

McAllister Wellfield Numerical Model (Section 1-4)

Interim Report

April 2002

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Executive Summary

This Interim Report presents the results of steady-state numerical modeling Camp Dresser & McKee Inc. (CDM) produced for the City of Olympia. The City and major stakeholders will review this report and provide input that CDM will use to complete transient modeling of the McAllister Springs area and northeastern part of Thurston County. The purpose of the comprehensive, three-dimensional groundwater flow model is to provide a tool that simulates existing hydrologic conditions and reliably predicts potential impacts of planned ground water withdrawals on key hydrologic features.

The City currently holds water rights to extract up to 19.6 million gallons per day (mgd) at McAllister Springs and 6.5 mgd from nearby Abbott Springs, and obtains about 80% of its water supply from McAllister Springs. The hydrogeologic setting makes the Springs vulnerable to contamination from surface sources. To maintain the quality of this valuable resource, the City is planning to construct a wellfield upgradient from the Springs. The City may use new ground water supply to augment or replace the McAllister Springs. Before putting the wellfield into service, the City must obtain appropriate water rights from the State of Washington Department of Ecology.

To evaluate the City's water right application, Ecology must consider the potential impacts on other local water resource components. The completed numerical model will mathematically simulate ground water flow and quantify potential impacts on such features as McAllister Springs and Creek, the Nisqually River and Lake St. Clair. If necessary, the model will be used to evaluate the effectiveness of potential mitigative measures.

CDM developed the model using the U.S. Geological Survey (USGS) Thurston County Model as a starting point. The USGS Thurston County Model configuration—including the general aquifer and confining unit system and elevations, hydraulic properties, precipitation-derived recharge, stream and lake features, and lateral boundary conditions—was used to guide construction of the McAllister Model outside the area of highest interest. CDM used information from the *McAllister Baseline Monitoring Program* to configure the model in the immediate McAllister Springs area. This configuration included an improved hydrogeologic representation of the McAllister Springs complex, the McAllister Gravel aquifer unit, Lake St. Clair, the Tri-lakes area, and the Nisqually River.

The McAllister Model uses the numerical code *MODFLOW*, and consists of nine layers, 236 rows and 157 columns, with 226,000 active cells. The cell dimensions range from 100 ft by 100 ft in the McAllister area to 1,000 ft by 1,000 ft at the model margins. CDM designated the upper five model layers as either confined or unconfined (depending on the local potentiometric head), thereby enabling the model to predict water level and flow impacts due to wellfield pumping more accurately than the USGS model. The lower four layers were all assigned fully confined conditions.

CDM used the *MODFLOW-SURFACT* solver (HydroGeoLogic, 1996) to overcome numerical instabilities associated repeated wetting / drying while maintaining mass continuity. *MODFLOW-SURFACT* is a modification of the *MODFLOW* code, and handles relatively complex stratigraphic situations better than the standard *MODFLOW* solver, and lessens convergence problems. The City, technical reviewers and Ecology formally accepted the use of *MODFLOW-SURFACT* for model calibration and simulations.

The steady state model is calibrated to a set of long-term average hydrologic conditions. The model reliably imitates ground water flow through the system and simulates representative water levels, gradients, and spring and streams discharges. The calibration set includes the same water level and flows used by the USGS and consisted of 211 water levels from the fall of 1988. This set was augmented by monitoring data collected during the *McAllister Baseline Monitoring Program* between 1994 and 1999 for 29 wells in the McAllister area. Calibration consisted of systematically adjusting the most sensitive parameters to obtain a satisfactory match between the flow directions and gradients, individual water levels, discharge rates at the McAllister area springs and seeps, and stream-aquifer and lake-aquifer flow relationships. The final steady-state (or equilibrium) calibration met the specific goals and targets developed by the stakeholders and technical review team.

CDM also used the steady-state model to determine McAllister Springs' 10-year capture zone under existing hydrologic conditions. For the McAllister Gravel unit this zone extends to Lake St. Clair. For ground water in the undifferentiated (TQu) aquifer the zone extends about 1 mile south of the lake. The analysis also shows some water recharging the Lake Pattison-Long Lake area will be discharged at the Springs within 10 years.

Transient model calibration will involve running the model through the period 1988 to 1999 by applying precipitation-derived hydrologic stresses to reproduce the time-varying water levels and flows reported in the *McAllister Baseline Monitoring Program*. Achieving verifiable transient calibration will improve steady state model accuracy and justify confidence in the model. CDM will use the fully calibrated model to simulate a series of potential Wellfield operational scenarios with a range of climatic conditions.

Section 1

Introduction

1.1 Background

This report presents the findings of numerical modeling performed by Camp Dresser & McKee Inc. (CDM) for the City of Olympia's (the City) application to Washington State Department of Ecology (Ecology) for a revised water permit. The scope of work for the study is outlined in CDM's proposal dated September 18, 2000.

The City currently obtains about 80 percent of its water supply from McAllister Springs, located in the northeast part of Thurston County, Washington. McAllister Springs discharges from a highly permeable, unconsolidated sand and gravel deposit at an average rate between 23 and 40 cubic feet per second (cfs), or 14.9 and 25.8 million gallons per day (mgd). The City holds water rights to withdraw up to 19.6 mgd from McAllister Springs and 6.5 mgd from nearby Abbott Springs.

Since development in 1947, McAllister Springs has provided the City with a reliable supply of high quality water. The natural water is low in dissolved minerals and free of contaminants. However, the topographic position and hydrogeologic setting make the spring vulnerable to contamination from accidental and other surface sources.

To maintain the quality of its supply, the City has determined its best option is to replace the Spring supply with groundwater from an upgradient wellfield (the McAllister Wellfield). Other consultants conducted preliminary wellfield investigations in 1998. These included installation of several test and production wells and short-term pumping to evaluate the potential capacity of a future Wellfield (PGG, 1997). In 1999, the City retained CDM (formerly AGI Technologies) to further investigate and monitor the resource to establish the baseline hydrologic conditions in the area. The results of this work are described in a series of five Technical Memoranda that chronicle seasonal variations in surface water and groundwater levels, habitat characteristics, and hydrologic conditions in a 20-square-mile area centered around McAllister Springs and Wellfield.

Local water resources support McAllister Springs and numerous other hydrologic features. Other springs emerge near and downstream from McAllister Springs and support McAllister Creek and extensive wetlands. Upgradient, the City of Lacey extracts groundwater from high capacity production wells. Further upgradient, numerous shallow ponds and a series of kettle lakes (notably Pattison, Hicks, and Long) intercept shallow groundwater. Eton Creek flows northward into the multi-basin Lake St. Clair, whose perched level is about 50 feet above the adjacent water table. North of McAllister Springs, groundwater discharges to McAllister Creek, Puget Sound, and probably to the lower reaches of the Nisqually River.

During initial evaluations, the City recognized that changing its water source from the springs to the wellfield could potentially alter the flow and water levels in some of these local resources. The City retained CDM to develop a comprehensive numerical flow model (McAllister Model) of the aquifer system to quantify possible changes to the local hydrology under a series of wellfield operational scenarios and under anticipated variable climatic conditions. The City also retained S.S. Papadopoulos and Associates to provide third-party technical review of model development to assure an unbiased approach.

1.2 Purpose and Objectives of the Model

The purpose of the numerical McAllister Model is to develop a tool that simulates existing hydrologic conditions in the area and reliably predicts potential impacts of future withdrawals on key hydrologic features.

Specific objectives of the model are outlined below.

- Mathematically simulate groundwater flow as described in the conceptual model
- Quantify the potential impacts of future groundwater withdrawals on:
 - Lake St. Clair
 - Nisqually River
 - McAllister Springs and Creek
 - Other water users in the area
- Successfully address the questions and issues raised by local stakeholders, including:
 - Nisqually Indian Tribe
 - Lake St. Clair Homeowners Association
 - Thurston County
 - City of Lacey
 - State of Washington Department of Ecology (Ecology)
 - State of Washington Fish and Game (McAllister Creek Hatchery)
- Enable mitigation measures to be evaluated, if necessary.
 - Provide Ecology with the information and analysis needed to effectively and fairly evaluate the City's application for wellfield water rights.
 - Provide a regional- and local-scale water resources management tool that the City can update and improve as new data become available.

The purpose and objectives of the project are accurately described in the Mission Statement developed and accepted by the City and stakeholders at the inception of the project:

Develop, calibrate, and use for predictive purposes a groundwater model that incorporates relevant data on water budget and the hydrologic framework in the area of McAllister Springs. This model must extend to a sufficient distance to allow projection of impacts of the proposed Olympia Wellfield and other regional groundwater production on critical water resources issues at a sufficient level of certainty to allow a decision on the Olympia water rights application and determine appropriate mitigation measures for adverse impacts, if any, of this development. This model must be well documented, defensible, and incorporate input from the State and Third Party Reviewer. Uncertainties in the model predictions should be identified and the impact of uncertainties quantified using sensitivity analyses.

1.3 Interim Report Organization

This interim report has been organized into sections that generally mirror the work scope.

Section 2 summarizes the conceptual model for the hydrologic system based on earlier reports and new information.

Section 3 describes the methods CDM used to construct the numerical flow model.

Section 4 describes CDM's calibration methods, calibration results, and the model's limitations and sensitivity.

The report includes figures illustrating the pertinent data used for conceptual and mathematical model construction, and the structure and output of the model. Tables are also included summarizing model input and output.

The final report will include descriptions of the transient calibration (Section 4), and the application of the model to simulate the Wellfield scenarios and final results (Section 5).

Section 2

Conceptual Model Development

A conceptual model is a descriptive characterization of the hydrogeological setting, the hydrologic processes that are active in the surface and subsurface environments, and the relationships between the components of the hydrologic system. This description includes definitions of the areal and vertical extent of aquifers and aquitards, and quantification of hydraulic properties for these units. The sources and quantities of recharge and discharge are also defined as a component of this conceptual model.

The geologic history and environments of deposition responsible for formation of the aquifers are addressed in the conceptual model to aid in understanding this complex system. The conceptual model was refined and became more quantitative as the study progressed, culminating in the formulation of a numerical groundwater flow model using a commercial modification of the U.S. Geological Survey (USGS) numerical groundwater codes *MODFLOW* (McDonald and Harbaugh, 1988) and *MODFLOW-SURFACT* (HydroGeoLogic, 1996). The model area is shown in **Figure 2-1**.

2.1 Description of Model Area

This section describes the physiography and the main hydrologic features of the model area. The first part of the description addresses the entire study area; the second part focuses on the important details of the McAllister area of interest, a 7- by 9-mile area centered on McAllister Springs, the proposed wellfield, and Lake St. Clair. This detailed area has been fully described in the following key documents on which the conceptual model was based:

- *McAllister Baseline Monitoring Program – Conceptual Model of the McAllister Springs Area (TM#3)*, prepared by CDM for the cities of Olympia and Lacey (August 18, 1999).
- *McAllister Baseline Monitoring Program – Results of the McAllister Springs Baseline Monitoring Program (TM#5)*, prepared by CDM for the cities of Olympia and Lacey (May 17, 2001).

2.1.1 Entire Model Area

The model area covers about 210 square miles (540 km²) in the northern part of Thurston County, where unconsolidated sediments are at land surface. The area is bounded by the Puget Sound at the north, the Nisqually and Deschutes Rivers to the east and west, respectively, and a southern boundary line southeast of Yelm near Lake Lawrence (**Figure 2-1**).

The topographic surface is largely the result of deposition and erosion during and since the Vashon Stage of the Frasier Glaciation (during the last 15,000 years). The land surface is a mostly low-lying, drift covered glacial plain ranging in elevation from sea level to nearly 500 feet above mean sea level (MSL) to the south of Yelm. The relief on the plain is generally low, although the margins terminate in steep bluffs along the Puget Sound shoreline and along the Nisqually River. The plain has been dissected by small to medium-sized streams, such as Woodland and Woodard Creeks in the north and Spurgeon Creek in the central area. Numerous closed depressions exist, many of which are occupied by lakes, ponds, and wetlands (such as Lake St. Clair).

2.1.2 McAllister Area Description

Figure 2-2 shows key features of the McAllister area of the model. **Figure 2-3** is a surficial geologic map of the McAllister area developed from the Thurston County surficial soil map. The McAllister area contains three major landforms: the Lacey Upland area, the kame and kettle areas, and the Nisqually-McAllister Valleys. These are important components of the hydrologic and hydrogeologic systems, and the physical features and geologic history are summarized in the following sections. A more thorough description of these sub-areas is presented in Technical Memorandum No. 3 (CDM, 1999).

2.1.2.1 Lacey Upland

The upland around the City of Lacey is a broad rolling plain at elevations between 220 and 300 feet above MSL. It extends east of Lake St. Clair and north toward the community of Nisqually.. This northward projection is a nearly flat surface at elevations approximately 240 above feet MSL, projecting northward between the McAllister and Nisqually Valleys.

Sediments deposited during the last glaciation by the Vashon glacier form the Lacey Upland. These sediments include Vashon Till, deposited by the glacial ice that mantles the northern portion of the plain. Sandy, gravelly recessional outwash overlying Vashon Till covers the remainder of the upland.

Several broad, shallow, northeasterly-trending valleys are located between McAllister Valley and Long Lake. Meltwater streams and outlet channels of an ancient Nisqually River eroded these valleys. The Nisqually Terrace is underlain by sandy and gravelly sediments and Vashon Till. These sediments were deposited by an ancestral Nisqually River, which flowed along the edge of the melting glacier.

2.1.2.2 Kame and Kettle Areas

The Lacey Upland contains two areas that consist of numerous small hills (kames) and closed depressions (kettles). Some kettles contain wetlands, ponds, or lakes, the largest lake being Lake St. Clair. Sandy, gravelly outwash and water-washed till, with numerous lenses of silt, clay, and till underlie these areas. The Lake St. Clair kame and kettle area extends northward from Lake St. Clair to Lost Lake. Its elevations are

less than those of the adjacent Lacey Upland and Nisqually Terrace, ranging from 40 feet below MSL at the bottom of the deepest kettle to 200 feet above MSL for the highest kame. The Fort Lewis kame and kettle area is a hilly region at the south end of the Nisqually Terrace. It rises above the terrace to elevations more than 400 feet above MSL.

2.1.2.3 McAllister-Nisqually Valleys

The Nisqually Valley extends southward from Puget Sound to its glacial headwaters on Mount Rainier. McAllister Creek flows along the west margin of the lower Nisqually Alluvial Fan and Delta. The McAllister Valley joins the Nisqually Valley about 3 miles upstream from its mouth. In the model area, the valley floors lie between sea level and 10 feet above MSL (McAllister Valley) or 80 feet above MSL (Nisqually Valley). The Nisqually Terrace separates the two valleys. The lower Nisqually Valley contains three large landforms: delta, alluvial fan, and floodplain. The Nisqually Delta occurs at the mouth of the valley and merges southward with the Nisqually Alluvial Fan, which in turn merges with the Nisqually River floodplain. The delta and alluvial fan extend westward into the lower McAllister Valley. Within the McAllister Valley, the alluvial fan extends southward to merge into the wetlands around McAllister Springs at the head of the McAllister Valley.

2.2 Geologic History

This section summarizes the more detailed descriptions presented in the *McAllister Baseline Monitoring Program* reports (CDM, 1999; 2000) and the USGS Thurston County model report (Drost et al., 1999).

The landforms and surface sediments in the model area are due to the most recent (Vashon) glaciation and post-glacial events. During the preceding interglacial interval, the Nisqually River flowed northward through a valley now occupied by the Lake St. Clair kame and kettle area and the McAllister Valley. The depth of this valley is unknown. However, it likely extended to at least 40 feet below present sea level because the floor of the deepest kettle lake is at this elevation. As the Vashon glacier advanced southward, meltwater streams deposited outwash sand and gravel in front of it. These advance outwash sediments were gravelly adjacent to the ice, and sandy farther away. The advancing glacier overrode the outwash, depositing a till that was compressed by the weight of the glacier to become extremely dense (hardpan). The boundary between the two southern sublobes of the Vashon glacier (the Yelm lobe on the East and the Olympia lobe on the west) coincided with the ancestral Nisqually Valley.

By 13,000 years ago, the Vashon glacier advanced just beyond the southern limits of the study area and began to retreat. As the front of the Vashon glacier retreated northward, water shaped the land surface. Meltwater streams transported sand and gravel from the ice and deposited it across the Lacey Upland as a thin continuous sheet of recessional outwash. The meltwater streams flowed southwestward toward the Chehalis River, eroding a series of southwesterly trending valleys (meltwater

channels) that became partially filled with sand and gravel. As the glacier melted, blocks of stagnant ice were left in the ancestral Nisqually Valley and buried by recessional outwash and Nisqually River sediments. During this time, the Nisqually River flowed northward from Mount Rainier to the glacier terminus and then westward along the terminus to the Chehalis River. A series of shallow valleys mark its northward progression along the retreating ice front. During this period, stream sediments buried the ice blocks in the Lake St. Clair kame and kettle area. Once the ice front retreated north of the present Nisqually Valley, fresh water lakes formed. The first lake – Lake Nisqually – formed between the eastern and western glacial lobes. As the ice front retreated northward, the lake grew larger. This larger lake – Lake Russell – rose to an elevation of 160 feet above MSL to flood the lower Nisqually and McAllister Valleys. The Nisqually River deposited a delta (the Sherlock Delta) where it flowed into the lake at the north end of the Nisqually Terrace. As these events unfolded, the buried ice blocks were melting to form the kettles. Other kettles around Lake St. Clair were partially to completely filled with silt and clay from the Nisqually River slack waters and slow moving water in Lake Russell.

When the Vashon Glacier retreated, Lake Russell drained and was replaced by marine waters. Sea level at this time was about 300 feet lower, and the rivers draining into Puget Sound rapidly deepened their valleys. It is likely that the Nisqually River and McAllister Creek eroded deep valleys. Little information about the depth and extent of these valleys is available.

As sea level gradually rose, the deepened valleys were flooded. The Nisqually River deposited its abundant sediments from Mount Rainier in the estuary, rapidly filling it. As the delta extended northward, the river deposited sediments on the floodplain. Some of these sediments form the Nisqually Alluvial Fan in the northern part of the McAllister and Nisqually Valleys.

McAllister Creek has a different postglacial history. As Lake Russell drained, hydrologic entities developed to form McAllister Springs. The springs probably undermined the freshly exposed glacial and delta sediments, causing them to erode and extend the valley headward. This process would not produce abundant sediments, and McAllister Creek probably could not keep up with rising sea level and remained an estuary. The rapidly growing Nisqually Delta eventually extended across both valleys. As the delta extended northward, the Nisqually Alluvial Fan spilled into the lower part of McAllister Valley, causing McAllister Creek to pond and form wetlands. More than 125 feet of silt, clay, and organic matter were deposited in the wetlands. The Nisqually Delta is accreting outward very slowly. The Nisqually Alluvial Fan is no longer rapidly aggrading. Hillslope development continues through soil erosion and small landslides around springs. Sediments eroded from the surrounding slopes are slowly filling in the kettles.

2.3 Geologic and Hydrogeological Units

This section describes the geological and hydrogeologic units in the model area. The geological units have been differentiated into aquifers and confining units based on

the predominant lithologies, permeabilities, water levels, and well yields. Key features of each unit are summarized.

2.3.1 Holocene Alluvial and Deltaic Sediments (Sand and Gravel)

- Found along valley bottoms of main streams; has relatively limited areal extent.
- Has minimal significance in storing or transmitting groundwater.

2.3.2 Vashon Recessional Outwash (Qvr)

- Consists of poorly to moderately sorted sand and gravel laid down by streams emanating from the melting and receding glacier.
- Laterally extensive in study area; between 10 and 40 ft thick.
- Supports kettle lakes in hummocky terrain where underlain by end moraine. Often above the shallowest water table level, so most kettles are dry.
- Mostly unconfined and unsaturated where Till is absent (around Tri-lakes).
- Supports wells for mostly domestic use where sediments are coarse grained. Twelve wells identified in the study area; highest known pumping rate of 300 gpm, or 480 acre-feet per year (AFY). Total production of about 1,100 AFY (Figure 2-4a).

2.3.3 Vashon Glacial Till (Qvt)

- Consists of unsorted sand, gravel, and boulders encased in a silt-clay matrix.
- Compact where laid down beneath heavy glacial mass; less compact where formed by ice melting.
- The till is exposed in many areas along the Puget Sound, above incised stream valleys and in upland areas to the southeast.
- Acts as an extensive confining bed with occasional permeable windows; between 20 and 55 ft thick.

2.3.4 Vashon Advance Outwash (Qva)

- Consists of fine- to coarse-grained sand and gravel grading upward to poorly to moderately sorted; deposited at the front and sides of the Vashon glacier ice mass as it advanced to the southwest.
- Laterally extensive in the study area, but exposed only along steep river and Puget Sound bluff faces.
- Forms the first water-bearing unit of economic value; supplies some municipal and industrial wells.

- Confined by the Qvt unit; does become unsaturated in the north near Puget Sound, along McAllister Valley and smaller stream valleys (Woodland Creek)
- Between 10 and 45 ft thick; relatively thin and unconfined in northern area (few wells). Tapped by many wells in the Yelm area.
- Total of 89 wells identified in the study area; highest pumping rate of 750 gpm (1,200 AFY, City of Lacey well No. 4). Total unit production of 4,600 AFY (**Figure 2-4b**).

2.3.5 Kitsap Formation (Qf)

- Consists of an assemblage of fine-grained clay and silt unit with minor sand, gravel, peat, and wood. Deposited in shallow lakes and swamps; likely of non-glacial origin.
- Exposed along Sound shorelines.
- Laterally extensive in study area, acts as a confining unit (with one major window beneath Tri-lakes). Not an aquifer.

2.3.6 Salmon Springs Formation (Sea Level Aquifer, Qc)

- Consists of coarse, stratified sand and gravel deposited during the pre-Vashon (“Penultimate”) glaciation
- Laterally extensive; exposed along the bottom of the Nisqually River between the confluence with the McAllister Valley and Muck Creek.
- Although rarely more than 50 ft thick (between 15 and 70 ft), forms the principal economic (mostly confined) aquifer in the area tapped by wells.
- Combination of the Salmon Springs, penultimate, and other formations; is a widely used aquifer.
- A total of 112 wells identified in the model area; highest pumping rate of 720 AFY (450 gpm; City of Lacey well No. 10). Total production of 7,700 AFY (**Figure 2-4c**).

2.3.7 McAllister Gravel

- Consists of pebble- to boulder-sized sediments as a channel fill deposit due to the ancestral Nisqually river channel; cut after the Kitsap formation was deposited. More than 400 ft thick.
- Extends northeastward from McAllister Springs beneath the kame and kettle landscape containing Lost Lake to join the Nisqually Valley aquifer system near the Burlington Northern Railroad (BNRR) bridge.

- Natural (visible) discharge point is at McAllister Springs (the largest single public water supply in the area). Is capable of yielding significant amounts of water to production wells.
- Extends north of the spring beneath the Nisqually Delta. Is in hydrologic contact with the Qvr, Qva, Qc, and TQu units.

2.3.8 Undifferentiated Quaternary and Tertiary (TQu)

- Consists of fine- to coarse-grained unconsolidated sediments extending to bedrock; likely glacial and non-glacial origin.
- The base of this unit ranges from about 300 ft above MSL in the southeast to more than 1,500 feet below MSL along the Puget Sound.
- Consists of a sequence of aquifers and confining beds; tapped by only a few water wells locally (Figure 2-4d).

Beneath the TQu unit, the Tertiary (Miocene and Eocene) bedrock consists of sedimentary sandstone, siltstone and claystone, and some igneous bodies of andesite and basalt. The closest bedrock outcrop to the study area is found to the southwest, along the Deschutes River. The bedrock is considered to be relatively impermeable and does not contribute to the groundwater flow system.

2.4 Climate

The climate of northern Thurston County is typically mid-latitude, West Coast marine, characterized by warm, dry summers and cool, wet winters. During the winter months, rainfall is usually light to moderate intensity. The long-term average annual precipitation at Olympia Airport is about 52.2 inches (**Figure 2-5**), but ranges from less than 40 inches in the drier northeastern part of the area to more than 55 inches in the south and northwest. About 75 percent of the annual total falls during the 6 months from October to March. Precipitation during the period June through August is about 7 percent of the annual total. Between 1980 and 1999, July was on average the driest month (about 0.78 inch) and November was the wettest month (8.9 inches) (**Figure 2-6**).

2.5 Groundwater Flow

The general hydrologic model for the area shows precipitation falling on the inland glacial-drift plain, infiltrating the land surface, percolating past the plant root zone, and recharging the groundwater system. Groundwater moves vertically and horizontally from recharge areas to discharge areas at hydrologic features such as springs and seeps, streams and rivers, and Puget Sound at and below sea level. Generally, groundwater moves vertically in lower permeable confining units (such as the Qvt and Qf units) and horizontally in the higher permeable and transmissive aquifers (Qvr, Qva, Qc, TQu, and McAllister Gravel).

Figures 2-7 through 2-10 show the average groundwater flow conditions in the principal water-bearing units. The potentiometric contours are interpreted from groundwater level measurements in wells:

- (1) During 1988 by the USGS for the Thurston County Model and
- (2) Between 1994 and 1999 by CDM and the City of Olympia in the McAllister area as part of the *McAllister Baseline Monitoring Program*.

These data also formed the basis for the model calibration data set (described in Section 4). In all units, groundwater flows from the southeastern part of the area (recharge area) toward the McAllister and Lacey areas, discharging either at numerous springs or kettle lakes, the Nisqually and Deschutes Rivers, or into Puget Sound. Significant flow convergence occurs in the highly transmissive McAllister Gravel, which feeds McAllister Springs and other nearby wetland and creek-supporting springs.

2.6 Hydraulic Properties

The hydraulic conductivity of an aquifer is the measure of its ability to transmit water. The transmissivity of a unit is a product of its hydraulic conductivity and its saturated thickness. Horizontal hydraulic conductivity is the volume of water that moves in the horizontal direction under a unit head gradient through a unit area. The USGS conducted a significant investigation to determine the spatial distribution of hydraulic conductivities for the units within the study area (Drost et al, 1999). **Table 2-1** presents the range of horizontal hydraulic properties for the units from the Thurston County Model, based on specific capacity data.

Table 2-1 – USGS Thurston County Model Hydraulic Properties

Unit	No. Values	Hydraulic conductivity (ft/day)		
		<i>Min</i>	<i>Max</i>	<i>Median</i>
Qvr	43	14	2,100	150
Qvt	22	5.2	89	14
Qva	370	6.8	130,000	180
Qf	41	0.052	62	17
Qc	321	1.9	12,000	150
TQu	132	1.2	4,200	78

CDM developed a detailed database of records for 243 wells as part of the conceptual model portion of the *McAllister Baseline Monitoring Program*. These records included the following:

- Well name and owner details

- Survey information
- Well construction and driller information
- Lithologic and geologic unit interpretation
- Estimation of hydraulic properties
- Water level and well yield

CDM developed the hydraulic property estimates by first standardizing well logs based on lithologic descriptions to include primary and secondary litho-types. Hydraulic conductivity values were assigned to each interval in a well log based on these standardized descriptions. The well logs were examined and stratigraphic intervals defined based on the lithology, consistent with the units described in earlier sections. In some areas, recognition of unit boundaries was difficult due to ambiguities in log descriptions. For these ambiguous areas, surrounding wells were examined to assist in selection of unit boundaries.

CDM also examined wells in the USGS Thurston County Model database and compared unit boundaries to lithologies. Wells within the McAllister Model area were re-interpreted and, in some cases, unit boundaries were modified based on the actual well logs. Once unit boundaries were defined for each of these well logs, the individual lithologic intervals and their thicknesses were used to develop a weighted average hydraulic conductivity for a hydrostratigraphic unit encountered in a well. These weighted average hydraulic conductivity values were then mapped using geostatistical techniques to define property zones within the McAllister area. These interpreted property zones were then incorporated into the model framework during model construction (Section 3).

In June 1997, Pacific Groundwater Group (PGG, 1997) performed aquifer performance tests at the City of Olympia's newly installed 18-inch-diameter production well PW-24. The 3-day constant rate (3,500 gpm) test yielded transmissivity and storage coefficient estimates for the McAllister Gravel unit of 2,500,000 gpd / ft (334,200 ft² / day) and 0.15, respectively. Since the saturated thickness of the McAllister Gravel in this area is about 300 ft, the material has an estimated hydraulic conductivity of about 1,100 ft / day based on the pumping test results.

2.7 Groundwater Recharge

Recharge to the model area consist of the following:

- Recharge derived from precipitation
- Subsurface inflow from the area to the south of the model area boundary
- Seepage from perched and non-perched lakes to the shallow water table

2.7.1 Precipitation Recharge

Precipitation-derived recharge is the major source of water to the system. In general, recharge can be determined from the following relationship:

$$\text{Recharge} = \text{Precipitation} - (\text{Evaporation} + \text{Transpiration}) - \text{Surface Run-off}$$

The USGS has conducted many studies to determine relationships between precipitation and near-surface soil conditions. For the Thurston County Model, the USGS used the regression model of Bauer and Vaccaro (1987) for till and outwash (**Figure 2-11**). The USGS also recognized the geographical variation in annual precipitation, with annual totals ranging from 40 inches in the drier east to 55 inches in the wetter west and south. They estimated the annual recharge rates for the average precipitation year range from 14 inches in the Nisqually River valley to 40 inches in the City of Olympia and upper Deschutes River areas.

CDM used the same approach to develop a conceptual water budget for the McAllister Model area (see Section 2.9). Assuming a model area of 210 square miles, an average annual precipitation of 50 inches, and annual recharge rates of 25 inches (assuming 50 percent Till and 50 percent Outwash areas), the total recharge into the model area is 278,400 AFY (380 cfs).

2.7.2 Subsurface Inflow

The major subsurface inflow into the study area occurs in the principal aquifers from the area to the southeast of the communities of Rainier and Yelm. CDM assumed that the quantity of inflow across a southwest to northeast trending potentiometric contour line could not exceed the estimated recharge the unconsolidated sediments outside the model area. Using an average recharge rate of 25 inches per year (from the USGS Thurston County Model) and an upgradient area of 38 square miles, the recharge volume would be 51,000 AFY. The subsurface inflow into the model area is a product of the boundary length (4.8 miles), the combined aquifer and confining unit thickness (about 430 feet), the average conductivity (75 ft/day), and a hydraulic gradient estimated from the Thurston County Model (0.004). Under these conditions, the subsurface inflow rate is 24,600 AFY, which is 48 percent of the estimated upgradient area recharge.

2.7.3 Lake Seepage

Groundwater is known to recharge the shallower aquifer units from water contained in the numerous kettle lakes in the area. The most important of these lakes is Lake St. Clair. Lake St. Clair is of particular interest because the drawdown influence of the McAllister Wellfield could potentially increase lake seepage to the detriment of the lake's stage and ecology. An assessment of the potential lake impacts under Wellfield operation (PGG, 1997) assumed a groundwater origin for the lake; that is, the study concluded that the lake bottom is in continuous contact with the aquifer and the lake water is exposed to groundwater. Under these conditions, any lowering of the water table would result in a corresponding lowering of lake levels as the local hydraulic gradient is increased. Lake stage levels measured between 1992 and 2000 ranged between 65 and 71 ft above MSL (**Figure 2-12**), with annual fluctuations typically 1.5 to 3.5 feet.

The USGS calculated the annual seepage from Lake St. Clair for the year 1989 as 3.6 mgd (4,032 acre-feet) (Drost et al., 1999). The USGS study was based on an analysis of precipitation, Eaton Creek inflow, and evaporation. The USGS estimate neglected any groundwater inflow. Some seasonality would be expected and seepage would also vary from year to year as these factors change. The estimated seepage is the total quantity of water that seeps out of the lake through the bottom sediments in 1 year.

As part of the *McAllister Baseline Monitoring Program*, CDM conducted extensive seepage studies and developed an analytical model to determine the proportion of seepage below the water table (**Figure 2-13**). Seepage occurring above the water table will not be affected by changes in the local water table resulting from pumping at the McAllister Wellfield. The analysis indicated that 76 percent of the seepage is derived from the 59 percent of the lake floor located above the water table, which means that 76 percent of the seepage would not be affected by any water table changes induced by wellfield pumping.

2.8 Groundwater Discharge

Groundwater in the study area discharges in the following forms:

- Extracted by pumping wells
- Natural springs (such as McAllister and Abbott Springs) and seeps feeding streams, rivers, lakes, and wetland areas
- Discharge to streams and rivers along gaining reaches
- Outflow beneath the Nisqually and Deschutes Rivers to the east and west, respectively
- Subsurface flow to Puget Sound
- Evaporation and transpiration

2.8.1 Pumping

Groundwater pumping in the study area consists of a combination of small-scale “exempt” private wells supplying individual homes, some small businesses, and a few wells operated by public water purveyors (such as the City of Lacey). An exempt well is defined as one that supplies less than 5,000 gallons per day (gpd) and could supply up to six connections. Rural households each use about 250 gpd during the wetter months (275 days) and 750 gpd during the drier months (90 days), for a total of 147,500 gallons per year per well (0.45 AFY).

Figure 2-14 illustrates the relative proportions of groundwater pumping in the study area from each of the principal aquifers based on USGS data collected for the Thurston County Model. According to the USGS, groundwater withdrawals from all wells in the study area totaled about 15,000 AFY (20.7 cfs) in 1988-89. About 50 percent of all pumping occurs in wells tapping the Qc unit.

2.8.2 Springs and Seeps

The major natural spring in the study area is McAllister Springs, which currently provides about 80 percent of the water supply for the City of Olympia. McAllister and adjacent Abbott Springs are the major discharge points for the McAllister Valley aquifer system, and are located approximately 1,500 feet apart at the southern end of the valley. They are valley-floor springs with an average annual discharge between 23 and 40 cfs (McAllister) and between 5 and 10 cfs (Abbott). The change from gravel to silt and clay in the valley controls spring location by forcing groundwater underflow to the surface. Measured water levels at Abbott Springs confirm this upward flow. The springs are located at the junction of two high permeability zones – one from Long Lake to the southwest and the other from Lake St. Clair to the south. McAllister Springs receives groundwater from both areas.

McAllister Creek initiates at the weir from the City of Olympia water supply lagoon at McAllister Springs. Immediately downstream from the weir, the creek receives discharge from Abbott Springs and unnamed valley-floor springs along the west side of the valley, and numerous other seeps forming the McAllister-Abbott Springs wetland complex and the adjacent agricultural wetlands. Farther downstream, the creek receives additional discharge from Little McAllister and Medicine Creeks and from numerous valley-side springs to the west. Below McAllister wetland, the creek is isolated from the aquifer by thick, fine-grained sediments.

Since 1997, the City of Olympia has recorded daily discharge from McAllister Springs and the quantity of flow removed for use (**Figure 2-15**). The total flow out of the spring ranged between 30 and 50 cfs, with the City intercepting between 6 cfs (winter) and 17 cfs (summer). This was a relatively wet period with annual precipitation between 10 and 25 percent above the long-term average.

2.8.3 Major Rivers

Nisqually River

The Nisqually River forms the eastern boundary of the model area (**Figures 2-1 and 2-2**) and is a perennial glacial-fed stream flowing through an alluvium-filled valley. South of the BNRR bridge, the river generally flows on coarse-grained alluvium; north of the bridge, finer-grained sediments are present. Bridge borings along Red Salmon Creek on the Nisqually Delta encountered sand at depths of 10 to 20 feet below tideland silt. The alluvium appears to be in hydraulic continuity with the river.

The surface and groundwater in the Nisqually drainage area is different than in the McAllister area. The Nisqually River is largely glacial fed and temperature-dependent with higher natural summer flows. McAllister Spring is groundwater-derived and driven by local precipitation in the basin.

Tacoma Public Utilities' Alder Dam, which is located near the boundaries of Thurston, Pierce, and Lewis Counties, controls the flow of the Nisqually. The USGS records the river discharge at station No. 12089500 (RM 21.8) at McKenna, which is about 10 miles upstream from the McAllister area, and station No. 12089208 (RM 12.6) at the Centralia Canal confluence. USGS' regression analysis of upstream discharge data indicated that flow always exceeds 600 cfs at RM4.3 and that the river generally gains downstream. Within the McAllister area, the lower Nisqually River receives groundwater baseflow and spring discharge from the Nisqually Terrace on the west and Fort Lewis on the east. The USGS' seepage investigations determined that about 190 cfs of flow below the McKenna station is from groundwater discharge (Drost et al., 1999). Of this amount, approximately 36 to 44 cfs is from bluff-side springs. If the groundwater contribution is uniformly distributed along the river and is derived equally from either side of the river, the contribution from the Nisqually Terrace is estimated to be 7 cfs. As the McKenna gage is about 21.8 miles upstream, groundwater contribution on each side of the channel is 3.5 cfs per mile (150 cfs / 21.8 miles / 2). Based on this value, the 4 miles of the Nisqually River within the McAllister area of the model receive about 14 cfs of groundwater baseflow. Downstream from the BNRR bridge, the Nisqually River receives an additional 7 cfs of baseflow from the McAllister Valley aquifer system. These relationships indicate the Nisqually River is a groundwater discharge area throughout the reach lying within the model area.

Between August and November 2000, Ecology conducted a study of instream flows in the Nisqually River at RM 4.3, located at the mean annual high tide mark just south of the BNRR bridge (Culhane, 2001). Ecology's study concluded that flows at this location during the study period ranged between 816 and 1,700 cfs, but mostly ranged between 900 and 1,150 cfs.

Deschutes River

The Deschutes River forms the western boundary of the model area and enters Puget Sound via Capitol Lake and Budd Inlet near the City of Olympia (**Figure 2-1**). The river stage ranges from about 410 ft above MSL to sea level at Capitol Lake. Studies performed by USGS in August 1988 showed that groundwater discharge increased

river flow from 35 to 89 cfs (39,000 AFY increase) between sites in Rainier and “E” Avenue in Olympia (Drost et al., 1999).

2.8.4 Stream Discharge

Several of the streams in the model area receive groundwater. These include Eaton and Spurgeon Creeks (which drain to the south and southwest of Lake St. Clair), Woodland and Woodard Creeks (which drain to the north from the city of Lacey), and Thompson Creek (which drains into the Nisqually River near the City of Yelm).

Eaton Creek flows into Lake St. Clair from an area south and southwest of the McAllister area. The USGS recorded the discharge at a gaging station located at the Yelm Highway bridge over Eaton Creek during August 1989 as between 3.2 and 3.8 cfs.

Spurgeon Creek drains from east to west and joins the Deschutes River near the BNR crossing. The creek emerges in the northern part of the Fort Lewis Reservation near the same source as Eaton Creek. The USGS reported the baseflow at it enters the Deschutes River as 4.4 cfs during August 1988.

Woodland Creek drains northward in the area to the east of Lacey and enters Puget Sound at Henderson Inlet. The USGS reported flows as high as 12 cfs in the creek north of the outlet to Long Lake during August 1988. The average annual stream stage ranges from about 158 feet MSL to sea level. The creek is likely in hydraulic communication with the Qvr unit and is a gaining stream along most of its course.

Woodard Creek is located about 1½ miles west of Woodland Creek, and also enters Henderson Inlet. The USGS reported a baseflow of 3.5 cfs based on 1988-89 hydrograph records.

Thompson Creek drains northward along a course immediately east of the Fort Lewis upland area, and enters the Nisqually River near the Centralia Canal. No flow data are available for this stream. The stream stage likely grades from about 375 ft MSL at the source just west of Yelm to 300 ft MSL at the confluence with the Nisqually River.

2.8.5 Subsurface Flow to Puget Sound

CDM estimated the typical subsurface discharge to Puget Sound to be 50,000 AFY (68 cfs) using a Darcian approach with the following estimates:

- A discharge width of 8 miles
- An average hydraulic gradient of 0.002 ft / ft (shown on **Figures 2-8 and 2-9**)
- An average hydraulic conductivity for the Qc and TQu Aquifers of 100 ft / day
- An average saturated thickness of 700 ft (ranging from 300 ft in the east to 1,100 ft in the west).

Groundwater also outflows to Budd Inlet just north of the City of Olympia. Using the same Darcian approach as employed for Puget Sound, CDM estimated the outflow to be about 25,000 AFY (34 cfs):

- A discharge width of 4 miles.
- An average hydraulic gradient of 0.002 ft / ft (see **Figures 2-8** and **2-9**).
- An average hydraulic conductivity for the Qc and TQu Aquifers of 80 ft / day.
- An average saturated thickness of 500 ft.

The USGS Thurston County Model predicted a total subsurface outflow to the Sound of 88,000 AFY. The USGS estimate was made using a longer discharge width that included areas west of Budd Inlet.

2.8.6 Evaporation and Transpiration

Evapotranspiration (ET) is likely to occur in the model area where the groundwater table is very shallow. CDM did not make an independent estimation of these losses as the recharge-precipitation relationship described in Section 2.7.1 takes these processes into account. However, if 50 percent of incident precipitation is not recharged, about 380 cfs is lost annually to a combination of surface run-off to streams and lakes and as ET. The USGS Thurston County Model water budget included no explicit estimate for this component.

2.9 Water Budget Summary for Model Area

Table 2-2 summarizes the conceptual water budget for the model area under equilibrium conditions for an average hydrologic year. For the Thurston County model, the USGS estimated a total steady-state water budget of 660,000 AFY. The Thurston County Model area was about 450 square miles, whereas the McAllister Model area is about 210 square miles.

Table 2-2 - Conceptual Water Budget

Component	INFLOW		Component	OUTFLOW	
	cfs	AFY		cfs	AFY
Recharge	380	278,400	Pumping	20	15,000
Subsurface	38	24,600	Subsurface to Sound	104	75,000
Lakes and streams	7	5,000	Nisqually / Deschutes	166	120,000
			Lakes and streams	28	20,000
			Springs	107	78,000
Totals (est'd.)	425	308,000	Totals (est'd.)	425	308,000

Section 3

Model Construction

The objective of the McAllister Model is to mathematically simulate groundwater flow in the hydrologic system described by the conceptual model (Section 2). The McAllister Model is designed to allow assessment of the impact on water levels and components of the water budget for various wellfield development scenarios. The model used information from the USGS developed for the Thurston County Model, with significant updating to incorporate a greater level of detail around the proposed wellfield and McAllister Springs.

3.1 Model Code and Software Employed

CDM used the USGS modular, three-dimensional, cell-centered, saturated flow model *MODFLOW* (McDonald & Harbaugh, 1988; Harbaugh & McDonald, 1996a, 1996b) to simulate groundwater flow in the study area. The program uses a finite-difference approximation to solve the partial differential flow equation assuming fully saturated flow with a constant water density in a heterogeneous, anisotropic, porous medium.

To apply the finite-difference method used by *MODFLOW*, the major hydrostratigraphic units (aquifers and lower permeable aquitards) were discretized into rectangular cells, with each cell being assigned specific parameters (material properties and top and bottom elevations) and an initial potentiometric head to allow computation. The modular *MODFLOW* input system consists of a series of matrix data sets that describe the hydrostatic units and boundaries, recharge, discharge, and surface water features. *MODFLOW* then uses this information in an iterative solving process to compute, for each active model cell, a hydraulic head and a flow into and out of each cell. *MODFLOW* is well documented and the interested reader can obtain more information in references cited above.

The *MODFLOW* numerical code was selected to construct the McAllister for the following reasons:

- It is the same code used for the existing Thurston County groundwater model developed by the USGS (Drost et al., 1999) and the two models are thus compatible.
- *MODFLOW* is a widely used, extensively documented, and well-accepted numerical code.
- Modules to address the processes in the conceptual model are already incorporated in the model code.
- Graphical pre- and post-processors are commercially available to facilitate use of the model.
- Ecology staff, stakeholders, and technical reviewers are familiar with the assumptions and limitations of the code as applied to this hydrologic system and the goals of the study.

CDM used both pre- and post-processor software programs *GMS* (version 3.1; BYU, 1997) and *Groundwater Vistas* (version 3.12; ESI, 2001) to construct and calibrate the model, perform simulations, and view and document the model results. The model was initially run using the PCG2 (Hill, 1990) solver. However, a significant number of numerical instabilities resulted during steady-state runs that precluded the model from achieving a stable solution within a reasonable number of iterations. The PCG2 solver was unable to resolve the repeated wetting / drying in numerous cells in areas where (1) the aquifer layer was relatively thin and (2) the gradient of the layer bottom was relatively steep.

To overcome these problems, CDM tested the *MODFLOW-SURFACT* (version 2.2) PCG4 solver (HydroGeoLogic, 1996). *MODFLOW-SURFACT* is a modification of the USGS *MODFLOW* code. CDM selected this solver because it handles relatively complex stratigraphic situations better than the standard *MODFLOW* PCG2 solver, and therefore lessens convergence problems. *MODFLOW-SURFACT* also offered a potential solution to the difficulties with alternating wetting and drying cells, while maintaining mass continuity. The code applies a “pseudo-soil retention function” approach to avoid the instability associated with the alternate wetting and drying of cells. This method does not inactivate cells when they are dry (as in the standard *MODFLOW-96* approach), but considers the vertical movement of recharge through these dry cells. This realistic solution has the effect of simulating only a downward movement of recharge or leakage from overlying layers in zones that are “dry.” After presenting these details to the City, technical reviewers, and Ecology staff, and obtaining formal approval from the latter, CDM proceeded to apply *MODFLOW-SURFACT* for all model calibration and simulation runs.

3.2 Model Domain and Grid

The model area consists of approximately 210 square miles (545 km²) of northern Thurston County (**Figure 2-1**). The area is bordered to the north by the southernmost extent of Puget Sound, to the west by the Deschutes River and Budd Inlet, and to the east by the Nisqually River. The southeastern boundary on the upland between the Nisqually and Deschutes Rivers is along a groundwater contour southeast of the communities of Yelm and Rainier.

The *MODFLOW* program requires that the flow system be discretized, horizontally and vertically, into rectilinear blocks called cells. Hydraulic property values (horizontal and vertical hydraulic conductivity, storativity and porosity) are assigned to each cell. The model grid is shown in **Figure 3-1**, and consists of nine variable-thickness layers corresponding to hydrostratigraphic units. CDM aligned the grid north-to-south to parallel the predominant groundwater flow direction. The cell dimensions in plan view range from 100 ft by 100 ft (concentrated in the McAllister area; **Figure 3-2**) to 1,000 ft by 1,000 ft (at the outer areas). The finite difference method implemented in *MODFLOW* assumes that flows and heads are uniform within a cell and are represented at the center of the cell. This assumption requires that smaller cell dimensions be used in areas near changing hydraulic gradients, such

as near wells and springs, to more accurately represent these conditions. A smaller cell size also allows more accurate definition of features such as lakes, springs, and wells. The grid design in the USGS Thurston County Model incorporated a uniform 3,000 ft by 3,000 ft (**Figure 3-3**) cell size, which was not sufficient to evaluate the impact of the proposed wellfield. **Table 3-1** lists the nine model layers that represent the saturated unconsolidated sediments overlying the Tertiary bedrock.

Table 3-1 Model Layering and Hydrogeologic Units

Hydrogeologic Unit	Main Layer(s)	Notes
Vashon Recessional Outwash (Qvr)	1	Principal surface unit. Mostly unconfined conditions. Laterally discontinuous.
Vashon Till (Qvt)	2	Low permeable confining unit. Discontinuous beneath Tri-lakes region.
Vashon Advance Outwash (Qva)	3	Productive aquifer. Mostly confined.
McAllister Gravel	2 - 8	Very high permeable unit cut through surrounding units upgradient of McAllister Valley.
Kitsap Formation (Qf)	4 ⁽¹⁾	Low permeable confining unit.
Salmon Springs Drift & Penultimate Glaciation (Qc)	5 - 6	Key productive aquifer. Total unit thickness equally divided between two model layers. Sea Level Aquifer.
Undifferentiated Tertiary Deposits (TQu)	7 - 9	Uppermost 50 ft is low permeable confining unit. Greatest thickness near Puget Sound, thins to south. Glacial and non-glacial.

Note: (1) Layer 4 also contains Recent alluvial deposits in the McAllister Valley overlying Qc.

3.3 Model Structure

The model structure is defined by elevations for the top and bottom of each layer in the model. The top of layer 1 represents the land surface. The bottom elevation of each layer also represents the top elevation of the underlying layer. CDM considered three approaches to define the layer structure in the McAllister area.

The original work conducted during the *Baseline Monitoring Project* (CDM, 1999; 2001) interpreted hydraulic properties within a rectilinear grid with uniform 50-ft-thick layers. Hydraulic properties were assessed within each resulting cell to define the framework. This method resulted in a simple grid structure, since uniform layers are defined. It has the disadvantage of including multiple lithologies within a layer, limiting the ability to accurately represent the impact of confining units.

The second approach considered was to incorporate the layer elevations from the USGS Thurston County Model for the entire model, including the detailed evaluation area in the McAllister Valley. Information from the detailed area would then be used to assess hydraulic properties for each cell. This method would also result in the potential incorporation of multiple lithologies into a layer, since many more wells were available in the detailed area than were available to the USGS for its regional study.

The third alternative used a combination of USGS layer and stratigraphy definitions, with a re-interpretation of this information within the detailed study area. This hybrid method had the advantage of using the USGS model information and incorporating data from well logs in the detailed area, and retains comparability between the McAllister Model and the USGS Thurston County Model. CDM implemented this alternative to produce the final model layer structure presented in this report.

Layer elevations in areas outside the detailed area were developed using data from the USGS Thurston County Model. Within the McAllister area, CDM used the approximately 240 of the best quality well logs to define stratigraphic contacts. Lithologic descriptions from well logs were examined to select the contact between the defined hydrostratigraphic units. In some cases, ambiguous descriptions on driller's logs precluded reliable identification of these contacts and such wells were removed from the database. Other cases were observed where particular hydrostratigraphic units were absent, such as within the McAllister Gravel unit. For these cases, continuity of layers was maintained by interpolating elevations from adjacent areas where a unit was present. A database consisting of USGS model layer elevations for peripheral areas and the log-based interpretations were used to define final model layer elevations. Interpolation from this point database to the continuous model grid was performed using kriging and ring-average smoothing in the software program *SURFER* (Golden Software, 1999) to avoid discontinuities. Some manual smoothing of layer elevations was conducted in areas with highly irregular interpolated surfaces. **Figures A-1 through A-9 in Appendix A** show the final base elevations for layers 1 through 9. The top of layer 1 was interpolated from the USGS DEM (digital elevation model) database.

3.4 Material Properties

CDM determined the hydraulic conductivity values for the aquifers and lower-permeable confining units from a number of sources. The property values and distribution incorporated into the USGS Thurston County Model were used as a basis for the outer model areas. CDM imported these data into GMS and created property polygons for the McAllister Model domain. Initially, the polygons were assigned the same horizontal conductivities (K_h) as the Thurston County Model. CDM developed the material properties in the McAllister area as part of a detailed study of about 240 selected drillers' log and borehole descriptions that were collated into a database.

CDM developed hydraulic conductivity estimates for each hydrostratigraphic unit as a thickness-weighted average of individual described layers encountered in the well. The individual point estimates of hydraulic conductivity were krigged to define areas of like properties. These areas were smoothed and used to define polygon coverages representing the high, medium, and low values within each analyzed layer in the detailed model area. These interpretations were then imported into GMS and merged with existing Thurston County material polygons to create each layer property set. The initial vertical conductivities (K_v) were assigned for each layer zone based on the following ratio ranges:

- Upper aquifers (Qvr, Qva, Qc) K_h / K_v from 10:1 to 50:1
- Confining units (Qvt, Qf) K_h / K_v from 50:1 to 500:1
- Lower aquifer (TQu) K_h / K_v from 10:1 to 100:1

CDM adjusted these ratios during initial efforts to stabilize the model. However, CDM made more formal property value adjustments during calibration (Section 4), and the final material property zones are shown in **Figures 3-4** through **3-11** (plan view) and **Figures 3-12** through **3-14** (in cross-section).

3.5 Precipitation Recharge

As discussed in Section 2.7, the majority of the recharge to the groundwater system in the model area is derived from infiltration and percolation of precipitation. Recharge occurs almost everywhere in the model area except where groundwater discharges and where the surface is relatively impermeable such as asphalt and concrete surfacing. The percentage of these impervious areas in the model area is very small and no special allowance was made for these features.

CDM used the recharge from the USGS Thurston County Model as a basis for formulating recharge into the McAllister Model. The Thurston County Model recharge method used the relationships between local average annual precipitation and surficial soil conditions developed by Bauer and Vacarro (1987), which are as follows:

- Till (Qvt, Qf, and TQu areas) $R_t = 0.542P - 6.16$
- Outwash (Qvr, Qva, and Qc areas) $R_o = 0.838P - 9.77$

These relationships reflect the greater ability of the coarser-grained outwash soils to allow more infiltration but a higher evaporative capacity. Precipitation was spatially defined by an isohyetal map shown in Figure 4 of the Thurston County Model report (Drost et al., 1999), where annual precipitation in the study area ranged from 40 inches in the east to 55 inches in the west and south.

To produce a recharge set for the McAllister Model, CDM digitized the areal recharge distribution zonation shown in the Figure 17 of the Thurston County Model report into polygons in GMS, assigned the same recharge rates, and created a single coverage file. CDM then transformed the coverage file to a *MODFLOW Recharge* array, and assigned a single recharge rate to each model cell in plan view. The resulting recharge rates ranged between 14 and 48 inches per year (**Figure 3-15**).

The modeled recharge rates were assigned to the highest active model layer. This enabled the model to accept all recharge even if either (1) model layer 1 was inactive (such as in the McAllister Valley or Fort Lewis upland areas) or (2) if the uppermost layer became dry at any time during simulations.

CDM did not assign groundwater pumping return flows as a recharge flux. The USGS included these return flows for the Thurston County Model by assuming that they constituted 10 percent of the total pumping in an attempt to account for the effect of unsewered residences. The USGS assigned local returns directly at wells. CDM did not include these as 10 percent of 15,000 AFY (or 1,500 AFY) is only a small fraction of the estimated total precipitation-derived recharge of 278,400 AFY.

CDM also used the *MODFLOW Recharge* package to simulate the fixed (or non-head dependent) seepage that occurs through the steep sides of Lake St. Clair to the water table (see Section 2.7.3; **Figure 2-13**). This component of seepage from Lake St. Clair will not change as a result of pumping that causes a decline in water level, since this seepage takes place above the water table. CDM assigned a fixed recharge rate of 0.06 ft/day to the ring of cells surrounding the cells assigned as *MODFLOW River* (head-dependent) condition cells for the lake (**Figure 3-15**). This total flux was 3,060 AFY, which is about 76 percent of the annual average water that Lake St. Clair recharges to the aquifers under average hydrologic conditions.

3.6 Groundwater Pumping

For the steady-state calibration, CDM imported the 1988 pumping records and data developed by the USGS for the Thurston County Model into the McAllister Model. CDM also used the same method as the Thurston County Model for distributing the pumping for a quarter township area where no specific well exists. For the two cases where the total pumping for a quarter township was relatively high (18N/02W-NEQT at 980 AFY and 18N/02W-NWQT at 560 AFY), CDM divided the total pumping flux equally between a 3x3 block of nine 1,000-ft by 1,000-ft model cells to avoid numerically over-stressing a single model cell.

Several wells within the McAllister Model domain were located so close to the model boundaries that they were removed from the model to avoid numerical stability problems. The pumping in the Sea Level Aquifer was equally distributed between layers 5 and 6, which together represent this aquifer. Pumping identified as being from the undifferentiated Tertiary unit was assigned to model layers 8 and 9.

The total pumping within the McAllister Model domain is 15,000 AFY (20.7 cfs). The total pumping in the entire (larger) Thurston County Model was approximately 62,000 AFY (90 cfs). CDM assigned a total of 381 model cells using the MODFLOW *Well* condition to represent 246 wells in the domain. **Figures 3-16** through **3-23** show the location of model cells assigned pumping. **Table 3-2** summarizes the vertical distribution of the pumping.

Table 3-2 Distribution of Pumping

Aquifer/Unit	No. Wells	Total Pumping		Percent of Total Production
		AFY	cfs	
Qvr (layer 1)	12	1,142	1.6	8
Qva (layer 3)	89	4,664	6.4	31
Qc (layers 5,6)	110	7,731	10.7	51.6
TQu (layers 8,9)	33	1,373	1.9	9
McAllister Gravel (layers 2-8)	2	62	0.09	0.4
Total	246	15,000	20.7	100

3.7 Springs

The model represents individual springs and larger-area seepage faces discharging water from the model using MODFLOW's head-dependent *Drain* package. Each cell is assigned an elevation (which is typically equal to the base elevation of the model layer or known discharge elevation) and a conductance value to resist outflow from the spring or seep. The conductance values for McAllister and Abbott Springs were developed during the calibration process. Spring elevations were based on actual land surface levels, and seep elevations were assumed to be 5 ft above the base of the model layer. CDM assigned the conductance to be equal to four times the horizontal conductivity for those cells that represent a general seepage area.

The Drain conductance term describes the quantity of flow that discharges from a cell for a unit head difference between the cell's average head and the *Drain* elevation. This conductance term is a function of both the cell length-to-width ratio, the assumed seepage face and the hydraulic conductivity of the aquifer. To estimate a *Drain* conductance, CDM used a model perimeter cell to represent a typical cell (where the length-to-width ratio was 10:1), with discharge taking place along the shorter face of the cell. The *Drain* elevation was set to 5 feet above the base of the layer. Darcy's law was solved for the case where the head at the cell center was one foot above the drain elevation, or six feet above the layer bottom. As the gradient to the seepage face occurs between the cell center and the boundary, the resulting gradient is 6-feet / 1/2 the longest cell dimension. The average saturated thickness between the center of the cell and the seepage face was used with the cell width to estimate the area over which

flow takes place. These factors were reduced to a multiplier of 4 for the typical drain cell and the drain conductance was set to 4 times the horizontal hydraulic conductivity. The controlling factor on saturated thickness as the outcrop is approached is the hydraulic conductivity, since even if conductance were set to a very high value, the drain elevation is the minimum that will occur at the cell center.

CDM assigned *Drain* conditions to the following areas:

- Specific known springs or groups of springs in the upper McAllister Valley area, such as McAllister and Abbot Springs, and seeps discharging water to adjacent wetlands.
- Along the east-facing face of the lower McAllister Valley in layers 1 and 3 to simulate seepage from the Qvr and Qvr Aquifers situated above the valley floor.
- Lines of springs above the Nisqually River in the Qva Aquifer (the entire river reach) and the upper part of the river for the Qc Aquifer layers where the base of the model layer is above the river stage.
- Along Puget Sound in model layers 1 (Qvr) and 3 (Qva), whose base elevations are above sea level, to allow shallow groundwater to exit the model.

3.8 Kettle Lakes

The model represents the principal kettle lakes using MODFLOW's *River* package. This function calculates the flow between a lake and surrounding aquifer using a head-dependent relationship involving the head in the aquifer in the adjacent cells, a fixed lake stage, a bed elevation, and a lake bed conductance coefficient representing flow resistance provided by lake bed deposits. So, when the lake stage is higher than the surrounding aquifer head, flow will take place from the lake to the aquifer, and vice-versa. CDM assigned stage and bed elevations for Hicks, Pattison, Long, Southwick, and St. Clair using the lake records provided in the USGS Water-Supply Bulletin 43 (USGS, 1976). Model data for the lakes not covered in this report were based on the Thurston County Model.

Lake St. Clair presents a special case of a suite of linked kettle lakes with bottoms below the local water table and lake level as much as 50 ft above the water table. This lake is of interest in the study because of the potential for the cone of influence from the proposed pumping to impact the ambient flow relationship between the lake and aquifer system.

As discussed earlier, CDM estimated as part of the *McAllister Baseline Monitoring Program* that 76 percent of the total seepage is derived from 59 percent of the lake floor located above the water table under average annual conditions. The total flux of water from Lake St. Clair to the McAllister Gravel unit was estimated as 4,032 AFY by the USGS (Drost et al., 1999). CDM employed a combination of MODFLOW's *River* and *Recharge* packages (Section 3.5) to represent this discharge in the model. The *River* package represented the head-dependent flow of water between the lake and aquifer in response to changing water table levels. Under average conditions, this

total flux was estimated to be approximately 970 AFY. The *Recharge* package simulated the remaining 3,060 AFY that is believed to seep through the steep lakebed sides. The *River* condition cells were assigned to cells in model layers 4, 5, and 6 (**Figures 3-19, 3-20 and 3-21**). The lake bed conductance term of these cells was a primary variable calibration parameter.

Table 3-3 summarizes the other key kettle lakes incorporated into the model.

Table 3-3 Key Kettle Lake Details

Kettle lake	Ave. Stage (ft MSL)	Bottom Elevation (ft MSL)	Unit
Pattison	158	135	Qvr, Qvt
Long	158, 154	137, 149	Qvr, Qvt
Hicks	162	127	Qvr, Qvt
Hewitt	128	122	Qvt
Ward	126	122	Qvt
Chambers	187	182	Qvr, Qvt
Lake St. Clair	73	20 (north kettles) -20 (south kettle)	McAllister Gravel

3.9 Streams and Rivers

CDM used MODFLOW's *River* package to represent the main internal streams and rivers in the model area. This required assignment of a river stage and river bed elevation for each cell, and a river bed conductance value that represents the generally low permeable sediments, which provide resistance to flow between the river and aquifer. The stage elevations were based on those assigned in the USGS Thurston County Model and were confirmed using the USGS topographic sheet. **Table 3-4** summarizes the features of the main internal rivers used in the model.

Table 3-4 Key River and Stream Details

Stream/River	River Stage (ft MSL)	River Bed (ft MSL)	Model Layer/Aquifer
McAllister / Medicine	8.0	7.0	Layer 4 (Clay Cap)
Eaton Creek	150 – 201	151 – 202	Layer 1 (Qvr)
Thompson River	307 – 330	306 – 329	Layer 1,2 (Qvr, Qvt)
Spurgeon Creek	194 – 211	193 – 210	Layer 1 (Qvr)
Woodard Creek	110 – 161	109 – 160	Layer 1 (Qvr)
Woodland Creek	19 – 159	18 – 158	Layer 1 (Qvr)

CDM estimated the average annual river stages using the USGS topographic sheet. The boundaries for the Deschutes River were no-flow conditions for all layers apart from layer 3 (Qva), which was assigned a constant head of between 108 and 220 ft MSL. The Nisqually River was represented using constant heads in the layers that are in communication with the river and *Drain* conditions for layers that are above the river stage. No flow conditions were assigned to boundary cells in layers 7 through 9 along the entire reach of the Nisqually River in the model area (**Figures 3-22 and 3-23**).

3.10 Other Boundary Conditions

Puget Sound/Budd Inlet

The model represents the aquifer boundaries that are above sea level along the Puget Sound and Budd Inlet using *Drain* cells (as seeps and springs). Freshwater equivalent constant heads (0.5 ft MSL) are used to represent the boundaries for the Qc and TQu Aquifers along the Puget Sound and Budd Inlet.

Upgradient Boundary

No natural hydrologic feature exists at the upgradient model extent that could be used as a boundary. However, to allow groundwater to freely enter the model from the higher upland area south of Yelm and Rainier, CDM assigned constant heads to the boundary cells in layers 2, 3, and 5 through 9. The head elevations ranged from 320 to 420 ft MSL and were determined based on the USGS Thurston County Model results.

Section 4

Model Calibration

4.1 Calibration Objectives

Calibration of a groundwater flow model involves adjusting specific model components to adequately represent field-observed piezometric heads, flows, and gradients. The primary calibration objectives for the McAllister Model were to:

- (1) First achieve a steady-state calibration based on a set of long-term average hydrologic conditions (in this case, a combination of primarily fall 1988 and averaged fall 1994-99).
- (2) Then achieve a transient calibration in which monthly / annually simulated heads at specific observation wells in the wellfield area and flows at key springs, rivers, and lakes reasonably match historical observed values over the period 1989-99.

To achieve steady-state calibration described here, CDM adjusted specific model properties and stresses to simulate an average set of groundwater conditions. Hydraulic properties were varied within a reasonable range for the lithologies present. Truly static conditions never occur in the model area, as piezometric heads in all aquifers are continually changing in response to changing recharge and discharge stresses. Therefore, CDM assumed that average conditions may be approximated by averaging the winter high and summer low water levels during the available time period.

Transient (or dynamic) calibration will be conducted following steady-state calibration, and will involve adjusting the model to simulate the monthly varying conditions, and reproduce heads and gradients, within a reasonable range, over a longer period. This will test the model's ability to mimic actual historical conditions under the full range of seasonal stresses.

4.2 Steady-State Calibration

4.2.1 Targets

At project start-up, CDM, with stakeholder input, designated the key steady-state calibration targets as:

- Reproduce model-wide groundwater flow directions and gradients similar to those defined in the conceptual model (**Figures 2-6 through 2-9**). These consisted of a principal flow direction from south to north, with flow exiting the model area at the Puget Sound, Budd Inlet, and Nisqually and Deschutes River boundaries.
- Match, to a reasonable degree, the available field-observed water levels in wells located (1) primarily in the detailed McAllister area, and (2) secondly in the entire model area.

- Reproduce the groundwater divide between the McAllister and Nisqually Valleys, whereby northward flow diverges at the nose of the Fort Lewis uplands toward the Nisqually River and the McAllister Springs area.
- Achieve a reasonable simulated flow at McAllister Springs of 23 to 40 cfs and total upper McAllister Valley spring discharge of 50 to 60 cfs.
- Simulate water in Lake St. Clair recharging the aquifer system at a total rate of 4,030 AFY, which consists of about 970 AFY from head-dependent sources and 3,060 AFY from fixed recharge.

CDM generated a water level calibration set consisting of 243 measurements (**Figures 2-6** through **2-9**). Because the McAllister area is considered of highest importance to achieving the model objectives, CDM generated a smaller observation data set consisting of 94 observation wells within a rectangular area of approximately 16 square miles centered on the McAllister Wellfield. Two data sets are available for steady-state calibration.

USGS' Thurston County Model Dataset

The largest water level data set was developed and used by the USGS for the Thurston County Model, and generally covers the period from June to October 1988. For the purpose of this model, CDM considered these data to reasonably represent long-term average annual levels. However, during measurement, the USGS recorded that the wells were either flowing, actively pumping, recently pumped, or near an active pumping well. Also, the USGS documented that many of the wellhead reference elevations and locations used to calculate the water level elevation were not surveyed and were estimated based on topographic maps. These factors cast some doubt on the accuracy and reliability of the reported water levels for use as calibration targets. Because of these uncertainties of the true water level elevation, reliability weighting factors were developed for use in statistical characterization of model calibration (discussed later). Sixty-eight of the 211 USGS model water levels were located in the detailed area of the model.

McAllister Baseline Monitoring Program Water Levels

The second calibration data set included recent water levels in 29 wells measured by CDM and the City of Olympia as part of the *McAllister Baseline Monitoring Program*. These data consist of multiple measurements collected at varying frequencies, depending on the well owner. For example, the City collected daily water levels between 1992 and 1999 in its monitoring wells MW-1 through MW-4, located in the McAllister Wellfield area. Conversely, quarterly readings were available from several private wells between 1995 and 1999.

To determine a single representative water level for these wells, CDM calculated the average measured water level for the period of record. Twenty-six of the *McAllister Baseline Monitoring Program* water levels are located within the detailed study area.

Figures 4-1 and **4-2** show the locations of key observation wells used for the calibration in the McAllister and Lake St. Clair areas.

Statistical Reliability Weighting

As mentioned above, the calibration water levels for the entire model and McAllister area contain varying degrees of uncertainty in the accuracy of the measurements. These inaccuracies potentially include:

- Inaccurate wellhead or ground surface elevation references.
- Nearby pumping wells could influence water levels.
- Selection of a single, average annual water level based on a range of available data.

To account for this uncertainty, CDM developed a weighting system to apply to water levels as part of the statistical analysis for the model calibration output results. The weighting system also included a geographical weighting so that the wells located within the McAllister area were assigned a higher importance than those nearer the model margins. **Tables 4-1** and **4-2** list the weighting system, and **Figures 4-3** and **4-4** show the geographical sub-areas. The difference between the observed and model-predicted water level (also referred to as the residual) was multiplied by the appropriate weighting factor to give the weighted residual.

Table 4-1 Statistical Weighting for Observation Well Water Levels in Entire Model

Model Area	USGS Data	Baseline Monitoring Program
McAllister Area	See Table 4-2	
N of McAllister	0.3	0.5
NW of McAllister	0.3	NA
West/Olympia area	0.3	NA
Yelm/Rainier (SE/SW)	0.2	NA

Note: NA – no wells in this group

Table 4-2 Statistical Weighting for Observation Well Water Levels in McAllister Area

Model Area	USGS Data	Baseline Monitoring Program
McAllister Gravel	0.75	1
Tri-lakes	0.6	0.8
SW of McAllister Gravel	0.5625	0.75
SE of McAllister Gravel	0.6	0.8
N of McAllister Gravel	0.5625	0.75

The steady-state head calibration criteria defined in CDM's work scope were:

- Level 1 – target residual = ± 5 feet. Most wells in the McAllister area.
- Level 2 – target residual = ± 10 feet. Most wells in the lower McAllister and Nisqually River area.

- Level 3 – target residual = ± 15 feet. Most wells in the western portion of the Lacey uplands and cells adjacent to the USGS model.

4.2.2 Calibration Methodology

CDM grouped the main model parameters for the purpose of calibration as follows:

- Primary calibration parameters:
 - Aquifer and confining unit hydraulic conductivity (K_h and K_v)
 - Precipitation-derived recharge
 - Lake St. Clair and McAllister Valley spring conductance values
- Secondary calibration parameters:
 - Other river, kettle lake, and spring conductance values
 - Constant head elevations for Nisqually River and southeast boundary
- Non-variable:
 - Other river and kettle lake stage and bed elevations
 - Constant head elevations for Puget Sound, Budd Inlet, and Deschutes River
 - Well pumping rates

After achieving an initial stable steady-state model, CDM performed a series of test runs to determine the relative sensitivity to the primary and secondary calibration parameters. This involved varying each parameter individually by between ± 10 percent from the initial values, running the model to steady-state, and recording (1) the change in modeled heads at the observation well set and (2) the model-predicted flows at the key hydrologic features (Lake St. Clair seepage, McAllister Springs discharge, and lateral boundary flows). The results of these runs indicated that the heads and fluxes were most responsive to changes in layers 8 and 9 (TQu) material properties, the McAllister Gravel properties, and precipitation-derived recharge. CDM then tested the capabilities of the automatic parameter estimation tool PEST (Hill, 1992) to assist with formal steady-state calibration. However, as the model run times were prohibitively long (more than 24 hours), CDM did not perform any additional assessment using PEST. Therefore, CDM employed standard heuristic calibration methods, which involved manually adjusting sensitive parameters within a reasonable range and noting the impact on heads and flows.

4.2.3 Steady-State Calibration Results

4.2.3.1 Groundwater Flow Results

Figures 4-5 through **4-8** illustrate the steady-state calibrated flow fields in the Qvr, Qva, Qc and TQu units in the model domain. In each case, the groundwater flow conditions are generally similar to those for the conceptual model described in Section 2. **Figures 4-9** and **4-10** show the groundwater flow conditions in north-south and west-east sections.

Qvr (Layer 1, Figure 4-5)

Key feature of the flow in the Recessional Outwash (Qvr) aquifer are:

- Northward flow toward the McAllister and Tri-lakes areas, discharge via high-elevation seeps above Budd Inlet and Puget Sound (combined 7.2 cfs), and discharge into shallow Woodland (6.3 cfs) and Woodard Creeks (3.3 cfs).
- A relatively flat head gradient near Long and Hicks Lakes where heads are about 160 to 165 ft MSL. Groundwater recharge occurs to the Qvr at Chambers Lake.
- Both Spurgeon and Eaton Creeks receive water from the Qvr unit (6.2 and 3.1 cfs, respectively).
- No water exits the model from the *Drains* assigned to cells along the east-facing slope of the McAllister Valley.

Qva (Layer 3, Figure 4-6)

Key feature of the flow in the Advance Outwash (Qva) aquifer are:

- Groundwater moves northward toward the McAllister and Tri-lakes areas, then either discharges along the Nisqually River, Puget Sound, and McAllister Valley (as high-elevation springs and seeps); enters the McAllister Gravel unit; or moves downward to the Qc Aquifer beneath the Tri-lakes area.
- Springs and seeps located above the Nisqually River discharge at about 19.4 cfs. The Qva unit discharges a net of 28 cfs along the Deschutes River to the south of Olympia.
- Modeled heads across the Tri-lakes area range from 159 to 166 ft MSL. These three lakes combined receive about 3.1 cfs (2,550 AFY) net from the Qvr Aquifer. Only Hicks Lake delivers water to the aquifers (about 0.5 cfs). The relatively permeable “window” through the Qvt unit allows heads in Qva to be similar to those in the Qvr unit (**Figure 4-9**).
- The springs along Budd Inlet and Puget Sound discharge a combined 4.6 cfs (3,310 AFY) from the Qva. The springs along the western McAllister Valley discharge a combined 3.1 cfs (2,260 AFY).

Qc (Layers 5 and 6, Figure 4-7)

Modeled heads in the Sea Level (Qc) Aquifer indicate:

- Groundwater moves northward from the southeastern boundary toward the McAllister region, and either converges on the McAllister Valley or moves northward to discharge into the Puget Sound.
- modeled heads in the McAllister Gravel range from 13 feet MSL near McAllister Springs to 70 ft MSL south of Lake St. Clair.
- The springs above the upper Nisqually River discharge a combined 19 cfs from the Qc unit, and about 13 cfs discharges from this unit into Puget Sound via constant head cells.
- Despite contributing 50 percent of the total groundwater pumping in the entire model, the pumping in the Qc unit has minimal impact on regional flow pattern.
- Whereas heads in the Qva and Qc units are similar in the area south of Lake St. Clair, a head difference of 80 ft exists between these two units in the Tri-lake region (**Figure 4-10**).

TQu Unit (layer 8, Figure 4-8)

Modeled heads in the undifferentiated (TQu) aquifer indicate:

- Groundwater moves northward from the southeastern boundary toward the McAllister region, and either converges on the McAllister Valley or moves northward to discharge into Puget Sound.
- The TQu unit discharges about 112 cfs to Puget Sound and Budd Inlet.
- Inflow across the southeastern boundary in the TQU unit is about 26,900 AFY, which is 88 percent of the total for all units.

4.2.3.2 Calibration Head Results

Figures 4-11 through **4-12** present modeled flow fields and weighted residual (observed minus modeled) head values at wells in the McAllister area for model layers 3 and 5 (which both include part of the McAllister Gravel unit). Statistical summaries of these results for wells by layer are shown in **Tables 4-3** (for the McAllister area) and **4-4** (for the entire model). These tables summarize the calibration in terms of the following statistics:

- *Obs. range* is the range of observed water levels (in feet) for all wells in the layer or group of layers.
- *Residual mean (Res. Mean)* is computed by dividing the sum of residuals by the number of residuals.
- *Residual standard deviation (Abs. SD)* is a measure of the overall spread of residuals.

- *Absolute residual mean (Abs. RM)* is calculated using the absolute value of the error (only positive values) and is a measure of the average error in the model.

Table 4-3 Weighted and Unweighted Calibration Statistics for McAllister Area

Layer(s)	No. Obs. Wells	Obs. Range (ft)	McAllister Area – Weighted			McAllister Area - Unweighted		
			Res. Mean	Res. SD	Abs. RM	Res. Mean	Res. SD	Abs. RM
1-9	96	204.2	0.56	14.57	9.6	0.27	19.81	13.9
1	8	54.4	-3.79	9.08	7.1	6.31	15.13	11.8
3	23	95.6	-0.05	10.75	8.8	-0.08	18.53	15.0
4-6	49	134.6	0.25	12.67	8.5	-0.24	16.53	11.8
7-9	16	181.2	4.78	23.07	16.1	5.99	29.8	19.9

Table 4-4 Weighted and Unweighted Calibration Statistics for Model

Layer(s)	No. Obs. Wells	Obs. Range (ft)	Entire Model – Weighted			Entire Model – Unweighted		
			Res. Mean	Res. SD	Abs. RM	Res. Mean	Res. SD	Abs. RM
1-9	243	361.7	0.65	11.87	8.1	2.15	30.46	20.9
1	16	80.2	-4.66	7.48	6.3	-12.86	17.53	15.6
3	91	336.7	-2.77	8.85	6.8	-9.59	26.03	19.5
4-6	100	317.8	2.78	11.32	8.2	9.44	26.65	19.9
7-9	36	360.0	6.04	17.13	11.9	19.33	39.49	29.8

Figures 4-13 and **4-14** plot the calibration results in terms of the (1) observed head versus the modeled head and (2) observed head versus the weighted residual for the McAllister area and the entire model.

- The weighted residuals for more than 50 percent of the modeled water levels for 53 wells located in the proposed McAllister Wellfield and McAllister Gravel unit area (measured heads between 10 and 75 ft MSL) were within the ± 5 feet range (**Figure 4-13**).
- More than 75 percent of the weighted residuals for these 53 wells were within the ± 15 feet range.

- The weighted residuals for the 28 wells located upgradient of the McAllister Gravel with observed heads between 150 and 200 feet above MSL also mostly fall within the ± 5 feet range and all within the ± 15 feet range.
- Within the entire model domain, 85 percent of the weighted residuals for the 243 wells fall within ± 15 feet (**Figure 4-14**).

Those wells with a residual greater than ± 15 feet in the McAllister area are:

- (1) Three wells in the TQu unit with observed heads between 130 and 180 feet above MSL (modeled heads too low; weighted residual >0). These wells are located near the Tri-lakes, and this result indicates that the model over-predicts the vertical head gradient between the Qc and TQu units in this area.
- (2) Five wells in the Lacey Uplands area with observed heads between 25 and 40 feet MSL (modeled heads too high; weighted residual <0). These results indicate that the modeled gradient from this area toward the McAllister Gravel area in the Qc unit is higher than observed.
- (3) Four wells in the Nisqually Terrace area with observed heads between 40 and 65 feet above MSL (modeled heads too low). This indicates that model under-simulates the groundwater divide between the lower Nisqually River and upper McAllister Valley.

Nisqually Flow Divide

Figure 4-6 illustrates how the model reproduces the flow divide between the McAllister Springs area and the Nisqually River identified in the conceptual model. Although the model heads at the key observation wells named Casebolt and Lakeside are too low by as much as 17 ft, the model simulates a reasonable representation of the divide. CDM made attempts during calibration to better simulate the divide by (1) lowering K_h and K_v properties in the Qva and Qc Aquifers and (2) increasing local recharge. However, these efforts were unsuccessful in raising the modeled heads to the desired level. Currently, insufficient reliable lithologic and observation well water levels data exist in this area to improve the model.

Flow in the McAllister Gravel

Figures 4-11 and **4-12** present the groundwater flow conditions in the McAllister Gravel area and surrounding Qva and Qc Aquifers. The model simulated dry conditions in model layers 2 and 3 (the base elevation of layer 3 between the McAllister Springs and Lake St. Clair is between 17 and 30 ft MSL). Flow converges from the surrounding units to the higher-permeable gravel and a sharp drop in head is evidenced from the Qva to Qc zones.

McAllister and Nearby Springs

According to the conceptual model, the McAllister and Abbott Springs on average discharge between 23 and 7.5 cfs (16,650 and 5,430 AFY). Numerous other seeps exist in the upper McAllister Valley area that discharge to the surrounding wetlands and flow in the McAllister Creek. Also, many higher elevation springs exist above the

valley floor. The spring conductance values were adjusted during calibration runs to obtain the target discharge rate.

Lake St. Clair

As discussed in Section 3, the model represents the transfer of water between the kettle lakes and the surrounding McAllister Gravel Aquifer using a combination of fixed recharge (3,060 AFY) for lake perimeter cells and a head-dependent term for the central cells, where an estimated annual 970 AFY is recharged from the higher lake stage to the aquifer. During calibration, CDM adjusted the lakebed sediment conductance term for the central cells to achieve this flux.

4.2.4 Water Budget

Tables 4-5 and **4-6** present the steady-state calibration water budget, separated for each *MODFLOW* component and for the key hydrologic features. The model shows the following results:

- The overall inflow and outflow compare favorably to the conceptual water budget summarized in **Table 2-2**. The difference between the conceptual and modeled flow (83,000 AFY) is largely due to higher than expected lateral flows across constant head boundaries. These flows are often the most difficult to estimate from available field data.
- Precipitation-derived recharge (246,400 AFY) is the largest single contributor of inflows to the model area.
- The exchange between the internal streams, creeks, and kettle lakes and the aquifer system is relatively small, providing a net outflow from the system of 23 cfs (16,700 AFY).
- The major springs (including the McAllister area springs) and seeps (such as those located above the Nisqually River and Puget Sound) together discharge about 130 cfs, which is about 25 percent of the total steady-state outflow.
- Pumping (14,970 AFY) contributes less than 4 percent of the total system outflows.
- Of the total net flux exiting the model as flow across the Nisqually River (77,700 AFY), 38,000 AFY discharges through the 2-mile contact with the McAllister Gravel.
- The inflow across the southeastern constant head boundary (30,240 AFY) is about 60 percent of the estimated precipitation recharge that occurs for the roughly 38-square-mile area underlain by unconsolidated sediments outside this boundary line, assuming an average recharge rate of 25 inches per year.

Table 4-5 Mass Balance Summary

Feature	INFLOW		OUTFLOW		Notes
	cfs	AFY	cfs	AFY	
Constant heads	179	129,700	353	253,400	Includes SE boundary, Puget Sd., Budd Inlet, and Nisqually and Deschutes R.
Recharge	345	249,640	-	-	Includes 3,200 AFY for Lake St. Clair.
Pumping	-	-	21	14,970	Based on 1988-89 conditions.
Rivers	5	3,660	28	20,340	Includes streams and lakes.
Drains	-	-	130	94,300	Includes springs, side-valley seeps.
Totals	529	383,000	529	383,010	

Table 4-6 Mass Balance Summary for Key Hydrologic Features

Feature	Net Flux		Notes
	Cfs	AFY	
McAllister Springs	-29.6	-21,400	<i>Drain</i> cells, elevation 6.5 ft MSL; layers 4 and 5.
McAllister-area spring / seeps	-69.6	-50,400	Includes McAllister, Abbott Springs, and seeps supporting local wetlands / streams.
W. McAllister Valley	-3.1	-2,300	<i>Drain</i> cells in layers 1 and 3.
Lake St. Clair	+5.2	+3,770	Combined <i>River</i> cells and fixed <i>Recharge</i> (3,060 AFY).
Tri-lakes	-3.1	-2,550	Pattison, Long, and Hicks (all <i>River</i> cells; layers 2 and 3).
Eaton Creek	-2.1	-1,520	<i>River</i> cells in layer 1
Spurgeon Creek	-6.2	-4,475	<i>River</i> cells in layer 1
McAllister / Medicine Creeks	-1.9	-1,360	<i>River</i> cells in layer 4
Southeastern boundary	+41.8	+30,240	Constant head inflow (layers 2, 3, 5-9)
Puget Sound	-65.4	-47,400	Constant heads and <i>Drains</i>
Budd Inlet	-59.8	-43,300	Constant heads and <i>Drains</i>
Deschutes River	-31.5	-22,800	Constant heads (layers 3, 5)
Nisqually River – above Muck Creek	-68.8	-49,800	Combined Constant head and <i>Drain</i> cells;
Nisqually River – below Muck Creek	-38.6	-27,900	Combined Constant head and <i>Drain</i> cells

Note: (-) = net flow out of model; (+) = net flow into model.

4.3 McAllister Springs Capture Zone Analysis

CDM used the steady-state calibrated model to determine the capture zone for McAllister Springs under existing hydrologic conditions. This involved the following:

- Inserting a ring of 12 particles (radius 125 feet) into the model surrounding the *Drain* cells representing McAllister Springs. The particles were inserted in model layers 4 and 5.
- Assigning porosity values of 0.35 for the McAllister Gravel unit, 0.25 for the other aquifers (Qvr, Qva, Qc, and lower TQu), and 0.15 for the aquitards (Qvt, Qf, and upper TQu layer).
- Using the transport advection code *MODPATH* to calculate the migration pathlines of these particles in the flow field for a maximum of 20 years, using a computational time-step of one month.

The capture zone results for the McAllister Springs under existing conditions are shown in **Figure 4-15** (after 1 year), **4-16** (after 5 years) and **4-17** (after 10 years). These plots show the tracks of all particles released in the system, regardless of the model layer in which the particle is traveling at any time. **Figure 4-18** shows the pathlines for the particles initially released in layer 5 with the layer identified by the line color. For example, a group of particles initiates as recharge water between Pattison and Long Lakes in layer 4 (blue), migrates downward into the Sea Level Aquifer (layers 5 and 6, orange and purple), enters the McAllister Gravel and heads northward in layers 7 and 8 (maroon and olive) before moving upward to discharge at McAllister Springs in layer 5. Many of the particles discharged by McAllister Springs enter the system at Lake St. Clair before heading northward, and some initiate in the TQu (layer 8) south of the lake and migrate beneath the lake once in the McAllister Gravel. **Figure 4-19** shows the flowpaths for particles along a north-south section through McAllister Springs.

The effective 10-year capture zone for McAllister Springs is defined as the outer envelope of these tracks in three dimensions. The zone is about 0.5 mile wide within the McAllister Gravel and barely extends to the wellfield area. No particles track upgradient to the Nisqually River, which reflects the effect of the Nisqually groundwater divide.

4.4 Transient Calibration

This section will appear in the Final Report.

Section 8

References

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Appendix A

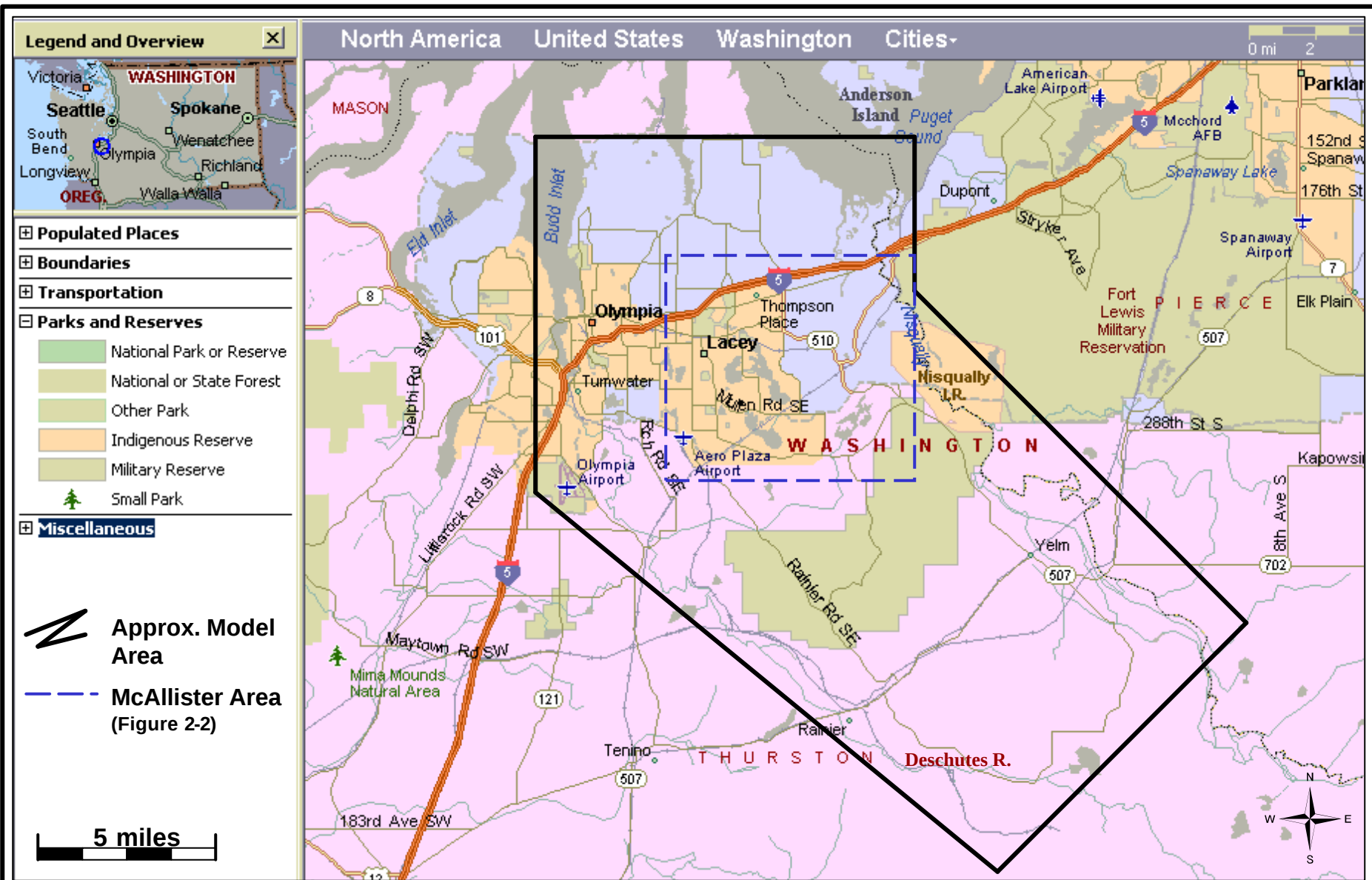
Model Layer Surface Elevation Figures

Appendix B

Time-Varying Water Levels for Key Calibration Wells

Appendix C

Technical Review Comments Response

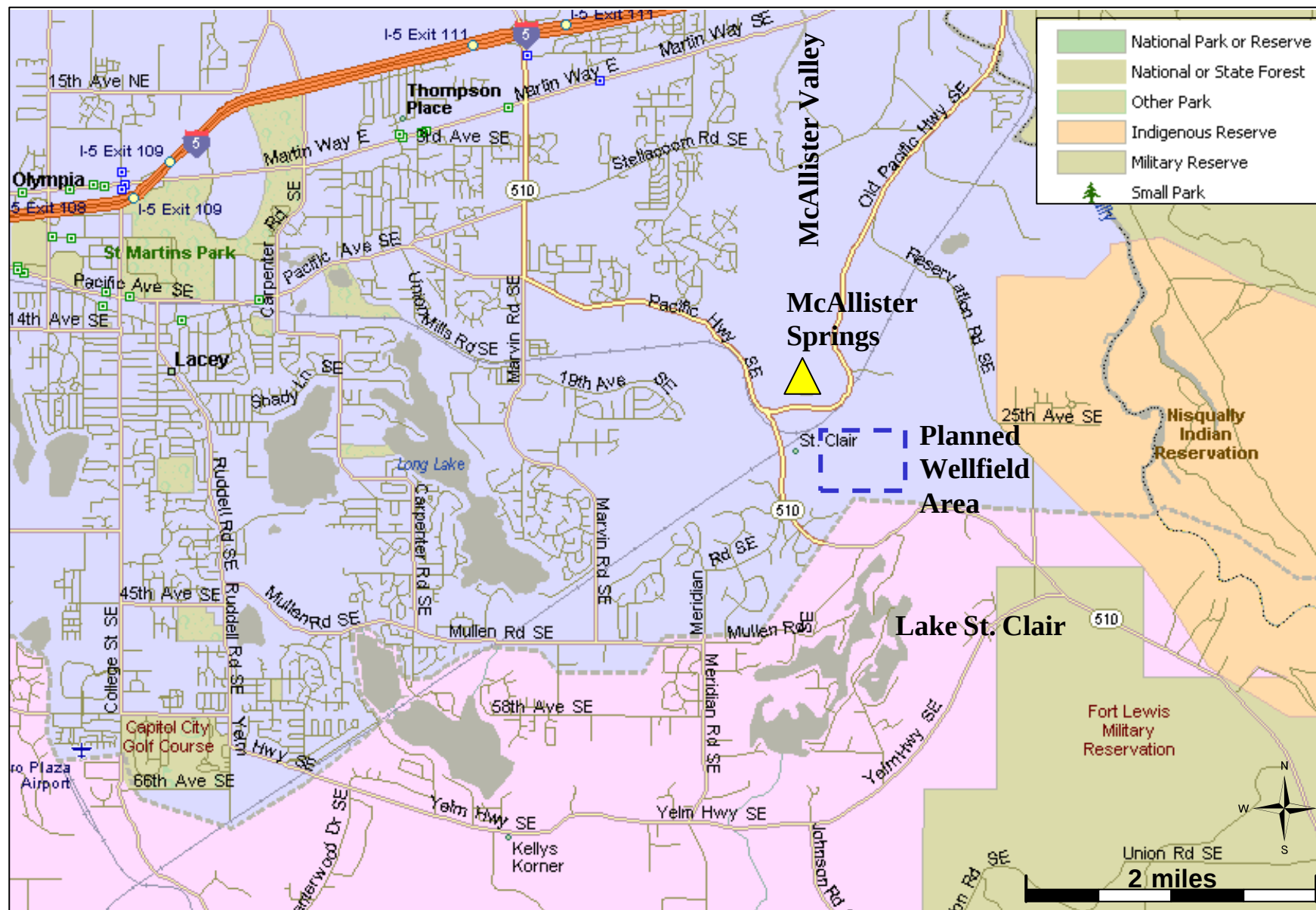


CDM

City of Olympia – McAllister Wellfield Numerical Model

McAllister Model Area

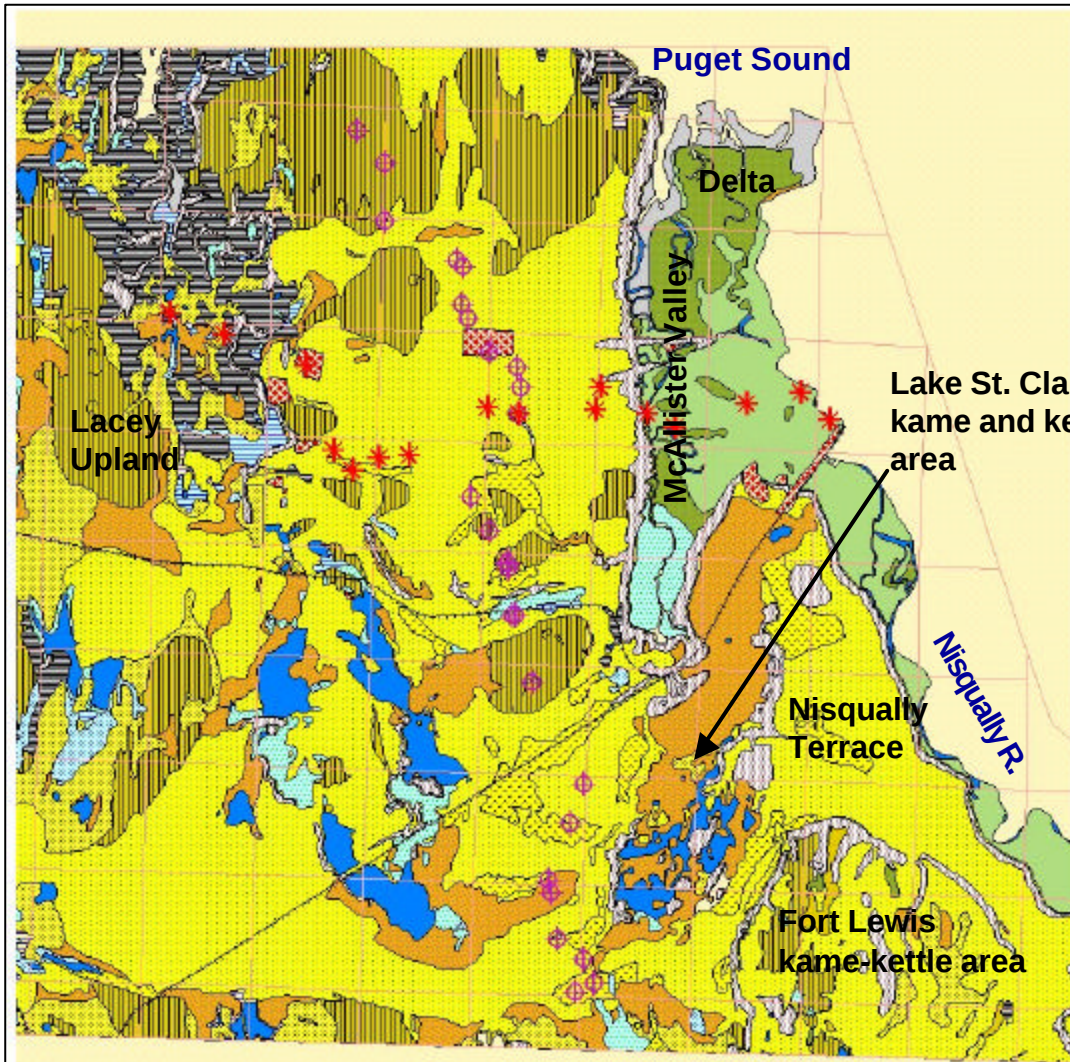
Figure 2-1



City of Olympia – McAllister Wellfield Numerical Model

McAllister Area

Figure 2-2



Legend

- Alluvium - Poorly Drained
- Alluvium - Well Drained
- Bedrock - Basalt
- Depression Fill - Alluvium
- Depression Fill - Lacustrine
- Depression Fill - Organic
- Disturbed Land
- Drainageways - Poorly Drained
- Ice Contact (kames, etc.)
- Outwash - Coarse
- Outwash - Coarse - Steep
- Outwash - Fine
- Outwash - Fine - Steep Slopes
- Outwash - Fine/Lacustrine
- Outwash - Lacustrine
- Tidal Flats
- Till - Compact
- Till - Compact - Depression
- Till - Loose
- Till - Steep Slopes
- Water

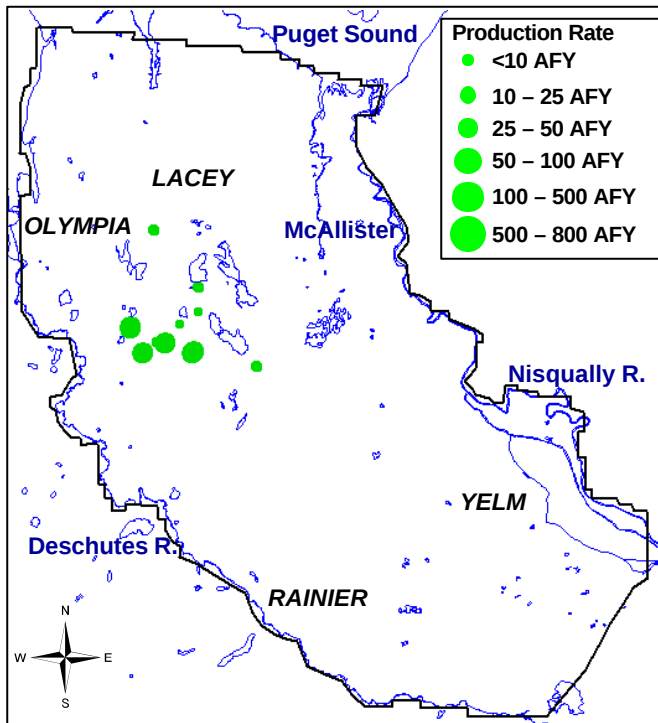
2 miles

Reference: *Baseline Monitoring Study* (CDM, 1999)

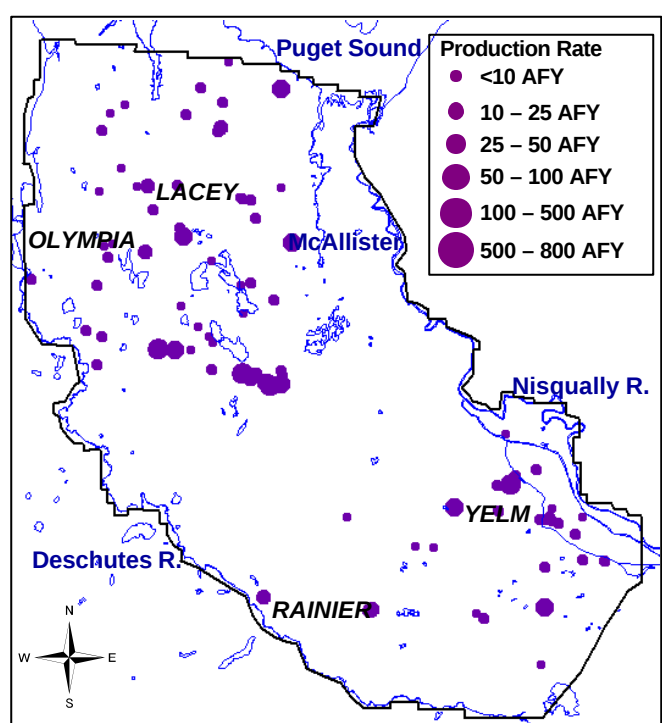


City of Olympia – McAllister Wellfield Numerical Model
Surficial Geology of McAllister Area

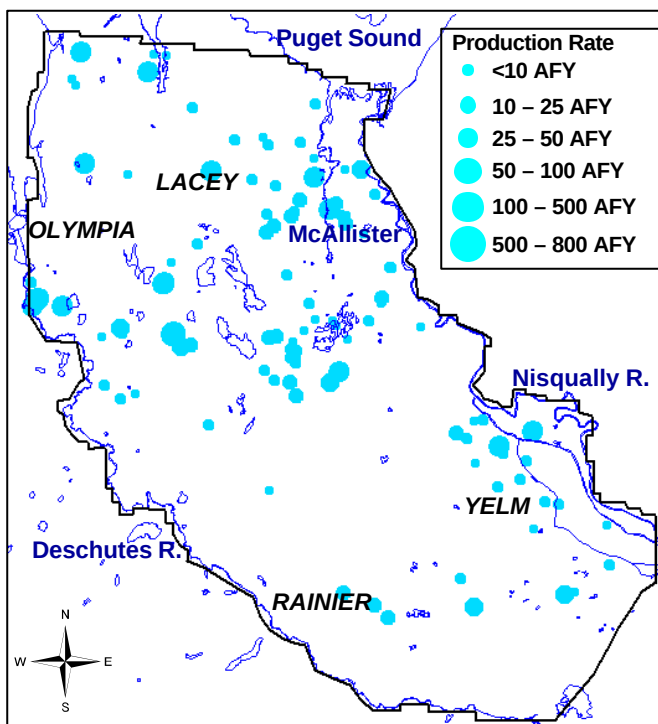
Figure 2-3



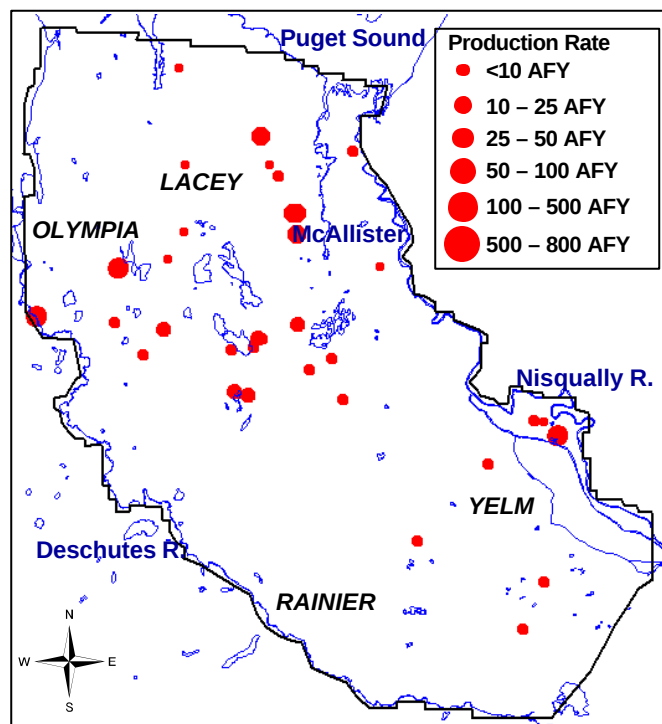
(a) Recessional Outwash Aquifer (Qvr)



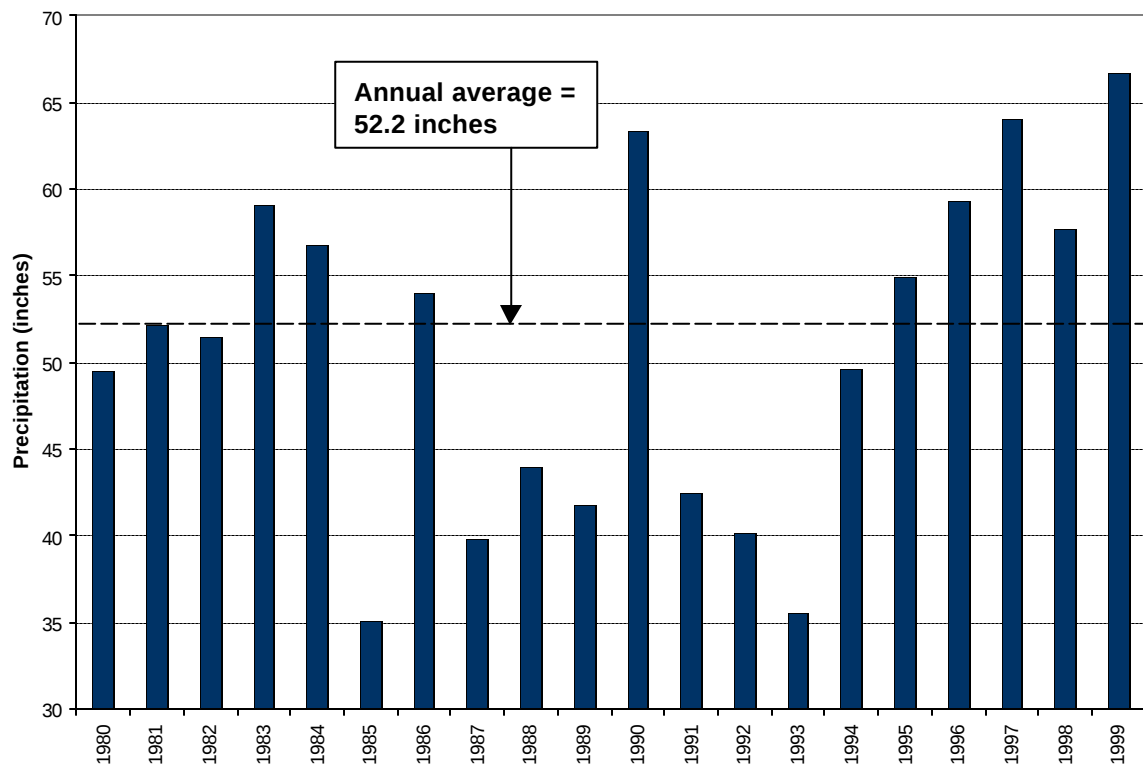
(b) Advance Outwash Aquifer (Qva)



(c) Sea-level Aquifer (Qc)

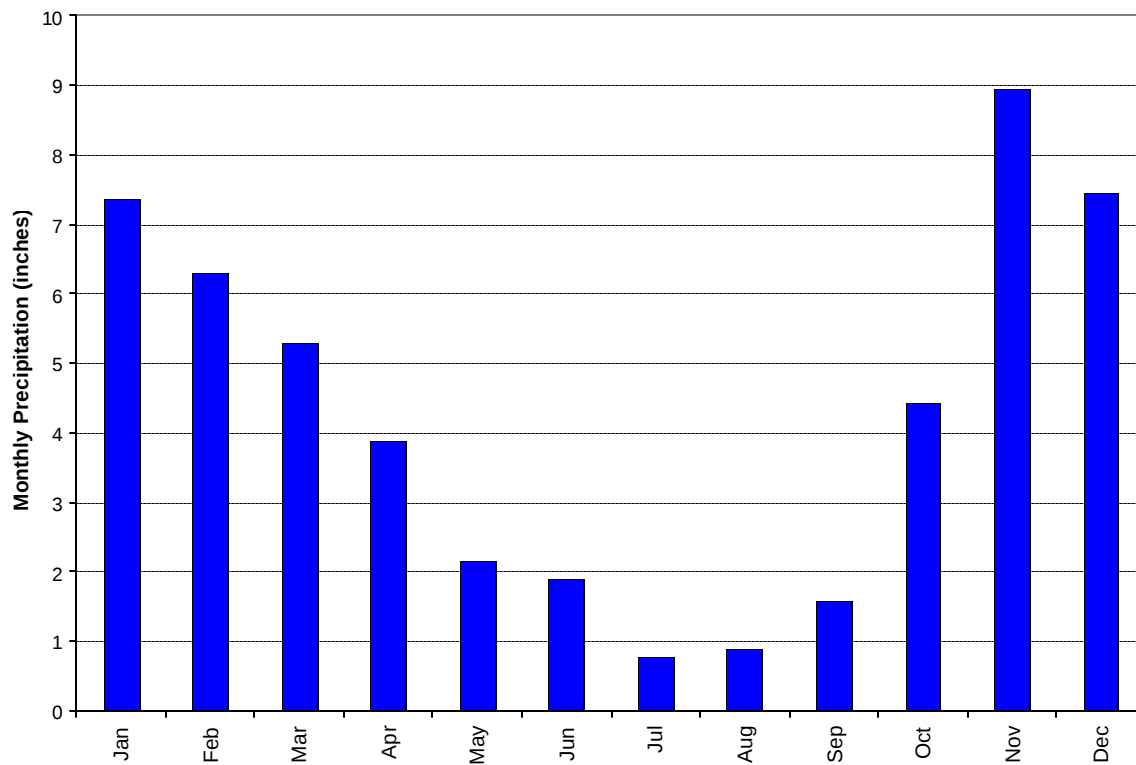


(d) Undifferentiated Aquifer (TQu)



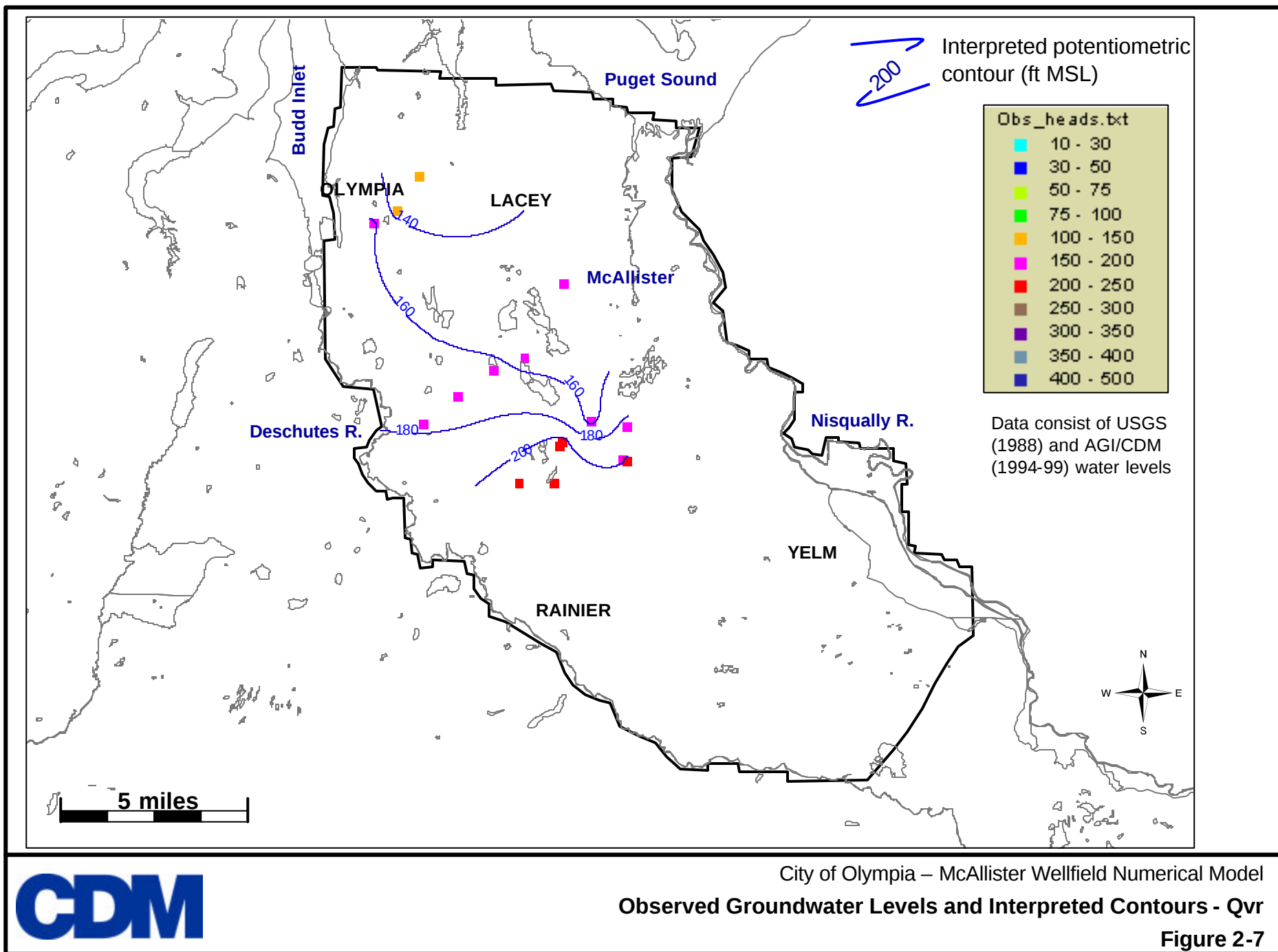
City of Olympia – McAllister Wellfield Numerical Model
Annual Precipitation at Olympia Airport (1980-99)

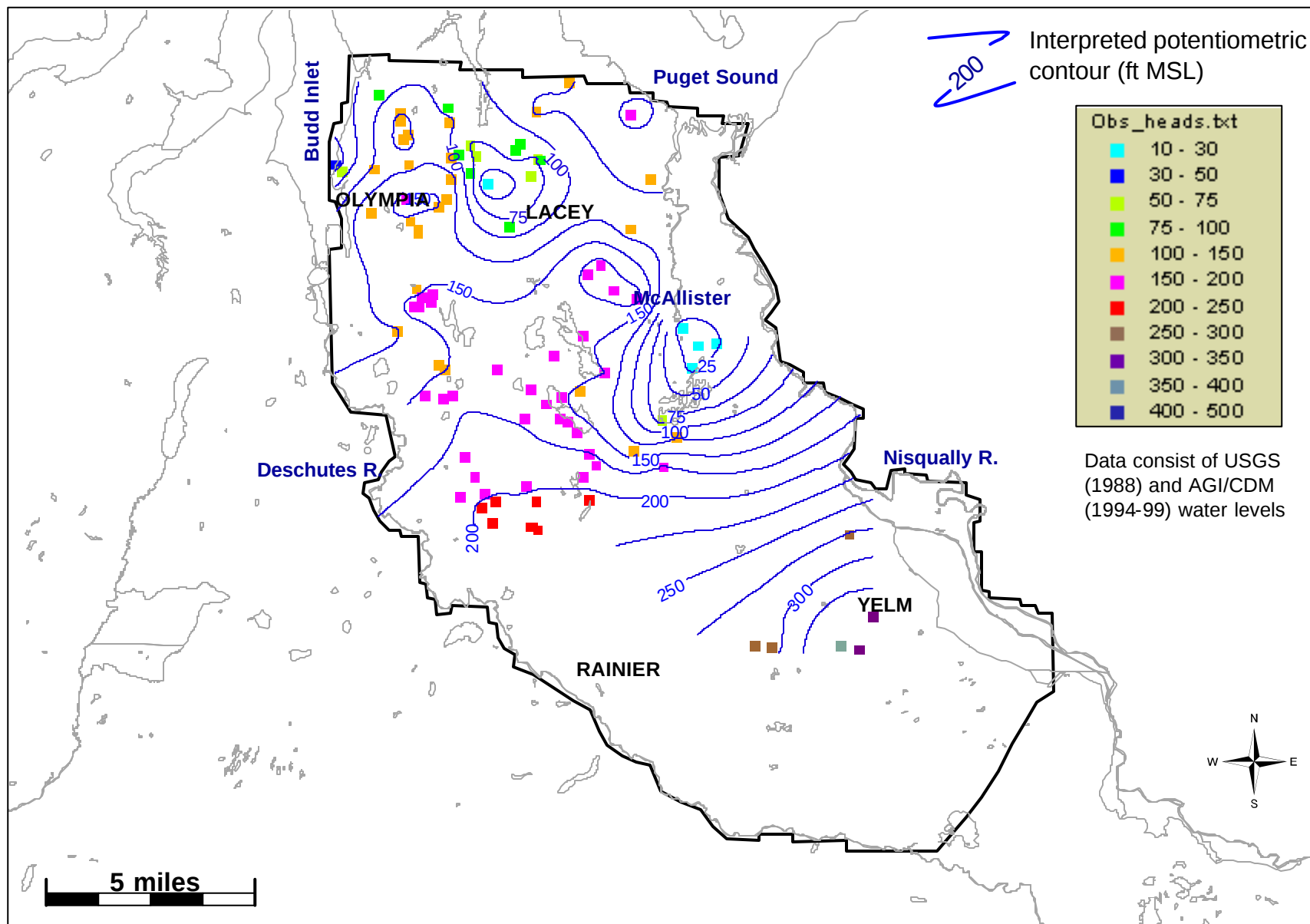
Figure 2-5

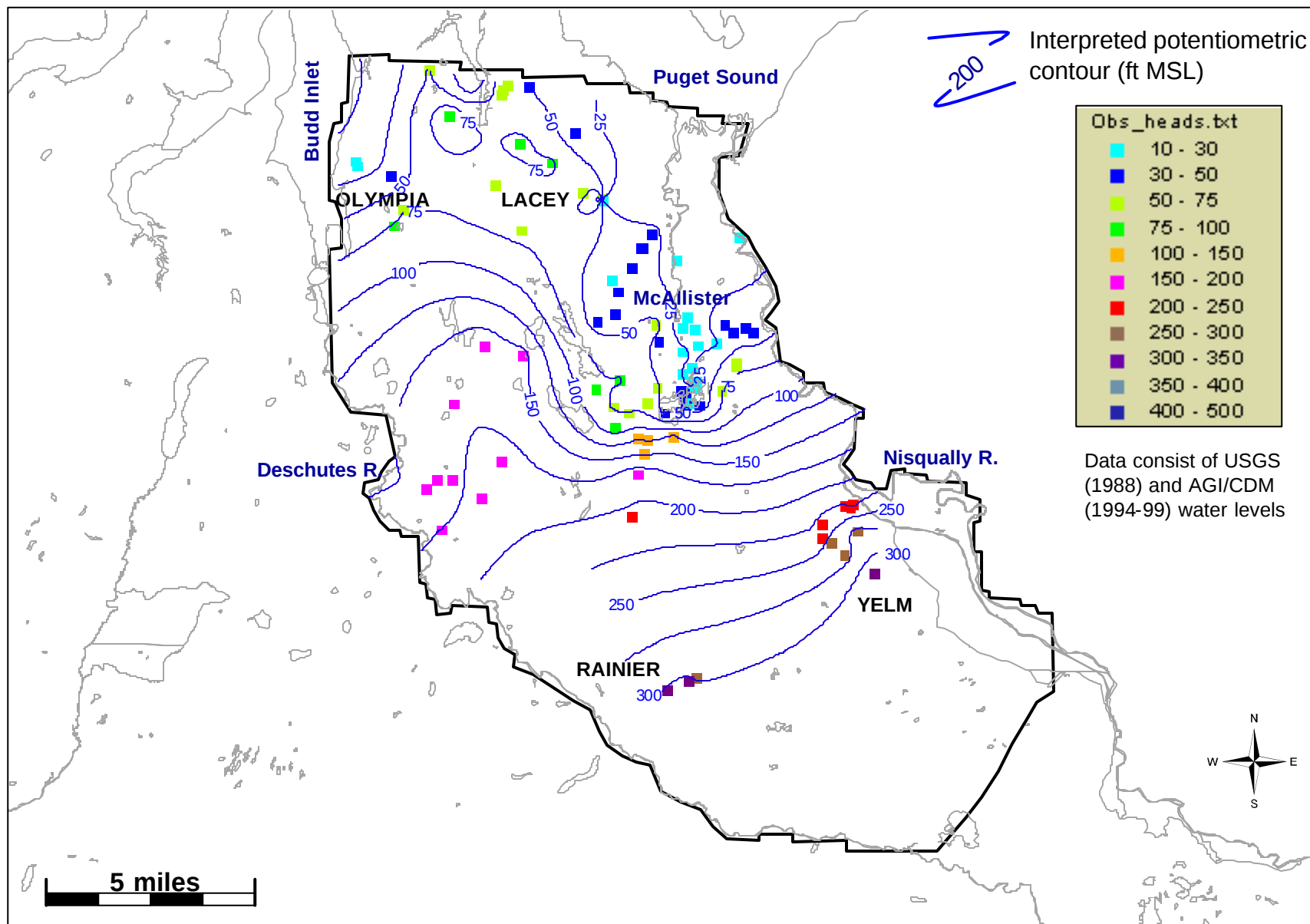


City of Olympia – McAllister Wellfield Numerical Model
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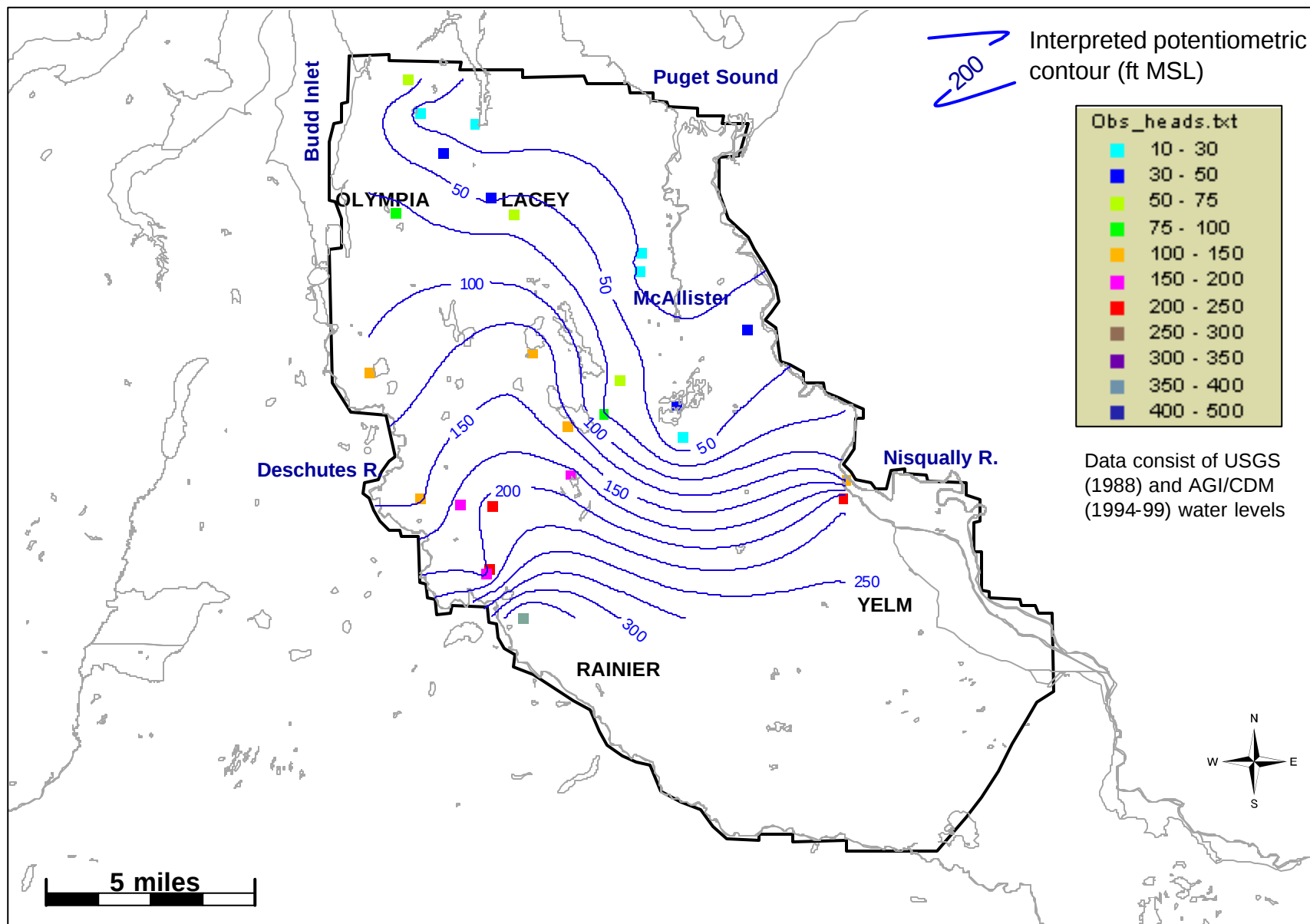
Figure 2-6



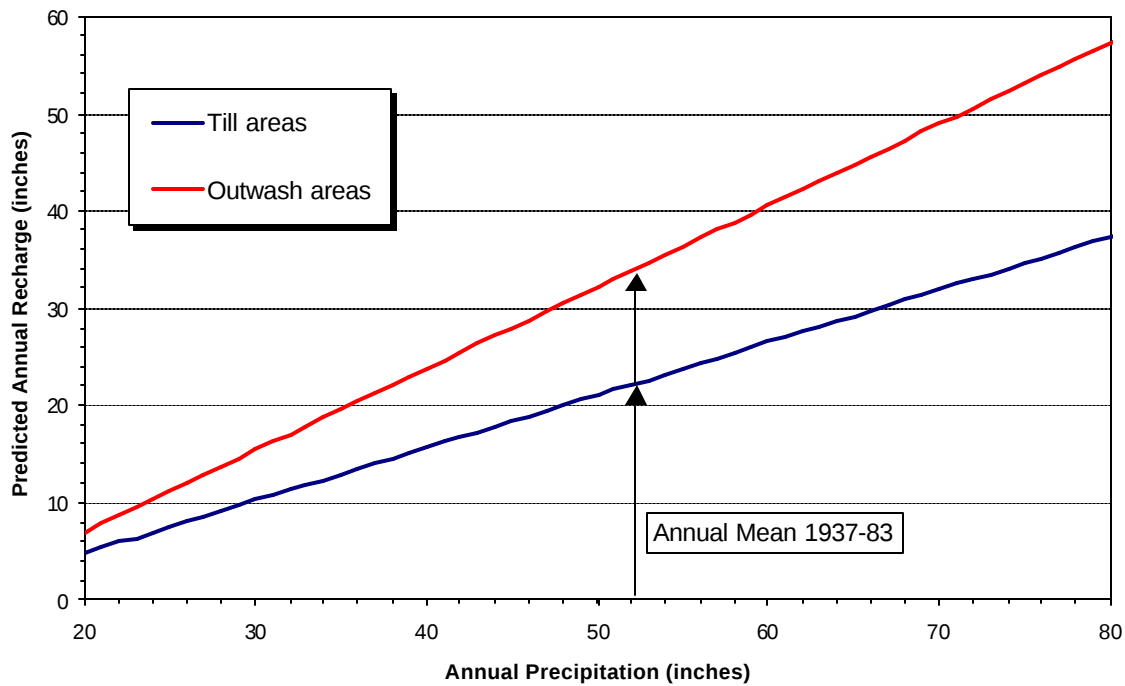




City of Olympia – McAllister Wellfield Numerical Model
 Observed Groundwater Levels and Interpreted Contours - Qc
 Figure 2-9

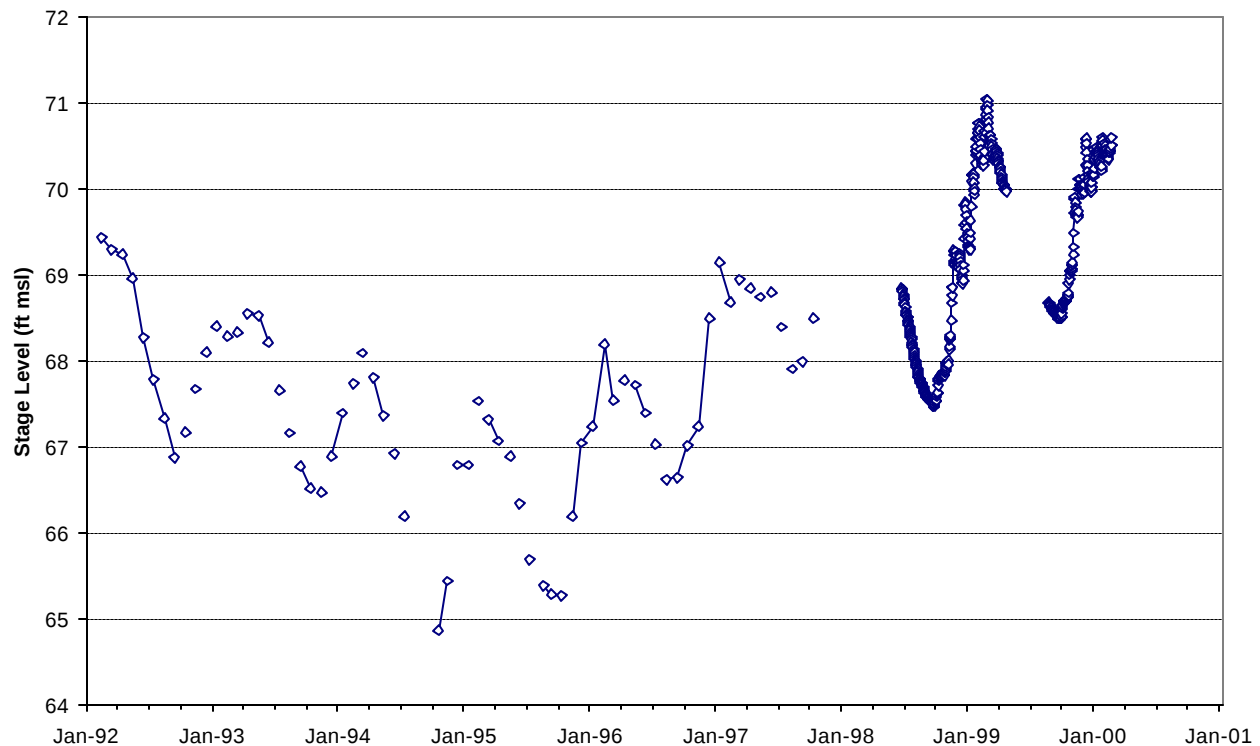


Data consist of USGS (1988) and AGI/CDM (1994-99) water levels



City of Olympia – McAllister Wellfield Numerical Model
Precipitation-Groundwater Recharge Model

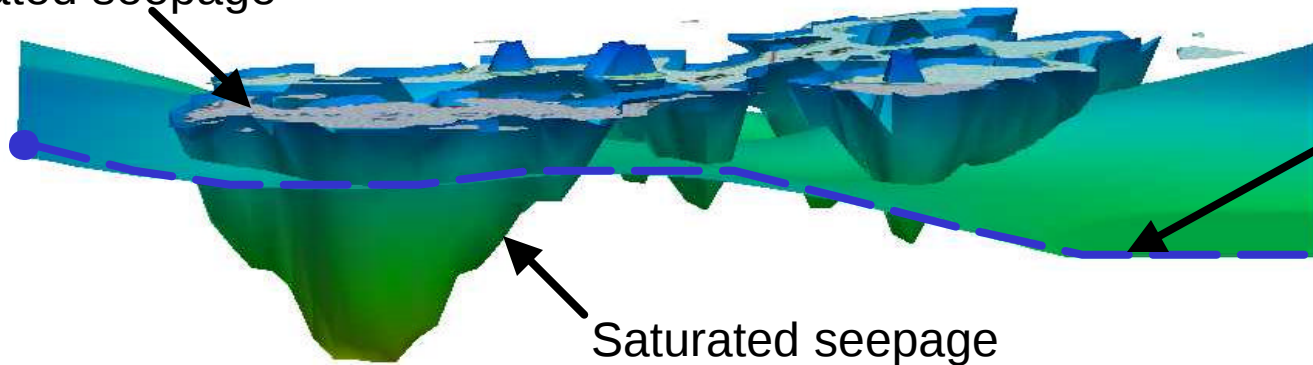
Figure 2-11



City of Olympia – McAllister Wellfield Numerical Model
Lake St. Clair Stage Level 1992-2000

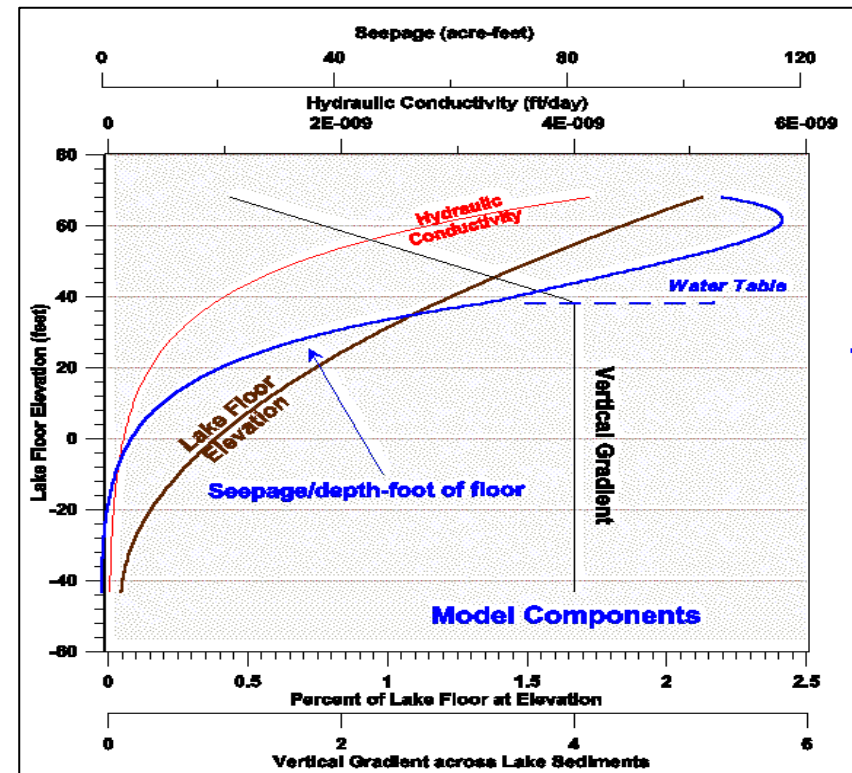
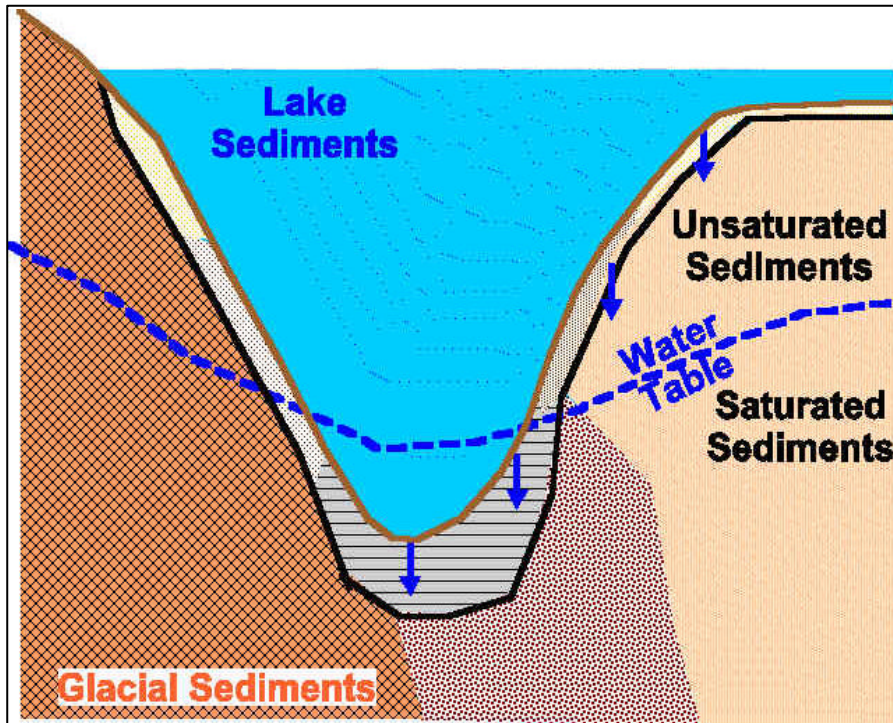
Figure 2-12

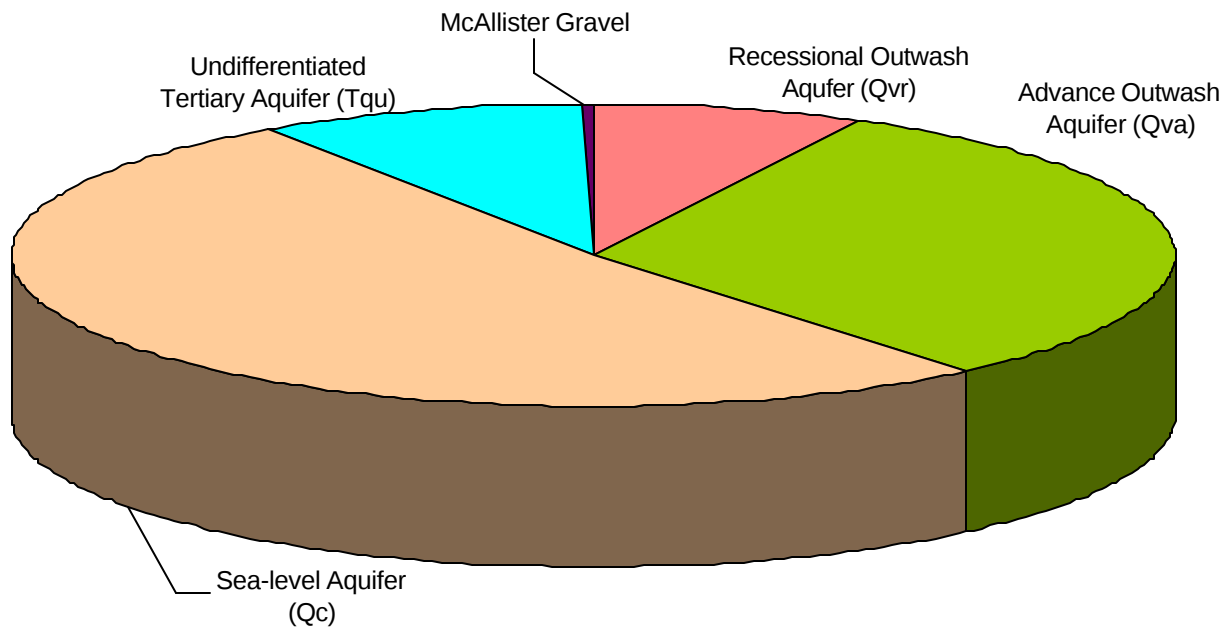
Unsaturated seepage



Water table

Saturated seepage

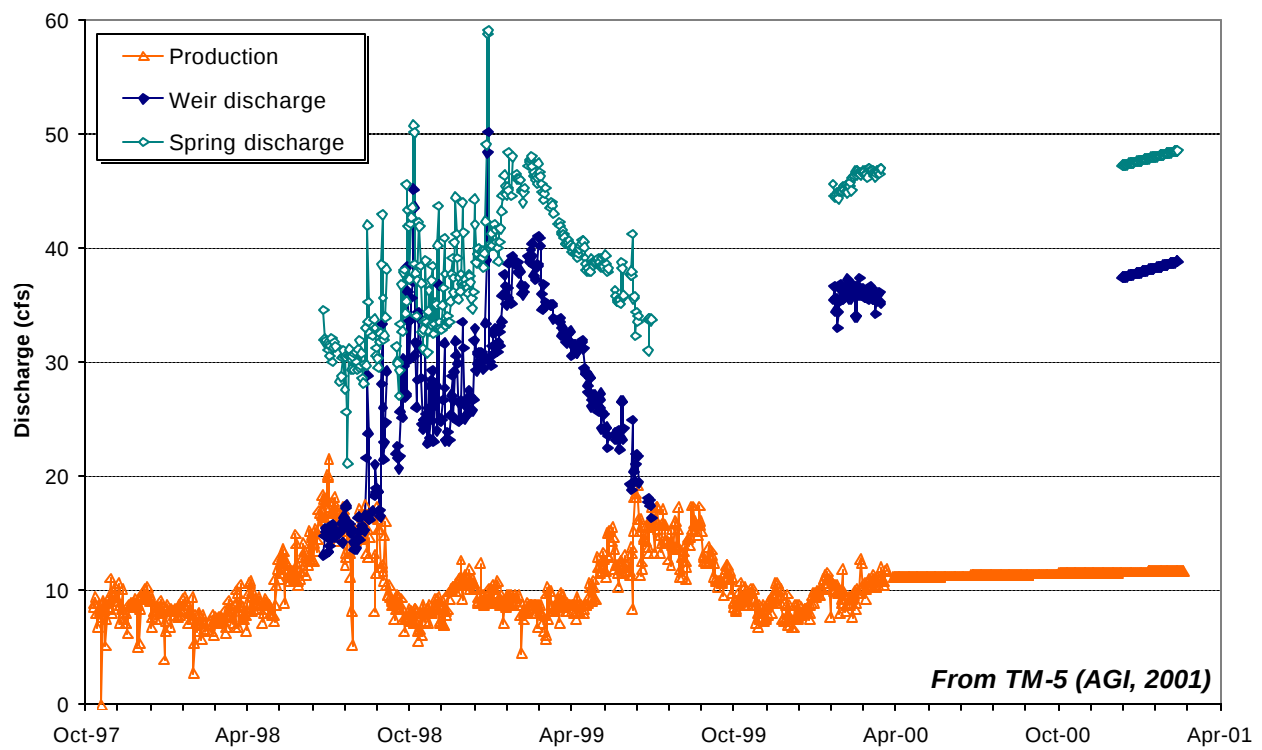




City of Olympia – McAllister Wellfield Numerical Model

Aquifer Pumping by Aquifer

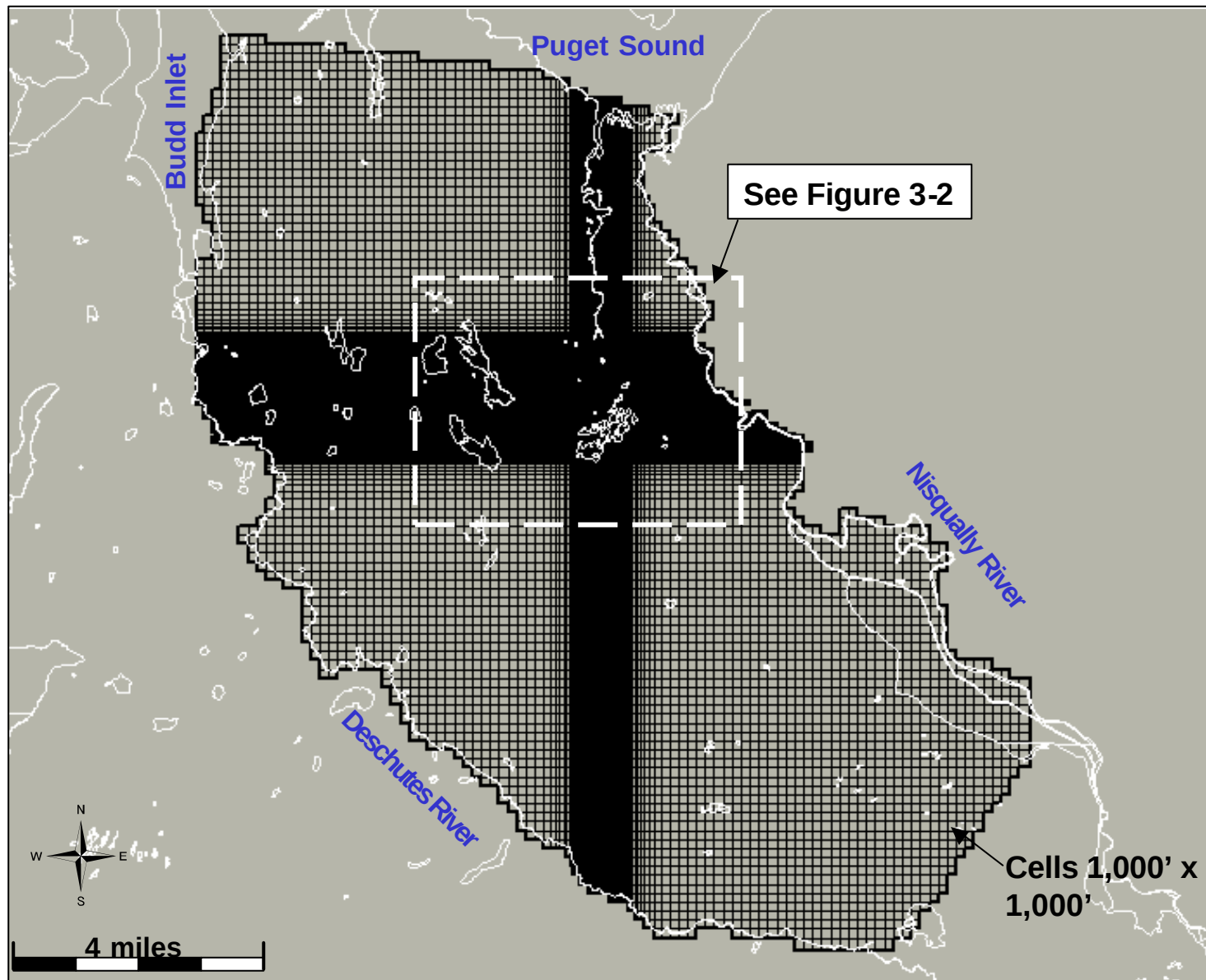
Figure 2-14



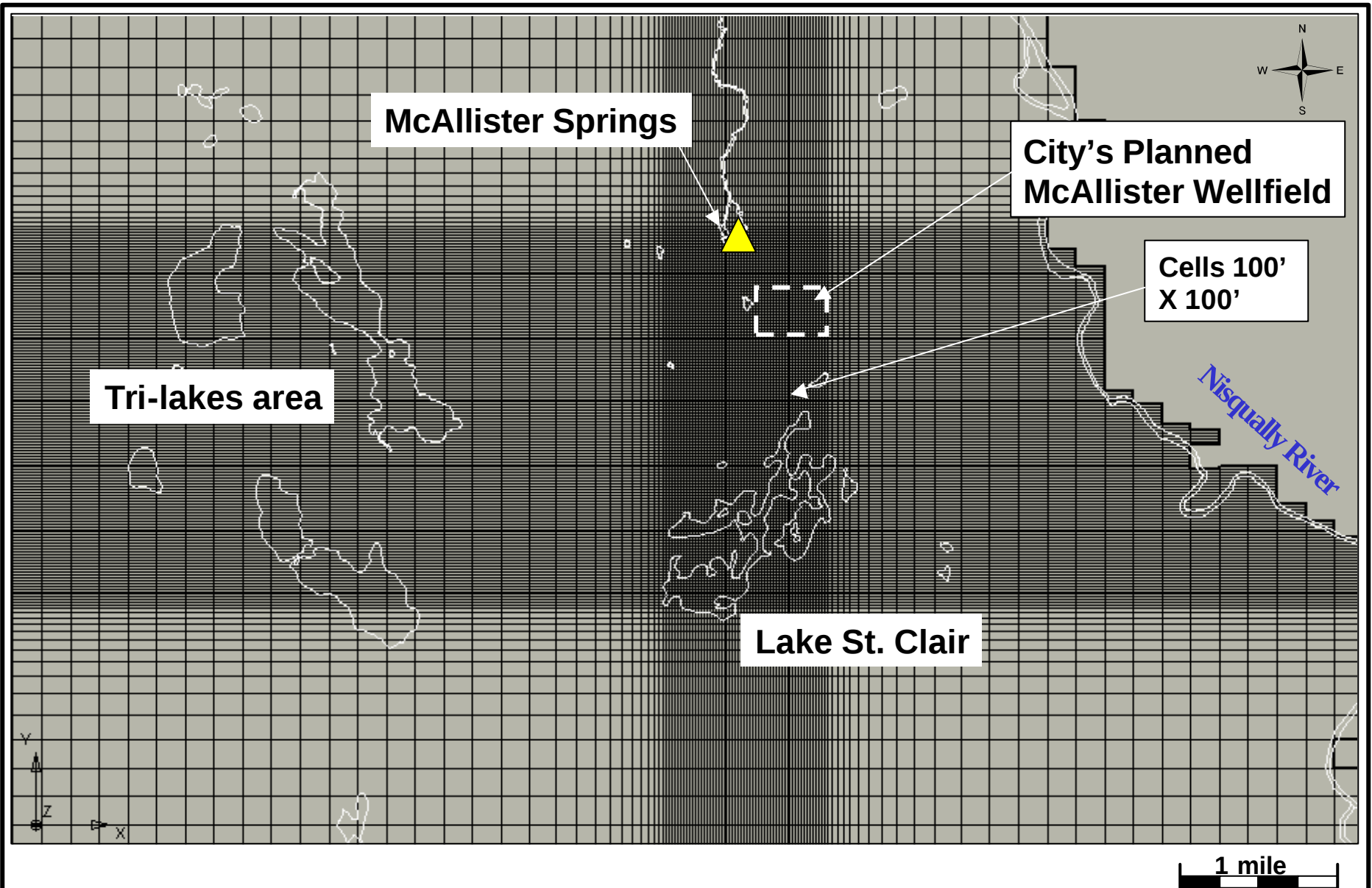
City of Olympia – McAllister Wellfield Numerical Model

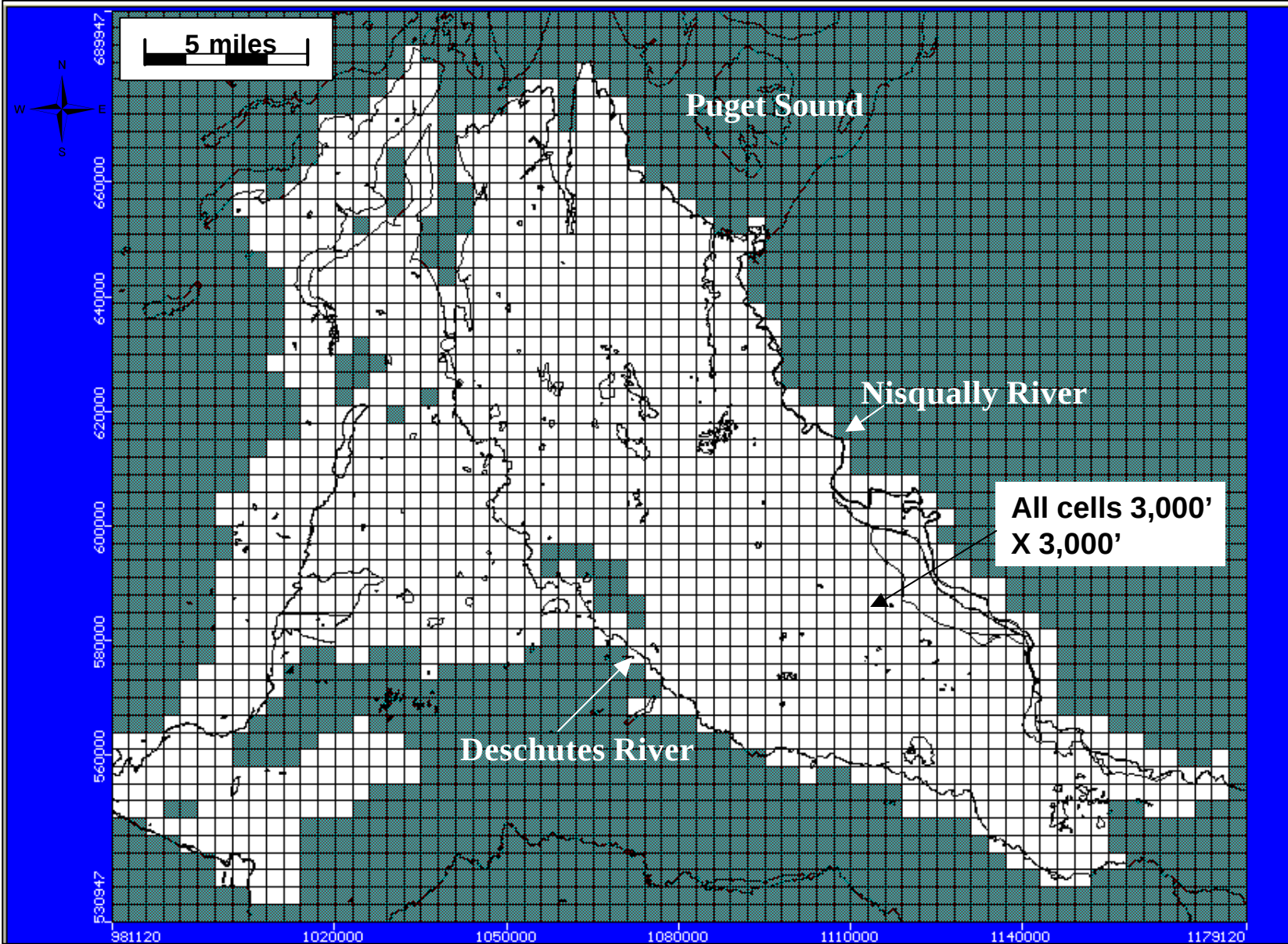
McAllister Spring Discharge 1997-2001

Figure 2-15

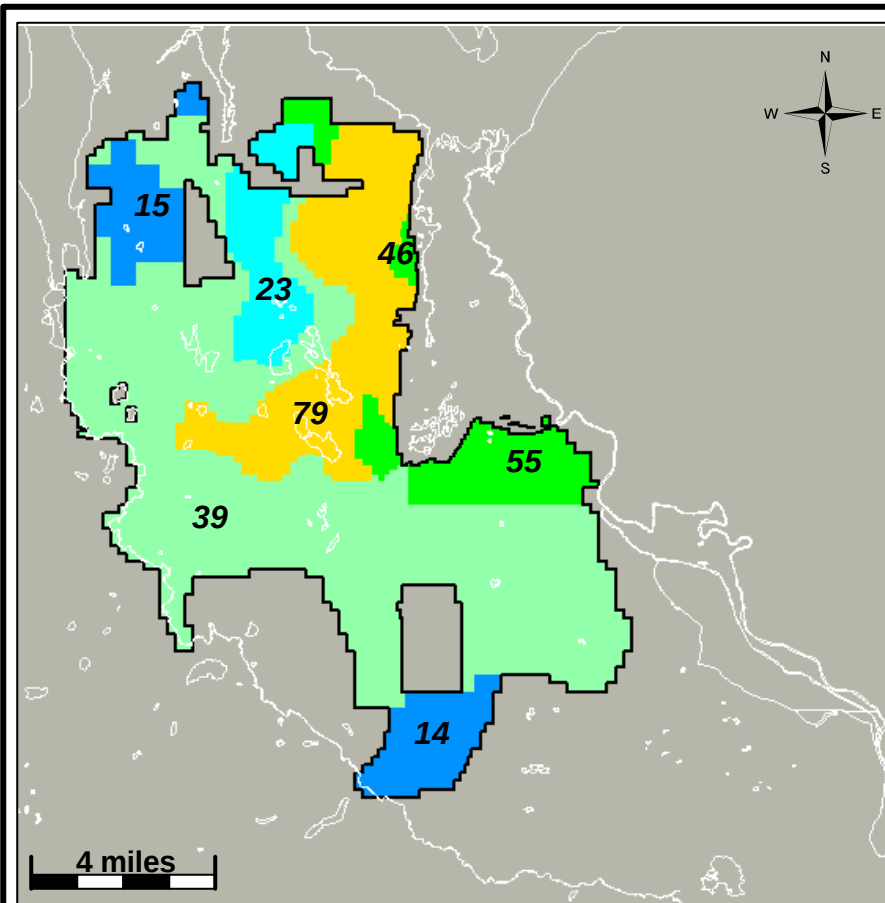


City of Olympia – McAllister Wellfield Numerical Model
Finite-difference Grid for the Model Domain
Figure 3-1





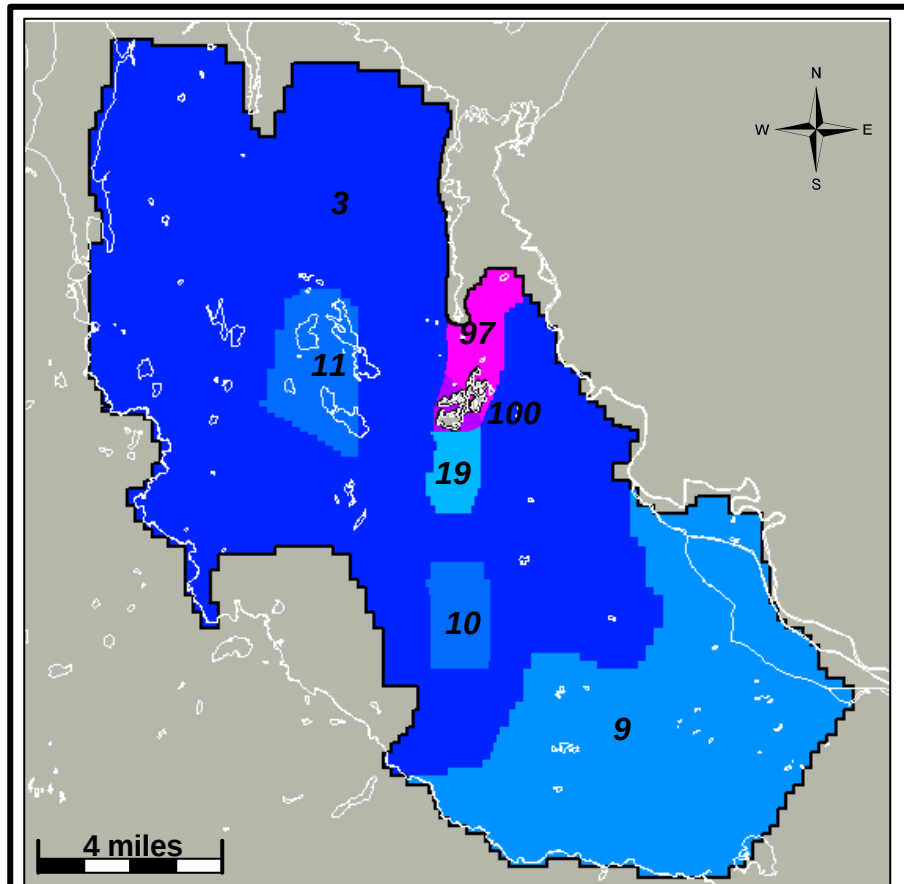
City of Olympia – McAllister Wellfield Numerical Model
USGS' Thurston County Model Grid
Figure 3-3



Zone No.	K_h	K_v		Zone No.	K_h	K_v	(ft/day)
14,15	16	4		46	60	15	
23	32	8		55	120	25	
39	100	25		79	100	50	



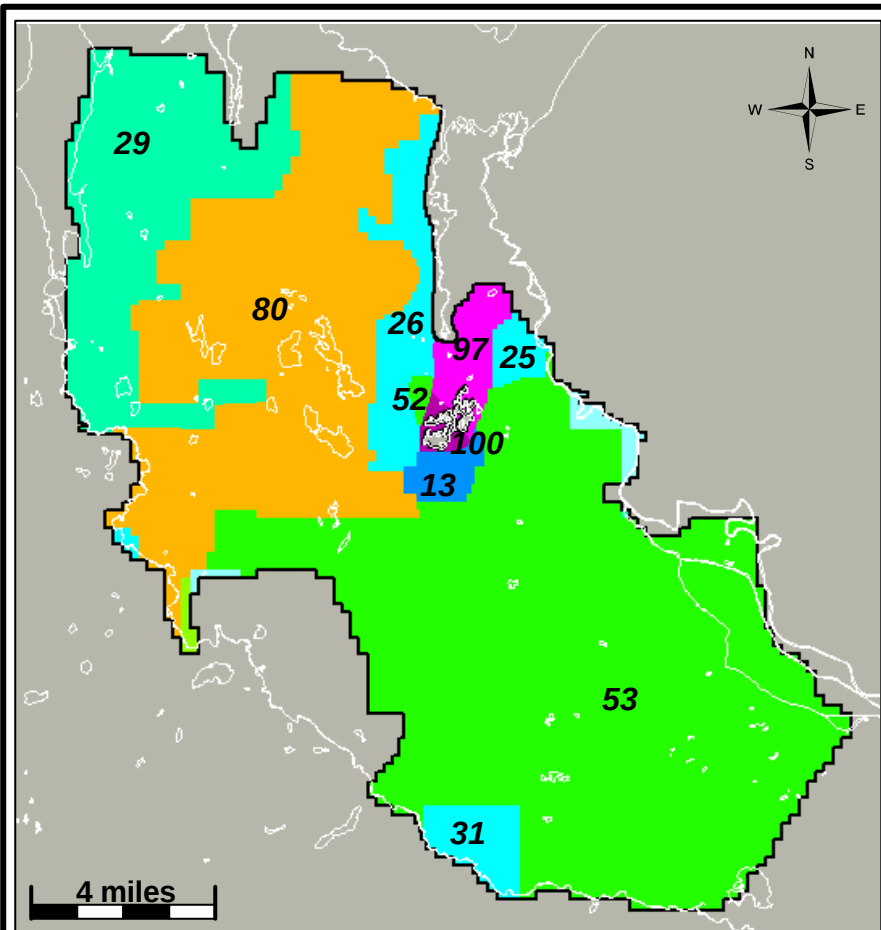
City of Olympia – McAllister Numerical Model
Hydraulic Conductivities in Layer 1 (Qvr)
Figure 3-4



Zone No.	K_h	K_v		Zone No.	K_h	K_v	(ft/day)
3	1	0.0025		19	20	2	
9,10	3	0.015		97	2000	400	
11	1	0.1		100	100	10	



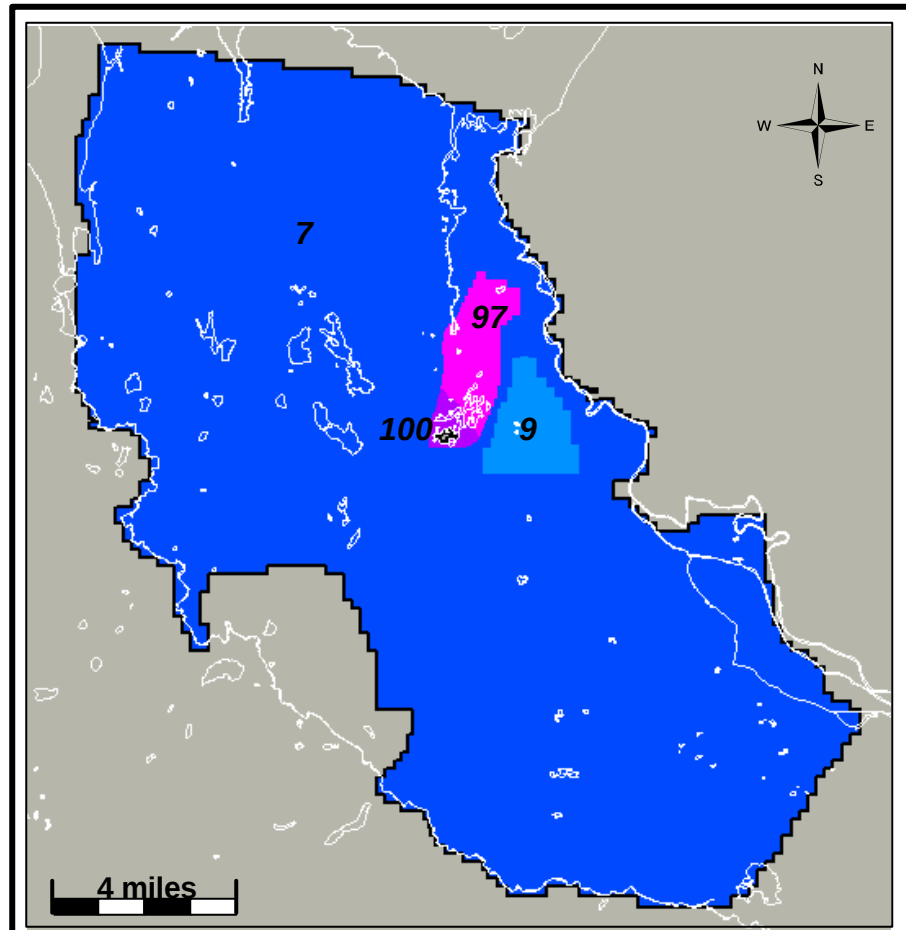
City of Olympia – McAllister Numerical Model
Hydraulic Conductivities in Layer 2 (Qvt)
Figure 3-5



Zone	K_h	K_v		Zone	K_h	K_v	(ft/day)
13	50	5		53	70	7	
25,29,31	35	5		80	252	36	
26	60	6		97	2000	400	
52	77	11		100	100	10	



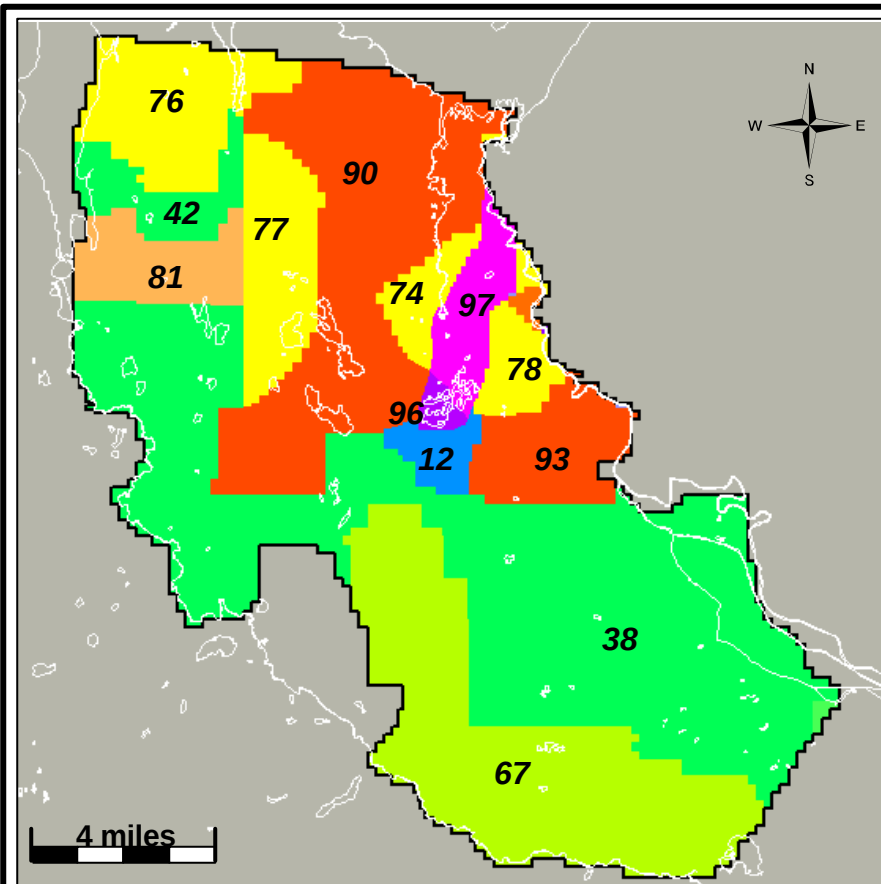
City of Olympia – McAllister Numerical Model
Hydraulic Conductivities in Layer 3 (Qva)
Figure 3-6



Zone No.	K_h	K_v		Zone No.	K_h	K_v	(ft/day)
7	1	0.0025		97	2000	400	
9	3	0.015		100	100	10	



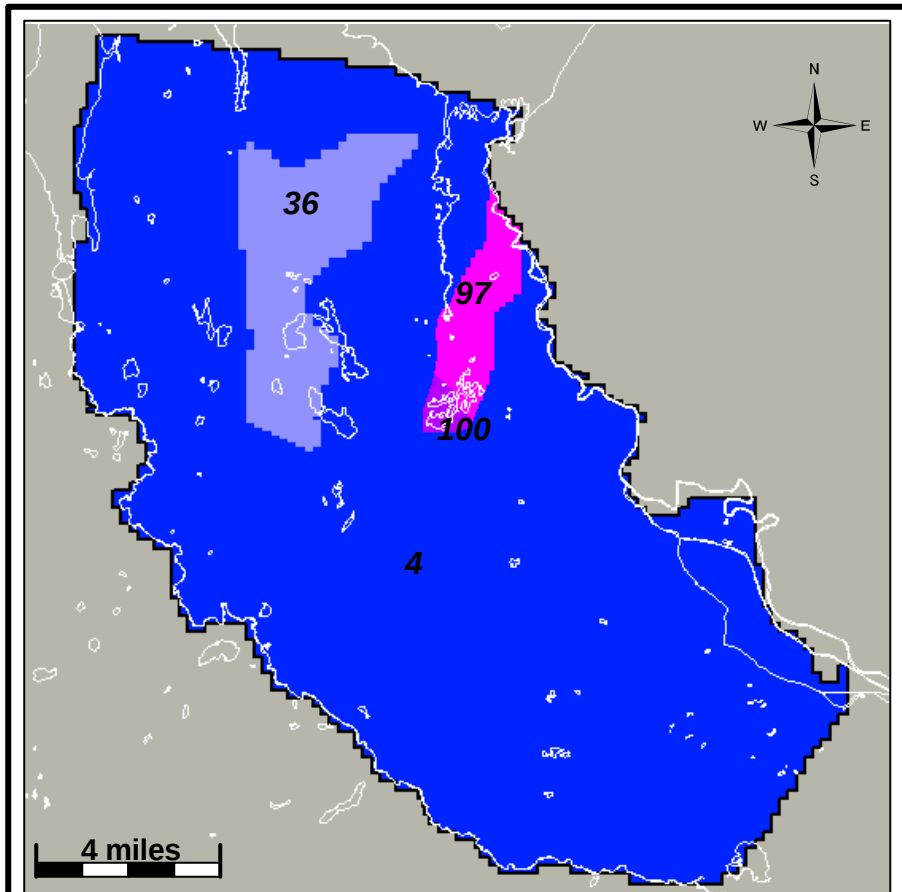
City of Olympia – McAllister Numerical Model
Hydraulic Conductivities in Layer 4 (Qf)
Figure 3-7



Zone	K_h	K_v	Zone	K_h	K_v	(ft/day)
12	10	1	81	300	30	
38	47	4.7	90,93	640	64	
67	180	18	96	250	125	
42	60	6	97	2000	400	
74-78	200	20				



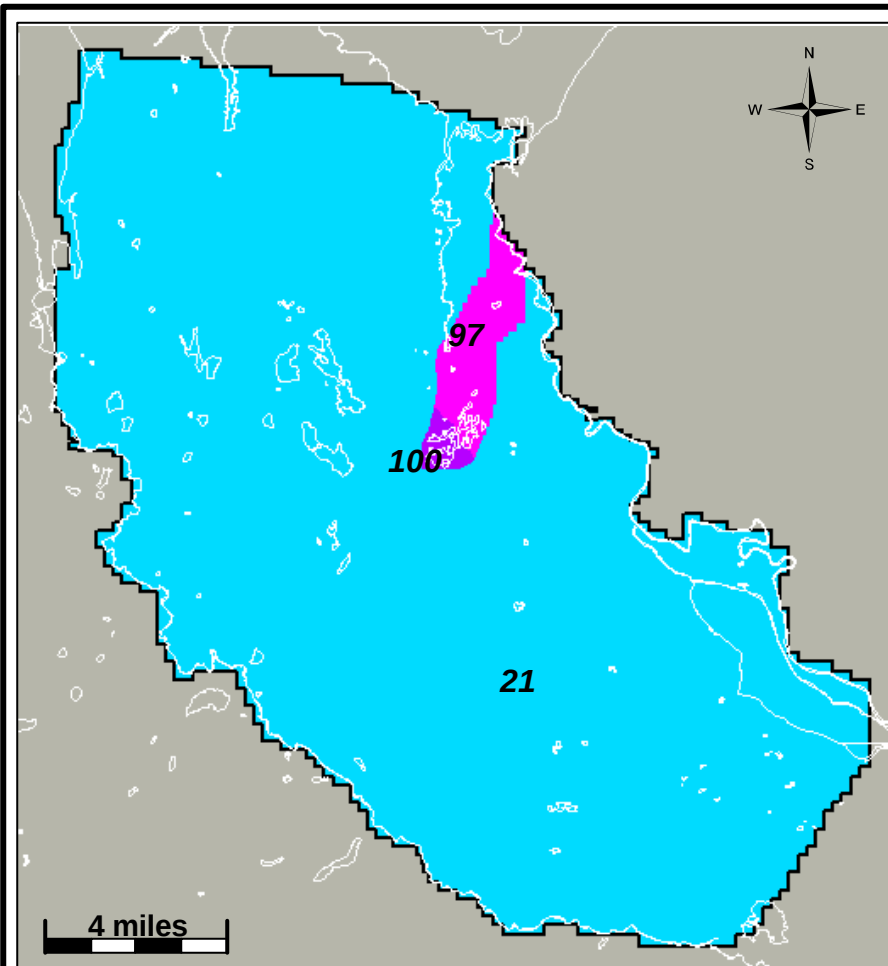
City of Olympia – McAllister Numerical Model
Hydraulic Conductivities in Layers 5-6 (Q_c)
Figure 3-8



Zone No.	K_h	K_v	Zone No.	K_h	K_v	(ft/day)
4	1	0.005	97	2000	400	
36	40	0.2	100	250	125	



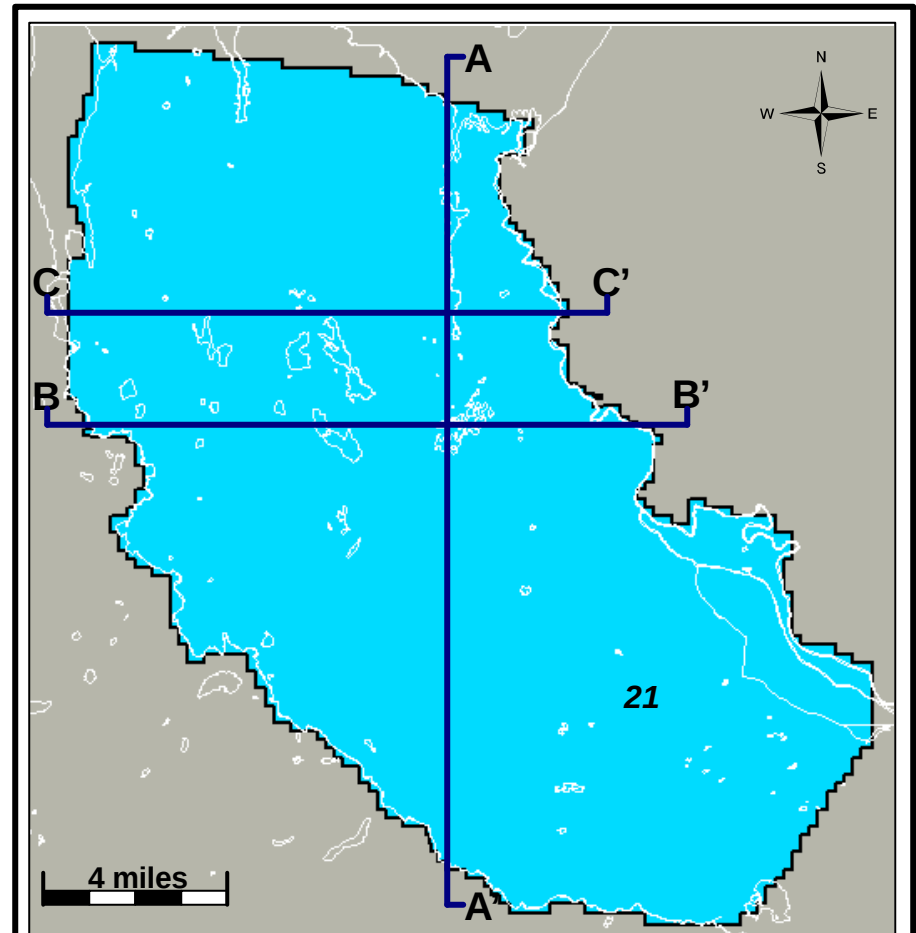
City of Olympia – McAllister Numerical Model
Hydraulic Conductivities in Layer 7 (T_{Qu})
Figure 3-9



Zone No.	K_h	K_v		Zone No.	K_h	K_v	(ft/day)
21	75	0.03		100	250	125	
97	2000	400					



City of Olympia – McAllister Numerical Model
Hydraulic Conductivities in Layer 8 (TQu)
Figure 3-10

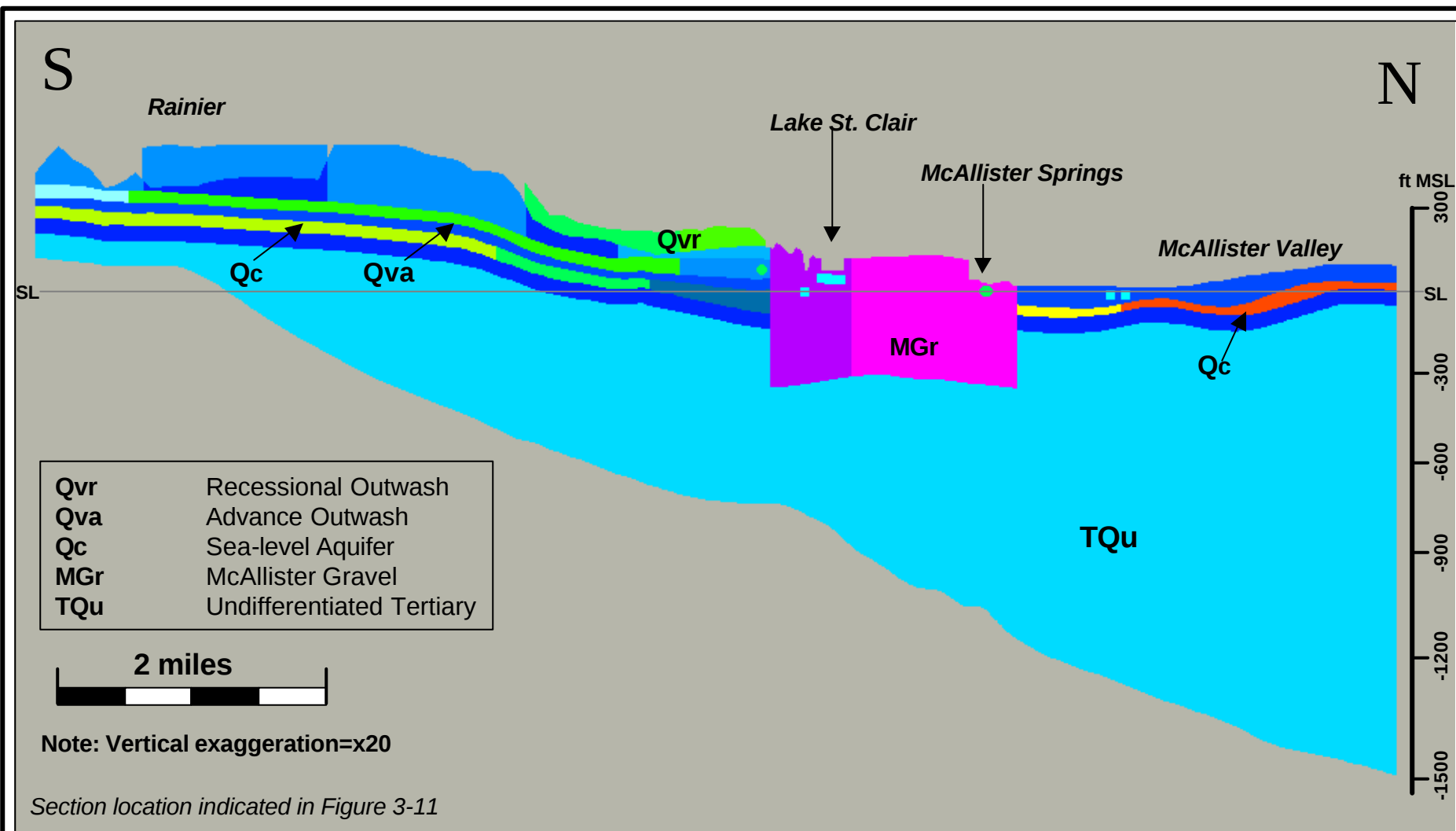


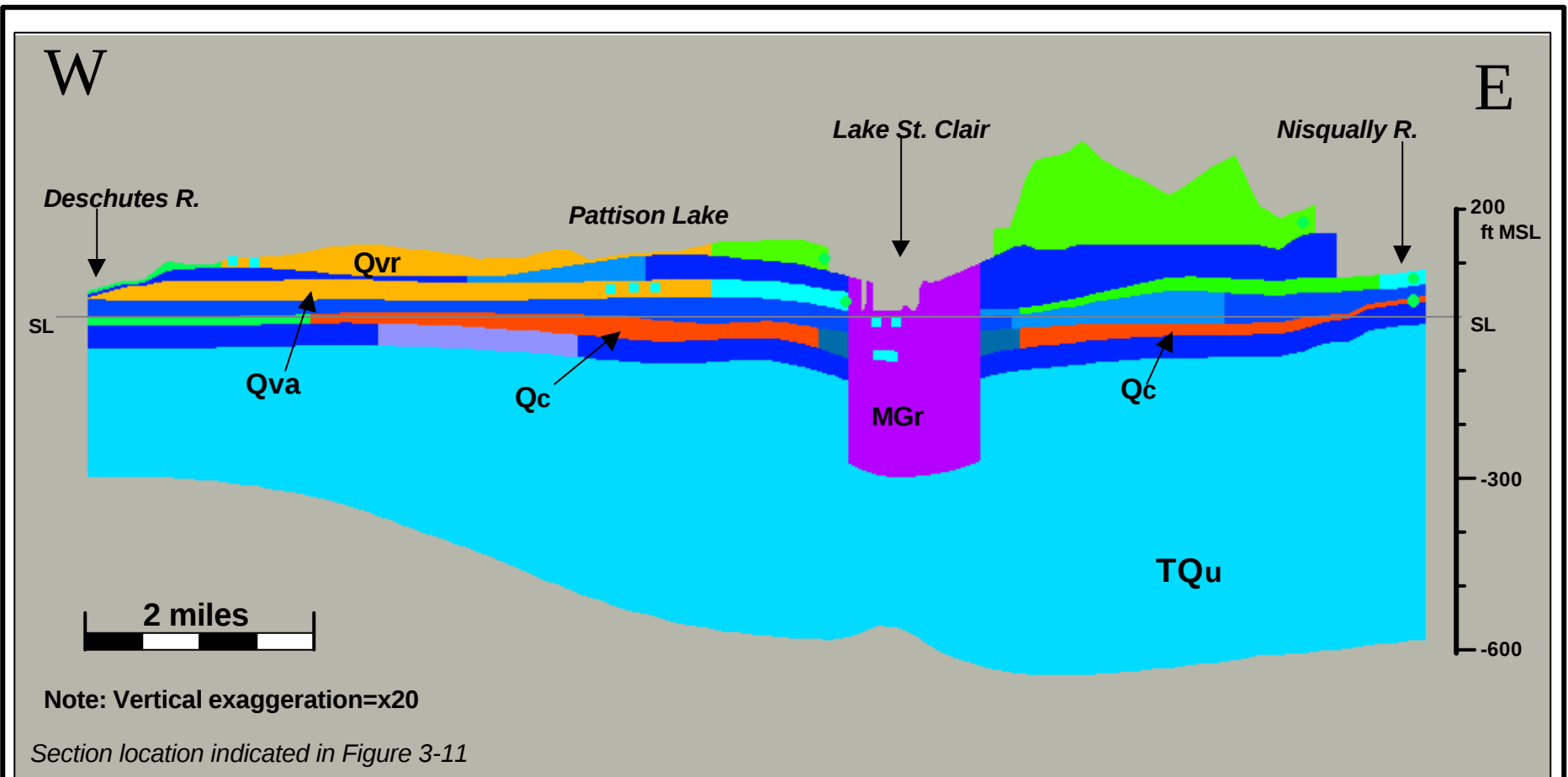
Zone No.	K_h	K_v	(ft/day)
21	75	0.03	

Section line
(see Figures 3-12 – 3-14)

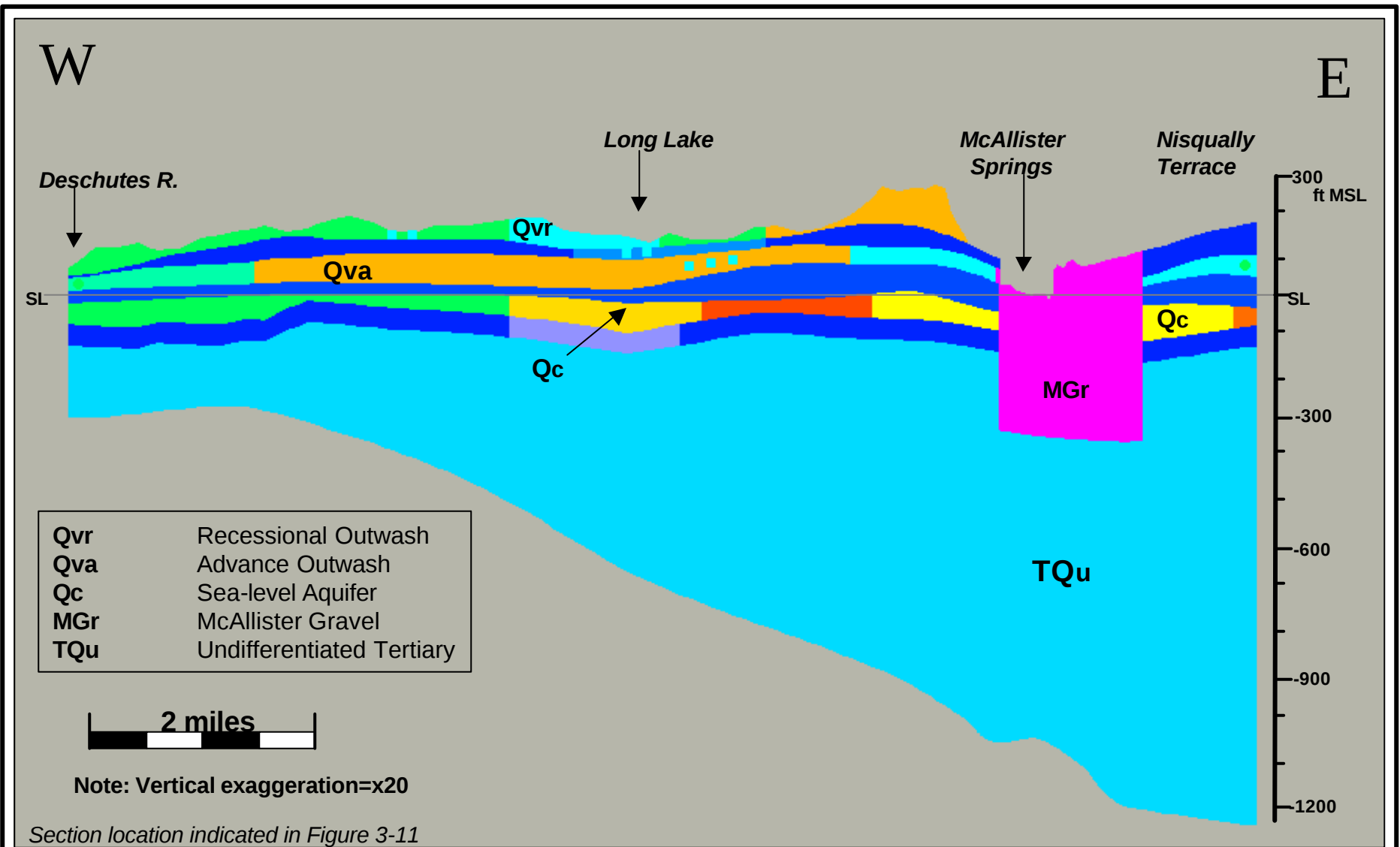


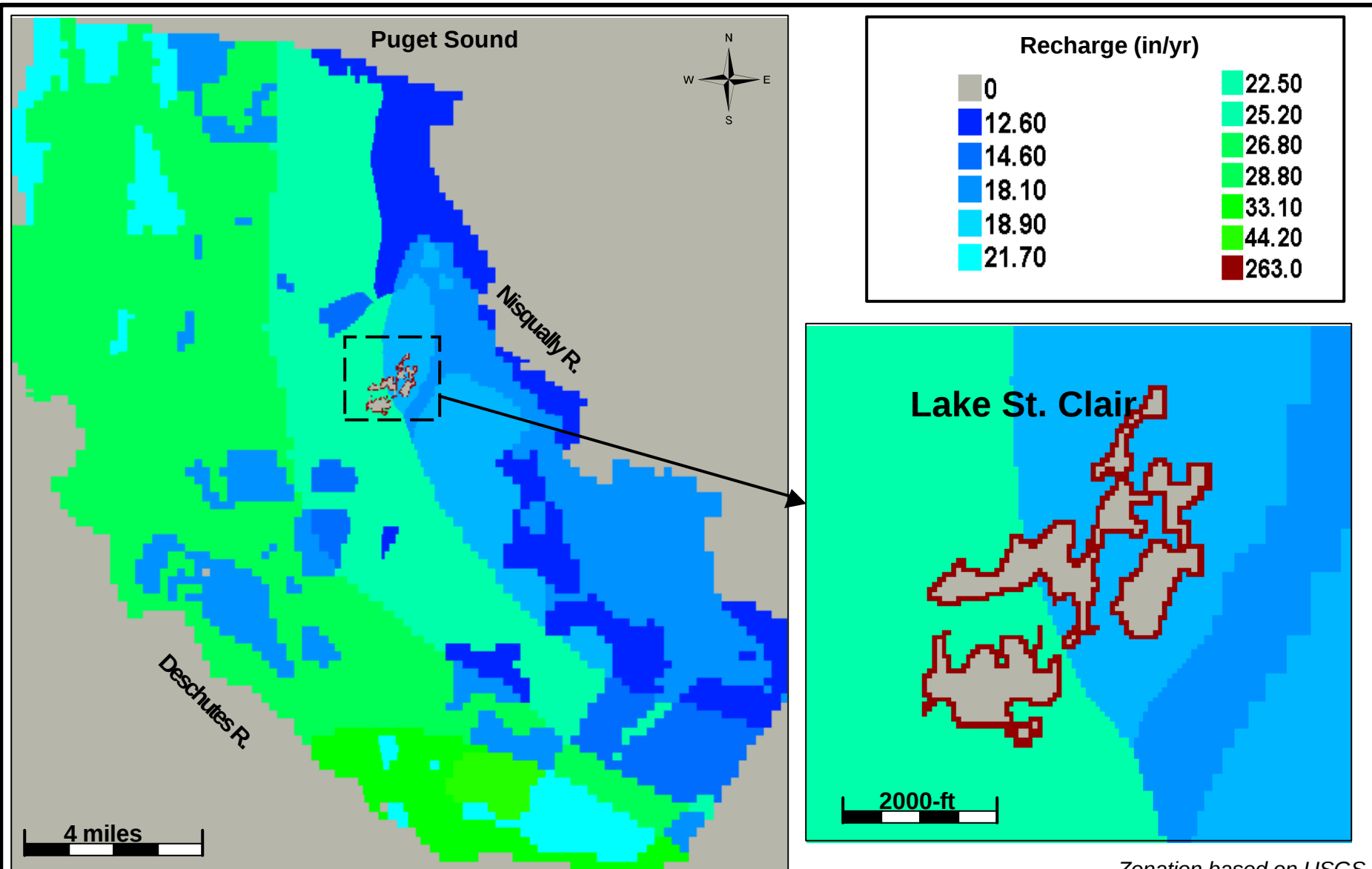
City of Olympia – McAllister Numerical Model
Hydraulic Conductivities in Layer 9 (TQu)
Figure 3-11



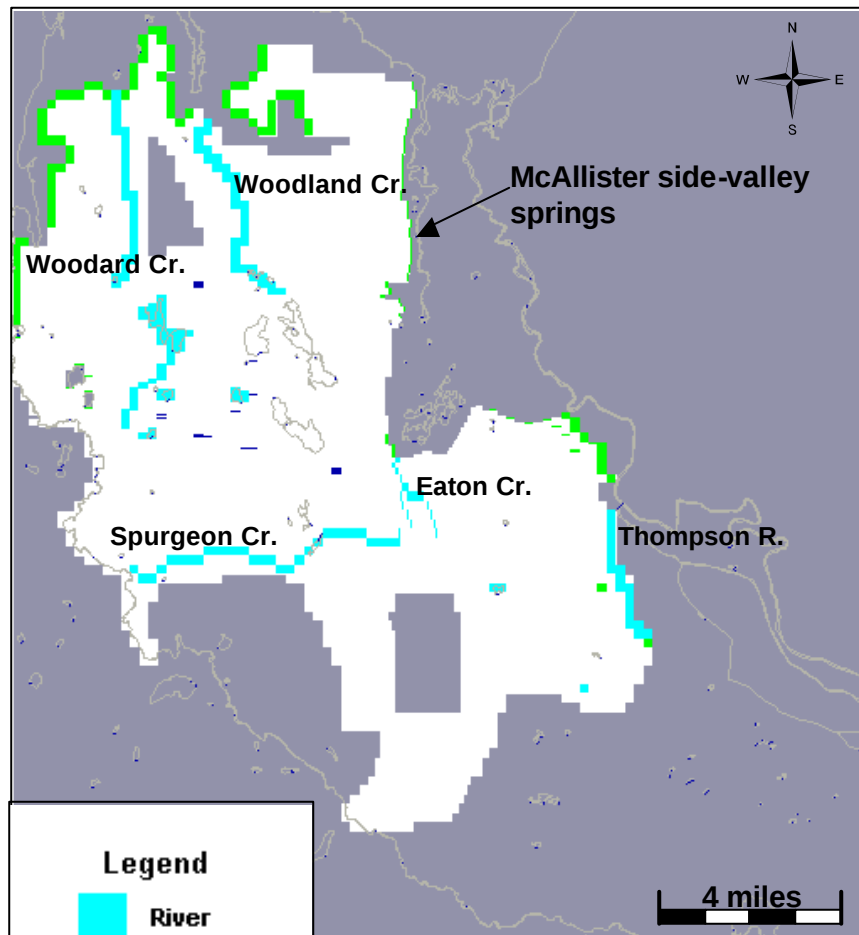


Qvr	Recessional Outwash
Qva	Advance Outwash
Qc	Sea-level Aquifer
MGr	McAllister Gravel
TQu	Undifferentiated Tertiary





*Zonation based on USGS
Thurston County model*

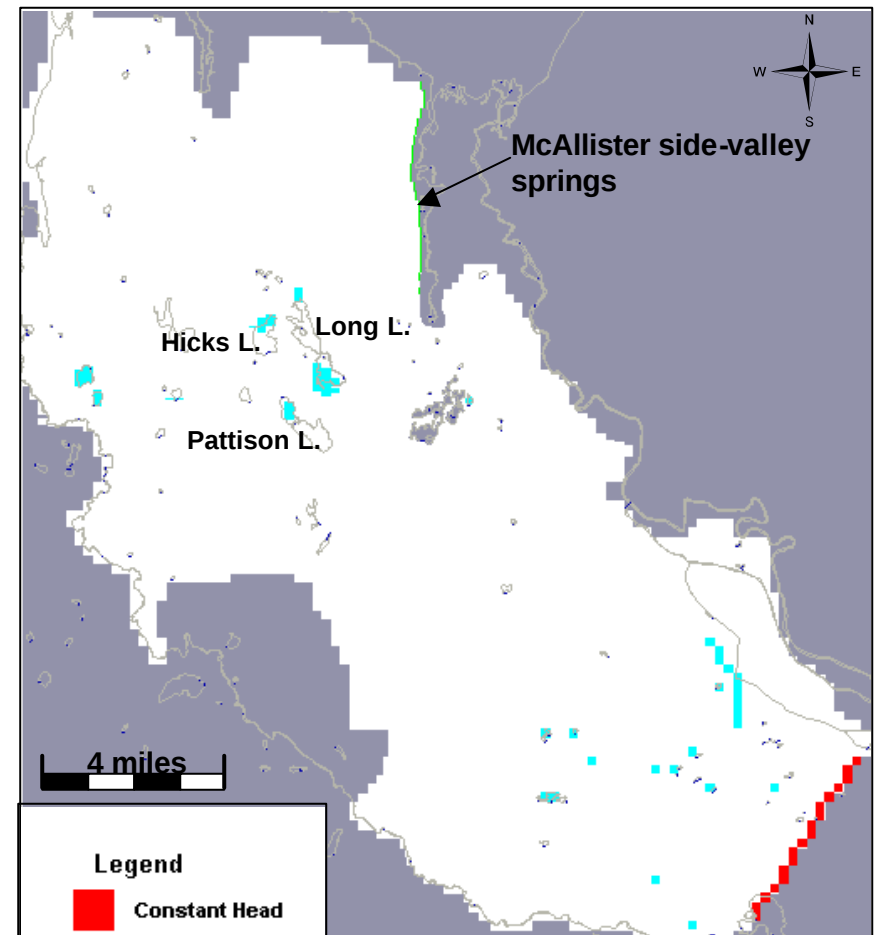


Legend

- River
- Well
- Drain
- No Flow

CDM

City of Olympia – McAllister Numerical Model
Model Boundary Conditions - Layer 1
Figure 3-16

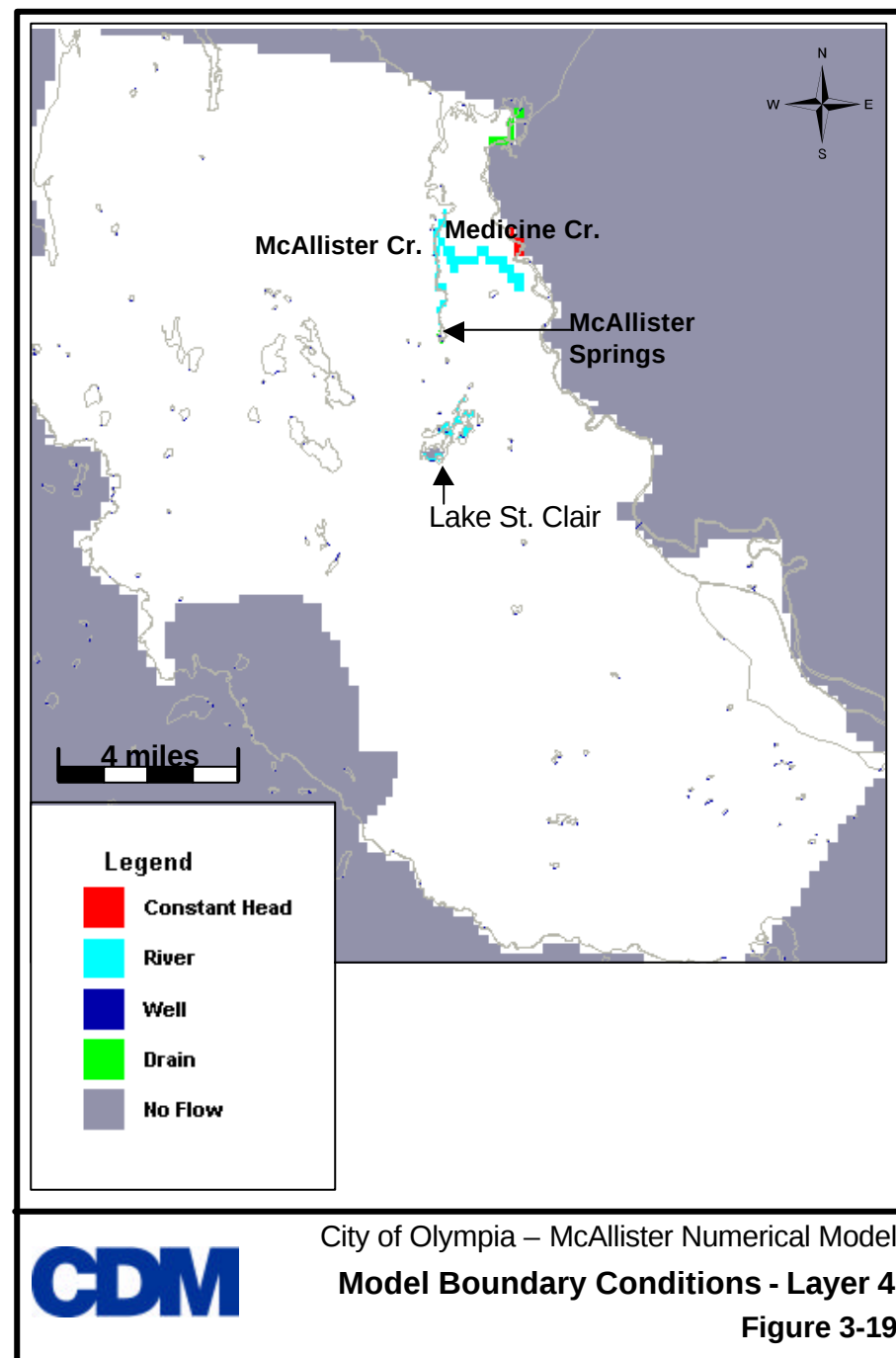
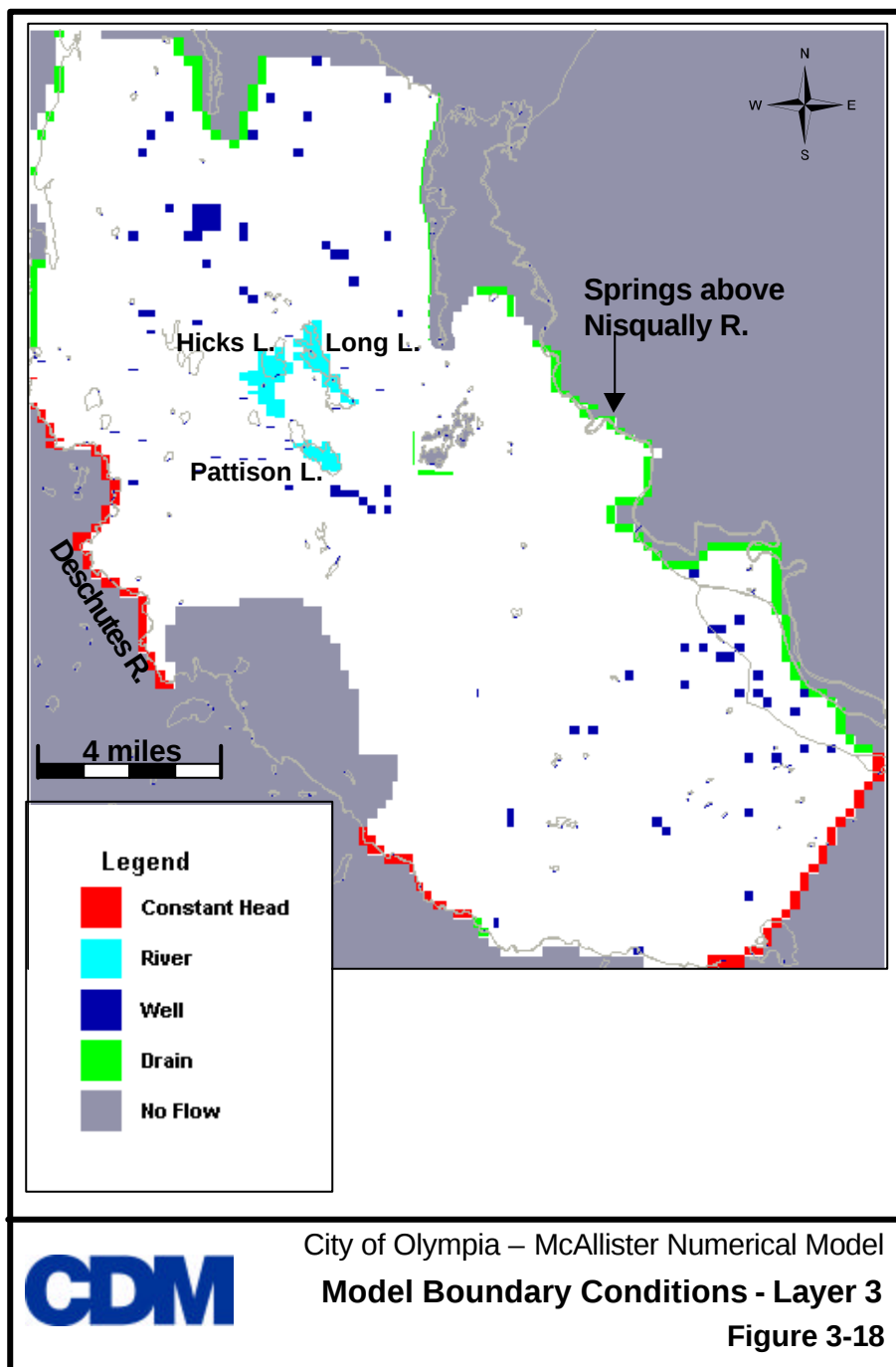


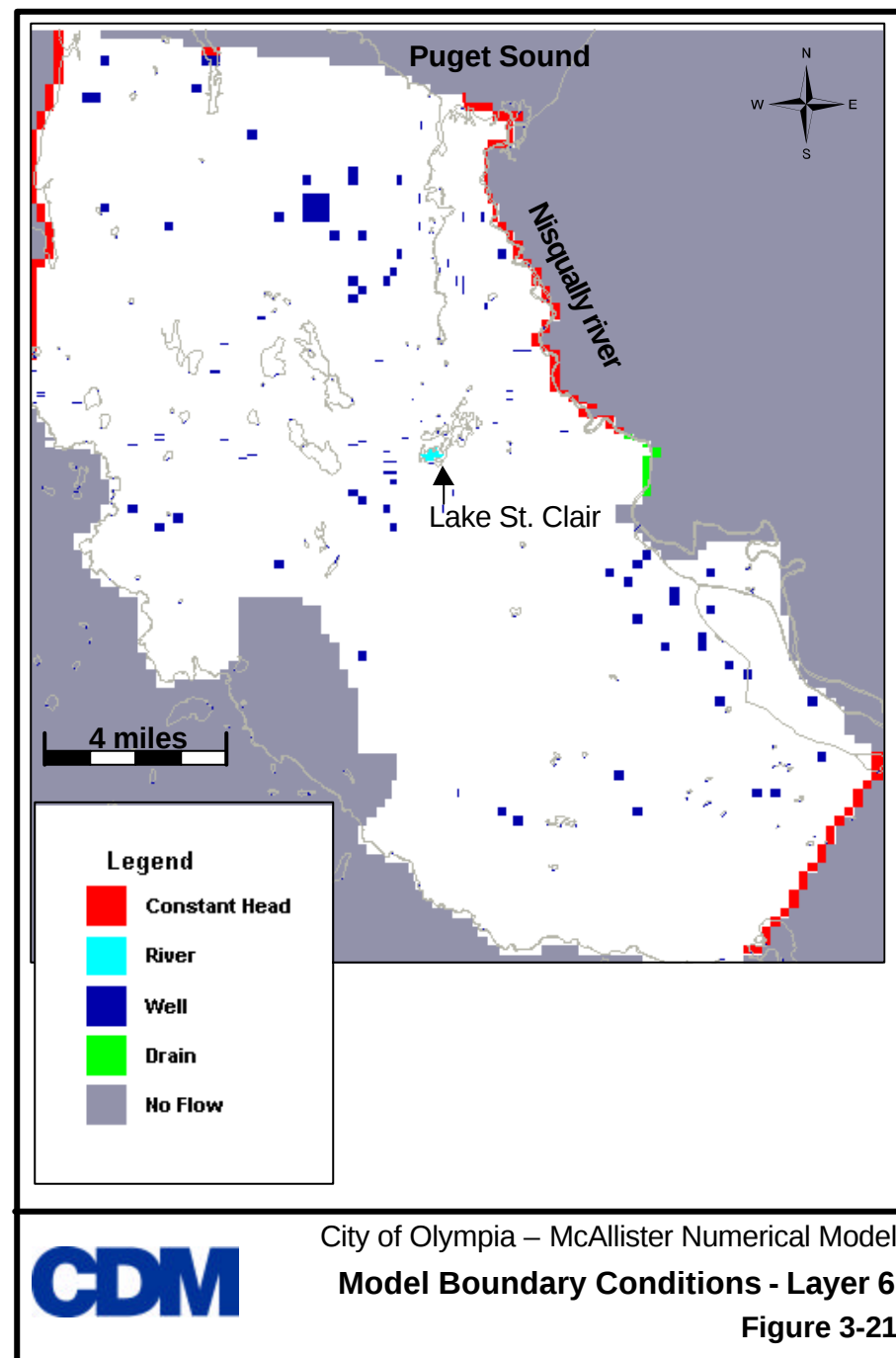
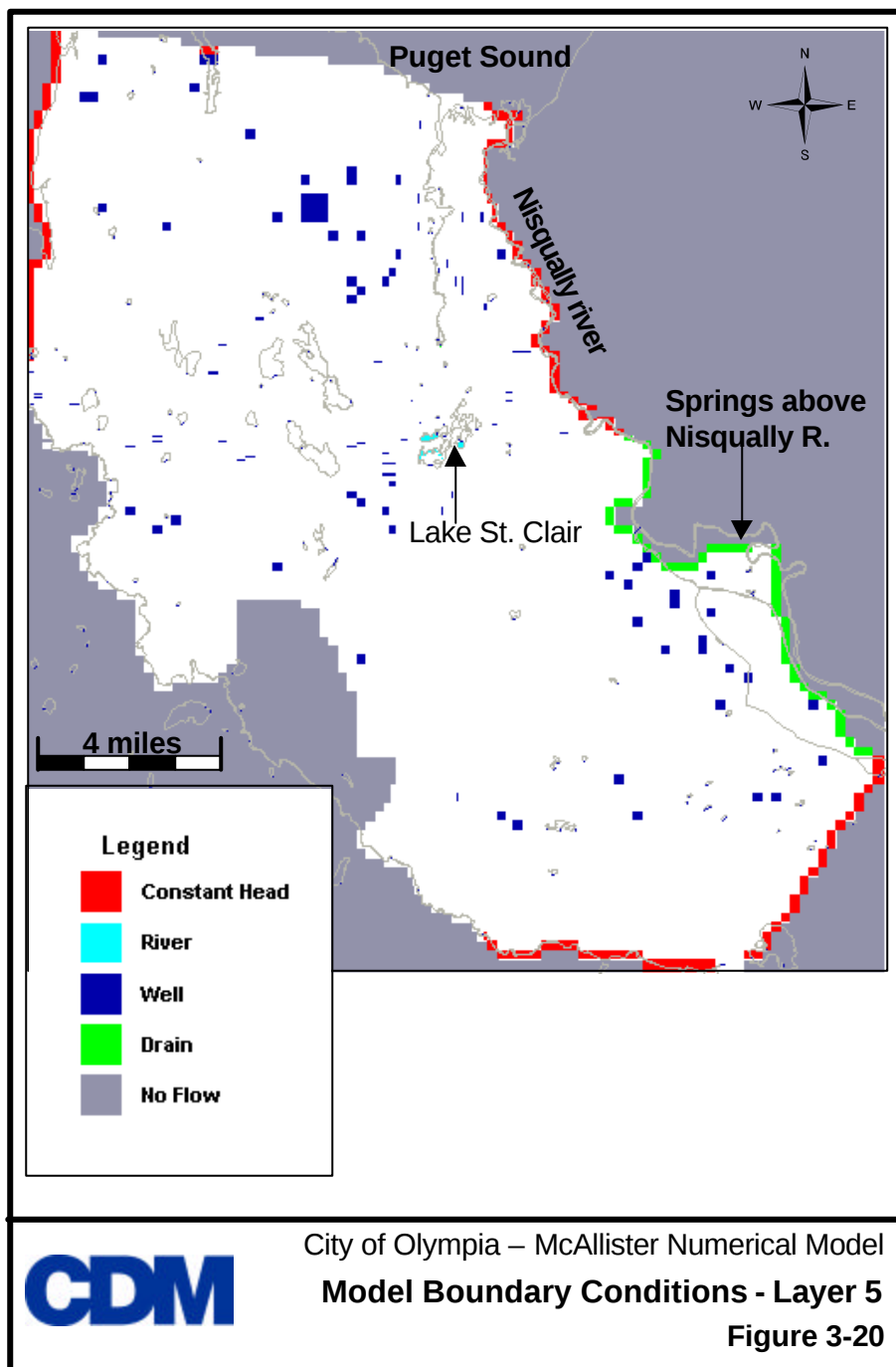
Legend

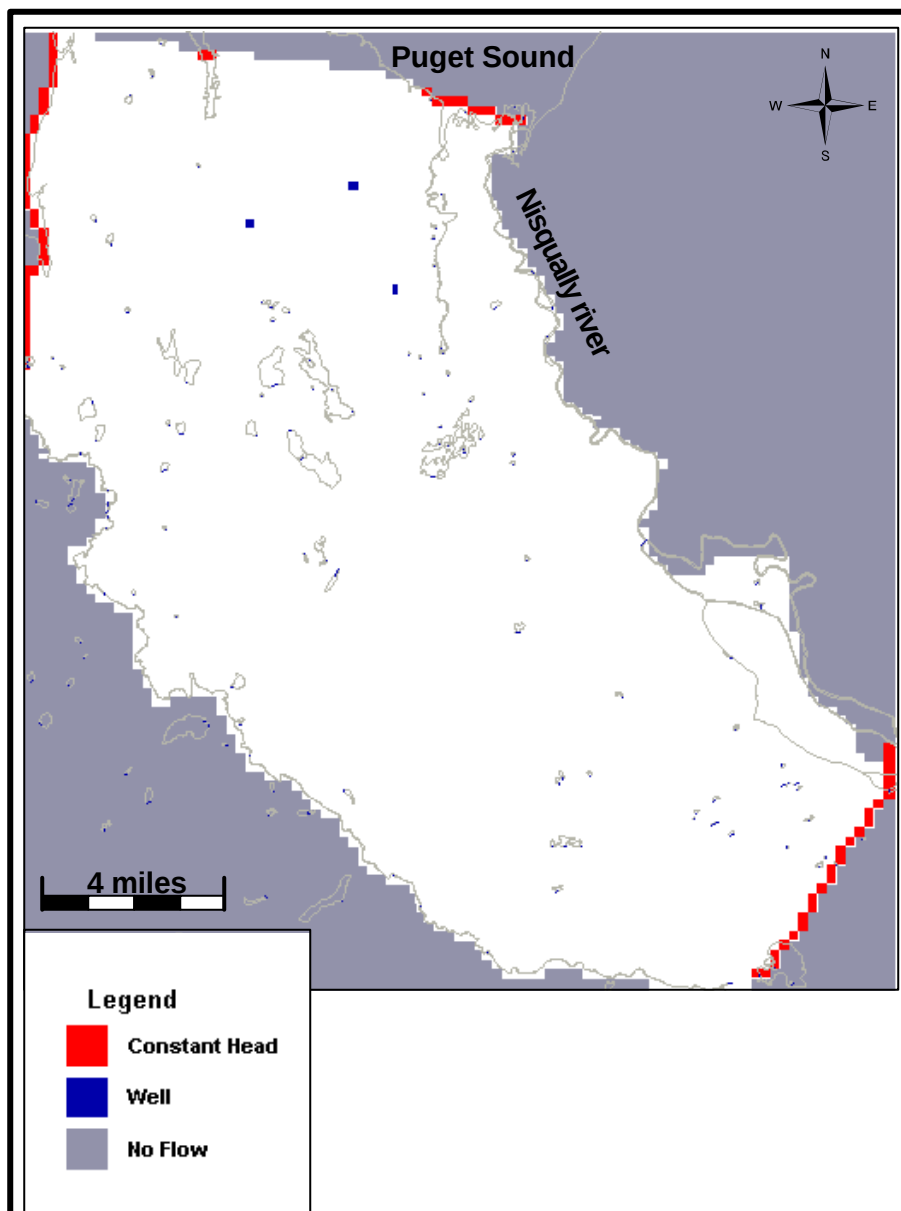
- Constant Head
- River
- Well
- Drain
- No Flow

CDM

City of Olympia – McAllister Numerical Model
Model Boundary Conditions - Layer 2
Figure 3-17

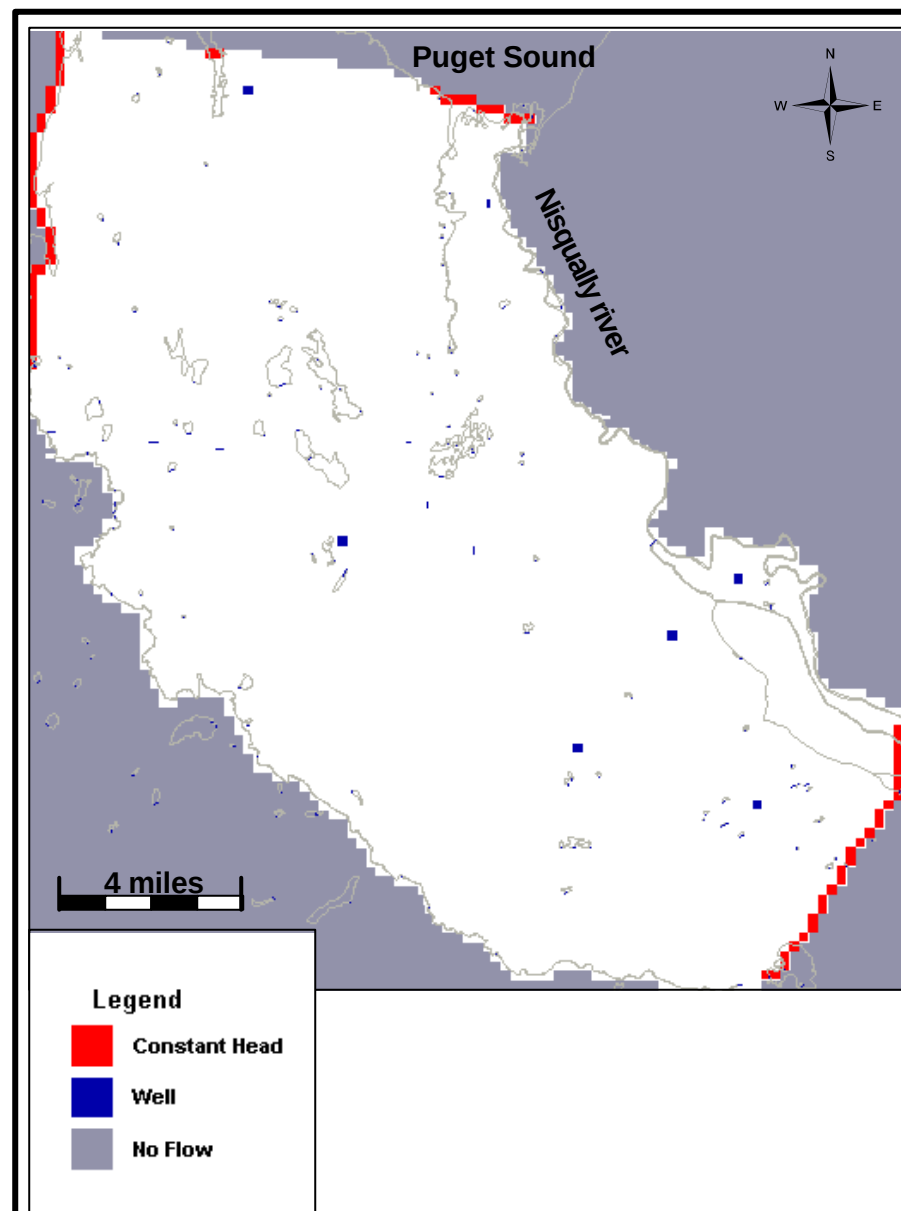






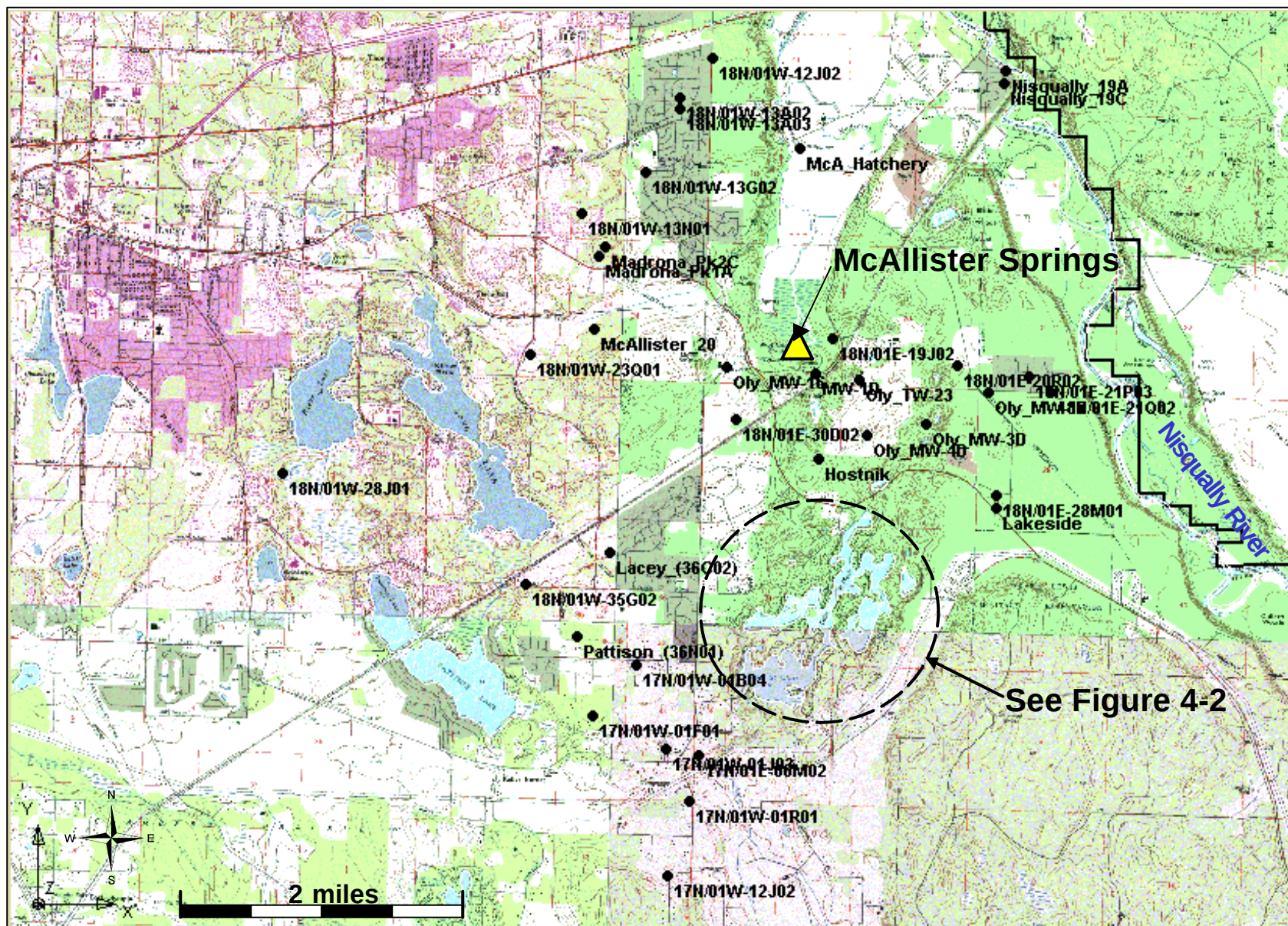
CDM

City of Olympia – McAllister Numerical Model
Model Boundary Conditions - Layer 7
Figure 3-22

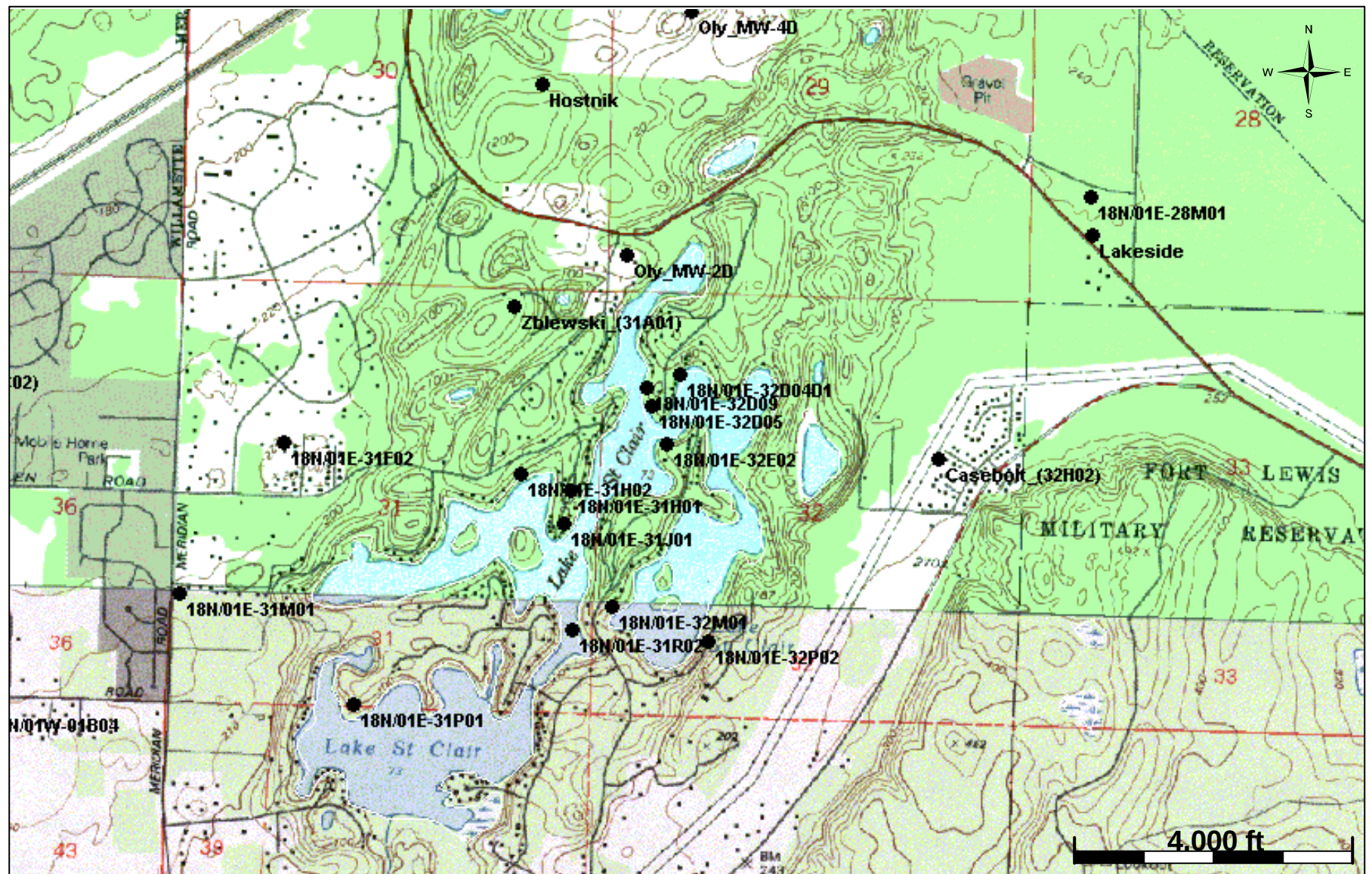


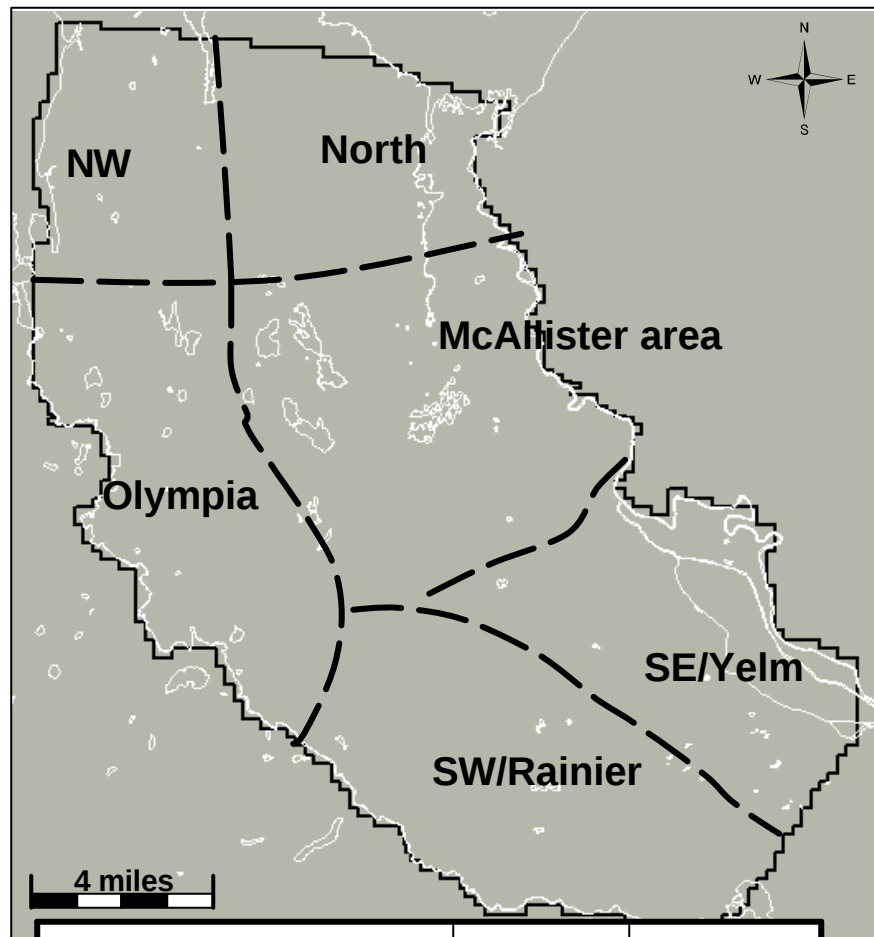
CDM

City of Olympia – McAllister Numerical Model
Model Boundary Conditions – Layers 8 & 9
Figure 3-23



City of Olympia – McAllister Wellfield Numerical Model
 Steady-state Calibration Wells in McAllister Area (McAllister Gravel and Sea Level Aquifers)
 Figure 4-1





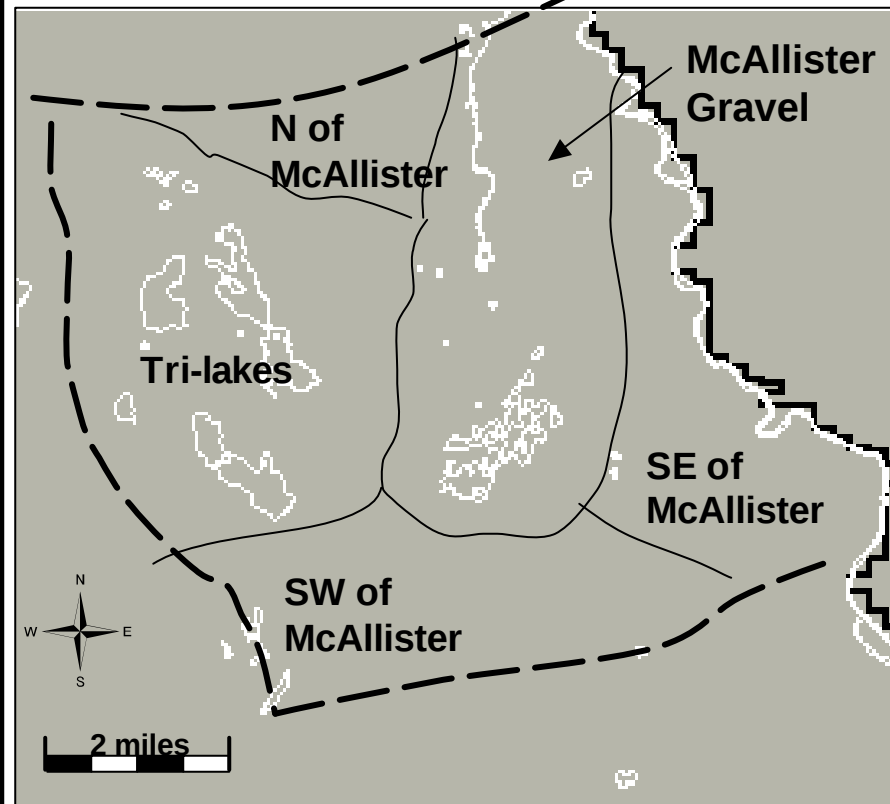
Area	Baseline	USGS
McAllister	See Figure 4-4	
North	0.5	0.3
Northwest	no wells	0.3
Olympia	no wells	0.3
SW/Rainier, SE/Yelm	no wells	0.2



City of Olympia – McAllister Wellfield Numerical Model

Calibration Data Weighting Zones

Figure 4-3



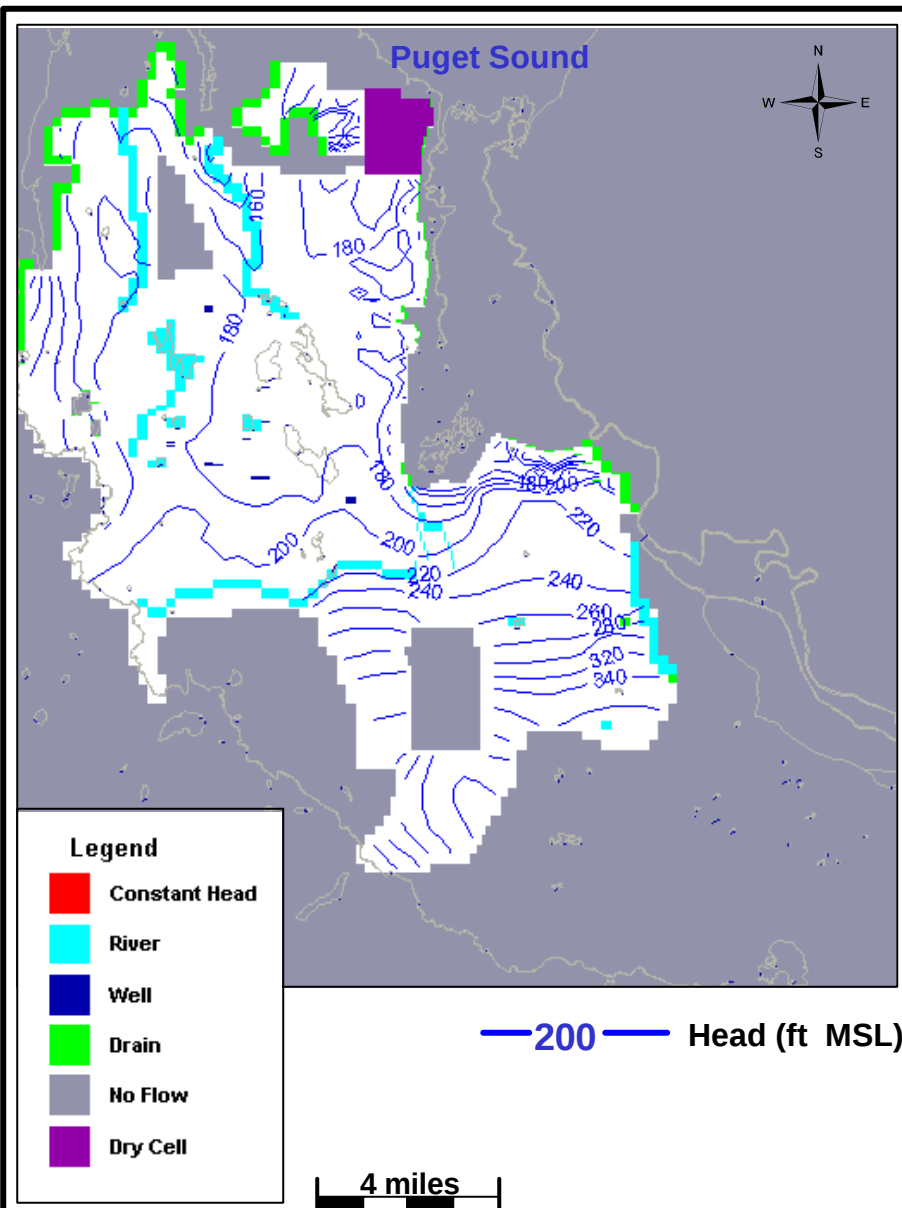
Area	Baseline	USGS
McAllister Gravel	1	0.75
North of McAllister	0.75	0.5625
Tri-lakes	0.8	0.6
SW of McAllister	0.75	0.5625
SE of McAllister	0.8	0.6



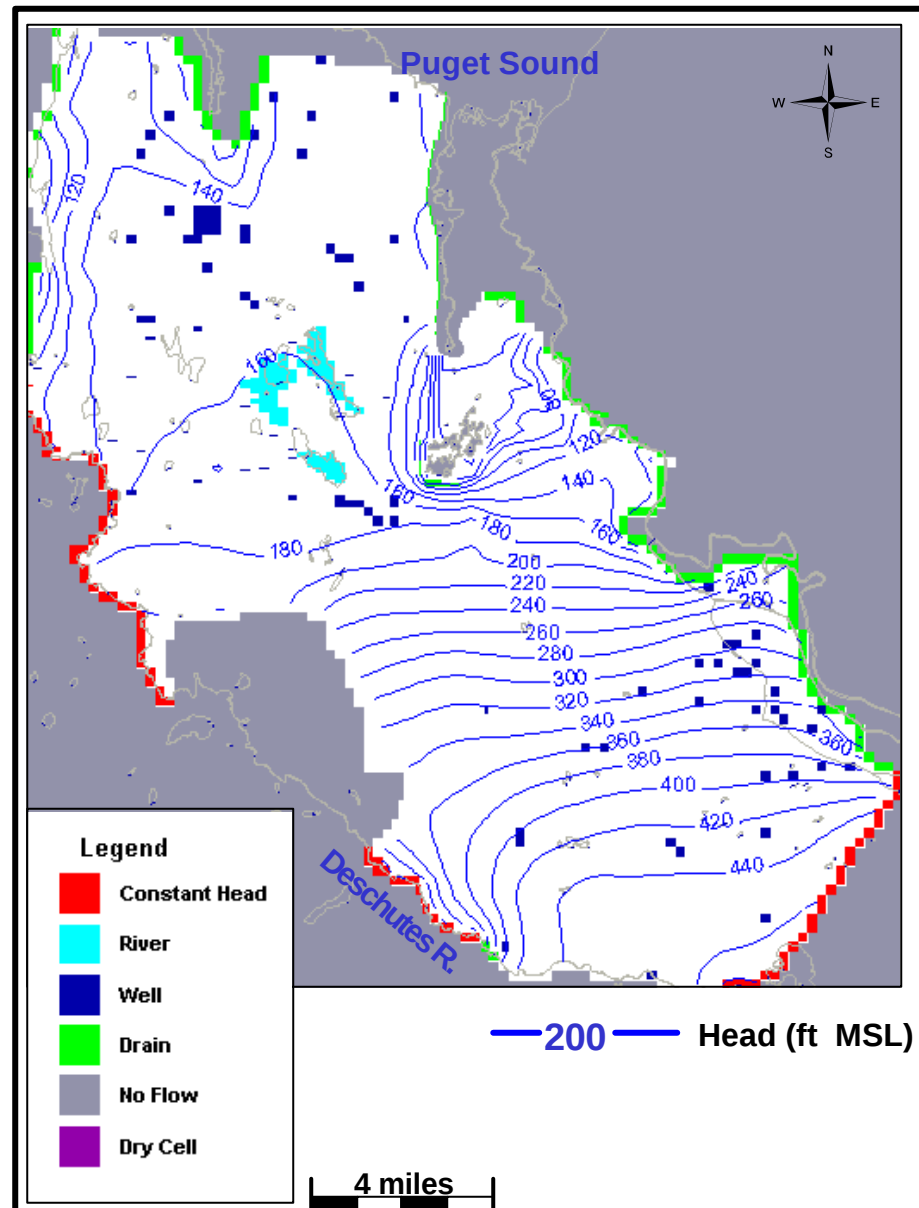
City of Olympia – McAllister Wellfield Numerical Model

McAllister Area Weighting Zones

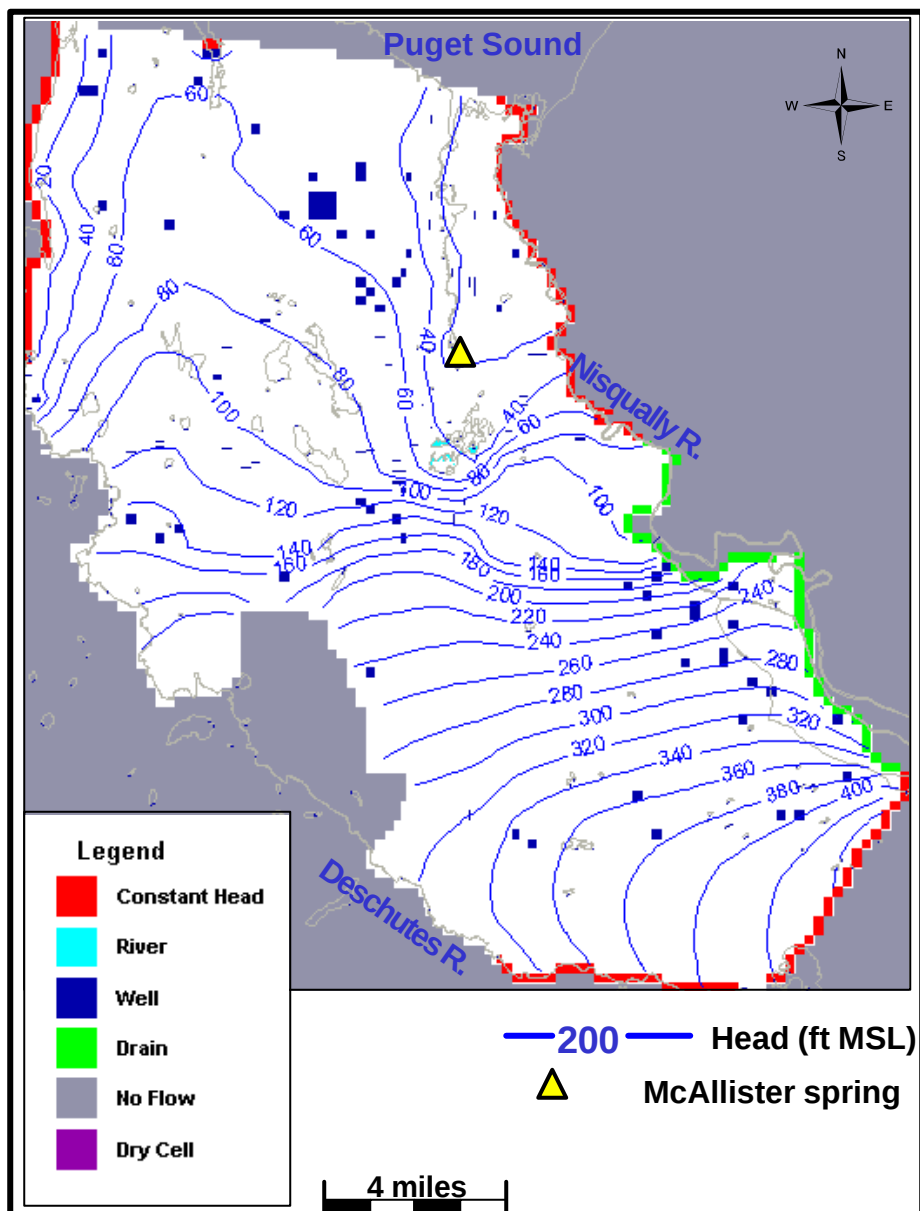
Figure 4-4



CDM City of Olympia – McAllister Numerical Model
 Steady-state Modeled Heads (Qvr-layer 1)
 Figure 4-5



CDM City of Olympia – McAllister Numerical Model
 Steady-state Modeled Heads (Qva-layer 3)
 Figure 4-6



City of Olympia – McAllister Numerical Model
Steady-state Modeled Heads (Qc-layer 5)
Figure 4-7

CDM

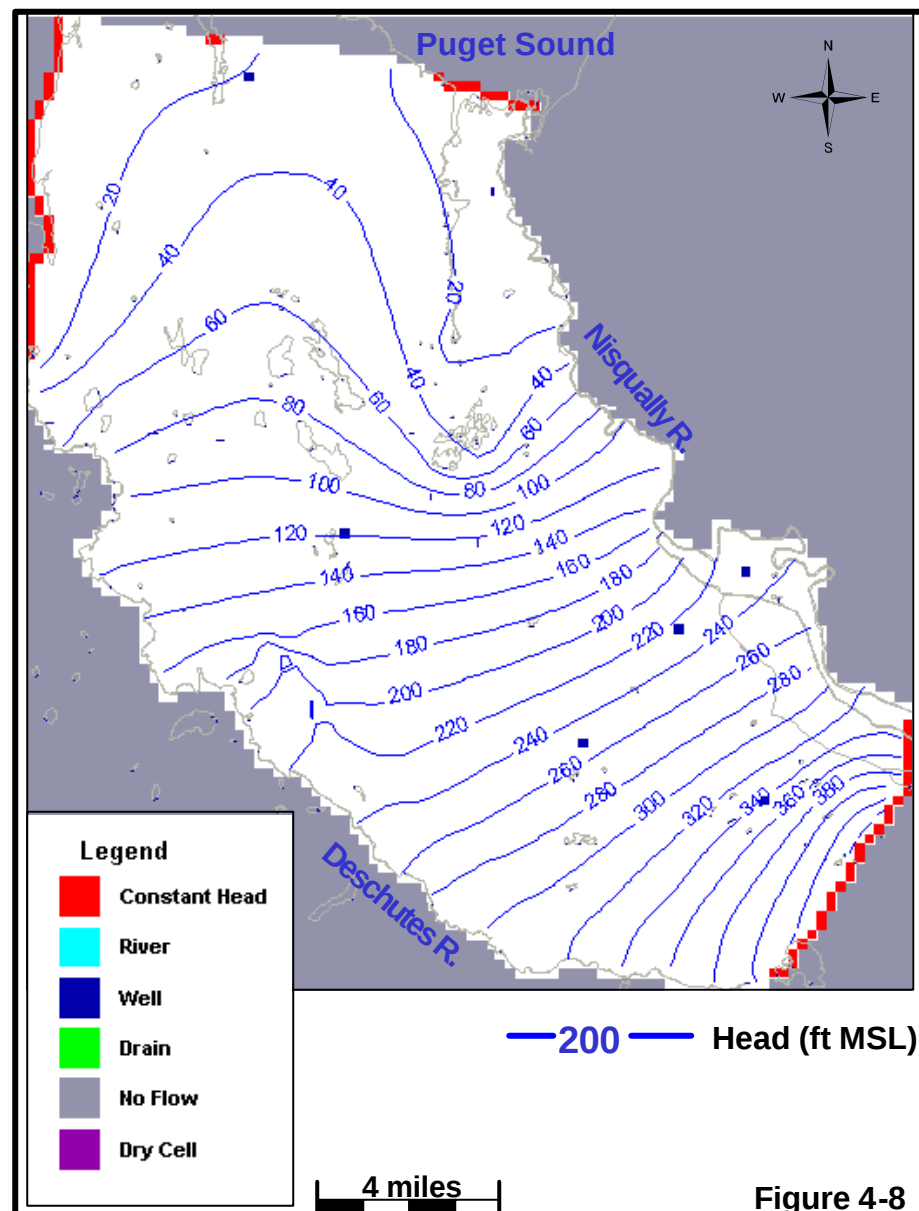
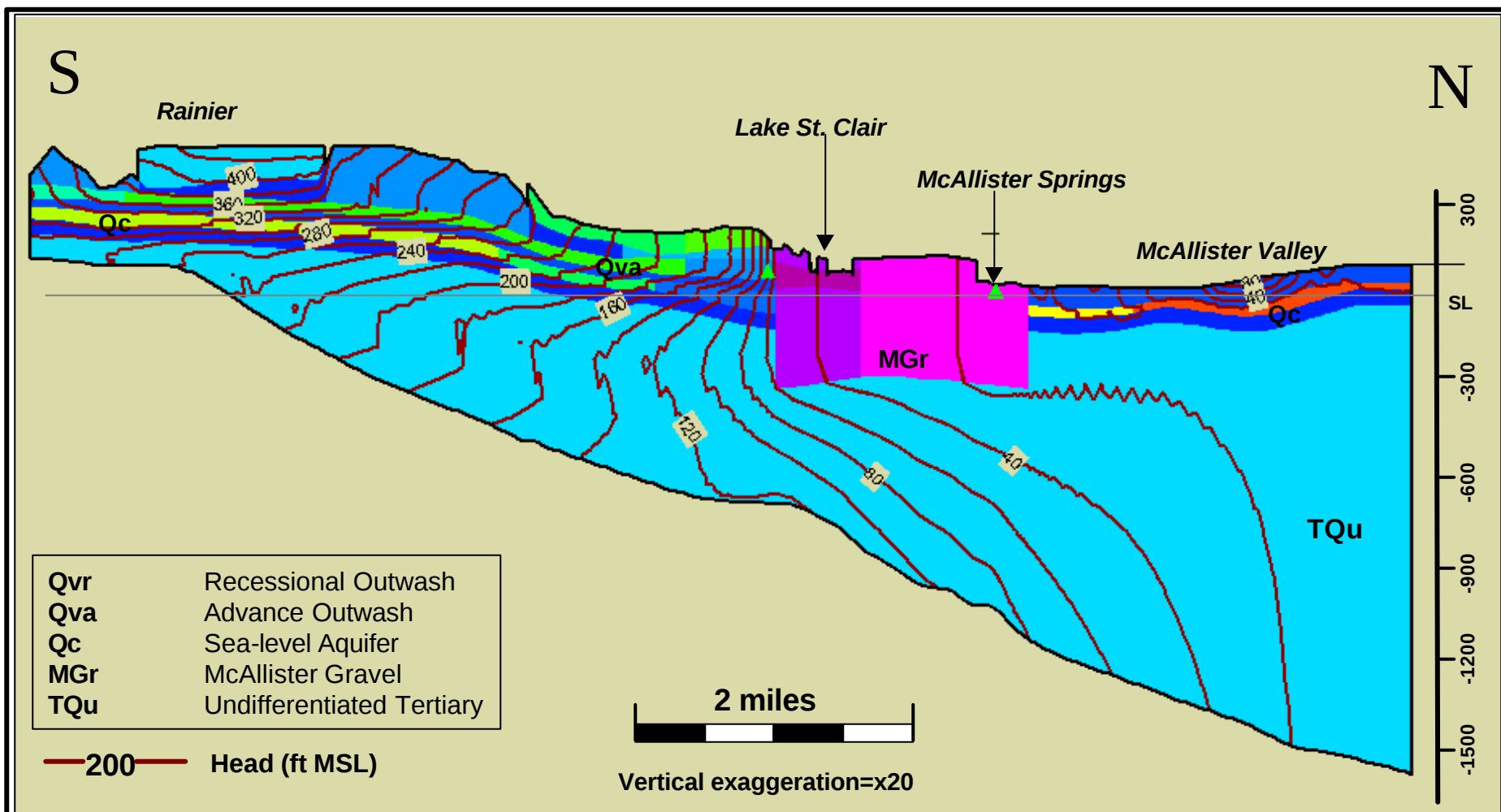
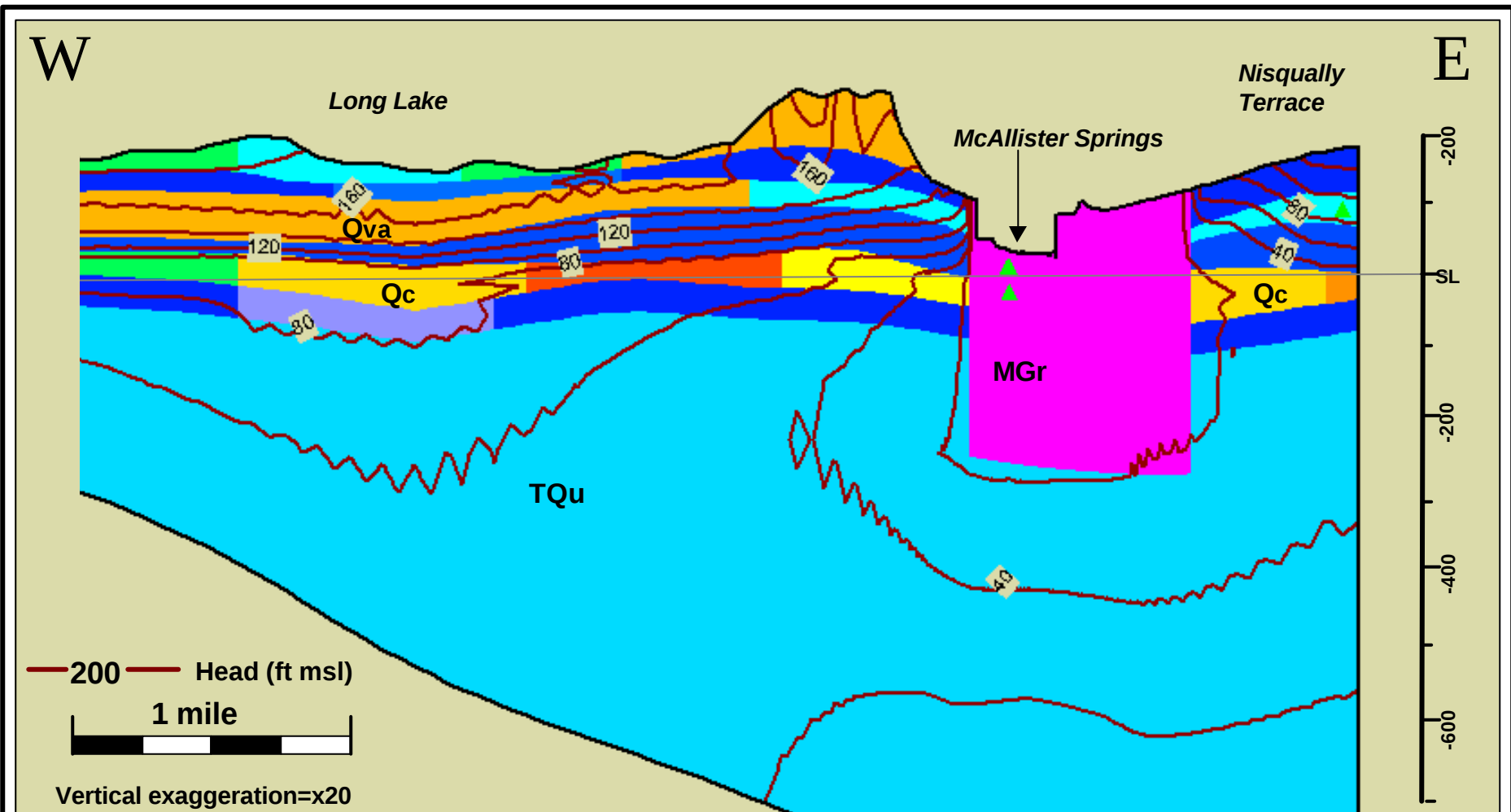


Figure 4-8

City of Olympia – McAllister Numerical Model
Steady-state Modeled Heads (TQu-layer 8)
Figure 4-8

CDM

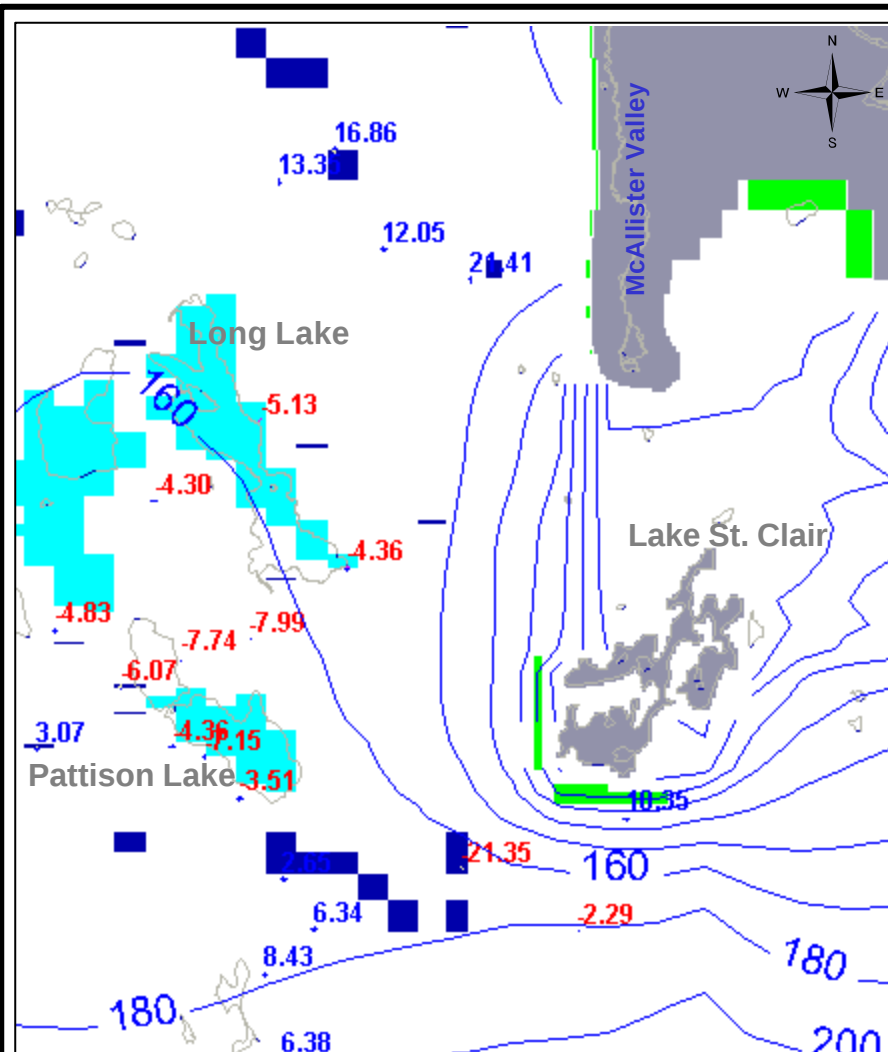




Note - the irregular piezometric contour lines reflect the limitations of the software in section mode



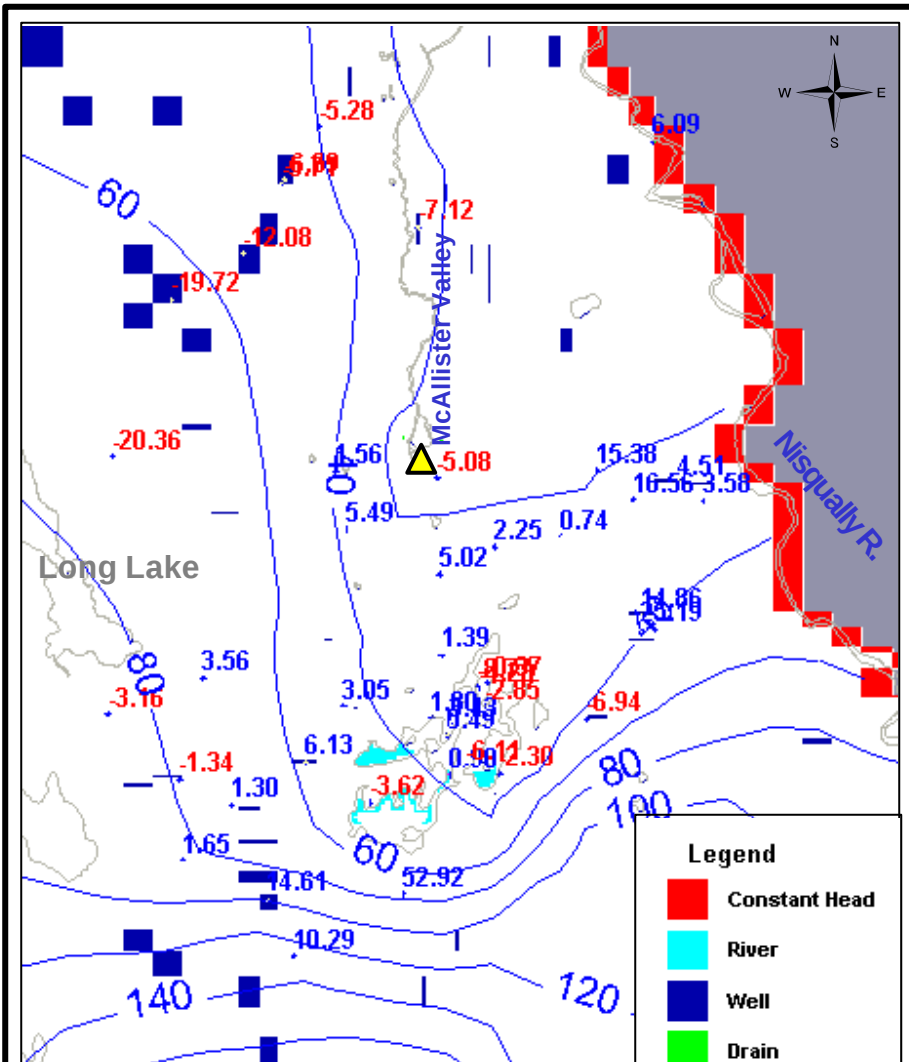
City of Olympia – McAllister Wellfield Numerical Model
 Potentiometric Heads in Section C-C' through Model
 Figure 4-10



Weighted residual (ft) 2.63 obs>model
 -3.28 model>obs
 -200 Head (ft msl)



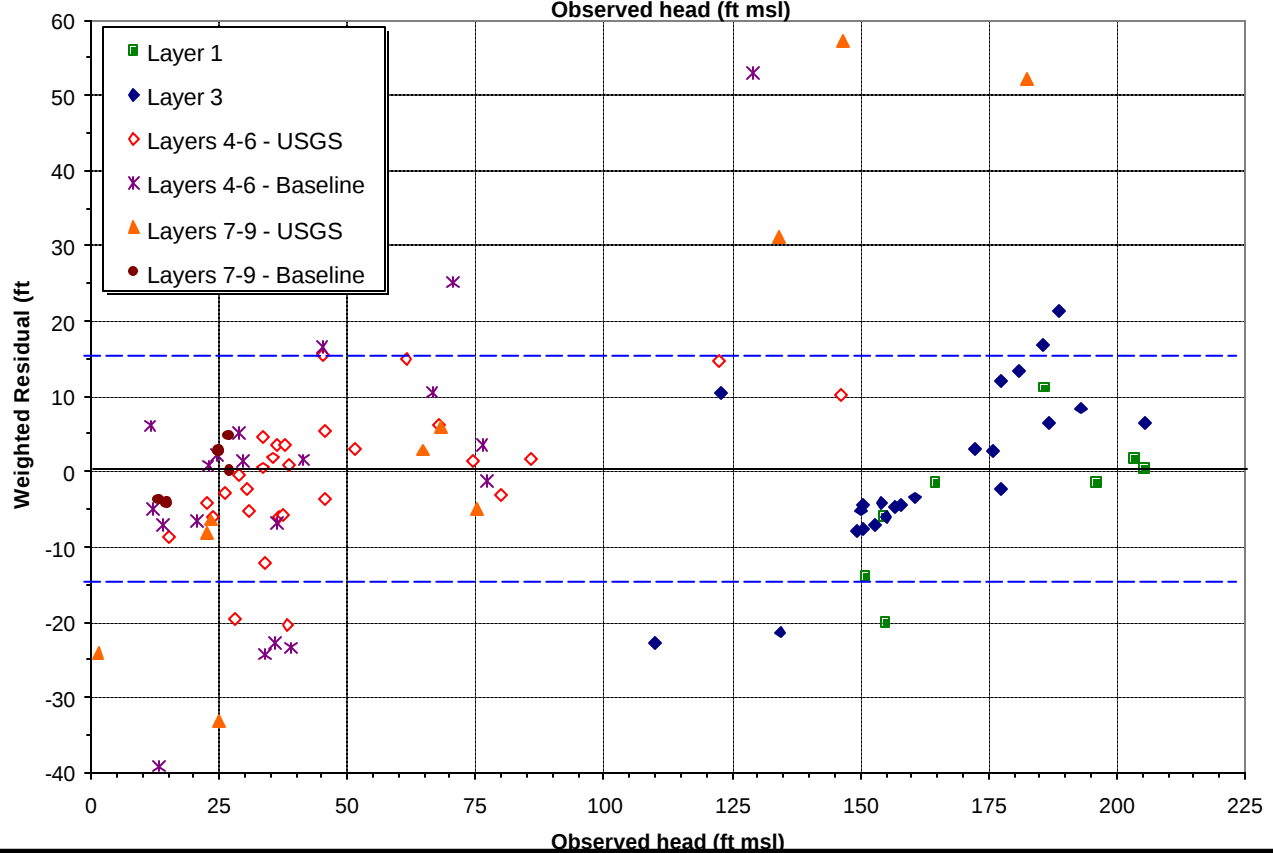
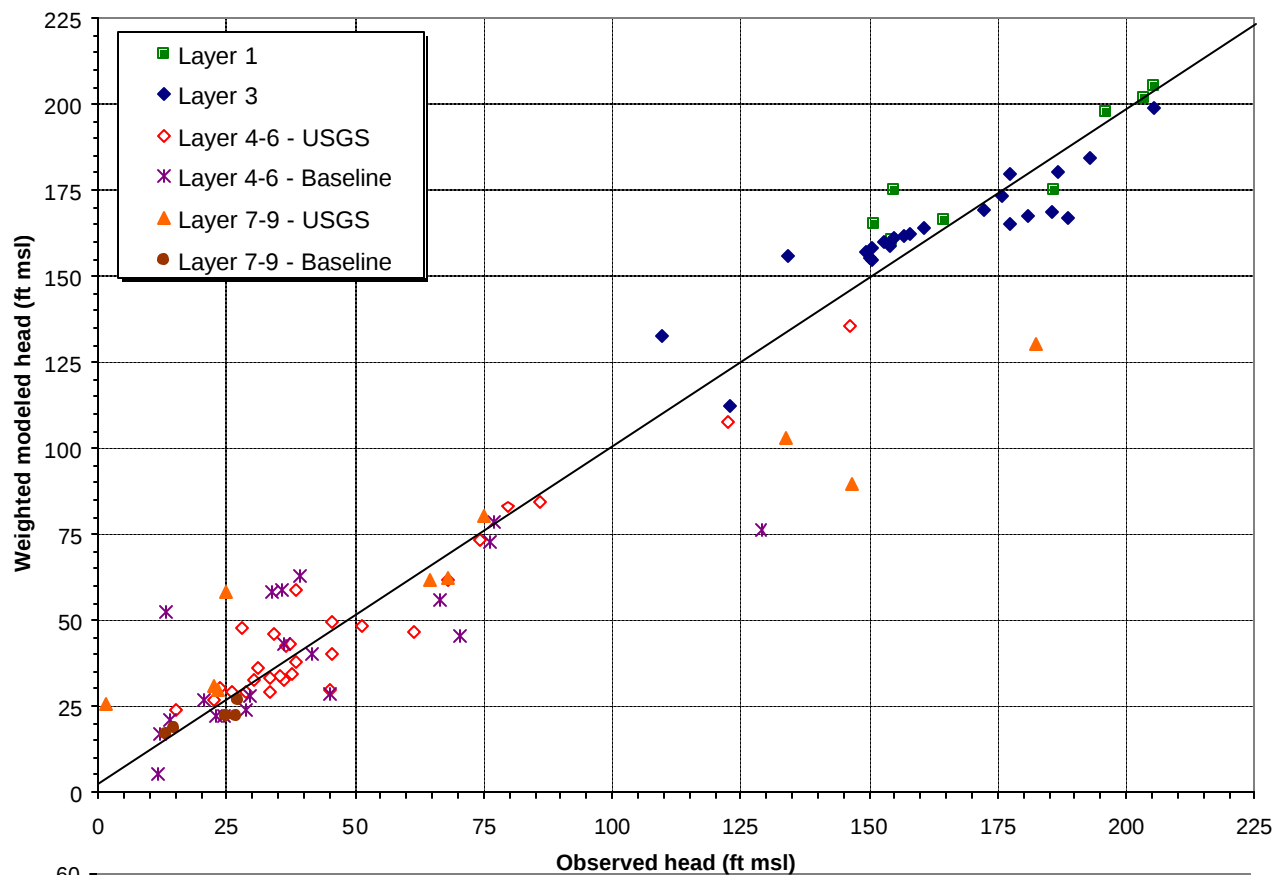
City of Olympia – McAllister Numerical Model
 Steady-state Calibration – Qva (layer 3)
 Figure 4-11



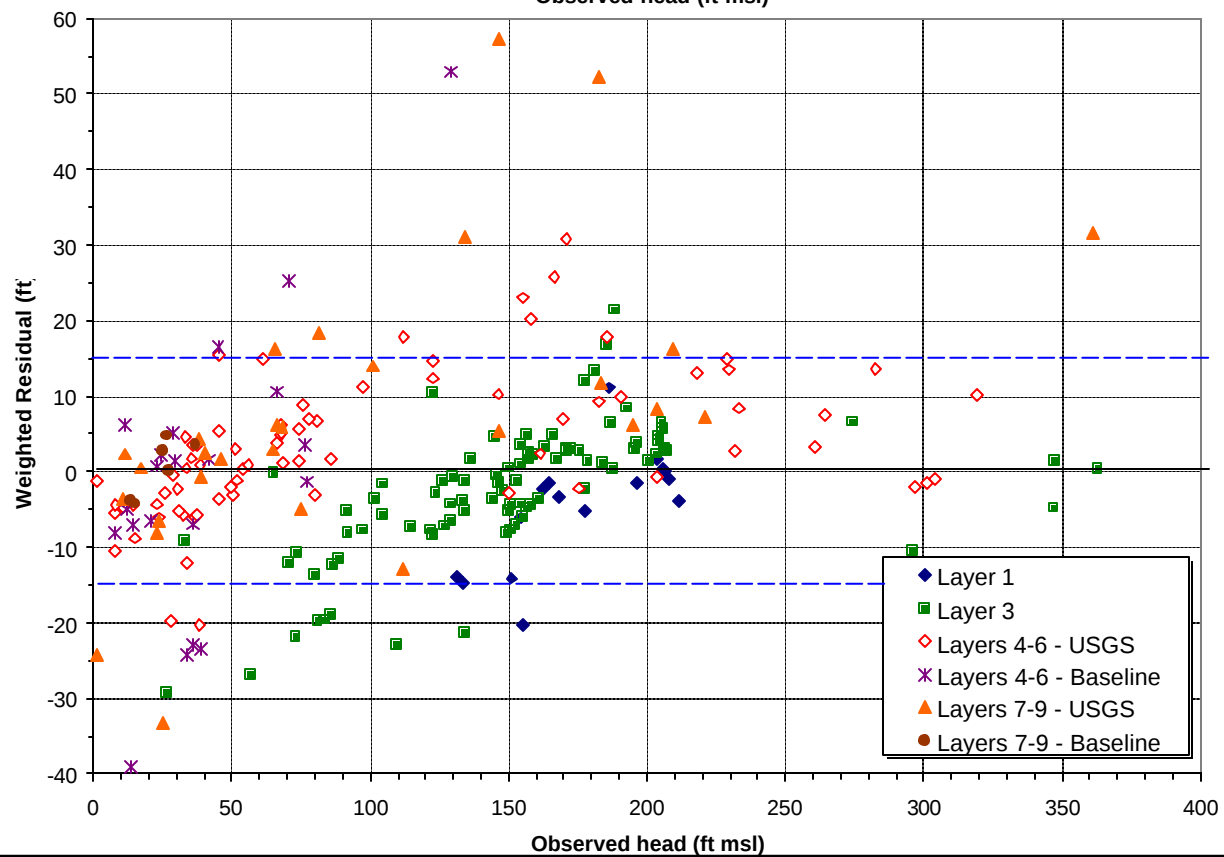
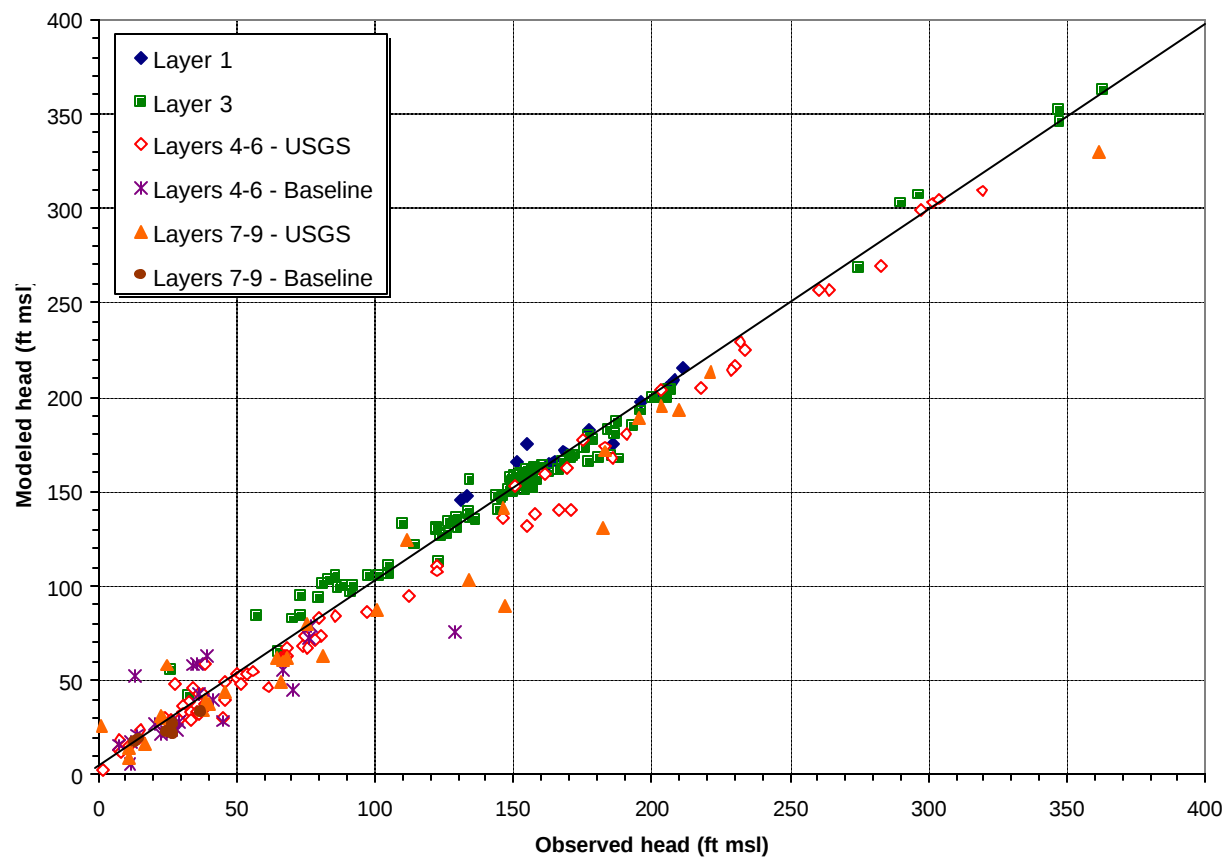
Weighted residual (ft) 2.63 obs>model
 -3.28 model>obs
 -200 Head (ft msl)
 Δ McAllister Springs

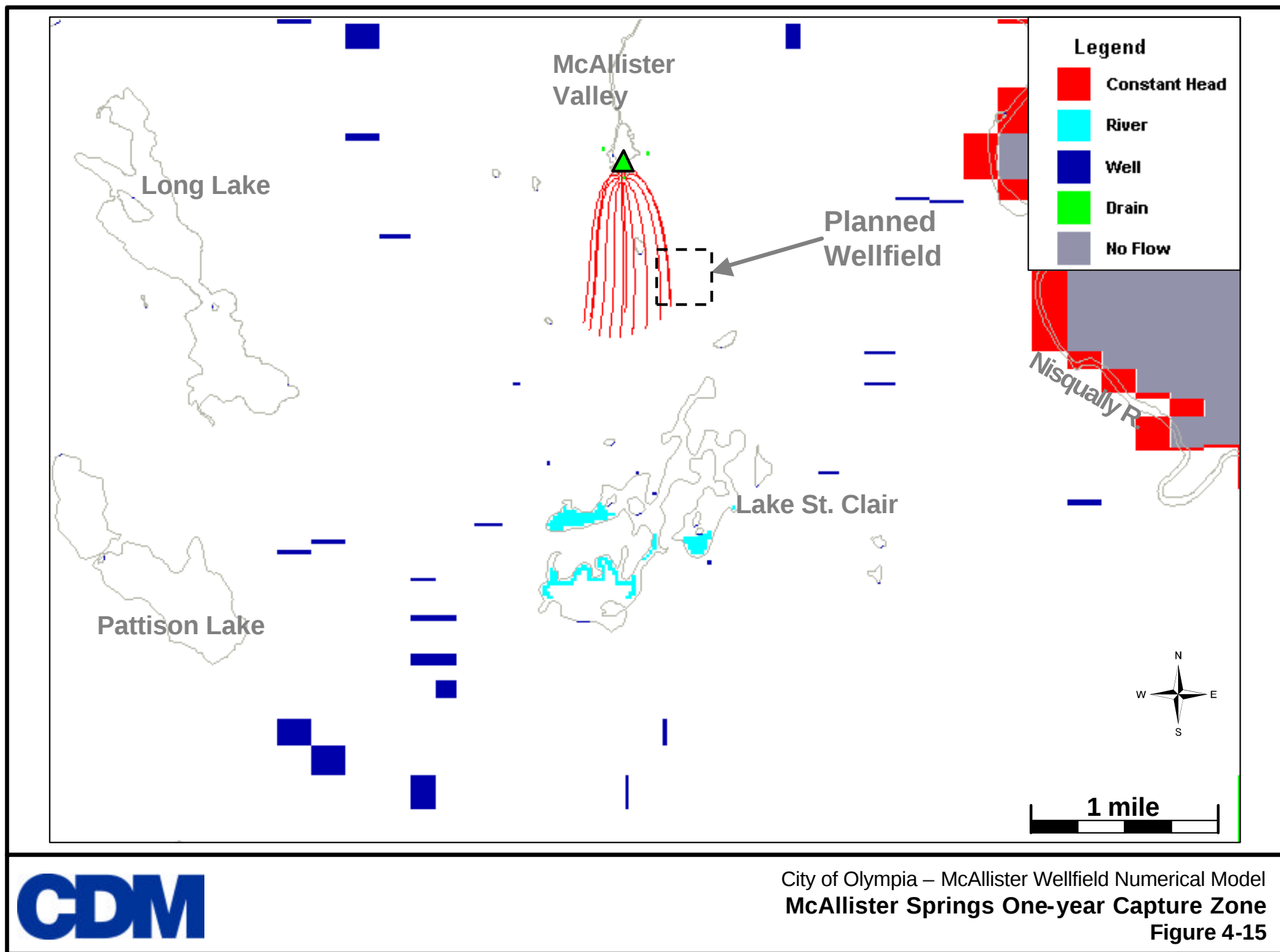


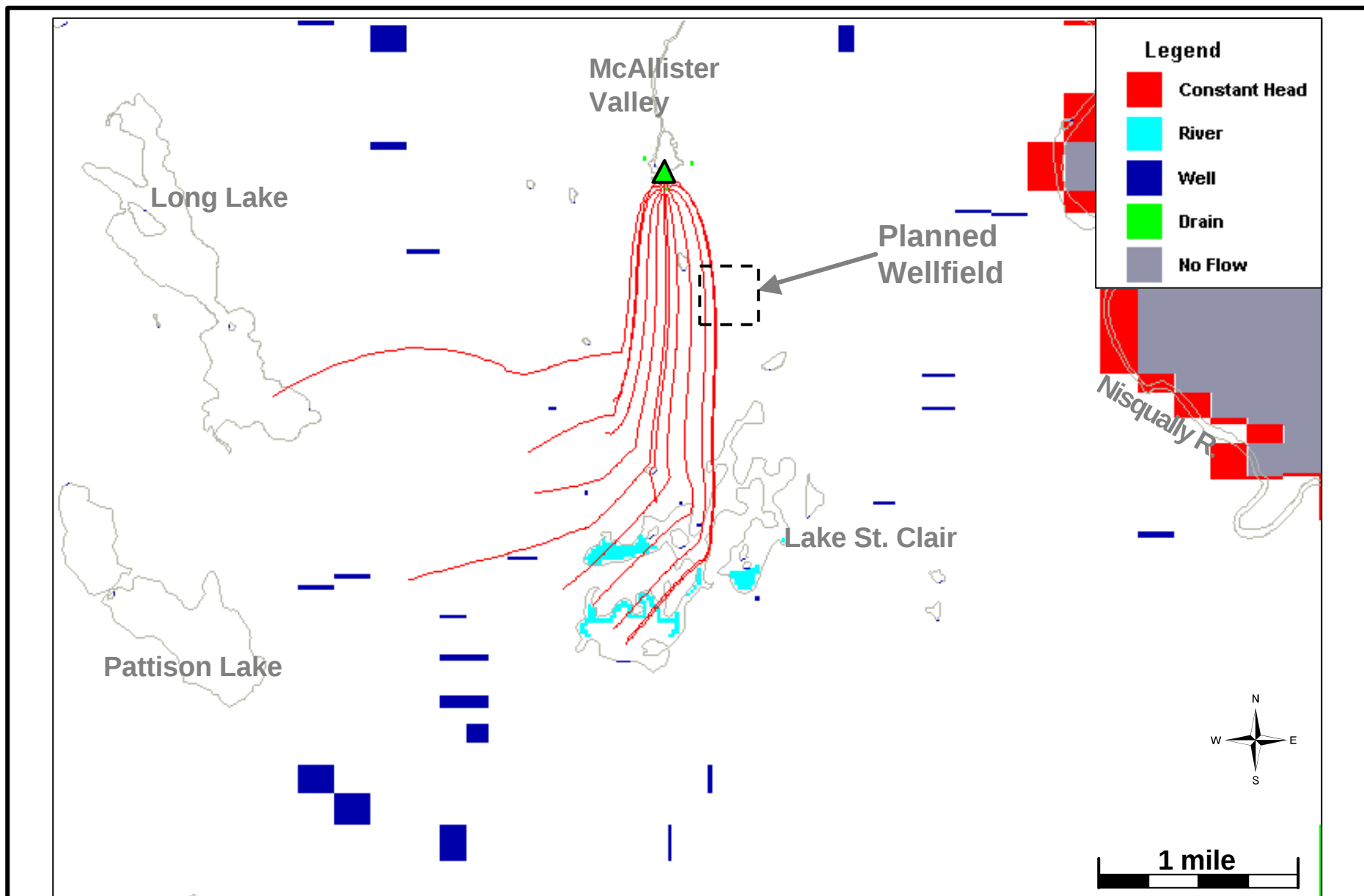
City of Olympia – McAllister Numerical Model
 Steady-state Calibration – Qc (layer 5)
 Figure 4-12

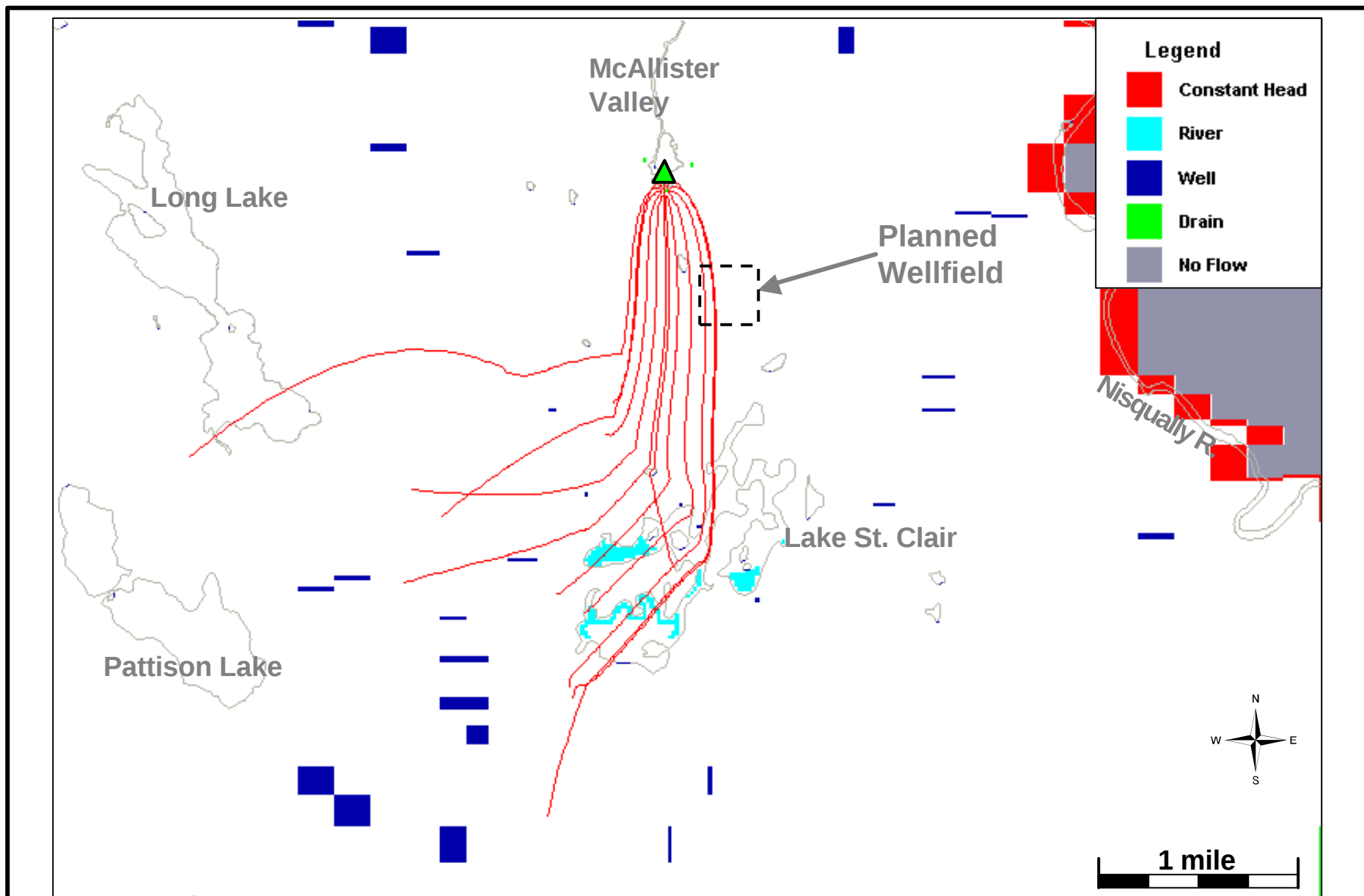


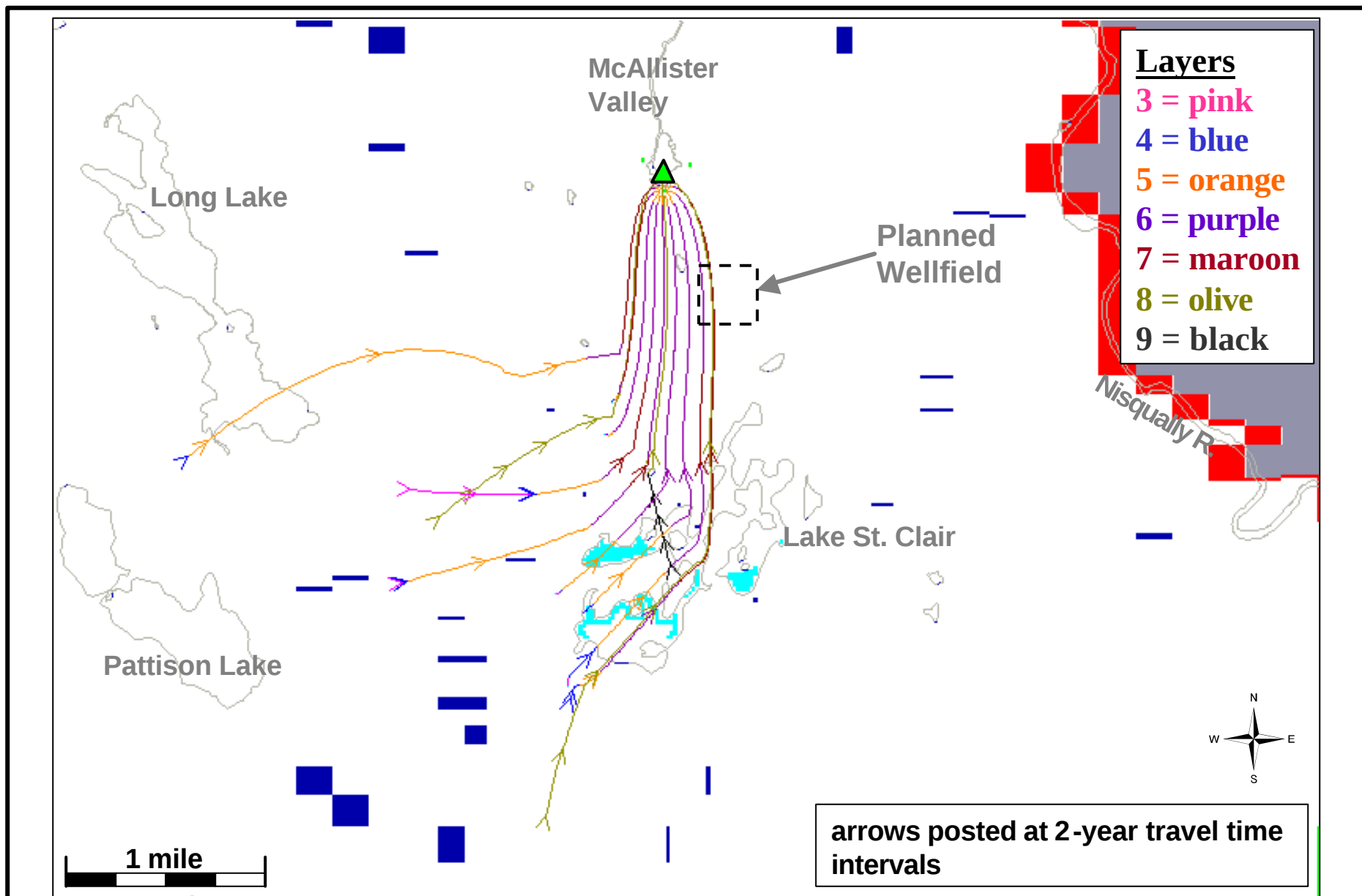
City of Olympia – McAllister Wellfield Numerical Model
Weighted Observed vs. Modeled Results - McAllister Area
Figure 4-13

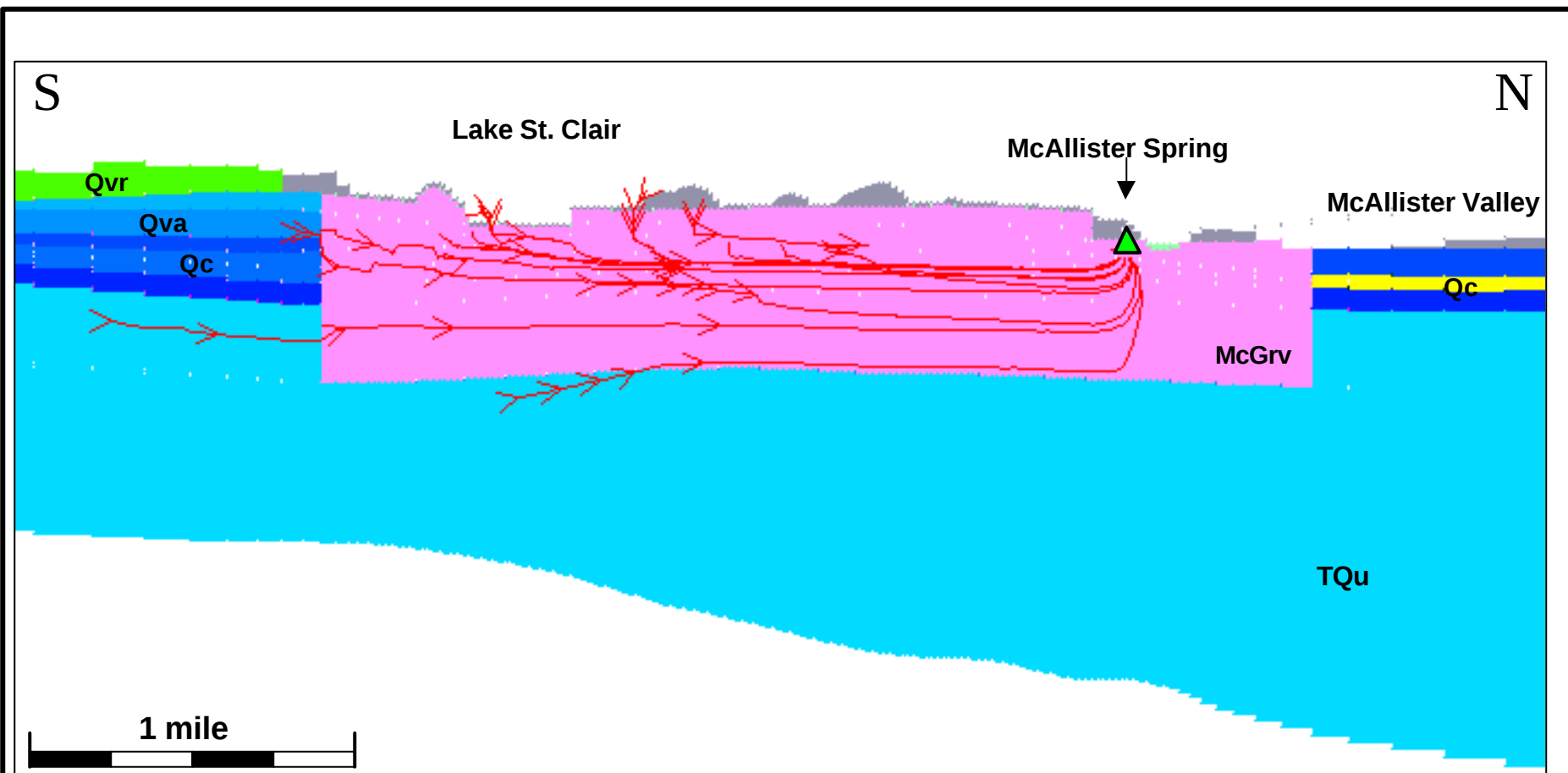












Qvr	Recessional Outwash
Qva	Advance Outwash
Qc	Sea-level aquifer
McGrv	McAllister Gravel
TQu	Undifferentiated Tertiary


 arrows posted at 2-year travel time intervals