

TABLE OF CONTENTS

FORWARD		1
EXECUTIVE SUMMARY		ES-1
ACRONYMS AND ABBREVIATIONS		VII
1. BACKGROUND		1-1
1.1 Introduction		1-1
1.2 River Augmentation Concepts		1-2
1.2.1 Aquifer Storage and Recovery Systems		1-2
1.2.2 Direct Augmentation using Groundwater		1-3
1.2.3 Indirect Groundwater Augmentation		1-3
1.2.4 Stream Augmentation Profile		1-4
1.3 Select Case Studies		1-5
1.3.1 Select Case Studies – Great Britain		1-5
1.3.1.1 West Berkshire		1-5
1.3.1.2 Shropshire		1-5
1.3.1.3 River Ouse		1-6
1.3.1.4 River Itchen		1-6
1.3.1.5 Waveney and Deben		1-6
1.3.2 Select Case Studies - United States		1-7
1.3.2.1 Washington State		1-7
1.3.2.2 Oregon		1-8
1.3.2.3 Idaho		1-8
1.3.2.4 Colorado		1-8
1.3.2.5 Florida		1-9
1.3.2.6 Pennsylvania		1-10
1.4 Hydrogeologic Factors to Consider		1-11
1.4.1 Aquifer Extent and Drainage Basin Geometry		1-11
1.4.2 Groundwater Storage		1-12
1.4.3 Groundwater Surface Water Interaction		1-13
1.4.4 Dynamic Equilibrium		1-14
1.5 Watershed Factors to Consider		1-14
1.5.1 Hydrologic Indicators		1-15
1.5.2 Ecosystem Indicators		1-16
1.5.2.1 Water Quality		1-17
1.5.2.2 Habitat Indicators		1-18
1.6 Ecosystem Models		1-19
1.6.1 Properly Functioning Condition Assessment		1-19
1.6.2 Ecosystems Diagnosis and Treatment (EDT)		1-20
1.6.3 Instream Flow Incremental Methodology		1-21

1.7	Assessing the Effects of River Augmentation using Groundwater	1-22
1.7.1	Assessing Watershed Effects	1-22
1.7.2	Assessing Groundwater Effects	1-22
1.8	Groundwater Models	1-24
1.8.1	Conceptual/Water Balance Models	1-24
1.8.2	Analytical and Numerical Models	1-24
1.8.3	Modeling Process	1-26
1.9	Summary and Conclusions	1-26
2.	INTRODUCTION	2-1
2.1	History	2-1
2.2	Approach	2-2
2.3	Data Collection Activities	2-3
2.3.1	Climate Data	2-3
2.3.2	Hydrologic Data	2-3
2.3.3	Geologic Data	2-3
2.3.4	Groundwater Data	2-3
2.4	Modeling	2-4
2.4.1	MODFLOW – Steady State	2-4
2.4.2	MODFLOW – Transient	2-4
3.	SNOQUALMIE RIVER AND AQUIFER SYSTEM	3-1
3.1	Regional Setting and Hydrostratigraphy	3-1
3.2	Stream Ecology	3-4
3.2.1	Habitat/Fisheries	3-6
3.3	River Morphology and Habitat	3-7
3.4	Precipitation	3-9
3.5	Stream Hydrology	3-9
3.5.1	North Fork Snoqualmie River	3-10
3.5.2	Middle Fork Snoqualmie River	3-10
3.5.3	South Fork Snoqualmie River	3-10
3.5.4	Hydrologic Variability	3-11
3.5.5	River-Bed Properties	3-11
3.6	Other Surface Water Bodies	3-12
3.7	Groundwater Flow	3-12
3.7.1	Hydrographs and Trends	3-13
3.7.2	Variability	3-13
3.7.3	Flow Paths	3-14
3.8	Groundwater Recharge	3-15
3.8.1	Precipitation Recharge	3-15
3.8.2	Recharge from Masonry Pool Seepage	3-16
3.9	Groundwater Pumping	3-16
3.10	Aquifer Parameters	3-16
3.10.1	Aquifer Pumping Test Results	3-17
3.10.2	Passive Aquifer Monitoring Results	3-19

3.10.2.1	Diffusivity and Storativity Estimates – Shallow Aquifer	3-19
3.10.2.2	Diffusivity and Storativity Estimates – Deep Aquifer	3-20
3.10.3	Aquifer Boundaries	3-20
3.10.3.1	Recharge Boundaries	3-20
3.10.3.2	No Flow Boundaries	3-21
3.11	Water Quality	3-21
3.11.1	Major Ions	3-21
3.11.2	Isotopes	3-22
3.11.3	Temperature	3-22
3.11.4	Modeling	3-22
3.12	Summary	3-23
4.	GROUNDWATER MODELING	4-1
4.1	Purpose	4-1
4.2	Conceptual Model	4-1
4.3	Steady-State Groundwater Model	4-2
4.3.1	Construction	4-2
4.3.2	Boundary Conditions	4-3
4.3.3	Model Calibration	4-4
4.3.4	Results	4-6
4.3.4.1	Simulated Hydraulic Heads	4-6
4.3.4.2	Hydraulic Conductivity	4-6
4.3.4.3	Water Balance	4-7
4.3.5	Sensitivity	4-8
4.4	Transient Groundwater Model	4-9
4.4.1	Construction	4-9
4.4.2	Calibration	4-10
4.4.2.1	Storage Coefficients	4-10
4.4.2.2	Recharge	4-11
4.4.2.3	Specified Flux and Head Boundaries	4-11
4.4.2.4	Other Hydraulic Boundaries	4-12
4.4.3	Calibration Results	4-13
4.4.3.1	Potentiometric Heads	4-13
4.4.3.2	River Discharge Calibration	4-13
4.4.4	Seasonal Augmentation Scenarios	4-14
4.4.5	Augmentation Scenario Results	4-15
4.4.5.1	Simulation 1	4-15
4.4.5.2	Simulation 2 – Decreased pumping rates	4-17
4.4.5.3	Simulation 3 – Late Season Augmentation	4-17
4.4.5.4	Simulations 5 and 6 – Wellfields	4-18
4.5	Overall Model Assessment	4-19
5.	SUMMARY AND CONCLUSIONS – SNOQUALMIE SYSTEM	5-1

6.	CONCLUSIONS – APPLYING STREAMFLOW ENHANCEMENT CONCEPTS IN WASHINGTON	6-1
6.1	Introduction	6-1
6.2	Applicability in Washington State’s Flow Limited Basins	6-2
6.2.1	Cedar/Sammamish Basin	6-3
6.2.2	Duwamish/Green Basin	6-4
6.2.3	Puyallup/White Basin	6-6
6.2.4	Chambers/Clover Basin	6-7
6.2.5	Walla Walla Basin	6-8
6.2.6	Yakima Basin	6-9
6.2.7	Methow Basin	6-9
7.	REFERENCES	7-1

LIST OF TABLES

Table 1-1	River Augmentation Projects in Great Britain based on Groundwater
Table 1-2	Minimum Instream Flows Set for the Jackson Hydroelectric Project under the PUD’s FERC License
Table 1-3	Summary of RVA Parameters
Table 3-1	Precipitation at Snoqualmie Falls and Grouse Ridge
Table 3-2	Snoqualmie River Water Balance
Table 3-3	USGS Streamflow Gauges
Table 3-4	Range of Variability Analysis (RVA) at Snoqualmie Falls Gauge 12144500
Table 3-5	Range of Variability Analysis (RVA) at Carnation Gauge 12149000
Table 3-6	Range of Variability Analysis (RVA) at Monroe Gauge 12150800
Table 3-7	Pump Test Results
Table 4-1	Steady State Model Construction Details
Table 4-2	Steady State Model Observed and Simulated Heads
Table 4-3	Calibrated Hydraulic Conductivity and Storage
Table 4-4	Steady State Model Hydrologic Budget
Table 4-5	Surface Water Discharge
Table 4-6	Steady State Model Outflow Flux Sources and Model Calculations
Table 4-7	Select Steady State Model Parameter Sensitivity Analysis Results
Table 4-8	Monthly Recharge from Precipitation Across the Model Domain
Table 4-9	Well TW-5 Streamflow Augmentation Scenarios
Table 4-10	Wells TW-1 and TW-2 Streamflow Augmentation Scenarios
Table 4-11	Well field Simulation Results
Table 6-1	Potential for Streamflow Enhancement in Priority Stream Reaches

LIST OF FIGURES

Figure 1-1	Aquifer Storage and Recovery
Figure 1-2	Aquifer Infiltration Configurations
Figure 1-3	Augmentation Concept – Groundwater Storage for Streamflow Enhancement
Figure 1-4	Augmentation Concept - Infiltration Return Flow
Figure 1-5	Comparison of Augmentation Operational Profiles to Streamflow Conditions
Figure 1-6	Direct Augmentation Streamflow and Groundwater Profiles
Figure 1-7	Streamflow Augmentation Projects in Britain
Figure 1-8	Shropshire Groundwater Scheme
Figure 1-9	Jackson Hydroelectric Project
Figure 1-10	Wetland Augmentation Using Groundwater in Klamath National Wildlife Refuge
Figure 1-11	Streamflow Augmentation Using Recharge Basin at Tamarack Demonstration Project
Figure 1-12	Example Simulated Water Budget for Lake Augmentation Using Groundwater
Figure 1-13	Various Scales of Groundwater Flow Systems
Figure 1-14	Groundwater Storage
Figure 1-15	Modes of Stream Aquifer Interaction
Figure 1-16	General Modeling Process
Figure 2-1	Upper Snoqualmie River Basin Overview
Figure 2-2	Important Features of the Upper Snoqualmie Basin
Figure 3-1	Surficial Geology within the Model Domain
Figure 3-2	Geologic Cross-Section
Figure 3-3	Chinook Stocks Distribution in WRIA 7
Figure 3-4	PRISM Precipitation Map of the Upper Snoqualmie Basin
Figure 3-5	Representative High, Average and Low Streamflows in the North, Middle, and South For Snoqualmie River
Figure 3-6	Flux Magnitude Along Stream Reaches within the Model Domain during August
Figure 4-1	Layer 1 – Hydraulic Conductivity Zones
Figure 4-2	Layer 2 – Hydraulic Conductivity Zones
Figure 4-3	Layer 3 – Hydraulic Conductivity Zones
Figure 4-4	Layer 4 – Hydraulic Conductivity Zones
Figure 4-5	Layer 5 – Hydraulic Conductivity Zones
Figure 4-6	Steady-State Model Water Table
Figure 4-7	Steady State Model Observed Versus Simulated Heads
Figure 4-8	Transient Model – Monthly Recharge Distribution
Figure 4-9	Annual Precipitation Input for Stream Augmentation Scenarios
Figure 4-10	Simulation 1 – Streamflow Augmentation During July through September with Groundwater Withdrawals from Well TW-5
Figure 4-11	Baseline and Simulation 1 Heads – Well TW-5

Figure 4-12	Baseline and Simulation 1 Heads – Well MW-5
Figure 4-13	Simulation 1a – Streamflow Augmentation During July through September - Groundwater Withdrawals Every Second Year
Figure 4-14	Simulation 3g – Streamflow Augmentation During September and October
Figure 4-15	Simulation 6d – Streamflow Augmentation During September and October from a Well Field with 10 Wells
Figure 6-1	Potential Streamflow Enhancement Basins using Groundwater

LIST OF APPENDICES

Appendix A	Precipitation in the Upper Snoqualmie River Basin
Appendix B	Anadromous Salmonids in Water Resource Inventory Area 7
Appendix C	Stream Hydrology, Properties, and Morphology of the Snoqualmie River and its Tributaries
Appendix D	Report on Long-Term Water-Level Measurements in East King County
Appendix E	Existing Water Rights within the Model Domain
Appendix F	Report on Tanner Road Mitigation Well (TW-5) Drilling and Testing
Appendix G	Geologic Units and Aquifer Parameters within the Model Domain
Appendix H	Passive Aquifer Monitoring in the Upper Snoqualmie River Basin
Appendix I	Water Quality: Well NB-3, Well TW-5, and the Middle Fork Snoqualmie River
Appendix J	Static Groundwater Model/ Groundwater Recharge Modeling within the Model Domain
Appendix K	Transient Groundwater Model

ACRONYMS AND ABBREVIATIONS

AF	acre-feet
AFY	acre-feet per year
ASR	Aquifer Storage and Recovery
bgs	below ground surface
BLM	United States Bureau of Land Management
CaCO ₃	Calcite
cfs	cubic feet per second
DO	dissolved oxygen
DOH	Department of Health (Washington State)
DEM	Digital Elevation Model
EDT	Ecosystems Diagnosis and Treatment
EKCRWA	East King County Regional Water Association
EPA	U.S. Environmental Protection Agency
ESA	Endangered Species Act
Fe(OH) ₃	ferrihydrite
FERC	Federal Regulatory Commission
ft/d	feet per day
ft ² /d	square feet per day
ft ² /min	square feet per minute
ft/s	feet per second
GIS	Geographic Information Systems
GMS	Groundwater Monitoring System
gpd	gallons per day
gpm	gallons per minute
gpm/ft	gallons per minute per foot
GWML	global meteoric water line
HPA	Hydraulic Project Approval
IFA	Instream Flow Agreement
IFC	Instream Flow Commission
IFIM	Instream Flow Incremental Methodology
IFN	instream flow needs
ISF	instream flow

in/year	inches per year
K_h	horizontal hydraulic conductivity
$K_h:K_v$	anisotropy ratio
K_v	hydraulic conductivity
LGS	Limerick Generating Station
LiDAR	Light Detection and Ranging
LWD	large woody debris
m^3/day	cubic meters per day
Mgal	million gallons
mgd	million gallons per day
MISF	minimum instream flow
MnOOH	manganite
msl	mean sea level
NRC	National Research Council
NTU	nephelometric turbidity unit
PFC	Properly Functioning Condition
PRISM	Parameter-elevation Regressions on Independent Slopes Model
PSTC	Potential Sediment Transport Coefficient
PUD	Public Utilities District (Snohomish County)
pvc	polyvinyl chloride
Q_a	annual quantity
Q_i	instantaneous quantity
RM	river mile
RVA	Range of Variability Analysis
SDF	Stream Depletion Factor
SMOW	Standard Mean Ocean Water
s.u.	Standard units
t_l	time lag
TMDL	total maximum daily load
T/S	aquifer diffusivity
UK	United Kingdom
USBOR	United States Bureau of Reclamation
$\mu S/cm$	micro Siemens per centimeter
USDI BLM	U.S. Department of the Interior Bureau of Land Management
USGS	United States Geological Survey

WAC	Washington Administrative Code
WAGS	Waveney Augmentation from Groundwater Scheme
WDFW	Washington Department of Fish and Wildlife
WDOE	Washington State Department of Ecology
WRIA	Water Resource Inventory Area
WRTS	Water Rights Tracking System (Washington State)
Ybp	years before present
