

SUMMARY REPORT  
TO  
EAST KING COUNTY  
REGIONAL WATER ASSOCIATION  
  
ON  
  
SNOQUALMIE BASIN  
GROUNDWATER  
SUPPLY EVALUATION  
GEOPHYSICAL SURVEY

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## EXECUTIVE SUMMARY

This report presents the results and interpretations of geophysical investigations performed to determine the potential to develop a groundwater source of between 10 to 40 MGD, or more in two areas of the Snoqualmie Basin. Based on the results of the geophysics and preliminary hydrogeological analysis, recommendations for future groundwater exploration are presented. The geophysical survey is the second step in the identification and evaluation of groundwater resources. The first step, the feasibility study, identified the likely range in groundwater quantities available and the potential cost of development.

A time-domain electromagnetic geophysical survey was carried out in two areas known as Area 2 and Area 3 of the Upper Snoqualmie Basin. Area 2 is located east of the community of Tanner and includes part of the Middle and South Fork Snoqualmie valleys. The area investigated covers approximately 16 square miles. Area 3 is located on the North Fork of the Snoqualmie and covers an area of about 10 square miles from the headwaters of Beaver Creek east to approximately the confluence of Phillipa Creek and the North Fork Snoqualmie.

The time-domain method and transmitter configuration used for this survey provides information on the resistivity of the earth materials to a depth of about 1,000 feet. The data are interpreted to develop a layered-earth model from which interpretations of the sub-surface geology are made. Permeable sand and gravel is of moderate to high resistivity, while less-permeable silts and clays are of low resistivity. The local bedrock exhibits very high resistivities, many times greater than that of sand and gravel. The geophysical method was calibrated to the geologic logs of existing wells to develop interpretations regarding the hydrogeology of the areas investigated. Drilling will be required to verify the geophysical interpretations and to provide site-specific hydrogeologic information on the groundwater supply potential at particular sites.

In addition to the geophysical survey, data on the geologic and hydraulic properties of the sediments underlying Areas 2 and 3 were obtained from existing reports and well logs. Estimates of recharge to, and the potential groundwater supply from the particular aquifers were made based on these data.

### Study Results

#### Area 2

The results of the study indicate that there are two potential aquifers in Area 2. These aquifers are termed the Middle Fork Snoqualmie Channel Aquifer and the South Fork Snoqualmie Channel Aquifer. These two aquifers appear to converge and become one aquifer system downstream of Sallal Prairie.

The Middle Fork Aquifer is interpreted to be between 200 to 400 feet in thickness and to be composed of sand and gravel of moderate to high hydraulic conductivity. The aquifer is likely in hydraulic communication with the Middle Fork because there is no evidence of a confining layer between the river and the aquifer. The groundwater supply potential from this aquifer is estimated at between 10 to 60 MGD.

The South Fork Aquifer is interpreted to be between 200 to 400 feet in thickness and to be composed of sand and gravel of moderate to high hydraulic conductivity. The aquifer is likely in hydraulic communication with the South Fork Snoqualmie because there is no evidence of a confining layer

between the river and the aquifer. The groundwater supply potential is estimated at between 5 to 20 MGD.

There does not appear to be an extensive permeable confined aquifer capable of yielding 40 MGD in Area 2 without impacts on streamflow. There is the possibility that a confined aquifer may be present beneath the silty clay that underlies the aquifer and overlying bedrock (a depth of 1,000 feet or more) that has little hydraulic communication with surface water. However, given the likely limited extent of this zone, the groundwater supply from such an aquifer is likely less than 5 MGD.

Two areas are recommended for exploration in Area 2 to determine the hydrogeologic conditions and groundwater supply potential of the South Fork and Middle Fork Aquifers, and potential aquifer at the bedrock/overburden contact. The exploration program should include the drilling and testing of an exploratory/test well followed by pump testing and water quality sampling.

### Area 3

The results of the study indicate that there are two potential aquifers in Area 3. These aquifers are termed the North Fork Snoqualmie Channel Aquifer and the North Fork Headwaters Aquifer. The Headwaters Aquifer appears to be separated from the Channel Aquifer by the North Fork Embankment, however there is a component of groundwater movement from the Headwaters Aquifer to the Channel Aquifer.

The North Fork Channel Aquifer is interpreted to be up to 450 feet in thickness and to be composed of silty sand and gravel of low to moderate hydraulic conductivity with isolated lenses of high permeability material. The aquifer appears to have low to moderate hydraulic communication with surface waters because of the relatively low permeability of the materials that comprise the aquifer. The groundwater supply potential from this aquifer is estimated at between 1 to 5 MGD.

The North Fork Headwaters Aquifer is interpreted to be between 100 to 150 feet in thickness and to be composed of silty sand and gravel of low to moderate hydraulic conductivity with localized areas of sand and gravel of high hydraulic conductivity such as at the mouth of Phillipa and Sunday Creek. The aquifer is likely in hydraulic communication with the North Fork Snoqualmie because there is no evidence of a confining layer between the river and the aquifer. The groundwater supply potential is estimated at between 5 to 10 MGD.

A third potential aquifer may be present within limestone which may underlie Area 3 at depths in excess of 1,000 feet. The presence of this aquifer is highly speculative, but if present, may offer a groundwater source with little or no impact on streamflows. The groundwater supply potential of this aquifer cannot be estimated at this time.

There does not appear to be an extensive permeable confined aquifer capable of yielding 40 MGD in Area 3 without impacts on streamflow.

Two areas are recommended for exploration in Area 3 to determine the hydrogeologic conditions and groundwater supply potential of the North Fork Channel Aquifer and the North Fork Headwaters Aquifer. The exploration program should include the drilling and testing of an exploratory/test well followed by pump testing and water quality sampling.

Assessment of the potential limestone aquifer could be carried out using geophysical techniques similar to that used in this study but employing a higher-powered transmitter to penetrate to greater depths within bedrock. If the geophysics indicates the presence of limestone, an exploration/test well should be constructed.

## 1. INTRODUCTION

This report presents the results and interpretations of geophysical investigations performed to determine the potential for groundwater development in two areas of the Snoqualmie Basin. The work was performed by Golder Associates Inc., under contract to the East King County Regional Water Association (RWA) based upon a scope of work developed in May, 1993. Two areas were selected by the RWA for exploration based on recommendations prepared in a feasibility study (CH<sub>2</sub>M Hill, 1993). These areas are shown on Figure 1-1 as Area 2 and Area 3. Area 1 was not investigated as part of the geophysical survey.

The objective of this phase of the study is to determine, for each area:

- Hydrogeologic conditions, based on geologic, geophysical and hydrologic reconnaissance-level information and previous studies;
- The potential to develop a groundwater source providing between 10 and 40 MGD or more; and
- Possible locations for subsequent exploratory wells to be drilled in later phases of this investigation to further evaluate the groundwater supply potential.

The evaluation of each area was carried based on the following:

- Existing data and reports obtained from various sources;
- A geophysical survey, designed to determine depths to bedrock and estimate aquifer thickness and character; and
- Preliminary hydrologic and hydrogeologic analyses based on available information. Analyses included estimates of groundwater flow directions, aquifer properties, and groundwater recharge.

### 1.1 Geophysical Survey Objectives

The objective of the geophysical investigation was to provide reconnaissance-level information on the thickness and extent of sub-surface materials focussing on the presence of potentially coarse-grained aquifer materials. Specifically, the geophysical investigation was designed to:

- Determine the depth to bedrock to a maximum depth of 1,000 feet;
- Distinguish coarse-grained potential aquifer materials from fine-grained materials in the overburden; and

- Efficiently explore a 10 square mile area comprising Area 3, and 16 square mile area in Area 2.

To achieve these objectives, a time-domain electromagnetic (TDEM) survey was carried out. Details of this exploration method are included in Appendix A.

## 1.2 Geophysical Interpretation Approach

Geophysical surveys do not produce results that are immediately indicative of the depth, extent and properties of the underlying sediments. Consistent interpretation of geophysical data is important in developing a good description of the sub-surface. Interpretation of the TDEM survey is based on computer modeling applied to the data collected during the survey. The computer model predicts the response of the TDEM instrument based on a layered-earth model provided by the interpreter. This predicted response is compared to the observed response until a good match is produced. This model is then assumed to be an accurate representation of sub-surface conditions. As a check, a series of perturbations of the model are run which also match the data within a specified tolerance (e.g. 10% error), thus describing a set of "equivalent" models that could also represent sub-surface conditions. Contour maps and cross-sections can then be developed from the set of models produced to match the data. Contour maps of the data itself are not produced using this approach to interpretation.

## 1.3 Hydrogeologic Analysis

A refined hydrogeologic analysis was performed for each area based on the updated information obtained from the geophysics and from additional geologic and hydrogeologic information not presented in the feasibility study. The objective of this analysis was to update the estimates of hydrogeologic properties and potential quantities of groundwater available presented in the feasibility study. This refined analysis was not part of the scope of work but was performed to assist in decision making with regard to future exploration.

## 1.4 Report Organization

This report is organized as follows:

- Section 1 - Introduction, including details of the study objectives and generalized methods of geophysical data interpretation.
- Section 2 - Results of investigation of Area 3, including geological conditions, calibration geophysics, interpretation of the geophysical results, and interpreted hydrogeological conditions.

- Section 3 - Results of investigation in Area 2, including geological conditions, calibration geophysics, interpretation of the geophysical results and interpreted hydrogeological conditions.
- Section 4 - Recommendations for further exploration.
- Section 5 - References.
- Appendix A - Geophysical survey design and methodology, including a discussion of the TDEM survey procedures, instrumentation, data collection and interpretation.
- Appendix B - Geophysical sounding results.
- Appendix C - Geologic Logs, cross sections and gravity survey results prepared by the U.S. Army Corps of Engineers for the North Fork Snoqualmie.
- Appendix D - Hydraulic inflow testing of boreholes at the North Fork Snoqualmie by the U.S. Army Corps of Engineers.

## 2. RESULTS OF AREA 3 INVESTIGATION - NORTH FORK SNOQUALMIE RIVER

Area 3 is located in the upper reaches of the North Fork Snoqualmie River. The area under investigation encompasses approximately 10 square miles of the basin, from the southwestern edge of the "Beaver Plug" area to the upper reaches of the North Fork Snoqualmie River. A topographical high area bisects Area 3, and is referred to as the North Fork Embankment. Figure 2-1 is a topographic map of the exploration area.

### 2.1 Sources of Data

The hydrogeology of the North Fork Snoqualmie Basin has been summarized, in part, in the feasibility study. Data sources used for the feasibility study included:

- Geophysical investigations by Geo-Recon (1962), Twelker and Associates (1962c, 1965), and Converse Ward Davis Dixon (1979);
- One well log from the U.S. Army Corps of Engineers (USCOE) (1983) study of dam sites in the area; and
- Streamflow data from the United States Geological Survey (USGS) gage 12.1430.00 (N. Fork Snoqualmie near North Bend), and gage 12.1420.00 (N. Fork Snoqualmie near Calligan Lake).

The revised hydrogeologic evaluation of Area 3 presented here is based on the aforementioned data and additional information, specifically:

- The results of the TDEM and resistivity survey performed as part of this study (Section 2.3 and Appendix A and B);
- 25 well logs of borings and wells installed as part of the USCOE study of dam sites in the area (Appendix C);
- Four geologic cross-sections prepared by the USCOE (Appendix C)
- Hydraulic inflow testing of two 140-foot borings performed by the USCOE (Appendix D);
- The results of a gravity survey (USCOE, 1983) of the area; and
- Visual reconnaissance and flow estimates of springs near Little Beaver Lake, and flow estimates by USCOE (1983) and Golder Associates.

Using these data, a revised evaluation of the hydrogeology of the area has been prepared, including a more detailed water budget and groundwater recharge estimate, an estimate of hydraulic properties of the aquifer, and an estimate of the groundwater supply potential. The results of this evaluation are described below.

## **2.2 Geologic Conditions**

### **2.2.1 Conceptual Geologic Model**

The geologic processes that influenced sediment deposition in Area 3 are complex. The area was affected by both continental and alpine glacial conditions during the Pleistocene. Alpine glaciers descended from the Cascade Crest, westward through the Upper North Fork valley scouring bedrock. The Puget Lobe of the Cordilleran ice sheet descended from the north and deposited sediment into the upper valley creating the North Fork Embankment, and at times blocked the westward drainage of the North Fork establishing an ice-dammed lake in what is now the upper valley. This lake environment was probably somewhat dynamic as a result of minor fluctuations in the position of the continental and alpine glacial fronts. When the Cordilleran ice sheet retreated, the North Fork drainage was re-established at the south end of the Embankment.

The geologic history suggest three areas of sediment deposition, each containing relatively different materials:

- In the upper valley (east of the Embankment), fine grained silts and clays were likely deposited during lacustrine periods, possibly interbedded and/or overlain by coarser materials deposited when the lake disappeared because of temporary northward recession of the blocking Continental ice sheet;
- At the margin of the Cordilleran ice sheet, large quantities of sediment were shed, forming a terminal moraine. This moraine forms the North Fork Embankment now present between the Upper valley and the Beaver Plug area. These sediments were likely highly variable and unsorted, ranging from cobbles to silts; and
- To the west of the North Fork Embankment overconsolidated glacial tills were deposited beneath the Cordilleran ice sheet, containing a wide variety of sediment types ranging from cobbles to silts. During periods of retreat, this same area was likely re-worked by meltwater and subsequently covered with glacial outwash sand and gravel.

### **2.2.2 Well Logs and Geologic Cross Sections**

The surficial geology of Area 3 is dominated by Quaternary-aged sediments of glacial and fluvial origin which overlie bedrock (Booth, 1990). Bedrock outcrops at the surface at both the north and south margins of the valley, and along both sides of Deep Creek prior to its confluence with the North Fork. Most of the bedrock has been mapped as Tertiary and pre-Tertiary sedimentary rocks categorized as graywacke, argillite, and siltstone with some slate and phyllite (Booth, 1990). Paleozoic rocks, including limestones and

marbles, are exposed north (near Stevens Pass) and south (near Snoqualmie Pass) of Area 3 (Livingston, 1971). The North Fork makes a southward bend at its confluence with Deep Creek and several bedrock knobs are present where it establishes a southward drainage.

A number of boreholes were drilled by the USCOE as part of their evaluation of dam sites in Area 3. Well logs and geologic cross sections developed by the USCOE are presented in Appendix C. The majority of well logs in the area describe the sub-surface material as highly variable silty sand, gravel and cobbles. This is consistent with the conceptual understanding of depositional processes in the area. Bedrock was encountered at relatively shallow depths in several borings.

Geologic cross-sections were prepared by the USCOE from the geologic data obtained from these borings. In the upper part of the basin (east and upstream of the Embankment), the materials are characterized as interbedded gravel layers, separated by glacial till, silty outwash, and lacustrine silty sand. A silty fine sand unit is present throughout the upper basin, as well as beneath the North Fork Embankment. This unit is relatively flat-lying and is interpreted to be a lacustrine unit deposited in the upper valley when it was dammed by the Cordilleran ice sheet.

Downstream of the Embankment, the materials reported in well logs are characterized by interbedded sandy and silty gravel. The materials are generally coarser, but virtually all materials below about 40 feet contain silt. The upper gravels may represent "clean" outwash gravel, while the deeper materials likely correspond to glacial till or reworked glacial till.

## **2.3 Geophysical Survey Results and Interpretation**

### **2.3.1 Calibration and General Response**

A total of 28 TDEM soundings were conducted in Area 3 (Figure 2-2). In addition, two direct current resistivity soundings were performed. Appendix A contains a technical description of the survey methods and procedures. Appendix B contains the results of the soundings and models which fit the observed data. The following is a description of the survey results and interpretation.

### Calibration Soundings

Calibration soundings in the vicinity of Area 3 were performed at three locations, as discussed below.

Site 3-1 is located at the Tolt Wellfield Well TW-2. Well PW-1 was originally identified in the scope of work for a calibration sounding, but has been covered over by a logging operation and was inaccessible. The TDEM model at Well TW-2 consists of four layers. A resistive (900 ohm-m) upper layer (0 to 154 ft) correlates with the unsaturated sands and gravels on the borehole log (0 to 175 ft). The less-resistive (400 ohm-m) second layer (154 to 285 ft) correlates with the saturated sand and gravels below the water table. The relatively-conductive (25 ohm-m) third layer (285 to 413 ft) correlates with the silt layer (285 to 365 ft) on the borehole log. The top of the conductive layer at 285 ft is in excellent agreement with the top of the silt layer from the borehole log. The interpreted bedrock depth (413 ft) from the TDEM model agrees reasonably well with the bedrock depth of 365 ft on the borehole log. There is some speculation on the borehole log that the basaltic rock fragments may be a bedrock erratic. A seismic refraction survey at this location estimated bedrock at 450 ft (Hart Crowser, 1989).

Additional calibrations were obtained at three USCOE borings (79-RD-101, 79-RD-102, and 83-RD-115) drilled as part of investigations in 1979 and 1983. Logs were obtained for these borings as part of our work, but were not available when the scope of work was developed.

Site 3-9 is near boreholes 79-RD-101 (602 feet deep) and 79-RD-104 (440 feet deep). A upper resistive (800 ohm-m) layer to a depth of 344 feet corresponds to unsaturated silts, sand, and gravels. The second layer is less resistive (100 ohm-m) and does not correlate with a stratigraphic unit on the borehole logs. However, it is at approximately river level and may indicate the water table. The top of the lacustrine silty sand unit is not resolved by the TDEM sounding. This layer is consistently seen at other sites east of the North Fork Embankment. The reason for this lack of resolution is not known. Bedrock is interpreted at a depth of about 1,000 feet. Bedrock was not encountered in the borehole logs, but the bedrock elevation is consistent with surrounding TDEM sites.

Site 3-11 is near borehole 79-RD-102 (600 feet deep). An upper resistive layer corresponding to unsaturated sediments was not observed. The uppermost layer is less resistive (139 ohm-m) than at Site 3-9 and is interpreted as a composite resistivity of unsaturated and saturated materials. A conductive second layer (32 ohm-m) is interpreted at elevation 1,315 ft above mean sea level (amsl). This corresponds to the lacustrine silty-sand observed in the borehole at a elevation 1,260 ft amsl. Uncertainty in the elevation of borehole 79-RD-102 (which was not field located and no elevation was provided on the log) may account for some of the elevation difference of the top of the silt layer. Also, the sounding is approximately 1,000 feet away from the approximate borehole location. Bedrock is interpreted at a depth of 548 feet. Bedrock was not encountered in the borehole logs, but the bedrock elevation estimated from the geophysics is consistent with surrounding TDEM sites.

Site 3-19 is near borehole 83-RD-115 (144 feet deep). An upper resistive layer corresponding to unsaturated sediments was not observed. The upper layer (105 ohm-m) represents a bulk resistivity for the saturated sand and gravels indicated on the borehole log. Bedrock is interpreted at a depth of 203 feet. Bedrock was not encountered in the borehole log but the bedrock elevation estimated from the geophysics is consistent with surrounding TDEM sites.

Comparison of these TDEM models to the borehole logs indicates that the TDEM method resolves the major lithological units (recessional sand/gravel, and lacustrine silty sand and bedrock) with reasonable

accuracy. Smaller-scale lithological changes consisting of thin layers of sand, gravel or silt are averaged into the bulk resistivity of the major lithological unit and cannot be distinguished.

### General Response

The TDEM models for the soundings in Area 3 show a resistivity range from 20 to 750 ohm-m for the overburden and 550 to 5,000 ohm-m for the bedrock. Overburden resistivities greater than about 200 ohm-m were found mainly in the upper 40m (131ft) of sediment at a few locations and in the first 100 m (328ft) at the crest of the North Fork Embankment. These high overburden resistivities are interpreted as unsaturated sediments beneath the embankment and possible saturated sand and gravel, for example near the mouth of Phillipa Creek. The inability to record information at early decay times (see Appendix A) prevented resolution of the saturated/unsaturated contact at most locations. In essence, the signal passed through the unsaturated zone before the receiver could measure a response. This is common in resistive environments. The remainder of the overburden resistivities ranged from 18 to 205 ohm-m. A model consisting of 2 to 4 layers was produced for each sounding which fit the observed data with an error of less than 10 percent. The modeled resistivities agree well with the interpretation of the geology based on well logs.

On a number of soundings, a response consistent with deep conductive material (at a depth in excess of 1,000 feet) was suggested in the model. Declining signal strength and loop size prevented a thorough field assessment of this response but its presence in the model interpretation may be significant. The model resistivities needed to fit the data are in the range of 2 to 5 ohm-m. These values are typical of saline materials, graphite schists, and limestones. A preliminary hypothesis may be that the response is due to a deep limestone, consistent with the limestone outcrops at Stevens Pass and Snoqualmie Pass. If this were the case, the deep limestone could represent a potential aquifer.

DC resistivity soundings were conducted at two locations to resolve shallow bedrock interpretations from the TDEM. A DC resistivity sounding at Site 3-16 produced an apparent resistivity curve with a characteristic bedrock rise in the curve at a depth of 9m (30ft). This agrees well with the 9.5m (31ft) depth interpreted from the TDEM data. A DC resistivity sounding at Site 3-2 produced poor signal response and a rise in the apparent resistivity curve was not observed. Additional resistivity soundings were not performed in Area 3 because of the poor signal response observed at Site 3-2. In addition, the results of the TDEM soundings were generally consistent at all locations and any additional resolution of shallow features would not improve sounding correlations and the regional interpretation of the survey.

### 2.3.2 Bedrock Elevation

Bedrock outcrops at a number of locations in Area 3. Downstream of the North Fork Embankments the North Fork Snoqualmie River flows southwest along the large bedrock outcrop to the southeast. At River Mile 10, the river turns south flowing through a narrow valley between the bedrock ridge to the east and a much smaller bedrock knoll to the west. Deep Creek flows through the middle of the west area from a narrow valley between bedrock outcrops to the north and converges with the North Fork Snoqualmie River at River Mile 11. Upstream of the North Fork Embankment, the North Fork Snoqualmie River meanders through a relatively flat river valley with low surface gradients. Bedrock crops out along the northern and southern ridge of the river valley forming a valley of nearly constant width between River Miles 12 and 16.

The interpreted bedrock elevation is summarized on Figure 2-2. Bedrock depths determined from the TDEM model for each sounding were subtracted from the surface elevation (based on the USGS quadrangle map), plotted, and hand contoured to produce the map. The map shows a bedrock channel feature trending south-southwest from the North Fork Embankment. The channel is between 2,000 and 4,000 feet wide. Pertinent features of the bedrock configuration are as follows:

- The channel configuration is similar to that interpreted by the USCOE based on gravity geophysical investigations, but is defined in greater detail;
- The lowest bedrock elevation appears to be located downstream of the North Fork Embankment, beneath and just northwest of the present course of the North Fork Snoqualmie;
- A shallow bedrock channel exists beneath Deep Creek as it joins the main valley, but Deep Creek is essentially "perched" on a bedrock shelf (hanging valley), without appreciable underlying sediment;
- A bedrock nose extends north from the bedrock outcrop at River Mile 10 toward Site 3-19;
- Bedrock rises steeply to the north beneath the North Fork Embankment, from an elevation of 900 feet near Wagner Bridge to about 1,700 feet at Site 3-29. This is consistent with the topography of the present bedrock exposures; and
- East of the North Fork Embankment the bedrock is relatively flat lying, forming a broad bedrock channel east of River Mile 14. The bedrock channel gradually steepens and narrows between River Miles 14 and the North Fork Embankment.

### 2.3.3 Geo-electric Cross-Sections

Three cross-sections (A-A', B-B', C-C'-C'', Figures 2-3, 2-4, and 2-5, respectively) were prepared based on the interpreted TDEM models (Appendix B), and are discussed below.

#### Cross-Section A-A'

This cross-section is aligned along the North Fork Snoqualmie and depicts the major geo-electric (lithologic) units corresponding to the geologic model of Area 3.

Between Beaver Creek and the North Fork Embankment the section consists of a two-layer model with a moderately-resistive overburden overlying a more-resistive bedrock (Figure 2-3). Overburden resistivities range from 63 to 125 ohm-m and are interpreted as saturated sand and gravel with an increasing silt content near the North Fork Embankment.

Between the North Fork Embankment and Site 3-27 the section consists of three layers with two layers of overburden overlying bedrock:

- The overburden comprises a resistive upper layer (70 to 757 ohm-m). The highest resistivities in this layer exist beneath the crest of the North Fork Embankment and are interpreted as unsaturated sediments. The unsaturated upper layer could not be resolved at many of the other sites and the lower resistivities (70 to 206 ohm-m) correspond to a composite of unsaturated and saturated sediments;
- A less-resistive second layer (18 to 32 ohm-m) is laterally continuous throughout the upper river valley and pinches out beneath the west face of the North Fork Embankment. This layer is interpreted to be the lacustrine silty sand unit identified in several borings. The consistency of the elevation and resistivity agrees well with a lacustrine depositional environment;
- A transition zone beneath the North Fork Embankment is shown as gradually increasing resistivities within Layer 2. This layer becomes contiguous with the upper resistive layer west of the embankment; and
- A poorly-resolved third layer, even less resistive than the second layer, is interpreted just above the bedrock at Sites 3-21 and 3-23. This lowest layer is interpreted to be a uniform lacustrine clay deposited in a shallow depression in the bedrock.

The upper layer of the cross-section (with the exception of the highly resistive sediments immediately below the Embankment) represents the potential aquifer in this portion of Area 3. The underlying lacustrine sediments east the Embankment are not expected to be viable aquifer material. There is no evidence of a resistive sand and gravel layer beneath the lacustrine sediments which could represent a deep aquifer.

### Cross-Section B-B'

Cross-section B-B' is transverse to the axis of the valley and shows the deepest portion of the ancestral channel of the North Fork Snoqualmie River. The section crosses the river valley along Deep Creek from the bedrock outcrop to the north to the bedrock ridge south of the river.

The section consists of a two-layer model with a moderately-resistive overburden overlying bedrock (Figure 2-4). A resistive-and laterally-discontinuous layer near Site 3-30 is interpreted as unsaturated sand and gravel. Resistivities in the remainder of the overburden range from 80 to 159 ohm-m and are interpreted as saturated silty sand to sand and gravel. Bedrock remains relatively shallow and flat-lying along Deep Creek before it steepens into the channel at Site 3-8. At Site 3-7, bedrock begins to rise steeply towards the bedrock exposures on the southeast side of the valley.

The materials in the deepest portion of the valley have a resistivity of 125 ohm-m. This is similar to all other resistivities in the area and indicates no major lithologic changes in the sub-surface. This also suggests that the geologic and hydrogeologic conditions observed in the shallow boreholes drilled by the USCOE likely persist in deeper portions of the overburden. The unconsolidated materials represent the potential aquifer in this portion of Area 3.

### Cross-Section C-C'-C''

Cross-section C-C'-C'' extends along the axis of the river valley from just north of the North Fork Embankment to River Mile 17.3 (Figure 2-5).

Between C and Site 3-12, the section consists of a two-layer model with a moderately-resistive overburden overlying bedrock. From Site 3-12 to C, the bedrock is interpreted to gradually rise in the direction of the bedrock ridge to the north. From Site 3-12 to C'', the section consists of a two-layer overburden overlying bedrock. The bedrock is relatively flat lying between Site 3-12 and C''. Resistivities in the upper layer of the overburden range from 83 to 203 ohm-m and are interpreted as saturated silty sand to sand and gravel. Resistivities in the lower layer of the overburden range from 20 to 29 ohm-m and are interpreted as saturated silty sand and clay. This clay and silt layer is interpreted to pinch out against bedrock west of Site 3-12.

The upper layer of the cross-section represents the potential aquifer in this portion of Area 3. The underlying lacustrine sediments east of the embankment are not expected to be viable aquifer material. There is no evidence of resistive sand and gravel layer beneath the lacustrine sediments which could represent a deep aquifer.

## **2.3.4 Potential Aquifer Thickness**

As discussed previously, coarse-grained unconsolidated materials are generally resistive in comparison to finer grained deposits, but are less resistive than bedrock. The results of the TDEM survey show the presence of a low-resistivity layer (probably silt and clay) generally less than 100 ohm-m overlying bedrock in the upper reaches of the North Fork. The low-resistivity layer is in turn overlain by a more-resistive layer (resistivities greater than 100 ohm-m). This more-resistive layer is present both upstream and downstream of the Embankment and represents the potential aquifer in Area 3. Area 3 may be

separated into two aquifers as shown on Figure 2-3 by the transition zone of lower resistivity materials. However, it is difficult to determine hydraulic conditions from the geophysical information.

Potential aquifer thickness was calculated as the thickness of the sediments above the low-resistivity layer (if present). If no low-resistivity layer is interpreted, resistive sediment thickness is based on the depth to bedrock. The sediment thicknesses for each of the TDEM sounding locations were plotted on the USGS quadrangle maps and hand contoured (Figure 2-6). In the area around the North Fork Embankment, sediment thickness calculations were adjusted for topography, by subtracting the thickness of the potentially unsaturated sediments which likely occur above the elevation of the North Fork Snoqualmie River.

The contour map of potential aquifer thickness for Area 3 shows that the North Fork Embankment appears to separate Area 3 into two potential aquifers:

- Upstream of the North Fork Embankment there is between 100 and 150 feet thickness of resistive sediment which represents the potential aquifer. The aquifer overlies less-resistive material interpreted as saturated lacustrine sediments (clay and silt), which are not suitable for a large groundwater development. This is consistent with boring logs in the area and the conceptual geologic model of Area 3. The aquifer maintains a relatively constant thickness throughout the center of the river valley. The aquifer thins to the north, south, and west as it approaches the bedrock outcrops and the North Fork Embankment. The aquifer covers a total area of approximately two square miles within the area investigated, and likely occupies the valley floor to the east covering a total area of about four to five square miles.
- Downstream of the North Fork Embankment the potential aquifer is not underlain by a lacustrine layer, and extends to bedrock. The sediments in this area are modelled as a single-resistivity layer with resistivities consistent with saturated silty sand and gravel, as determined from the calibration soundings. The aquifer is thickest (450 feet) just northwest of the existing river at River Mile 10.7. The thickest portion of the aquifer is slightly elongated to the northeast and west-southwest. The aquifer covers a total area of approximately two square miles with an average thickness of about 250 feet within the area investigated. The aquifer likely continues further to the west, but its extent downvalley is unknown.

The two potential aquifers may be separated by a less-resistive layer (silty sand and clay) underlying the Embankment which may restrict the hydraulic connection between the two aquifers.

## 2.4 Hydrogeologic Review and Interpretation

### 2.4.1 Groundwater Conditions

Based on the geologic and geophysical information, the following groundwater conditions have been interpreted for Area 3:

- A potential aquifer (here termed the North Fork Snoqualmie Headwaters Aquifer) between 100 to 150 feet in thickness is located east of the Embankment and occupies the valley bottom of the North Fork Snoqualmie. The aquifer is interpreted to be silty sand to sand and gravel;
- A potential aquifer (here termed the North Fork Snoqualmie Channel Aquifer) occupies the bedrock depression created by the ancestral North Fork Snoqualmie downstream of the North Fork Embankment. The aquifer is up to 450 feet in thickness and appears to be composed of silty sand and gravel;
- A lacustrine silt to silty clay aquitard is present below the Headwaters Aquifer with bedrock as its lower surface. The aquitard ranges up to 350 feet in thickness; and
- Bedrock, consisting of unfractured and fractured sedimentary and metamorphic rock, underlies the entire region of Area 3.

Precipitation over the North Fork Snoqualmie Basin is the source of recharge to the North Fork Headwaters Aquifer and the North Fork Channel Aquifer. In addition to recharge within the Upper North Fork Snoqualmie Basin, the bedrock may receive some recharge from outside the topographic limits of the basin where the sedimentary and metamorphic rocks outcrop

The Headwaters Aquifer receives recharge via precipitation over the surface exposure of the aquifer and by recharge from streams which descend the bedrock-lined flanks of the valley and infiltrate into the more permeable sediments in the valley. Infiltration from the North Fork Snoqualmie may also occur, particularly during high flows. However, given the generally flat gradient of the river and high water table (as observed from the water-filled abandoned meanders and wetlands) losses from the North Fork Snoqualmie in this region are not expected to contribute significant recharge to the aquifer. An estimate of recharge to the Headwaters Aquifer is presented in Section 2.4.3. The Headwaters Aquifer discharges downvalley to the Channel Aquifer and also likely provides base flow to the North Fork Snoqualmie River.

The Headwaters Aquifer transitions downvalley into a thicker sequence of sediments infilling a deep narrow channel eroded into bedrock by the ancestral North Fork Snoqualmie. The North Fork Channel Aquifer is recharged by direct precipitation over the aquifer, downvalley flow from the Headwaters Aquifer, and potentially by infiltration from the North Fork Snoqualmie River, Deep Creek, and Black Lake (which is located to the north of the ancestral North Fork Snoqualmie and has no surface water outlet). An estimate of the amount of groundwater flow within the North Fork Channel Aquifer is presented in Section 2.4.3.

The Channel Aquifer likely continues westward or southwestward following the ancestral North Fork

drainage. Its westward extent is unknown. The aquifer in part discharges as springs surrounding Beaver Lake and provides base flow to Beaver Creek (and potentially to Tokul Creek), downstream of the lake.

Groundwater occurrence and movement within bedrock is difficult to interpret given the absence of data. It is possible that the limestones postulated to lie in excess of a thousand feet below the surface may represent a potential aquifer, provided their intrinsic and secondary permeability has been lost as a result of geologic processes occurring since deposition.

### **2.4.2 Hydraulic Properties**

Inflow tests were performed by the USCOE in boreholes RD-113 and RD-115 (located in the Channel Aquifer) to evaluate hydraulic properties and possible seepage quantities from a man-made reservoir in the area.

The tests were conducted during drilling and were performed by exposing the lower five feet of borehole and then filling the borehole with water up to ground-surface. The rate of inflow required to keep water levels at ground-surface was then recorded over a fifteen minute period. This test is equivalent to a constant-pressure injection test, and can be analyzed using standard aquifer test analysis. A total of 25 intervals were tested in this manner from the two boreholes.

Unfortunately, the short duration of the test prohibits a rigorous analysis and an approximation must be used to obtain an estimate of hydraulic properties. An approximation utilizing specific capacity was used (Lohman, 1964), which is based on standard aquifer test methods (Cooper and Jacob, 1946). An estimate of specific capacity was obtained for a given test interval based on the flow rate and depth of the test interval. This specific capacity was then used to calculate hydraulic conductivity. The major limiting assumption in the method is that the calculated specific capacity is based on a steady-state condition, which is unlikely given the short test duration. However, aquifer properties estimated using the flows after a shorter duration will be higher than those estimated at steady state. Hydraulic conductivities range from 0.05 ft/day to 0.4 ft/day in the upper 150 feet of aquifer at wells RD-113 and RD-115.

The average hydraulic conductivity of all zones encountered is on the order of 0.1 ft/day. Conductivities of this magnitude are typical of a silty sand or glacial till (Freeze and Cherry, 1979), which is consistent with the geologic setting and well log descriptions. The higher hydraulic conductivities were encountered in thin zones less than 10 feet thick. As discussed in Section 2.3, there is no evidence from the geophysical survey to suggest a significantly different sediment composition below a depth of 150 feet, and hydraulic properties are likely to be similar. The maximum bulk transmissivity (aquifer thickness multiplied by hydraulic conductivity) is therefore estimated at about 40 ft<sup>2</sup>/day (300 gpd/ft). For comparison, the transmissivity of the Issaquah Aquifer is on the order of 40,000 ft<sup>2</sup>/d (300,000 gpd/ft).

There is no direct information on hydraulic aquifer properties in the upper basin, upstream of the Embankment, although based on similar geophysical properties to that of the Channel Aquifer, a similar range in hydraulic properties is probable.

### 2.4.3 Groundwater Flow Quantities

This section presents an estimate of the amount of groundwater flowing downvalley under the prevailing hydraulic gradient within the two aquifers identified in Area 3.

For aquifers with little or no hydraulic connection to surface water bodies, the quantity of downvalley flow is a crude approximation of the amount of groundwater potentially available without causing long-term groundwater level declines. This would be the case in a fully confined aquifer with no leakage or boundaries receiving recharge at distance from the pumping centers. However, in valley-fill aquifer systems such as the North Fork Snoqualmie where confining layers are at best discontinuous, the ultimate groundwater resource potential depends on the hydraulic connection that is established between the well and the river during pumping. Therefore, the quantity of groundwater that can be developed by a well or wellfield in such systems depends on the hydraulic conductivity and overall hydraulic connection to the river rather than the amount of downvalley groundwater flow under non-pumping conditions.

Downvalley flow within the Headwaters Aquifer above the Embankment and through the Channel Aquifer in the Beaver Creek Plug area was calculated using Darcy's Law where:

$$Q = KiA$$

where:

Q = groundwater flow, (ft<sup>3</sup>/d)

K = hydraulic conductivity, (ft/d)

i = hydraulic gradient, (dimensionless)

A = the cross-sectional area across which flow occurs (ft<sup>2</sup>).

#### 2.4.3.1 Groundwater Flow in the Headwaters Aquifer

The hydraulic gradient in the Headwaters Aquifer was estimated at 0.01 based on topographic information. Aquifer width was estimated at between 4,000 to 5,000 ft, and aquifer depth at between 100 to 150 feet. Hydraulic conductivity was estimated at between 0.5 to 5 ft/day, based on tests completed by the USCOE, and including a conservatively high margin of error.

Based on these assumed values, downvalley groundwater flow under the prevailing gradient is estimated to range from 0.01 to 0.2 MGD.

#### 2.4.3.2 Groundwater Flow in the North Fork Channel Aquifer

Based on the USCOE boreholes, groundwater elevations immediately down-valley from the North Fork Embankment are estimated to be a maximum of 1,150 ft amsl. The water table elevation at Beaver Lake is estimated at 1,000 ft based on the presence of springs at this elevation. The hydraulic gradient between the Embankment and Beaver Springs is therefore estimated to be about 0.02 (150-foot head drop over 8,000 feet).

The average cross-sectional width across which flow occurs was estimated based on the geophysical survey results (see Section 2.3.3) at about 3,000 ft. The thickness of the aquifer was also estimated from the geophysical survey at an average of 250 feet. The hydraulic conductivity of the aquifer was estimated at between 0.5 and 5.0 ft/day, based on the hydraulic tests completed by the USCOE and including a conservatively high margin of error.

Based on these assumed values, estimated groundwater flow through the aquifer is 0.06 to 0.6 MGD). This range is similar to the spring discharge (several hundred gallons per minute) reported by the USCOE (1983). There is undoubtedly additional downvalley groundwater flow that is not captured by the springs, but this flow component may be only two or three times greater than the spring discharge based on aquifer thickness (i.e., a maximum of say 2 to 3 MGD).

#### 2.4.3.3 Groundwater Development Potential

The majority of the sediments which comprise the North Fork Snoqualmie Headwaters and Channel Aquifer are silty sand and gravel of relatively low to moderate hydraulic conductivity with isolated pockets of more-permeable material. As such, the amount of downvalley groundwater flow under natural conditions is relatively small. There does not appear to be an extensive highly-permeable confined aquifer capable of yielding 40 MGD that could be developed as a regional supply source without impacts on instream flows.

The geologic information however does suggest that there are localized areas within the North Fork basin underlain by relatively permeable sediments. One such area is at the confluence of Phillipa and Sunday Creeks in the Headwaters area where some of the highest resistivities were measured. These resistivities are more typical of sand and gravel rather than silty sand and gravel. This area potentially has the greatest chance of yielding groundwater quantities suitable for a regional supply (5 to 10 MGD, or more) within the North Fork basin. However, the geophysics suggests that there is little or no confining layer between the river and the aquifer and hence the aquifer is likely to be in direct hydraulic connection to the river. Under these conditions, a greater groundwater supply could be developed than that indicated by the downvalley flow calculation, because pumping will induce flow from the river into the aquifer. However, groundwater development might only be possible at times when minimum instream flows were exceeded unless in streamflow impacts were mitigated to permit year-round use. Another possibility (which would be dependent on the hydrogeological conditions) would be to use the wellfield on a seasonal basis, and to rely on the transient pumping effect to delay the on-set of impacts until instream flows increased in response to precipitation.

## 2.5 Summary and Conclusions

The following is a summary of the hydrogeologic conditions in Area 3, and conclusions related to groundwater supply potential:

- Three potential aquifers exist in Area 3: 1) the Headwaters Aquifer located east of the North Fork Embankment; 2) the Channel Aquifer, located west of the North Fork Embankment and occupying the ancestral channel of the North Fork Snoqualmie; and 3) an aquifer within Palaeozoic-aged limestones.

- The North Fork Snoqualmie Headwater Aquifer is interpreted to be composed of silty sand and gravel of moderate hydraulic conductivity. There are potentially localized areas of more permeable sand and gravel such as the alluvial fan developed at the mouth of Phillipa Creek and Sunday Creek. The aquifer is potentially between 100 and 150 feet in thickness and occupies an area of approximately five square miles. Recharge to the aquifer is limited by basin area runoff, and the apparent high groundwater levels which maximize surface runoff at the expense of infiltration. The aquifer discharges downvalley to the Channel Aquifer and probably as base flow to the North Fork above the Embankment. Groundwater is likely in direct hydraulic communication with the North Fork Snoqualmie River, since there appears to be no apparent confining layer between the river and the aquifer.

Groundwater flow within the aquifer is estimated to range from 0.1 to 0.2 MGD, but possibly as high as 2 MGD under prevailing hydraulic gradients. There does not appear to be air extensive permeable confined aquifer that could provide 40 MGD without impact on instream flows. In areas where localized highly-permeable sand and gravel is present, well yields may be greater than downvalley groundwater flow (5 to 10 MGD, or more) because of induced infiltration from the river, but will have a direct influence on streamflows.

- The North Fork Snoqualmie Channel Aquifer is interpreted to be composed of silty sand and gravel of moderate hydraulic conductivity. There may be thin isolated zones of more permeable materials within rechannel but those are not expected to be extensive. The aquifer is potentially up to 450 feet in thickness, but in general averages between 200 to 250 feet thick. The aquifer has an average width of 3,000 feet and extends westward for an unknown distance. Recharge to the aquifer is from down-valley flow from the Headwaters Aquifer, direct precipitation over the aquifer outcrop, and potential infiltration from Deep Creek, the North Fork Snoqualmie and Black Lake. This aquifer likely has less hydraulic communication with the Snoqualmie River, especially if influent conditions and/or unsaturated conditions are present between the river bed and water table.

Groundwater flow within the aquifer is estimated to range from 0.06 to 0.6 MGD but possibly as high as 6 MGD. There does not appear to be an extensive permeable confined aquifer that could provide 40 MGD without impact on instream flows. In areas where localized highly permeable sand and gravel is present, well yields may be greater than down-valley flow, because of induced infiltration from the river.

- A third potential aquifer may be present within limestone which may underlie Area 3 at depths in excess of 1,000 feet. The assessment of this material as a potential aquifer is highly speculative, but potentially the limestone may offer an aquifer hydraulically isolated from the North Fork Snoqualmie that receives recharge over an area potentially greater than the North Fork Snoqualmie Basin. Groundwater supply potential cannot be estimated at this time. Additional geophysical work and the construction and testing of a deep borehole would be required to evaluate this option. The limestone is not recommended for further exploration at this time. This potential aquifer may be considered at a later time depending on the results of investigation at other sites.

### **3. RESULTS OF AREA 2 INVESTIGATION - MIDDLE AND SOUTH FORK SNOQUALMIE RIVER**

Area 2 is located in the lower reaches of the Middle and South Fork Snoqualmie River. The area under investigation encompasses approximately 16 square miles of the basin, from the Mine Creek Campground area southwest to Boxley Creek and west to the community of Tanner. Two topographically high areas flank Area 2, and are referred to as the Middle Fork Embankments. The easternmost embankment is contiguous with Grouse Ridge. Figure 3-1 is a topographic map of Area 2.

#### **3.1 Sources of Data**

The hydrogeology of Area 2 has been summarized, in part, in the feasibility study (CH<sub>2</sub>M Hill, 1993). Data sources used for the feasibility study included:

- Geophysical investigations by Twelker and Associates (1962c, 1965);
- Well logs in the area; and
- Streamflow data from the USGS gages 12.1413.00 (Middle Fork Snoqualmie Mine Creek), 12.1415.00 (Middle Fork near Tanner), gage 12.1439.00 (Boxley Creek), 12.1436.00 (South Fork at Edgewick) and gage 12.1440.00 (South Fork at North Bend).

The revised hydrogeologic evaluation of Area 2 presented here is based on the aforementioned data and additional data, specifically:

- The results of the TDEM survey performed as part of this study (Section 3.3 and Appendices A and B);
- Well logs of borings and wells obtained from WDOE;
- Hydraulic inflow testing of one boring by the USCOE during investigation of a potential dam site on the Middle Fork Snoqualmie (Appendix D);
- Pumping test results from a recent well at the Cascade Golf Course; and
- Regional gravity maps prepared by the USGS.

Using these data, a revised evaluation of the hydrogeology of the area has been prepared, including a more detailed water budget and groundwater recharge estimates, an estimate of hydraulic properties of the aquifer, and an estimate of down-valley groundwater flow. The results of this evaluation are described below.

## 3.2 Geological Conditions

### 3.2.1 Conceptual Geologic Model

Glacial process similar to those discussed for Area 3 were operative in the development of the geologic conditions in Area 2. Alpine glaciation initially overdeepened the Middle and South Fork valleys creating typical "U" shaped valleys bounded by bedrock. The exact glacial course of these drainages is uncertain. Glacial drift deposits of till, outwash or lacustrine sediments at times infilled and were later re-worked and/or eroded from these valleys during subsequent advance and retreat of the alpine glaciers.

During later periods of glaciation, the Cordilleran ice sheet extended southward blocking the westward drainage of the Middle and South Forks to the east of North Bend. Meltwater from the Cordilleran glacier developed deltaic outwash plains eastward into the Middle Fork, South Fork and Cedar Lakes, and discharged from them into ice-marginal channels. Further upvalley, east of the ice front, lacustrine deposits were laid down in pro-glacial lakes that fluctuated in response to the advance and retreat of the ice front. Subsequent to the glacial period, downcutting by the Middle and South Forks is responsible for the present topography.

Portions of the ancient deltas remain intact and are manifested as two large embankments located several miles east of North Bend along the eastern margin of Area 2. One of these embankments forms Grouse Ridge, while the second is located directly north of Grouse Ridge forms the Middle Fork Embankment. The embankments rise roughly 1,000 feet above the valley floor and are comprised primarily of gravel, sand, and silt. The embankments appear to be very permeable based on the observation that several streams which drain the embankments infiltrate into the surface and disappear.

The geologic history described above suggests three areas of sediment deposition, each containing relatively different materials:

- In the upper Middle and South Fork valleys (east of the Embankments), and possibly at depth in the bedrock scoured valley bottoms, fine grained silts and clays were likely deposited during lacustrine periods, possibly interbedded and/or overlain by coarser materials deposited when the lakes disappeared because of temporary recession of the blocking Cordilleran ice sheet;
- At the margin of the Cordilleran glacier, large quantities of sediment were shed, forming terminal delta moraines. These delta moraines form the Middle Fork Embankment and Grouse Ridge. These sediments were likely highly variable, ranging from cobbles to silts; and
- To the west of the Embankments overconsolidated glacial tills were deposited beneath the ice sheet, containing a wide variety of sediment types ranging from cobbles to silts. During periods of retreat, this same area was likely re-worked by meltwater and subsequently covered with glacial outwash sand and gravel.

### 3.2.2 Well Logs and Geologic Cross Sections

Review of a geologic map of King County (Livingston, 1971) shows that the majority of Area 2 is covered by Quaternary-aged sediments of glacial and fluvial origin which overlie older bedrock. Bedrock outcrops at the surface along the northern margin of the Middle Fork valley as well as at several locations along the base of Grouse Ridge, and to the east of Grouse Ridge. Most of this bedrock has been mapped as Mesozoic to early Cenozoic sedimentary rocks categorized as graywacke, argillite, and siltstone with some slate and phyllite (Livingston, 1970).

Well logs obtained from the Washington State Department of Ecology (WDOE) were reviewed and used to construct three geologic cross-sections. The wells in Area 2 range in depth from 50 to 320 feet and generally do not encounter bedrock. However, several wells located along the northern, eastern and southern margins of Area 2 do encounter bedrock. Most of these wells are located along the flanks of the Snoqualmie valley near the contact between bedrock and the glacial/alluvial material found in the Snoqualmie valley.

The deepest well in Area 2 is well 23/09-28C, which is located on the top of Grouse Ridge and extends to a depth of 758 feet. This well extends through silt, sand, and gravel before penetrating bedrock at a depth of 758 feet. Well 23/08-13N, which was drilled to an elevation of roughly 380 feet above sea level, appears to be completed to the lowest elevation of any well within Area 2. This well encounters a thick sequence of sand and gravel interbedded with clay at an approximate elevation of 460 feet above mean sea level (amsl).

Figure 3-1 shows the location of three cross-sections which were prepared in order to characterize the geology in Area 2 and assist in the geophysical interpretation. Due to the relatively shallow nature of most of the wells in this area, the cross-sections are intended to characterize only the upper portion of the geologic section.

In general, well data show that the shallow geology of Area 2 is characterized by predominantly coarse-grained materials such as sand, gravel, and boulders with interbedded silt and clay present in places. Several of the wells penetrate a possibly continuous layer of sand and gravel at an elevation of roughly 450 to 500 ft amsl, although the vertical and lateral extent of this layer is uncertain. Wells located along the southern and western margins of Area 2 indicate that the sub-surface may become more fine-grained in these areas.

Cross-section A-A' (Figure 3-2) begins on the northern edge of Area 2 and extends southward across the Snoqualmie valley along Edgewick Road and past Derry Lake. Most of the material encountered by wells along the northern half of this cross-section appears to be coarse-grained materials such as sand, gravel, and boulders, although some silt and clay are present in places. A zone comprised primarily of gravel and boulders is present near the surface in several wells located on Salla l Prairie. Below this boulder zone, a layer of sand and gravel is encountered in well 23/08-24A at a depth of approximately 180 feet (approximate elevation of 500 feet amsl), but the thickness and extent of this layer are unknown. The sub-surface materials found along the southern half of cross-section A-A' are more fine-grained, with mostly clay, silt, and sand-sized materials.

Cross-section B-B' (Figure 3-3) begins near the western edge of Sallal Prairie (near the community of Tanner) and extends in a south-eastern direction across Sallal Prairie to the western base of Grouse Ridge. Several of the wells located on the Sallal Prairie encounter a zone of gravel and boulders at the surface which extends to a depth of up to 120 feet in places. This zone of gravel and boulders appears to be correlated with a topographic ridge located to the west of Grouse Ridge which separates the Middle Fork from the South Fork of the Snoqualmie River. This zone of gravel and boulders appears to grade into an underlying unit which contains silt, sand, and gravel as well as boulders in places. Wells 23/08-14G, 23/08-13N, and 23/08-24A penetrate a sand and gravel unit along cross-section B-B' which is interbedded with clay in places. The top of this sand and gravel unit varies in depth from roughly 50 feet in well 23/08-14G (470 ft amsl) to roughly 180 feet in well 23/08-24A (500 ft amsl). The lateral continuity and thickness of this unit along cross-section B-B' are uncertain.

Cross-section C-C' (Figure 3-4) begins near the western margin of Area 2 and extends in a north-eastern direction across the Middle Fork to the western base of the northern embankment. The sub-surface geology along this cross-section can be generally characterized as consisting of interbedded layers of silty sand and gravel, sand and gravel, and gravel and boulders. A layer of sand and gravel is encountered at a depth of 50 feet in well 23/08-14G (470 feet amsl), however, the lateral and vertical extent of this layer are unknown.

In summary, the interpretation of the cross-sections shows:

- A potentially continuous unit of sand and gravel which is encountered over much of the northern portion of Area 2 at an elevation of roughly 450 to 500 ft amsl. This sand and gravel unit could be a significant regional aquifer depending on its extent, thickness, and hydraulic properties;
- A zone of gravel and boulders is encountered on cross-sections A-A' and B-B' which appears to be correlated with a topographic ridge located to the west of Grouse Ridge. This boulder zone extends to a depth of roughly 120 feet and appears to be mostly unsaturated. Drilling through the boulder zone would likely be difficult and should be avoided; and
- Properties of sediments below an elevation of about 400 ft amsl are unknown based on well-log information.

### 3.3 Geophysical Survey Results and Interpretation

#### 3.3.1 Calibration and General Response

A total of 24 TDEM soundings were conducted in Area 2 (Figure 3-5). Appendix A contains a technical description of the survey methods and procedures. Appendix B contains the results of the soundings and models which fit the observed data. The following section describes the survey results and interpretations.

##### Calibration Soundings

The majority of wells in Area 2 are private wells drilled to a depth of less than 200 ft. These wells offer little calibration for the TDEM soundings since most of the TDEM information is below these depths. The inability to record information at early decay times prevents the resolution of layering in the near surface (see Appendix A). However, a few deeper wells near TDEM soundings do exist. Calibration soundings in the vicinity of Area 2 were performed at 3 locations, as discussed below.

Site 2-7 is located at the Department of Corrections well 23/09-28C (758 ft deep). This well is the only well in Area 2 that provides a deep calibration to the bedrock interface. The TDEM model consists of four layers. A relatively-resistive (346 ohm-m) upper layer (0 to 209 ft) correlates with the unsaturated sand, clay, and till on the borehole log (0 to 214 ft). A more-resistive (722 ohm-m) second layer (209 to 345 ft) correlates with the unsaturated silty sand on the borehole log (214 to 375 ft). A relatively-conductive (52 ohm-m) third layer (345 to 786 ft) correlates with the partially saturated silt and sand on the borehole log (375 to 758 ft). The borehole log indicates wet sediments at 375 ft. It is not clear whether this is the water table or just an increase in the water production. The interpreted bedrock depth of 786 ft is in excellent agreement with the bedrock depth on the borehole log of 758 ft.

Site 2-4A is near the private well 23/08-24A drilled to 207 ft. A resistive (300 ohm-m) upper layer (0 to 155 ft) corresponds to the unsaturated gravel and boulders on the borehole log. The less-resistive (115 ohm-m) second layer (155 to 475) correlates reasonably well with the saturated gravel and boulders below the water table. The relatively-conductive (6 ohm-m) third layer is below the depth of the borehole. Bedrock is interpreted at a depth of 722 ft. Bedrock was not encountered in the borehole logs, but the bedrock elevation is consistent with surrounding TDEM sites.

Site 2-10B is near the Sallal Water District well 23/09-18P drilled to 255 ft. A resistive (952 ohm-m) upper layer (0 to 80 ft) corresponds to the unsaturated silty sand, gravel, and boulders on the borehole log. A less-resistive (400 ohm-m) second layer does not correlate with a stratigraphic unit on the borehole log. However, it is within 120 feet of the water-level reported on the well log and may indicate the water table. The discrepancy is likely due to a combination of accuracy limitations of the TDEM, the 1,000-foot offset between the sounding and the well, and a different water-level than indicated on the well log. The well is not deep enough to provide geologic information on the conductive (3 ohm-m) third layer or bedrock. Bedrock is interpreted at a depth of 666 ft. The bedrock elevation is consistent with surrounding TDEM sites.

A calibration sounding was performed outside Area 2 at the location of the Sammamish Plateau Water and Sewer District pumping wells SP-7 and SP-8 near Issaquah, Washington. These wells offer a calibration to sediments that are proven to produce high yield. A relatively conductive (16 ohm-m) upper

layer (0 to 55 ft) correlates with a silty sand, gravel, and clay layer on the borehole logs (0 to 75 ft). A more resistive (220 ohm-m) second layer (55 to 221 ft) is in excellent agreement with the productive sand or gravel zone (75 to 227 ft) on the borehole logs. A relatively conductive (8 ohm-m) third layer (221 to 395 ft) correlates with the clay layer (227 to the bottom of log). Bedrock was not encountered on the borehole log, but the interpreted bedrock elevation is in excellent agreement with the bedrock elevation extrapolated from nearby wells that did encounter bedrock.

Comparison of these TDEM models to the borehole logs indicate that the TDEM method resolves two major lithological units (recessional sand/gravel and lacustrine sediments) and bedrock with reasonable accuracy. Smaller scale lithological changes are averaged into the bulk resistivity of the major lithological unit. No borehole control on the lacustrine unit exists in Area 2, but, as discussed later, the continuity of the unit throughout the area strongly suggests its presence. The high resistivity surface layer at Sites 2-4A and 2-10B correlate with a boulder zone observed in well logs in that area.

### General Response

The quality of the TDEM data in Area 2 is considered good. A smooth apparent resistivity curve was observed out to 1 to 10 msec at most soundings (refer to Appendix B). A rising limb in the apparent resistivity curve at later time is observed on most soundings, and is a typical response to resistive bedrock. Beyond the rising limb, the data are noisy due to the rapid loss of signal in the resistive bedrock. On many of the curves the first few points deviate from the smooth curve. These points are interpreted as part of the primary transmitter signal and are not used in the modeling. The curves at sites with shallow bedrock (e.g. Sites 2-5, and 2-6A) show an immediate rising limb in the apparent resistivity curve and the onset of noise at earlier time.

The TDEM models for soundings in Area 2 show a resistivity range from 1 to 950 ohm-m for the overburden and 1,000 to 5,300 ohm-m for the bedrock. Overburden resistivities greater than about 300 ohm-m were found mainly in the upper 50m (165 ft) of sediment in a few locations and in the first 105m (345 ft) at the crest of Grouse Ridge. These high resistivities are interpreted as unsaturated sediments. The high near-surface resistivities in the vicinity of Sites 2-14 and 2-4A (Figure 3-6, geoelectric cross-section A-A') correlate with a boulder zone defined by the shallow wells in that area.

The inability to record information at early decay times (see Appendix A) prevented resolution of the saturated/unsaturated contact at most locations. This is common in resistive environments where the signal passes through the unsaturated zone before the receiver can measure a response. The remainder of the overburden resistivities ranged from 1 to 300 ohm-m. A model of 2 to 5 layers was produced for each sounding which fit the observed with an error of less than 15 percent in 70 percent of the soundings. The fitting error exceeded 25 percent on only two soundings.

### **3.3.2 Bedrock Elevations**

Bedrock outcrops along much of the perimeter of Area 2. The bedrock ridge forming Mt. Si is present north of the Middle Fork of the Snoqualmie River at Tanner and strikes northeast behind the Middle Fork Embankment at River Mile 53. Bedrock ridges east of Grouse Ridge and south of the South Fork form the eastern and southern perimeters of Area 2. Bedrock outcroppings can also be seen along SE Middle Fork Road as it traverses the northern end of Grouse Ridge. The valleys converge at the west end of

Area 2 between these bedrock ridges. The South Fork flows west through a relatively narrow and steep river valley and intersects with Boxley Creek west of Twin Falls State Park. Boxley Creek flows northeast through a small valley originating at a bedrock knoll (Cedar Butte) in the vicinity of the Chester Morse Reservoir. The Middle Fork flows westerly along the bedrock ridge east of Grouse Ridge eroding a valley between Grouse Ridge and the Middle Fork Embankment.

The interpreted bedrock elevations are summarized on Figure 3-5 as a contour map. Bedrock depths interpreted from the TDEM models were subtracted from the surface elevation (based on the USGS quadrangle map), plotted, and hand contoured to produce the map. The map shows two ancestral channel features beneath the Middle and South Forks.

The Middle Fork channel is between 2,000 and 4,000 feet wide and extends from the present river location beneath the Middle Fork Embankment north of the river. The lowest bedrock elevation of the channel appears to be beneath the Middle Fork Embankment and at the confluence with the ancestral South Fork channel. A poorly resolved bedrock nose in the vicinity of Site 2-14 appears to separate the ancestral Middle and South Forks.

The South Fork channel deepens west of Twin Falls State Park. From the confluence of Boxley Creek and the South Fork, the channel trends north-northwest to the confluence with the Middle Fork channel. The width of the channel is not well defined because access limitations prevented soundings west of the South Fork. The channel appears to be at a relatively constant elevation north of Boxley Creek with the lowest bedrock elevations at the confluence with the Middle Fork channel.

The bedrock elevation map shows that Grouse Ridge is underlain by a relatively flat bedrock shelf. This bedrock shelf extends to the west edge of the ridge then deepens rapidly west of Grouse Ridge to form the South Fork Channel. Twin Falls is the surface expression of the edge of this bedrock shelf in the South Fork valley.

Site 2-1 (near Tanner) indicates shallower bedrock to the west the confluence of the Middle Fork and South Fork channels. Additional soundings outside of Area 2 would be needed to further define the form of the channel in this area and its extension west of the confluence.

### 3.3.3 Geo-electric Cross-Sections

Three geo-electric cross-sections (A-A', B-B'-B'', C-C'-C'', Figures 3-6, 3-7, and 3-8, respectively) were prepared based on the interpreted TDEM models and are discussed below. The geo-electric cross sections correspond to the locations of the geologic cross sections, but cover a greater lateral distance.

#### Cross-Section A-A'

This cross-section is transverse to the axis of the river valleys and shows the ancestral channels of the South and Middle Forks of the Snoqualmie River. The section crosses the river valleys east of Boxley Creek and west of Grouse Ridge from the bedrock ridge south of the South Fork to the bedrock ridge north of the North Fork Embankment.

The section consists of a three-layer model over most of the section as follows:

- A moderately-resistive upper layer overlies a relatively-conductive second layer which in turn overlies a highly-resistive bedrock. Resistivities in the upper layer range from 115 to 280 ohm-m and are interpreted as a composite of unsaturated and saturated sand and gravel of between 300 to 400 feet in thickness beneath the valley bottom;
- Resistivities in the conductive second layer range from 3 to 11 ohm-m and are interpreted to be lacustrine silty sand and clay. The consistency of the elevation and resistivity values agree with a lacustrine depositional environment;
- At Sites 2-4A, 2-14, and 2-17 a more-resistive (300 to 850 ohm-m) layer exists in the first 200 ft. This layer correlates with a boulder zone observed in well logs in this area; and
- A poorly-resolved rise in the bedrock beneath Site 2-14 suggests that a bedrock saddle may separate the ancestral bedrock channels of the Middle and South Forks.

The moderately-resistive (115 to 280 ohm-m) upper layer of the section represents the potential aquifer in this portion of Area 2. The underlying lacustrine sediments are not expected to be viable aquifer material. It is possible that there may be a relatively thin (less than 50 foot thick) aquifer below the lacustrine deposits and overlying bedrock that is not detected using geophysics.

#### Cross-Section B-B'-B''

This cross-section is aligned sub-parallel to the axis of the South and Middle Forks and bisects the area separating the two rivers. The section starts at Site 2-1, crosses the Sallal Prairie and Grouse Ridge and ends at the bedrock outcrop east of Grouse Ridge.

Between B and Site 2-2 the section consists of a three-layer model with a moderately-resistive (77 to 200 ohm-m) upper layer overlying a less-resistive (1 to 10 ohm-m) second layer overlying bedrock (Figure 3-7). This is essentially the same model as in section A-A'. This model continues to Site 2-4A with the addition of shallow surface layers at Sites 2-3A and 2-4A. The 300 ohm-m layer at site 2-4A is the unsaturated boulder zone described in section A-A'. The 86 ohm-m surface layer at Site 2-3A is of unknown origin, but may be a localized silty layer. The deepest portion of the ancestral South Fork

channel is beneath Site 2-3A.

Between Sites 2-4A and 2-5A the bedrock rises steeply to within 100 feet of the surface. East of Site 2-5A the bedrock remains relatively flat, forming a shelf beneath Grouse Ridge. East of Site 2-7 the bedrock is interpreted to rise steeply to the bedrock outcrop at B". Site 2-7 is a calibration site and was calibrated with a borehole drilled to bedrock (Section 3.3.1). The resistive (346 to 722 ohm-m) upper layers correlate with unsaturated silt, sand, and till. The less-resistive (52 ohm-m) third layer correlates with a silt layer and the presence of water in the sediments. There is some uncertainty in the borehole log as to whether this is the water table.

#### Cross-Section C-C'-C''

This section starts at Site 2-1 and extends through the base of the Middle Fork Embankment to the bedrock ridge north of the embankment.

Between C and Site 2-15 the section consists of a three-layer model with a moderately-resistive (77 to 171 ohm-m) upper layer overlying a less-resistive (1 to 7 ohm-m) second layer overlying bedrock (Figure 3-8). As has been consistent throughout this area, the upper layer is interpreted as saturated sand and gravel and the second layer lacustrine silts and clays. The more-resistive (135 to 227 ohm-m) upper layer (0-175 ft) east Site 2-15 may indicate unsaturated sediments.

The resistivities of the upper layer in this cross-section are lower than the resistivities of the upper layer at sites just to the south (i.e. Sites 2-17 and 2-11) and may indicate a higher silt concentration.

### **3.3.4 Potential Aquifer Thickness**

The results of the TDEM survey show the presence of a low-resistivity layer (silt and clay) overlying bedrock throughout Area 2. Potential aquifer thickness (resistive sediment thickness) was calculated as the thickness of sediments above this low-resistivity layer (if present). If no low-resistivity layer is present, resistive sediment thickness was based on depth to bedrock. The resistive sediment thicknesses for each TDEM sounding were plotted on the USGS quadrangle maps and hand contoured (Figure 3-9). All resistive sediment thicknesses in Area 2 were corrected for the unsaturated zone by subtracting the thickness of sediments above the water table. Water table elevations were taken from the closest well log or river elevation.

The contour map of resistive sediment thickness for Area 2 shows the thickest resistive sediments to be along the ancestral channels of the Middle and South Fork Snoqualmie River. The aquifer thins over the bedrock nose separating the two channels and to the north, east, and south as it approaches the bedrock outcrops and Grouse Ridge. The ultimate extent of the aquifer cannot be determined since the aquifer appears to extend further west along the South Fork Snoqualmie River. More TDEM soundings would be required to further define the extent of the aquifer. The total area of the aquifer within the area of investigation is approximately 3 to 4 square miles with an average thickness of about 300 feet.

The flat-lying bedrock shelf beneath Grouse Ridge indicates that an ancestral bedrock channel does not exist beneath the ridge.

### **3.4 Hydrogeologic Review and Interpretation**

#### **3.4.1 Groundwater Conditions**

Based on the geologic and geophysical information, the following groundwater conditions have been interpreted for Area 2:

- A potential aquifer (here termed the Middle Fork Snoqualmie Channel Aquifer) between 200 and 400 feet in thickness occupies the valley bottom of the Middle Fork Snoqualmie. The aquifer is interpreted to be primarily sand and gravel;
- A potential aquifer (here termed the South Fork Snoqualmie Channel Aquifer) occupies the valley bottom of the South Fork Snoqualmie. The aquifer is also between 200 and 400 feet in thickness and appears to be composed of sand and gravel;
- A lacustrine silt to silty clay aquitard is present below both the Middle and South Fork Channel Aquifers with bedrock as its lower surface. The aquitard ranges up to 400 feet in thickness; and
- Bedrock, consisting of unfractured and fractured sedimentary and metamorphic rock, underlies the entire region of Area 2.

The Middle and South Fork Channel Aquifers appear to converge in the Sallal Prairie area just east of Tanner. Downvalley from this area, these two aquifers may merge into one aquifer.

Precipitation over the Middle and South Fork Snoqualmie Basins is the source of recharge for groundwater in Area 2. In addition to recharge within the basin, some recharge may enter from seepage from Chester Morse Lake to the south (located within the Cedar River drainage).

The aquifers receive recharge via precipitation over the surface exposure of the aquifer and from streams which descend the bedrock-lined flanks of the valley and infiltrate into permeable sediments (such as the Middle Fork Embankment) in the valley. Infiltration from the Middle and South Fork Snoqualmie Rivers may also occur where the groundwater level next to the river is below river elevation. An estimate of recharge to the Middle and South Fork Channel Aquifers is presented in Section 3.4.3.

Based on topography and the available well-log data, the general direction of groundwater flow within Area 2 mimics topography and is generally toward the west converging near the western boundary of Area 2. Water levels in the lower elevations of Area 2 typically range from 0 to 100 feet below ground surface. Water levels in wells located in the upland areas are deeper, and generally range from 100 to 200 feet below ground surface.

Groundwater flow below the present well depths in the deeper unconsolidated aquifer would be expected to generally mimic the shallow groundwater system, but could be different depending on geologic and hydraulic conditions at depth. Recharge to a deeper aquifer would likely be derived from shallow groundwater and possible inflow from bedrock. Discharge from the aquifer system likely occurs to the Snoqualmie River above Snoqualmie Falls, although it is possible that some deep groundwater flow may leave the Upper Snoqualmie basin and discharge in the Snoqualmie valley below Snoqualmie Falls.

Groundwater occurrence and movement within bedrock is difficult to interpret given the absence of data. Based on a knowledge of the regional bedrock geology, it is unlikely that an aquifer capable of yielding quantities required for municipal purposes is present in the bedrock in Area 2.

### **3.4.2 Hydraulic Properties**

Little information concerning the aquifer properties in Area 2 is currently available. A review of the well logs on file with WDOE provided some information concerning drawdown in several of the wells during bail tests, although this information is generally inadequate to determine hydraulic properties.

Based on observations in similar areas (for example Issaquah), the hydraulic conductivity of the aquifer is expected to be between 10 and 500 ft/d based on the coarse-grained material found in many of the wells in the area. Analysis of a pump test conducted at the Cascade Golf Course (Township 23 N, Range 8 E, Section 15, just west of Area 2) suggests that the aquifer transmissivity at that location is on the order of 100,000 ft<sup>2</sup>/d (750,000 gpd/ft). Using an assumed aquifer thickness of 150 feet, the corresponding value of hydraulic conductivity would be roughly 650 ft/d. This is substantially higher than the estimates for Area 3 (see Section 2.4.2), and more similar to the properties of the Issaquah Aquifer.

### 3.4.3 Water Balance/Groundwater Recharge

This section presents an estimate of the amount of groundwater which is potentially available to recharge the unconsolidated groundwater system in Area 2. Three primary sources of recharge were considered:

- Groundwater entering Area 2 as down-valley flow in unconsolidated aquifers present along the channels of the Middle and South Forks of the Snoqualmie River;
- Direct precipitation falling over Area 2 which infiltrates through permeable surface material and percolates to groundwater. Recharge is estimated to be especially high over the surface of the large embankments located within Area 2; and
- Streamflow within the Middle Fork and the South Fork of the Snoqualmie River which infiltrates into the subsurface within Area 2 and becomes groundwater.

These components of recharge are summarized in the following sections, and estimates of the components are presented in Table 3-1.

#### 3.4.3.1 Down-valley Groundwater Flow

It is assumed that all of the groundwater which enters Area 2 from the Middle Fork and the South Fork drainages flows through unconsolidated aquifers present along the channels of the Middle and South Forks of the Snoqualmie River. Regional geologic maps (Livingston, 1970; Booth, 1990) show that with the exception of narrow bands of alluvium present along the Middle and South Forks, most of the surficial geology in the upper Snoqualmie Basin (above Area 2) is bedrock. The amount of groundwater which enters Area 2 through these alluvial aquifers was estimated using an application of Darcy's Law:

$$Q = KiA$$

where:

Q = groundwater flow (ft<sup>3</sup>/d),

K = hydraulic conductivity (ft/d),

i = hydraulic gradient (ft/ft),

A = the cross-sectional area across which flow occurs (ft<sup>2</sup>).

For the Middle Fork aquifer, Darcy's Law was applied using estimated hydraulic properties, depth, and width of the shallow aquifer at USGS gage 12.1413.00 (located up-valley from Area 2, see Figure 1-1). The hydraulic gradient in the aquifer was approximated by the slope of the river channel near the stream gage, and was assumed to be 0.01 based on a topographic map of the Chester Morse Quadrangle. The cross-sectional area across which flow occurs was estimated based on a valley width of 2,000 feet along the river and an estimated thickness of the aquifer of 150 feet. The thickness of the shallow aquifer was based on borehole data from a well located roughly three miles down-valley from USGS gage 12.1413.00 which penetrates bedrock at a depth of 150 feet. The hydraulic conductivity of the shallow aquifer is unknown, but was estimated to be in the range of 50 to 500 ft/day.

Based on these assumed values, estimated groundwater flow in the unconsolidated aquifer at Mine Creek is expected to range between 1.1 and 11 MGD. Based on the 154 square mile drainage area of the

Middle Fork above this location, the basin-averaged recharge to the shallow aquifer is estimated to be between 0.15 to 1.5 inches/year. This estimate does not include potential recharge into the bedrock which may ultimately recharge a deeper flow system.

The estimated range of recharge presented here for the Upper Middle Fork basin is one to two orders of magnitude lower than the recharge estimates presented in an evaluation of the Snoqualmie and Issaquah valley aquifers completed by CH<sub>2</sub>M Hill (1993). In the CH<sub>2</sub>M Hill study, recharge over the Middle Fork basin was assumed to be 15 percent of precipitation, which was assumed to range between 80 and 160 inches annually. Based on the estimates of down-valley flow presented in this report, the recharge estimates presented in the previous report (CH<sub>2</sub>M Hill, 1993) significantly over-estimate actual recharge in the upper reaches of the Middle Fork basin.

A similar calculation was made of the potential down-valley flow within the alluvial aquifer under the South Fork. The calculation was made using a location roughly two miles upstream from USGS gage 12.1436.00. For this location, the estimated aquifer width was 800 feet and the estimated aquifer thickness was 100 feet. Assuming a hydraulic gradient of 0.02 (based on the approximate slope of the South Fork) and a range of hydraulic conductivities as estimated for the Middle Fork, estimated groundwater inflow from the upper reaches of the South Fork ranges from 0.6 to 6 MGD.

#### 3.4.3.2 Recharge from Direct Precipitation Over Area 2

A water budget approach was used to estimate the amount of water which recharges the groundwater due to precipitation which infiltrates over permeable material within Area 2. Neglecting the effects of storage, recharge the groundwater system can be expressed as follows:

$$Re = P - Ea - R$$

where:

- Re = Recharge to groundwater (ins),
- P = Precipitation (ins),
- Ea = Actual Evapotranspiration (ins),
- R = Runoff (ins).

Precipitation falling over Area 2 was estimated using long-term average annual precipitation data from stations at Snoqualmie Falls (elev. 440 ft.) and Cedar Lake (elev. 1,560 ft.). The long-term average annual precipitation at Snoqualmie Falls is 60.3 inches and at Cedar Lake is 104.4 inches (Washington State University, 1968). The elevation of Area 2 generally ranges from roughly 500 feet to 1,600 feet, so a reasonable estimate of the average precipitation over this area can be obtained by averaging the data from the above stations. The resulting estimate of average annual precipitation over Area 2 is 82.3 inches.

Actual evapotranspiration was estimated to be 22.6 inches, based on the estimated actual evapotranspiration at Cedar Lake (Washington State University, 1968).

Recharge is expected to occur to a certain extent over all areas within Area 2 where glacial or alluvial material is present at the surface, but is expected to vary spatially depending partly on the permeability of surface materials. Recharge is expected to be relatively large in areas where the surface material is comprised primarily of coarse-grained materials such as sand, gravel, and boulders. As discussed in Section 3.2, the most permeable areas within Area 2 are associated with two large embankments located

several miles east of North Bend, as well as a topographic ridge located to the east of Tanner (Sallal Prairie) which separates the Middle Fork from the South Fork. The estimated surface area of this permeable area is 12 square miles, of which roughly 8.1 mi<sup>2</sup> are within the Middle Fork drainage and 3.9 mi<sup>2</sup> are within the South Fork drainage.

It is difficult to estimate the runoff from the permeable embankments due to the absence of stream gaging information. However, a review of a topographic map of the area indicates that few streams drain the area, and that several existing streams infiltrate completely into the ground on the west side of the Middle Fork Embankment. Well logs from the area confirm that much of the surficial deposits found along the embankments appear to have a high permeability. It also seems likely that runoff from the adjacent bedrock may be directed to the more permeable surface deposits and infiltrate to groundwater. It therefore seems likely that a significant proportion of the precipitation not lost to evapotranspiration infiltrates and thereby recharges groundwater.

An upper limit of the amount of precipitation over the embankments which recharges the groundwater in Area 2 can be obtained by assuming that the surface runoff in this area is negligible. Using the estimated values of precipitation and actual evapotranspiration, this results in an annual average recharge rate of about 60 inches. If this estimated recharge rate is applied over the area of the embankments, the resulting groundwater component from this recharge is 34 MGD (23 MGD within the Middle Fork drainage and 11 MGD within the South Fork drainage).

Recharge will also occur over areas within Area 2 where less-permeable materials are present at the surface, although in these areas recharge will likely be significantly less than it is over the permeable embankments. Well logs indicate that the near-surface materials generally found to the south of Interstate 90 are typically comprised of silt, sand and clay and as such have lower permeabilities than the coarse-grained materials found on the embankments. Recharge over these areas can be estimated using a water balance approach.

Streamflow data obtained from gages on Boxley Creek (USGS gage 12.1439.00) and the South Fork at Edgewick Road (USGS gage 12.1436.00) and North Bend (USGS gage 12.1440.00) indicate that the tributary inflow to the South Fork between Edgewick Road and North Bend averages 45.6 cfs annually. This represents an average annual runoff of 50.7 inches over the ungaged catchment (12.2 mi<sup>2</sup>) between Edgewick Road and North Bend. Using the above estimate of runoff and the estimates of precipitation and evapotranspiration for Area 2, recharge can be calculated as a residual to be 9.1 inches annually. When applied to an area of roughly 6.3 square miles, this represents an average of 4.2 cfs of recharge to the shallow groundwater system in Area 2 (0.7 MGD within the Middle Fork drainage and 3.5 MGD within the South Fork drainage).

#### 3.4.3.3 Recharge Due to Losses from the Middle and South Forks

A third potentially-significant source of groundwater recharge within Area 2 is streamflow in the Middle and South Forks which infiltrates through permeable alluvium and becomes groundwater downstream of the locations discussed in 3.4.3.1, above. Potential losses to groundwater from the Middle Fork were evaluated using historical streamflow data from USGS gage 12.1413.00, located near the eastern boundary of Area 2, and USGS gage 12.1415.00, located roughly 1 mile down-river from Tanner. Streamflow records at these two stations were compared in order to determine if streamflow losses are occurring between gage 12.1413.00 (drainage area of 154 square miles) and gage 12.1415.00 (drainage area of 169

square miles). Since the streamflow records at these stations do not overlap, the comparison was made using two different periods of record. However, streamflow data obtained from a long-term record of the North Fork of the Snoqualmie River was used to adjust the data from gage 12.1415.00 so that a valid comparison could be made.

The comparison of streamflow data was made by comparing streamflow data from gage 12.1415.00 for the period 1907 to 1923 with data from gage 12.1413.00 for the period 1961 to 1971. For the above periods of record, the mean annual flow at gage 12.1415.00 was 1,207 cfs, while at gage 12.1413.00 the mean annual flow was 1,276 cfs. However, these values were computed from different periods of record such that a direct comparison of them is not strictly valid.

Data are available from a gage operated on the North Fork (gage 12.1430.00) which was operated during 1907 to 1923 and 1961 to 1971. The data from this gage show that the average flow on the North Fork during 1961 to 1971 was higher than the average flow during 1907 to 1923 by a factor of 1.02. Assuming that runoff in the North Fork basin is strongly correlated to runoff in the Middle Fork basin (which is a good assumption considering their proximity and hydrologic similarity), this factor can be used to adjust the average flow on the Middle Fork at gage 12.1415.00 (1907 to 1923) to account for natural variability in the period of record.

The adjusted average flow at gage 12.1415.00 is 1,231 cfs (1,207 cfs multiplied by 1.02). A direct comparison of the adjusted record from gage 12.1415.00 (1,231 cfs) to the record at gage 12.1413.00 (1,276 cfs) shows that the average flow at the upstream gage (gage 12.1413.00) is 45 cfs higher than the average flow at the downstream gage. This implies that an average of roughly 29 MGD from the Middle Fork recharges the groundwater in Area 2.

A similar comparison was made for the South Fork, in which streamflow data were compared from USGS gage 12.1439.00 on Boxley Creek near Edgewick Road, USGS gage 12.1436.00 on the South Fork at Edgewick Road, and USGS gage 12.1440.00 on the South Fork at North Bend. The comparison was made using data from the period 1984 to 1992, which was a common period of record for the three stations. During this period, the combined average flow of the South Fork and of Boxley Creek at Edgewick Road was 481.6 cfs, while the average flow of the South Fork at North Bend was 527.2 cfs. The difference in flow (45.6 cfs) can likely be accounted for by tributary runoff which enters the South Fork over the 12.2 mi<sup>2</sup> ungaged catchment area between Edgewick Road and North Bend. Although some losses may be occurring from the South Fork to groundwater, they appear to be small.

#### 3.4.3.4 Water Budget Summary and Groundwater Development Potential

An estimate of the total amount of groundwater flowing under natural gradients through the unconsolidated deposits in Area 2 can be made by combining the three potential sources of groundwater recharge outlined in above. This results in a combined groundwater flow through Area 2 of roughly 69 to 84.5 MGD). It is estimated that roughly 75 percent of this potential recharge is occurring within the Middle Fork drainage, while roughly 25 percent occurs within the South Fork drainage. This estimate is based on the assumption that runoff from the permeable embankments in Area 2 is negligible, which appears to be a valid assumption based on streamflow data which show that the Middle Fork loses water to the groundwater through Area 2 (i.e., no tributary runoff occurs over the embankments). Additional sources of recharge to groundwater not accounted for in the given estimate include groundwater inflow due to seepage losses from Chester Morse reservoir, and groundwater inflow to the unconsolidated aquifer from deep bedrock aquifers.

As indicated in Section 2.4.3, in valley-fill aquifer systems such as the Middle and South Fork Snoqualmie, the ultimate groundwater resource potential depends on the hydraulic connection that is established between the well and the river during pumping rather than the amount of downvalley groundwater flow under non-pumping conditions.

In the Middle and South Fork Channel Aquifers, there appears to be a mixture of highly permeable sand and gravel and less permeable silty sand and gravel within the upper 300 to 500 feet. Less permeable silty clay is interpreted to be present below the sand and gravel. There is the possibility of a relatively thin (less than 50 foot) aquifer below the silty clay overlying bedrock, however this could only be determined by drilling. There appears to be a greater amount of downvalley groundwater flow under the prevailing gradient than in the North Fork because of the more-widespread presence of permeable material. However, there does not appear to be an extensive highly-permeable confined aquifer capable of yielding 40 MGD that could be developed as a regional supply source without impacts on instream flows.

The greatest chance to develop a groundwater source with little impact on surface water would be if an aquifer is present beneath the silty clay deposits. Based on information developed to date, we believe that only limited quantities of groundwater (say 1 to 5 MGD at the most) could be developed from such a source, if present.

The greatest quantities of groundwater will likely be developed from the permeable sand and gravel deposits in the upper 300 to 500 feet. However, because of the permeable nature of the deposits, and absence of continuous confining layer, pumping will likely induce additional surface water to flow into the aquifer (or reduce groundwater discharge back to the river), and hence have an impact on instream flows. Therefore, groundwater development might only be possible at times when minimum instream flows were exceeded unless instream flow impacts were mitigated to permit year-round use. Another possibility (which would be dependent on the hydrogeological conditions) would be to use the wellfield on a seasonal basis, and to rely on the transient pumping effect to delay the on-set of impacts until instream flows increased in response to precipitation.

### **3.5 Summary and Conclusions**

The following is a summary of the hydrogeologic conditions in Area 2, and conclusions related to groundwater supply potential:

- Two potential aquifers exist in Area 2: 1) the Middle Fork Snoqualmie Channel Aquifer located in the valley floor of the Middle Fork; 2) the South Fork Snoqualmie Channel Aquifer, located in the valley floor of the South Fork. These aquifers appear to converge and become one aquifer system downstream of Sallal Prairie. There is the potential that a relatively thin aquifer may exist below the silty clay which underlies the sands and gravel, however drilling would be required to determine its presence.
- The Middle Fork Snoqualmie Channel Aquifer is interpreted to be composed of sand and gravel of moderate to high hydraulic conductivity. The aquifer is potentially between 200 and 400 feet in thickness and occupies an area of approximately one to two square miles before merging with the South Fork Aquifer. Recharge to the aquifer is from direct

precipitation over the aquifer and surrounding permeable Embankments, groundwater inflow from upvalley, and infiltration from the Middle Fork and its tributaries. The aquifer discharges downvalley as base flow to the Snoqualmie River above Snoqualmie Falls.

Groundwater recharge to the aquifer is estimated to range from 54 to 64 MGD. Wells may induce greater recharge to the aquifer from the river by lowering groundwater levels beneath the North Fork, but will likely have an influence on streamflows because there is little evidence of a confining layer between the river and the aquifer. Groundwater supply potential from this aquifer will depend on the hydraulic connection that is developed between the well and the river during pumping.

- The South Fork Snoqualmie Channel Aquifer is interpreted to be composed of sand and gravel of moderate to high hydraulic conductivity. The aquifer is potentially between 200 and 400 feet in thickness. The aquifer occupies an area of one to two square miles in Area 2, before merging with the Middle Fork Aquifer and extending further downstream for an unknown distance. Recharge to the aquifer is from direct precipitation over the aquifer outcrop, downvalley groundwater flow from the upper reaches of the South Fork and potential infiltration from the South Fork Snoqualmie and Chester Morse Lake/Boxley Canyon. The aquifer discharges downvalley as base flow to the Snoqualmie River above Snoqualmie Falls. Groundwater is likely in hydraulic communication with the South Fork Snoqualmie River, since there appears to be no apparent confining layer between the River and the aquifer.

Groundwater recharge to the aquifer is estimated to range from 15 to 21 MGD. The groundwater supply potential from this aquifer will depend on the hydraulic connection that is developed between the well and the river during pumping. Wells may induce greater recharge to the aquifer from the river by lowering groundwater levels beneath the South Fork, but will likely have an influence on streamflows.

- These does not appear to be an extensive permeable confined aquifer capable of yielding 40 MGD in Area 2 without impact on instream flows. There is the possibility that an aquifer may be present beneath the silty clay overlying bedrock. However, given its likely limited extent (i.e. constrained by bedrock), the groundwater supply potential from this aquifer is likely to be less than 5 MGD.

#### 4. RECOMMENDATIONS FOR FURTHER EXPLORATION

The results of the geophysical investigation combined with revised hydrogeological interpretation indicate that Area 2 appears to have the greatest potential to supply groundwater in the quantities required for a regional groundwater supply source. Table 4-1 presents a summary of the groundwater supply potential in the two areas, and the potential for hydraulic continuity with surface water for each potential source. This table is based on a qualitative assessment of each potential source using existing information and professional judgement. Exploratory drilling and testing will be required to confirm the groundwater supply potential and degree of hydraulic continuity with surface waters.

It is apparent that those sources with the greatest groundwater supply potential also have the greatest potential to affect surface water. The deeper aquifers although less likely to be in hydraulic communication with surface water do not appear to be capable of supplying groundwater in the quantities required for a regional groundwater supply source.

The next step in the evaluation of groundwater resources in both areas is the drilling and testing of exploratory/test wells. The drilling and testing program should be in a phased approach designed based on the overall goals of the EKCRWA considering budgetary limitations and hydrogeologic conditions. Exploration to identify the greatest quantity of groundwater available in each area should concentrate on the Headwaters Aquifer in Area 3 and the Middle and South Fork Channel Aquifers in Area 2. If identifying a source with little impact on instream flows is the primary objective, exploration should focus on the North Fork Channel Aquifer and the possible presence of a deep aquifer overlying bedrock in Area 2. The limestone aquifer within bedrock in Area 3 is considered highly speculative and should not be investigated further until the unconsolidated materials have been evaluated.

##### 4.1 Area 2

Area 2 appears to be the most favorable for development of a regional groundwater source. The Middle and South Fork Channel Aquifers appear similar in composition based on the geophysical survey. Both aquifers should be investigated as part of future exploration. The Middle Fork should receive priority because of the greater groundwater supply potential.

##### Middle Fork Snoqualmie Channel Aquifer

The objective of an exploratory/test well would be to evaluate the groundwater conditions in the deepest part of the Middle Fork Channel Aquifer. The recommended exploration site is a roughly triangular area bounded by geophysical sites 2-17, 2-11 and 2-12B. The exploratory/test well should be drilled to bedrock (estimated depth of between 650 and 1,050 feet). The well should be designed to test both a deep aquifer overlying bedrock (if present) and a shallow aquifer within the upper 300 to 500 feet (Middle Fork Channel Aquifer). If sufficient groundwater is encountered, the different aquifers should be pump tested separately to determine aquifer properties and water quality. Additional work required

to evaluate the groundwater resource potential of the Middle Fork Aquifer should be determined once the results of the exploratory well are analyzed.

#### South Fork Snoqualmie Aquifer

The objective of an exploratory/test well would be to evaluate the groundwater conditions in the deepest part of the South Fork Channel Aquifer. The recommended exploration site is in the vicinity of geophysical Site 2-18. The exploratory/test well should be drilled to bedrock (estimated depth of between 650 and 750 feet). The well should be designed to test both a deep aquifer overlying bedrock (if present) and a shallow aquifer within the upper 300 to 500 feet (South Fork Channel Aquifer). If sufficient groundwater is encountered, the different aquifers should be pump tested separately to determine aquifer properties and water quality. Additional work required to evaluate the groundwater resource potential of the South Fork Aquifer should be determined once the results of the exploratory well are analyzed.

### **4.2 Area 3**

The recommended exploration areas in Area 3 are as follows.

#### North Fork Snoqualmie Channel Aquifer

The objective of the exploratory/test well would be to evaluate the groundwater conditions in the deepest part of the Channel Aquifer. The recommended exploration site is in the vicinity of geophysical Site 3-13. The exploratory/test well should be drilled to bedrock (estimated depth 450 feet). If sufficient groundwater is encountered, the well should be pump tested to determine aquifer properties and water quality. Additional work required to evaluate the groundwater resource potential of the Channel Aquifer should be determined once the results of the exploratory well are analyzed.

#### North Fork Headwaters Aquifer

The objective of the exploratory/test well would be to evaluate the groundwater conditions in the area of Phillipa and Sunday Creek where the sediments appear to be the most resistive (indicative of sand and gravel). The recommended exploration site is in the vicinity of geophysical Site 3-24. The exploratory/test well should be drilled about 25 feet into the lacustrine sediments (estimated depth 200 feet). There is no evidence that a deeper aquifer exists on top of bedrock beneath the lacustrine sediments in this area based on the geophysics or USCOE boreholes. If sufficient groundwater is encountered, the well should be pump tested to determine aquifer properties and water quality. Additional work required to evaluate the groundwater resource potential of the Headwaters Aquifer should be determined once the results of the exploratory well are analyzed.

### Deep Limestone Potential Aquifer

It is at present highly speculative whether a deep limestone aquifer exists in Area 3. The most appropriate means to further evaluate its possible presence is additional geophysics using a higher-powered transmitter than that used as part of this survey. If geophysics indicates its possible presence, an exploratory/test well should be drilled and pump tested if groundwater is encountered.

### **4.3 Area 1**

Area 1 was not investigated as part of this study. However, once exploration of Areas 2 and 3 is complete, we recommend giving Area 1 consideration for future geophysical exploration because of the potential quantities of groundwater available (CH<sub>2</sub>M Hill, 1993).

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## TABLES

TABLE 3-1

ESTIMATED RECHARGE TO AREA 2 IN MGD

Source	Middle Fork	South Fork
Down Valley Groundwater Flow	1.1 to 11	0.6 to 6.0
River Losses	29	Negligible
Direct Recharge Over Permeable Sediments	23*	11*
Direct Recharge Over Less Permeable Sediments	0.7	3.5
Total	54 to 64	15 to 20.5
*Maximum value.		

SUMMARY OF POTENTIAL GROUNDWATER SUPPLY SOURCES

	Groundwater Supply Potential (MGD)	Potential for Hydraulic Continuity with Surface Water
<b>North Fork</b>		
- Headwaters Aquifer	5 - 10+	Moderate to High
- Channel Aquifer	1 - 5+	Low to Moderate
- Limestone (?)	Unknown	Low
<b>Middle/South Fork</b>		
- Middle Fork Channel	10 - 60+	Moderate to High
- South Fork Channel	5 - 20+	Moderate to High
- Deep Aquifer (?)	1 - 5(?)	Low

- Groundwater supply potential is based on evidence to date and could be more or less than indicated. Drilling is required to determine the supply potential.
- Potential for hydraulic continuity with surface water is subjective and is based on qualitative hydrogeologic and geophysical information. Drilling, pump testing and water level monitoring is required to determine hydraulic continuity.