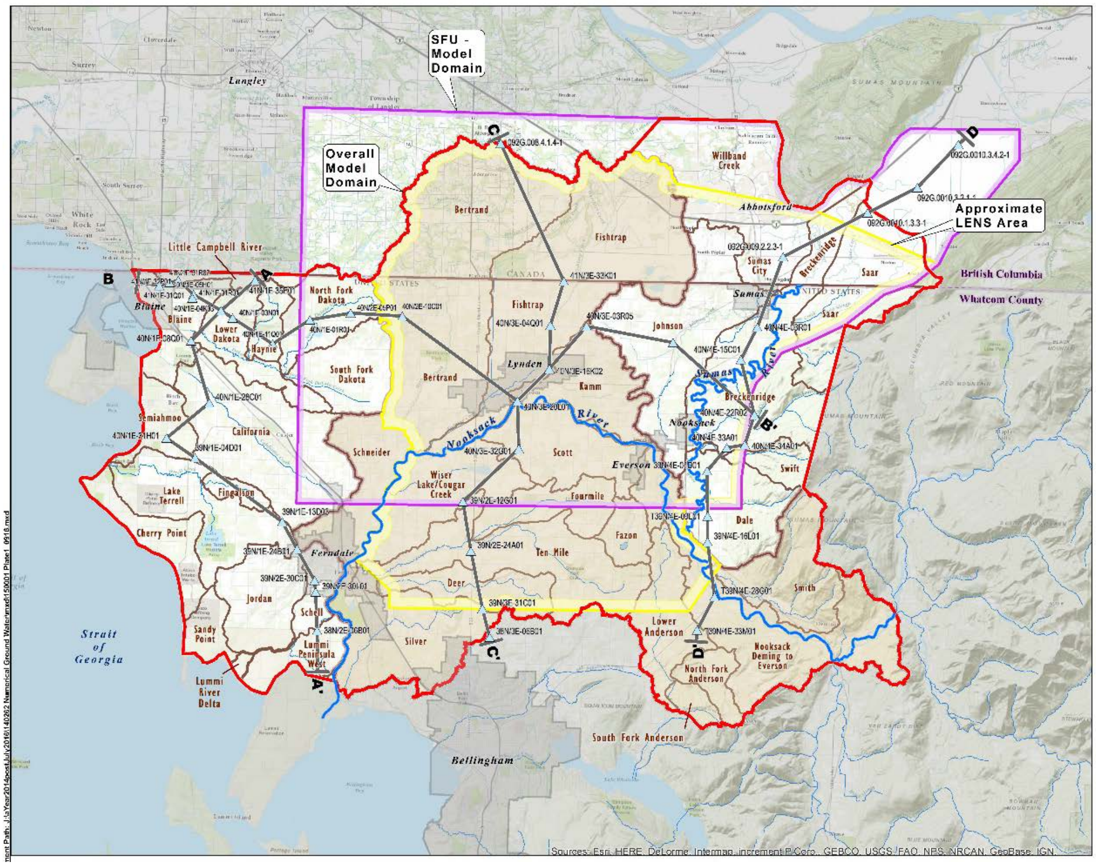
QUALITY ASSURANCE PROJECT PLAN

Numerical Groundwater Model of the LENS Area
Whatcom County, Washington

November 2017



Prepared by:

Associated Earth Sciences, Inc.
S.S. Papadopulos & Associates, Inc.

Prepared for:

Whatcom County Flood Control Zone District

Publication Information

This Quality Assurance Project Plan (QAPP) has been prepared to support the development of a numerical groundwater model of the Lynden/Everson/Nooksack/Sumas (LENS) area of Whatcom County. The QAPP describes the objectives of the study and the procedures to be followed to achieve those objectives. The numerical groundwater modeling project is partially funded by the U.S. Environmental Protection Agency (US EPA) National Estuary Program (US EPA, NEP; Award No. PC-01J22301) through the Washington State Department of Fish and Wildlife (WDFW; Contract No 17-08284).

This QAPP has been prepared in general accordance with the US EPA's *Guidance for Quality Assurance Project Plans* (EPA QA/G-5M, December 2002) and Ecology's *Template for Quality Assurance Project Plans*. The QAPP is available on request from the authors, Whatcom County or Ecology's Bellingham Field Office, as will be the final modelling data and report.

The contents of this document do not necessarily reflect the views and policies of the Environmental Protection Agency, nor does mention of trade names or commercial products constitute endorsement or recommendation for use.

Authors and Contact Information

Charles S. Lindsay, L.G., L.E.G., L.Hg.
Senior Principal Geologist/Hydrogeologist
Associated Earth Sciences, Inc.
2911 ½ Hewitt Avenue, Suite 2
Everett, Washington 98201
425-285-2883

Christopher J. Neville, M.Sc., P.Eng.
Senior Hydrogeologist (Associate)
S.S. Papadopulos & Associates, Inc.
90 Frobisher Drive, Unit 2B
Waterloo, Ontario N2V 2A1
519-579-2100

A. PROJECT MANAGEMENT

A1. Title and Approval Sheet

QUALITY ASSURANCE PROJECT PLAN

Numerical Groundwater Model of the LENS Area
Whatcom County, Washington

November 17, 2017 Final
November 14, 2017 Second Draft
September 21, 2017 Draft

Approved by:

Signature: Date: 11/22/17
Charles S. Lindsay, L.G., L.E.G., L.Hg, Senior Principal Hydrogeologist
Associated Earth Sciences, Inc.

Signature: Date: 11/22/17
Christopher J. Neville, M.Sc., P.Eng., Associate Hydrogeologist
S.S. Papadopulos & Associates, Inc.

Signature: Date: 11/27/17
Gary Stoyka, Natural Resources Manager
Whatcom County

Signature: Tom Culhane Date: 11/22/17
Tom Culhane, Hydrogeologist
Washington State Department of Ecology

Signature: for BILL KAMMIN Date: 11-22-17
Bill Kammin, Quality Assurance Officer
Washington State Department of Ecology

A2. Table of Contents

Page

A3. Distribution List

Copies of this document will be distributed to the following individuals. Additional copies can be distributed to other agencies and individuals upon request (including other state and federal agencies, consultants, universities, etc.).

Gary Stoyka
Natural Resources Manager
Whatcom County Public Works Department
322 North Commercial Street, Suite 110
Bellingham, WA 98225
360-778-6218
gstoyka@co.whatcom.wa.us

Steve Jilk
General Manager
Public Utility District No. 1 of Whatcom County
1705 Trigg Road
Ferndale, WA 98248
360-384-4288, Ext. 12
stevej@pudwhatcom.org

Kasey Cykler
Water Master
Washington State Department of Ecology
1440 10th Street, Suite 102
Bellingham, WA 98225
360-715-5222
kasey.cykler@ecy.wa.gov

Thomas H. Gries
NEP QA Coordinator
Washington State Department of Ecology
P.O. Box 47600
Olympia, WA 98504-7600
360-407-6327
tom.gries@ecy.wa.gov

Tom Culhane
Hydrogeologist
Washington State Department of Ecology
P.O. Box 47600
Olympia, WA 98504-7600
360-407-7679
tom.culhane@ecy.wa.gov

Charles S. Lindsay
Senior Principal Hydrogeologist
Associated Earth Sciences, Inc.
2911 ½ Hewitt, Suite 2
Everett, WA 98201
425-285-2883
clindsay@aesgeo.com

Christopher J. Neville
Senior Hydrogeologist (Associate)
S.S. Papadopulos & Associates, Inc.
90 Frobisher Drive, Unit 2B
Waterloo, Ontario N2V 2A1
519-579-2100
cneville@sspa.com

Gilbert Barth
Senior Hydrogeologist
S.S. Papadopulos & Associates, Inc.
3100 Arapahoe Avenue, Suite 203
Boulder, CO 80303-1050
303-939-8880, Ext. 106
gbarth@sspa.com

Christina Bandaragoda
Senior Research Scientist
University of Washington
P.O. Box 359472
Seattle, WA 98195
425-501-4191
cband@uw.edu

A4. Problem Definition, Background, and Goals

The central part of Element A of the QAPP is the Problem Definition/Background. This is an overview of the work to be performed, products to be produced, and the schedule for implementation. The problem definition, background, and goals for the groundwater modeling project are presented here. The discussion is consistent with the Consultant Scope of Services that the Project Team has submitted previously, *Consultant Scope of Services for the Development of a Numerical Groundwater Model of the Lynden/Everson/Nooksack/Sumas (LENS) Area of Whatcom County* (Associated Earth Sciences Inc., 2016) and information presented in *Final Draft Technical Report, Phase 2 – Data Collection and Conceptual Model Development, Whatcom County* (Associated Earth Sciences, Inc. 2016.)

Increased population growth in Whatcom County (County) over the past several decades has led to an increase in the demand for surface and groundwater resources to meet the growing domestic, industrial, commercial, and agricultural needs of the County. This increase in demand for water use, along with other social/political changes, has led to a heightened level of concern regarding surface/groundwater interactions and the resulting effect on streamflows, which are necessary to sustain critical habitat for salmonid and other threatened aquatic species. To address this and other concerns, the WRIA 1 Watershed Management Plan – Phase 1 (Management Plan or Plan) was developed through the cooperative efforts of stakeholders including state, tribal, and local governments. The overall goal of the Plan is "to ensure sufficient quantity and quality of water to meet the needs of current and future human generations, including the restoration of salmonid populations to healthy and harvestable levels and the improvement of habitats on which fish rely."

The Management Plan outlined a suite of actions aimed at addressing the most important and pressing needs of WRIA 1 communities. The Lower Nooksack Strategy, approved by the WRIA 1 Watershed Management Project Joint Board (Joint Board; comprised of Whatcom County, Public Utility District No. 1 of Whatcom County, City of Bellingham, Lummi Nation, and the Nooksack Indian Tribe) in late 2010, presented several action items necessary to meet the Plan goals identified for the Lower Nooksack Subbasin (LNS). The action items included the development of an updated water budget for the area that would provide a platform from which prior technical work completed earlier in the decade could utilize more contemporary data and analysis tools, and be made available in a more accessible and useable format. Furthermore, it has long been recognized by the Joint Board and others that a groundwater model of portions of the LNS should be developed to gain a better understanding of the hydrogeology and ground/surface water interaction potential in the region.

In the summer of 2014, the Joint Board in cooperation with the Bertrand Watershed Improvement District (Bertrand WID) and the Washington State Department of Ecology (Ecology) began a project designed to characterize the groundwater flow system in the LNS.

The project was proposed to be completed in the following four phases:

Phase 1 – Project Definition and Scoping
Phase 2 – Data Collection and Conceptual Model Development
Phase 3 – Conceptual Model Analyses and Documentation
Phase 4 – Numerical Model Development

The project definition and scoping portion of the project (Phase 1) was completed in the fall of 2014. Phase 2 and 3 activities were completed in the fall of 2016. The results of the Phase 2 activities are presented in the AESI *Phase 2 – Data Collection and Conceptual Model Report,* dated September 30, 2015. During Phase 2, a detailed conceptual groundwater flow model of the area in and around the LNS was developed and the data important for the development of a numerical groundwater flow model (Phase 4) were organized into GIS linked databases. The Phase 2 activities also included the development of a groundwater data collection network for the acquisition of long-term groundwater level information was established. The protocols established for the on-going groundwater data collection activities are described in *Quality Assurance Project Plan, Task 2.5 – Groundwater Conceptual Model Project, Whatcom County, Washington,* prepared for the Whatcom County Public Works Department and the Bertrand Watershed Improvement District, signed and authorized on May 11, 2016.

The key findings of the Phase 2 study indicated that sufficient geologic, hydrogeologic, and water use information was available to develop a numerical groundwater model of the LNS area. The Phase 2 study also indicated that the overall resolution of the groundwater model would likely be limited in certain areas of the model domain due to a sparsity of existing data. Consequently, it is anticipated that the reliability of the numerical model to predict impacts to groundwater resources will be better for large-scale changes rather than for small-scale changes.

The results of the Phase 3 activities are presented in the University of Washington *Phase 3 Conceptual Model Analysis and Documentation: Update of Lower Nooksack River Topnet-WM Surface Water Model for Bertrand Creek* report dated September 30, 2016. Phase 3 activities included refining a previously completed surface water quantity hydrologic model (TOPNET-WM) for the LNS to develop a more detailed surface water model of the Bertrand Creek drainage of the proposed groundwater model domain. The completion of Phase 3 resulted in an increased spatial discretization of surface water modeling elements in the Bertrand Creek drainage from a single spatially averaged drainage model to 46 topographically delineated model subbasins. This resulted in an improved representation of the spatial variability of precipitation, water use, land use/soil parameters, and groundwater recharge in the Bertrand Creek drainage.

The Phase 4 activities were authorized in June 2017 and are scheduled for completion in December 2018. The primary goal of Phase 4, which is the subject of this QAPP, is to integrate the results of Phases 2 and 3 into a numerical groundwater flow model for the LENS area of Whatcom County that ultimately can be used to estimate potential temporal and spatial impacts to surface water resources from activities such as general (large-scale) changes in land use and groundwater withdrawals. It is anticipated that Whatcom County decision makers will utilize the numerical groundwater flow model to evaluate potential water resource use/impact options in support of their decision-making process with regard to land use and water resource planning, and potential impacts to instream flow and other water rights regulations.

The numerical model domain lies within what is referred to as the Fraser-Whatcom Lowland, which is a transborder region of the United States and Canada (Cox and Kahle, 1999). The conceptual groundwater model domain covers a total of approximately 426 square miles (mi^2) of the Fraser-Whatcom Lowland with roughly 346 mi^2 in western Whatcom County, Washington and roughly 80 mi^2 in southern British Columbia, Canada (Figure 1). The model domain is generally bounded on the west by the Strait of Georgia and extends eastward to Sumas Mountain, southward to near Lake Whatcom, and northward to near the City of Abbotsford. The approximate location of the conceptual model domain relative to surrounding physiographic features is presented on the "Model Domain Location" map, Figure 1. A more detailed map of the model domain, including primary physiographic features, is presented on Plate 1 of the AESI (2016) Phase 2 report.

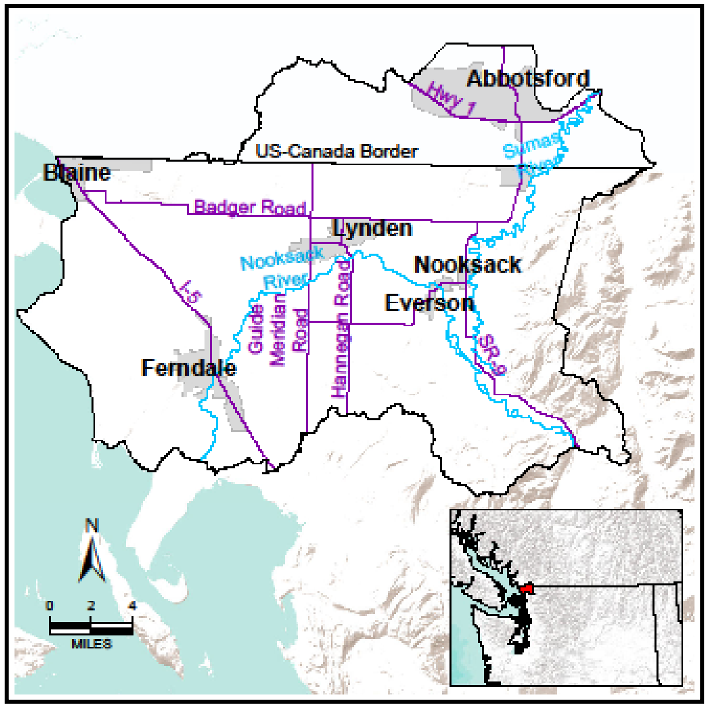


Figure 1. Model Domain Location Map

The primary sources of data for the Phase 4 activities are presented in the previously referenced Phase 2 and 3 reports. The Phase 2 and 3 reports summarize information and data that were used to characterize the conceptual hydrogeologic framework of the model domain and vicinity; groundwater recharge and discharge; groundwater elevations and flow directions; seasonal groundwater fluctuations; and surface-groundwater interaction potential. Where possible, the anticipated primary input parameters for the Phase 4 numerical model were organized into GIS-linked databases that were structured in a manner to facilitate data input into the numerical model.

The numerical modeling platform to be used in Phase 4 is the widely used MODFLOW platform. MODFLOW is the United States Geological Survey's (USGS) modular groundwater flow simulator and is considered an international standard for simulating and predicting groundwater conditions and groundwater-surface water interactions. MODFLOW was chosen for this project because it is capable of representing the key groundwater processes in the study area, is widely used, has an open source code, continues to be actively supported and extended by the USGS and is supported by accessible graphical user interfaces.

The results from the MODFLOW simulations will be used to refine critical input to the surface water model (Topnet-WM). Topnet is a semi-distributed hydrological model used to simulate catchment water balance and river flow. Topnet-WM is a version of Topnet that includes a water management model developed by Utah State University. Topnet-WM was chosen as the surface water modeling platform for this project because its capabilities are compatible with the Phase 4 project goals and because it is the surface water model that was previously used by Whatcom County to define detailed water balance characteristics of the LNS. Additional information regarding the Topnet model can be found at https://teamwork.niwa.co.nz/display/IFM/Topnet.

One of the primary outputs of the Topnet-WM surface water model is an estimate of groundwater recharge. The values and distribution of groundwater recharge are vital input parameters for the numerical groundwater model. The Topnet-WM groundwater recharge information will be specified as input for the initial version of the MODFLOW model. The MODFLOW model in turn will be used to calculate the depth to the regional groundwater table across the model domain. The depth to groundwater is an important input parameter to the Topnet-WM model. This loose-coupling of the two models will be instructive regarding the consistency of simulated water budgets and will improve the overall reliability of both models.

A5. Project/Task Organization

A5.1 Key Personnel and Responsibilities

Key project roles are filled by those persons responsible for (1) project oversight/management; (2) hydrologic and hydrogeologic analyses in support of model development; (3) surface and groundwater model development and interaction; and (4) approving and accepting final products and deliverables. An organization chart for the numerical modeling project is presented in Figure 2, which includes relationships and lines of communication among key personnel. A summary of the roles/responsibilities of key personnel involved in the Numerical Groundwater Model for the LENS area of Whatcom County is presented on Table 1.

Table 1. Summary of Key Personnel and Responsibilities

Key Personnel	Project Title	Responsibilities
Gary Stoyka Whatcom County Public Works Phone: 360-778-6218	Client Project Lead	Manages and clarifies scope/budget of the project. Provides internal review of the QAPP and approves the final QAPP.
Tom Culhane WA State Dept. of Ecology Phone: 360-407-7679	Ecology QAPP Reviewer	Provides external review of the QAPP and approves the final QAPP.
Thomas Gries WA State Dept. of Ecology Phone: 360-407-6327	NEP Quality Coordinator	Reviews and comments on draft QAPP. Recommends approval of final draft QAPP. May conduct project audits and comment on final project report.
Bill Kammin WA State Dept. of Ecology Phone: 360-407-6964	Ecology QA Officer	Reviews draft and approves final QAPP.
Charles Lindsay Associated Earth Sciences, Inc. Phone: 425-285-2883	Project Principal Investigator	Overall project management and technical review. Prepares draft and final QAPP.
Christopher Neville S.S. Papadopulos & Associates Phone: 519-579-2100	Groundwater Modeling Principal Investigator	Groundwater model preparation and QA/QC. Prepares draft and final QAPP. Explains modeling results.
Gilbert Barth S.S. Papadopulos & Associates Phone: 720-572-4670	Groundwater Modeler	Model creation, data preparation, implementation of model simulation, and analysis of groundwater flow.
Christina Bandaragoda University of Washington Phone: 425-501-4191	Surface Water Modeler	Model creation, data preparation, implementation of model simulation, and analysis of surface water flow.
Katherine Beeler Associated Earth Sciences, Inc. Phone: 425-827-7701	Staff Geologist	Data organization, transfer and reporting.

A5.2 Special Training Requirements and Certifications

Charles S. Lindsay, L.G., L.E.G., L.Hg
Senior Principal Hydrogeologist - Associated Earth Sciences, Inc.
Project Principal Investigator

Chuck Lindsay has provided geologic/hydrogeologic services in the western United States since 1983. He is a licensed geologist, hydrogeologist, and engineering geologist in the State of Washington. Chuck has been evaluating the geology and hydrogeology of western Whatcom County since completing his Master of Science thesis on the water budget and hydrogeology of the Fishtrap Creek drainage in 1989. Since that time, he has successfully completed dozens of detailed geologic/hydrogeologic evaluations for projects located in the proposed project area. He is a recognized expert on the geology and hydrogeology of western Whatcom County.

Christopher Neville, M.Sc., P.Eng
Senior Hydrogeologist (Associate) – S.S. Papadopulos and Associates, Inc.
Groundwater Modeling Principal Investigator

Christopher Neville has over 25 years of experience, with particular emphasis on quantitative analysis of groundwater flow and solute transport. He has synthesized hydrogeologic data, evaluated and designed protection programs for groundwater resources, developed regional groundwater flow models, and analyzed and designed remedial measures. Chris has developed and documented large-scale three-dimensional numerical models for industrial, mining, and government clients, and has reviewed numerous site-specific hydrogeologic analyses and groundwater modeling codes. Chris is an expert with the MODFLOW family of groundwater flow simulators.

Gilbert Barth, PhD
Senior Hydrogeologist – S.S. Papadopulos and Associates, Inc.
Groundwater Modeler

Dr. Gilbert Barth has over 15 years of experience as a hydrogeologist with specialization in hydrologic investigations assessing subsurface flows and the exchange between surface and groundwater. Dr. Barth has developed numerous regional models to evaluate surface/groundwater interaction and specializes in the application of sensitivity and prediction uncertainty methods to improve calibration, and to help understand the limitations of the numerical methods used. He is an expert with the MODFLOW family of codes and with the computer-assisted calibration tools UCODE and PEST. His expertise also includes a wide range of field, laboratory, analytical, and numerical techniques that he uses to develop conceptual models of flow, to evaluate surface/groundwater interaction, and to identify contaminant risks.

Christina Bandaragoda, PhD
Senior Research Assistant – University of Washington
Surface Water Modeling Principal Investigator

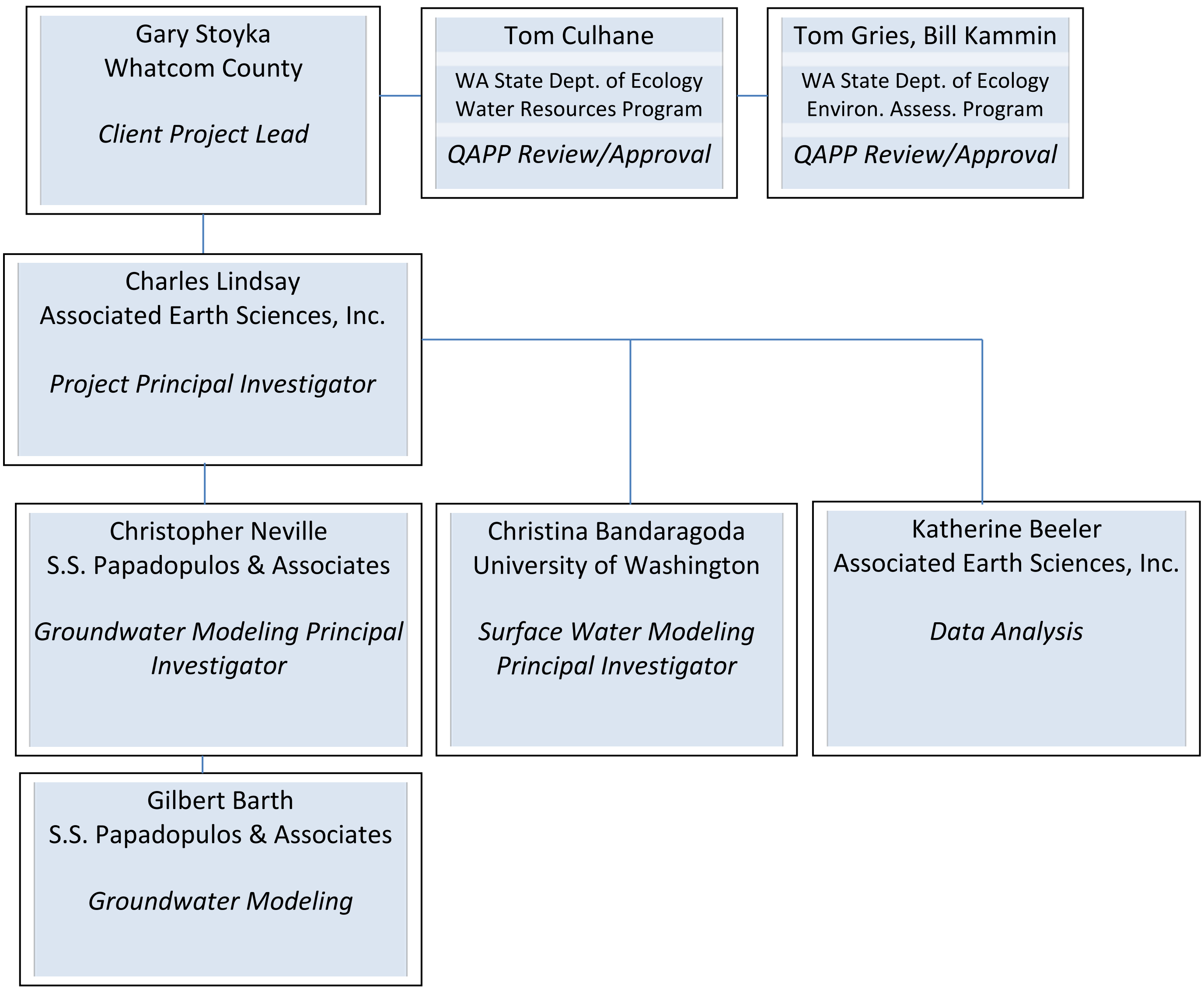
Dr. Christina Bandaragoda is an expert in numerical hydrologic modeling, including participatory and collaborative watershed modeling, instream temperature modeling, glacier modeling, with expertise in spatially distributed model development and calibration with over 30 publications on these topics. Along with other members of the Project Team, Christina led the development of the WRIA 1 Water Budget (2012), WRIA 1 Groundwater Data Assessment (2013), and the Data integration of Water Resource Inventory Area 1 Hydraulic, Fish Habitat, and Hydrology Models (2013; updating in progress for 2014) – all of these projects required expert knowledge of the WRIA 1 rainfall runoff model Topnet, and WRIA 1 data resources.

Katherine J. Beeler, L.G.
Senior Staff Geologist - Associated Earth Sciences, Inc.
Staff Geologist

Katherine Beeler has expertise regarding the compilation and analyses of data for water rights analyses, surface water and groundwater characterizations, and a conceptual groundwater model of northwest Whatcom County and southwest British Columbia.

A5.3 Organization Chart

Figure 2. Organization Chart



A6. Project/Task Description and Schedule

A6.1 Task Description

The contract tasks that will be completed for the Phase 4 - Numerical Groundwater Model of the LENS Area project will include the following:

TASK 1 – QUALITY ASSURANCE PROJECT PLAN: A Quality Assurance Project Plan (QAPP) will be developed prior to the start of the development of the numerical model. The QAPP will be developed to build confidence in the model that is developed, by ensuring that the model is scientifically sound, robust, and defensible. The QAPP will be prepared in general accordance with the US EPA's *Guidance for Quality Assurance Project Plans* (EPA QA/G-5M, December 2002) and Ecology's *Template for Quality Assurance Project Plans*.

TASK 2 – SURFACE WATER - GROUNDWATER MODEL EXCHANGES: One of the primary outputs of the existing Topnet-WM surface water model is an estimate of groundwater recharge. The values and distribution of groundwater recharge is a vital input parameter for the MODFLOW numerical groundwater model. The Topnet-WM groundwater recharge information will be specified as input for the initial version of the MODFLOW model. The MODFLOW model in turn will be used to calculate the depth to the regional groundwater table across the model domain. The depth to groundwater is an important input parameter to the Topnet-WM model and the results from the initial MODFLOW model will be used to refine the input to the Topnet-WM model. A comparison of the original and refined inputs/outputs will be instructive regarding the consistency of simulated water budgets.

TASK 3 – DEVELOPMENT AND CALIBRATION OF THE MODFLOW MODEL: The groundwater model will be constructed based primarily on the data/information developed in Phase 2 and 3 of this project. The MODFLOW model will be calibrated under steady-state conditions to match both "hard" and "soft" targets. The steady-state model calibration hard targets will include average groundwater levels estimated from dedicated observation wells and production wells, and estimates of groundwater discharge to surface water features inferred from changes in any available baseflow estimates between gaging stations. The soft targets will include regional, long-term average interpretations of groundwater flow patterns and any one-time (spot) measurements of water levels in private wells and stream flows. During the calibration, the hydraulic conductivities assigned for different hydrostratigraphic units and areas of the model will be adjusted systematically and within realistic bounds to match the calibration targets. The calibration will focus on selected areas of the model. As the analyses evolve, they may be extended to examine seasonal variations in groundwater flow conditions and streamflows.

The MODFLOW model will incorporate the stream network in the study area. Preliminary analyses may be conducted with a simplified approach based on the MODFLOW River Package. Based on the availability of data, later versions of the MODFLOW model will incorporate streamflow routing using the MODFLOW SFR Package.

TASK 4 – CONCEPTUAL AND NUMERICAL MODEL TECHNICAL REPORTS: The conceptual model report completed under Phases 2 and 3 of this project will be revised as appropriate based on feedback from the MODFLOW model regarding model parameters. The revised conceptual model report will be first issued as a draft for review by the WRIA 1 Watershed Management Board (the successor to the Joint Board with membership expanded to include all cities in Whatcom County and the Washington State Department of Fish & Wildlife). This task also includes providing technical support to the groundwater modelers on an as-needed basis within the limitations of the scope and budget. A detailed formal report will be prepared documenting the calibration process and model "goodness of fit", the contents of the calibrated groundwater model and the results. The report will include maps that will facilitate application of the scientific results by local water resource managers. The report will also include a discussion regarding limitations associated with the use of the numerical model within the model domain. The final technical report will be first issued as a draft for review by the WRIA 1 Board.

TASK 5 – PROJECT MEETINGS AND TEAM INTERACTIONS: The Project Principal Investigator (Charles Lindsay) will communicate weekly with Client Project Lead (Gary Stoyka) via phone and/or email regarding project status and progress. In addition, selected members of the Consultant Team will participate in the following meetings during the completion of the project.

<u>Preliminary Numerical Model Meeting:</u> We will meet with the Client Project Lead and others identified by the Client Project Lead after steady-state calibration is completed. The purpose of the meeting will be to present the numerical modelling design and discuss project progress.

<u>WRIA 1 Watershed Management Board Numerical Model Meeting:</u> We will prepare briefing sheets and presentation slides for the Client Project Lead to present to the WRIA 1 Watershed Management Board within three months after the completion of the draft conceptual and numerical model reports. The Consultant Team will participate in the meeting with the WRIA 1 Watershed Management Board to support the Client Project Lead in answering questions as needed. The purpose of the meeting will be to brief the WRIA 1 Watershed Management Board on the development of the conceptual and numerical models, their functions and constraints/limitations, and respond to questions/comments regarding the draft technical reports.

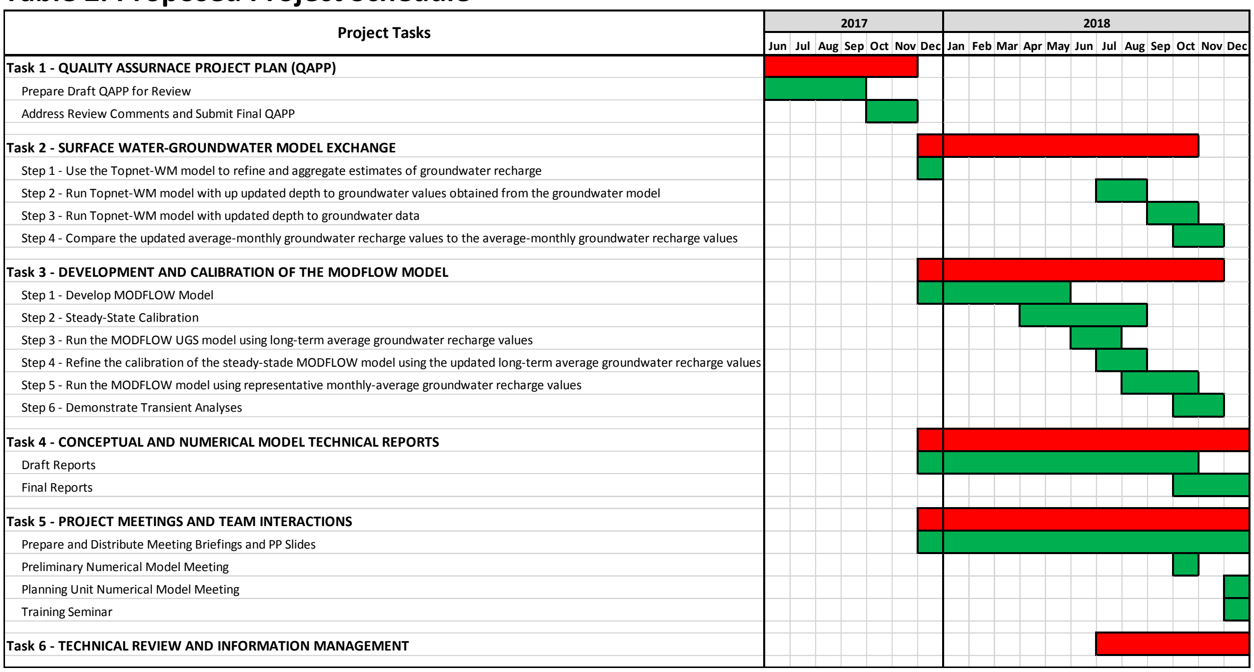
<u>Training Seminar:</u> The Consultant Team will complete a training seminar regarding the use of the numerical model for an audience selected by the Client Project Lead.

TASK 6 – TECHNICAL REVIEW AND INFORMATION MANAGEMENT: Draft conceptual and numerical model report outreach for technical review and local knowledge input will be conducted by the Client Project Lead using briefing materials and comment compilation tools provided by the Consultant Team and with assistance provided by the Consultant Team. The technical review representatives will be selected by the Client Project Lead. Review instructions will be prepared by the Consultant Team and provided to the Client Project Lead for distribution to appropriate parties.

A6.2 Project Schedule

A detailed breakdown of the timing associated with the various tasks of this project is presented in Table 2. Some aspects of this project including, project management, data organization/transmission, and preparation of this QAPP have been conducted to date. However, the specific activities for this project that are described in this QAPP will not commence until the QAPP has been approved. Assuming that the QAPP is approved in November 2017, it is anticipated that Phase 4 will be completed in December 2018.

Table 2. Proposed Project Schedule



A6.3 Budget and Funding

This project is funded through a contract with the Whatcom County Flood Control Zone District (Contract No. 201705028) and has a total budget of $336,526.

A7. Quality Objectives and Criteria for Model Inputs/Outputs

This element of the QAPP for modeling usually introduces the quality criteria that the expected outcomes of the modeling effort need to achieve to meet the user's needs. These criteria are typically specified within performance and/or acceptance criteria that are developed in a systematic planning process. This is usually an iterative process involving at least the modelers and users of model results.

It is understood that the decision makers (users) will utilize the Phase 4 model to evaluate potential water resource use/impact options in support of their decision-making process with regard to land use and water resource planning. It logically follows that the model output is only one part of the decision making process. It is impossible to set specific model performance/acceptance standards prior to development of the model where specific regulatory-based modeling scenarios have not been identified or described in detail, and when ultimately the regulatory decisions will be based only partially on model output. Consequently, specific performance and/or acceptance criteria were not established for Phase 4 of this project.

By its inherent nature involving the deliberate simplification of complex natural system, the development of a groundwater model always involves tradeoffs between resolution (e.g., temporal, spatial) and processing capability (e.g., model size, run time). The appropriate balance of resolution and processing capability is found iteratively for each modeling effort and is only identified after the process has advanced. Similarly, model performance/acceptance criteria are difficult to establish in advance due to the variable quality and sparseness of data to support modeling input parameters. Rather, sensitivity studies and uncertainty analyses are typically used to interpret model predictions considering the limitations of available data used to develop the model. For example, the uncertainty of model results may be assessed by sensitivity studies in which input data will be varied through ranges consistent with the uncertainty of the input data.

For the numerical model of the LENS Area, Whatcom County, model results will include the predicted spatial distributions of groundwater levels and groundwater discharge to surface water features. The general performance/acceptance criterion for these predictions will be their consistency with the input data. The performance/acceptance criteria will reflect the availability of high-quality data from historical and ongoing data collection efforts, and independent estimates of baseflows in key streams. The uncertainty of the predicted values will be assessed by sensitivity studies in which input data will be varied through ranges consistent with the uncertainty of the input data. Specific criteria that will be applied to assess the consistency of model results with observations are discussed in Section B7.

The model will be designed and constructed in a manner that provides the greatest level of reliability based on the available data. The reliability/performance of the model throughout the model domain will be assessed once the model is completed. Ultimately it will be up to the decision makers and the regulatory community to determine if the model performance/acceptability is adequate to support specific regulatory decisions.

A8. Special Training Requirements/Certification

See Section A5.2.

A9. Documentation and Records

To ensure that all personnel identified in the project have the current version of the QAPP, email will be used to distribute electronic copies of the QAPP and to record acknowledgment of receipt.

Files and documents

The following files and documents will be stored electronically on computers assigned to the analysts:

1) Model files created during development of the model, including site geographic and geological map files;
2) Gridded surfaces, corresponding to the interpolation of the geographic and geological map files onto the model grid;
3) Data quality assessment results (if not found in a previous document);
4) Final MODFLOW input and output files used to generate results;
5) Records documenting planning and milestone communication between project team members; and
6) Records documenting in-house review of draft and final reports.

All documentation shall provide enough detail to allow for reconstruction of the project activities.

A detailed formal report will be prepared documenting the calibration process and model “goodness of fit”, the contents of the calibrated groundwater model and the results obtained with it. The report will include maps that will facilitate application of the scientific results by local water resource managers. The report will also include a discussion regarding the variability of limitations to the accuracy of the numerical model within the model domain. The final technical report will be first issued as a draft for review by the WRIA 1 Watershed Management Board. The draft and final project reports will contain the following elements.

1. Background and description of the scope of the analyses;
2. Summary of the elements of the Conceptual Site Model, with appropriate references to the Conceptual Model Report;
3. Mapping of the stratigraphic model onto the layer structure of the numerical model;
4. Descriptions of the data quality and data used to constrain the development of the groundwater model;
5. Documentation of the components of the water budget for the groundwater system: hydraulic sources and sinks;

6. Calibration procedures for the groundwater flow model;
7. Assessment of the match of the calibrated model to observations and consistency between the model parameter values inferred through calibration and parameter values inferred from independent interpretations, for example, transmissivities and hydraulic conductivities inferred from the interpretation of pumping test data (pumping rates and changes in groundwater levels that are attributed solely to pumping);
8. Model testing. The final report will include a discussion of why the calibrated groundwater model is considered fit-for-purpose; that is, the model can be applied with a reasonable degree of confidence for predictive analyses in areas where reliable groundwater level and streamflow data are abundant, and where the predictive uncertainty may be relatively large (areas where data are limited);
9. Applications of the calibrated model for predictive scenarios;
10. Conclusions and recommendations, including any limitations on model usability; and
11. References.

Document control and distribution procedures

Work will be done on personal computers and backed up automatically on remote servers. Copies will be maintained of all work documents, including script codes, input files, and output files necessary for a qualified individual to reproduce the work.

Description of the change control process: Any change to this QAPP will be approved by the Client Project Lead, Ecology QAPP Reviewer, Ecology QA Officer, and NEP Quality Control, as described in Table 1. The revised QAPP will be distributed to all participants of this project.

All records will be delivered in electronic format at the end of the project, and will be archived for a period of at least five years. The record package will include a directory to facilitate location of particular records.

B. MEASUREMENT AND DATA ACQUISITION

The Group B elements focus on the quality procedures that are implemented when acquiring, generating, and handling data to develop the numerical groundwater flow model. Data and interpretations for the model have been assembled during the development of the LENS conceptual model and are described in the previously referenced Phase 2 and 3 technical reports. No new data collection is anticipated. If new data is collected during the development of the numerical groundwater model, it will be collected and analyzed in accordance with procedures outlined in a separate QAPP, an Addendum to this QAPP, or a detailed work plan, whichever is deemed appropriate. It is assumed that the QAPP/work plan developed for the additional data collection activities will be compatible with the procedures utilized for data collection activities completed for Phase 2 and 3 of this project. Therefore, Section B of the QAPP is customized to reflect that the groundwater model is being developed to synthesize the data assembled in the Groundwater Conceptual Model Report (Associated Earth Sciences, Inc., September 2016).

For completeness, the outline for the Group B element presented in the U.S. Environmental Protection Agency (EPA) guidance document is retained. The EPA guidance suggests that elements not represented within the QA Project Plan for modeling projects be labeled as "not relevant".

B1. Sampling Process (Experimental) Design

This section is not relevant to this project. A separate QAPP, an Addendum to this QAPP, or a detailed work plan will be prepared to describe collecting new data to fill known gaps and improve model outputs.

B2. Sampling Methods

This project includes no sampling. This section is not relevant.

B3. Sample Handling and Custody

This project includes no sampling. This section is not relevant.

B4. Analytical Methods

This project includes no analysis of samples. This section is not relevant.

B5. Quality Control

This project includes no direct measurement or data acquisition. Therefore, this section is not relevant.

B6. Instrument/Equipment Testing, Inspection, and Maintenance

This section is not relevant to this project.

B7. Model Calibration

According to the US EPA guidance document, general QA Project Plan guidance indicates that Element B7 (Calibration) for data collection addresses calibration of the analytical instruments that will be utilized to generate analytical data. This is not relevant for the current study. However, calibration is an essential component of groundwater modeling. For modeling projects, by analogy the "instrument" is the predictive tool (the model) that is to be developed and/or applied. All models, by definition, are a deliberate simplification of the complex natural processes and setting they are intended to represent. To match observations, it is necessary to infer representative values of model parameters, a process referred to as model calibration.

Appropriate calibration involves varying model parameters, for example hydraulic conductivity, within physically realistic bounds that are consistent with the geological descriptions of the materials.

US EPA (2002) states "Similar to an analytical instrument, models are calibrated by comparing the predictions (output) for a given set of assumed conditions to observed data for the same conditions. This comparison allows the modeler to evaluate whether the model and its parameters reasonably represent the …" regional and local groundwater flow conditions. The need for model calibration and the approach that will be adopted for Phase 4 are discussed in the following sections.

In an ideal world, a groundwater simulation would replicate exactly the groundwater system with model parameters specified completely from independent evaluations. In such a world, we would not require a discussion of the adjustment of model parameters or an evaluation of the match between observations and model calculations. In reality, the natural groundwater system is dynamic and can never be characterized completely. The measurements we make can never be truly representative. Water levels in wells may change rapidly, and errors may arise in their measurement. Furthermore, a well is an imperfect instrument for determining water levels in the subsurface. Parameter estimates are generally sparse, and determined from tests that "sample" the properties of the subsurface at different scales. The interpretations of these tests are generally based on idealized analyses, and are inherently approximate.

The confidence with which a numerical groundwater model can be applied for predictive purposes is strengthened if it can be shown that the model can match observed water levels for different conditions, and the model parameters are constrained by the available data. Since a groundwater model can provide only an approximate representation of a complex physical system, calibration of the model and an evaluation of the match between the observations and the model calculations is an essential part of model development.

Overview of model calibration

The most defensible model is obtained when as few parameters as possible are adjusted and all of the available data are considered. The process of model calibration should be approached with a deliberate reluctance to add complexity to the model unless clearly warranted. A key guideline has been to make as many simplifications as necessary, but not more. We believe that this is the single most important element in developing a model that is useful for predictive purposes. A model that incorporates all available detail is generally unwieldy and may ultimately be useless.

Three key questions that must be addressed in developing a calibration strategy are:
1. What are the calibration targets?
2. What parameters will be adjusted?
3. How will the parameters be adjusted?

Targets will be selected based on their ability to constrain the model adjustment process. As discussed below, targets typically consist of both water level and flow observations, but can include other information.

Parameters to be adjusted will be determined by establishing:
- What parameters must be specified?
- What parameters will be assigned fixed values based on independent estimates?
- What parameters can be assigned fixed values based on literature ranges (i.e., assuming reasonable “textbook” values)?
- Of the parameters that will be adjusted, what information is available that can constrain their values? Can any of this information be used to establish ranges over which parameter values may be adjusted?
- How will the values of the distributed parameters be zoned?

Parameter adjustments, as discussed in the section on Model Calibration Strategy, will be performed both through a manual, trial-and-study process, and through the use of automated parameter adjustment as driven by residuals and parameter sensitivity.

Model calibration strategy

Model calibration will be approached through a “trial-and-study” approach. The primary parameters that will be adjusted will be the hydraulic conductivities of the hydrostratigraphic units. The analyses will begin with parameter distributions that are deliberately simplified, with the distributions of hydraulic conductivities following the outlines of the zones that have been delineated during the development of the Conceptual Model (Phase 2).

The hydraulic conductivities will be adjusted through a combination of manual parameter adjustments and the application of the model independent, nonlinear parameter estimation code PEST (Doherty, 2004). Hydraulic conductivity will be applied through a combination of zonation, reflecting hydrogeology, and pilot points (*Rama Rao, 1995*). Pilot points allow the potential for the available information to dictate additional complexity in the distribution of hydraulic conductivity within each hydrogeologic zone. Complexity in the distribution of hydraulic conductivity will be introduced only as required, with the results of alternative model structures reviewed carefully to evaluate the consistency of the model results with the conceptual model. As will be discussed in more detail in the following sections, PEST is to minimize a quantitative measure of the overall goodness-of-fit of the model to the weighted observations. This is not to say that the model is “correct” only that for the assumed model structure no further adjustment in the values of the parameters will yield an improved match to the calibration targets.

Additional parameters that may be initially considered for adjustment, either manually or with PEST, include:

- Streambed conductance;
- Vertical hydraulic conductivity, or vertical anisotropy ratio;
- Transbasin boundary condition terms; and
- For transient representations of the system, storage term (e.g., specific yield and specific storage).

Adjustments of any parameter will be dictated by the available information, both the information on the parameter value, and information on targets that constrain observations dependent on the parameter.

For the initial analyses, the recharge from the TOPNET-WM model will be assigned and not adjusted. As the calibration proceeds, the groundwater modeling team will collaborate with the surface water modelers to always specify consistent recharge distributions.

Calibration targets

In a typical groundwater flow model, the objective of calibration is to adjust the model so that is achieves an acceptable match to observed water levels. However, many observations may serve as appropriate targets for the calibration of groundwater models, including water levels, discharge rates, groundwater age, and solute concentrations and travel times. It is anticipated that for Phase 4 the primary calibration targets will be time-averaged groundwater levels from dedicated observation wells and estimates of changes in baseflow between stream gauges. The estimates of changes in baseflow will be interpreted to develop independent estimates of exchanges between the groundwater and surface water systems.

The agreement between a model and an individual observation (target) is expressed as a model residual, defined as the difference between the calculated and observed value at the particular location of observation well *i*.

$$R_i = (cal_i - obs_i)\, w_i^{1/2} \tag{1}$$

Here cal_i denotes the model-calculated value at location *i*, obs_i represents the corresponding observation, and w_i is the weighting assigned to this target. According to the sign convention of the definition above, a positive residual indicates over-calculation by the model, and a negative residual indicates a model under-calculation. Not all modeling packages adopt this sign convention. For example, some programs define it as the difference between observed and calculated water levels. It is important to understand what positive and negative residuals represent in a particular context. Whenever values of residuals are presented in interim or final reporting, care will be taken to indicate the sign convention.

As indicated in Equation (1), it is appropriate to assign different weights to the residuals. This will have the effect of placing more emphasis on achieving a match to some targets and discounting the importance of other targets (Hill, 1998). For example, more emphasis might be directed towards matching water levels derived from time series from dedicated monitoring wells than spot measurements from private water wells at the time they were drilled. The weights may serve more than one purpose:

- The weights may account for the reliability that the groundwater modeler assigns to specific observations in the calibration; and/or
- The weights may be used to allow combined consideration of different types of measurements that have different units and significantly different magnitudes (heads and flow rates for example).

Evaluation of model goodness-of-fit

There is no standard methodology for assessing when the match between the observations and model results is acceptable, that is, evaluating the model goodness-of-fit. The calibration process necessarily requires the judgment of an expert modeler. The final assessment of the calibration will be a determination of whether the model is “fit for purpose”, that is, whether the model can be applied to achieve the objectives for which it was developed. See *Qualitative assessment of model accuracy* below.

The techniques that will be used to compare the results of a model against observations are described here. The American Society for Testing and Materials (ASTM) has published guidelines for comparing model results against observations (ASTM Standard Guide D5490 93). It is the opinion of the groundwater modeling Team that the ASTM guidelines are a good starting point, but should be used <u>only</u> as a starting point.

Model calibration will be evaluated considering both the evaluation of quantitative measures of goodness-of-fit and qualitative aspects of the match. Although qualitative measures necessarily involve judgement, they are not inferior to quantitative measures. Rather, they should be regarded as being complementary.

<u>Quantitative assessment of model adequacy</u>

Model calibration, as an objective, reflects the quality of information available to constrain adjustments. As such, model calibration will be considered complete when additional parameter adjustments produce only marginal improvements in residuals. This approach provides a calibration metric consistent with both the quality and quantity of data available. Any other combination of metric and specific target level would tend to impose objectives that may be irrelevant to the given system and information and ignore professional judgement. For example, general anecdotal objectives, such as reducing the water-level residual RMSE below ten percent of the overall water level range within the simulation domain, ignore specifics of the given model that may preclude their application and can therefore be misleading.

The quantitative evaluation will consist of assessing the statistics of the residuals of a simulation. Statistical measures calculated with the residuals provide the modeler with a means of determining whether revisions to the model have yielded a demonstrably better match to the observations. However, it is important to note that no single statistic adequately quantifies the match between observations and model calculations. The following measures of overall goodness-of-fit will be evaluated. A brief discussion of the guidance for assessing each measure is included. All the measures may be expressed in terms of either the original or weighted residuals.

1. Mean residual (*MR*)

The mean residual is defined as the arithmetic average of the residuals:

$$MR = \frac{1}{N}\sum_{i=1}^{N} R_i \qquad (2)$$

Here *N* is the number of observations.

It is desirable that the mean residual be relatively close to zero. A mean residual of zero indicates that the calculated water levels are at the right average level. Although a mean residual that is close to zero is desirable, it is not a sufficient indicator of a good match, because large negative and positive residuals may cancel out. The members of the modeling team are not aware of any quantitative guidance in the literature on what "close to zero" means. The assessment will be guided by professional judgment incorporating an assessment of the consistency of targets. The targets for the model calibration will include groundwater levels and inferred rates of groundwater exchange between the streams and the groundwater system, as inferred from changes in baseflow between stream gauging stations.

2. Mean absolute residual (*MAR*)

The mean absolute residual is defined as the arithmetic average of the absolute value of the residuals:

$$MAR = \frac{1}{N}\sum_{i=1}^{N} |R_i| \qquad (3)$$

The vertical bars denote the absolute value. The mean absolute residual is a more useful measure of overall goodness-of-fit than the mean residual, as positive and negative residuals do not cancel. This is a measure in some sense of how wrong the model might be average at any one location in the model.

It is desirable that the absolute residual be relatively close to zero: A mean absolute residual of zero indicates that the calculated water levels are at the right average level, and that the scatter of residuals is relatively small. Similar to the assessment of the mean residual, the members of the modeling team are not aware of any quantitative guidance in the literature on what “close to zero” means. The evaluation will be guided by professional judgment.

3. Root-Mean-Squared Residual (*RMSR*)

The root-mean-squared residual is calculated according to:

$$RMSR = \left[\frac{1}{N}\sum_{i=1}^{N} R_i^2\right]^{1/2} \tag{4}$$

The Root-Mean-Squared Residual (*RMSR*) provides a quantitative measure of the scatter of the residuals. It is desirable that the *RMSR* be relatively close to zero. An *RMSR* deviation that is close to zero indicates that the calculated water levels are both at the right average level, and that the scatter of residuals is relatively small. Professional judgement will be used to evaluate whether the scatter in the residuals is acceptable or can be reduced by the incorporation of additional detail in the analyses, for example, the incorporation of areas within hydrostratigraphic units of the groundwater model to which distinct properties are assigned (these areas are referred to as zones) and/or the refinement of the limits of these zones.

4. Normalized root-mean-squared residual (*nRMSR*)

There is no fixed definition of the normalized root mean squared residual, *nRMSR*. However, the *nRMSR* is a key quantitative measure of the overall goodness-of-fit, as it places the *RMSR* in the appropriate context. The definition of the *nRMSR* that will be adopted for this study is:

$$nRMSR = \frac{1}{(O_{max} - O_{min})}\left[\frac{1}{N}\sum_{i=1}^{N} R_i^2\right]^{1/2} \tag{5}$$

The terms O_{max} and O_{min} denote the maximum and minimum observed water levels at target locations across the model area; therefore, (O_{max} - O_{min}) in Equation (5), represents the *range* in the observed groundwater levels across the model area.

Spitz and Moreno (1996; corrected 2003) have suggested that the *nRMSR* should be less than 10% of the range of the observations.

5. Sum of squared residuals (*SSR*)

The sum of the squared residuals, *SSR*, (more precisely the sum of the squared weighted residuals) is defined as:

$$SSR = \sum_{i=1}^{N} R_i^2 \qquad (6)$$

The magnitude of the sum of the squared residuals depends on the number of observations. Therefore, it is not possible to provide guidance with respect to its value for model acceptance. However, it is important to note that the sum of the squared errors is still a crucial quantity. Computer-assisted calibration techniques are designed to minimize the sum of the squared residuals, or the sum of the weighted squared residuals. In other words, the match between a model and the observations cannot be improved with further adjustment of parameter values when no significant change in the sum of the square residuals is achieved between successive simulations.

<u>Qualitative assessment of model adequacy</u>

Qualitative evaluation consists of judging whether the results of the modeling are sensible and consistent with the overall conceptual model. The qualitative assessment of the match between the model results and the observations will be made with visual comparisons and will include examination and evaluation of:

- The overall match between observed and calculated time-averaged water levels;
- Residuals at individual wells;
- The shape of the water level contours;
- Flow patterns;
- Hydraulic gradients;
- Absolute groundwater levels; and
- Consistency between the calibrated parameters and parameter estimates that have been obtained independently of the calibration.

Qualitative evaluation includes the visual comparison of groundwater flow directions and key hydrologic features, such as groundwater flow divides. Qualitative evaluation also includes checking the calculated flow balance to ensure that its components fall within physically realistic bounds that are consistent with the site conceptual model.

The qualitative evaluation will include the preparation of scatterplots of computed versus observed water levels. Scatter plots are a standard method of providing a visual impression of the quality of fit for a steady state model (American Society for Testing and Materials, 1993). In a standard scatterplot, the abscissa (x-axis) represents the observed water level, and the ordinate (y-axis) represents the calculated water level at the location of the well. For a perfect match between the model calculations and the observation, the points fall on a straight line. The points on a scatterplot should be scattered randomly about the line of perfect agreement, with a relatively narrow scatter about that line. The scatterplot will be inspected for deviations of the data from the line of equality. The data points on the scatterplot will also be inspected for patterns. For example, if the slope of a line through the data points is steeper or shallower than the solid line, this suggests an error in the overall hydraulic gradient. As with the visual comparison of water level contours, examination of the scatterplot is a qualitative assessment.

A cumulative probability plot of the residuals will be developed. Spitz and Moreno (1996, p. 244-245) and Hill (1998) have suggested that the residuals from a calibration should be normally distributed, with a mean of zero. This is interpreted here to mean that the largest portion of the residuals plotted on a probability plot should approximate a straight line, with the residual that corresponds to a cumulative probability of 50% is close to zero. The cumulative probability plot is particularly useful for identifying targets that are likely to be either unreliable or unrepresentative.

<u>Additional considerations in the assessment of whether the calibrated groundwater model is fit for purpose</u>

- The residuals will be displayed on contours of calculated water levels to assess whether there are any areas of systematic mismatch. The patterns of residuals should suggest that there is an inherent variability in the calibration targets that cannot be resolved in the analysis. In the case of fractured-rock, for example, it is common to observe that in some locations relatively large positive and negative residuals are located close together;

- Inferred hydraulic conductivities should be constrained by geologic interpretations, and consistent with the results of hydraulic testing; and

- The cumulative recharge should be consistent with inferred surface water baseflow (minus surface and groundwater consumption). In general, the recharge should be a fraction of the water surplus, the difference between the average annual precipitation and the average annual evapotranspiration.

As indicated previously, during the initial development of the groundwater model in Phase 4 of this project, the calibration targets will consist primarily of time-averaged water levels and estimates of changes in long-term estimates of stream baseflows. It is recognized that seasonal changes in groundwater and surface water conditions may be important for the management of water resources. However, as additional long-term continuous monitoring data become available, we expect that the capabilities of the model will be expanded to consider seasonal effects. At that time, the model calibration will be revisited to confirm that it is capable of providing reliable transient results at the scale of seasons. Reliable observations of water level fluctuations will be used to constrain storage terms and provide refinement opportunities for parameters such as hydraulic conductivity and streambed conductivity. It is likely that it will be particularly important to demonstrate that the model is capable of matching conditions during the dry season.

B8. Inspection/Equipment Calibration for Supplies and Consumables

This section is not relevant.

B9. Non-Direct Measurements

This project has completed acquiring data as part of the previously referenced Phase 2 and 3 projects. Input data for the models will be acquired from these two projects and from scientific literature. Applicable data quality assurance procedures are described in the Phase 2 and Phase 3 reports.

B10. Data Management and Hardware/Software Configuration

Input data for this project will be acquired from the Phase 2 and Phase 3 project reports described previously. The quality of the input data has been evaluated as part of these two previously completed projects. Data quality from both these sources will be accepted for use on this project. The previously collected input data was enter into Microsoft (MS) Excel® spreadsheets for organization and manipulation purposes. Pre-processing of the data will consist of reformatting model data for direct input without modification. Accurate transcription of these data into input files will be verified by line-by-line hand checking (direct comparison of input files with the source data). Post-processing will consist of extracting specific data sets and formatting into graphs for visualization. A generalized process flow diagram for data handling is shown in Figure 3 (adapted from USEPA, 2002; Figure 10).

During the development of the numerical groundwater model, brief technical memoranda will be prepared to document the sources and treatment of the data that are used to constrain the analyses. The documentation will be intended to permit tracing of the data from their source and acquisition through to their final use on the project. This will simplify coordination of efforts between the members of the Project Team, review of interim model results, and preparation of the final documentation.

MODFLOW, PEST and Topnet-WM programs are proposed for use on this project. MODFLOW is a modular finite-difference flow model. The source code is free public domain software, written primarily in Fortran, and can compile and run on Microsoft Windows operating systems. PEST (**P**arameter **EST**imation) is a general purpose parameter estimation utility developed by John Doherty of Watermark Computing that is used to assist in data interpretation, model calibration, and predictive analysis. Topnet-WM is a semi-distributed hydrological model developed by Utah State University that is used to simulate catchment water balance and river flow. The MODFLOW, PEST and Topnet-WM programs are highly credible sources. Code verification is unnecessary.

The project files for the models will be archived and documented in the project reports. GIS (Geographic Information System) will be used to manage ground surface elevation, water wells location and hydrological features of the study area. The project team will provide all data electronically to the Client Project Lead through email and/or the hand delivery of flash drives containing the data.

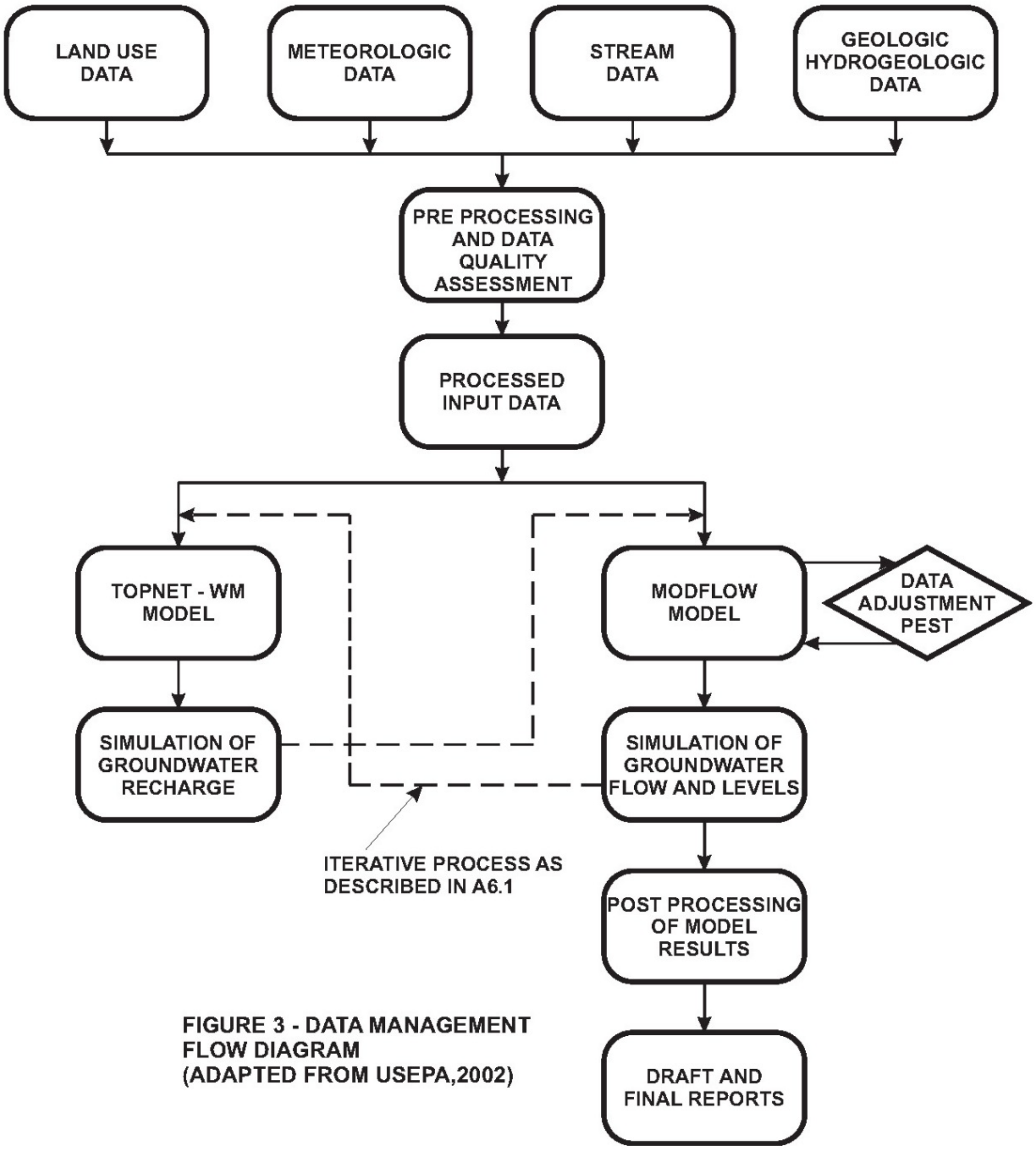


FIGURE 3 - DATA MANAGEMENT FLOW DIAGRAM (ADAPTED FROM USEPA,2002)

C. ASSESSMENT AND OVERSIGHT

Section C of the QAPP refers to tasks required to assess the effectiveness of the modeling project implementation and associated QA and QC activities.

C1. Assessment and Response Actions

The WRIA 1 Watershed Management Board is in the process of developing a formal peer review process for this project. It is anticipated that the peer review process will be completed prior to finalizing any significant technical products. Stakeholder review will be conducted in accordance with the procedures and schedule discussed in Sections A6.1 and A6.2 of this QAPP.

Project assessment and oversight will be accomplished in the following manner. The lead groundwater modeler (Dr. Gilbert Barth) for the project will report to Christopher Neville, who will be responsible for project review and quality assurance. Mr. Neville will ensure that appropriate resources are devoted to the project, including time required to confirm the reliability of data that are used to constrain the analyses. Mr. Neville will be responsible for the coordination of activities needed to detect errors and to help ensure that the use and application of the model addresses user requirements. Mr. Neville will report regularly to the Project Principal Investigator (Mr. Charles Lindsay), keeping him apprised of progress and impediments that are encountered. Identified project related issues will be resolved via email correspondence and/or conference calls between the Consultant Team, as necessary.

C2. Reports to Management

Here the “Reports to Management” are interpreted as regular updates to the Client Project Lead and the WRIA 1 Watershed Management Board. The reports to management will be conducted as outlined in Sections A6.1 and A6.2 of this QAPP.

D. DATA VALIDITY AND USABILITY

The primary purpose of element D of the QAPP is to describe the process of assessing model-results usability. In the US EPA guidance document, it is indicated that the activities in element D refer to quality procedures that occur near or at the *end* of the modeling project. In our opinion this is ineffective. All work conducted *throughout* the development of the groundwater model, its assembly, calibration and testing, will be guided by the objective of useable results.

The following subsections identify elements relevant to the scope associated with this QAPP. As appropriate, responses identify the methods and extent of efforts that will be implemented during the entire model development process to work towards data validity and usability.

D1. Departures from Validation Criteria

The modeling associated with the scope of this QAPP will be performed using the United States Geological Survey's MODFLOW model (e.g., Hanson et al., 2014). The mathematical basis, numerical implementation, and coding have been extensively tested and demonstrated. This QAPP does not include any effort to supplement the extensive literature supporting the validity of the MODFLOW implementation.

Modeling inputs have, as described in B9 and B10, been subjected to acceptance criteria as part of the QAPP associated with Phase 2 and 3. This QAPP, associated with Phase 4, relies on the inputs vetted through the Phase 2/3 QAPP process.

The scope associated with this QAPP does not include any specific regulatory tasks. As a result, there is no specific uncertainty criterion that can be evaluated. Model output results will be evaluated in relative terms, as discussed in B7, with objectives identified relative to the availability and quality of observational information.

D2. Verification and Validation Methods

The project updates will document that the steps of the modeling process are followed correctly and that the intermediate and final results meet the project objectives. These steps will include the matching of both "hard" and "soft" targets. The hard targets will include average groundwater levels estimated from dedicated observation wells and production wells, and estimates of groundwater discharge to surface water features inferred from changes in baseflows between gaging stations. The soft targets will include regional interpretations of groundwater flow patterns and any one time (spot) measurements of water levels in private wells and stream flows. During the calibration, the hydraulic conductivities assigned for different hydrostratigraphic units and areas of the model will be adjusted systematically and within realistic bounds to match the calibration targets. The goodness of fit of the model to the observations will be assessed through multiple statistical measures. Maps will also be prepared to indicate the magnitudes of the differences between the target and simulated groundwater levels. These maps will serve to demonstrate that there are no areas of the model where the simulation results have a systematic bias and to identify areas where data coverage is limited.

Given the limitations on available data to constrain the model, and the lost opportunities for improving calibration, all of the available data will be used to calibrate the model. No subset of observations will be reserved for a verification or validation process. In addition to being motivated by the limited observations, this approach is consistent with efforts to avoid misleading public perception regarding the calibrated model results (*Bredehoeft and Konikow*, 1993).

The modeling approaches will be consistent with the available guidance documents, including:

- ASTM (2010);
- ASTM (2013);
- ASTM (2013);
- ASTM (2014);
- ASTM (2008);
- Hill (1998); and
- Anderson, Woessner, and Hunt (2015).

D3. Reconciliation and User Requirements

By following the procedures outlined in Sections B7, B9 and D2, the Project Team is confident that the groundwater model that is to be developed will meet the project objectives. The model that is developed will serve as an appropriate framework for achieving user requirements beyond the immediate period of model development.

Particular attention will be directed towards applications of the model in areas where it is presently data poor, that is, in areas where there is a high uncertainty in model inputs and consequently in model outputs. It is especially important that procedures are in place to address whether the high levels of uncertainty that are likely can allow user requirements to be met, and if not, the actions needed to address this issue. The final documentation of the model will include a section in which these areas are identified, providing an appropriate perspective for decision-making. The section will include a discussion regarding the treatment of the model results as working hypotheses. The discussion will also include guidance regarding the collection and interpretation of data to test the hypotheses.

REFERENCES

American Society for Testing and Materials (ASTM), 2008: Standard Guide for Calibrating a Groundwater Flow Model Application, American Society for Testing and Materials, D5981 96 (2008), West Conshohocken, Pennsylvania.

American Society for Testing and Materials (ASTM), 2010: Standard Guide for Application of Groundwater Flow Model to a Site-Specific Problem, D5447 04 (2010), American Society for Testing and Materials, West Conshohocken, Pennsylvania.

American Society for Testing and Materials (ASTM), 2013: Standard Guide for Documenting a Groundwater Flow Model Application, D5718-13, American Society for Testing and Materials, West Conshohocken, Pennsylvania.

American Society for Testing and Materials (ASTM), 2014: Standard Guide for Comparing Groundwater Flow Model Simulations to Site-Specific Information, D5490 93 (2014), American Society for Testing and Materials, West Conshohocken, Pennsylvania.

Anderson, M.P., W.W. Woessner, R.J. Hunt, 2015: **Applied Groundwater Modeling**, 2nd edition, Academic Press, London, UK.

Armstrong, J.E., 1980, Surficial Geology Map of Mission, British Columbia, Geological Survey of Canada.

Associated Earth Sciences, Inc. (AESI), 2016, Quality Assurance Project Plan for Task 2.5 – Groundwater Conceptual Model Project, Whatcom County, Washington, Report to Whatcom County Public Works Department and the Bertrand Watershed Improvement District, May.

Associated Earth Sciences, Inc. (AESI), 2016, Development of a Numerical Groundwater Model for the Lynden/Everson/Nooksack/Sumas (LENS) Area of Whatcom County, Final Draft Technical Report, Phase 2 – Data Collection and Conceptual Model Development, Whatcom County, Washington, Report to WRIA 1 Watershed Management Joint Board, September.

Bredehoeft, J. D. and Konikow, L. F. (1993), Ground-water Models: Validate or Invalidate. GroundWater, 31: 178–179. doi:10.1111/j.1745-6584.1993.tb01808.x.

Cox, S. and S. Kahle, 1999, Hydrogeology, Ground-Water Quality, and Sources of Nitrate in Lowland Glacial Aquifers of Whatcom County, Washington and British Columbia, Canada, US Geological Survey Water-Resources Investigations Report 98-4195.

Hanson, R.T., Boyce, S.E., Schmid, Wolfgang, Hughes, J.D., Mehl, S.M., Leake, S.A., Maddock, Thomas, III, and Niswonger, R.G., 2014, One-Water Hydrologic Flow Model (MODFLOW-OWHM): USGS Techniques and Methods 6–A51, 120 p., https://dx.doi.org/10.3133/tm6A51.

Hill, M.C., 1998: Methods and Guidelines for Effective Model Calibration, U.S. Geological Survey, Water-Resources Investigations Report 98 4005.

Hill, M.C., and C.R. Tiedeman, 2002: Weighting observations in the context of calibrating groundwater models, in *Calibration and Reliability in Groundwater Modeling: A few steps closer to reality, ModelCARE'2002*, Prague, Czech Republic, June 17-20, 2002, International Association of Hydrologic Sciences, Publication No. 277, pp. 196-203.

Rama Rao, B. S., LaVenue, A. M., de Marsily, G., and Marietta, M. G. 1995, Pilot point methodology for automated calibration of an ensemble of conditionally simulated transmissivity fields: 1. Theory and computational experiments, Wat. Resour. Res., 31, 475:493.

Spitz, K., and J. Moreno, 1996: **A Practical Guide to Groundwater and Solute Transport Modeling**, John Wiley & Sons, Inc., New York, New York.

United States Environmental Protection Agency (US EPA), 1997. Glossary of Quality Assurance Terms and Related Acronyms. http://www.ecy.wa.gov/programs/eap/qa.html

United States Environmental Protection Agency (US EPA), 2002: Guidance for Quality Assurance Project Plans for Modeling, EPA/240/R-02/007, Office of Environmental Information, Washington, DC.

United States Environmental Protection Agency (US EPA), 2006. Guidance on Systematic Planning Using the Data Quality Objectives Process EPA QA/G-4. http://www.epa.gov/quality/qs-docs/g4-final.pdf

Washington State Department of Ecology, 2004, Guidelines for Preparing Quality Assurance Project Plans for Environmental Studies, Publication 04-03-030.

Washington State Department of Ecology, 2016, Water Quality Assessment in Support of 303d Listings, http://www.ecy.wa.gov/programs/Wq/303d/currentassessmt.html, approved July 22, accessed December 16, 2016.

Washington State Department of Ecology, 2017, Water Quality Standards for Surface Waters of the State of Washington, Chapter 173-201A WAC, Publication 06-10-091, Adopted August 1, 2016, Revised March 2017.

Woessner, W.W., and M.P. Anderson, 1990: Setting calibration targets and assessing model calibration – Room for improvement: An example from North America, in *Calibration and Reliability in Groundwater Modeling*, K. Kovar (ed.), International Association of Hydrologic Sciences, Publication No. 195, pp. 279-288.

Woessner, W.W., and M.P. Anderson, 1992: Selecting calibration values and formulating calibration targets for ground-water flow simulations, in *Proceedings of the Fifth International Conference on the Use of Models to Analyze and Find Working Solutions to Groundwater Problems*, National Groundwater Association, Groundwater Management Series Book 9, pp. 199-212.

APPENDICES

Appendix A: Quality Assurance Glossary

Accuracy - the degree to which a measured value agrees with the true value of the measured property. US EPA recommends that this term not be used, and that the terms precision and bias be used to convey the information associated with the term accuracy. (USGS, 1998)

Bias - The difference between the population mean and the true value. Bias usually describes a systematic difference reproducible over time, and is characteristic of both the measurement system, and the analyte(s) being measured. Bias is a commonly used data quality indicator (DQI). (Kammin, 2010; Ecology, 2004)

Comparability - The degree to which different methods, data sets and/or decisions agree or can be represented as similar; a data quality indicator. (US EPA, 1997)

Dataset - A grouping of samples, usually organized by date, time, or analyte. (Kammin, 2010)

MAR – Mean absolute residual, as defined in text.

MR – Mean residual, as defined in text.

Measurement Quality Objectives (MQO) - Measurement Quality Objectives are qualitative and quantitative statements derived from systematic planning processes that clarify study objectives, define the appropriate type of data, and specify tolerable levels of potential decision errors that will be used as the basis for establishing the quality and quantity of data needed to support decisions. (US EPA, 2006)

Measurement result - A value obtained by performing the procedure described in a method. (Ecology, 2004)

Method - A formalized group of procedures and techniques for performing an activity (e.g., sampling, chemical analysis, data analysis), systematically presented in the order in which they are to be executed. (US EPA, 1997)

nRMSR – Normalized root-mean-squared residual, as defined in text.

Precision - The extent of random variability among replicate measurements of the same property; a data quality indicator. (USGS, 1998)

Quality Assurance (QA) - A set of activities designed to establish and document the reliability and usability of measurement data. (Kammin, 2010)

Quality Assurance Project Plan (QAPP) - A document that describes the objectives of a project, and the processes and activities necessary to develop data that will support those objectives. (Kammin, 2010; Ecology, 2004)

RMSR – Root-mean-squared residual, as defined in text.

Sensitivity – Magnitude, or relative magnitude of a simulation result response to the adjustment of model parameters.

Uncertainty – Quantification of the estimated error associated with a set of simulation results or predictions.

Standard Operating Procedure (SOP) – A document which describes in detail a reproducible and repeatable organized activity. (Kammin, 2010)

Appendix B: Acronyms and Abbreviations

The following are acronyms and abbreviations used in this report.

AESI	Associated Earth Sciences, Inc.
Ecology	Washington State Department of Ecology
US EPA	United States Environmental Protection Agency
LCS	Laboratory Control Sample
MODFLOW	A Modular Three-Dimensional Finite-Difference Ground-Water Flow Model
MQO	Measurement Quality Objective
RPD	Relative Percent Difference
QA	Quality Assurance
QAPP	Quality Assurance Project Plan
QC	Quality Control
Topnet	Topnet is a semi-distributed hydrological model for simulating water balance and river flow. Read more at https://teamwork.niwa.co.nz/display/IFM/Topnet
Topnet-WM	Topnet-WM is a version of the model where Utah State University added a Water Management Model. A comprehensive description of the model can be found at https://www.hydroshare.org/resource/d15b9934f34e4c57913b3cb53966d5c7/
USGS	United States Geological Survey
WAC	Washington Administrative Code
WDFW	Washington State Department of Fish and Wildlife
WID	Watershed Improvement District
YSI	Yellow Springs International

Units of Measurement

afy	acre-feet per year
°C	degrees Celsius
cfs	cubic feet per second
ft	feet
gpm	gallons per minute
mg/L	milligrams per liter
mL	milliliters
NTU	Nephelometric Turbidity Units
µg/L	micrograms per liter
µS/cm	microSiemens per centimeter