Working Draft

Lowered Groundwater Levels in King County, Washington: A Preliminary Review of Reports

Revised April 2010

King County

Department of
Natural Resources and Parks
Wastewater Treatment Division

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Prepared for:

Planning and Asset Management Unit
Wastewater Treatment Division
Department of Natural Resources and Parks

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Department of Natural Resources and Parks

Citation:

King County Department of Natural Resources and Parks. 2010. *Working Draft: Lowered Groundwater Levels in King County, Washington: A Preliminary Review of Reports.* Water and Land Resources Division. Seattle, Washington.

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EXECUTIVE SUMMARY

King County conducted a preliminary assessment of water resource conditions to support the preparation of a reclaimed water comprehensive plan. The assessment focused on identifying streams and rivers with summer low flows that are lower than historical summer low flows, wetland areas that are not classified as bogs or forested coniferous wetlands and that are likely to have altered hydrology, and groundwater resources that are reported to have lower groundwater levels. The assessment is intended to provide preliminary information on water resources that might potentially benefit from additional water inputs, with an understanding that further investigation may be needed to understand if, or how, these water resources might benefit from additional water. The planning area includes the county's wastewater service area and areas immediately surrounding the service area.

This report documents the groundwater portion of the assessment. There are many ways to evaluate where groundwater may possibly benefit from additional water inputs in King County. Methods include noting trends of declining water levels; reviewing groundwater well usage through metering; measuring stream baseflows, discharge, and depletion; studying or modeling effects of drought on groundwater resources; modeling possible climate change impacts on groundwater levels or freshwater discharges; reviewing proliferation of wells; and forecasting water supply demands based on projected population growth trends for the region.

For this groundwater assessment, a preliminary review was completed of readily available literature for references to areas where groundwater levels are lower than in the past or aquifers are known to be producing less water than before. No attempt was made to review water level data, well discharge data, water supply data, well logs, and geologic and hydrogeologic maps, or to compare historical to current water levels. Many of these data are not systematically available for either the entire county or for the reclaimed water planning area.

Results of the assessment reveal that multiple studies have documented lowered groundwater levels in specific locations of the reclaimed water planning area. However, groundwater levels, both current and trends, are poorly documented in relatively large portions of the area. No regional groundwater monitoring program is currently in place from which general statements can be made regarding trends in groundwater levels, and much is left to learn regarding factors that may influence the levels—factors such as the availability of the resources, the response to urban and suburban development, the effects of increases in groundwater pumping and interbasin transfer, and the effects of climate change on shallow aquifers. For example, in many of the documents reviewed, references to the lateral and vertical extent of aquifers are general and often one-time water levels are given without discussion of historical trends.

The assessment also identified many data and information gaps, discrepancies, and inaccuracies. Comprehensive, site-specific follow-up studies to address information gaps should be conducted prior to developing any proposals to provide water that would benefit groundwater resources.

1.0. INTRODUCTION

King County conducted a preliminary assessment of water resource conditions to support the preparation of a reclaimed water comprehensive plan. State law (Chapter 90.46 RCW—the Reclaimed Water Act) authorizes the use of reclaimed water for environmental purposes, including augmenting streamflows, creating or enhancing wetlands, and recharging groundwater aquifers.

The assessment focused on identifying streams and rivers in the reclaimed water planning area with summer low flows that are lower than historical summer low flows, wetland areas that are not classified as bogs or forested coniferous wetlands and that are likely to have altered hydrology, and groundwater resources that are reported to have lower groundwater levels. The assessment is intended to provide preliminary information on water resources that might potentially benefit from additional water inputs, with an understanding that further investigation may be needed to understand if, or how, these water resources might benefit from additional water.

This report documents the groundwater portion of the assessment. Groundwater resources were evaluated because RCW 90.46.080 specifically allows for the beneficial use of reclaimed water:

> …for surface percolation provided the reclaimed water meets the state drinking water contaminant criteria as measured in groundwater beneath or down gradient of the recharge project site, and has been incorporated into a sewer or water comprehensive plan, as applicable, adopted by the applicable local government and approved by the department of health or department of ecology as applicable.

For this groundwater assessment, a preliminary review was completed of readily available literature for references to areas where groundwater levels are lower than in the past or are known to be producing less water than before. The information on groundwater resources in the reclaimed water planning area is more limited than for streams and wetlands.

The reclaimed water planning area includes the county's wastewater service area and areas immediately surrounding the service area (Figure 1). The information presented in this report is grouped into four geographic areas in and near the planning area: East King County, Eastside and Lake Sammamish, Seattle and North, and South King County. Some documents covered regional areas such as the entire Puget Sound region or King County. Information from these documents is included in the five areas where applicable. As shown in Figure 1, the boundaries of these areas overlap in some places because of the geographic extent of documents reviewed.

Comprehensive follow-up studies to address information gaps are recommended prior to developing any proposals to provide water that would benefit groundwater resources. As noted in the appendices, numerous studies have focused on much smaller areas than the reclaimed water planning area. Such studies could aid in determining whether opportunities may exist for groundwater recharge or inputs in these smaller areas. Once opportunities are identified, the studies, as well as existing or new data, could aid in evaluating whether additional water inputs could improve the status of groundwater resources.

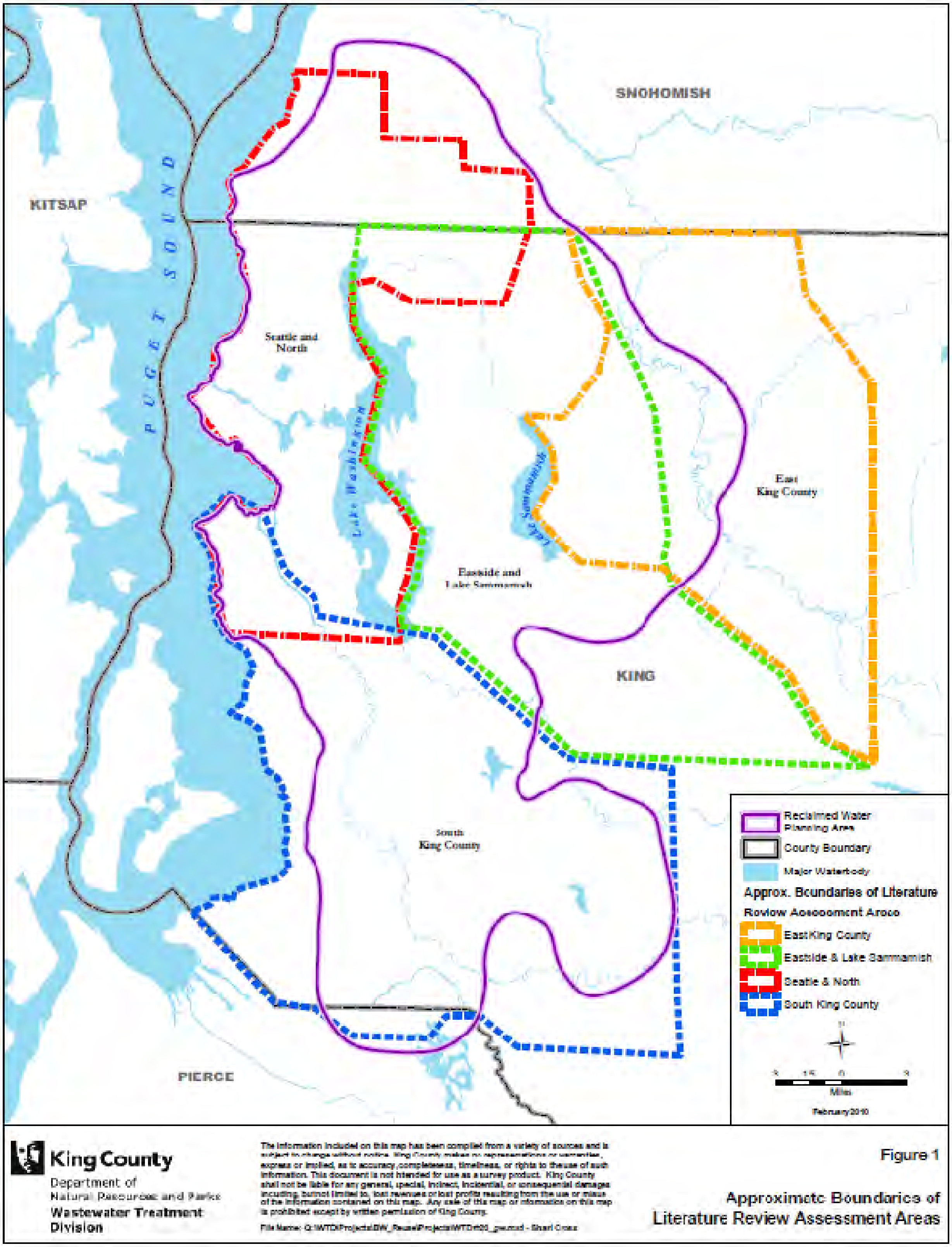

Figure 1. Approximate Boundaries of Literature Review Assessment Areas

2.0. METHODS

King County staff completed a preliminary review of documents that were readily available—either in hardcopy form in the King County Water and Land Resources Division's offices or in electronic form on King County's website—for references to changes in groundwater levels. The documents include reports by consultants, local and state government agencies, and academic researchers who have completed studies or reviews related to groundwater in the King County area and Puget Sound region. The 53 documents reviewed are listed in Table 1. Seven of the documents assessed groundwater conditions over the entire region; the remaining documents assessed conditions in specific locations of the reclaimed water planning area.

This report documents only references to lowered groundwater levels found in the literature. No attempt was made to review water level data, well discharge data, water supply data, well logs, and geologic and hydrogeologic maps, or to compare historical to current levels. Also noted in this report are references to information and data gaps, such as areas with insufficient information to evaluate an aquifer, wells lacking long-term water level data, studies with insufficient data to evaluate flow directions, and unclear relationships between surface water bodies (lakes and streams) with groundwater.

Table 1. Documents Reviewed for the Groundwater Assessment

EAST KING COUNTY
Golder Associates (Golder). 1995. *Geophysical and Hydrogeologic Investigations in East King County Groundwater Management Area*. Prepared for Public Health−Seattle & King County.
Golder. 2001. *Sampling and Analysis Plan for the East King County Groundwater Management Area*. Prepared for KCDNR. Prepared for King County Department of Natural Resources.
Golder. 2007. *Stream Enhancement Using Groundwater: A Case Study of the Upper Snoqualmie River Basin. Volume 1 Report.* Prepared for East King County Regional Water Association.
Hart Crowser. 1988. *Tolt River Pipeline Groundwater Development Study, King County, Washington.* Prepared for Seattle Water Department and CH2M HILL Northwest.
King County Department of Natural Resources (KCDNR) 1998. *East King County Ground Water Management Plan: Management Strategies-Final.* Prepared for East King County Ground Water Advisory Committee.
KCDNR. 1998. *East King County Ground Water Management Plan: Supplement 1: Area Characterization-Final.* Prepared for East King County Ground Water Advisory Committee.
King County Department of Natural Resources and Parks (KCDNRP), Water and Land Resources Division. 2005. *East King County Groundwater Level Survey.*
PEI/Barrett Consulting Group. 1991. *Lake Alice Plateau: Neighboring Water User Study for Snoqualmie Ridge Parkway.* Prepared for Snoqualmie Ridge Associates.
Turney G.L., S.C. Kahle, and N.P. Dixon. 1995. *Geohydrology and Ground-Water Quality of East King County, Washington.* U.S. Geological Survey Water-Resources Investigations Report 94-4082. 123 pp.
EASTSIDE AND LAKE SAMMAMISH
AGI Technologies. 1998. *Sammamish Plateau Water and Sewer District: Artificial Recharge Testing of the Plateau Aquifer System Zone IV (through Well 5), Phase III*. Prepared for Sammamish Plateau Water and Sewer District.
CDM. 2003. *Sammamish Plateau Water and Sewer District Report Describing Numerical Model of the Plateau Aquifer System.* Prepared for Sammamish Plateau Water and Sewer District, Sammamish, Washington.

EASTSIDE AND LAKE SAMMAMISH (continued)

Golder. 1995. *Preliminary Evaluation of Aquifer Storage and Recovery in the (Little) Bear Creek Drainage*. Prepared for Northshore Utility District, Kenmore, WA

Golder. 2000. *Groundwater Exploration and Pumping Test: Lower Issaquah Valley.* Prepared for City of Issaquah.

Golder. 2000. *Sampling and Analysis Plan for the Issaquah Creek Valley Groundwater Management Area.* King County Department of Natural Resources.

Golder. 2001. *Sampling and Analysis Plan for the Redmond–Bear Creek Groundwater Management Area.* Prepared for King County Department of Natural Resources.

KCDNR. 1999. *Issaquah Creek Valley Ground Water Management Plan: Area Characterization. Supplement 1: Area Characterization – Final*. Prepared for Issaquah Creek Valley Ground Water Advisory Committee.

KCDNR. 1999. *Issaquah Creek Valley Ground Water Management Plan: Management Strategies – Final*. Prepared for Issaquah Creek Valley Ground Water Advisory Committee.

KCDNR. 1999. *Redmond – Bear Creek Valley Ground Water Management Plan: Management Strategies – Final*. Prepared for Redmond – Bear Creek Ground Water Advisory Committee.

KCDNR. 1999. *Redmond – Bear Creek Valley Ground Water Management Plan. Supplemental 1: Area Characterization – Final.* Prepared for Redmond – Bear Creek Ground Water Advisory Committee.

KCDNRP, Water and Land Resources Division. 2005. *Sammamish River Valley Groundwater Study: 2003–2004 Data Report.*

Massmann, J. 2000. *Effects of Groundwater Extraction on Stream Flow in Bear-Evans Creek Watershed.* Prepared for the Muckleshoot Indian Tribe Fisheries Department, Auburn, WA.

Massmann, J. 2001. *Effects of Groundwater Extraction on Stream Flow in Issaquah Creek Watershed.* Prepared for the Muckleshoot Indian Tribe Fisheries Department, Auburn, WA.

Pacific Groundwater Group, Inc. 1992*. Issaquah Ground Water Management Program: Data Collection and Analysis Plan (DCAP)−Final.* Prepared for Seattle−King County Department of Environmental Health.

Robinson & Noble, Inc.1979. *Ground Water Evaluation of East Lake Sammamish Area*. Prepared for King County Water District 82.

Sweet-Edwards/EMCON, Inc. 1990. *Redmond–Bear Creek Ground Water Management Area: Data Collection and Analysis Plan (DCAP)–Revision 3*. Prepared for Public Health−Seattle & King County.

SEATTLE AND NORTH

Liesch, B. A., C. E. Price, and K. L. Walters. 1963. *Geology and Ground-Water Resources of Northwestern King County, Washington.* Water Supply Bulletin Number 20. Prepared by State of Washington Department of Conservation, Division of Water Resources, in cooperation with U.S. Geological Survey Ground-Water Branch. 241 pp.

SOUTH KING COUNTY

Brown and Caldwell. 1992. *Effluent Reuse Pilot Project Report.* Prepared for Cities of Renton and Tukwila

Carlson, C. 1994. *Big Soos Creek Low Flow Trend and Water Right Analysis*. Muckleshoot Indian Tribe Fisheries Department, Auburn, WA.

Carollo Engineers. 2006. *Lakehaven Utility District Water Reclamation Related Engineering Services: Feasibility Study – Final.*

City of Auburn Water Division website: *http://www.ci.auburn.wa.us/utilities/water/index.asp.* Accessed 2008.

City of Renton Aquifer Protection Program website: *http://www.renton-wa.gov/living/default.aspx?id=144*. Accessed 2008.

CH2M HILL. 1988. *Well Field Monitoring Study.* Prepared for City of Renton,WA.

Covington Water District (CWD). 1995. *Lake Sawyer Wellhead Protection Plan: Covington Water District.* Prepared in association with Robinson & Noble, Inc., and Economic & Engineering Services, Inc.

Harper-Owes. 1985. *Duwamish Ground Water Studies: Waste Disposal Practices and Dredge and Fill History.* Prepared for Sweet-Edwards and Associates.

SOUTH KING COUNTY (continued)

Hart Crowser. 1996. *Wellhead Protection Program: Clark, Kent, and Armstrong Springs; City of Kent.* Prepared for City of Kent,WA.

Massmann, J. 2000. *Description and Evaluation of Groundwater Monitoring Activities in the Vicinity of the Witte Well Field.* Prepared for The Muckleshoot Indian Tribe Fisheries Department, Auburn, WA.

Northwest Hydraulics Consultants, Inc. 2005. *Assessment of Current Water Quantity Conditions in the Green River Basin.* Prepared for the WRIA 9 Steering Committee.

Pacific Groundwater Group. 1999. *Hydrogeologic Characterization Report, City of Auburn*. Prepared for City of Auburn Department of Public Works Water Utility Engineering, Auburn, WA.

R2 Resource Consultants, Inc. 2006. *Clark Springs Water Supply System Habitat Conservation Plan: Preliminary Draft*. Prepared for City of Kent, WA.

RH2 Engineering. 1987. *Analysis Report for the City of Renton Cedar River Valley Aquifer Test.*

Robinson & Noble, Inc. 1992. *Hydrogeologic Analysis of the Federal Way Area, Washington. Volume 1.*

Sweet-Edwards and Associates, Inc. 1985. *Duwamish Ground Water Studies.* Prepared for Municipality of Seattle.

TCW Associates, Inc., HLA/Harper-Owes, University of Washington College of Forest Resources, and Municipality of Metropolitan Seattle. 1989. *Hydrogeology & Water Quality Evaluation: Metro Section 16 Silvigrow Project.* Prepared for Public Health−Seattle & King County.

Washington State Department of Ecology (WA Ecology). 2006. *Aquifer Storage and Recovery Application R1-28083A Amended Report of Examination* (Lakehaven Utility District).

WA Ecology. 2006. *Aquifer Storage and Recovery Permit R1-28083P* (Lakehaven Utility District)..

Woodward, D.F., F.A. Packard, N.P. Dion, and S.S. Sumioka. 1995. *Occurrence and Quality of Ground Water in Southwestern King County, Washington.* U.S. Geological Survey Water-Resources Investigations Report 92-4098. 69 pp.

REGIONWIDE

Bauer, H. H, and M. C. Mastin.1997. *Recharge from Precipitation in Three Small Glacial-Till-Mantled Catchments in the Puget Sound Lowland, Washington*. U.S. Geological Survey Water-Resources Investigations Report 96-4219. Prepared in cooperation with Washington State Department of Ecology.

King County Department of Development and Environmental Services, Environmental Division, Regional Planning Section, and Public Health−Seattle & King County, Environmental Health Division, Drinking Water and Ground Water Section. 1995. *Mapping Aquifer Susceptibility to Contamination in King County.*

KCDNRP, Water and Land Resources Division. 2005. *Ambient Groundwater Monitoring 2001–2004 Results.*

Morgan, D. S., and J. L. Jones. 1995. *Numerical Model Analysis of the Effects of Ground-Water Withdrawals on Discharge to Streams and Springs in Small Basins Typical of the Puget Sound Lowland, Washington*. U.S. Geological Survey Open-File Report 95-470.

Vaccaro, J. J., A. J. Hansen, and M. A. Jones. 1998. *Hydrogeologic Framework of the Puget Sound Aquifer System, Washington and British Columbia: Regional Aquifer System Analysis—Puget-Willamette Lowland*. U.S. Geological Survey Professional Paper 1424-D.

WA Ecology. 1988. *Report of the Technical Advisory Committee on the Capture of Surface Water by Wells (Draft); Recommended Technical Methods for Evaluating the Effects of Ground-Water Withdrawals on Surface Water Quantity.* Prepared with the assistance of Ross & Associates Environmental Consulting, Ltd. http://www.ecy.wa.gov/biblio/98154.html.

WA Ecology Water Quality Program. 2005. *Critical Aquifer Recharge Areas: Guidance Document*. Publication Number 05-10-028.

3.0. FINDINGS AND RECOMMENDATIONS

This section summarizes the findings of the preliminary review of readily available documents for references to areas where groundwater levels are reported as lower than in the past or aquifers are known to be producing less water than before. After summarizing the findings, the section presents information gaps reported in the documents, discusses factors such as population growth that could affect future groundwater levels, and recommends more detailed, site-specific assessments prior to developing any proposals to provide water that would benefit groundwater resources.

3.1 References to Lowered Water Levels

Groundwater is the portion of precipitation that soaks into the ground and gets stored in underground geological water systems called aquifers. Every groundwater system is unique and depends on both internal and external factors. Examples of internal factors include the type of geologic formation (such as loose sand and gravel or volcanic rock), the mineral composition of the formation, the size of the material that makes up the aquifer (such as sand grains versus pebbles), and the amount of water in the aquifer. Examples of external factors include the rate of precipitation, the interaction of groundwater with streams and other surface water bodies, the rate of evapotranspiration, and, in the case of an island, interactions with the surrounding surface water.[1]

Results of this assessment reveal that in general, groundwater conditions are poorly understood in relatively large areas of the reclaimed water planning area. While numerous studies have been completed on groundwater resources in the area, no comprehensive groundwater monitoring program exists and much is left to learn regarding the availability of the resources, the responses to urban and suburban development, the effects of increases in groundwater pumping and interbasin transfer, and the effects of climate change on the shallow aquifers. Multiple studies note lowered groundwater levels associated with groundwater withdrawals at specific locations. Although the Washington State Department of Ecology (Ecology) has demonstrated the hydraulic continuity between groundwater and surface water throughout Washington State (WA Ecology, 1998), details can vary greatly between different locations and highly disparate levels of information are available in the reclaimed water planning area. In many of the documents reviewed, references to the lateral and vertical extent of aquifers are general and often one-time water levels are given without discussion of historical trends.

The planning area is known to have several water-bearing geologic units. Most, if not all, of these units are used for water supplies to some degree. However, because groundwater levels are not usually recorded on a regular basis (unless part of an ongoing funded program), it is difficult to identify trends, whether related to development or to natural processes, and to ascertain whether water levels are lower than in the past. It is likely that the more shallow aquifers would be most affected by climate change and development. However, increased pumping may be lowering levels in the deeper aquifers. Where lowering of aquifer levels has been documented,

[1] Evapotranspiration = the sum total of loss of water primarily from water bodies, wet soil, and wet plants (evaporation) and their respective vegetation (transpiration).

further assessment of existing data and additional site-specific studies could help determine whether the aquifers would benefit from additional water inputs.

The information in this subsection is organized according to the four geographic areas described earlier in this report. Further details on results of the document review are given in Appendix A.

3.1.1 East King County

Nine studies were reviewed that assessed groundwater conditions in East King County. A study conducted by the U.S. Geological Survey (USGS) in eastern King County (Turney et al., 1995) noted that not only were wells in some areas showing declining water levels but also wells receiving water from bedrock aquifers can go dry in the summer or when under high use. Since then, new development and consequent demand on groundwater supplies have increased.

In 1998, the King County Department of Natural Resources (KCDNR) completed a groundwater management plan and an area characterization for the East King County Groundwater Management Area (GWMA).[2] (Figure 2 shows the locations of King County GWMAs.) KCDNR concluded that based on estimated future demands, the major shallow aquifers have the potential for overuse (KCDNR, 1998a and 1998b). Some wells were reported as having gone dry or as having declining water levels. In addition, the deeper bedrock aquifers east of the Duvall area were reported to go dry, even though use as a water supply was limited.

Early in 2005, a King County report on ambient groundwater monitoring from 2001 through 2004 of 14 wells in the East King County GWMA found that water levels were generally stable with no significant declines (KCDNRP, 2005a). However, another King County study in late 2005 found that water levels in 19 out of 20 wells in areas of the shallow Vashon advance outwash sand and gravel aquifer in East King County had declined since 1995 between 1 to 5 feet (KCDNRP, 2005b). The study also found that in the alluvium and Vashon recessional outwash sand and gravel aquifer, 4 out of 25 wells showed significantly lower water levels than in 1995. The study found that some well owners had recently deepened their wells to address the lowering water levels and others had reported that at times when the water in a nearby river or stream was lower than usual, the water level in their wells was also lower than usual.

In 2007, Golder Associates reported on a study of water levels from 1996 to 2007 of wells located in North Bend. Results indicated that groundwater elevations declined slightly. However, it appears that the lowering of water levels was related to the relatively wet years in the beginning of the study period from 1996 to 1999 (Golder, 2007).

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[2] Five GWMAs were proposed and designated in King County in 1986–1987 under the provisions of a Washington State regulation. The GWMAs were initiated to ensure that long-term water quality and quantity issues were addressed in areas where no coordinated groundwater management occurred. For each GWMA, a committee of local stakeholders was formed and groundwater management plans were created. Currently, the only active GWMA is the Vashon–Maury Island GWMA because of lack of funding for continued activities in the other areas. The Vashon–Maury Island GWMA is not discussed in this report because it is outside the reclaimed water planning area.

Figure 2. King County Groundwater Management Areas

3.1.2 Eastside and Lake Sammamish

A total of 16 reports and studies were reviewed that assessed groundwater conditions on the eastside of Lake Washington and the Lake Sammamish region. A 1963 report on geology and groundwater resources in northwestern King County indicated that withdrawals in the Newcastle Hills area had exceeded the recharge of the principal aquifer and also expressed concern about meeting the water supply demands of projected increases in population (Leisch et al., 1963).

In 1999, KCDNR completed a groundwater management plan and an area characterization for the Issaquah Creek Valley GWMA (Figure 2). The characterization found that although the deeper bedrock aquifers are usable, they do not yield high quantities (KCDNR, 1999a and 1999b). Long-term and recent water level data for the lower Issaquah Creek Valley aquifer indicate a downward trend in water table elevations (Massmann, 2001), possibly resulting from over pumping or from climatic influences (KCDNR, 1999b).

Similar documents for the Redmond–Bear Creek Valley GWMA (Figure 2), also published in 1999, reported that the East King County coordinated water system plan had concluded that the water supply potential for the Redmond, Evans Creek, and Sammamish Plateau aquifers was not sufficient to meet future regional demands (KCDNR, 1999c and 1999d). In addition, it was recommended that new water sources in some areas of these aquifers should not be developed because over pumping would reduce water levels and that continued growth will require additional water supply and land use control to recharge areas to maintain aquifer quantity (KCDNR, 1999d). The reports also indicated that according to consultants, the planned changes to land use would impact both water quantity and quality (Novelty Hill area) (KCDNR, 1999d). In early 2005, however, water level monitoring of 16 wells in the same GWMA indicated that from 2001 through 2004, water levels were generally stable with no significant declines (KCDNRP, 2005a). This monitoring was conducted where access was available, mostly at privately owned wells but also at some public water purveyor wells, so results from these wells are not necessarily representative of conditions throughout the entire GWMA.

As of 1999, not much data had been recorded to substantiate concerns that private wells established in Vashon till in the Redmond−Bear Creek area were "drying out" (KCDNR, 1999d).

A report on the effects of groundwater extraction in the Bear–Evans Creek and the Issaquah Creek Valley watershed indicated that streamflows and temperatures are impacted, particularly during summer months when groundwater water supply wells are pumping at highest extraction rates (Massmann, 2000b and 2001). It was reported that because of the proximity of these wells to the streams and because of the hydrogeologic conditions, the response of the streams to reductions in the extraction rate was relatively short, on the order of days or weeks.

3.1.3 Seattle and North

Only a few documents were available for the Seattle and North area. A report produced by the State of Washington Department of Conservation in 1963 discussed the geology and groundwater resources for northwestern King County (Liesch et al., 1963). Much of the report focused on geologic and well data.

3.1.4 South King County

Although many reports are available on Auburn, Kent, Covington, Black Diamond, Renton, Federal Way, and Tacoma area aquifers, only a few of the reports provided information relevant to this assessment. A total of 20 reports were reviewed that assessed groundwater conditions in South King County.

A hydrogeologic analysis of the Federal Way area (Robinson and Noble, 1992) indicated the following:

- Water levels in one well declined by up to 12 feet over 14 years.
- Water level records from another well showed 10 feet of water level decline in response to moderate production of the Valley aquifer system.
- Production and land use changes had induced water level declines from the major shallow aquifer (beneath the upper confining unit), but the water levels had stabilized by 1987. However, stabilization of water levels did not continue past 1987. Levels declined through 1988 to about 7 feet lower than at the end of 1987. Water levels had recovered slightly by the time of the report in 1992.
- When production began (1981) in Well 20 in the Mirror Lake aquifer, water levels had declined 50 feet by 1987 and slightly less by 1992.
- The Eastern Upland aquifer was also reported as affected by production, but not as much as the Mirror Lake aquifer.

A more recent historical review of the Mirror Lake aquifer system was presented in the *Aquifer Storage and Recovery Application R1-28083A Amended Report of Examination* submitted by the Lakehaven Utility District to Ecology in 2006 (WA Ecology, 2006a). The report indicated that water levels in the Mirror Lake aquifer fell from about 204 feet above mean sea level in the early 1980s to a low of about 125 feet above mean sea level in the 1990s. Curtailed production and groundwater injection between 1995 and 1999 brought water levels up to about 185 feet above mean sea level. Water levels have steadily decreased to about 145 feet above mean sea level in

2004 (WA Ecology, 2006a). These changes in water levels are likely due to the intentional activities of the OASIS Aquifer Storage and Recovery Project, as indicated in the amended report and permit (WA Ecology, 2006a and 2006b, respectively).

The Lake Sawyer Wellhead Protection Plan indicated that portions of the Lake Sawyer wellfield (Covington Water District) in the shallow aquifer may completely drain by late summer (CWD, 1995). The regional aquifer that supplies water to the Lake Sawyer wellfield also supplies the Kent and Clark Springs aquifer systems for the City of Kent.

Low streamflows in Big Soos Creek were reported to occur in late summer and early fall, when groundwater is the only source to sustain flows (Carlson, 1994). Because of the proximity of wells and of hydrogeologic conditions that support a connection between groundwater and surface water, groundwater rights appropriation usage appeared to be the main source asserting influence on low flow declines of Big Soos Creek from 1967 through 1992, with a pronounced decline in the latter period (Carlson, 1994).

A study of 420 wells in the Green River basin was undertaken to qualitatively assess whether groundwater withdrawals would impact streamflows (NHC, 2005). Impacts resulted from most wells to streamflows on the basin or subbasin level and, in some cases, in adjacent or downgradient basins. As expected, the largest impacts occurred during low-flow conditions.

A USGS study in southwestern King County looked at the occurrence and quality of groundwater (Woodward et al., 1995). The study noted that some wells showed declining water levels over decades and that some wells in the Vashon till may go dry in late summer. Since completion of this study, the area has experienced increased development and demand on groundwater supplies.

3.2 Information Gaps

This assessment identified many information gaps, both in time (water level data) and space (data coverage across King County). The following subsections describe information gaps in four categories:

- Surface water and groundwater interactions
- Water level trends
- Groundwater flow
- Geology and hydrogeology

3.2.1 Surface Water and Groundwater Interactions

Many streams and lakes may be receiving or losing water depending on groundwater levels, but accurate locations along stream reaches or lake shores were not identified in reports. Relations and interactions between surface water and groundwater systems are not well understood in many small basins of the Puget Sound area (Morgan and Jones, 1995). In a 1995 USGS report, the Tolt and Raging Rivers in East King County were identified as losing reaches (Turney et al., 1995). In addition, the Snoqualmie River between Carnation and Monroe, also in East King County, was noted as seeming to be a losing reach (KCDNR, 1998b). A report by Golder Associates of the Lower Issaquah Valley in the Eastside and Lake Sammamish area documented losing and gaining reaches of Issaquah Creek at differing times (Golder, 2000). Additional withdrawals in the area could result in lower groundwater levels and in decreases to springs and other surface water bodies.

A document by Hart Crowser on the Wellhead Protection Program for the City of Kent reported that flow patterns north of Armstrong Springs, Lake Sawyer, and Ravensdale Lake in East King County were unclear. The effect of Lake Sawyer on groundwater flow was noted as not well studied, nor was the relationship clear between Jenkins Creek and the aquifer (Hart Crowser, 1996).

Available information suggests a limited stream-groundwater connection south of the gap in the upper valley of Issaquah Creek, but this connection was not confirmed (KCDNR, 1999b).

A report by Golder Associates in 2007 of a study of the Upper Snoqualmie River basin discusses conjunctive management of resources to improve or ensure adequate stream habitat during critical low-flow periods (Golder, 2007). The report recommends that a thorough understanding of basin morphology and stream-groundwater interactions is needed and that a performance metric is necessary for evaluating sustainability of augmentation concepts and comparing scenarios.

3.2.2 Water Level Trends

The literature contains little information on long-term water level trends, and the records in the databases reported are not consistent enough to establish trends.

Data are too sparse to establish trends and to substantiate the following references:

- Wells drying out in till in the Redmond−Bear Creek area (KCDNR, 1999d) and in southwestern King County (Woodward et al., 1995).
- Seasonal variations in the Lake Sawyer wellfield shallow system in South King County (CWD, 1995).
- Downward trends seen in water level data (lower Issaquah Creek Valley aquifer in the Eastside and Lake Sammamish area) (KCDNR, 1999b). It was noted that more data were needed over time to evaluate trends and to clarify areas in this aquifer that had missing information (KCDNR, 1999b).

Early in 2005, King County published a report on ambient groundwater monitoring from 2001 through 2004 of water levels in both private and public wells in East King County, Issaquah Creek Valley, Redmond–Bear Creek, and Vashon–Maury Island GWMAs (KCDNRP, 2005a). The report noted limitations of the study: (1) the study included more shallow wells than deep wells, (2) the frequency of the monitoring was limited, and (3) pump usage prior to measurement was unknown.

Similarly, another King County report documented a one-time measurement in late 2005 of water levels in wells in East King County and compared them to USGS measurements in 1995 at the same wells (KCDNR, 2005b). While some wells had lower water levels relative to 1995, the lack of routine water level measurements made it impossible to assess long-term trends that also account for annual differences in water use and weather.

3.2.3 Groundwater Flow

Groundwater flow directions and patterns are evaluated using water level measurements in wells and surface water bodies. When a document notes that information related to flow direction or patterns is unknown or unclear, it is likely that water level data are sparse over time and/or space.

Flow in alluvium and Vashon recessional outwash units on the Sammamish Plateau in the Eastside and Lake Sammamish area and in some areas of South King County is not well defined because much of it is unsaturated (KCDNR 1998b). The flow direction in the deeper aquifers in the Issaquah Creek area, also in the Eastside and Lake Sammamish area, is not fully understood (KCDNR, 1999b). The population in the upper Issaquah Creek area is sparse, and there are no known high-capacity wells.

Flow to the deeper regional system in East King County is unknown, but may be significant (Turney et al., 1995); upward flow is likely in many areas (KCDNR, 1998b). A 1995 USGS and 1998 KCDNR report recommended that a groundwater model of the Snoqualmie Valley would help to determine the capacity of the aquifers (Turney et al., 1995; KCDNR, 1998b).

Other places where information on flow is limited include the Grand Ridge and Tradition Lake area in the Eastside and Lake Sammamish area (flow direction) (KCDNR, 1999b) and the Clark Springs area in South King County (undefined groundwater divide) (Hart Crowser, 1996).

3.2.4 Geology and Hydrogeology

The documentation and accuracy of characteristics, extent, and presence of geologic and hydrogeologic features in the reclaimed water planning area are varied and limited. Having a clear understanding of the geology and hydrogeology improves evaluation of whether groundwater resources may need additional water. Obtaining this understanding often involves drilling wells, identifying geologic units in the underlying units, reviewing maps, mapping saturation of geologic units, measuring water levels in wells, and correlating geologic and hydrogeologic information across wells and across large areas. When a document notes that the geology and hydrogeology are unknown or unclear, it is possible that information on water levels and saturated geologic units is missing.

The following reports commented on general lack of information available for developing an understanding of aquifer systems and/or noted the sparseness of geologic or hydrogeologic data:

- Cedar River Valley (Golder, 2007; RH2 Engineering, 1987; Woodward et al., 1995)
- Cascade Foothills and Cherry Creek Valley in East King County (KCDNR, 1998b)
- Duwamish/Green basin (Golder, 2007; Sweet-Edwards and Associates, Inc., 1985)
- East Lake Sammamish area (Robinson & Noble, 1979)
- Northeast Snoqualmie Valley and East King County (Golder, 2007; KCDDES and SKCPH, 1995)

Little information is available on the pre-Vashon deposits (lower coarse-grained unit and deep undifferentiated unit) in areas like Issaquah Creek (KCDNR, 1999b), on the yields of the same deep undifferentiated unit in East King County (Turney et al., 1995; KCDNR, 1998b) and in southwestern King County (Woodward et al., 1995), and on the capacity of some aquifer systems in the area served by the Sammamish Plateau Water and Sewer District, the City of Issaquah, and the Snoqualmie Valley aquifer (KCDNR, 1999b).

Various studies identified gaps in geologic and hydrogeologic data from deep wells in the lower Snoqualmie River Valley, Sammamish Plateau, and Cascades Foothills (Turney et al., 1995), Des Moines Plains areas (Woodward et al., 1995), and Puget Sound lowlands (Vaccaro et al., 1998). A report by Golder Associates in 2007 indicated that the vertical extent of the sand layer beneath the till in the Duwamish/Green basin is not well known. The report also noted that the full extent and the recharge characteristics of the deep channel deposits in the Cedar/Sammamish basin, particularly in the Maplewood areas of the lower Cedar River, are not known and need further evaluation (Golder, 2007).

Information on deep aquifer systems is limited (Golder, 2007; Hart Crowser, 1988). A report by the Covington Water District in 1995 indicated that the deep aquifer in the Covington area in the South King County area is poorly delineated (CWD, 1995). Further, it is not known whether a deeper aquifer exists at bedrock interface at Carnation (KCDNR, 1998b) and whether an aquifer exists beneath the artesian aquifer in the Eastside and Lake Sammamish area (Robinson & Noble, 1979). The Redmond–Bear Creek GWMA management plan indicated that there are not enough data to determine whether impacts would occur from large-scale developments on deep aquifer systems in the Redmond−Bear Creek area in the Eastside and Lake Sammamish area (KCDNR, 1999c). The Federal Way deep aquifer in the South King County area was noted as having not been adequately studied (Robinson & Noble, 1992).

3.3 Future Changes and Assessments

It is likely that the trend of population increase along with increased demands on water supply will continue in King County (Boland and Boland, 2008; CDM, 2008; CPSWSF and R.W. Beck, 2001), as well as increased development and the resulting likely reduction of infiltration into the shallow aquifers (Turney et al., 1995; Woodward et al., 1995). In addition, future changes in climate may result in lower groundwater levels (Alexander and Palmer, 2007; Geller, 2007; WA Ecology, 2006b) and reduction in stream baseflow. Because there are no ongoing long-term programs studying groundwater levels in the Puget Sound region or throughout King County, it is difficult to identify the location and degree of effects these future changes may have on groundwater in the reclaimed water planning area without in-depth review of existing and future literature.

Additional information, such as indications of environmental impacts not seen in earlier hydrogeologic studies or indications of replenishment of historically lowered levels, may be gained from future phases of aquifer storage and recovery programs (WA Ecology, 2006a).

Future assessments could include resolving differences in the studies reviewed and reviewing other documents. An additional 122 reports were inventoried and are referenced in Appendix B. The information presented in these reports may be helpful in identifying groundwater likely to benefit from additional water inputs. Many other sources can be obtained, if necessary, for more in-depth future assessments of groundwater in specific locations of the reclaimed water planning area.

It is recommended that comprehensive follow-up studies to address information gaps or to identify alternative approaches for providing additional water inputs be done prior to developing any proposals to provide water that would benefit groundwater resources in the reclaimed water planning area. The following are various methods that could be used in such studies:

- Reviewing groundwater well usage through metering (Geller, 2007; WA Ecology, 2009)
- Measuring stream baseflows, discharge, and depletion (Cuo et al, 2008; Dai et al., 2009; Keta Waters, 2008; Massmann, 2000a and 2001; Vaccaro et al., 1998)
- Studying or modeling effects of drought on groundwater resources (CDM, 2008; WA Ecology, 2006b)
- Modeling possible climate change impacts on groundwater levels (Alexander and Palmer, 2007; CDM, 2008; Dai et al., 2009)
- Reviewing proliferation of wells (KCDNRP, 2007; SWSTC, 2007)
- Forecasting water supply demands based on projected population growth trends for the region (Boland and Boland, 2008; CDM, 2008; CPSWSF and R.W. Beck, 2001)

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Appendix A
Summary of Reviewed Documents

Documents Reviewed	Information Indicating Lowered Water Levels	Presented Information Gaps	Notes
EAST KING COUINTY			
Golder Associates. 1995. *Geophysical and Hydrogeologic Investigations in East King County Groundwater Management Area.*	None Presented	None Presented	• Report presents geophysical results, test well results, and development of conceptual geologic model, near Carnation. • Good correlation between wells and seismic investigation.
Golder Associates, 2001. *Sampling and Analysis Plan for the East King County Groundwater Management Area.*	None Presented	None Presented	• Water quality generally excellent. • Goal is to evaluate regional scale water quality and overall conditions of groundwater. • Emphasis on most susceptible, which was based on land use.

Golder Associates Inc. 2007. Streamflow Enhancement Using Groundwater: A Case Study of the Upper Snoqualmie River Basin. Volume 1 Report.	• A long term study of 16 wells from 1996-2007 in vicinity of North Bend, WA. indicated groundwater elevations declined slightly; appears to be caused by relatively wet years in beginning of monitoring period from 1996-1999 (Appendix D).	• Thorough understanding of the basin morphology and aquifer-stream interactions is needed in the upper Snoqualmie Basin (with respect to Streamflow augmentation during critical time periods)
		• A performance metric was recommended as necessary for evaluating sustainability of augmentation concepts to compare scenarios.
		• Full extent and recharge characteristics of deep channel deposits, particularly in Maplewood areas of lower Cedar River (Cedar/Sammamish Basin), are not known and require further evaluation.
		• Vertical extent of sand layer beneath till is not well known. (Duwamish/Green Basin)
			• EKCRWA has been studying upper Snoqualmie River Basin groundwater system in WRIA 7 for ~10 years. First considered the deep Snoqualmie Aquifer as the regional municipal water supply source and then evaluated enhancement of river using the river to convey groundwater to downstream extraction points.
			• Suggests managing resources conjunctively to improve or ensure adequate stream habitat during critical low-flow periods.
			• Report includes results of technical analyses during last 10 years and a groundwater model of aquifer and stream systems in the basin; case studies, describes settings where augmentation can best be applied, and identifies basins could be applied in WA State
			  • Cedar/Sammamish Basin--Deep channel deposits, particularly in Maplewood areas of lower Cedar River, appear to be well connected to upland recharge areas.
			  • Duwamish/Green Basin—recommends augmentation on small and medium tributaries.
			  • Puyallup/White Basin---Lake Tapps important recharge area
			• Basin is ~375 square miles; 3 sub-basins; North Fork, Middle Fork, and South Fork. Three rivers converge to form main stem above Snoqualmie Falls. Detail on geology, ecology, hydrology, precipitation of basin.
			• Two peak streamflow seasons; November-January (results from high rainfall) and April- June (results snowpack melt).
			• Data from 32 wells analyzed for trends in groundwater elevations. Results showed seasonal trends following precipitation patterns. Some wells fluctuate by more than 25 feet while others vary less than 5 feet in a year. Upper valley wells fluctuate show greater seasonal fluctuations; Lower valley wells end to peak earlier and respond more directly to changes n streamflows and precipitation.
			• Steady-state and transient MODFLOW model were completed to investigate seasonal variability and possible stream augmentation scenarios.
			• Model results indicated: distributing groundwater withdrawals over a larger are of the aquifer results in greater Streamflow augmentation and helps maximize recovery; and that as duration of augmentation increases, the time required to reach equilibrium increases…indicating that Streamflow augmentation is sustainable in the basin and will not result in long-term impacts to resources.

Hart Crowser. 1988. *Tolt River Pipeline Groundwater Development Study, King County, Washington.*	None Presented	• Little data available at start of study. • Results of existing data review indicated potential to develop deeper aquifers (little data available).	• Hydrogeologic evaluation near Tolt River Pipeline from South Fork Tolt Dam and Bothell/Kirkland area. • Purpose was to develop source for peak demand groundwater supply of 10 MGD and supply Suring winter months of excess surface water turbidity. • Investigations included drilling deep wells (> 200 ft deep), mapping, geophysical surveying, and well testing. Results of existing data review indicated low yields from principal aquifer.

Documents Reviewed	Information Indicating Lowered Water Levels	Presented Information Gaps	Notes
EAST KING COUNTY (continued)			
King County Department of Natural Resources, 1998. *East King County Ground Water Management Plan: Management Strategies-Final.*	• Major aquifers have potential for over-use based on future demands.	• Need to address interaction between shallow groundwater and stream flow. • Additional withdrawals could result in lower levels/ decreases to springs and other surface water.	• A large potential regional groundwater supply is located in this GWMA. • >50% precipitation falls on land and recharges groundwater. 1% from wells and 2% to springs. • Almost 90% water from groundwater is used for private, municipal, industrial and agricultural purposes. • Principal sources of groundwater are Qal, Qvr, Qva, Qac and bedrock. • Most productive aquifers are the high permeability sand and gravel outwash deposits. • Snoqualmie Valley alluvial aquifer is being investigated as potential water supply (North Bend aquifer). • More than half of the precipitation falls on land and recharges groundwater.
King County Department of Natural Resources, 1998. *East King County Ground Water Management Plan: Supplement 1: Area Characterization-Final.*	• Little water is available in thin unit in east Snoqualmie Valley • Bedrock wells can go dry northeast of Duvall. • Some wells had groundwater decreases and dry wells. • Single source (Mt. Si spring) for North Bend is vulnerable. Does not meet future demands. • Between Carnation and Monroe. Snoqualmie River seems to be a losing reach. • Raging and Tolt Rivers are losing reaches. (Turney-USGS Report) • Many streams may receive/lose, but were not measured.	• Data gaps identified in the U.S. Geological Survey study seen in lower Snoqualmie River valley, Sammamish Plateau and Cascade foothills. • Recommended a groundwater model of Snoqualmie Valley to determine capacity of aquifer. (Turney-USGS Report) • Flow in Qal-Qvr unit on the Sammamish Plateau is not well defined because much of it is unsaturated. • Lack of data points on foothills and in Cherry Creek Valley. • Upward flow is likely in many areas. • Too short of a period to note long term trend for water levels • Still unknown about whether deeper aquifer exists at bedrock interface at Carnation. • Qbc and Qc were not mapped. • Qc - Little data available to say what yield. • Aquifer in Carnation Farms area has channel like shape; may extend beneath Tolt Hill. Recharge is slow in relation to ability to draw from them. Water is as old as when deposited. If aquifers were pumped the recharge would be much later.	• Primary source of drinking water is stored precipitation recharged through permeable soil. • ~54% of precipitation recharges groundwater. 73% of total recharge in water budget flows out of the area as groundwater or recharges local surface water. • Three aquifers identified=Fall City, Tolt Delta and Cedar Falls Aquifer. Fall City did not meet requirement of 5MGD. Tolt Delta met the requirement, but is remote from the network. Cedar Falls is too far south. • Two subregional aquifers are in Snoqualmie Flats and Falls areas. In 1992, confluence of Snoqualmie, Middle Fork and the North Fork. North Fork was 5 MGD. It was estimated that 20MGD could be provided by Snoqualmie Aquifer and another 20 MGD where North Fork converges. Middle Fork has good quality and quantity. Golder has groundwater model of this area. • *Principal sources of groundwater* are Qal along Snoqualmie River and glacial deposits underlying plateaus to east and west of the alluvial lowlands. (Qvr, Qva, Qac and bedrock). Usable amounts of groundwater can be obtained from Qvt, Qaf, Qbf and Qbc. • Most productive aquifers are the high permeability sand and gravel outwash deposits. • Buried valleys in Snoqualmie Valley, evidenced from geophysics surveys. *HYDROSTRATIGRAPHIC ZONES.* *Qal*- Snoqualmie River valley and tributaries; sand, gravel and silt; highly productive, unconfined upstream of Snoqualmie Falls. Downstream, the aquifer has lower permeability, wells downstream from the falls in landslide or alluvial fans have less yield and less predictable. Wells on lower valley floor are subject to periodic flooding. Flow is substantial. Recharge is mostly discharged to southwest. A fraction reaches deeper aquifers underlying till. *Qvr*-sand, gravel, ice-contact deposits on margins in east; lacustrine deposits of ice-dammed lakes. Mostly unconfined and perched conditions. Can be productive where thick. *Qvt*-low permeability barrier. Soils above the till serve as aquifer due to slow rate of infiltration. Perched aquifer with limited use. Occasional sand lenses produce water. Considered confining bed. Upper part is more permeable and can yield more usable short term quantities. Yields are variable. *Qva*-well graded gravelly sand – fine grained sand. Principal aquifer, mostly confined. *Qaf* -usable amounts, mostly Qtb and Qpf. Thin lenses of sand and gravel yielding small quantities for domestic use. Serves as confining unit for Qac. *Qac*-principal aquifer, strongly oxidized sand and gravel, mostly confined. *Deepest unconsolidated units* Qbf-usable amounts/rarely used; Qbc-sand and gravel, some fines. Probably confined; Qc *Bedrock*-sandstone, siltstone, conglomerate. Unreliable source. Not fractured enough to yield large quantities. • Higher recharge rates in east and southeast parts of GWMA. Receives about 31 in/year of recharge.

Documents Reviewed	Information Indicating Lowered Water Levels	Presented Information Gaps	Notes
EAST KING COUNTY (continued)			
King County Department of Natural Resources and Parks, Water and Land Resources Division, 2005. *East King County Groundwater Level Survey: Fall 2005.*	• Water levels were either about the same or on average up to 5 ft lower. • Qva–19/20 wells were 1 - 5 ft lower with one at 9 ft lower than 1995. • Qal/Qvr–4/25 had significantly lower water levels than 1995.	• Only 45 wells were accessed, coverage was low. • One time measurement compared to 1995 only. No long term trend data.	• Water levels in Qal, Qva, Qvr for a one time measurement to compare to U.S. Geological Survey report. • Qal and Qvr were considered one unit due to hydrologic connection.
PEI/Barrett Consulting Group. 1991. *Lake Alice Plateau: Neighboring Water User Study for Snoqualmie Ridge Parkway*	None Presented	None Presented	• Presents background information on geology and groundwater. • Focuses on potential water quality impacts to surface and groundwater near Snoqualmie Ridge that may results form development within Snoqualmie Ridge.
Turney G.L., S.C. Kahle, and N.P. Dixon, 1995. *Geohydrology and Ground-Water Quality of East King County, Washington.*	• Some declining water levels in wells, may be due to pumping. • Bedrock wells can go dry in summer or under high use. • Raging and Tolt rivers lose water to groundwater.	• Flow to deeper regional system is unknown, but may be significant. • Not many long term water level data sets. • Unknown depth to bedrock in many areas of Snoqualmie River valley. • Snoqualmie River valley, Cascade foothills and Sammamish Plateau has lack of deep well data (500-1000 deep). • Qc–has few wells, unknown productivity. • Groundwater model of entire Snoqualmie valley would help estimate effects of development. • The modeled amount discharged to north and west out of study area is high due to lack of information.	• Some flowing wells in Snoqualmie Valley. • Withdrawn water used for aquaculture, beneficial use, class ½ public supply systems, domestic, irrigation, dairy cattle. HYDROGEOLOGY *Qal*-major aquifer, highly productive unconfined upstream of falls, less permeable and productive downstream. *Qvr*-major aquifer where saturated, mostly unconfined, some local perched zones. *Qvt* -confining bed with some sand and gravel lenses that produce water, conductivity can be higher due to heterogeneity of unit and that wells in Qvt tend to be in more coarse units. *Qva*-major aquifer, mostly confined, flow is discontinuous. *Qaf*-confining bed with some sand and gravel lenses that produce water. *Qac*-major aquifer, confined. *Qbf* -confining bed, few wells.. *Qbc*-few wells, aquifer where saturated, probably confined *Qc*- probably confined. *bedrock*-some usable water, not reliable source, low hydraulic conductivity, low fracture density, likely unconfined at surface and confined when overlain. • Water quality is typical of west Washington. • Discharge from groundwater to rivers, Lake Sammamish, springs, etc.
EASTSIDE AND LAKE SAMMAMISH			
AGI Technologies. 1998. *Sammamish Plateau Water and Sewer District: Artificial Recharge Testing of the Plateau Aquifer System Zone IV (through Well 5), Phase III*	None Presented	None Presented	• Results of a three month testing and monitoring program indicated Plateau Aquifer Zone IV can be used to store artificially recharged water (up to 10 to 30 %). • Recommendations were to develop model and pump test monitoring. • Boundary of aquifer was about 11000 ft from well. (well 5). • Test indicated confined aquifer conditions. • Injection of 16.7 million gallons caused 13 ft of water level rise (no change in overlying aquifer zones). • Has capacity for up to 10 to 30 % of storage capacity of aquifer.

Documents Reviewed	Information Indicating Lowered Water Levels	Presented Information Gaps	Notes
EASTSIDE AND LAKE SAMMAMISH (continued)			
CDM. 2003. *Sammamish Plateau Water & Sewer District Report Describing Numerical Model of the Plateau Aquifer System*.	None Presented	None Presented	• CDM completed a MODFLOW and DYNFLOW model covering 94 square miles bound to the west by Lake Sammamish, to the east by Cascade Foothills, and to the south by Grand Ridge. Model based n USGA model (WRI Report 94-4082), and refined it using over 400 wells in area. • Model simulates flow through glacial and interglacial sediments, comprising of 4 aquifers, 3 aquitards overlying bedrock. Upper aquifer (Zone II lies entirely beneath Plateau) and deeper aquifer (zone IV) lies in northern part of plateau and extends northward. • District plans to use model to evaluate impacts and pumping scenarios on local springs, streams and wetlands. • CDM developed detailed database of wells and log data to build 3D models. • Zone IV is about 200 ft and was divided in to 3 layers for model. Model reasonably reproduced aquifer responses for to changing pump and recharge stresses. • Simulated flow patterns indicated in Zone III flow to the east toward Snoqualmie Valley with a large upward component near the northern portion of Lake Sammamish. • There were no evident impacts of surface water features on Zone IV groundwater flow. • Simulated heads in Zones II and IV are above those in Zone III. • Total annual average inflow/outflow is about 85,000 gpm. Pumping accounts for 1%. • Pumping District Wells 4 and 11.2 indicated 130 ft drawdown in Zone IV, 6 ft in Zone III and negligible response in Zones I and II.
Golder Associates Inc. 1995. *Preliminary Evaluation of Aquifer Storage and Recover in the (Little) Bear Creek Drainage.*	None Presented	None Presented	• Documents project reviewing aquifer and storage recovery development in Bear Creek watershed. • Scope was to complete hydrogeologic evaluation (sampling, gaging, analysis), cost estimates, regulatory concerns). • Aquifer storage potential in Bear Creek was found to be potentially very good. Significant water storage capacity may exist. • Aquifer storage recovery design included 11 wells and two diversion channels at higher elevations. • Two water rights are required, one for recharge source and artificial recharge of aquifer: the other for withdrawal of stored water from aquifer.
Golder Associates, 2000. *Sampling and Analysis Plan for the Issaquah Creek Valley Groundwater Management Area*.	None Presented	None Presented	• Goal is to evaluate regional scale water quality and overall conditions of groundwater. • Emphasis on most susceptible, which was based on land use. • Water quality generally excellent.
Golder Associates. 2000. *Groundwater Exploration and Pumping Test: Lower Issaquah Valley*.	• Issaquah Creek is perched in parts of year and is disconnected to water table. • Losing reaches of Issaquah Creek at times during the year (leakage from stream to groundwater) • Issaquah Creek is gaining reach at times of year when streambed elevations are lower than water table.	None Presented	• Reports on well installation and pumping test; includes hydrogeologic and engineering information. • Indicated that at one well, W-1, no summer groundwater Baseflow discharges to Issaquah Creek in the vicinity of the City Shop site. • Recommends deep wells at City Shop area to evaluate mode and magnitude of groundwater discharge into Lake Sammamish. • Conceptual model indicated aquifers and two aquitards. Upper aquifer in close communication with ground surface. • Long term responses (since 1996) indicate maximum levels in Jan-April time period and minimum in August – September. Total fluctuations at around 10-12 ft.

Documents Reviewed	Information Indicating Lowered Water Levels	Presented Information Gaps	Notes
EASTSIDE AND LAKE SAMMAMISH (continued)			
Golder Associates, 2001. *Sampling and Analysis Plan for the Redmond - Bear Creek Groundwater Management Area.*	None Presented	None Presented	• Water quality generally excellent. • Goal is to evaluate overall conditions of groundwater and compare to past studies.
King County Department of Natural Resources, 1999. *Issaquah Creek Valley Ground Water Management Plan: Area Characterization. Supplement 1: Area Characterization – Final.*	• Bedrock (not yield high quantities, but usable, declining water levels indicate recharge is slower). • Lake Tradition loses water to system. • Valley aquifers- some losing streams. • Long term water level data for lower Issaquah Creek valley aquifer indicate a downward trend in water table elevations.	• Long term water level data for lower Issaquah Creek valley aquifer indicate downward trend . Maybe pumped too much, or maybe climatic influences. Need more information to evaluate. • Qbc and Qc (little information, rarely used as source, probably confined. • Flow direction in Grand Ridge and Tradition Lake area is less known. • Limited stream/groundwater connection, but need more data to confirm; upper valley (south of gap; no known high capacity wells, but due to sparse population, unknown) flow direction in deeper aquifers not fully understood. • Capacity of aquifer systems that Sammamish Plateau Water and Sewer District and City of Issaquah get their water from is unknown. • Valley aquifers- lower valley groundwater system more work needed for trends and to clarify areas missing information.	• More 98% of withdrawals went to public water systems. STRATIGRAPHIC UNITS *Qb; Qal* Stream deposits of sand to cobble along channels, floodplains, fan yields of high quantity; landslide deposits. *Qvr* gravel, sand and some silt; delta deposits. Productive where thick and saturated. *Qvr lacustrine* leaky aquitard, discontinuous. *Qvi* (mix of Qvt and outwash, cannot generalize on hydraulic conductivity); upper portions can have perched and semi-perched water tables in isolated lenses, low yield to shallow wells, slow recharge. *Qva* sand and cobble gravel, generally high hydraulic conductivity, large quantities of water. *unconsolidated pre-Vashon* (Qtb, Qpf, Qob). *bedrock* some mineralized, saline, brackish water quality. • Groundwater in Issaquah basin, various outwash deposits (sand and gravel). Some shallow aquifers formed in Qvr and ice-contact deposits (high hydraulic conductivity). Soil on top of Qvt has high infiltration. In lower Issaquah valley, a ice-dammed lake formed deltaic deposits which provide recharge to the area where Issaquah and Sammamish Plateau pump wells. AQUIFERS *Mountain aquifers* – mostly bedrock for individual water supplies. Some permeable glacial sediments, small public water supply is possible, steep gradients, springs. *Upland/Sammamish Plateau Aquifers* – numerous domestic wells in unconsolidated sediments with various yields; Qva, Qac, Qal-Qvr discontinuous, flow is downward; Qbc and Qc rarely used as source, probably confined; bedrock-suspect not highly fractured, low hydraulic conductivity, poor source. *Valley aquifers- lower valley groundwater system* – (north of the gap=*A1 - upper fluvial*, *A2 - lower glacio-fluvial*, *A3 - deep alluvial*) Several high production wells, highly permeable, flow direction not well known, deltaic sediments of North and East Forks transmit downward into lower Issaquah valley from upland areas (Flow through the Tiger Mountain Gap –limits drainage from southern part of GWMA to about 50% of total discharge; responds quickly to precipitation and pumping. • Water quality generally excellent
King County Department of Natural Resources, 1999. *Issaquah Creek Valley Ground Water Management Plan: Management Strategies – Final.*	None Presented	None Presented	• Groundwater comes from precipitation in basin. • 30% of recharge to lower Issaquah Valley groundwater system is from eastern plateau (Grand Ridge and Lake Tradition).100% water used for private, municipal, industrial and agricultural purposes provided by groundwater sources. • High production wells in lower Issaquah Valley. Three major aquifer zones (upper, lower and deep zone). • Limited hydraulic connection, but some pumping in deeper wells can cause downward flow in upper aquifer. • Water quality in lower valley is generally excellent. • Most significant areas of infiltration are sand and gravel deposits east of Issaquah on the uplands between East and North Forks of Issaquah Creek.

Documents Reviewed	Information Indicating Lowered Water Levels	Presented Information Gaps	Notes
EASTSIDE AND LAKE SAMMAMISH (continued)			
King County Department of Natural Resources, 1999. *Redmond – Bear Creek Valley Ground Water Management Plan: Management Strategies- Final.*	• New water sources in some areas should not be developed due to over pumping reducing water levels. • Continued growth will require additional water supply and land use control to recharge areas to maintain aquifer quantity. • According to consultants, planned changes to land use will impact both water quality and quantity (i.e. Novelty Hill).	• More data of deep aquifer system are needed to determine if there will be impacts from large scale developments.	• ~100% water used for private, municipal, industrial and irrigation purposes provided by groundwater sources. • Primary beneficial uses of groundwater are for domestic and public water supply, fire suppression, and recharge to streams and lakes. • Major production wells for City of Redmond and Union Hill Water Association are located in alluvial aquifers, shallow depths in deposits along Bear Creek and Evans Creek. • Production wells for NE Sammamish Sewer and Water District are located in alluvial and in deeper sea level and regional aquifers in areas of moderate infiltration. • Major aquifer zones include alluvial, local upland, sea level and regional aquifers. • Highest infiltration occurs in areas Cottage Lake Creek, Bear Creek and Evans Creek valleys. • Several City of Redmond wells located downtown. • Potential other sources are: Redmond, Evans Creek and Sammamish Plateau aquifer. Redmond and Evans Creek in relatively shallow deposits. Plateau aquifer is deeper.
King County Department of Natural Resources, 1999. *Redmond – Bear Creek Valley Ground Water Management Plan. Supplemental 1: Area Characterization – Final.*	• Potential other water Sources are: Redmond, Evans Creek and Sammamish Plateau aquifer. Redmond and Evans Creek are in relatively shallow deposits(<200 ft). Sammamish Plateau Aquifer is deeper (<400). Coordinated Water System Plan concluded that the water supply potential from these aquifers was not significant enough to meet future regional demands. • Private wells in Qvt (till) may dry up in summer.	• Only comments on water available to remove, not where might be missing. (For areas mentioned that might be able to be pumped but need to look at base flows of streams etc, would need long term data to evaluate this.) • Too short of a period to note long term trend for water levels. • Private wells in Qvt (till) may dry up in summer.	• Existing water demand – nearly all of rights have been issued for public water supply use. AQUIFERS *Alluvial* Primary producing aquifer along stream channels (Cottage Lake, mostly Bear Creek and Evans Creek) *Sea level aquifer* consists of Qob and Qc near sea level. *Local upland aquifers* are discontinuous Qva and permeable zones of Qvt. *Upland aquifers* underlie ridges on east, west and south boundary. *Regional aquifers* are Qc glacial and interglacial deposits. • GROUNDWATER SYSTEMS: Shallow groundwater systems are alluvial deposits along major streams and shallow upland aquifers. Intermediate groundwater systems are sea level aquifers and deeper portions of the local upland aquifers; deeper groundwater systems are below the int. and shallow aquifers. HYDROSTRATIGRAPHIC ZONES. *Qal*-Water level at <10-100 ft bgs. Vary up to 6 ft with seasonal changes in precipitation. Unconfined and semi-confined. Flows to discharge along streams, Sammamish River and Lake Sammamish (south along Bear Creek and Cottage Lake Creek and west along Evans Creek). *Qvt*–low permeability barrier. Shallow water may occur at base of upper 8 ft of weathered till (or perched on top of the unit). Discontinuous lenses of sand/gravel. Mostly private wells at 25 gallons per minute, seasonal fluctuations. Usually causes swampy areas when near surface. *Local upland aquifers*–occurs beneath ridge and may be discontinuous. Controlled by topography. Mostly Qva and some Qvt. DTW ranges <10 in perched zones to about 350 ft bgs. Aquifers may recharge the alluvial aquifer along valley walls. Unconfined/confined. Flows from highland area north of Redmond towards alluvial. Aquifer along Sammamish River and Bear Creek. On east side of GWMA, flow towards Bear Creek and Evans Creek. *Qtb*-important unit. Aquitard, 50-100s ft of continuous lake bed deposits. Scattered sand lenses locally capable of 100GPM of water. Recharged by Qva and from below. *Sea level aquifers*-Qob and Qc are ~50-135 ft thick. Regional in size. DTW 50–400 ft bgs. Groundwater higher in autumn than spring. Seasonal variations of 10-120 ft due to precipitation. Confined. Flows west from high elevation to low elevations in east. In south end of GWMA, flows to Lake Sammamish *Regional aquifers*-Qc. > 400 ft thick. Below Qob and Qtb, usually confined. DTW 100-400 ft bgs. Confined. Discharge to Puget Sound? • Water quality generally meets standards. Problems are elevated iron and manganese, particularly in deeper wells; bad tasting or odorous water caused by hydrogen sulfide.

Documents Reviewed	Information Indicating Lowered Water Levels	Presented Information Gaps	Notes
EASTSIDE AND LAKE SAMMAMISH (continued)			
King County Department of Natural Resources and Parks, Water and Land Resources Division, 2005. *Sammamish River Valley Groundwater Study: 2003-2004 Data Report*.	None Presented	• Only one year of data. No long term trend data.	• Installed 21 wells in Sammamish River area, took water levels along river and Evans, Bear and Little Bear Creeks during 2003-2004. • Seasonal fluctuations, responding to precipitation in all shallow wells. • Flow is towards Sammamish River and down river corridor. Seasonal upward gradient from deep to shallow. • Trends – seasonally higher in winter and lower in summer due to increased precipitation and lower evapotranspiration in winter resulting in higher recharge to groundwater and surface water. *Marymoor Park Subarea* - Sammamish River level has higher levels in winter, due to precipitation. Seasonal vertical gradients, generally during rainy season. There is downward movement, suggesting recharge from precipitation. Vice versa and may discharge to surface water. Somewhat impacted water quality. *60-acres Subarea* – Deeper units did not show clear response to precipitation. Upward gradient due to confining silt above deeper unit. Impacted water quality. *Woodinville Subarea* – Seasonally upward and downward vertical gradient. Less impacted water quality than in other subareas. Groundwater discharges to Sammamish River in eight of nine study locations. At an area north of Marymoor Subarea, surface water appears to be source for recharge to groundwater.
Massmann, J. 2000. Effects of Groundwater Extraction on Stream Flow in the Bear-Evans Creek Watershed.	• During low groundwater recharge summer months, groundwater extractions are highest.	None Presented	• Presents summary of hydrogeology of watershed – groundwater derived from precipitation and infiltration; system is for the most part self contained; groundwater system is leaky; comprises of series of higher and lower permeability units • Identifies primary water supply wells in watershed • Presents estimates for time-lag between extraction at a groundwater well and reduction in stream flow – time lag is relatively short on the order of days or weeks • Suggestions for addressing impacts of wells on stream flow and temperatures – reductions of extractions during summer months should stream flow fall below critical levels
Massmann, J. 2001. Effects of Groundwater Extraction on Stream Flow in the Issaquah Creek Watershed.	• Water levels in the Lower Issaquah Creek Valley Aquifer have shown a downward trend in recent years. • Future water demands are expected to exceed current water rights. • During low groundwater recharge summer months, groundwater extractions are highest.	None Presented	• Presents summary of hydrogeology of watershed – groundwater derived from precipitation and infiltration; system is hydraulically closed; groundwater system is leaky; comprises of series of higher and lower permeability units; groundwater recharge is ~20-25 cfs • Identifies primary water supply wells in watershed – 2 city systems resulting in net loss of water out of Issaquah GWMA • Presents estimates for time-lag between extraction at a groundwater well and reduction in stream flow – time lag is relatively short on the order of days or weeks • Suggestions for addressing impacts of wells on stream flow and temperatures – reductions of extractions during summer months should stream flow fall below critical levels
Pacific Groundwater Group, Inc. 1992. *Issaquah Ground Water Management Program: Data Collection and Analysis Plan (DCAP)-Final.*	None Presented	None Presented	• Report includes plan for long term monitoring and concern for future availability of supply. • Geophysical exploration precipitation monitoring at nine sites, stream gaging (13 sites), water sampling (25 wells), water level monitoring (50 wells), and installation of four to six wells (lower Issaquah valley) and Squak Tiger Mountain Gap area). • Some areas required more data to monitor and manage resources.
Robinson & Noble, Inc.1979. *Ground Water Evaluation of East Lake Sammamish Area.*	None Presented	• Unknown potential of aquifer beneath artesian aquifer. Deeper drilling required to gain more information. • Information for area is insufficient to precisely define systems.	• Presents probable extent of gravel aquifer, based on review of previous work. • Indicated notable artesian aquifer at shallow depths. • Proposes four well installations.

Documents Reviewed	Information Indicating Lowered Water Levels	Presented Information Gaps	Notes
EASTSIDE AND LAKE SAMMAMISH (continued)			
Sweet-Edward/EMCON, Inc. 1990. *Redmond-Bear Creek Ground Water Management Area: Data Collection and Analysis Plan (DCAP)-Revision 3.*	None Presented	• Although there were aquifers in the valley portions of study area, the overall hydrogeology of the study was not well understood at the start of study. • Lower Evan's Creek valley, Woodinville study area had lack of deep hydrostratigraphic data	• Report prepared comprehensive goals for a basin wide aquifer study (develop database, model, plan, outreach program). • Geophysical exploration, deep well borings, water sampling (20 parameters), water level monitoring (40 wells), stream monitoring (five creeks) and collection of contaminant source and land use data is planned.
SEATTLE AND NORTH			
Liesch, B. A., C. E. Price and K. L. Walters. 1963. *Geology and Ground-Water Resources of Northwestern King County, Washington*	• On Newcastle Hills, withdrawal has exceeded recharge of principal aquifer (Tertiary rocks).	None Presented	• Includes maps and cross sections. • Detailed descriptions of geology. • Groundwater in consolidated rocks. • For 1950-1960, no serious overdraft of unconsolidated northwestern KC.
SOUTH KING COUNTY			
Brown and Caldwell Consultants. 1992. *Effluent Reuse Pilot Project Report.*	None Presented	None Presented	• Provides city demands and potential uses of effluent water, including design criteria and alternatives.
Carlson, C. 1994. *Big Soos Creek Low Flow Trend and Water Right Analysis.*	• Low stream flows occurred in late summer and early fall when groundwater is only source to sustain flows.	None Presented	▪ Presents a water rights analysis of Soos Creek Basin – indicated increases in single family withdrawals ▪ Presents low flow trend analysis of Big Soos Creek, Newaukum Creek, Huge Creek and Raging River to determine existence of a low flow trend for 1967 to 1992 time period. Results indicated Big Soos Creek flows declined, others did not; pronounced decline in latter period. ▪ Likely causes proposed were declining precipitation trend, increased impervious cover, reduced recharge from urbanization, increased water appropriations. (groundwater appropriations increased 16 times); Groundwater and springs rights appear to be asserting largest influence on low flow decline ▪ Suggests conservative approach to future groundwater appropriations
Carollo Engineers. 2006. *Lakehaven Utility District Water Reclamation Related Engineering Services: Feasibility Study – Final.*	None Presented	None Presented	▪ Purpose of study was to plan best use of water available form District's two wastewater treatment plants and determine feasibility of implementing and operating system to help realize long-term water resource goals. ▪ Population growth expected to outpace regional water supplies. ▪ District wants to offer ASR program at Mirror Lake Aquifer, up to 78 mgd of water during high demand summer season. ▪ 7 uses were identified 1) irrigation 2) groundwater recharge by surface percolation 3) Streamflow augmentation through wetlands 4) recharge to Redondo Milton Channel aquifer 5) or deep aquifer 6) industrial purposes 7) institutional. (Suggested most feasible were groundwater recharge by percolation and irrigation). ▪ Presents discussion of alternatives, history of district, study area characteristics, climate watersheds, economic analysis ▪ Hydrogeology summarized from other reports: 6 layers (3 confining units, Regional Milton and Auburn West Hill Springs Aquifers, Mirror Lake and Well 8 Aquifers, and Federal Way Deep Aquifer). ▪ Included a partial report in appendices of groundwater recharge potential in Lakehaven Utility District Area

Documents Reviewed	Information Indicating Lowered Water Levels	Presented Information Gaps	Notes
SOUTH KING COUNTY (continued)			
City of Auburn Water Division *http://www.ci.auburn.wa.us/utilities/water/index.asp*	None Presented	None Presented	▪ Auburn's water comes from a combination of wells drawing water from deep below the City and springs located near the walls of the valley. The valley wells and springs serve customers in the valley, Lea Hill and the Forest Villa/Academy area. Additional wells are located in the Lakeland Hills area and serve customers south of the White River in the Lakeland Hills neighborhood. It is not dependent on the Cascade Mountain's snow pack replenishing open reservoirs. As per their Comp. Plan Amended 1995; Chapter 5; Goal 13: ▪ CF-51 The City shall seek opportunities where feasible to reintroduce treated urban runoff back into groundwater system as new and redevelopment occurs to minimize urbanization impacts to the hydrology of the natural river systems. ▪ CF-53 The City shall seek to minimize the impacts to the natural river system's hydrology by encouraging pre-treatment of surface flows of new development and re-introduction into the groundwater where feasible.
City of Renton Aquifer Protection Program. *http://www.renton-wa.gov/living/default.aspx?id=144*	None Presented	None Presented	▪ About 87% of water is supplied by Cedar Valley Aquifer with rest coming from Springbrook Springs, in south Renton. The aquifer is a sole source aquifer as per USEPA. The sand and gravel aquifer is about 3.5 miles long and produces about 7.3 MGD. In some areas, the water table is <25 ft bgs. The aquifer is recharged by rain and snow and from groundwater flow from Cedar Valley. ▪ Web research indicated two reports that may be of interest to King County WTD: ▪ City of Renton Water System Plan, Appendix Q, Wellhead Protection Plan, May 1999. This report include information on capture zones, the program, water supply sources, a description of the Renton Groundwater Model, Particle Tracking Approach and Model Input Parameters. ▪ "Explanation of Aquifer Code Amendments, August 2002" by City of Renton Water Utility. This document summarizes the results of a computer model simulating groundwater flow in three dimensions related to the Cedar Valley Sole Source Aquifer and the Maplewood Production Aquifer.
CH2M Hill. 1988. *Well Field Monitoring Study City of Renton.*	• When well field is active, groundwater movement on south side of river is influenced (especially when wells PW1 & PW2 are operating).	None Presented	• Objectives of report are to determine rate and direction of groundwater movement under differing pumping conditions and to determine the interactions between Cedar River and aquifer, delineate boundaries of aquifer and well field, and to sample to evaluate exiting conditions. • General flow direction to southwest and west, with a component to the northwest. • Cedar River acts as minor source of recharge for aquifer: In vicinity of well field , amount of recharge is small compared to flow.
Covington Water District, 1995. *Lake Sawyer Wellhead Protection Plan: Covington Water District – Final.*	• In portions of study area, shallow system unit may completely drain by late summer.	• Deep aquifer poorly delineated • Water levels in shallow system have seasonal variation of several feet. In portions of study area, unit may completely drain by late summer.	• Former studies indicated prolific aquifers at both Kent Springs and Lake Sawyer Wellfield sites. • Plan is divided into three areas: wellhead protection area delineation; existing and potential hazards and strategies and implantation tasks. • Used 426 wells to develop conceptual model. Aquifer area that contributes is 11 square miles. • Regional aquifer that supplies Lake Sawyer Wellfield also supplies Kent and Clark Springs for the City of Kent. Capture zones can not be separated. • Basin boundaries formed by Green and possibly Cedar Rivers, by groundwater divides, and bedrock. • Western portion of aquifer, leakage to deeper aquifers can occur. • 74% of wells are installed in the shallow aquifer system (mostly unconfined) • Report has detailed descriptions of hydrostratigraphic units.
Harper-Owes. 1985. *Duwamish Ground Water Studies: Waste Disposal Practices and Dredge and Fill History.*	None Presented	None Presented	• Presents a review of waste disposal and dredge/fill practices in Duwamish River area. • Refers to shoreline changes creating conduits for ground water movement (i.e. unconsolidated fill deposits)

Documents Reviewed	Information Indicating Lowered Water Levels	Presented Information Gaps	Notes
SOUTH KING COUNTY (continued)			
Hart Crowser. 1996. *Wellhead Protection Program: Clark, Kent, and Armstrong Springs; City of Kent.*	None Presented	• The effect of Lake Sawyer on groundwater flow is not well-studied. • Interaction between aquifer and surface waters needs better understanding. • Relationship of Jenkins Creek and aquifer is unknown. • Flow patterns north of Armstrong Springs, Lake Sawyer and Ravensdale Lake needs better understanding. • Groundwater divide for Clark Springs area is undefined.	• Plan presents wellhead protection area delineation, contaminant sources, and management strategies. • City gets water from shallow, highly transmissive glacial outwash aquifers. • Main recharge is infiltration in study area, with additions from Lake Sawyer and runoff from uplands. • Groundwater flow is towards the east and west from high recharge area of foothills east of Clark Springs through Vashon recessional outwash and deeper glacial deposits. • City of Kent coordinates with Covington Water District and Water District No. 111 due to proximity of aquifer. • Kent's water sources are a combination of spring infiltration galleries and wells from Clark Springs, Kent Springs and Armstrong Springs. • Kent Springs usage is primarily during wetter months and in drier summer and early fall months the deeper coarse aquifer is more reliable. • Clark Springs 1year WHPA is about 11000 ft; Kent and Armstrong Springs have 1 year WHPA is about 5000 ft. • Clark Springs was closed due to water quality degradation. • Plan proposes potential sources: Georgetown area, Ravensdale area, Ranney well field (near Green and White Rivers). • Water level changes are seasonal (up to 10 ft).
Massmann, J. 2000. *Description and Evaluation of Groundwater Monitoring Activities in the Vicinity of the Witte Well Field.*	• Pumping in transition period causes reversal of flow direction within hours (MW1) to days (MW2) • During pumping, flow is reversed at MW1 downward to Witte aquifer. At MW2, gradient is same, but magnitude reduced. Horizontal flow direction is reversed away from monitoring wells.	• Source of the water for the Witte well field • Discharge location for Qva and Q(A)c aquifers are located in vicinity of Big Soos Creek (may be discharging to seeps and streams closer to well field)	• Presents results of monitoring activities near Witte well field (owned and operated by Covington Water District) • Monitoring activities resulting from dispute over water permit granted to CWD. • An agreement between the tribe and CWD indicated that the well field would not be operated November – May; monitoring wells would be installed, pump tests conducted and a monitoring plan for a minimum duration of five years followed. • Report presents water level data collected to date, describes what data shows with respects to well field on flow direction, and infers longer term effects of the well field. • Non-pumping period, flow is upward from Witte aquifer to domestic aquifer. Horizontal flow direction is away from well field to monitoring wells. • Witte wells are in a leaky aquifer; well field extracts from Q(A)c; domestic wells use Qva. Units assumed dipping west. • Refers to hydrogeology from other reports. • Suggests that well field may affect discharge in streams several weeks to months after pumping is initiated.
Northwest Hydraulics Consultants, Inc. 2005. *Assessment of Current Water Quantity Conditions in the Green River Basin.*	• 420 wells were studied to assess whether qualitative groundwater withdrawals would impact streamflows. Report showed impacts from some wells to streamflows in basins or sub-basin level and in some cases, in adjacent or downgradient basins. Largest impacts occur during low flow conditions.	None Presented	• Report documents assessment of water quantity conditions of Green River Basin, areas upstream of River Mile 23.8; study focuses on upper Lower Green, the Middle Green, and the Upper Green River sub-watersheds. • Study identifies significant surface water and groundwater inputs and linkages to Upper, middle and Lower Green River.; provides water budget; presents 7-day low flow and mean monthly flows analysis statistics; and uses data to describe current and future potential extraction from wells and diversions; and to describe current and future conditions of effective impervious area. • Presents previous work indicated that two reaches along Green River had significant groundwater input from external/closed-depression sub-basins (near Auburn and at River Mile 48 to 52). Green River flows are expected to increase near these areas. • A review of several sources of data to identify wells and diversions was presented. Municipal and domestic water -demands are expected to increase. Non-municipal well demands are expected to remain ~ same. Existing water rights are generally insufficient to meet future demands. • Proposed management options to minimize degradation 1) manage impervious cover and forest cover 2) manage water supply withdrawals 3) manage stream morphometry 4) infiltrate stormwater in mainstem of middle and lower Green River and key tributaries, in addition to other areas 5) prepare a drought response program 6) maintain septic systems where feasible 7) develop uses for reclaimed wastewater 8) evaluate options for Tacoma Water diversion right.

Documents Reviewed	Information Indicating Lowered Water Levels	Presented Information Gaps	Notes
SOUTH KING COUNTY (continued)			
Pacific Groundwater Group. 1999. *Hydrogeologic Characterization Report, City of Auburn*.	None Presented	None Presented	• Objective was to produce conceptual understanding of groundwater flow and groundwater-river relationships in Auburn area and to serve as basis for a refined computer flow model covering 296 square miles in Auburn-Kent valley. Housing density and distribution demands in Auburn are increasing the need to protect, manage and conserve water resources. Annual growth rates for water consumption are expected to be less than in the past. • Completed work included identifying aquitards and aquifers, characterize aquifer properties, evaluating flow patterns, evaluate recharge, quantify flow, develop database, assess interaction between aquifers and between rivers and aquifers, and conducting investigations (installing and testing wells, measuring stream flows, collecting samples, and completing well inventory). • Major aquifers are alluvium(Qal) and deep deltaic valley aquifer (Qvrd). Qvrd is pumped by Auburn and can exceed 7mgd in a well. Qal is shallow (10-15 ft). Deposits are about 1300 ft thick beneath City of Auburn. (Report gives detailed descriptions of hydrostratigraphic units). • Flow is from uplands towards valley in Qvrd flow varies, but generally parallels the white and Green Rivers. Upland recharge is mostly from precipitation between October and March. • Water from the White River enters Qvrd, flow north and discharges into the Green River. Although no measurable effects were detected in White River after 2 weeks of pumping of the Qvrd, further modeling was recommended. Additional pumping was stated to reduce levels in the Green River. • Degree of continuity between valley groundwater system and the rivers varies with season and location. White River and Green River showed some gains and loses in same locations over different seasons. • Discharge occurs via pumping wells; springs, seeps along bluffs; to creeks, streams, rivers as base flow; and deep groundwater leaving area.
R2 Resource Consultants, Inc. 2006. *Clark Springs Water Supply System Habitat Conservation Plan: Preliminary Draft*.	None Presented	None Presented	• Purpose of report is to propose plan to operate system while maintaining habitat and not compromise water supply demands to customers. Proposed plan is to augment flow in fall months, improve passage, enhance wetlands conditions, and develop management programs. • Periodic inability of the system to sustain rates …affects ability to meet emergency standby supply requirement and impair ability to meet existing and project demands. • Changes in basin from forested land to more urbanization have reduced watershed quality. Some evaluation of water quality details. • Report presents operations constraints (i.e. constrains based on demands, overpumping, etc), deficit solutions, factors contribute to decline of fish, (i.e. Roads, logging, urbanization, etc), restoration activities, habitat measures to implement (i.e. flow augmentation, wetland improvement, passage improvement, etc); effects of measures (i.e. increase in flow in fall in Rock Creek, high water quality, increase fish quantity, passage, etc); • Report suggests that Instream flow targets would be met with a few exceptions due to low water levels. • Clark Springs Water Supply System (CSS) provides 60% of supply for Kent, WA. Comprised of three wells and infiltration gallery in Rock Creek Basin. • Kent added an augmentation system to assist with spawning salmon during low flow periods. • Operation of the system does affect groundwater levels and surface flows in Rock Creek, however, highly variable and dependent on precipitations patterns and aquifer levels. • CSS pulls water from shallow unconfined aquifer. Infiltration gallery withdraws from 18 ft deep in gravel sand cobbles from Rock Creek hyporheic zone. When groundwater is high, water captured in gallery instead of Rock Creek. Pumping lowers the water levels and causes "perching" of the stream. • Much of watershed is on glacial outwash. Soils are mostly well drained soils. Highly permeable outwash channels form shallow aquifers serving as preferential flow paths. Groundwater contributes little if any flow to lower Rock Creek below Clark Springs. Groundwater levels in wells reflect seasonal recharge. • 80% of precipitation falls between October and April. Groundwater and surface water runoff during main precipitation events are major sources to Rock Creek. Flows are highest in streams in late fall and winter, then gradually decline through spring and summer and are lowest in September and October.
RH2 Engineering. 1987. *Analysis report for the City of Renton Cedar River Valley Aquifer Test*.	None Presented	• Absence of wells in the southwest portion of the aquifer	• Low specific yield and decrease in aquifer hydraulic conductivity west of well field. • Boundaries of aquifer described. • No measurable change in river due to changes in channel of Cedar River. • Pumping influence was about 1000 to 2000 ft from well into aquifer. • Report included recommendations for new wells, further pump tests, additional well installation, and modeling. • Describes relationship of well and river during pumping.

Documents Reviewed	Information Indicating Lowered Water Levels	Presented Information Gaps	Notes
SOUTH KING COUNTY (continued)			
Robinson & Noble Inc. 1992. *Hydrogeologic Analysis of the Federal Way Area, Washington. Volume 1.*	• Valley aquifer system: water level records of Well16 shows aquifer has lost 10 ft of head in response to moderate production and is now under water table conditions. • Production and land use changes have induced water level declines from the major shallow aquifer (beneath the upper confining unit) but has stabilized by 1987. Stabilization of water levels did not continue past 1987, they declined through 1988, about seven ft lower than in end of 1987. Water level shave recovered slightly since then. • Water level at Well23A has declined about 12 ft over the last 14 years. • Water levels in Mirror Lake aquifer (deep) are greatly affected. (up to 50 ft by 1987) and slightly less by now. • Eastern Upland Aquifer is affected by production, but not as much as in Mirror Lake aquifer.	• Federal Way deep aquifer not adequately studied due to lack of data.	• Presents a numerical groundwater flow model for Federal Way area. Developed conceptual geohydrologic model. • 230 wells and springs used for database. • Upland geology was simplified for model. Report presents detailed destructions of geology and layers. • Model indicated septic system recharge component was recognized as important for regional water balance; magnitude that leakage occurs in upper aquifers when deeper aquifer levels are reduced was larger than exacted, and Puyallup Valley was realized as natural drain for Federal Way aquifers. • Eastern Upland Aquifer is affected by production, but not as much as in Mirror Lake aquifer. There has been a general rise in water levels in central and northern portions since 1960s.
Sweet-Edwards & Associates, Inc. 1985. *Duwamish Ground Water Studies.*	None Presented	• Initial data review indicated little relevant groundwater data. • Insufficient data to define number of aquifers. • No wells in bedrock of upland regime. • Unsure of groundwater flow directions.	• Investigation to evaluate contaminant contribution to river from groundwater between Elliot Bay and Black River. • No regional ground water studies of Duwamish had been completed at the time of the report. • Goals: provide general characterization of surface and groundwater, identify hydraulic parameters and data gaps and develop ground water monitoring and analysis strategy. • Model based on limited data and assumptions on the groundwater flow in the basin. • Two groundwater regimes. (upland glacial and interglacial material and bedrock (no wells in bedrock); valley floor regime is primary focus of study, thick sand and gravels). • Includes hydraulic parameters.
TCW Associates, Inc., HLA/Harper-Owes, University of Washington College of Forest Resources, and Municipality of Metropolitan Seattle. 1989. *Hydrogeology and Water Quality Evaluation: Metro Section 16 Silvigrow Project.*	None Presented	None Presented	• Report presents information and data for application of a sludge fertilizer and results of a study of application of the sludge and environmental effects. • Groundwater flows to north and discharges to springs along Green River. • Worst case scenario of application and impacts was an extremely small impact to groundwater quality. • Groundwater at site recharged by precipitation in vicinity. Shallow groundwater levels (about 13 ft deep). • Discharge rates of springs vary. • Rivers and aquifers are very closely connected.

Documents Reviewed	Information Indicating Lowered Water Levels	Presented Information Gaps	Notes
SOUTH KING COUNTY (continued)			
Washington State Department of Ecology. 2006a. *Aquifer Storage and Recovery Application R1-28083A Amended Report of Examination* (Lakehaven Utility District). May.	• Water levels in the Mirror Lake Aquifer (MLA) initially fell from about 204 ft MSL in the early 1980s to a low of about 125 ft MSL in the 1990s. Due to curtailed production and groundwater injection between 1995 and 1999, water levels rose to about 185 ft MSL and have been steadily decreased to about 145 ft MSL in 2004.	• Uncertainties of technologies and limited amount of site specific data did not allow for fully qualified assessment of whether the project was in best interest of the public at that point. However, provided all plans are followed, the project should not prove detrimental to the public. • More information is needed on environmental impacts before can be fully addressed.	• Lists source water rights, groundwater and surface water rights, maximum injection rates, maximum withdrawals rates, and acre-feet per year storage/recovery for phases of pilot study and project. • Water is to be stored within Mirror Lake Aquifer (MLA). Project is briefly described (OASIS ASR Project). Permit is to request continuing testing and development of project. Initially for 12 years. • Provides background of OASIS project, presents investigation history, and presents needed requirements to Chapter 90.03 RCW. • Discusses hydrogeological system • Outlines the Provisions, Project Operational Plan, Project Management Plan, Project Mitigation Plan, and Environmental Assessment (EA). • Possible areas of impact (as per the EA) are; induced drawdown in overlying aquifers and hydraulically connected surface water bodies, increased groundwater seepage through lower MLA increasing chance of slope failure along west of project area; dewatering and compaction of upper MLA; overpressuring of MLA, and potential for hydrogeochemical differences of injected water and groundwater.
Washington State Department of Ecology. 2006b. *Aquifer Storage and Recovery Permit R1-28083P* (Lakehaven Utility District) September.	None Presented	None Presented	• Lists source water rights, maximum injection rates, maximum withdrawals rates, and acre-feet per year storage/recovery for phases of pilot study and project. Lists locations of injection wells. • Water is to be stored within Mirror Lake Aquifer. Project is briefly described (OASIS ASR Project). Permit is to request continuing testing and development of project. Initially for 12 years. • Provisions are presented in detail.
Woodward, D.F., F.A. Packard, N.P. Dion, and S.S. Sumioka, 1995. *Occurrence and Quality of Ground Water in Southwestern King County, Washington.*	• Some wells showed reducing water levels over decades. • Qvt may go dry in late summer. • Some areas of Green and White Rivers near Auburn have losing reaches in the Qal.	• Data lacking in the Des Moines Plains area • Mapping in Cedar River Valley was difficult, less confidence in map results in this area. • Qbc-not much information • Qc-unknown hydraulic characteristics • Qvt may go dry in late summer.	• 80% of recharge to shallow groundwater in Big Soos Creek basin is returned to streams as baseflow. • ~97% of total groundwater pumped used for public and domestic water supply, < 3% used for irrigation, the rest for commercial, industrial/institutional. Mostly from the Qal aquifer, then Qva and Qac. • No widespread water quality degradation • HYDROGEOLOGIC UNITS • Qal water table aquifer, generally low yield. Fan deposits in the Cedar River Valley near Renton and the southern part of the Green-Duwamish Valley near Auburn yield lots of water to wells, many wells in these units. • Qvr water table aquifer at land surface, minor aquifer because thin and sporadically located, sometimes hard to find with respect to sand rich Qvt/till areas. • Qvt confining bed, some areas are sandy and friable, can have small producing zones of sand lenses, some dug wells still in use. • Qva sand & gravel, confined, important aquifer where saturated, several cities have wells in this unit, can merge with Qac. • Qaf confining bed with some sand and gravel lenses with water. • Qac contains silt lenses, saturated, heterogeneous, in direct connection with Qva in parts of the Covington and Des Moines Plains; confined. • Qbf confining bed. • Qbc deepest units studied, King County Water District and City of Federal Way have wells in this aquifer: confined. • Bedrock relatively impermeable units (sandstone with shale / coal), some volcanic and intrusive igneous rocks. • GROUNDWATER FLOW SYSTEMS Local; intermediate-flow above bedrock and below deep part of local system; regional controlled by Cascades, Olympic Mountains and Puget Sound and starts at the crest of Cascades.

Documents Reviewed	Information Indicating Lowered Water Levels	Presented Information Gaps	Notes
REGIONWIDE			
Bauer, H. H. and M. C. Mastin .1997. *Recharge From Precipitation in Three Small Glacial-Till-Mantled Catchments in the Puget Sound Lowland, Washington.*	None Presented	None Presented	•Water budgets computed for southern portion of Puget Sound to estimate groundwater recharge from precipitation through till. •Use of tritium for recharge rate estimation.
King County Department of Development and Environmental Services, Environmental Division, Regional Planning Section, and Public Health−Seattle & King County, Environmental Health Division, Drinking Water and Ground Water Section. 1995. *Mapping Aquifer Susceptibility to Contamination in King County*.	None Presented	•A few wells existed in the northeast portion of Snoqualmie Valley and eastern portions of East King County.	•Provides information regarding methods to update map (groundwater quality concerns). •Presents metadata for development of criteria and maps.
King County Department of Natural Resources and Parks, Water and Land Resources Division, 2005. *Ambient Groundwater Monitoring 2001-2004 Results.*	•East King County, Redmond-Bear Creek and Vashon-Maury Island water level plots indicated groundwater depths were generally stable during the period of record, with no significant declines.	•Frequency of water level monitoring and the unknown pump usage prior to measurement. •More shallow wells than deep wells.	•Sampling focused on East King County, Issaquah Creek Valley, Redmond Bear Creek and Vashon-Maury Island GWMAs. •Monitors private and public wells. Some volunteers do the level measuring. •92 wells had water levels and sampling. •EKC had 14 wells and Redmond-Bear Creek had 16 wells, VMI had 16 wells: showing unchanged water levels. •Issaquah had 11 wells, showing seasonal changes in water levels. •Results in dictated water levels were stable in areas monitored.
Morgan, D. S. and J. L. Jones. 1995. *Numerical Model Analysis of the Effects of Ground-Water Withdrawals on Discharge to Streams and Springs in Small Basins Typical of the Puget Sound Lowland, Washington.*	None Presented specific to King County	•Details of interactions between surface water and groundwater systems are not well known.	•Presents detailed description of Puget Sound lowlands glacial history and hydrogeologic characteristics of small basins. •Comments that development of groundwater as water supply may lower levels in baseflows in some basins, causing reduction of surface water availability to existing users and reducing baseflows below minimum flows at times. •Purpose of study was to gain better understanding of relations and interactions between groundwater and surface water systems in small basins, hoping to identify some factors controlling response to groundwater withdrawals. •Report presents a 13 layer MODFLOW numerical groundwater flow model; includes geologic framework and various calibrations to predevelopment conditions and used to simulate effects of pumping. •Simulations ran were: variations of distances of wells from streams, pumping rates, depth of pumped aquifer, distance of well from bluff, well density, and recharge rate. •Results were discussed in general terms, not basin specific.
Vaccaro, J. J., A. J. Hansen, and M. A. Jones. 1998. *Hydrogeologic Framework of the Puget Sound Aquifer System, Washington and British Columbia: Regional Aquifer System Analysis—Puget-Willamette Lowland.*	None Presented	•Sparse data for deep wells (>250 ft) in Lowlands. •Methods, descriptions, and division of aquifer systems vary widely. •Extrapolation of local results to regional scale is problematic and difficult. •Water level maps in are compilations and represent composite water levels.	•Presents simplified conceptual model (included nine alluvial valley aquifers, the surficial semi-confining unit, Fraser aquifer, confining aquifer, Puget aquifer, and the basement confining unit. •Goals were to describe geology, hydrogeology, regional groundwater flow system and major hydrologic controls. •Water quality review included. •Review of bibliography included (First time review was conducted of entire area was in 1970s). •Thicknesses are highly variable, flow direction is generally horizontal within aquifer units and vertical within semi-confining and confining units. •Seasonal water level fluctuations of 1-10 ft are in uppermost aquifer and show rapid recharge. Deeper aquifers have fluctuations less than 4 ft and lag about three months in response to recharge. •Reports on hydraulic parameters, water budget parameters, model results.

Documents Reviewed	Information Indicating Lowered Water Levels	Presented Information Gaps	Notes
REGIONWIDE (continued)			
Washington State Department of Ecology. 1988. *Report of the Technical Advisory Committee on the Capture of Surface Water by Wells (Draft); Recommended Technical Methods for the Evaluating the Effects of Ground-Water Withdrawals on Surface Water Quantity*.	None Presented Specific to King County	None Presented Specific to King County	•Committee charged to seek agreement among technical experts on appropriate technical methods for assessing and quantifying the effects of groundwater withdrawals and surface water sources. •Only addressed quantitative effects of capture. •Report presents framework for problem-solving approach to evaluate capture of surface water by wells. •Described six generalized hydrogeologic settings describing most settings in WA State. •Describes three levels of basin analysis, depending on urgency of problems and level of demand of water. •Recommends a long-term monitoring data collection and monitoring strategy be defined in each basin; systematic measurement of actual water-use and collection of basic hydrologic and geologic information.
Washington State Department of Ecology Water Quality Program. 2005. *Critical Aquifer Recharge Areas: Guidance Document.*	None Presented	None Presented	• Provides guidance to regulators and private land and well owners on requirements for protecting local groundwater resources under Growth Management Act. •Best available science, resources, and contacts are provided.

Notes:

***Main Geologic Units for King County** **Abbreviations and Symbols**

Qb	bogs	Qal	alluvium	bgs		below ground surface	
Vashon Stade	Qvr	Vashon recessional outwash				ft	feet
	Qvt	Vashon till				GWMA	groundwater management area
	Qva	Vashon advance outwash				MSL	mean sea level
	Qtb	Vashon transitional beds				<	less than
	Qvi	Vashon ice-contact deposits				+	plus or more than
Older Glacial/Nonglacial Deposits		Qpf	pre-Fraser deposits	Qob	Olympia gravels	DTW	depth to water
		Qaf	pre-Vashon deposits upper fine grained unit	Qac	pre-Vashon deposits upper coarse grained unit		
		Qbf	pre-Vashon deposits lower fine grained unit	Qbc	pre-Vashon deposits lower coarse grained unit		
		Qc	pre-Vashon deposits deep undifferentiated unit	Bedrock	Tukwila Formation, Rattlesnake Mountain Formation		

Appendix B
Additional References

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