in Abbotsford-Sumas aquifer (period of record varies from1990 to 2002 between piezometers). This graph brings all piezometers to the same elevation datum.



6.3. CALIBRATION TO TRANSIENT AND STATIC GROUNDWATER ELEVATIONS

6.3.1. CALIBRATION TARGETS

Model calibration employed the following strategies, but mostly by using (1) and (3), except for the transient model where (2) was attempted, but with limited success:

1. by considering the spatial distribution of residuals. These are static groundwater levels in all wells in the central Fraser valley. These are expected not to match perfectly due to static groundwater level errors (well elevation, location, time of sampling, pumping effects, and data entry errors).

2. by matching the observed hydrograph in the observation wells to that produced by the model. Two aspects were considered:

   - **vertical position** (absolute elevation) of the hydrograph. The vertical position of the simulated hydrograph may not match the observed elevation due to well surveying errors.
   - **amplitude and phase shift** of hydrograph were matched by adjusting K and Sy parameters in the model, allowing for model bias from observed to modelled hydrograph

3. by calculating the RMS of residuals and other estimates of goodness of fit (statistics).

6.3.2. CALIBRATION VARIABLES AND CALIBRATION RUNS

Recharge:

The calibration runs, and the final "calibrated" transient model had historical climate scenario for recharge, where recharge was spatially distributed in 65 zones and did not include irrigation return flow (production wells were inactive). Recharge was not adjusted during model calibration, as considerable effort had been made to calculate distributed recharge using physical constraints and accurate climate forcing using HELP. Recharge is only applied to the top active layer (or the top-most active cell if cells above are dry or inactive).

Hydraulic conductivity:

The steady-state model was calibrated by adjusting hydraulic conductivity values in the various zones, assuming horizontal isotropy Kx = Ky, but creating vertical anisotropy Kz < Kx. To improve local calibration fit, additional K zones were created and then the model re-calibrated by changing K values in the new zones.

6.4. FINAL CALIBRATION RESULTS

6.4.1. NEW HYDRAULIC CONDUCTIVITY ZONES

The final calibrated steady-state model had hydraulic conductivity distributions identical to the hydrostratigraphic unit distributions, and the calibrated values (that reduced RMS in the model residuals) are given in **Table 25**. MODFLOW Zone 9 and 14 were added during calibration, and can be considered a refinement of the other hydrostratigraphic units. The incorporation of flow tills in the Sumas Drift unit in the Abbotsford uplands had the most significant effect on the model results. The model is now able to predict the existence of kettle lakes at the observed elevations, where as the original model (with just sand or gravel Sumas Drift unit) could not, and the water table was greatly underestimated compared to observed in the uplands.

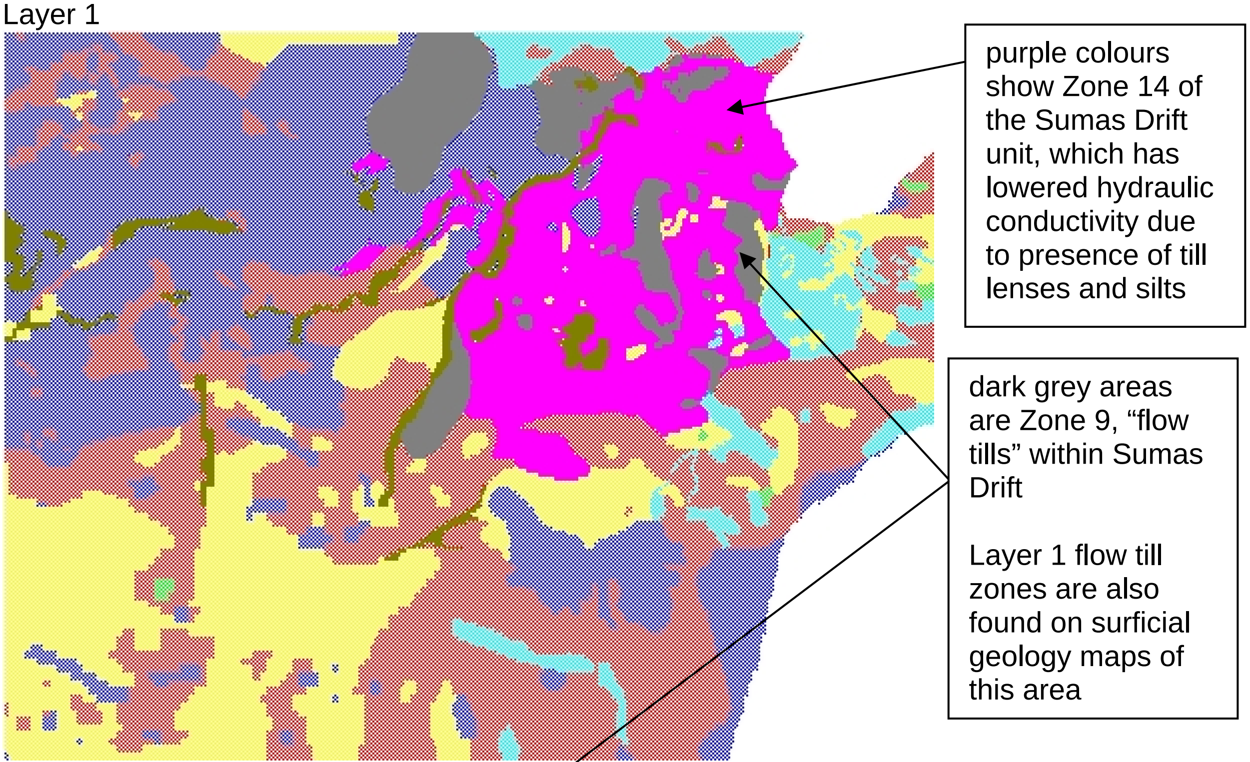
The modified hydraulic conductivity values and the added hydraulic conductivity zones in MODFLOW layers were exported from Visual MODFLOW to **Map 66** to **Map 69** for layers 1 to 7 of the model (layer 1 is the top layer). The flow tills act as aquitards to groundwater flow and help maintain high groundwater levels in the uplands, which show up as several lakes as surface bodies (also found at shallow depth in gravel pits). Without till areas, the groundwater would have drained west and south and equilibrated at much lower level as predicted by initial steady-state model.

Table 25 Hydraulic properties calibrated steady-state flow model, by MODFLOW zone and by hydrostratigraphic unit.

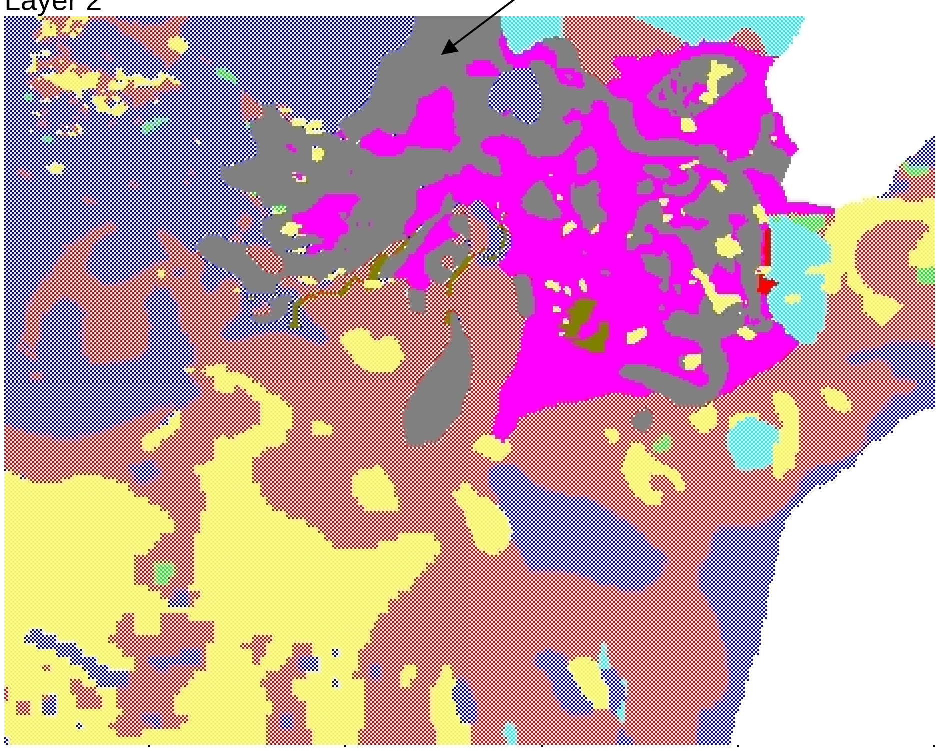
MODFLOW zone	Unit	Kx	Ky	Kz	Ss	Sy	Eff por	Tot por
		(m/d)			(1/m)			
7	Peat and channel GF deposits	10.0	10.0	5.0	1.0E-02	4.0E-01	0.45	0.45
9	Till (flow tills in Abbotsford uplands)	0.1	0.1	0.0	1.0E-03	3.0E-02	0.35	0.35
13	Gravel (high K zone - Sumas Valley)	150.0	150.0	100.0	1.0E-03	2.0E-01	0.25	0.25
14	Sumas Drift (uplands at Abbotsford)	15.0	15.0	5.0	1.0E-02	1.0E-01	0.30	0.30
23	Ft Langley fm (GM clay or till)	6.0	6.0	1.0	2.6E-03	5.0E-02	0.35	0.35
24	Lacustrine (silt and other)	3.0	3.0	0.3	1.0E-03	8.0E-02	0.35	0.35
25	GF floodplain deposits (silt) or till lenses	5.0	5.0	1.0	1.0E-03	5.0E-02	0.30	0.30
26	Sumas Drift (gravel)	50.0	50.0	20.0	1.0E-02	1.5E-01	0.25	0.25
28	Sumas Drift (sand)	60.0	60.0	30.0	4.1E-02	2.0E-01	0.25	0.25

Map 66 Modified hydraulic conductivity zones in MODFLOW model (layer 1 and 2) to improve local model calibration and to account for surface water bodies in Sumas Drift unit in the Abbotsford uplands.

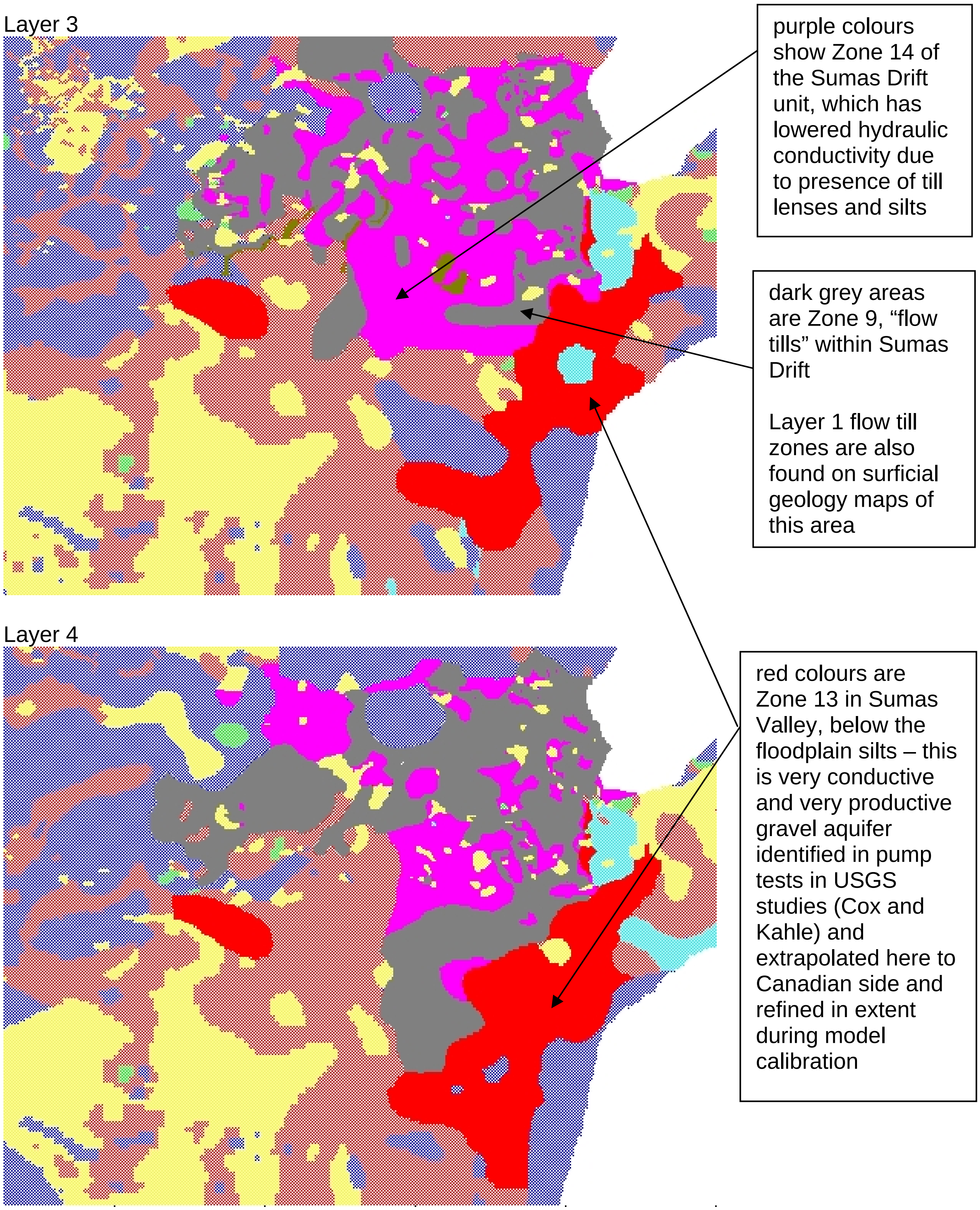
Layer 1



Layer 2

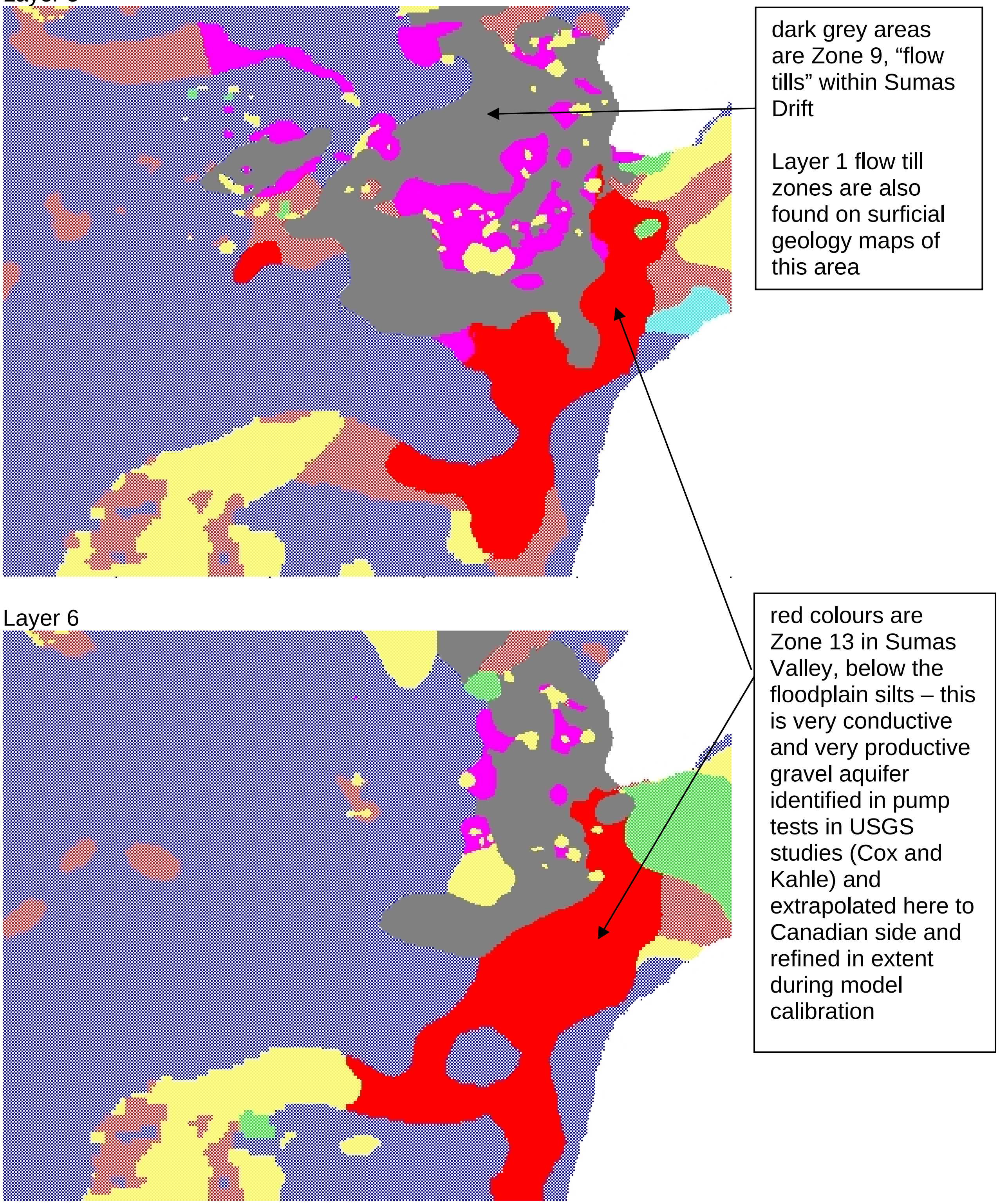


Map 67 Modified hydraulic conductivity zones in MODFLOW model (layer 3 and 4) to improve local model calibration and to account for surface water bodies in Sumas Drift unit in the Abbotsford uplands and Sumas Valley.



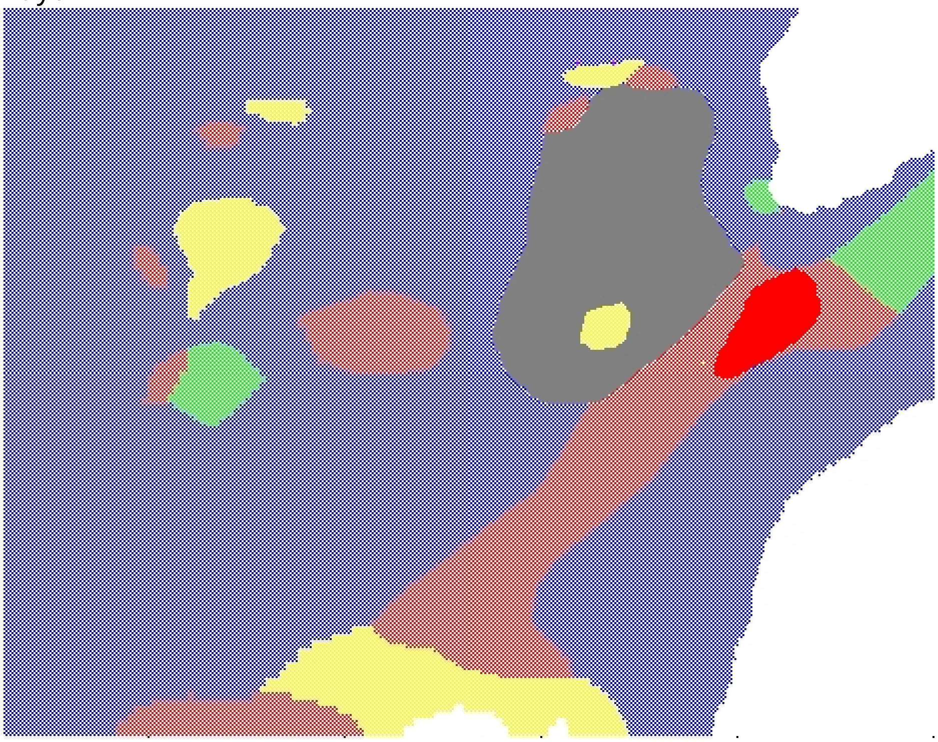
Map 68 Modified hydraulic conductivity zones in MODFLOW model (layer 5 and 6) to improve local model calibration and to account for surface water bodies in Sumas Drift unit in the Abbotsford uplands and Sumas Valley.

Layer 5



Map 69 Modified hydraulic conductivity zones in MODFLOW model (layer 7) to improve local model calibration and to account for surface water bodies in Sumas Drift unit in Sumas Valley and below the Abbotsford uplands.

Layer 7

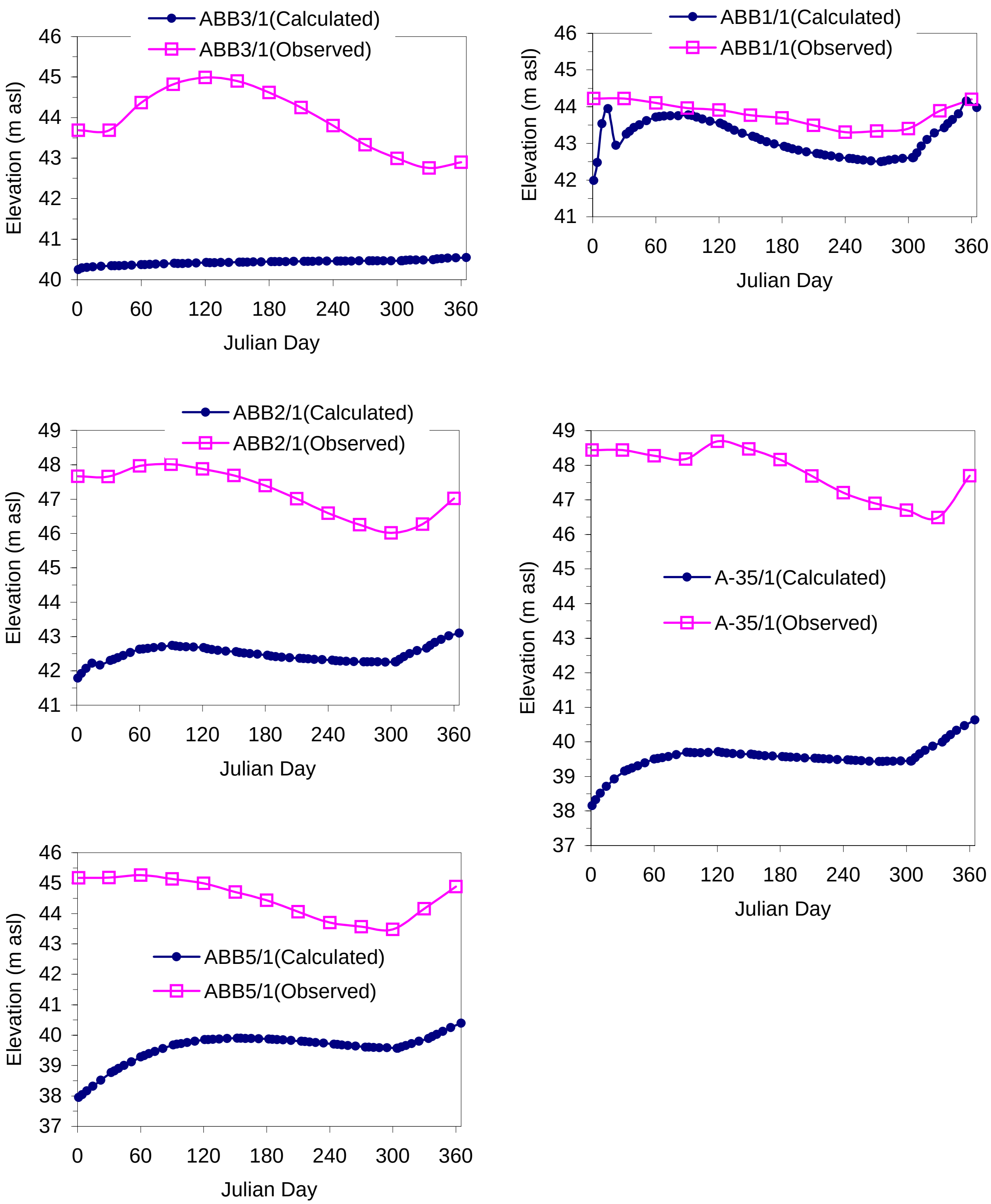


Specific Yield and Specific Storage:

In the unconfined aquifer the storage property is specific yield (Sy), and the MODFLOW model was only sensitive to Sy and not to specific storage. Specific storage values were kept at reasonable values appropriate for these types of sediments, but were not adjusted in model calibration, only Sy was. The model was very sensitive to combination of Sy and Kxy (and to a lesser extent to Kz).

Only limited attempts were made to calibrate the model to groundwater hydrographs at observation wells by adjusting storage properties (**Figure 39**). In some locations, the water table is still at wrong elevation, although the amplitude of seasonal variation in water levels is reasonable at most observation wells. Considerable more detailed information on the local hydrogeologic properties would be required to attain good calibrations at each of these locations.

Figure 39 Water levels predicted by transient model at 5 different observation wells in the Abbotsford uplands.



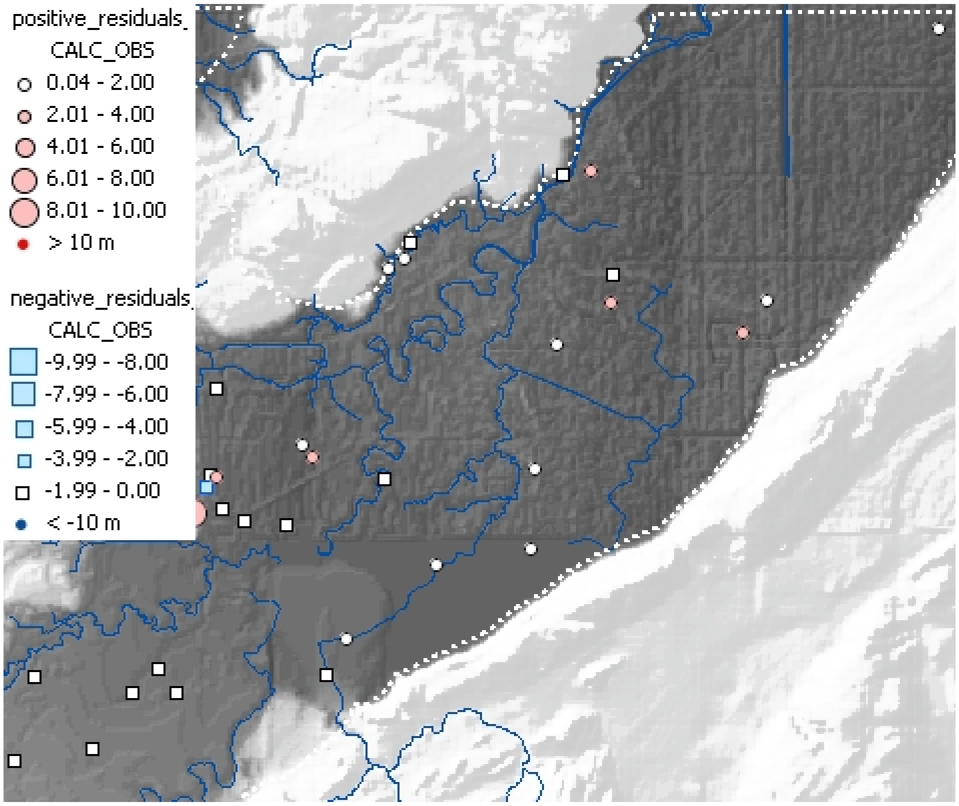
6.4.2. RESIDUALS FROM STATIC WATER LEVELS

Model residuals were exported from Visual MODFLOW and imported to a GIS. Residuals represent the difference between model water levels and observed static water levels for the calibrated model. On residual maps the residual values are represented by proportional symbols, which also differ in colour and fill for positive and negative residuals.

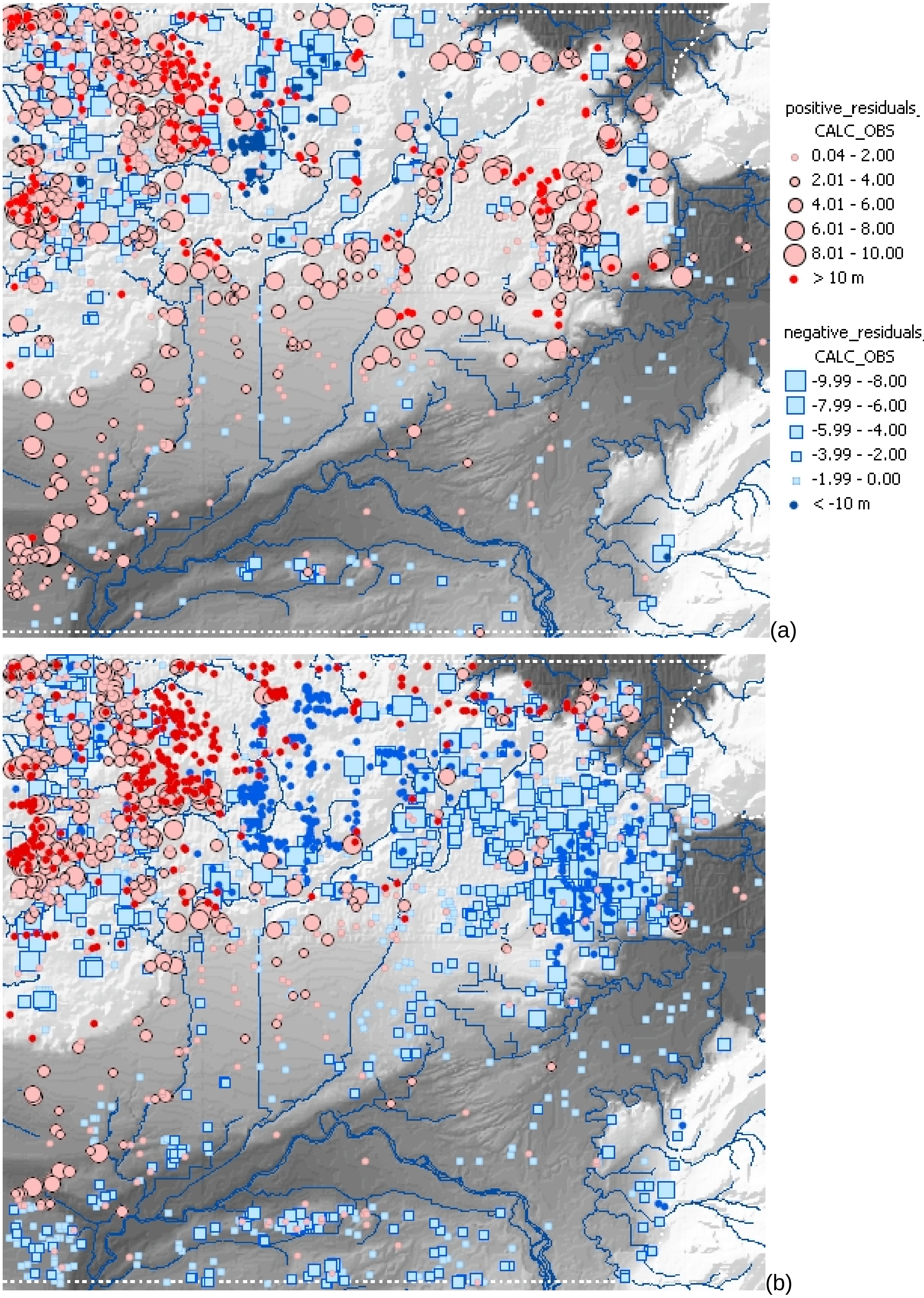
In Sumas Valley, there are only small positive and negative residuals (**Map 70**). This is not surprising, given that the valley floor is flat and so is the water table surface, as well as because the model is constrained by constant head boundary conditions.

In the uplands, there is a highly variable spatial distribution of residuals (**Map 71**). The new and improved zonation of hydraulic conductivity helped to calibrate the model in Abbotsford uplands (i.e., it aided in increasing the water table elevation in this area - **Map 71a**), compared to initial model calibration without flow tills in the uplands (**Map 71b**). There are clusters of large positive and negative residuals, suggesting poor local model fit. The geology is much more heterogeneous than assumed in this model, and there might be perched water tables where the calculated water table is below observed. Also see **Map 72** for a closer look at the Abbotsford uplands in vicinity of Abbotsford Airport and the various kettle lakes. It is interesting to see that there are very small and very large residuals mixed together. The observed water levels are “static” and were collected at various seasons, but seasonal water table fluctuations in that area would account for only 1 to 3 m of differences and some residuals are much larger. There might some some data quality issues such as wrong units reported or wrong ground elevations, or possibly there are effects related to pumping, but it is also likely there are local mounds or perched water tables.

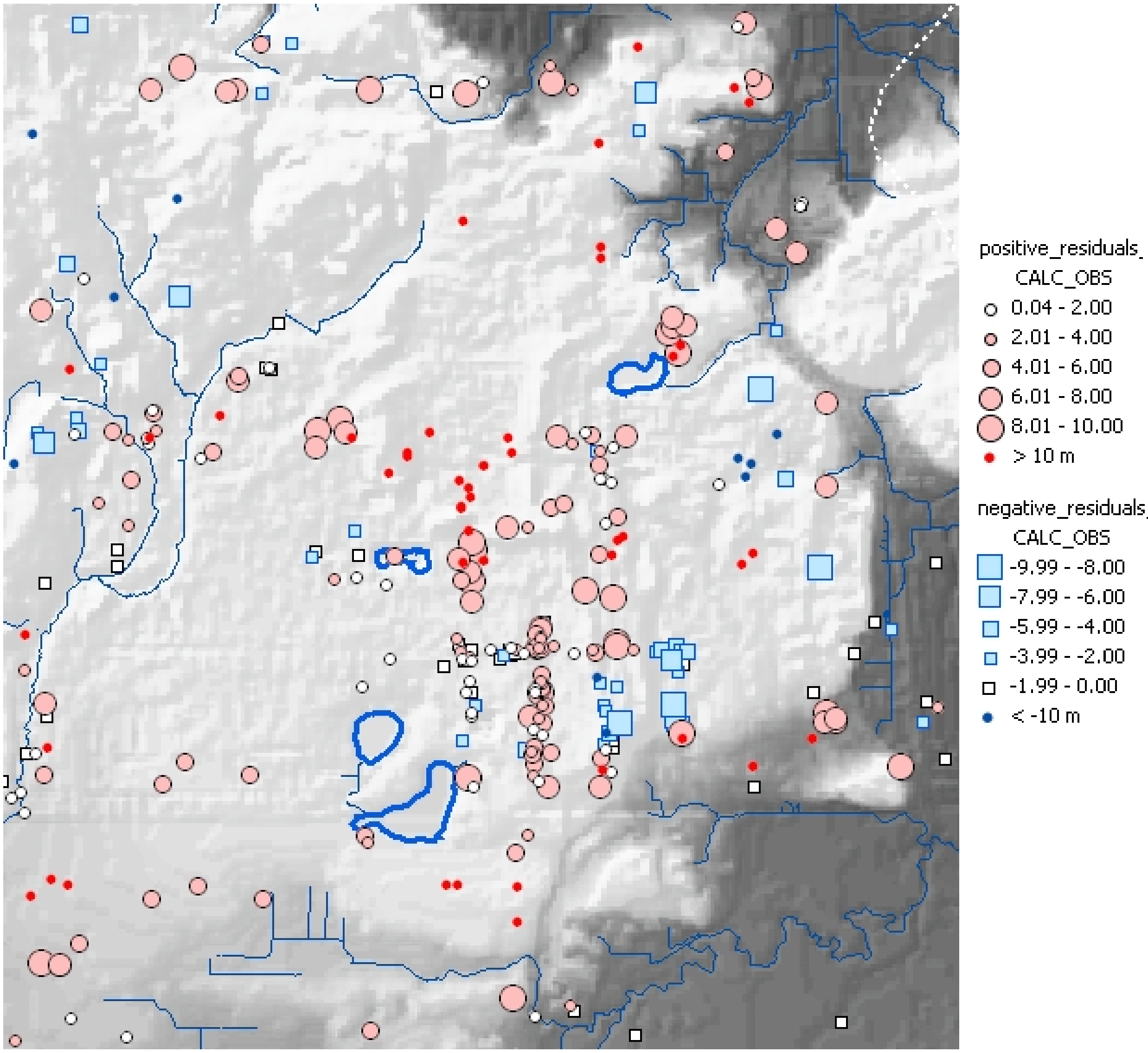
Map 70 Steady-state calibration residuals in Sumas Valley.



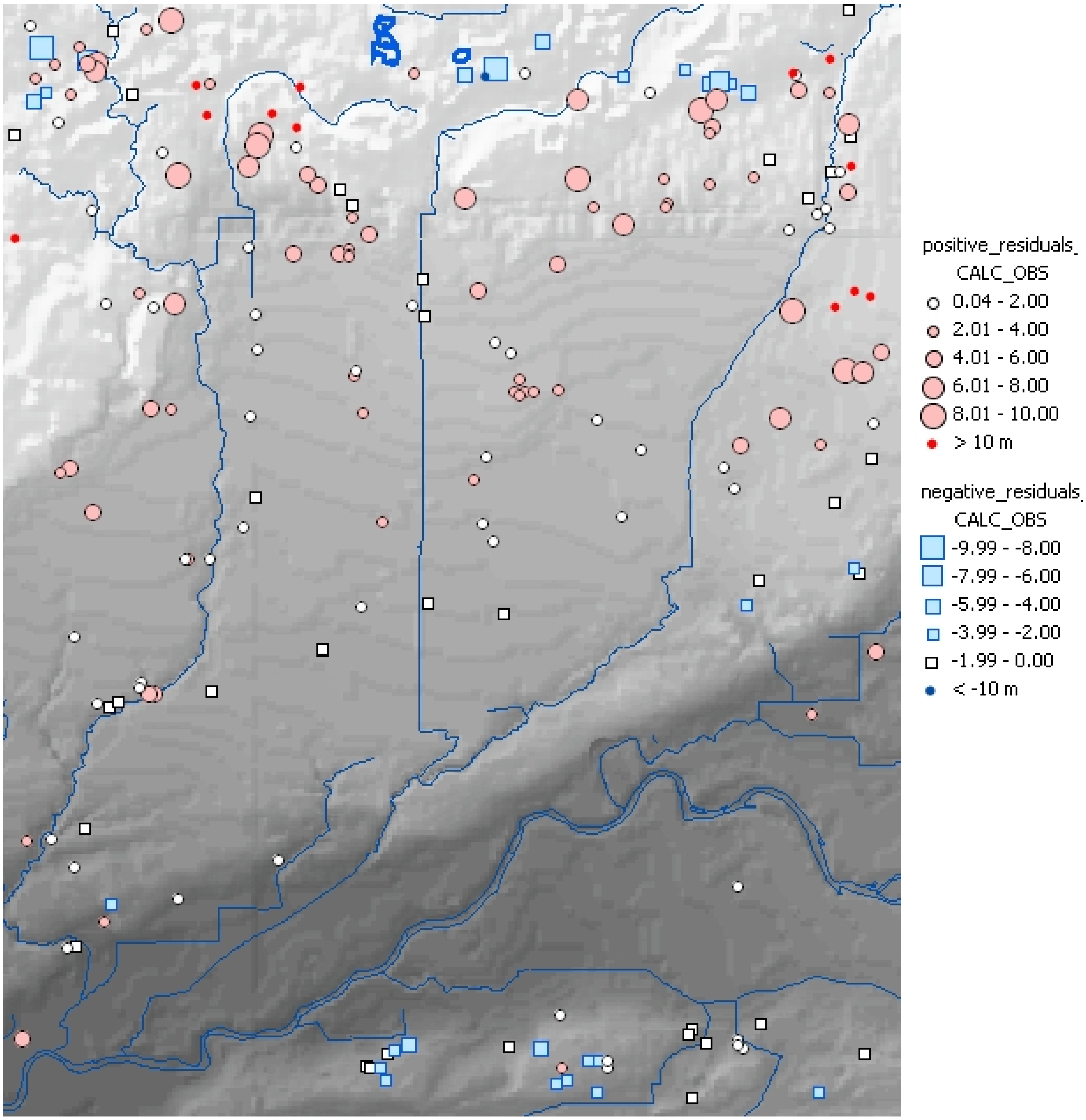
Map 71 Steady-state calibration residuals: (a) modified K zones, (b) initial K zones.



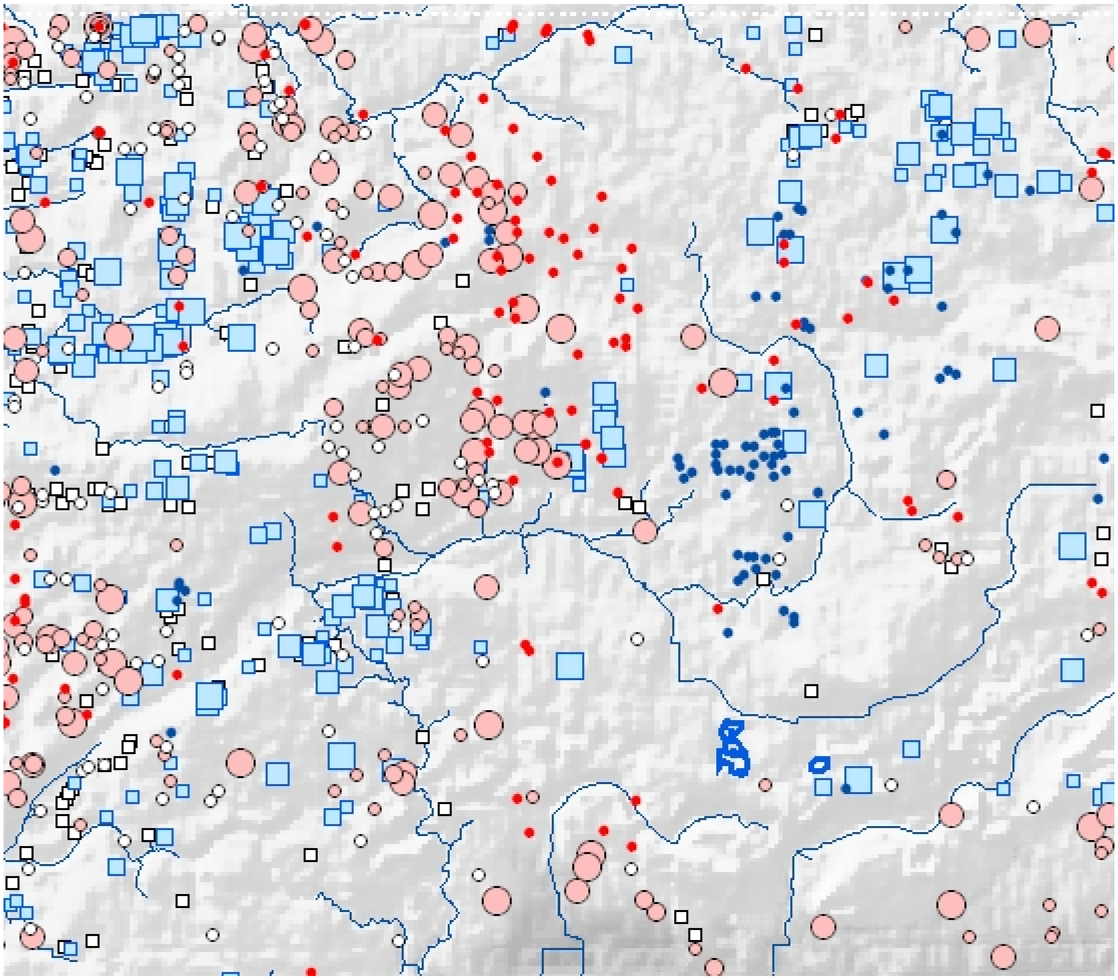
Map 72 Steady-state calibration residuals in Abbotsford uplands (city of Abbotsford).



Map 73 Steady-state calibration residuals on Lynden terrace (Fishtrap Creek to Bertrand Creek area) and Nooksack Valley.



Map 74 Steady-state calibration residuals in uplands between west Abbotsford and Langley (north-west of Abbotsford Airport).



7. MODEL RESULTS

7.1. GROUNDWATER FLOW PATTERNS AND GRADIENTS

7.1.1. RECHARGE AND DISCHARGE AREAS IDENTIFIED

Recharge areas were identified using flow vectors (directions) where the flow vectors had in-plane component of flow, and discharge areas where out-of-plane component of flow occurred (see **Map 75**). Discharge zones are found along stream and river channels in the lowlands, and also along streams in transition zones from uplands to lowlands (e.g., Fishtrap Creek and Bertrand Creek). Significant discharge of groundwater occurs as springs at the bases of escarpments along Sumas Valley and Nooksack Valley. The model results agree with observed spring locations and the fact that the south-flowing streams are dominated by baseflow supplied from groundwater discharge.

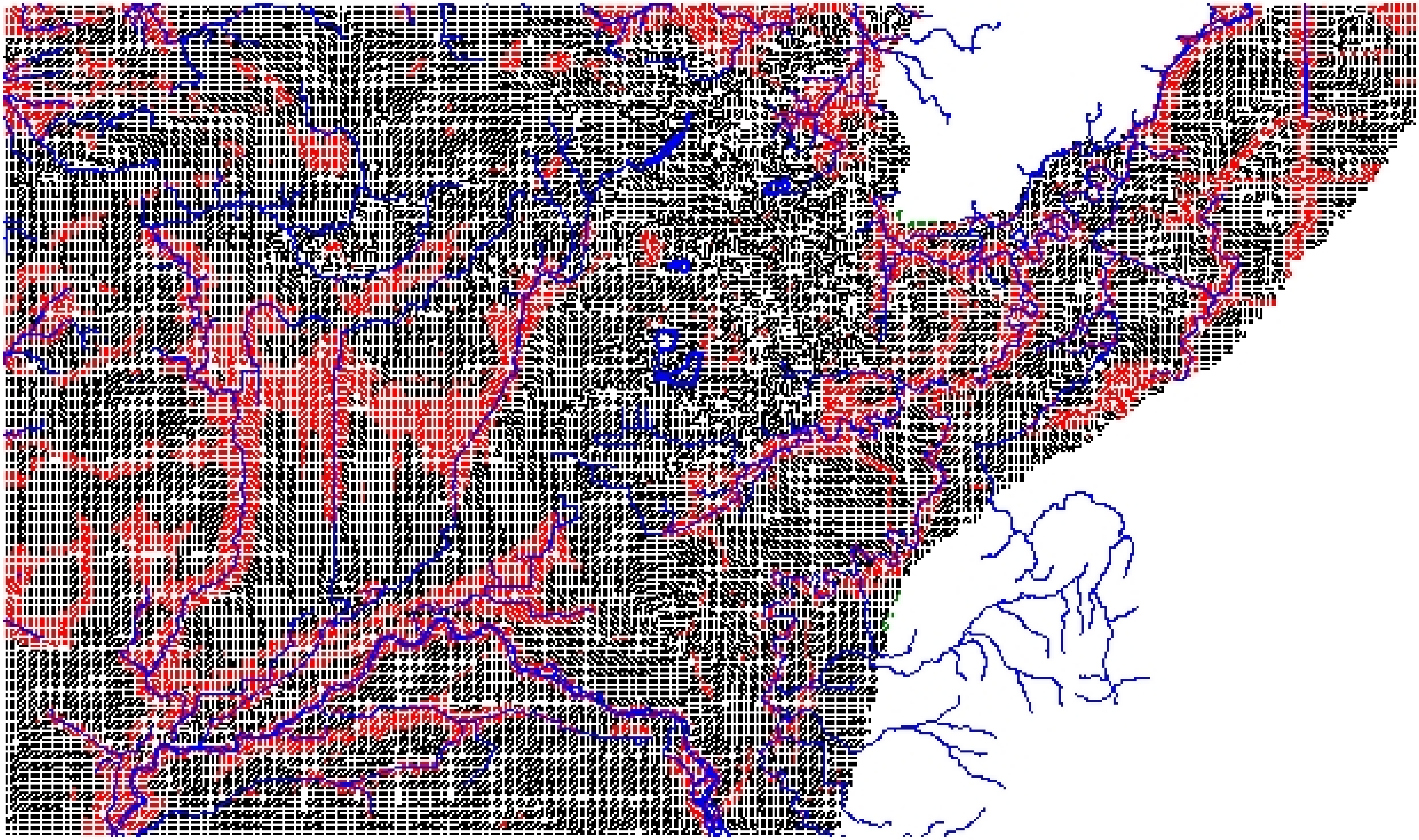
7.1.2. LOCAL FLOW PATTERNS IDENTIFIED

Groundwater flow velocities in this unconfined aquifer are controlled by hydraulic gradients. The modeling software Visual MODFLOW computes flow vectors for both direction and magnitude, and the resulting vectors can be displayed with vector arrows scaled to magnitude and oriented in the direction of flow. Flow directions are indicated by arrows of constant length, whereas magnitudes have scaled arrows.

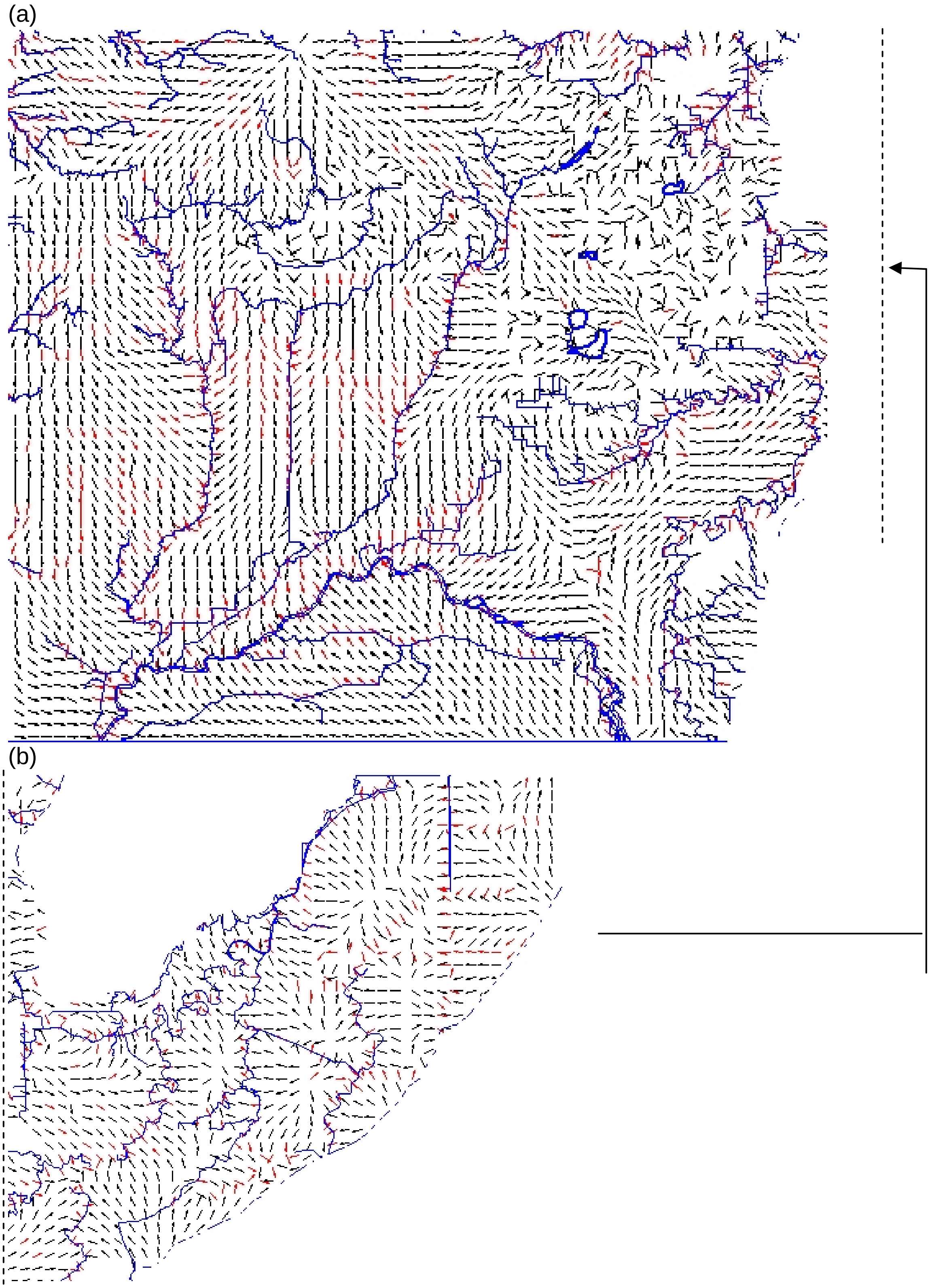
In plan view, horizontal flow directions are very complex in this aquifer (**Map 76**). Between the south-flowing streams (**Map 76a**) such as Fishtrap Creek and Bertrand Creek, that drain the uplands and flow south on Lynden Terrace and into Nooksack River valley, the flow directions are either southward or southward and then change to east-west and into the stream channels. In the Nooksack River floodplain, the flow directions are toward the river and west, following the river channel (and water surface) profile. In the Sumas Valley (**Map 76b**), the flow directions are very chaotic, and mostly toward drainage ditches, streams and the Sumas River. Hydraulic gradients in Sumas Valley are very small and flow patterns are locally controlled by recharge and drainage.

In Abbotsford uplands, the flow directions are southward and then turn east at the Abbotsford Airport (**Map 77**). Judson and Laxton lakes are in an area of mounded and flat hydraulic gradient, but just to the east, the flow is eastward and then into the Sumas Valley. Flow is also southward toward Johnson Creek drainage. In the City of Abbotsford area (**Map 78**), the flow directions are from west to east (from higher uplands) and then either north to Wilbrand Creek drainage, which flows north to Fraser River floodplain below the escarpments, or eastward to various creeks and ditches that feed Lonzo Creek in Sumas Valley. Abbotsford (Mill) Lake and the city centre are in a mound of groundwater and the gradients are small.

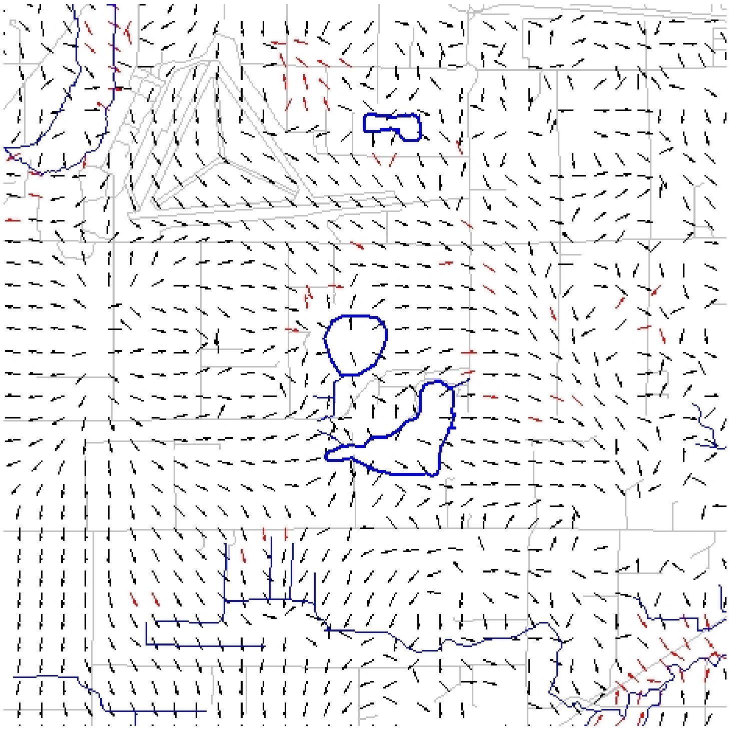
Map 75 Flow vectors (directions), showing recharge and discharge areas. Discharge areas have out of plane component of flow (red colour), and recharge areas have inplane flow component (black colour).



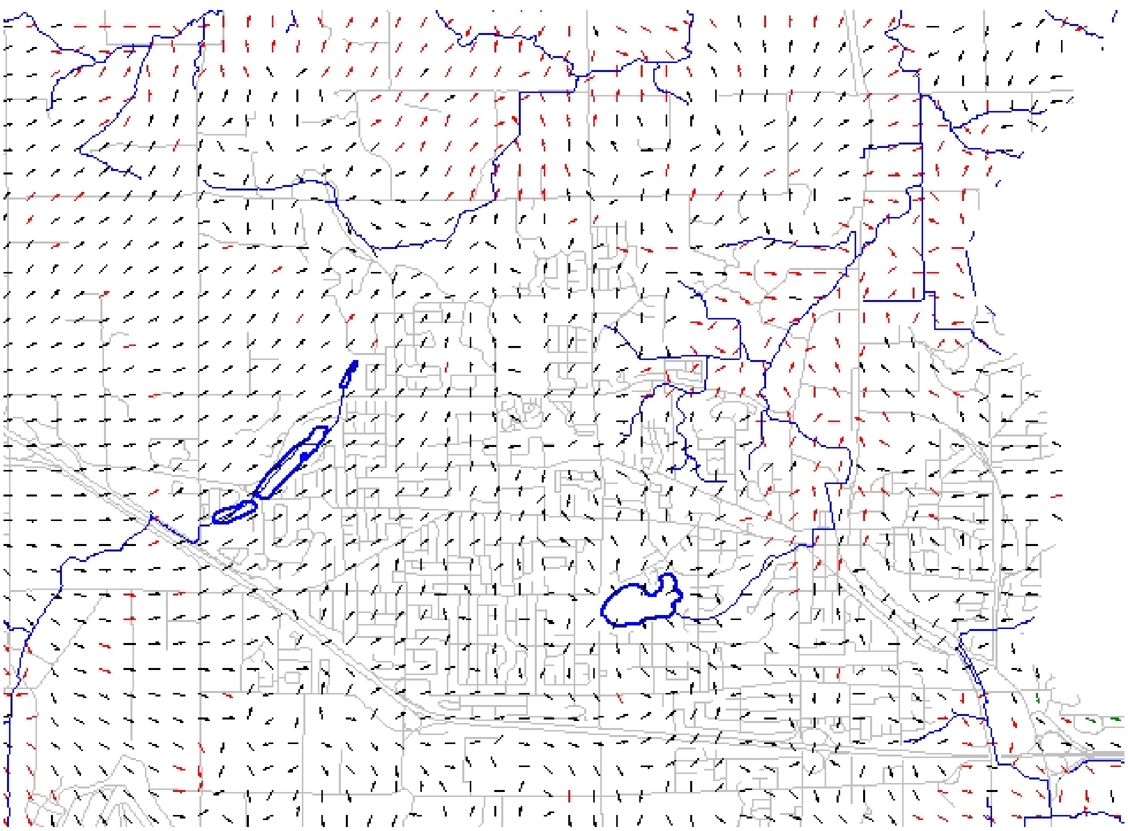
Map 76 Groundwater flow direction vectors (not scaled to magnitude) over model domain (a) central and western portion, (b) eastern portion – Sumas Valley only.



Map 77 Groundwater flow direction vectors (not scaled to magnitude) in selected areas in Abbotsford near Judson and Laxton lakes and the Abbotsford airport.



Map 78 Groundwater flow direction vectors (not scaled to magnitude) in selected areas in Abbotsford (a) city of Abbotsford, (b) town of Sumas, WA.



7.2. FLOW DIRECTIONS DETERMINED WITH PARTICLE TRACKING

Particle tracking was very useful for model calibration to local conditions. The model must replicate actual flow conditions, and also to be locally correct. Particle tracking allows us to identify calibration problem areas.

Model area (regional flows):

In deep aquifer layers, flow directions are mostly southward and to the southeast (**Map 79**). West of Bertrand Creek, the uplands drain to the west, but the groundwater divide runs a bit west of Bertrand Creek. Between Bertrand Creek and Fishtrap Creek, the groundwater flows from the uplands and south to Nooksack Valley. The City of Abbotsford area drains in many directions, southeast from airport area, east from city centre area, and north near Wilbrand Creek drainage. Sumas Valley drains mostly to the northeast, following the Sumas River and supplying baseflow to that river.

Abbotsford Uplands (Abbotsford Airport area):

Flow directions are to the southeast across the airport area of the uplands (**Map 80**), matching the directions of groundwater velocity vectors (**Map 81**).

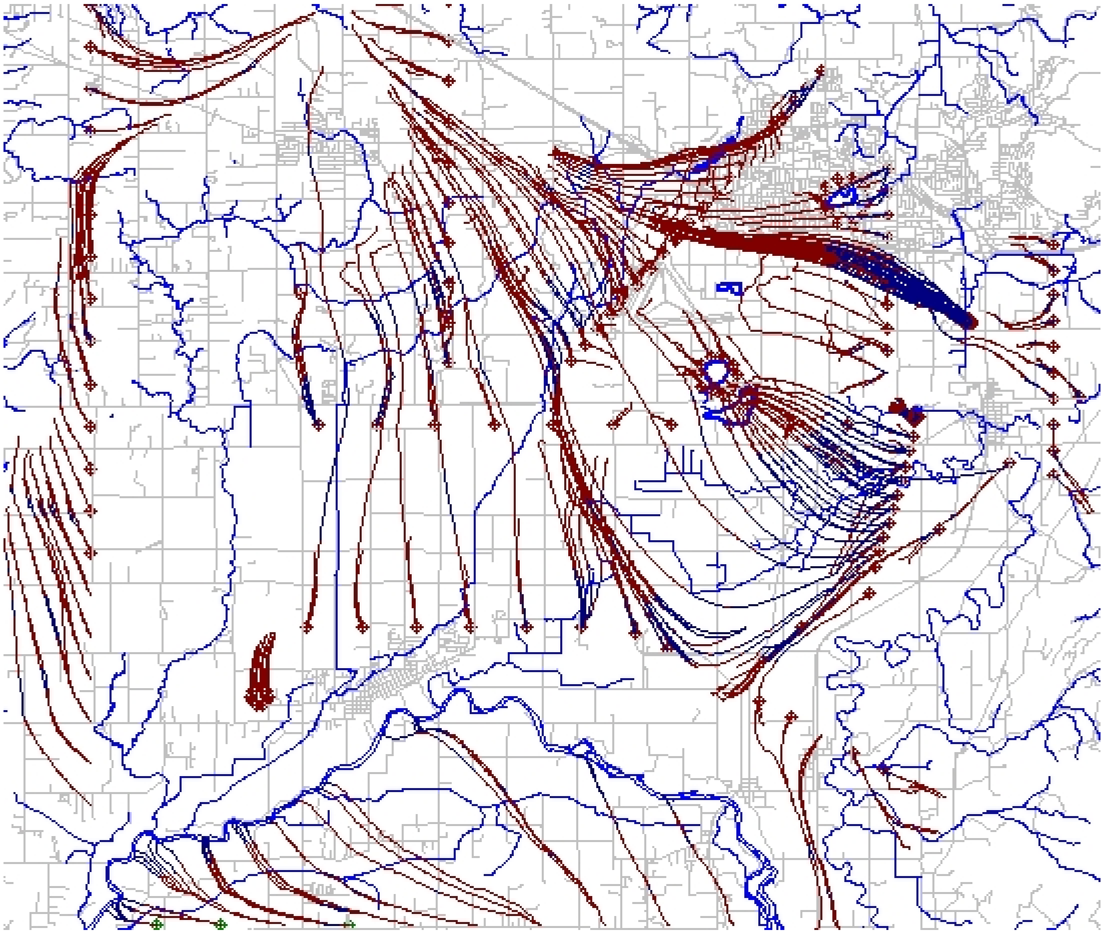
Lynden Terrace (Lynden, WA):

Flow directions are from north to south, and terminating in Nooksack River (**Map 82**). At shallow depth, some flow paths are toward streams draining that area.

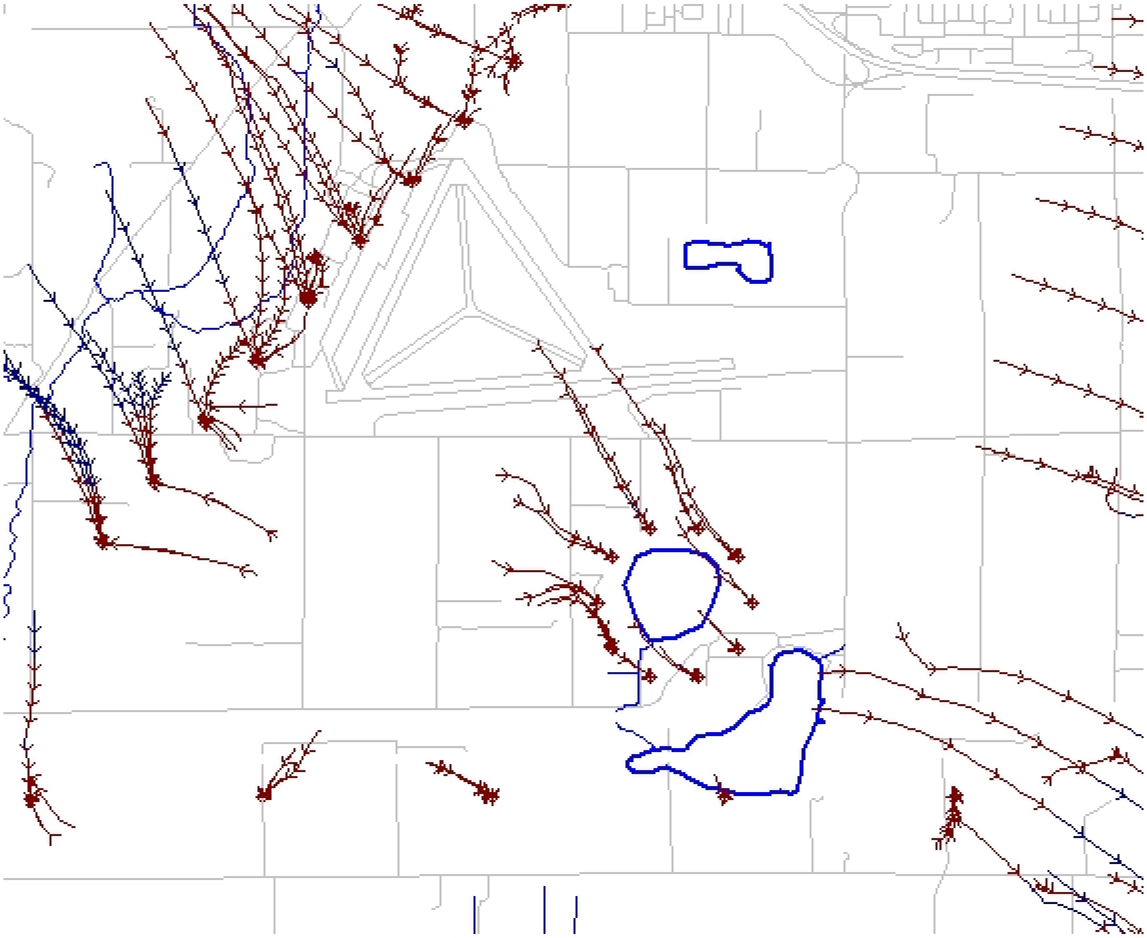
Sumas, WA

It was interesting to discover that the capture zone of the production well west of Sumas, WA, is very short (**Map 83**), as most of the water is supplied by buried highly permeable gravels under Sumas Valley floodplain. The water originates (over very long time) from Abbotsford Uplands, but it has a very three-dimensional path with major vertical flow components and very long travel times. The model predicts that the water supply to this well is not affected by near surface groundwater on the Abbotsford Uplands. This interpretation may not be correct, but the model was forced to simulate existence of Judson and Laxton lakes, the elevated water table on Abbotsford Uplands compared to Sumas Valley, and general flow directions. Previous models, particularly the Sumas Wellhead Protection study, assumed a very homogeneous aquifer with simplified hydraulic conductivity zones, and predicted capture zones stretching north past Abbotsford Airport. This study indicates at least that the groundwater flow patterns are much more complex and interesting than originally thought in this area. Thus, previous simplified well capture models should be re-evaluated. The authors suggest using tracers to delineate actual capture zones in such problematic areas.

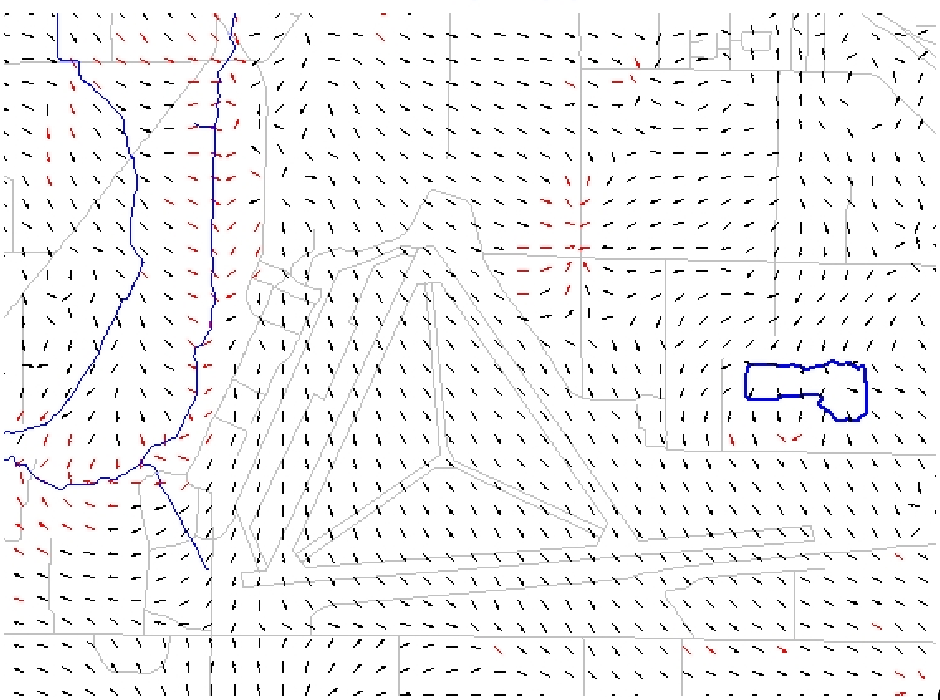
Map 79 Particle pathlines at steady state (infinite time of travel) in central part of the model area, showing all particle tracks of the released particles in all model layers. All particles are backward-tracking particles, except south of Nooksack River, which are forward-tracking particles.



Map 80 Particle pathlines at one year intervals in Abbotsford Uplands (a) near Abbotsford Airport and Judson/Laxton Lakes, and (b) flow direction vectors in Layer 4 of model at the same location.

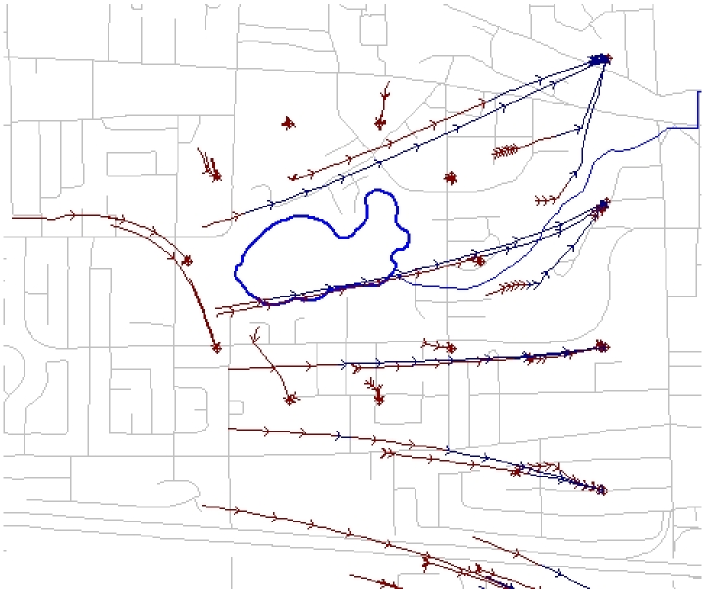


(a)

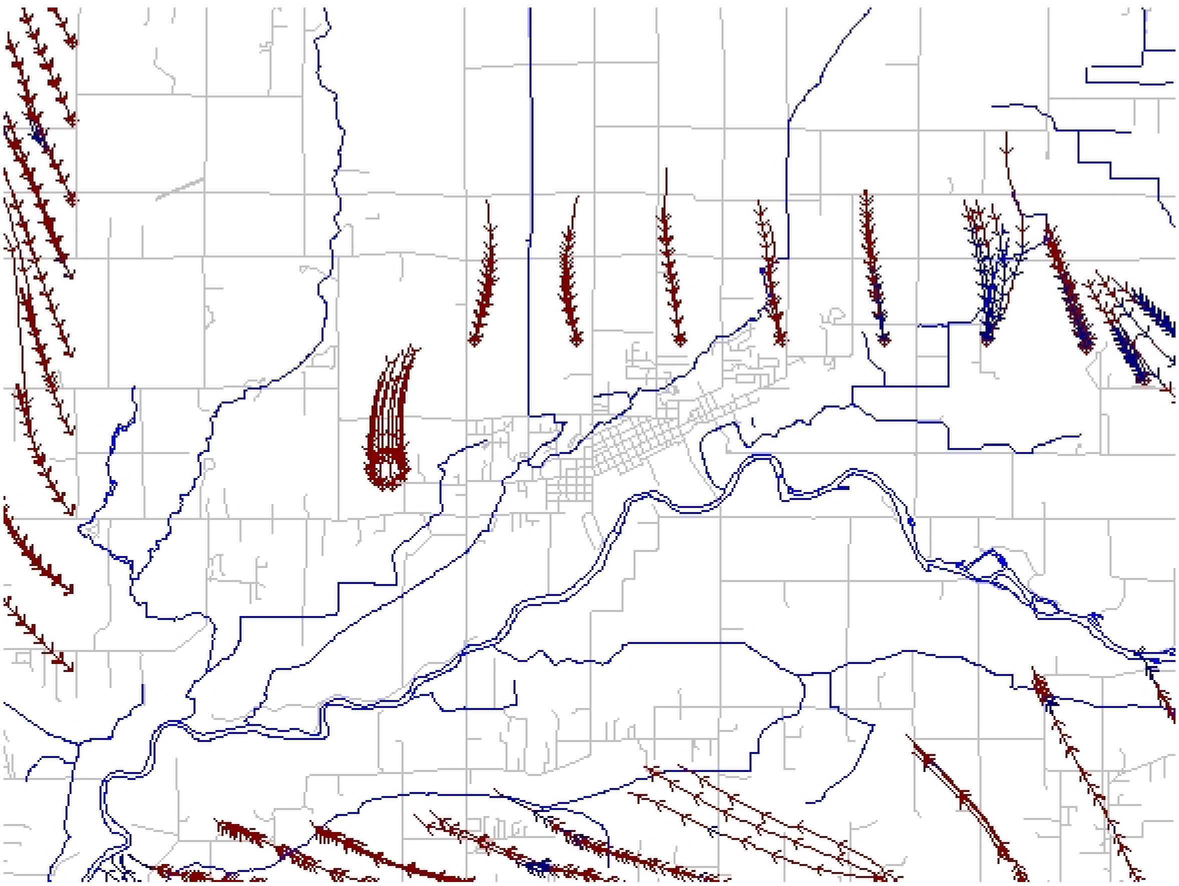


(b)

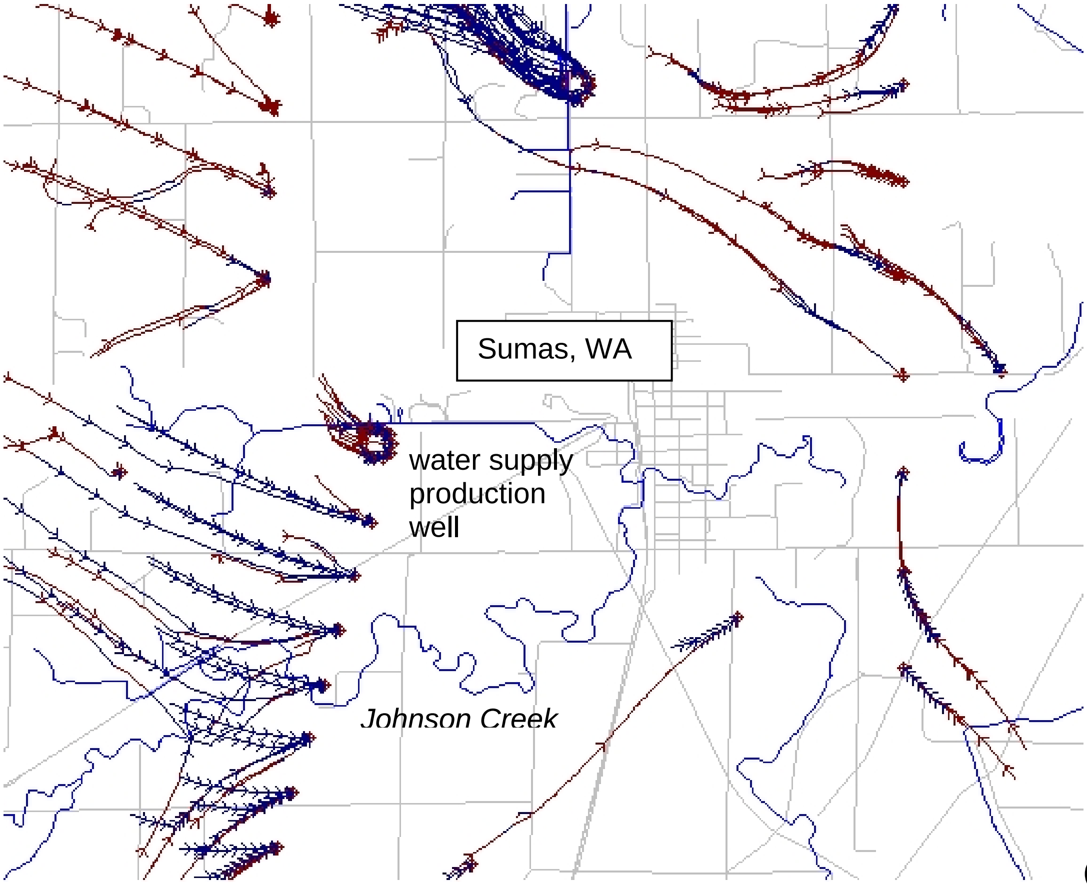
Map 81 Particle pathlines at one year intervals in Abbotsford Uplands near Abbotsford (Mill) Lake area.



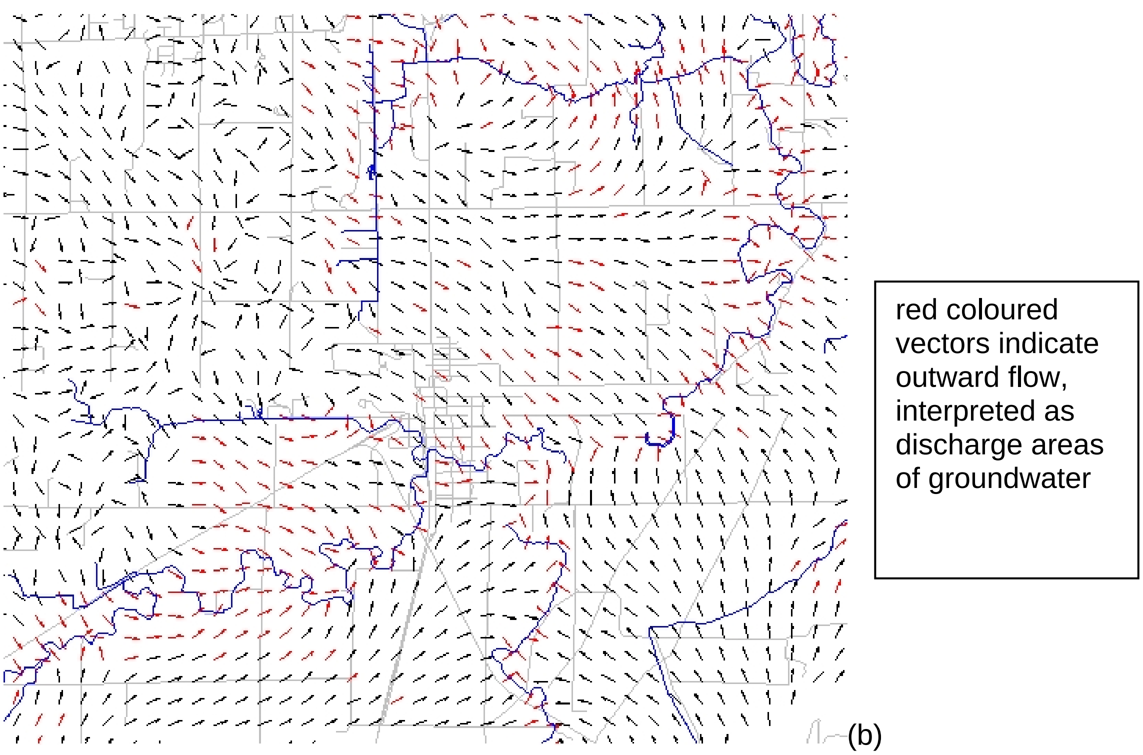
Map 82 Particle pathlines at one year intervals across Lynden Terrace and Nooksack Valley, including simulated well capture zone for one pumping well.



Map 83 Particle pathlines at one year intervals (a) across town of Sumas, WA, including simulated well capture zone for one pumping well, and (b) flow direction vectors.



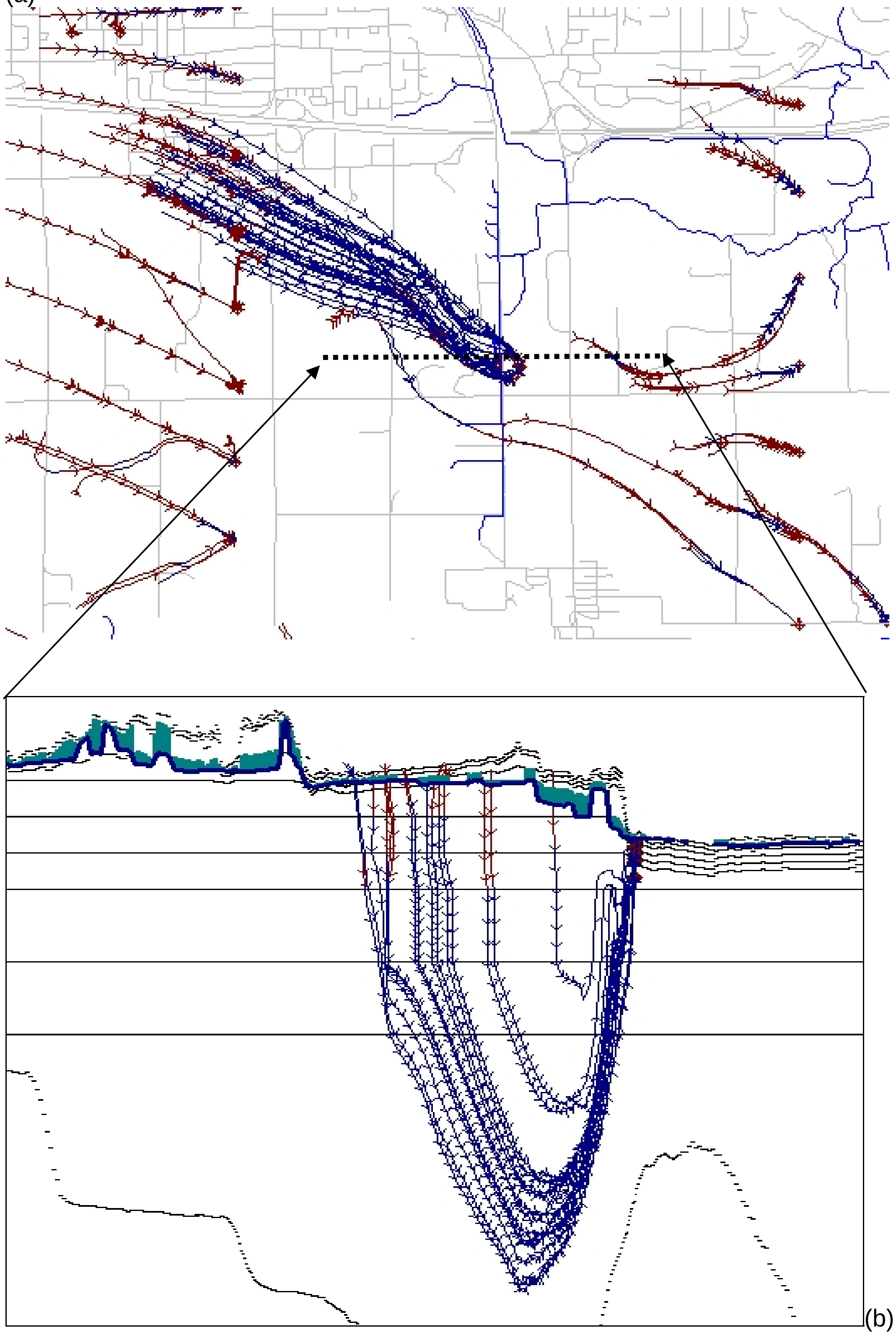
(a)



(b)

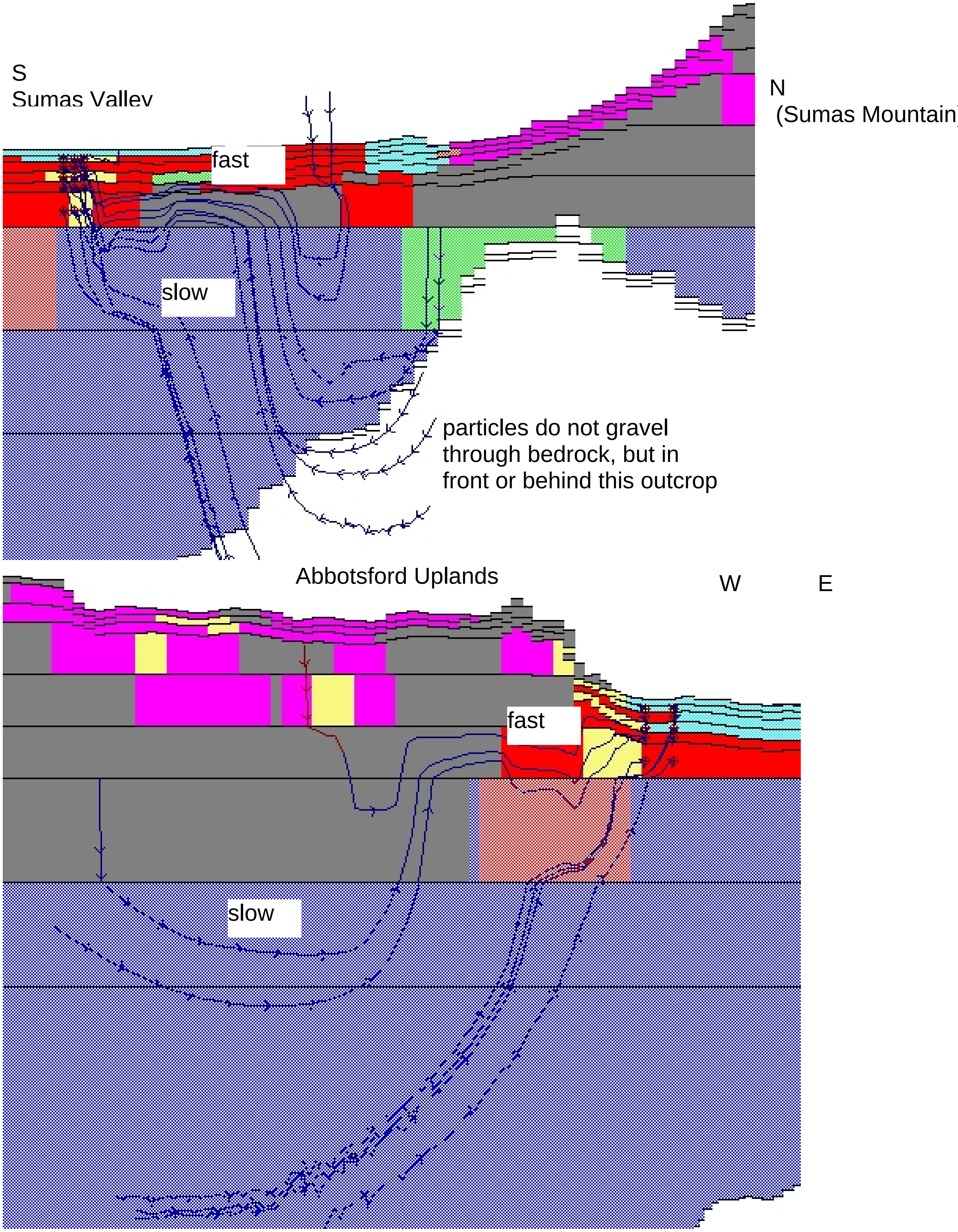
Map 84 (a) Particle pathlines at one year intervals showing simulated well capture zone for Fraser Valley Fish Hatchery well and nearby particle tracks, (b) cross-section view.

(a)



(b)

Figure 40 Pathlines traced by backward particles from Fraser Fish Hatchery well, showing hydrostratigraphic units in cross-section views: (a) south-north cross-section, (b) west-east cross-section. Shown are one year travel intervals along pathlines.



7.2.1. DRY AND WET CELL DISTRIBUTIONS AND DISCHARGE/RECHARGE AREAS

The distribution of dry cells by model layers 1 to 4 (**Map 85** and **Map 86**) depends on MODFLOW layer surfaces and layer thickness, relative to water table elevation in the calculated solution. Layer 1 was the thin, 3 m, surficial layer and in most areas it contains dry MODFLOW cells. Where cells are wet, the water table is very close to ground surface. The various areas of interest were labeled A to G on the maps and are referred to in the following text.

In eastern Sumas Valley (A), the water table is within 3 m of ground surface. That area is a discharge zone and up to the early 1900's it supplied discharge to a lake. The lake has been drained and now canals and ditches divert the excess water to Sumas River, or to Fraser River further north.

South of the Abbotsford uplands (B), water table depth is also shallow. In that area, drainage ditches run parallel to Fishtrap and Bertand creeks, and also perpendicular to US-Canada border, where there is a slope break from the uplands to lower areas. Visual inspection in Summer of 2002 confirmed that the ditches are partially full and partially dry, depending on topography and water table elevation – the water table intersects the ditches along lower lying areas compared to regional elevation. After rain events, these ditches can drain excess groundwater seepage, but in dry months, the ditches have discontinuous water levels and only a small amount of flow all year.

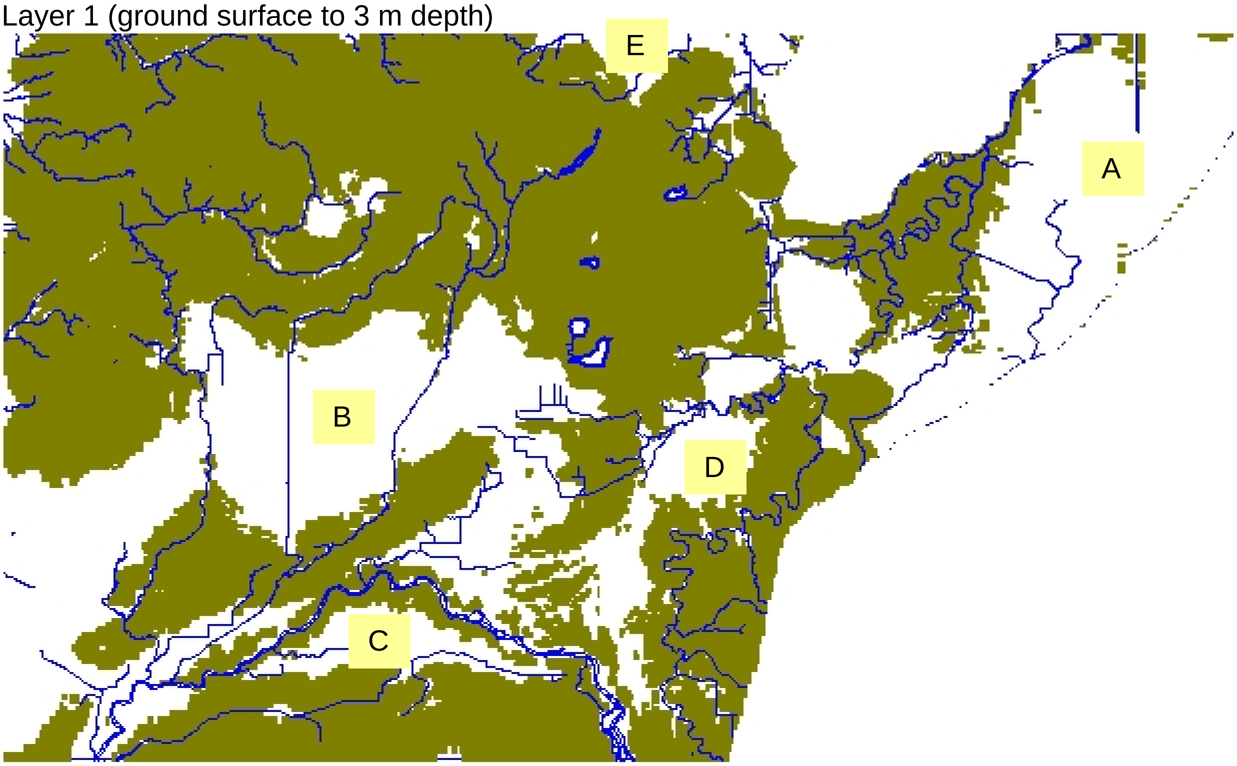
There are several other important discharge zones, although smaller in aerial extent and easily missed on such large maps. Where there are scarps and large changes in slope, large quantities of groundwater seep out in springs and supply baseflow to creeks and rivers. Those areas are: north edge of Nooksack River floodplain and valley, just below Lynden terrace (C), Sumas Valley and Sumas River floodplain (including Johnson Creek drainage, which is largely spring fed), below the scarps of Abbotsford uplands (D), and Fraser River floodplain below scarps on the north side of Abbotsford uplands (E). There, the groundwater table is also near ground surface, and it drops at a steep gradient from the upland areas, intercepts the scarps and drainage channels as springs and seepage flow, and is drained by drainage ditches in the lowlands.

In the uplands (F), the cell thickness in layer 2 is 5 to 10 m, deep enough to intercept the water table and wet the MODFLOW cells. There is a mound of groundwater in that area, as are perched water table zones, small ponds at ground surface, isolated from water table, and probably perched creeks as well. The model solution indicated that some of the upper reaches of Bertrand Creek and Pepin Brook are flowing, but perched above the water table – the model boundary conditions included these creeks as specified heads, but the upper reaches were "perched" above regional water table.

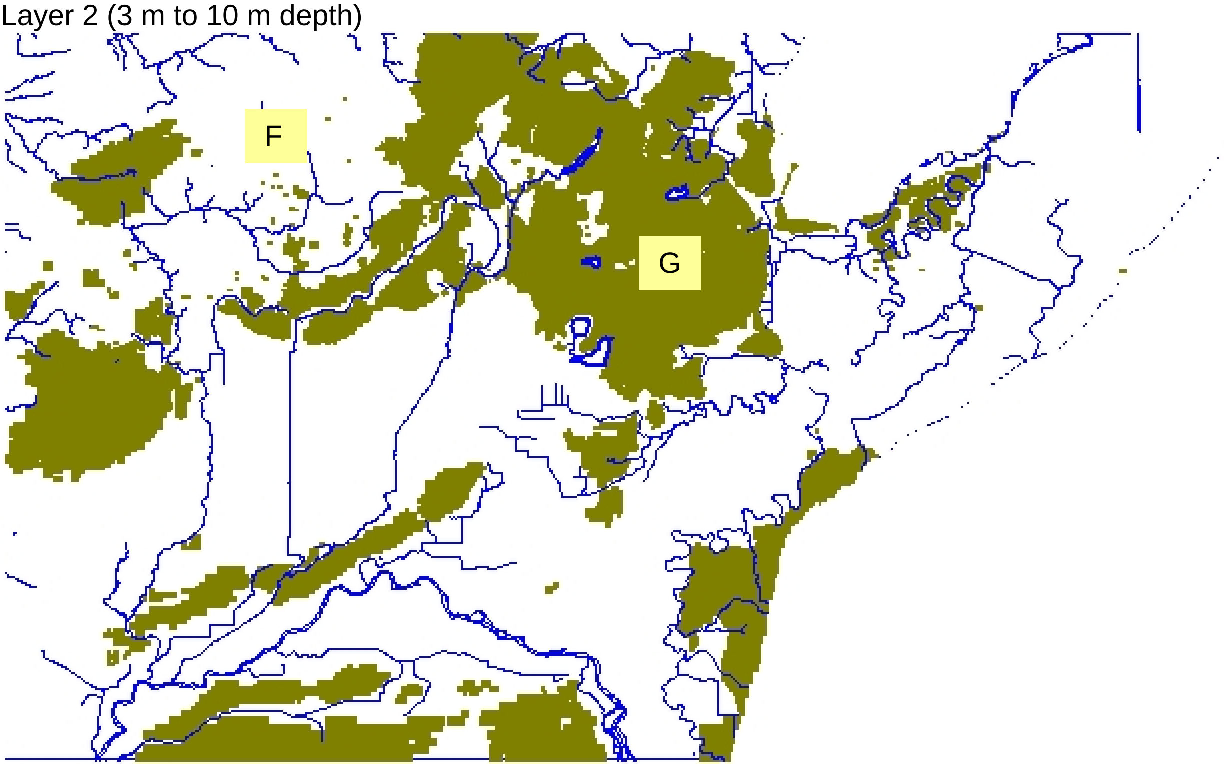
The largest depths to the water table occur in the area of Abbotsford uplands east of the Abbotsford Airport (area G). There, except near lakes, the water table drops through model layers 2 to 4 toward the escarpments and dry model cells persist to layer 4.

Map 85 Dry cells by model layer in steady state simulations of Abbotsford-Sumas aquifer.

Layer 1 (ground surface to 3 m depth)

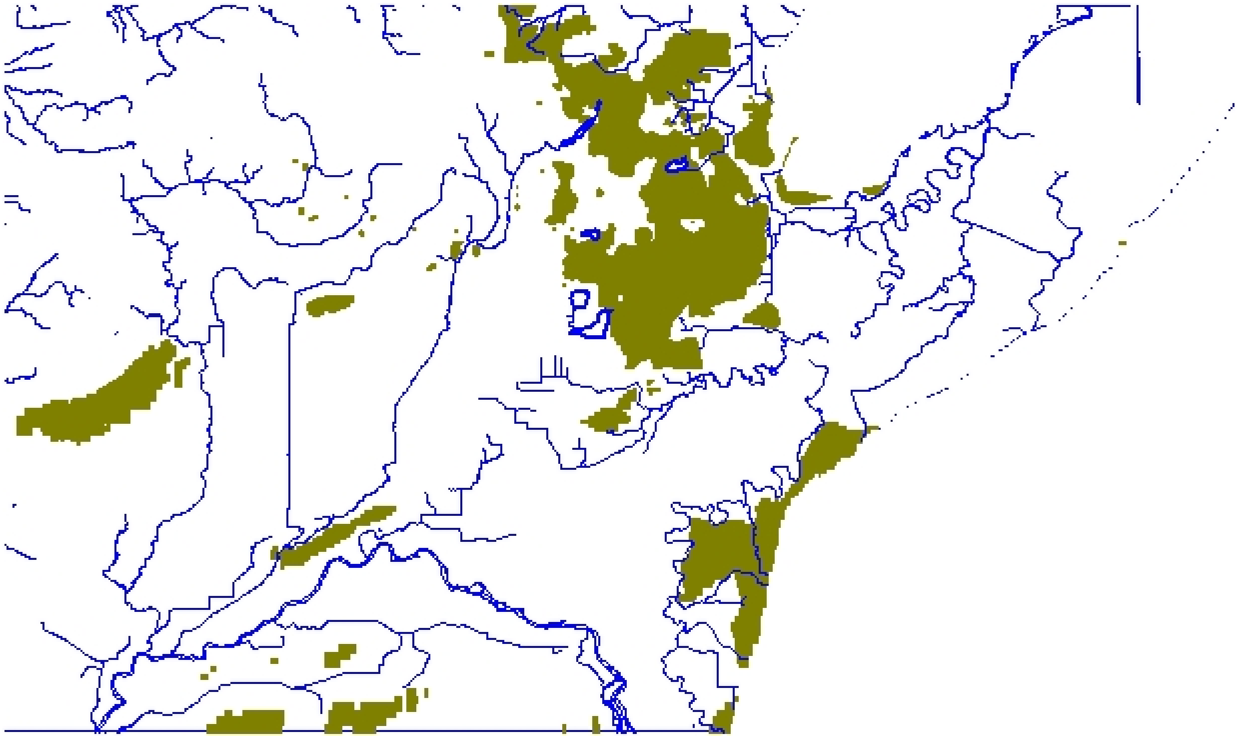


Layer 2 (3 m to 10 m depth)

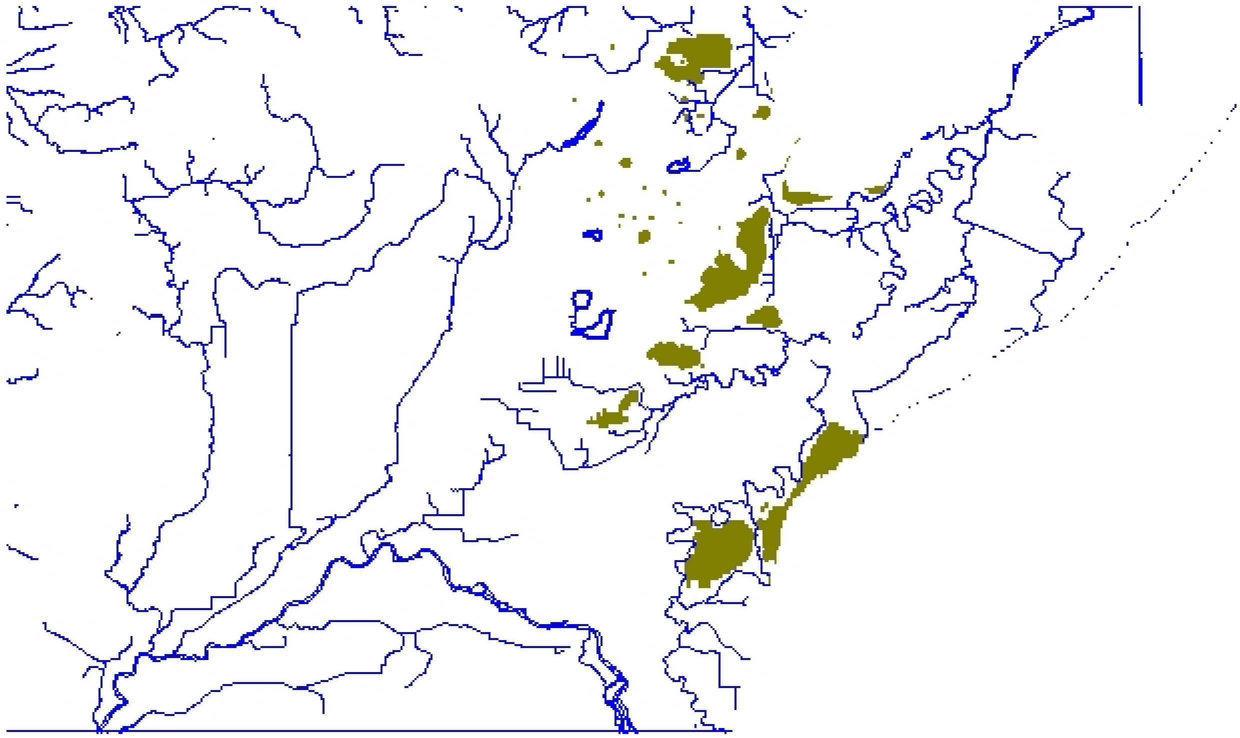


Map 86 Dry cells by model layer in steady state simulations of Abbotsford-Sumas aquifer.

Layer 3



Layer 4



7.3. MASS BALANCE OF MODEL

7.3.1. ZBUD ZONES

Zone Budget (ZBUD) in MODFLOW calculates sub-regional water budgets using results from MODFLOW simulations. ZBUD is documented in detail in Harbaugh (1988). Visual MODFLOW provides a graphical interface for assigning budget zones in model domain, layer by layer.

A total of 15 ZBUD zones were created in the model (**Table 26**), mostly along constant head and drain cells (boundary conditions) to count flow volumes into and out of streams, lakes, and ditches. The spatial extent of each zone in layer 1 and 2 of the model is labeled on **Map 87**. The background is all one zone, and other zones correspond to constant head and drain cells, subdivided into drainages to allow quantification of changes in stream-aquifer interactions.

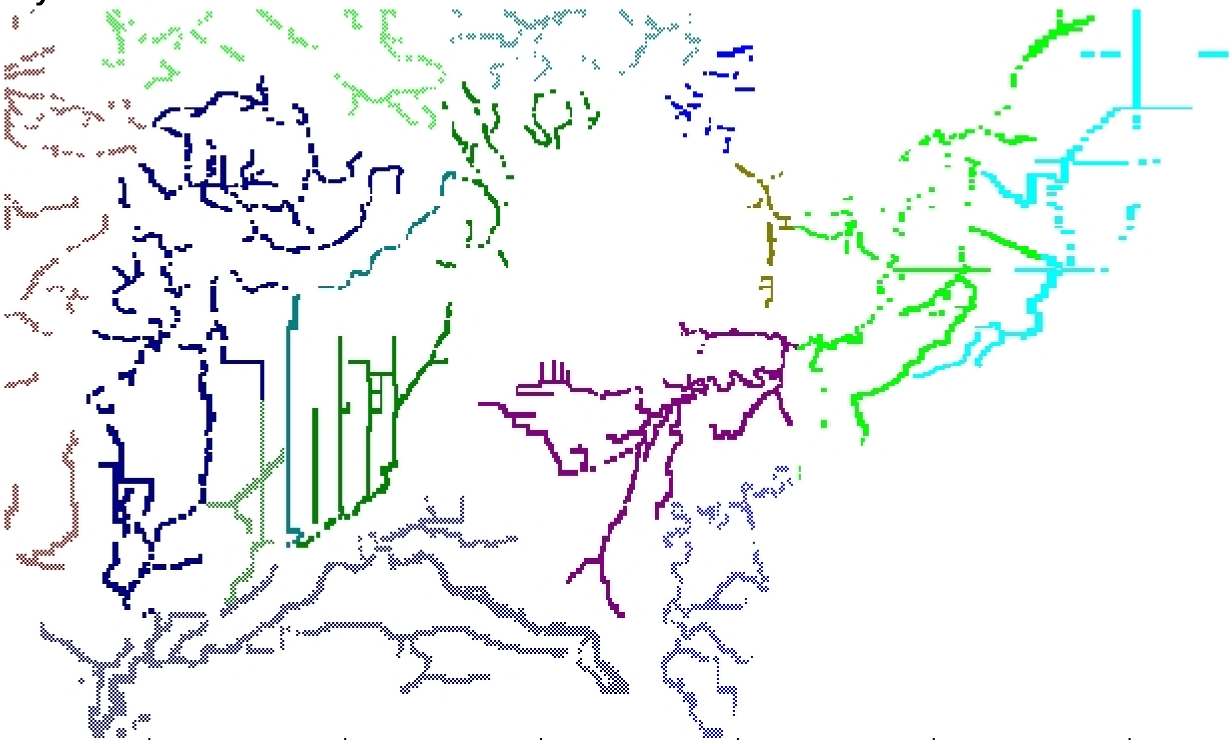
Preliminary results (**Figure 41**) suggest that flow rates into the streams and ditches are of the same magnitude as observed streamflows (e.g., in Lonzo Creek, drainage and flowing ditches draining from springs along east scarps from Abbotsford uplands). A better locally calibrated model with better mass balance would improve our ability to predict baseflow to streams from the aquifer and link aquifer recharge to streamflow.

Table 26 ZBUD zones and descriptions.

ZBUD zone	Description
1	all model cells except constant head or drain
2	Bertrand Creek
3	Fishtrap Creek
4	Pepin Brook
6	Johnson Creek and tributaries
7	flowing ditches draining scarps along Riverside Rd
10	Wilbrand Creek
11	Sumas River and tributaries
12	ditches in Sumas Valley
15	Nooksack River
16	ditches west of Lynden
17	ditches north of Wilbrand Cr drainage
18	streams draining west from uplands
23	upper Sumas River
24	streams draining north

Map 87 ZBUD zones in MODFLOW model in layer 1 and 2. The background is all one zone, and other zones correspond to constant head and drain cells, subdivided into drainages to allow quantification of changes in stream-aquifer interactions.

Layer 1



Layer 2

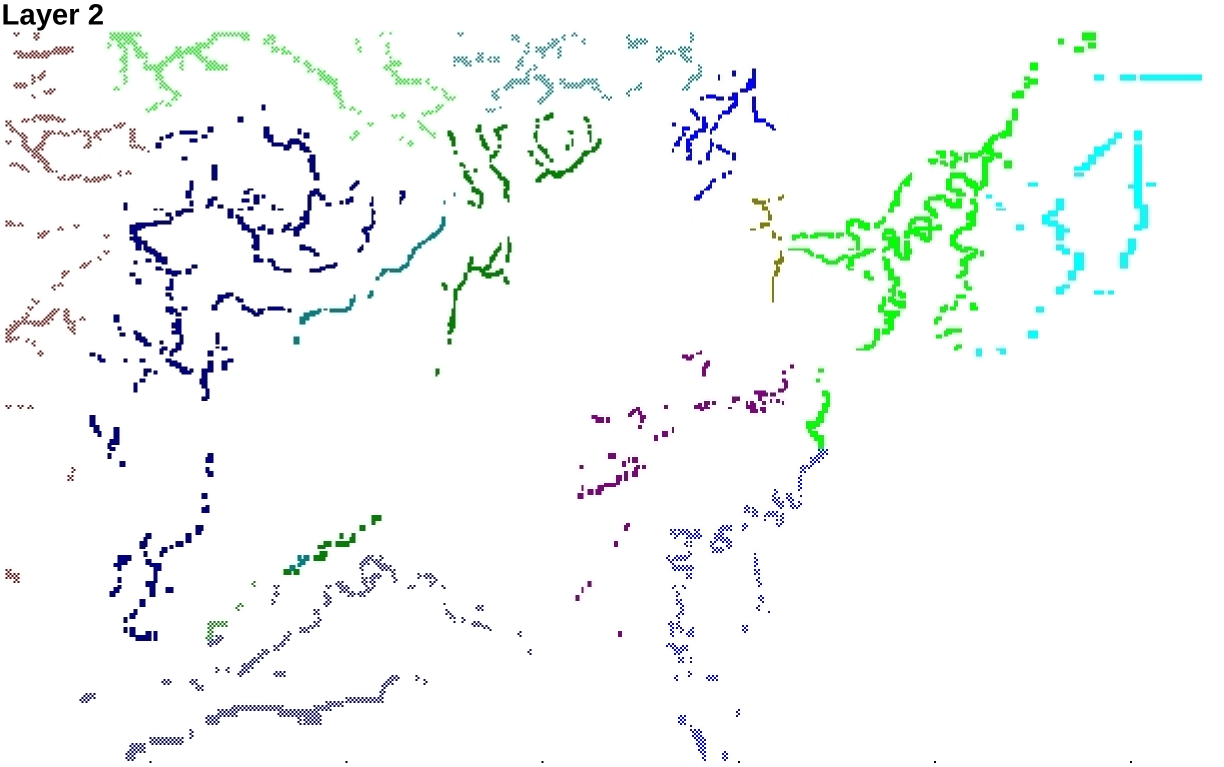
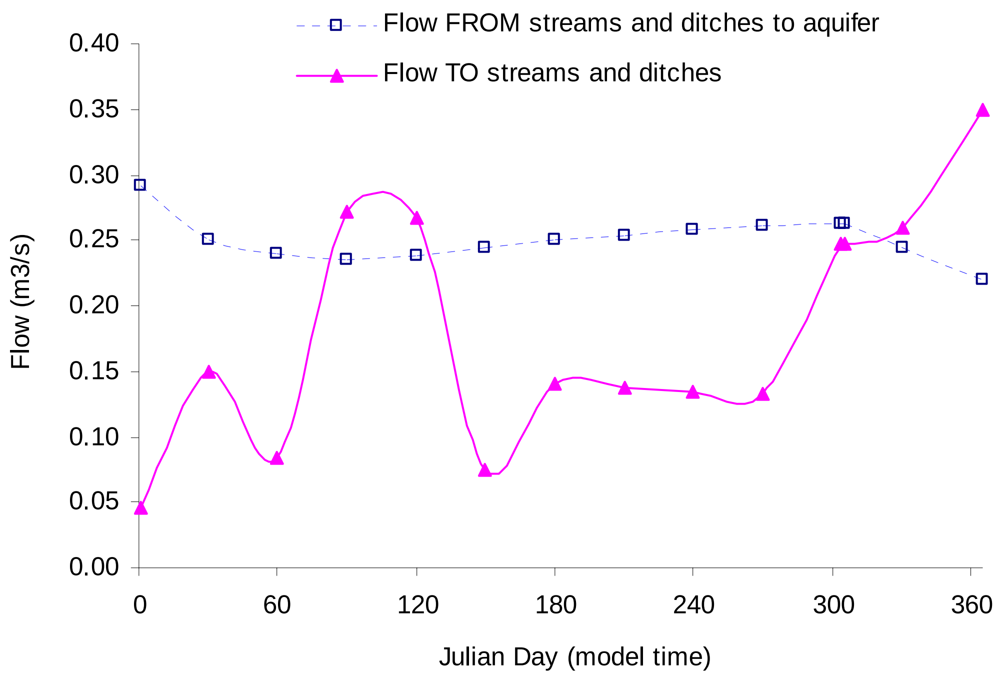


Figure 41 Flow rate between the aquifer and streams and ditches at the east escarpment of Abbotsford Uplands (Riverside Rd and tributaries to Lonzo Creek in Sumas Valley).



7.3.2. MASS BALANCE ERRORS

Mass balance is one of the key indicators of a successful simulation. If the mass balance error for a simulation is less than 2% the results may be considered to be acceptable, provided the model is also calibrated (WHI, Visual MODFLOW manual). If error is greater than 2%, then there may be some instabilities in the solution, and thus, inconsistencies in the results. Mass balance error will vary with time in a transient model and with location (e.g., with ZBUD zone). Since the MODFLOW model is based on flow equations that assume conservation of mass, the discrepancy between IN and OUT flow volumes and rates in model cells can be used to evaluate model performance. Mass flow discrepancy is expressed as percentage of total flow into and out of the entire system as a whole. The listing is organized by source and sink terms, such as constant head (cells) and recharge, which are included both in IN and OUT list of terms.

The steady state model after calibration had just under 2% mass balance error (discrepancy) and it was considered adequate after examining outputs from many model runs. Locally, the model could still be better calibrated.

The transient models typically had 2 to 15% discrepancies in flow terms for most time steps (**Figure 42**). This is rather poor result and is likely due to the fact that the steady-state head distribution was used as the initial head distribution. A better approach would be to two consecutive years of simulation and compare the results after the second year.

Flow volumes were largest for constant heads (and flow between zones and model layers – not shown on graph), and much smaller for recharge contribution or storage inflow. The smallest volumes of groundwater were taken out of storage, seeped to drains, or were pumped out. As much water was lost to drains (ephemeral streams) as to pumping in the model area. Storage inflow and outflow were not balanced, suggesting that the model is not equilibrated and more time steps and better solution should be used in the transient model or the model should be run for long time period and allowed to equilibrate.

Figure 42 Discrepancy (%) in flow terms in the entire flow model plotted against model time (Julian Day) in one of the transient models runs.

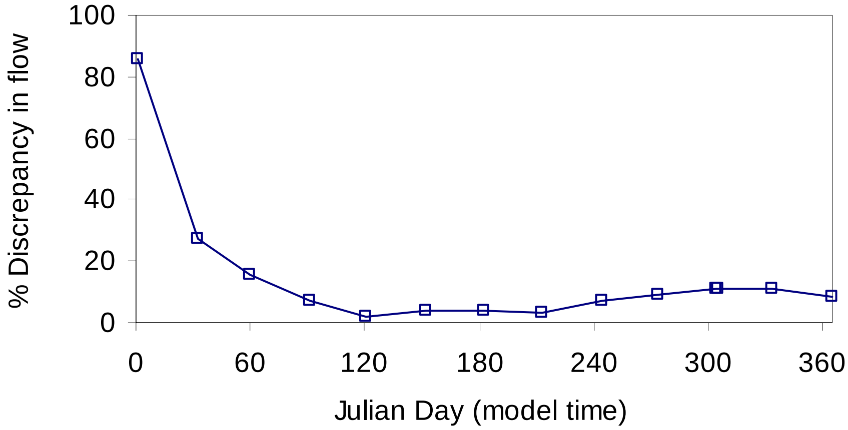
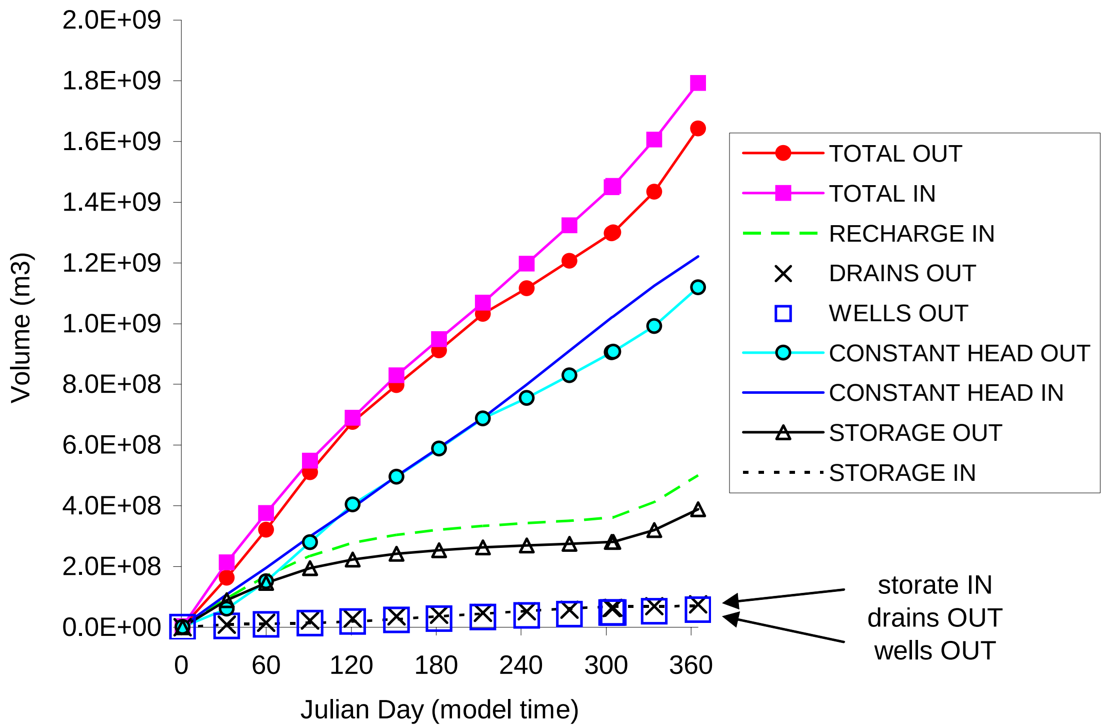


Figure 43 Flow volumes at model time steps showing mass balance components in transient model of Abbotsford-Sumas aquifer.



8. CONCLUSIONS

In this study, a three-dimensional groundwater flow model was constructed for the Abbotsford-Sumas aquifer. Development of this model would enable more detailed modeling studies to be undertaken by providing 1) a regional context for groundwater flow, 2) establishing boundary conditions at a regional scale that could be used in smaller scale models, 3) the geological framework for nitrate transport modeling, and 4) a base model for climate change impact studies on groundwater in the region.

The study is tied to M.Sc. research by J. Scibek at Simon Fraser University (SFU) in which the Abbotsford-Sumas aquifer was used as a repeat case study "experiment" for linking climate change predictions to groundwater flow models and quantifying the potential impacts on water supply, flow directions, well capture zones.

The model of the Abbotsford-Sumas aquifer will also be used in two ongoing research projects at SFU to examine issues related to nitrate transport in the aquifer. One study centers around defining permeable pathways for nitrate transport at a small scale (using geophysical techniques tied to borehole lithology logs) and making inferences on the role of permeable pathways in nitrate contamination data. The second is a regional study of nitrate transport, which will examine the transport and fate of nitrate from agriculture land use practices at a regional scale.

During the model development and calibration it became apparent that the aquifer is probably very heterogeneous and discrete units are not that different from each other, but there may be strong local differences. During model calibration, additional zones were to be created to account for local "problems" with calibration, on the Canadian side.

It was interesting to discover that the capture zone of the production well west of Sumas, WA, is very short, as most of the water is supplied by buried, highly permeable, gravels under Sumas Valley floodplain, and the water originates eventually (over very long time) from Abbotsford Uplands, but it has very three-dimensional path with major vertical flow components and very long travel times. The model predicts that the water supply to this well is not affected by near surface groundwater on the Abbotsford Uplands. Previous models, particularly the Sumas Wellhead Protection study, assumed very homogeneous aquifer with simplified hydraulic conductivity zones, and predicted capture zones stretching north past Abbotsford Airport.

This study indicates at least that the groundwater flow patterns are much more complex and interesting than originally thought, and thus, any previous simplified well capture models should be re-evaluated.

Ongoing improvements to the model may allow quantification of stream-aquifer interactions in all major streams draining the aquifer system. Preliminary results suggest that flow rates into the streams and ditches are of the same magnitude as observed streamflows. A locally calibrated model with better mass balance would improve our ability to predict baseflow to streams from the aquifer and link aquifer recharge to streamflow.

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Data sources

There were many data sources, and data integration, or just sifting through it all, was the main difficulty with this project.

BC Ministry of Water, Land and Air Protection

- TRIM maps, base maps, well locations
- Well Litholog Database for BC
- Pump test data, water levels

Environment Canada

- climate normals for Canadian weather stations
- climate data for selected climate stations
- stage and discharge data for selected hydrometric stations
- climate change scenarios (Whitfield P. and Gunn A. pers comm.)
- Digital Elevation Model for Fraser Valley area, 20 m grid (note: DEM became publicly available through NRC website recently – some 20 m DEM were added from that source) – see below “Fraser Valley DEM”
- water levels in piezometers, ditches, streams in Abbotsford area
- pump tests for Abbotsford aquifer

Natural Resources Canada

Fraser Valley DEM:
CDED1-092H06
Canadian Digital Elevation Data, Level 1 (CDED1)
2003/02/04
Government of Canada, Natural Resources Canada, Centre for Topographic Information
http://www.geobase.ca
Altimetric Accuracy (metre) = 5- Planimetric Accuracy (metre) = 25
Grid spacing 25 m
Elevation precision 1 m

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Colour Digital Orthophotos, Lower Mainland, BC (1 m resolution, colour):Copyright Triathlon Mapping Corporation, Greater Vancouver/Fraser Valley 1995 Coverage

USGS (public domain data accessed from GeoCommunity website)

- Digital Elevation Model for Whatcom County, 10 m
- Digital orthophotos of Whatcom County (B/W 1 m res.)

Washington State Department of Ecolology
- all GIS coverages of Washington State
- included surficial geology maps, rivers, roads

Digital data produced at Simon Fraser University (2004) from analysis results and other primary non-digital sources

- 3D hydrostratigraphic models of Abbotsford-Sumas aquifer, using Visual Modflow 3.1 and ArcGIS 8.3
- layer surfaces, sediment thickness maps
- standardized and interpreted litholog database (various versions)
- all groundwater modeling results in vector and raster format (converted from MODFLOW outputs), including MODFLOW grid cells mapped to GIS, and other links (river, recharge)
- soil map polygons, recharge scenario zones, depth to water table

- updated river extents, streams, river cross-section locations, updated water bodies
- irrigation districts, irrigated fields (from orthophotos)
- combined bedrock surface model with ground surface DEM (both US and Canada)
- valley cross-section lines
- contour maps (ground surface, water table, differences between heads in modeling scenarios)
- recharge model and results for central Fraser valley for all climate scenarios
- various base maps, 3D maps, animations, all spatial analyses presented in this report

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BC Energy & Mines

Digital Geology Map of British Columbia: Tile NM10 Southeast B.C., and NM11 Southwest B.C., British Columbia Ministry of Energy and Mines, Geofile 2003-3 by N.W.D. Massey, D.G. MacIntyre, and P.J. Desjardins - BC Geological Survey http://www.em.gov.bc.ca/Mining/Geolsurv/Publications/catalog/bcgeolmap.htm

- open file reports of oil and gas exploration wells and seismic surveys in central Fraser Valley area, deep boreholes reaching bedrock – Steven Glover contact

"We also have a limited number of open-file exploration reports available in the areas where both wells were drilled. Attached is a listing of the reports - with report No., title, author & year of each report. The reports together with the wellfiles are available for viewing in this office. "

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