CLARKS CREEK TMDL
DISPUTE RESOLUTION AGREEMENT

5-YEAR REASSESSMENT PROJECT

MODELING APPROACH AND DATA REQUIREMENTS
TECHNICAL MEMORANDUM

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5-Year Reassessment Project

Modeling Approach and Data Requirements Technical Memorandum

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List of Abbreviations

AFDM	ash-free dry mass
BOD	biological oxygen demand
CBOD	carbonaceous biological oxygen demand
CCSRAP	*Clarks Creek Sediment Reduction Action Plan*
County	Pierce County
CSOD	community substrate oxygen demand
DO	dissolved oxygen
DOD	dissolved oxygen deficit
DRA	Dispute Resolution Agreement
Ecology	Washington State Department of Ecology
EPA	U.S. Environmental Protection Agency
FEMA	Federal Emergency Management Agency
FIS	flood insurance study
HEC-RAS	Hydrologic Engineering Centers River Analysis System
HSPF	Hydrological Simulation Program-Fortran
MFA	magnitude-frequency analysis
PET	potential evapotranspiration
PSD	particle size distribution
QAPP	quality assurance project plan
SOD	sediment oxygen demand
TAC	technical advisory committee
TOC	total organic carbon
TSS	total suspended solids
TMDL	total maximum daily load
USGS	U.S. Geological Survey
WASP	Water Quality Analysis Simulation Program
WLA	waste load allocation
WQIP	water quality improvement project
WSU	Washington State University

Executive Summary

This technical memorandum describes the proposed water quality modeling and monitoring approach to support implementation of Pierce County's (County) *Clarks Creek Restoration Plan* (County 2017). The recommended approach will build upon prior analyses by using available, similar models (e.g., Hydrological Simulation Program-Fortran [HSPF], QUAL2Kw, Hydrologic Engineering Centers River Analysis System [HEC-RAS]), and critical conditions of interest. The recommended program will also seek to fill data gaps that limited previous evaluations, and significantly enhance the model capabilities and calibration. These capabilities, in turn, will greatly enhance decision-making on topics such as total maximum daily load (TMDL) formulation and public investments in water quality.

The recommended dissolved oxygen (DO) modeling approach requires linking a watershed rainfall-runoff model (e.g., HSPF) to a receiving water quality model (e.g., QUAL2Kw). HSPF will be used to model both watersheds loading and in-stream water quality in the major tributaries of Clarks Creek. A dynamic version of QUAL2Kw (version 6) will be applied to simulate DO in the Clarks Creek mainstem. The models will be set to simulate the major processes that affect DO in Clarks Creek, including sediment oxygen demand (SOD), *Elodea*, and tributary inflows. The modeling framework will be calibrated to new data collected for this project and applied to simulate various management scenarios under critical conditions for the TMDL.

This recommended approach requires a relatively large amount of hydrologic and water quality data for calibration at varying seasonal conditions. The comprehensive monitoring approach described herein was designed to provide concurrent flow and water quality data for mainstem Clarks Creek and the major tributaries (Rody, Diru, and Woodland creeks) in unincorporated Pierce County, and address the data gaps identified in prior analyses. The targeted water quality data, including diel variability, and supported by SOD measurements and an evaluation of *Elodea* effects, will provide confidence in establishing a better cause-and-effect relationship for watershed management solutions.

The recommended sediment modeling approach will build upon an existing HEC-RAS model of Clarks Creek and its tributaries. The sediment modeling will require additional channel sediment data, cross-section surveys, and channel roughness observations to refine the HEC-RAS model for developing a better understanding of particle transport in Clarks Creek.

This document provides an overview of the recommended modeling and monitoring approach, to be used to support consensus between the County, Washington State Department of Ecology (Ecology), and other stakeholders on the technical path forward. After agreement on the basic approach, additional details will be provided in a quality assurance project plan (QAPP) that will provide more specific information on topics such as monitoring methods, quality assurance components, and model calibration targets. As the efforts proceed, we recommend documenting results at key milestones (e.g., QAPP development, model calibration, scenario development) and allowing review by key parties, prior to moving to the next step.

Section 1: Introduction

This technical memorandum describes the proposed water quality modeling and monitoring approach to support implementation of the *Clarks Creek Restoration Plan* (County 2017). It also identifies the hydrologic, water quality, and other types of data needed to parameterize and calibrate the model. An objective of this memorandum is to achieve technical consensus on the modeling and monitoring approaches between the County and Ecology. This will allow the County to move forward with data collection activities and a related QAPP. The sub-sections below provide additional background on Clarks Creek TMDLs, the *Clarks Creek Restoration Plan*, and goals for modeling.

1.1 TMDL Background

Ecology issued the final *Clarks Creek Dissolved Oxygen and Sediment Total Maximum Daily Load Water Quality Improvement Report and Implementation Plan* in December 2014 (Ecology and Tetra Tech 2014). The U.S. Environmental Protection Agency (EPA) reviewed and certified the TMDL on May 27, 2015.

EPA's contractor (Tetra Tech) applied an HSPF watershed model and steady-state hydraulic version of QUAL2Kw to perform the TMDL technical evaluation. The technical analysis indicated DO in Clarks Creek was controlled by variety of factors that varied in importance under different flow conditions. The TMDL modeling predicted that DO will be improved by less *Elodea* (i.e., an aquatic macrophyte) under low-flow conditions, and by less stormwater runoff under high-flow conditions. The TMDL allocations included reduced dissolved oxygen deficit (DOD), *Elodea* controls, and increased riparian shade. An implementation target was set to reduce 50 percent of the stormflow volume or treat 50 percent of the untreated stormwater resulting from the October 21, 2003, storm event, which was deemed the "critical condition" for stormwater-induced DO excursions.

The TMDL also included a reduction target for sediment. The sediment TMDL target was based on a comparison of bottom sediment samples from Clarks Creek with samples collected from "reference" creeks in areas with little urban development (Hayslip 2013). The TMDL selected the 90th percentile value for fines and sand in the reference creek bottom sediments (37 percent) as the sediment target to support aquatic life use. That value was compared to the sand and fine percentages in sediment samples collected from the Clarks Creek channel. The sediment reduction target of 66 percent is based on the difference in sand and fines concentrations between the finest Clarks Creek sample and the 90th percentile of the reference creek samples, plus a 2 percent reserve for future growth. The target reduction for sand and fines in the bed material was then assumed to require an equivalent reduction in incoming sediment loads.

The County identified several issues and concerns regarding the final TMDL report. These related to data or modeling limitations that caused significant uncertainty in whether the TMDL allocations and implementation targets were appropriate. For example, the steady-state QUAL2Kw model used for the TMDL assumes that storm drain, and tributary inflow rates and water quality remain constant throughout each 24-hour simulation period. Consequently, the model could not simulate conditions during dynamic storm events (Ecology and Tetra Tech 2014). This is a significant limitation for the Clarks Creek DO TMDL because the waste load allocations (WLAs) were driven by QUAL2Kw simulations for a large and dynamic storm event that occurred on October 20–21, 2003. We cannot assume that instream DO-related processes are at equilibrium during such conditions, or that the diel variability in DO under a steady-state hydraulic condition is identical to the variability experienced under a dynamic hydrologic condition. In addition, the QUAL2Kw modeling framework was not capable of explicitly predicting the effects of stormwater treatment on DO in Clarks Creek.

Another limitation of the TMDL model is that it did not adequately characterize the effects of macrophytes like *Elodea* on DO in the water column (Ecology and Tetra Tech 2014). *Elodea* can affect DO directly through photosynthesis and respiration, as well as indirectly by reducing water velocities, trapping fine sediments, and contributing decomposable organic matter to the creek bed, thereby increasing SOD. Water levels in Clarks Creek have been observed to drop several feet immediately after *Elodea* cutting, suggesting that *Elodea* can have major impacts on flow velocities, sediment accumulation, and reaeration rates.

Other limitations of the TMDL DO model included:

- Does not simulate SOD sources or controls
- Does not simulate controls on DO in storm drains and tributaries
- Does not simulate the effects of storm-related variability in streamflow and loading

Key data gaps for the TMDL DO model included:

- Lack of recent streamflow data
- Few sediment SOD measurements (yet model is highly sensitive to SOD)
- Limited water quality data for tributaries (yet model is highly sensitive to tributary water quality)
- Grab samples in Clarks Creek were not coincident with diurnal DO measurements

Finally, the County had questions regarding whether the October 20–21, 2003, storm event was an appropriate "critical condition" for stormwater-induced excursions of the DO criteria. After evaluating precipitation data, streamflow data, and HSPF model results, the County concluded that the October 20–21, 2003, event might be a very infrequent event (i.e., rarer than once in 10 years).

The County and Ecology entered a dispute resolution process to address the County's concerns. This process culminated in June 2015 with a Dispute Resolution Agreement (DRA) between Ecology and the County. Under the DRA, Ecology agreed that the TMDL will be subject to a 5-year reassessment, and the County agreed to prepare and implement the *Clarks Creek Restoration Plan* (County 2017).

1.2 Clarks Creek Restoration Plan

The County submitted the draft *Clarks Creek Restoration Plan* to Ecology in November 2016, and Ecology approved the plan in March 2017. The content and criteria for approval of the plan are based upon the terms prescribed by the DRA. In brief, the plan identifies, quantifies, and prioritizes water quality improvement projects (WQIPs), enhanced inspection strategies, and advanced road operation practices that are expected to meet the County's WLAs for sediment reduction and stormwater treatment during a 20-year implementation schedule. The plan also details the County's preferred approach for conducting the 5-year reassessment process, which is a provision in the DRA for evaluating the County's progress and examining the metrics, models and data used under the original TMDL.

Section 5 of the *Clarks Creek Restoration Plan* details the County's alternative monitoring and modeling approach for enhancing the diagnostic understanding of the numerous mechanisms driving DO and sediment impairments in Clarks Creek (County 2017). The County will lead a 5-year reassessment with Ecology as an active participant and will also convene a technical advisory committee (TAC) to provide feedback on methods and results. The County proposes to design and conduct a monitoring program to address the key data gaps and support more robust modeling for the 5-year reassessment. As stated in the *Clarks Creek Restoration Plan*, the monitoring program will address the following data gaps:

- Lack of streamflow data on the upper mainstem and tributaries
- Limited SOD data
- Limited water quality data for tributaries and storm drains
- Limited wet weather water quality and flow data
- Limited information on *Elodea* impacts on flow velocities and sediment characteristics

The *Clarks Creek Restoration Plan* provides a high-level summary of potential modeling approaches and a tentative monitoring program. This technical memorandum builds upon the information in the plan to recommend a specific modeling approach and specific data needs for the 5-year reassessment (County 2017).

1.3 Goals for Monitoring and Modeling

The Clarks Creek monitoring and modeling efforts have four major goals, as follows:

1. Accurately simulate how water quality (including DO) in Clarks Creek and its tributaries varies diurnally, seasonally, and hydrologically under existing conditions.

2. Determine how different stormwater management practices will affect the quality of water entering Clarks Creek and its tributaries from the watershed.
3. Predict how different stormwater and riparian management practices will affect the water quality within Clarks Creek and its tributaries, under both low- and high-flow conditions.
4. Quantify the effects of *Elodea* and related management practices on the hydraulics and water quality of Clarks Creek.

Achieving these monitoring and modeling goals will allow the County to evaluate various stormwater and riparian management scenarios. This will support decisions on whether and how the TMDL and *Clarks Creek Restoration Plan* should be adjusted. The goals of the plan are to: (1) increase the diagnostic confidence to focus on the correct combination of problems; (2) implement a program that designs the optimal solutions; and (3) effectively prioritize and execute the right project, at the right scale, in the right place, for the right cost, and reliably maintain its functionality into the future. The goals for the modeling and technical analysis flow from these large programmatic goals, and in the context of limitation of the original TMDL models as described in Section 1.1.

Section 2: Modeling Approach

This section describes the technical basis for selecting a model code for Clarks Creek DO and describes the model's intended application. Upon approval of this approach, additional application details will be included in the QAPP (currently under development).

2.1 Dissolved Oxygen Model Selection

The model selected for this project must be able to simulate the major processes that affect in-stream dissolved oxygen, including temperature, biological oxygen demand (BOD), SOD, and algal/plant photosynthesis/respiration cycles. The daily variability in DO is of interest, and so the model must be capable of simulating short-term variability in temperature and DO. Because Clarks Creek is well-mixed under most conditions, a 1-dimensional stream network model can be utilized. However, the model must be capable of simulating dynamic flow conditions. This is intended to overcome the limitation of the previous (steady-state hydraulic) QUAL2Kw software in simulating Clarks Creek wet weather conditions.

Several modeling codes meet the general requirements listed above, including Water Quality Analysis Simulation Program (WASP), AQUATOX, CE-QUAL-W2, QUAL2Kw, and HSPF. In choosing among these models, one consideration is that a hydrologically variable simulation of water quality will require specification of a time series of wet weather flows and loads from the watershed to the receiving water. A watershed (rainfall-runoff) model such as HSPF would be a logical tool for simulating the effect of management practices in the watershed on flows and pollutant loads to Clarks Creek and its tributaries. An HSPF model for hydrology and sediment transport already exists for the watershed, although the water quality components must be expanded to meet project goals. Another consideration is that the previous TMDL analysis utilized a steady-flow version of QUAL2Kw to simulate water quality in Clarks Creek. Although that model would have to be modified to simulate dynamic flows, the retention of QUAL2Kw will provide continuity between this project and the prior analysis.

Based on the considerations above, the project team selected a linked modeling framework for Clarks Creek. HSPF will be utilized as the watershed (rainfall-runoff) component and for simulating water quality in major tributaries. The HSPF model will be linked to QUAL2Kw, which will the primary tool for simulating water quality in the mainstem of Clarks Creek. Additional details on the proposed modeling approach are provided in the following sections.

2.2 Dissolved Oxygen Model Domain and Options

This section provides of an overview of how the models will be set up with respect to spatial domain, simulation period, and major options. HSPF and QUAL2Kw are discussed in separate sub-sections below.

2.2.1 Hydrological Simulation Program-Fortran

The HSPF model spatial domain includes the entire Clarks Creek watershed above the Puyallup River. Stream segments that are explicitly simulated (as RCHRES) include the mainstem of Clarks Creek, Rody Creek, Diru Creek, Woodland Creek, and Meeker Ditch. The simulation period of the current HSPF model is January 1960 through December 2010. This period will be extended to include whatever additional years/months of data collection are performed for this project. As discussed in more detail in Section 3, that is expected to include at least 1 year of intensive stream gauging and water quality data collection. The HSPF model uses a 1-hour time step.

The current HSPF model will be expanded from simulating hydrology and sediment transport only, to also simulating water temperature, dissolved oxygen, and constituent concentration/loading in hydrologic inputs to streams (runoff, interflow, and baseflow) and in stream reaches. Constituents to be simulated are those needed as input for the QUAL2Kw DO simulation, including carbonaceous biological oxygen demand (CBOD) and nutrients. The PQUAL and IQUAL sections of the PERLND and IMPLND modules will be used to simulate water quality constituent transport using simple relationships. Decisions regarding specific sub-routines for the HSPF water quality simulation (e.g., sediment association versus accumulation-removal) will be based on an evaluation of modeling precedents and water quality/hydrologic data collected for this project. The PSTEMP and PWTGAS sections will be used to simulate water temperature and DO in runoff, interflow, and baseflow.

The HTRCH and RQUAL section of the HSPF RCHRES module will be used to simulate in-stream temperature and DO in Clarks Creek and its tributaries, although only the tributaries will be the focus of the HSPF water quality calibration. Nutrients and detritus will be simulated as generalized constituents (GQUAL) within the HSPF stream reaches. Decay rates will be applied as needed during calibration to improve the accuracy of CBOD/nutrient loading from tributaries to the mainstem of Clarks Creek.

2.2.2 QUAL2Kw

Version 6 of the QUAL2Kw model will be used to simulate dynamic flows and water quality, with a focus on DO and parameters that exert a strong control on DO (e.g., temperature, CBOD, SOD, and in-stream productivity). Only the mainstem of Clarks Creek will be explicitly simulated in QUAL2Kw. Four tributaries (Rody Creek, Diru Creek, Woodland Creek, and Meeker Creek) will be specified as continuous point source inputs to the mainstem reach, as will major stormwater outfalls. Both observed data and HSPF output will be used to specify continuous flows and constituent loads to the QUAL2Kw. For the period(s) for which streamflow data are available for Clarks Creek and its tributaries, the observed data will be used to specify inflows to reaches. For periods lacking streamflow data, the calibrated HSPF model output will be used to specify continuous inflows. Similarly, the water quality of continuous inflows will be characterized using a combination of observed data and HSPF output, depending on the availability of observed data and the quality of the HSPF calibration for each constituent.

A single QUAL2Kw model can simulate up to 1 year of dynamic flows. However, conditions from at least two different periods are of interest for this project: (1) 2003 (which includes the October 21 "critical condition" storm event), and (2) the period of new data collection for this project. It is also desirable to evaluate some of the low-flow periods that were used in the original TMDL analysis. We currently assume that the QUAL2Kw model will be set up to evaluate dynamic flow conditions for these two periods. The QUAL2Kw model will also be used to simulate up to four low-flow periods. The time step of the initial model will be 15 minutes, but this may be adjusted based upon model performance.

The decision on hydraulic model (rating curves versus Manning formula) will be partially based on an evaluation of new stream data collected for this project. Because the presence of *Elodea* has large impacts on the both the hydraulics and water quality of Clarks Creek, it may be necessary to run separate models that represent stream conditions either with or without large *Elodea* biomasses. SOD values will be prescribed based on data collected for the project, including measurements with and without the influence of *Elodea*. The initial simulation will use the internal reaeration model. Bottom growth will be characterized as macrophytes in reaches where *Elodea* is known to occur, and as benthic algae in reaches where field data indicate that macrophytes are largely absent. Following are some of the other options that will be used in the initial QUAL2Kw model:

- Level 1 simulation of hyporheic transient storage zone
- Simulation of the surface transient storage zone
- Dynamic diel output displayed
- No simulation of sediment diagenesis

2.3 Dissolved Oxygen Calibration Approach

The prior HSPF hydrologic calibration will be re-evaluated and adjusted as needed based on new data collected on Clarks Creek and its tributaries. The water quality aspects of HSPF will be calibrated to new data collected for this project and corroborated using other existing data. Parameters of interest for the water quality calibration include temperature, DO, CBOD, nutrient species, and sediment/detritus. During the first step, HSPF predictions of edge-of-stream concentrations (e.g., runoff, interflow, and baseflow) will be compared to local data and regional or literature-based values. This will help ensure that the model predictions of contribution from the watershed are reasonable for different land use/covers. In the second step, HSPF prediction of in-stream concentrations will be compared to observed values, with a focus on the predictions of fluxes from major tributaries to the mainstem of Clarks Creek.

Because the QUAL2Kw model will partially depend upon HSPF inputs, calibration of the HSPF model is a prerequisite to calibration of the QUAL2Kw model. The QUAL2Kw model will be calibrated to new data collected for this project and corroborated to other existing data. The QUAL2Kw model must be calibrated to data from both low- and high-flow conditions, and to conditions both with and without large *Elodea* biomass in the stream. Similarly, the QUAL2Kw model should be calibrated both to reproduce the longitudinal profile of daily average water quality, and diel variability of temperature and DO.

Both HSPF and QUAL2Kw will be calibrated by a combination of visual (i.e., graphic) fit to observed data, and evaluation of calibration statistics. After approval of the basic modeling approach, the QAPP developed for this project will identify specific calibration statistics and associated calibration goals. It is preferable to use the QUAL2Kw genetic algorithm for automatic calibration of major rate constants. The calibration will also be informed by a sensitivity analysis to identify which parameters and inputs have the most control on DO predictions in Clarks Creek and its tributaries. We recommend that the results of the sensitivity analysis and model calibration be submitted to Ecology for review before running management scenarios.

2.4 Model Scenarios and Application

Documentation of the sensitivity analysis mentioned in Section 2.3 is one of the first steps in using the modeling framework to diagnose management implications for Clarks Creek. This analysis is expected to provide important insights into how much of the DO variation is due to variations in runoff quality versus groundwater inputs versus in-stream processes, etc. After calibration, the linked HSPF-QUAL2Kw framework will also be applied to a series of management scenarios to be developed. Model scenarios will be constructed to evaluate the effect of different management practices (e.g., stormwater treatment, steam shading, *Elodea* removal) on DO in Clarks Creek under the critical conditions. Based on these results, more refined scenarios can be developed to inform the TMDL and *Clarks Creek Restoration Plan*. We recommend that after the model setup and calibration are complete, the County document the specific model scenarios of interest and gain agreement from Ecology on the specific scenarios to be run.

Section 3: Sediment Modeling

This section describes model selection for Clarks Creek sediment, and describes how the model is intended to be applied. Upon approval of this approach, additional details on the application will be include in the QAPP (currently under development).

3.1 Sediment Model Selection

As noted in Section 1.1, the sediment TMDL target is based on the difference between the particle size distribution of bottom sediments in Clarks Creek and the particle size distributions in bottom sediment samples from lightly developed reference creeks. Bed sediment composition is a function of the native material and the energy available to mobilize, sort, and/or deposit sediments along the channel bottom. This is a dynamic process that changes over time. A HEC-RAS hydraulic model will be used to perform hydraulic modeling of the stream channel. Sediment transport dynamics will be modeled using auxiliary spreadsheet tools.

The *Clarks Creek Sediment Reduction Action Plan* (CCSRAP) modified a HEC-RAS model that was developed by the Federal Emergency Management Agency (FEMA) for a Flood Insurance Study (FIS) published in 2009 (BC 2013; FEMA 2009). Modifications to the HEC-RAS model included the addition of new cross-sections along Upper Clarks Creek (BC 2012a). The modified HEC-RAS model from the CCSRAP will be used as a starting point for this study and will be updated with additional cross-sections in key locations on Clarks Creek and its tributaries. In addition to updating geometric data, the HEC-RAS model will be refined by adjusting effective conveyance limits, Manning's roughness parameters, and energy loss coefficients to obtain reasonable agreement between measured and computed hydraulic characteristics. The project QAPP will identify locations for the new cross-sections and provide more detailed descriptions of the HEC-RAS modeling and magnitude-frequency analysis (MFA) approaches.

3.2 Model Application

The proposed sediment modeling approach will address the need to analyze the processes affecting bed sediment composition and examine how different management scenarios (such as *Elodea* removal) are likely to change the gradation of bed sediments.

The presence of *Elodea* dramatically affects the hydraulic characteristics of Clarks Creek by reducing flow velocities and the energy available to transport sediment. Thus, the reduction or removal of *Elodea* can have appreciable effects on the bed channel composition by mobilizing finer sediments. The County proposes to evaluate the effects of *Elodea* removal by performing sediment mobility calculations (e.g., incipient motion, saltation, suspension) for before-and-after scenarios for a full range of sediment particle sizes including sands and fine sediment.

The County also proposes to perform an MFA to evaluate long-term sediment transport and channel stability, which will be based on the methods developed for the *Clarks Creek Sediment Reduction Action Plan* (BC 2013; Wolman and Miller 1960). MFA requires three primary inputs: (1) hydraulic rating tables, (2) long-term streamflow hydrographs or flow durations, and (3) bed sediment gradation curves. The HEC-RAS model will be used to perform hydraulic analyses to support sediment mobility calculations and will be used to develop hydraulic ratings tables. The HSPF model developed for the TMDL will be used to generate the long-term streamflow data (Tetra Tech 2012). Bed sediment gradation will be developed from in-field sediment sampling.

The project QAPP will identify locations for sediment samples and provide more detailed descriptions of the sediment mobility and transport analyses.

Section 4: Data Availability and Needs

The DO modeling approach described in Section 2 requires a relatively large amount of hydrologic and water quality data for setup and calibration. For example, the HSPF water quality model requires meteorological data as input, and the prediction of constituent concentrations in runoff and groundwater should be corroborated against local data. Both the HSPF and QUAL2Kw models must be calibrated against streamflow and in-stream water quality data under different seasonal and hydrologic conditions. To address limitations of the previous modeling analysis, it will be necessary to collect data on effects such as SOD, diel variability in water quality, *Elodea*, and water quality delivered to Clarks Creek from major tributaries. This section reviews the different types of data required by the models and proposes a Comprehensive Monitoring Program to support the *Clarks Creek Restoration Plan* (County 2017).

Water quality, sediment, and flow monitoring have been conducted at various times and locations in Clarks Creek and its tributaries since 1983. However, the data were not collected under a comprehensive plan designed to support model application. The spatial and temporal mismatches between the collection of different types of data results in model uncertainty and limits the model applicability to exploratory and sensitivity analyses. The comprehensive monitoring approach proposed in this section was designed to provide concurrent flow and water quality data for mainstem Clarks Creek and its major tributaries (Rody, Diru, and Woodland Creeks), address the data gaps identified in Section 1.2, and provide confidence in establishing a better cause and effect relationship for watershed management solutions.

Table 4-1 summarizes the proposed monitoring program parameters and locations.

Table 4-1. Proposed Clarks Creek Monitoring Program

Monitoring Element	Number of Locations			Parameter											
	Mainstem	Tributary Creeks	Storm Drains	Flow	TSS	N&P	BOD	DO	Temp.	Cond.	Turbidity	pH	PSD	TOC	Biomass
Stream gauging (continuous)	1	3		✓											
Continuous (datasondes)	2	3						✓	✓	✓	✓	✓			
Automated sampling	3	1			✓	✓	✓			✓	✓	✓			
Synoptic sampling: dry weather	4	9			✓	✓	✓	✓	✓	✓	✓	✓			
Synoptic sampling: wet weather	7–10 total				✓	✓	✓	✓	✓	✓	✓	✓			
SOD sampling	4	3						✓							

Table 4-1. Proposed Clarks Creek Monitoring Program

Monitoring Element	Number of Locations			Parameter											
	Main-stem	Tributary Creeks	Storm Drains	Flow	TSS	N&P	BOD	DO	Temp.	Cond.	Tur-bidity	pH	PSD	TOC	Bio-mass
Biomass estimate	6	6													✓
Channel sediment sampling	4–6	4–6											✓		
Channel cross-section survey	10	9													
Stage/velocity and time of travel	3			✓											

TSS = total suspended solids; N&P = nitrogen and phosphorus; BOD = biological oxygen demand; PSD = particle size distribution; TOC = total organic carbon

The following sections further describe the types of monitoring data to be collected to support modeling as part of the 5-year reassessment.

4.1 Reach Characteristics

Both HSPF and QUAL2Kw require information on stream channel cross-section geometry and bottom characteristics. Similarly, HEC-RAS requires channel geometry and hydraulic parameters to estimate flow velocities and shear stresses exerted by various stream discharges. Cross-section surveys will be conducted at locations in the stream network additional to those cross-sections that were obtained for the *Clarks Creek Sediment Reduction Action Plan* (BC 2013). Approximately 20 new cross-section surveys will be conducted primarily in the upper reaches of tributaries to Clarks Creek.

Manning's roughness coefficients will be estimated based on field observations at each cross-section. Observations will use the general method of Chow, which accounts for several factors, including channel material, degree of irregularity, variation in channel cross-section, obstructions, vegetation, and meandering (Chow 1959).

4.2 Streamflow

Previous modeling was limited by the lack of streamflow data on the upper mainstem and tributaries. The U.S. Geological (USGS) gage site on the mainstem at Tacoma Road has also had data concerns in the past due to large variations in stage height resulting from *Elodea* growth (and removal) impacting the validity of rating curves. The proposed monitoring program will establish continuous stream gaging sites near the mouths of Rody, Diru, and Woodland creeks as well as the upper mainstem of Clarks Creek. USGS staff will increase the frequency of rating curve analysis at the USGS gage site to improve data reliability. County staff will coordinate USGS activities with scheduled *Elodea* removal.

Continuous streamflow data will be used to develop a flow balance for the watershed, accounting for diffuse inflows/abstractions and point sources (e.g., fish hatcheries). Headwater flows for the mainstem and tributaries will be estimated based on the contributing drainage area at the same ratio of flow to area calculated from the gaging stations located downstream. Diffuse sources (either inflow or abstraction) will be applied proportionate to model reach length.

4.3 Stage/Velocity and Time of Travel

Creek stage/velocity and time-of-travel measurements will be collected at three mainstem streamflow monitoring sites before and after annual *Elodea* removal activities. These measurements will support the assessment of *Elodea* growth effects on stream hydraulics.

A time-of-travel study is recommended to support calibration/corroboration of the stream hydraulic simulation. The study will be performed using a slug release of a small amount of fluorescent dye near the headwater of Clarks Creek. Continuously recording in situ fluorometers will be located at each monitoring location. The mean travel time for the mainstem flow is the difference in elapsed time when the centroid of the dye concentration curve passes each monitoring location. The time-of-travel study will be performed under moderate flow conditions with *Elodea* present. If resources allow, a second time-of-travel study will be performed after *Elodea* removal. Study methods will be consistent with USGS guidance for time-of-travel studies (USGS 1989).

4.4 Meteorology

HSPF and QUAL2Kw require time series data inputs representing precipitation and potential evapotranspiration (PET) at a minimum over the watershed. In addition, time series data inputs for air temperature, dew point, wind speed, cloud cover, and solar radiation are required to simulate stream water temperature. Long-term time series are desirable to perform simulations that reflect a wider range of potential conditions. Table 4-2 and Table 4-3 summarize the meteorological data sources available for this effort.

Table 4-2. Meteorological Data Sources

Data	Model Units	Calibration Period Data Source	Long-term Simulation Data Source [a, b]	Source for Filling Data Gaps
Precipitation	inch(es) per hour	WSU Puyallup	Sea-Tac, WSU Puyallup, McMillin Reservoir, Canyon Road	Neighboring gages, based on the closest gage with available data (WSU Puyallup, Sea-Tac, or King County)
PET	inch(es) per hour	WSU Puyallup [c]	WSU Puyallup	Monthly average value
Air temperature	degree(s) Fahrenheit	WSU Puyallup	Sea-Tac, WSU Puyallup	Average of adjacent time steps; monthly average for large data gaps
Dew point temperature	degree(s) Fahrenheit	WSU Puyallup	Sea-Tac, WSU Puyallup	Average of adjacent time steps; average monthly daily minimum temperature for large data gaps
Wind speed	mile(s) per hour	WSU Puyallup	Sea-Tac, WSU Puyallup	Average of adjacent time steps; neighboring gages for large data gaps
Cloud cover	Tenths of sky dome (0–10)	Sea-Tac [d]	Sea-Tac	Mean monthly cloud cover estimates based on two cloud cover values: (a) 1 for days without precipitation; and (b) 1 for days with precipitation
Solar radiation	Langley per hour	WSU Puyallup	Sea-Tac, WSU Puyallup	Average of adjacent time steps; monthly average for large data gaps

a. Data sources are in addition to the calibration period data sources.

b. Pre-2010 data are from City of Puyallup 4th Ave. Model Calibration effort (Puyallup.wdm) or King County (Prec.wdm).

c. The daily PET series will be the WSU Puyallup station reported ET_r, divided by 0.85 to get pan evaporation, and then multiplied by a pan evaporation coefficient 0.75 to get PET. WSU Puyallup = Washington State University Agricultural Weather Network, Puyallup station (elevation 34 feet); generally, data are available from 1999–2015.

Table 4-2. Meteorological Data Sources				
Data	Model Units	Calibration Period Data Source	Long-term Simulation Data Source [a, b]	Source for Filling Data Gaps

d. Sea-Tac = National Weather Service Sea-Tac International Airport monitoring station (elevation 433 feet); generally, data are available from 1948–2015.

Table 4-3. Precipitation Data Sources		
Time Frame	Gage Location	wdm File History
10/1948–9/1961	Sea-Tac International Airport	Added for Flood Insurance Mapping Study for Clear and Canyon Creeks (nhc 2003)
10/1961–11/1980	McMillin Reservoir	USGS model (Mastin 1996)
12/1980–11/1985	Sea-Tac International Airport	USGS model (Mastin 1996)
12/1985–9/1989	McMillin Reservoir	USGS model (Mastin 1996)
10/1989–9/1992	Canyon Road	USGS model (Mastin 1996)
10/1992–9/1999	McMillin Reservoir	Added for Flood Insurance Mapping Study for Clear and Canyon Creeks (nhc 2003)
10/1999–12/2010	WSU Puyallup	Added for *City of Puyallup Comprehensive Storm Drainage Plan* (BC 2012b)
1/2010–3/2013	WSU Puyallup	Added for City of Puyallup for 4th Ave. Calibration effort (BC 2014)

4.5 Water Quality

Water quality data will be collected at continuous monitoring stations, via datasondes and automatic samplers, and during higher-density synoptic grab sampling as summarized in Table 4-1. The water quality data collection approach was designed to address data gaps for tributaries, stormwater sources, and wet weather conditions. Monitoring parameters support the model selection and calibration scenarios discussed in Section 2.

Continuous datasonde monitoring locations will include two mainstem sites and three tributary sites. The datasondes will provide the primary data set for model development and calibration. Supporting wet weather total suspended solids (TSS), nutrient and BOD data will be collected by automated samplers targeting three storm events that are representative of different seasonal conditions. Automated samplers will be deployed at three mainstem locations and near the mouth of Rody Creek.

Synoptic surveys will provide water quality data at more locations throughout the watershed, specifically in locations farther upstream on the tributaries. Dry weather synoptic surveys will span a 24-hour period when several samplers collect concentrated data throughout the watershed. Two (minimum) synoptic surveys will be scheduled during relatively stable dry weather conditions. Another two (minimum) wet weather synoptic surveys will be coordinated with automated sampler deployment. Wet weather synoptic sampling locations will be field-determined but will include between 7 and 10 locations including both instream and stormwater runoff sites.

4.6 Sediment Oxygen Demand and Biomass Estimate

Initial modeling analyses suggest that SOD is an important contributor to low DO concentrations within the watershed. SOD sampling performed in 2011, using the preferred chamber method, was possible only in open patches on sand/mud or sand/gravel without significant amounts of submerged aquatic vegetation, so these measurements do not include the full SOD that may be exerted underneath *Elodea* mats. Total community substrate oxygen demand (CSOD) measurements used to address this issue do not provide a full measurement of the oxygen demand exerted by the combination of sediment and decaying organic material within *Elodea* mats and are highly uncertain.

SOD will be measured at four mainstem locations and each of the tributaries. SOD measurements included in the proposed monitoring program will be performed before and after *Elodea* removal activities, and in areas both prone and not prone to *Elodea* growth. Both in situ and lab-based SOD measurements will be considered. Based on previous experiences in Clarks Creek, high densities of *Elodea* are problematic for the deployment of in situ chambers, and so sediment incubation in the laboratory may be the preferred technique.

A biomass estimate will be performed in coordination with SOD sampling. Biomass, as quantified by ash-free dry mass (AFDM), will be measured at six representative sites on the mainstem of Clarks Creek and another six representative sites (total) on the tributaries. The biomass measurements will be based on macrophytes at *Elodea*-dominated sites and benthic algae at sites where macrophytes are not common. Field teams will estimate the percent coverage by different types of growth at each site.

4.7 Bed Sediment Material

Bed material samples will be collected at key points within Clarks Creek and its tributaries, focusing on areas where data gaps exist and areas with known aggradation or degradation. Samples will be collected and analyzed for particle size distribution at approximately 10 key locations in the watershed. The HEC-RAS model will be updated to incorporate these new data, as well as sediment data collected for the *Clarks Creek Sediment Reduction Action Plan* (BC 2013).

Section 5: Summary and Conclusions

This technical memorandum describes a comprehensive monitoring and modeling approach to characterize and understand the water quality dynamics of Clarks Creek. The approach will build upon the prior analyses by using available, similar models (e.g., HSPF, QUAL2Kw), and critical conditions of interest. However, the recommended program will also seek to fill data gaps that limited previous evaluations, and significantly enhance the model capabilities and calibration. The linked watershed-water quality modeling framework will allow the County to explore the benefits of various management scenarios to Clarks Creek. The development of a flow-variable water quality model is expected to greatly improve the County's ability to predict the magnitude, frequency, and duration of components of water quality. The link between runoff, tributary, and mainstem water quality will be much better characterized, as will the effects of *Elodea*. These capabilities, in turn, will greatly enhance decision-making on topics such as TMDL formulation and public investments in water quality.

This document provides an overview of the recommended modeling and monitoring approach, and is intended for building consensus between the County, Ecology, and other stakeholders on the technical path forward. After agreement on the basic approach, additional details will be provided in the project QAPP, which will provide more specific information on topics such as monitoring methods, quality assurance components, and model calibration targets. As the efforts proceed, we recommend documenting results at key milestones (e.g., QAPP development, model calibration, scenario development) and allowing review by key parties, before moving to the next step. This will ensure that each stage of the evaluation rests upon a technical consensus regarding the prior steps.

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