TETRA TECH

Memo

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Date: March 19, 2018

Subject: Green-Duwamish River Watershed HSPF Models (DRAFT)

Models are being developed for the Green-Duwamish River watershed to support a Pollutant Loading Assessment (PLA) study being conducted by the Washington Department of Ecology (Ecology) and the U.S. Environmental Protection Agency (EPA). The Green-Duwamish River watershed is identified on Washington's Clean Water Act (CWA) Section 303(d) list as being impaired by over 50 different pollutants, including both toxic and conventional parameters. Portions of the study area are also on the National Priorities List and are in various stages of cleanup and remediation of contaminated sediments under the Comprehensive Environmental Response, Compensation, and Liability Act ("Superfund"), and Washington State Model Toxics Control Act programs. The watershed models will be used to examine the relationships between sources and stores of toxic pollutants and ambient concentrations of those pollutants in water, sediment, and fish tissue in the Green-Duwamish River watershed and Lower Duwamish Waterway (LDW).

Initial work to develop the Green-Duwamish watershed models was completed by Tetra Tech under contract with U.S. EPA ending in March 2018. Continued development of the models will be undertaken by Ecology. This memorandum documents the status of the models and is intended to provide a guide for the handoff of the model to Ecology. Specifically, the memorandum documents recent work accomplished since the modeling report released in February 2017 (Tetra Tech, 2017), including model platform conversion, temporal extension, delineation and hydraulic refinements, and the addition of the sediment simulation.

1.0 CONVERSION TO HSPF

Tetra Tech initially developed two Loading Simulation Program - C++ (LSPC; USEPA, 2009) models were recently developed for the Green-Duwamish River watershed that represent the drainage area and stream network from the Howard Hanson Dam to the Puget Sound (Tetra Tech, 2017). Newaukum Creek, Soos Creek, Black River, and other major tributary streams to the Green-Duwamish River are included in the LSPC watershed models. LSPC code for hydrology is based on HSPF code and the models are readily inter-convertible.

At the request of Ecology, the hydrologically calibrated LSPC models were converted to four linked Hydrological Simulation Program – FORTRAN (HSPF; Bicknell et al., 2014) models (Figure 1-1). Delineated catchments and reaches from the LSPC models were renumbered for HSPF because the LSPC numbering scheme used six digit codes and numbering in HSPF is limited to three digit codes (Figure 1-2 - Figure 1-5). Upland Hydrologic Response Units (HRUs), which represent unique combinations of soils/geology, land use/cover, and weather zone, were also renumbered for this reason. Hydrology parameters from the calibrated LSPC models were implemented in HSPF. Other key components of the hydrology simulation, including meteorological forcing series, boundary conditions, groundwater transfers, water appropriations, and reach hydraulics, were transferred to the HSPF models.

The four HSPF models are linked through binary Watershed Data Management files (WDMs). Each upstream model writes full time series of hourly output to the WDM, which is read in as an external source by the downstream model.

As part of this effort, the HSPF models were extended through Water Year 2016 so that recently collected water quality samples can be utilized for model calibration. Meteorological time series, including precipitation, air temperature, solar radiation, wind travel, cloud cover, dew point temperature, and potential evapotranspiration, were extended following the methods documented in Section 4 of Tetra Tech (2017). Time series for boundary flows, surface water diversions, and streamflow reductions due to groundwater pumping were also extended using methods described in Sections 5 and 6 of Tetra Tech (2017).

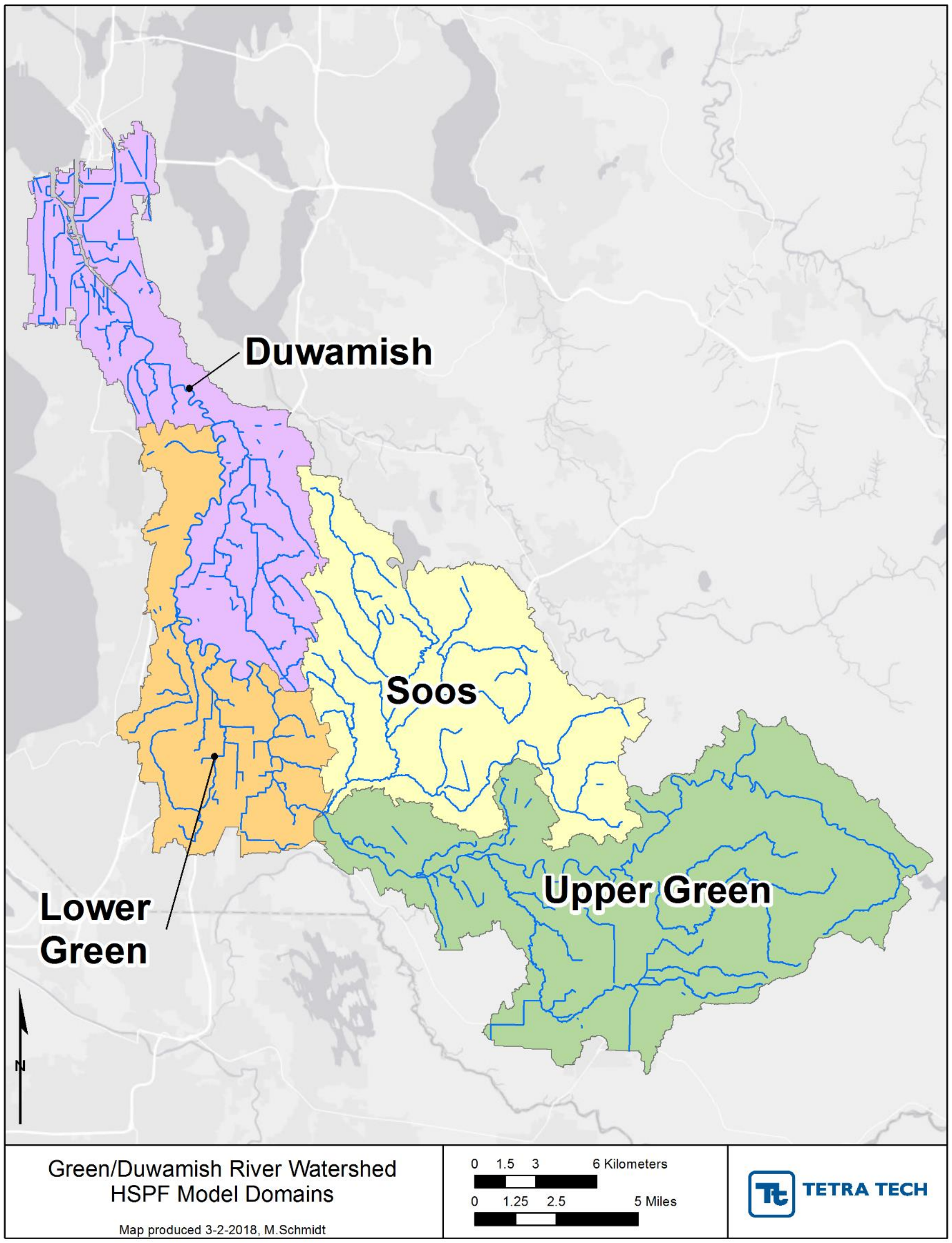
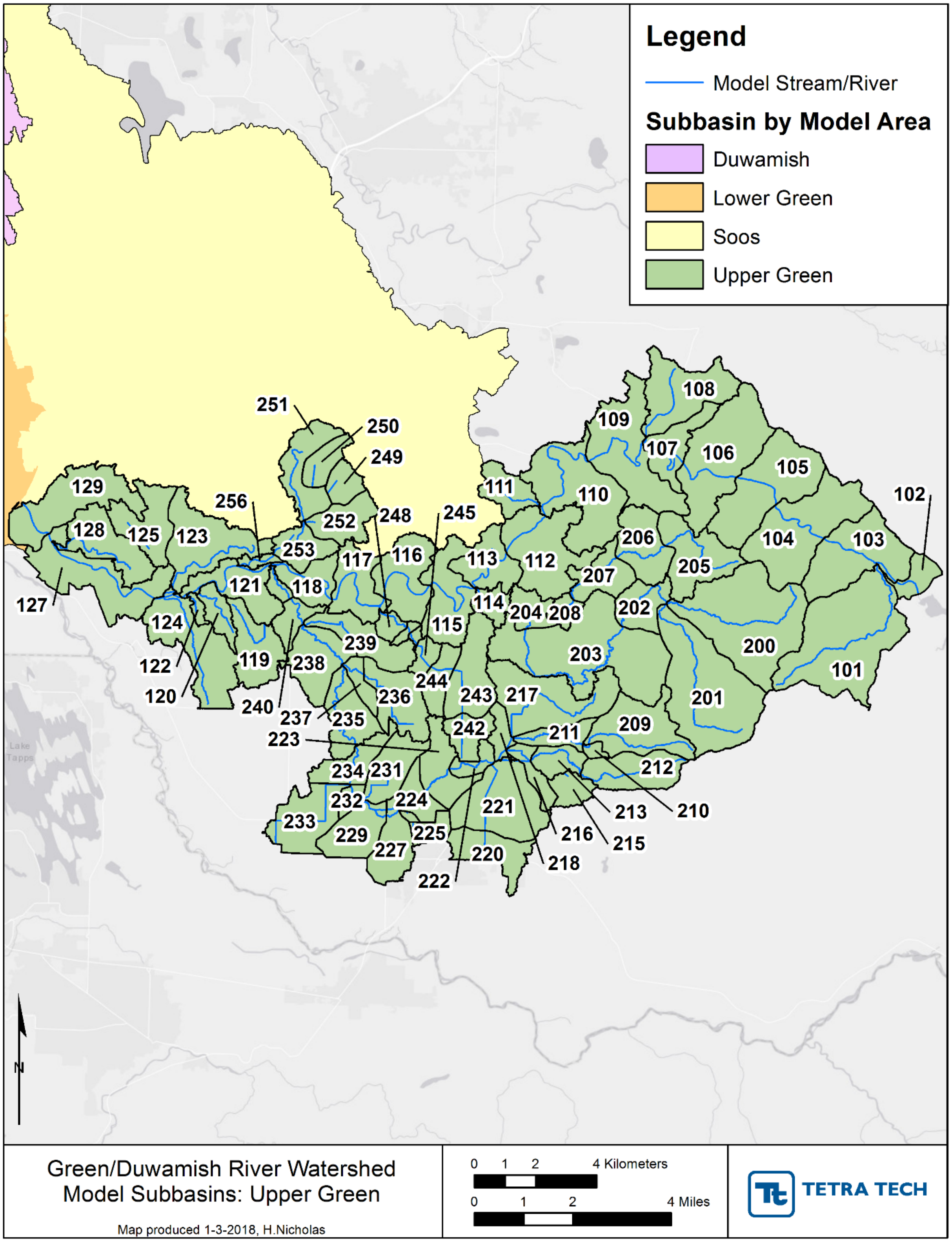


Figure 1-1. HSPF model domains for the Green-Duwamish River watershed



Green/Duwamish River Watershed
Model Subbasins: Upper Green

Map produced 1-3-2018, H.Nicholas

Figure 1-2. Upper Green River HSPF model extent

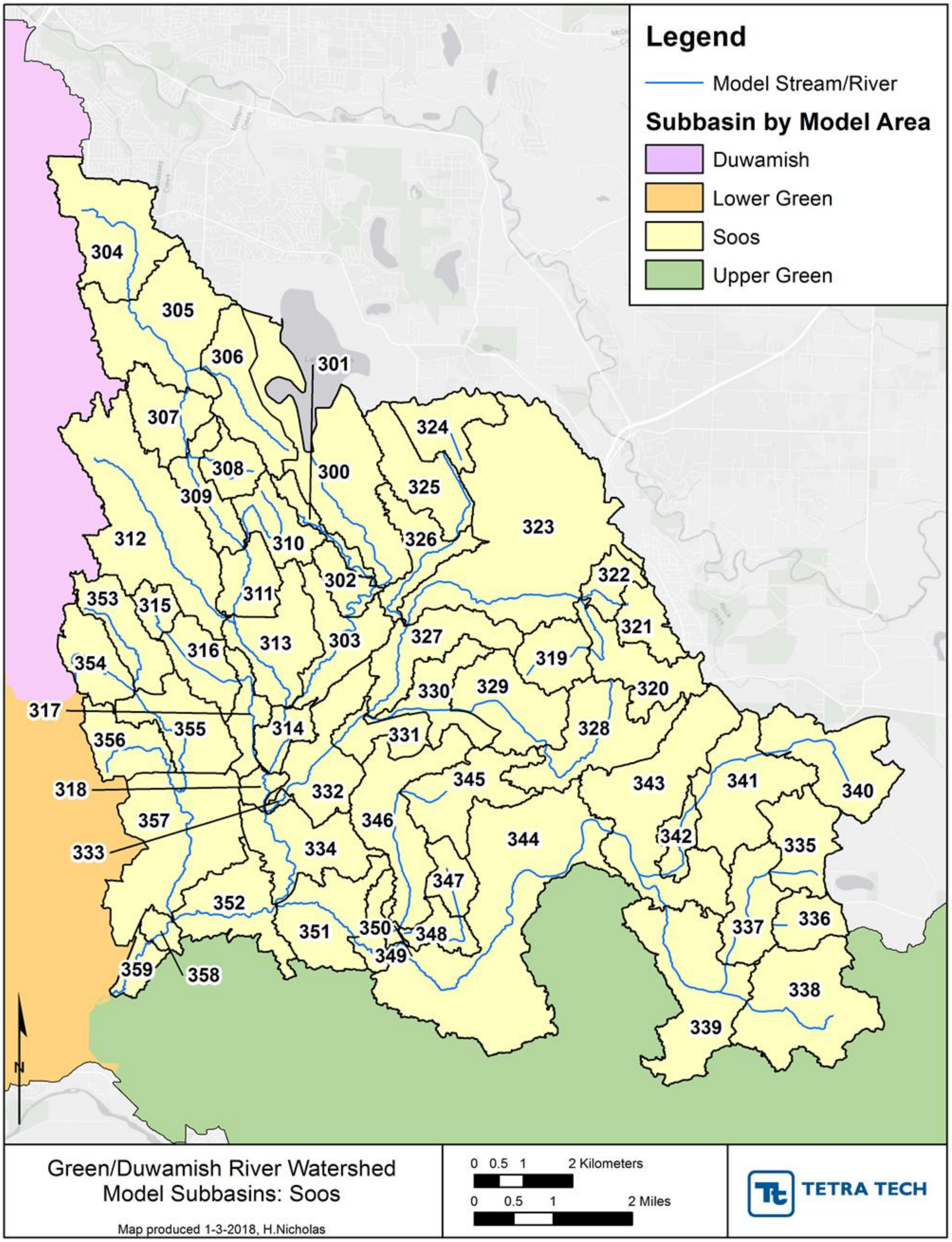


Figure 1-3. Big Soos Creek HSPF model extent

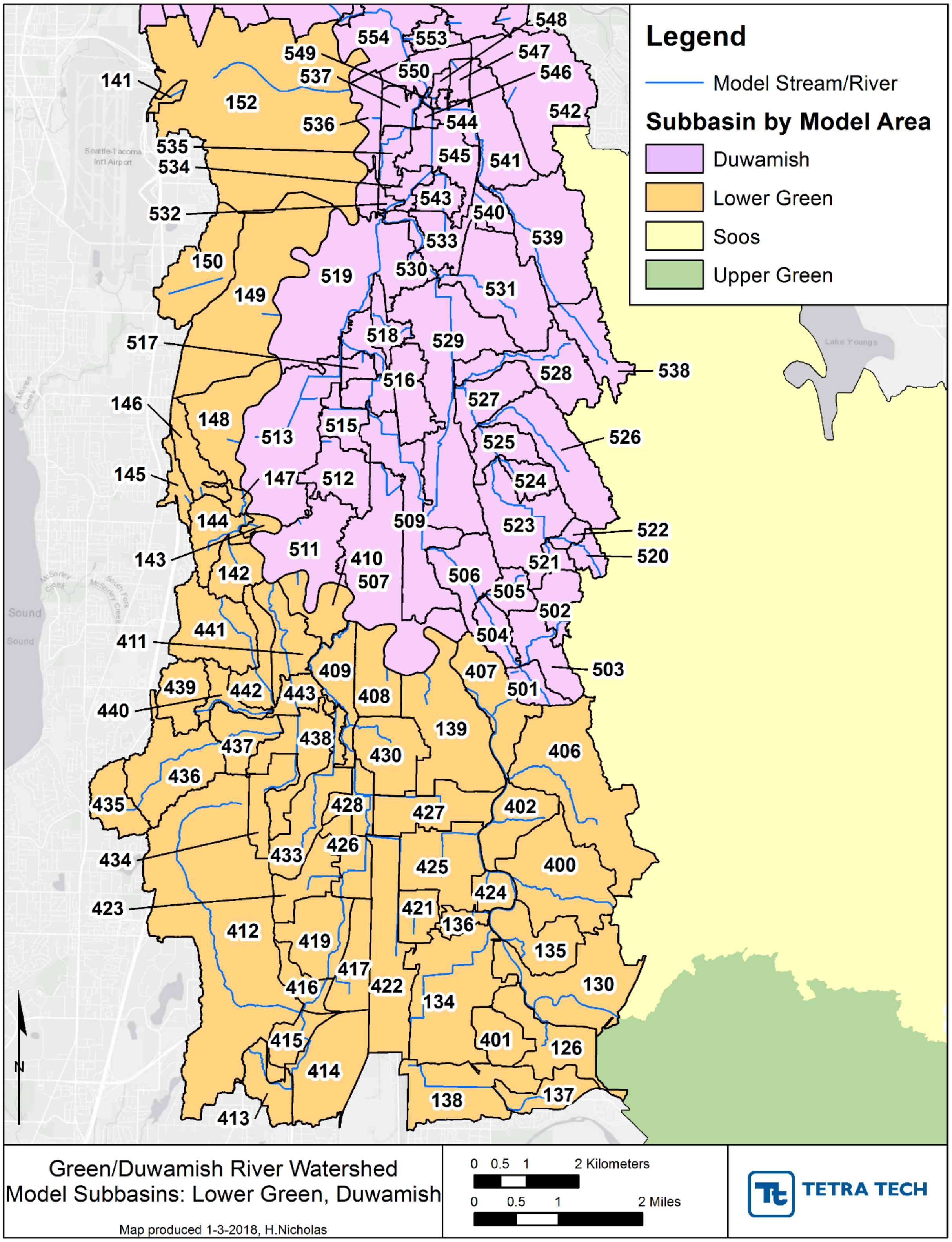


Figure 1-4. Lower Green River HSPF model extent

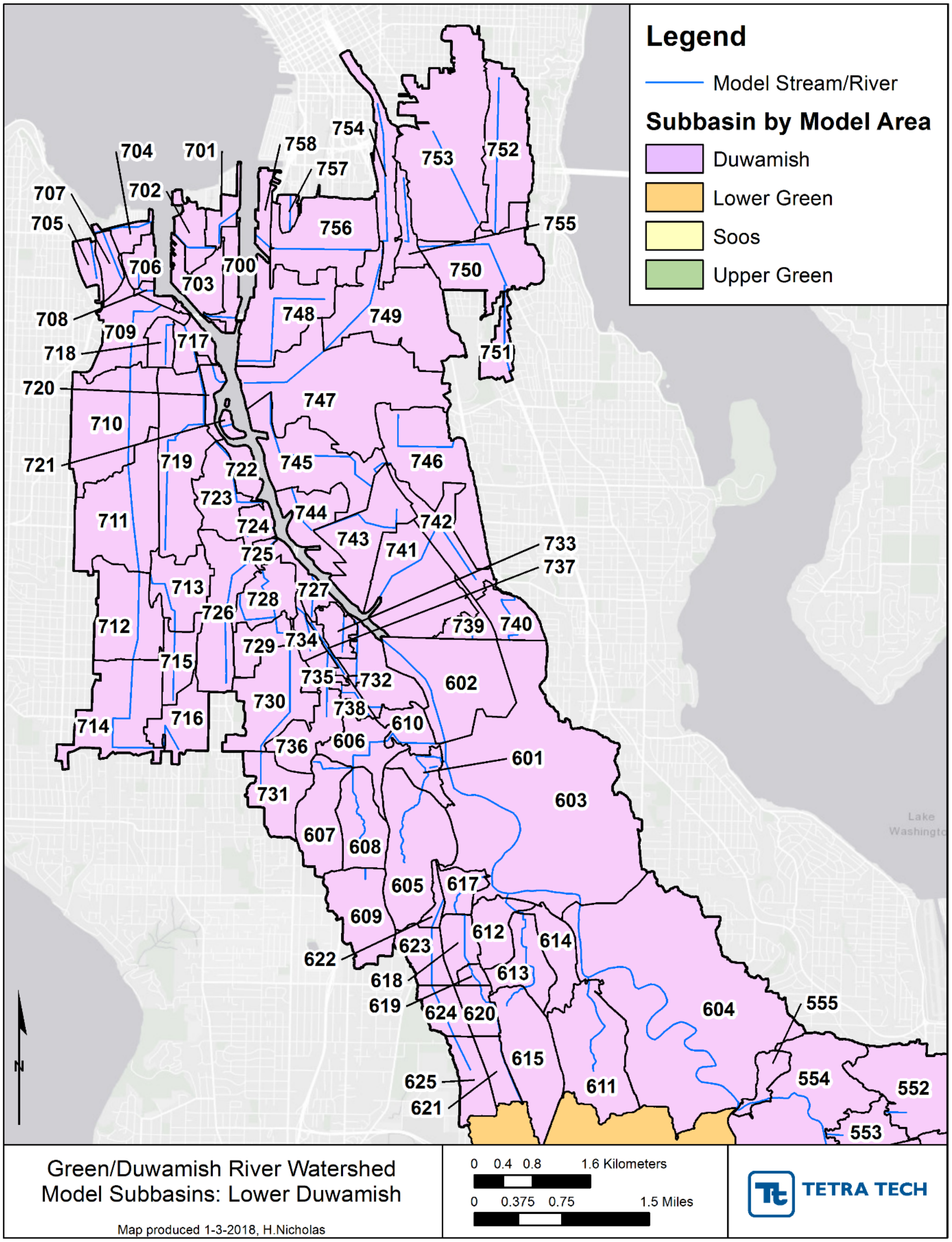


Figure 1-5. Duwamish River HSPF model extent

2.0 HYDROLOGY MODEL UPDATES

2.1 SUBBASIN AND REACH REFINEMENTS

Subbasin boundaries for the model area outside of the City of Seattle initially used the boundaries developed by King County for the WRIA 9 project (King County, 2013). The City of Auburn, WA, provided Washington Department of Ecology with stormwater related data, including a comprehensive stormwater management plan (Brown and Caldwell, 2015), several Storm Water Management Models (SWMM) of various locations in the City, and a GIS layer of drainage subbasins within the City. Examination of these materials indicated significant modification of natural flow pathways in the flat, low lying areas. The Auburn SWMM models and associated information were used to make updates to the HSPF model subbasins and reaches near Auburn. First, the boundary of the HSPF model was updated based on the Auburn information; some areas were added, while other areas were removed (Figure 2-1). Next, several sources of information were used together to determine the subbasin boundaries in the Auburn vicinity:

- GIS layer of drainage subbasins within the City
- GIS layers from SWMM models of subbasins, conveyances, and outfalls to streams
- King County GIS layer of watercourses
- Drainage Subareas map shown in the comprehensive stormwater management plan (Brown and Caldwell, 2015)

Primacy was given to the SWMM representation of subbasin boundaries and conveyance pathways. Next, the GIS layer of drainage subbasins was used for the interior portions of Auburn, with the King County watercourse layer providing reach locations. The boundaries of the Auburn drainage subbasins (which ended at City limits) did not exactly match the existing HSPF subbasin boundaries, so best professional judgment was used to combine the two into reasonable representation of subbasins. The Drainage Subareas map shown in the comprehensive stormwater management plan provided additional information for delineations at the edges of the Auburn data. Updated HSPF subbasins and reaches are shown in Figure 2-2.

The HRU coverage also needed to be updated due to changes in the model boundary near the City of Auburn. The HRU raster was extended to represent the area previously believed to drain to the White River following the original HRU processing approach (Tetra Tech, 2017). HRU areas for revised or new subbasins were then tabulated spatially and reassignments were made based on Effective Impervious Area (EIA) calculations (Tetra Tech, 2017). Reach parameters were also updated for model reaches with altered delineations.

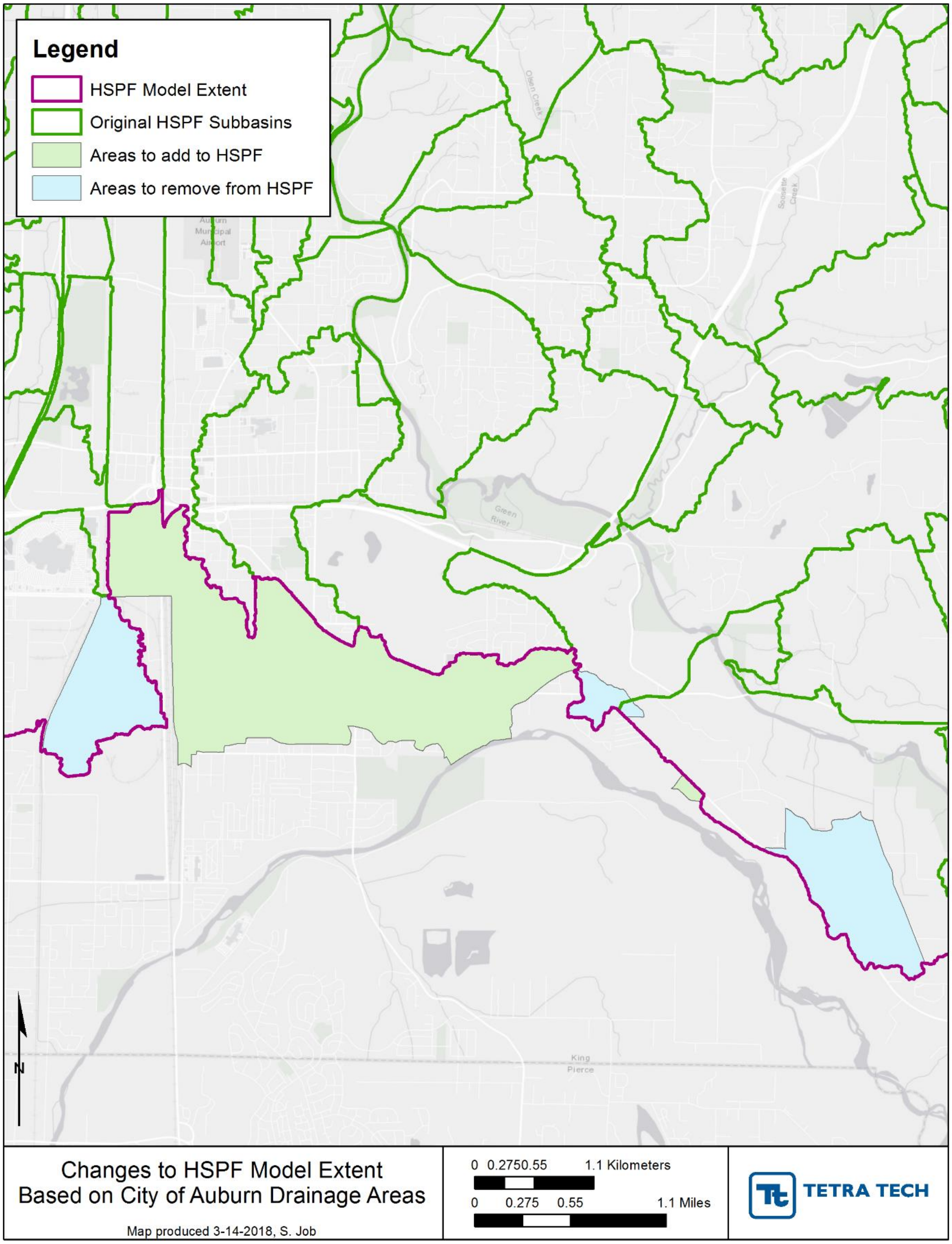


Figure 2-1. Updates to HSPF Model Boundary near Auburn

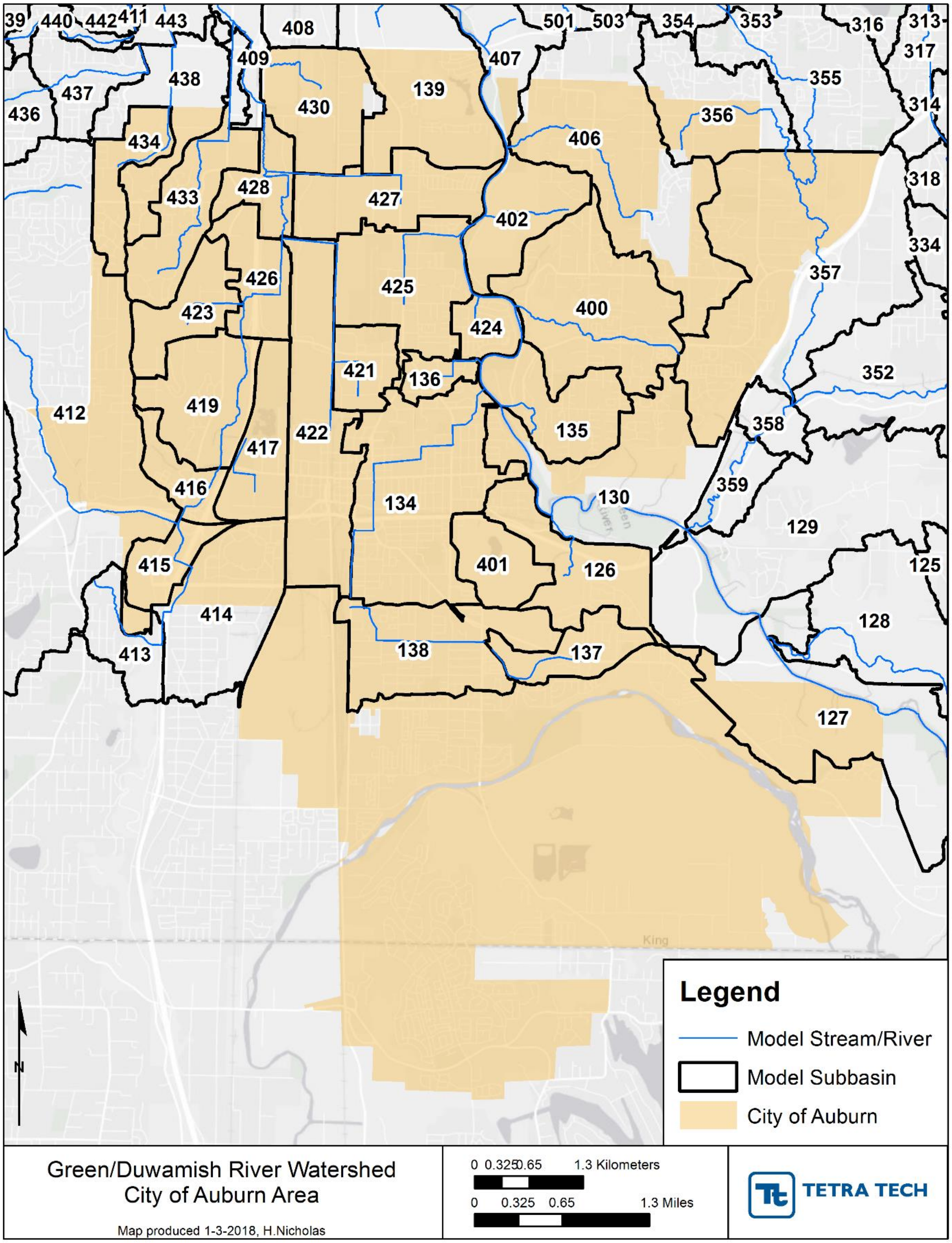


Figure 2-2. Revised HSPF model subbasins in the City of Auburn area

2.2 REACH HYDRAULICS

Hydraulic relationships were defined for new or altered reaches using a variety of methods. Because HSPF is a water balance (hydrologic) model and not a hydraulic model, stream reaches are represented as one-dimensional fully mixed reactors that maintain mass balance but do not explicitly conserve momentum. To simulate the details of hydrograph response to storm events HSPF relies on Functional Tables ("FTables") that describe the relationships of reach discharge, depth, and surface area to storage volume. At stable flow conditions, the model results are not particularly sensitive to the details of the FTable specification, as outflow tends to approximate the net inflows; however, the shape of the response to storm event peaks can be highly sensitive to FTable details.

The HSPF model (as does LSPC) requires explicit representation of FTables in the model input file. A variety of quantitative approaches were used to generate new FTables in the portion of the model affected by the updates near the City of Auburn. These include extracting information from calibrated HEC-RAS and SWMM models, representing large infiltration basins explicitly, using USGS and King County gage rating tables, and implementing the standard BASINS approach paired with regional hydraulic geometry relationships.

2.2.1 HEC-RAS Models

The lower and middle Green River HEC-RAS model (King County, 2010) was used to derive FTables for thirteen LSPC model reaches (Tetra Tech, 2017). To do this, a range of flow events were simulated under steady-state conditions as described in Section 7.1 of Tetra Tech (2017). Discharge was evaluated at cross sections that traverse the model reach and storage volume and area were summed along the length of the reach. HEC-RAS based FTables were recalculated for four mainstem model reaches that were affected by the delineation updates: 130, 131, 132, and 133.

2.2.2 SWMM Models

Brown and Caldwell (2015) developed a series of hydraulic models for drainage basins within the Auburn area using the SWMM version 5 modeling platform (Rossman, 2015). Like HEC-RAS, results from the SWMM model simulations are used to create reach/conveyance information for FTables. The SWMM models cover subbasins 134, 136, 417, 425, and 427 as shown above in Figure 2-2. One of the models also encompasses subbasins 137 and 138, but these are represented by infiltration basins as described in the next subsection.

The SWMM models include a detailed representation of conveyances and divert pipe flow to surface ponding when inlet capacity is exceeded. The resulting relationships between discharge and total storage volume often show significant hysteresis, with different relationships on the rising and falling limbs of the hydrograph due to pipe and inlet limitations. HSPF summarizes hydraulics as a relationship between storage volume and discharge and cannot fully represent hysteresis that results from conveyance limits interior to an HSPF reach. Therefore, we represent the average trend by fitting a locally weighted regression line (LOESS; Cleveland and Devlin, 1988) through the model output. The LOESS smoothing parameter, α, which is equivalent to the fraction of the total number of points used in the local regression, was varied on a case-by-case basis to minimize the average absolute discrepancy between SWMM output and the smoothed line. An example is shown in Figure 2-3, in which the red LOESS line, based on local fit to a moving set of 100 out of 4,321 points ($\alpha = 0.023$) represents the compromise relationship between total storage in the reach and discharge at the outlet. In this example, storage in excess of 24,000 ft^3 results in some surface flooding which delays discharge on the rising limb of the hydrograph.

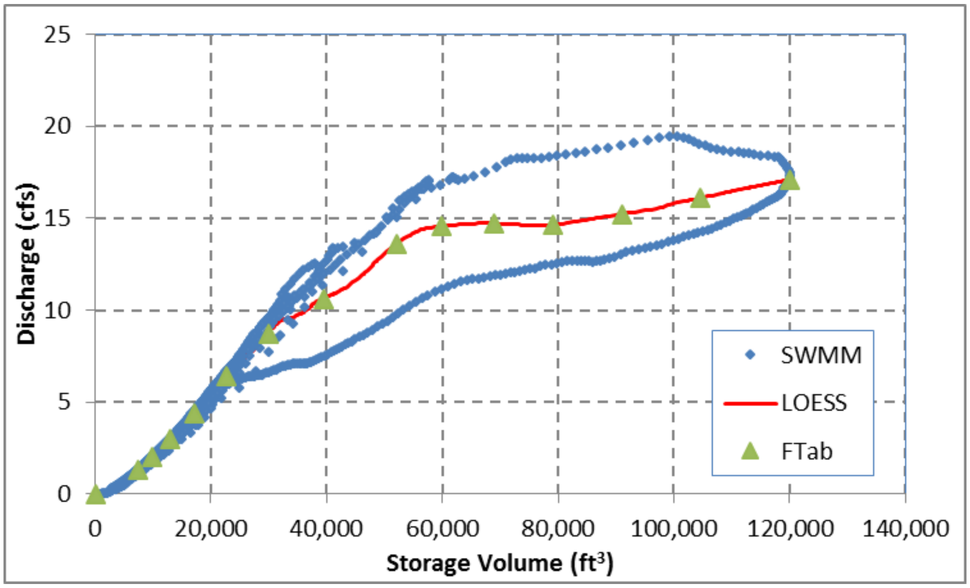


Figure 2-3. Example LOESS fit to SWMM output for HSPF Reach 417

2.2.3 Infiltration Basins

As described in the SWMM models, two subbasins drain to infiltration basins (137 and 138). Reach 138 drains to three infiltration basins, with infiltration and hydraulic properties contained within SWMM. Infiltration rates were specified as a function of stage, accounting for increasing surface area contact with increasing stage. Stage-area curves were also specified. The three infiltration basins were lumped into a single representative basin to simplify the HSPF model configuration. From the data provided in SWMM, stage, surface area, volume, and infiltration outflow were calculated for the FTable. A spillway configuration was not included in SWMM, so best professional judgment was used to estimate spillway outflow as a broad-crested weir. The resulting FTable has two exits – one for infiltration loss, and one for overflow to the downstream reach.

Reach 137 drains to a single infiltration basin. Properties of the infiltration basin were not available in SWMM, but the dimension of the basin could be estimated from GIS stormwater data. We assumed the reach 137 basins had the same properties as the reach 138 basins, but scaled proportionally to its smaller footprint. As was the case for reach 138, the reach 137 infiltration basin has two exits – infiltration loss and overflow to the downstream reach.

Groundwater contour profiles indicate that infiltration losses for reaches 137 and 138 likely flow northeastward feeding the mainstem Green River as baseflow. To represent this infiltration losses from these subbasins are routed to HSPF reach 130.

2.2.4 BASINS Approach Using Regional Regression

Where detailed hydraulic information is not available, regional hydraulic geometry regression equations were used for characterization of the remaining model reaches in the Auburn area. Bieger et al. (2015) provided the following equations for estimating bankfull width (W_m, in meters), and bankfull depth (Y_m, in meters) based on drainage area (DA, in square kilometers) within the Pacific Mountain System physiographic division:

$$W_m = 2.70 \cdot DA^{0.352}$$

$$Y_m = 0.30 \cdot DA^{0.213}$$

To develop FTables, the channel form is approximated as trapezoidal, with a flat bottom that is narrower than the top width. We also assume the following based in part on the standard method for FTables in BASINS Technical Note 2 (USEPA, 2007):

$m_F = 2.0$ (floodplain slope: inverse – expressed as run over rise)

$W_F = W_m$ (i.e., the bankfull width is the same as the floodplain side width)

$m_C = 1.5$ (channel side slope is assumed 1:1.5)

$Y_F = 1.25 \cdot Y_m$ (floodplain depth as a function of the channel depth)

Some algebraic manipulation can then be applied to estimate the bottom width of the channel:

b (bottom width of channel, ft) $= W_m - 2 \cdot m_c \cdot Y_m$

b' (bottom width of floodplain, ft) $= b + 2 \cdot m_c \cdot Y_F + 2 \cdot W_m$

This completes the bankfull geometry information. This information is then used in Tetra Tech's FTables_Batch Excel workbook, which calculates FTables based on the hydraulic geometry parameters and application of Manning's equation. In the absence of other information, Manning's roughness coefficient, *n*, is set to 0.04. A separate Manning's coefficient is assigned to overbank flow (defaulted to 0.06).

2.3 CHANGES TO FLOW CALIBRATION

The model revisions for the Auburn described in this section result in relatively small changes in the hydrologic calibration. The switch from LSPC to HSPF also causes changes. While LSPC and HSPF use the same algorithms, the resulting predictions are not identical. The primary cause of those differences is that various parts of the hydrologic simulation in HSPF are conducted using older single-precision FORTRAN code, while LSPC performs all calculations in higher-precision C++ code.

Comparison of the prior LSPC model calibration (Tetra Tech, 2017), the HSPF calibration prior to the Auburn updates, and the HSPF calibration after the Auburn updates is shown for stations in and around Auburn in Table 2-1. In general, the changes are small. Conversion from LSPC to HSPF resulted in the largest changes for Green River near Auburn – likely because of cascading small differences related to HSPF use of single precision code. Effects of the Auburn updates are most notable at the Mill Creek stations. Minor adjustments to hydrologic calibration may be considered but should proceed iteratively with the sediment calibration.

Table 2-1. Hydrologic Calibration Comparison

Statistic	LSPC	HSPF prior to Auburn Updates	HSPF after Auburn Updates
Green River near Auburn, USGS 12113000			
Error in total volume:	-5.47%	-8.40%	-8.24%
Error in 50% lowest flows:	-3.74%	-8.56%	-8.28%
Error in 10% highest flows:	-8.53%	-10.01%	-9.93%
Seasonal volume error - Summer:	-6.38%	-11.35%	-11.07%
Seasonal volume error - Fall:	0.05%	-3.30%	-3.10%
Seasonal volume error - Winter:	-6.05%	-8.81%	-8.68%
Seasonal volume error - Spring:	-9.73%	-11.93%	-11.82%
Error in storm volumes:	-12.49%	-13.15%	-13.06%
Error in summer storm volumes:	-9.30%	-11.11%	-10.13%
Nash-Sutcliffe Coefficient of Efficiency, E:	0.964	0.928	0.927
Baseline adjusted coefficient (Garrick), E':	0.853	0.799	0.799
Monthly NSE	0.978	0.967	0.968
Mill Creek at SR181, King Co. 41a			
Error in total volume:	-11.02%	-11.26%	-20.06%
Error in 50% lowest flows:	6.75%	6.03%	-5.02%
Error in 10% highest flows:	-3.29%	-3.15%	-13.47%
Seasonal volume error - Summer:	71.65%	70.85%	46.25%
Seasonal volume error - Fall:	-8.72%	-8.85%	-18.15%
Seasonal volume error - Winter:	-16.16%	-16.30%	-23.68%
Seasonal volume error - Spring:	-17.33%	-17.91%	-26.54%
Error in storm volumes:	38.37%	38.90%	15.06%
Error in summer storm volumes:	203.13%	201.03%	134.38%
Nash-Sutcliffe Coefficient of Efficiency, E:	0.676	0.671	0.689
Baseline adjusted coefficient (Garrick), E':	0.517	0.515	0.519

Statistic	LSPC	HSPF prior to Auburn Updates	HSPF after Auburn Updates
Monthly NSE	0.899	0.898	0.844
Mill Creek at Peasley Canyon, King Co. MF1			
Error in total volume:	-4.94%	-5.12%	-10.82%
Error in 50% lowest flows:	26.51%	25.42%	23.47%
Error in 10% highest flows:	-5.58%	-5.42%	-12.37%
Seasonal volume error - Summer:	16.94%	16.09%	9.92%
Seasonal volume error - Fall:	3.97%	3.91%	-3.42%
Seasonal volume error - Winter:	-7.06%	-7.16%	-12.12%
Seasonal volume error - Spring:	-23.48%	-23.98%	-28.15%
Error in storm volumes:	1.15%	1.24%	-14.30%
Error in summer storm volumes:	57.23%	52.58%	21.10%
Nash-Sutcliffe Coefficient of Efficiency, E:	0.763	0.763	0.769
Baseline adjusted coefficient (Garrick), E':	0.602	0.603	0.618
Monthly NSE	0.883	0.883	0.872
Mill Creek at Peasley Canyon RD, King Co. 41c			
Error in total volume:	-3.66%	-3.78%	0.34%
Error in 50% lowest flows:	-3.12%	-3.87%	-0.29%
Error in 10% highest flows:	-7.20%	-7.10%	-2.95%
Seasonal volume error - Summer:	18.05%	17.51%	21.54%
Seasonal volume error - Fall:	9.97%	9.88%	14.72%
Seasonal volume error - Winter:	-12.33%	-12.38%	-8.57%
Seasonal volume error - Spring:	-7.75%	-8.06%	-4.27%
Error in storm volumes:	-3.24%	-2.89%	0.99%
Error in summer storm volumes:	45.97%	44.49%	48.72%
Nash-Sutcliffe Coefficient of Efficiency, E:	0.836	0.836	0.840
Baseline adjusted coefficient (Garrick), E':	0.712	0.712	0.706

Statistic	LSPC	HSPF prior to Auburn Updates	HSPF after Auburn Updates
Monthly NSE	0.894	0.894	0.899
Olson Creek, King Co. 32c			
Error in total volume:	9.15%	9.10%	11.05%
Error in 50% lowest flows:	93.93%	93.76%	97.44%
Error in 10% highest flows:	-8.49%	-8.40%	-7.69%
Seasonal volume error - Summer:	216.18%	216.31%	211.33%
Seasonal volume error - Fall:	339.15%	337.64%	307.58%
Seasonal volume error - Winter:	19.94%	19.91%	21.14%
Seasonal volume error - Spring:	-15.76%	-15.83%	-12.28%
Error in storm volumes:	-22.14%	-21.72%	-25.43%
Error in summer storm volumes:	212.43%	205.09%	114.55%
Nash-Sutcliffe Coefficient of Efficiency, E:	0.797	0.800	0.793
Baseline adjusted coefficient (Garrick), E':	0.686	0.687	0.683
Monthly NSE	0.900	0.900	0.902

3.0 SUSPENDED SEDIMENT

The next step in the development of the Green-Duwamish watershed models is set-up and calibration for sediment. Sediment is one of the more difficult water quality constituents to represent accurately in watershed and stream models. Important aspects of sediment behavior within a watershed system include loading and erosion sources, delivery of these eroded sediment sources to streams, drains and other pathways, and subsequent instream transport, scour and deposition processes (USEPA, 2006).

Sediment calibration for watershed models involves numerous steps in estimating model parameters and determining appropriate adjustments needed to ensure a reasonable simulation of the sediment sources on the watershed, delivery to the waterbody, and transport behavior within the channel system. Rarely is there observed local data at sufficient spatial detail to obtain a unique calibration for all parameters for all land uses and each stream and waterbody reach. Consequently, model users focus the calibration on sites with observed data and review simulations in all parts of the watershed to ensure that the model results are consistent with field observations, historical reports, and expected behavior from past experience (Donigian and Love, 2003, AQUA TERRA, 2012).

Sediment calibration requires an iterative approach. The first step involves refining the upland sediment yields to values that align with reference and field data. The instream simulation is then tuned; this involves analyzing the shear stress simulation in the reaches and setting scour and deposition thresholds to expected typical values.

Next, the long-term behavior of sediment in the channels is constrained to ensure that degradation or aggradation amounts are physically realistic and consistent with available local information. The relative contribution of upland versus channel-derived sediment is calculated and adjustments made to achieve a balance that matches local data. The last component of the sediment calibration is to compare instream modeled sediment to stream samples that were gathered during the calibration period. The sediment parameters are refined after comparing modeled and observed sediment concentrations at the monitoring stations, as discussed in subsequent sections.

At this stage, only preliminary efforts at sediment calibration have been conducted – in part because the instream sediment monitoring database only recently became available.

3.1 PARAMETERIZATION

The initial sediment parameterization for the Green-Duwamish River watershed HSPF models was established from existing local HSPF models (King County, 2013) and BASINS/HSPF guidance documentation (AQUA TERRA, 2012; USEPA, 2006). The upland parameters for sediment are often differentiated by soil, topographic properties, and land use. HSPF simulates sediment yield to streams in two stages. First, HSPF calculates the detachment rate of sediment by rainfall (in tons/acre/hour) as

$$DET = (1 - COVER) \cdot SMPF \cdot KRER \cdot P^{JRER}$$

where *DET* is the detachment rate (tons/acre/hour), *COVER* is the dimensionless factor accounting for the effects of cover on the detachment of soil particles, *SMPF* is the dimensionless management practice factor, *KRER* is the coefficient in the soil detachment equation, *JRER* is the exponent in the soil detachment equation, which is recommended to be set to 2.0 (AQUA TERRA, 2012), and *P* is precipitation depth in inches over the simulation time interval. Direct addition of detached sediment (e.g., from wind deposition) can also be added via the parameter *NVSI,* and rates from local models were applied initially (King County, 2013) and then calibrated (note that *NVSI* has been adjusted in the Upper Green, Soos, and Lower Green HSPF models but not in the Duwamish HSPF model, although adjustments are likely warranted as Ecology progresses the sediment calibration). Actual detached sediment storage available for transport (*DETS*) is a function of accumulation over time and the reincorporation rate, *AFFIX,* which has a reasonable range from 0.001 to 0.1 per day (AQUA TERRA, 2012).

DET is similar in concept to the Universal Soil Loss Equation (USLE; Wischmeier and Smith, 1978), which predicts sediment detachment as a function of is the rainfall erosivity, *RE*, a soil erodibility factor, *K*, a length-slope factor, *LS*, a cover factor, C*,* and a practice factor, *P*:

$$DET = RE \cdot K \cdot LS \cdot C \cdot P.$$

Within the HSPF model, the parameter *KRER* refers to the erodibility or detachment coefficient dependent on soil properties, and can be specific uniquely for each PERLND unit. Based on EPA BASINS Technical Note 8 on “Sediment Parameter and Calibration Guidance for HSPF”, *KRER* may be approximated as *Kffact (*e.g., USLE *K)* which is a generally available soil erodibility property provided in soil surveys and summarized in soil spatial databases. To assign values for *KRER* to each PERLND, spatial soils data was obtained to cover the entire watershed. High-resolution coverage was available from the Gridded Soil Survey Geographic (gSSURGO) Database for the majority of the watershed, which was downloaded from the USDA Data Gateway. Kffact data was processed for all available soils in the model extent as the whole soil, dominant component of the top 100 cm of soil. Approximately 40% of the watershed had no available Kffact data through gSSURGO where co-located with the “outwash” geology classification. In these areas with no gSSURGO data, Kffact data was estimated from the coarser resolution Digital General Soil Map of the United States (STATSGO2) which is also available through the USDA Data Gateway. Kffact for most areas of the watershed is low (<0.2), while some areas of higher erodibility (0.2 – 0.5) are located in the far southern part of the watershed, and along the urban corridor along Valley Freeway (Washington State Route 167).

Once *KRER* is established, the transport capacity for detached sediment from the land surface (*STCAP*) is represented as a function of overland flow:

$$STCAP = KSER \cdot (SURS + SURO)^{JSER}$$

where *KSER* is the coefficient for transport of detached sediment, *SURS* is surface water storage (inches), *SURO* is the depth of surface outflow of water (in/hr), and *JSER* is the exponent for transport of detached sediment.

The key parameters controlling channel erosion, deposition, and sediment transport within streams and rivers are as follows (USEPA, 2006):

KSAND: Sand transport is represented with a power function based on average velocity, such that carrying capacity for sand = *KSAND* x $AVVEL^{EXPSND}$. *KSAND* is set to 0.2 and *EXPSND* to 1.5 (King County, 2013) to start calibration and adjusted to improve the comparison between simulated and observed suspended sediment concentrations at flows where cohesive silt and clay sediments do not scour as well as to ensure a reasonable evolution of sand storage over time.

TAUCD: HSPF calculates bed shear stress (TAU) during each model time step for each individual reach. The critical bed shear stress for deposition (lb/ft^2) represents the energy level below which cohesive sediment (silt and clay) begins to deposit to the bed. Initial values of TAUCD for silt and clay were estimated by reach by examining the cumulative distribution function of simulated shear stress and setting the parameter to a lower percentile of the distribution in each reach segment, as recommended by USEPA (2006). The 20th percentile was used for clay and the 25th percentile for silt for free-flowing reaches.

TAUCS: The critical bed shear stress for scour (lb/ft^2) represents the energy level above which scour of cohesive sediment begins. Initial values of TAUCS were set, as recommended, at upper percentiles of the distribution of simulated shear stress in each reach (the 90th percentile for clay and the 95th percentile for silt for free-flowing reaches). Values for some individual reaches were subsequently modified during calibration.

M: The erodibility coefficient of the sediment (lb/ft^2-d) determines the maximum rate at which scour of cohesive sediment occurs when shear stress exceeds TAUCS. This coefficient is a calibration parameter. It was initially set to 0.01 for silt and clay, and then adjusted during calibration.

3.2 SEDIMENT SOURCES

3.2.1 Boundary Conditions

The upstream boundary of the Green River model is the outflow from Howard Hanson Dam. Tacoma Public Utilities (TPU) withdrawals water from the Green River a few miles downstream of the dam and monitors water quality of its supply prior to treatment. At the request of Ecology, TPU provided turbidity data monitored between November 2008 and June 2015 and intermittent TSS observations to help characterize loads associated with dam outflow (2010-2012, n = 62). Daily flow records were also available for a USGS gage located downstream of where TPU diverts flow from the river near Palmer, WA (USGS 12106700). Turbidity data were not available for the full simulation period of the HSPF model (1/1/1996 – 9/30/2017) so estimating TSS concentration from turbidity using either a relative ratio or derived regression was not adequate to establish loads for the full period. Instead a regression to estimate TSS concentration from observed daily flow was derived:

$$c = 0.8378e^{0.0009f}, R^2 = 0.51$$

where c is TSS concentration (mg/L) and f is mean daily flow at USGS 12106700 (cfs). The coefficient on flow is significantly different from zero ($p<0.0001$), but the predictive ability of the model is limited (Figure 3-1). The root mean squared error is 25,8 mg/L, but is strongly affected by one high outlier with an observed TSS concentration of 200 mg/L. Eliminating this outlier reduces the root mean squared error to 7.4 mg/L

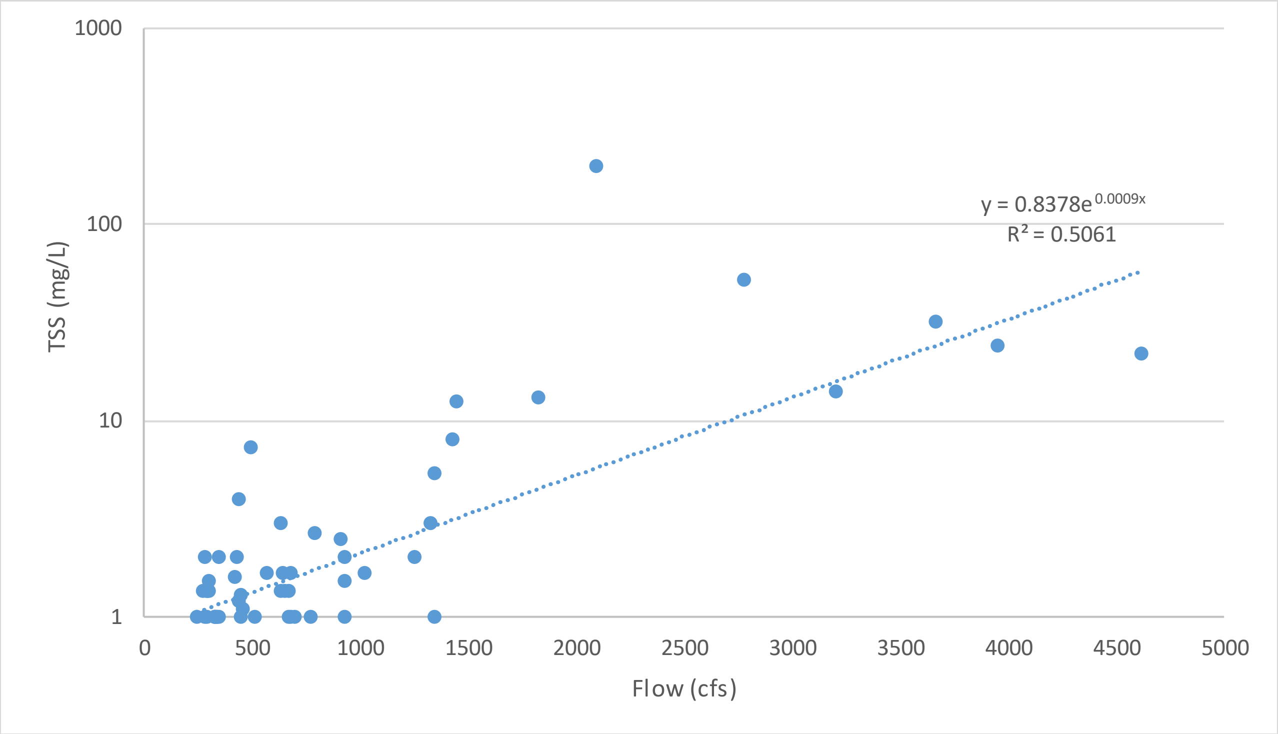


Figure 3-1. Regression Model for Predicting TSS in Discharge from Howard Hanson Dam

Estimated daily TSS concentrations (range 0.96 – 1184 mg/L, mean 6.81 mg/L) for the simulation period were paired with mean daily discharge at USGS 12106700 to compute the TSS (tons/day) boundary load time series for the model. Loads from the Howard Hanson Dam releases are input to reach 102 in the EXT SOURCES block of the Upper Green River HSPF model. Observed and model simulated TSS concentrations were compared for a calibration site on the upper Green River (reach 106) and as discussed in Section 3.3.3, results indicate that this approach provides a reasonable sediment boundary condition.

Outflow from Lake Youngs enters upper Little Soos Creek, which is represented in the Soos Creek HSPF model. Water quality monitoring records were not available for Lake Youngs so a constant TSS concentration of 1 mg/L was assumed to characterize the sediment load associated with Lake Youngs outflow. This estimate may be improved if lake or downstream monitoring data becomes available or it may need to be revisited by Ecology during the sediment calibration.

3.2.2 Upland Sediment Loading

Sediment on uplands is detached from the soil matrix by rainfall impact and transported to the stream network with runoff. Parameters governing the representation of these processes in HSPF are described in Section 3.1. Sediment loads from upland classes in the model should reflect differences in vegetative cover, soil type, and land slope. Upland sediment loading rates simulated by each model should be compared to reference rates found in the literature, and parameters calibrated to provide a reasonable representation of sediment derived from uplands. We modified upland sediment parameters in the Upper Green, Soos, and Lower Green models based on values reported in local modeling studies, which are summarized in Table 3-1. These HSPF models have not been fully calibrated for sediment at this time, and no changes have been made to the initial set of upland sediment parameters in the Duwamish model. The upland representation should be further enhanced for all four models. As discussed in Section 3.4, an iterative approach for adjusting the upland and instream sediment simulation should be implemented. Mean annual loading rates for the current version of the Upper Green River model are shown Figure 3-2. The simulated rates are generally consistent with the reference rates in Table 3-1.

The low loading rate predicted for barren land in this watershed reflects the fact that most of this land use consists of bare rock.

Table 3-1. Reference Upland Sediment Loading Rates

Land Use	Loading Rates (tons/ac/yr)		
	Minimum	Mean	Maximum
Agriculture	0.02	0.07	0.15
Commercial and industrial	0.36	0.36	0.36
Forest	0.00	0.03	0.15
High Density Residential	0.03	0.13	0.19
Low Density Residential	0.00	0.08	0.17

Sources: AQUA TERRA Consultants, 2003; Herrera Environmental Consultants, 2007; King County, 2013.

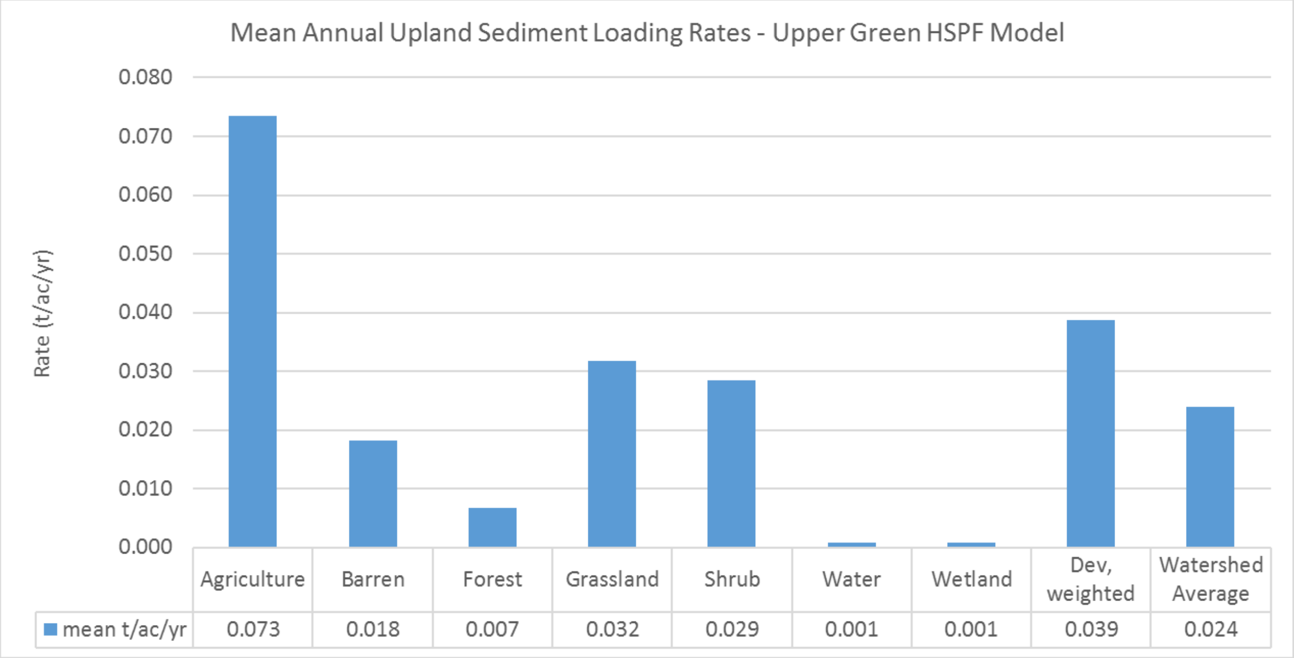


Figure 3-2. Mean Annual Upland Sediment Loading Rates for the Upper Green River HSPF Model (Initial Default Parameters)

3.2.3 Reach Sediment Balance

Net sediment scour and deposition should be analyzed on a reach-by-reach basis, consistent with recommendations in USEPA (2006), to ensure that significant amounts of scour and deposition occur only in areas where reasonably expected. Instream sediment parameters, including those discussed in Section 3.1, can be adjusted to improve the representation of scour and deposition within reach segments. As HSPF has a one-dimensional representation of stream reaches, all changes associated with deposition to or erosion of channel bed and banks are represented as a change in sediment thickness in the bed. Simulated change in bed depth of reaches is summarized by model in Table 3-2. Reaches in all four models exhibit reasonable change in bed depth due to sediment scour and deposition over the full 22-year simulation period. Additional checks on the reach sediment balance should be completed as the sediment calibration progresses.

Table 3-2. Simulated Change in Bed Depth for Reaches in the Green-Duwamish River HSPF Models (1996-2017)

Model	Change in Reach Bed Depth (ft)		
	Minimum	Mean	Maximum
Upper Green	-0.10	-0.01	0.02
Soos	-0.40	-0.03	0.05
Lower Green	-0.47	-0.03	0.19
Duwamish	-0.34	-0.02	0.00

3.3 INITIAL CALIBRATION TO SUSPENDED SOLIDS DATA

3.3.1 Calibration Sites

Total Suspended Sediment (TSS) data provided by Ecology was reviewed and processed to inform the sediment calibration and evaluation. Monitoring locations that had sufficient data to support the TSS calibration (minimum of 30 records collected during the simulation period) were identified and mapped in ArcGIS. Sites that did not align with a model reach were eliminated as potential calibration locations. Fifteen model reaches were established as TSS calibration sites (Table 3-3 and Figure 3-3). There were three reaches that aligned with multiple monitoring sites (model reaches: 153, 253, 710) and observed data from the corresponding monitoring sites were combined for these reaches.

Table 3-3. Monitoring sites for the Green-Duwamish HSPF model TSS calibration

Model Reach	HSPF Model	Monitoring Site ID(s)	TSS Sample Count	Start Date	End Date
106	Upper Green	9871	246	1/20/1997	9/11/2017
118	Upper Green	12307	130	1/14/2004	12/9/2015
129	Upper Green	3196	73	1/14/2004	12/9/2015
153	Lower Green	12301, 9865, 12297	374	1/22/1997	9/11/2017
240	Upper Green	12300	131	1/14/2004	12/9/2015
253	Upper Green	12299, 12312	98	1/14/2004	12/9/2015
303	Soos	12313	93	1/14/2004	12/9/2015
332	Soos	3399	125	1/14/2004	12/9/2015
344	Soos	12308	93	1/14/2004	12/9/2015
358	Soos	12306	128	1/14/2004	11/12/2015
409	Lower Green	12304	97	1/14/2004	12/9/2015
550	Duwamish	12298	130	1/14/2004	12/9/2015
604	Duwamish	12296	58	1/14/2004	12/3/2008
710	Duwamish	12309, 12556	251	1/14/2004	12/9/2015
711	Duwamish	12314	58	1/14/2004	12/3/2008

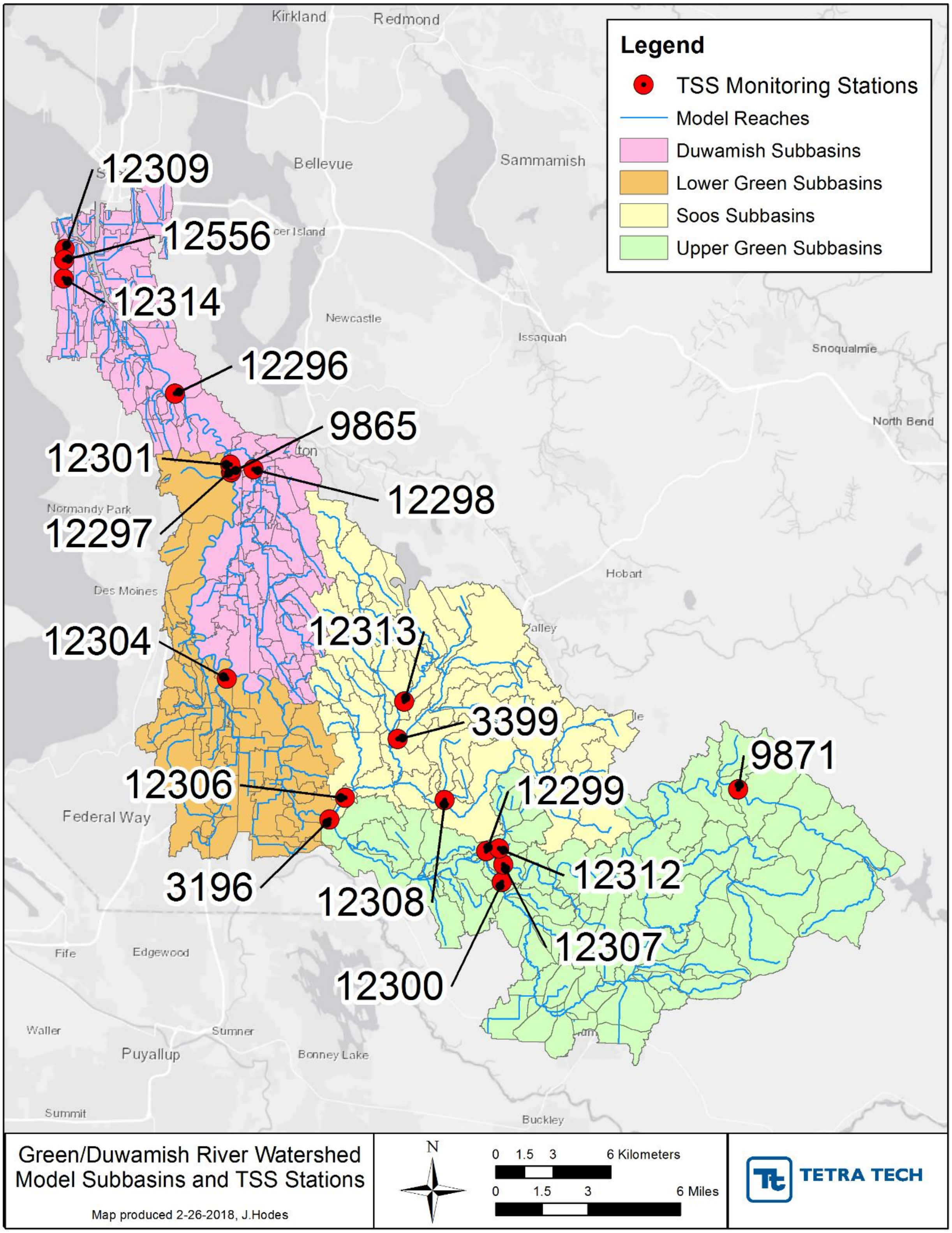


Figure 3-3. TSS Calibration Locations for the Green-Duwamish HSPF Models

3.3.2 Statistical Measures of Performance

Calibration for sediment and other water quality parameters differs from calibration for hydrology in that pollutant concentrations are in most cases not continuously monitored. Instead, observations typically provide measurements of conditions at a point in time and point in space via a grab sample. The discrete nature of these samples presents problems for model calibration: A sample that represents a point in time could have been obtained from a system where conditions are changing rapidly over time – for instance, the rising limb of a storm hydrograph. Such samples cannot be expected to be matched by a model prediction of a daily average concentration. On the other hand, there may be large discrepancies between dynamic model predictions of hourly concentrations and data that are a result of small timing errors in the prediction of storm event flow peaks. Spatially, grab samples reflect conditions in one part of a stream reach (which may or may not be composited over the width and depth of a cross section). HSPF model results, in contrast, represent average concentrations over the length of a stream reach which is assumed to be fully mixed. Model predictions and field observations inevitably have some degree of mismatch in space and time and, even in the best models, will not fully match. Accordingly, a statistical best fit approach is needed.

Performance targets for sediment calibration, based on Donigian (2000) and Duda et al. (2012), are summarized in Table 3-4. These performance targets are evaluated for both concentration and load (where load is estimated from concentration, on paired data), and should only be applied in cases where there are a minimum of 20 observations. Model performance is generally deemed acceptable where a performance evaluation of “good” or “very good” is attained.

Table 3-4. Performance Targets for HSPF Sediment Simulation (Magnitude of Relative Average Error (RE) on Daily Values)

Model Component	Very Good	Good	Fair	Poor
Suspended Sediment	≤ 20%	20 - 30%	30 - 45%	> 45%

3.3.3 Example Calibration Plots and Statistics

Suspended sediment calibration uses both visual and statistical approaches. Calibration should attempt to replicate the observed time series while at the same time minimizing relative errors associated with both concentration and load (as inferred from concentration and flow). Attention should be paid to matching observed and simulated relationships between load and flow through the use of power plots, while also examining the distribution of error terms relative to both season and flow. It is not uncommon for relative error to be strongly leveraged by one or more outliers (especially for load, which tends to be determined by concentrations at high flows); therefore, both the median error (which is not sensitive to outliers) as well as the average error should be reported. Performance targets for sediment calibration are discussed further in Table 3-4 in the previous section.

Example calibration plots are shown for Green River at model reach 106. This location is a short distance downstream of the Howard Hanson dam, which is used as the upstream boundary of the Green River in the HSPF model. As discussed in Section 3.2.1, a regression with flow as the independent variable was derived to estimate TSS concentrations in water released from the Howard Hanson Dam, and subsequently the mass of sediment entering the upstream boundary of the Upper Green HSPF model. As a result, the sediment from the upstream boundary dominates the simulated sediment concentration at reach 106. At this location, graphical and statistical summaries are essentially a measure of the goodness of fit of the derived upstream boundary time series. As one moves downstream, the contributing area plays a greater role for influencing sediment dynamics of the system.

A time series plot of modeled and observed TSS for reach 106 is shown in Figure 3-4 as an example. The range of concentrations predicted by the model match the range of observed values well. Modeled daily sediment load is plotted against flow in Figure 3-5, along with daily load estimated from grab sample monitoring. In general, a good match is obtained, though the observed data show more scatter than the modeled loads. Another useful diagnostic is a regression analysis on the load-flow plots. Ideally, observed and simulated data should show the same slope. A scatterplot of simulated load versus same day load estimated from point-in-time sampling shows good agreement (Figure 3-6), though the very highest loads (upper right corner of the plot) indicate some over-prediction by the model. Figure 3-7 is similar to Figure 3-5, but it shows concentration versus flow rather than load versus flow. Paired daily simulated and observed error versus flow is shown in Figure 3-8 which is useful for detecting bias in concentration across different flows. For the most part, concentration error does not appear to be biased across the range of flows, though there is some departure at the highest flows and a tendency for the model to over-predict loads. Table 3-5 provides statistical measures of performance for paired daily simulated and observed values. In this example, the calibration period is assumed to range from 2007 – 2017, while the validation period is set to 1997 – 2006. All of calibration statistics rate “Very Good”, and all the validation statistics rate “Very Good” except for the load average error, which rates “Poor” due to apparent over-estimation of TSS concentrations at the highest flows (Figure 3-8). This might be due to simulated channel bank scour or to the weaknesses of the boundary concentration regression. As noted previously, average load error is often influenced by a few outliers. It may also be the case that the TSS-turbidity relationship developed to represent the boundary sediment inflow does not predict high flow TSS well.

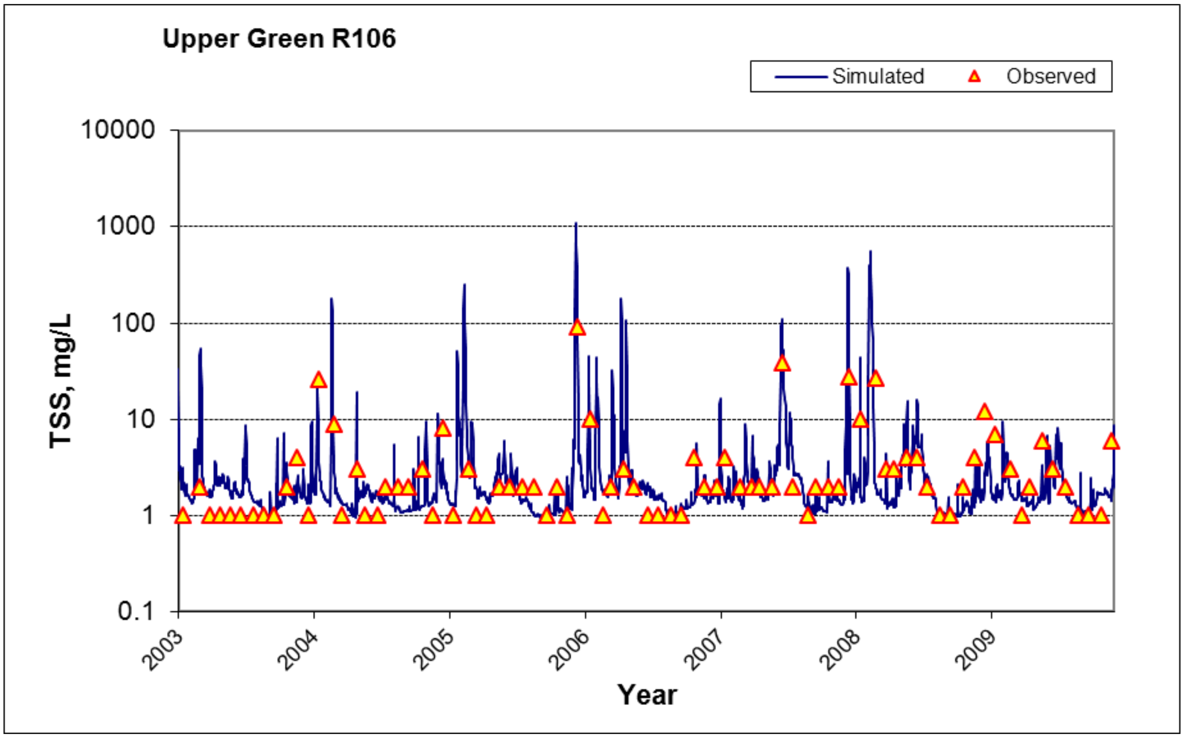


Figure 3-4. Time Series of Simulated and Observed Daily Average Sediment Concentrations for Green River Reach 106

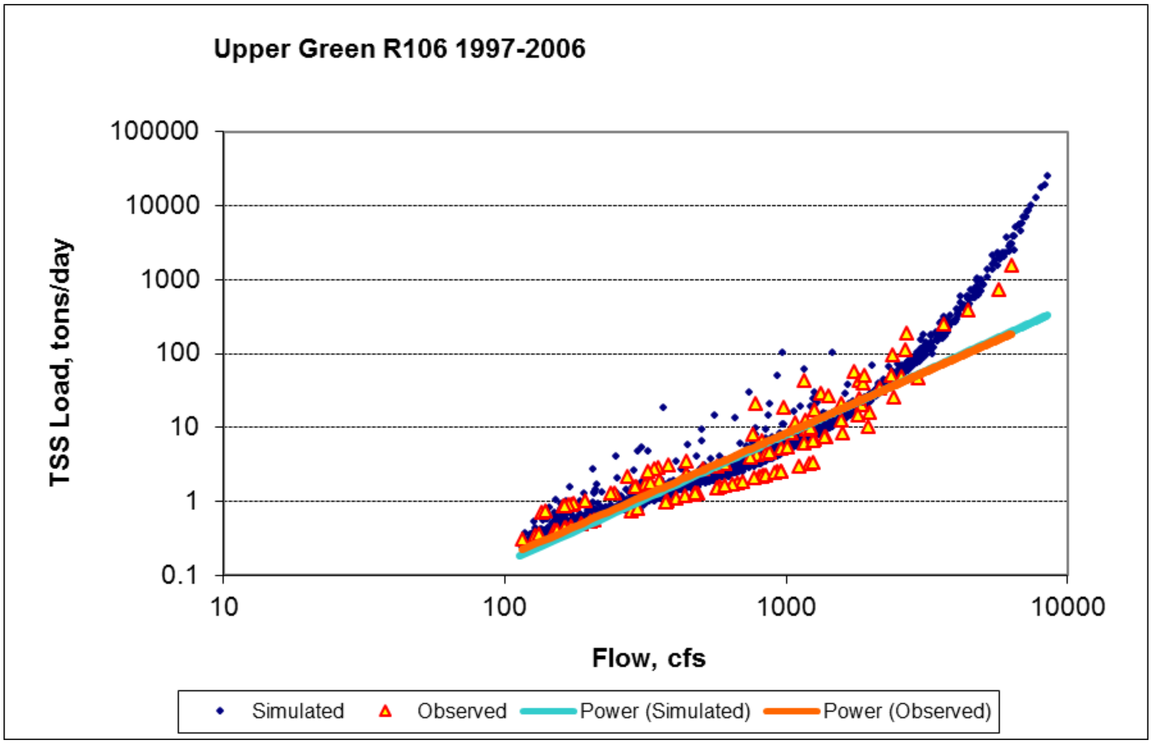


Figure 3-5. Sediment Load versus Flow, Green River, Reach 106

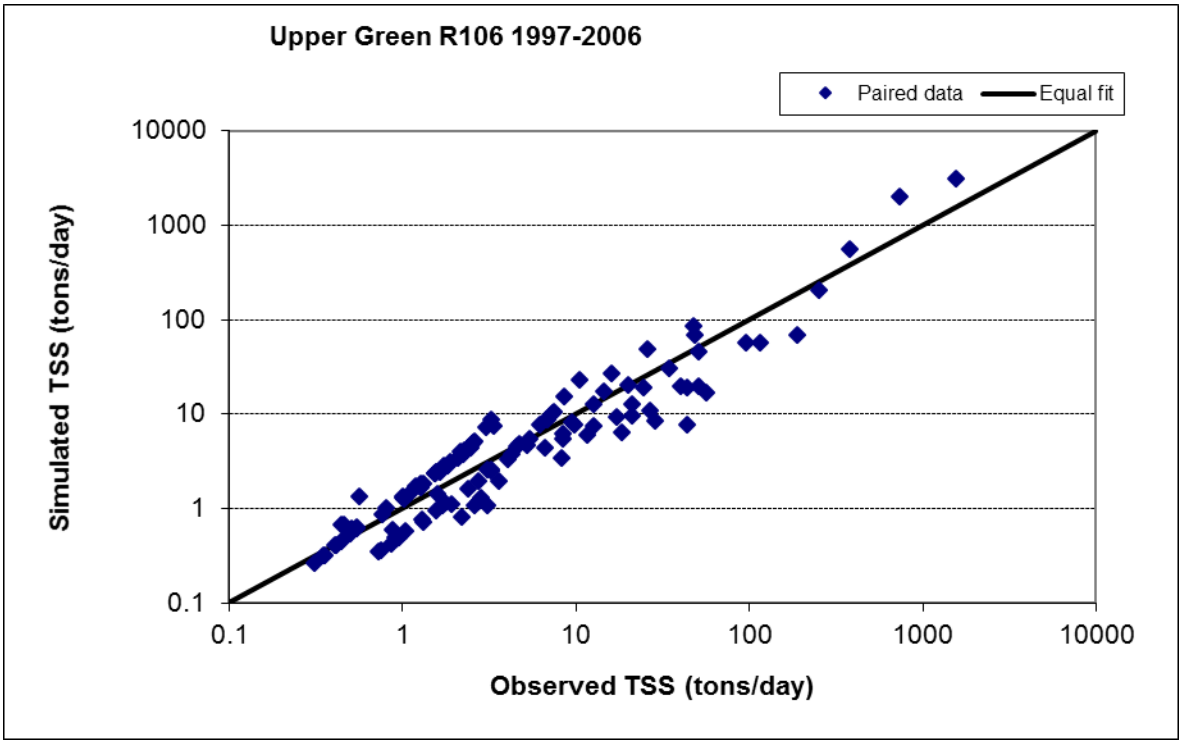


Figure 3-6. Simulated versus Observed Sediment Load, Green River, Reach 106

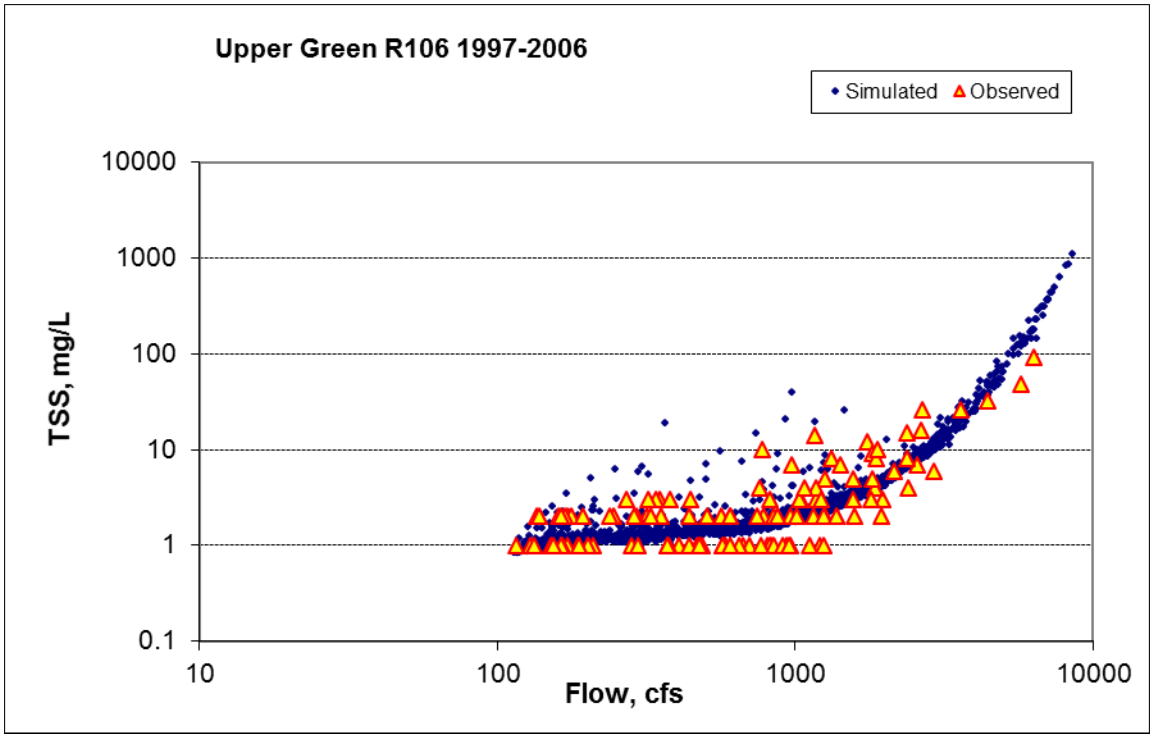


Figure 3-7. Sediment Concentration versus Flow, Green River, Reach 106

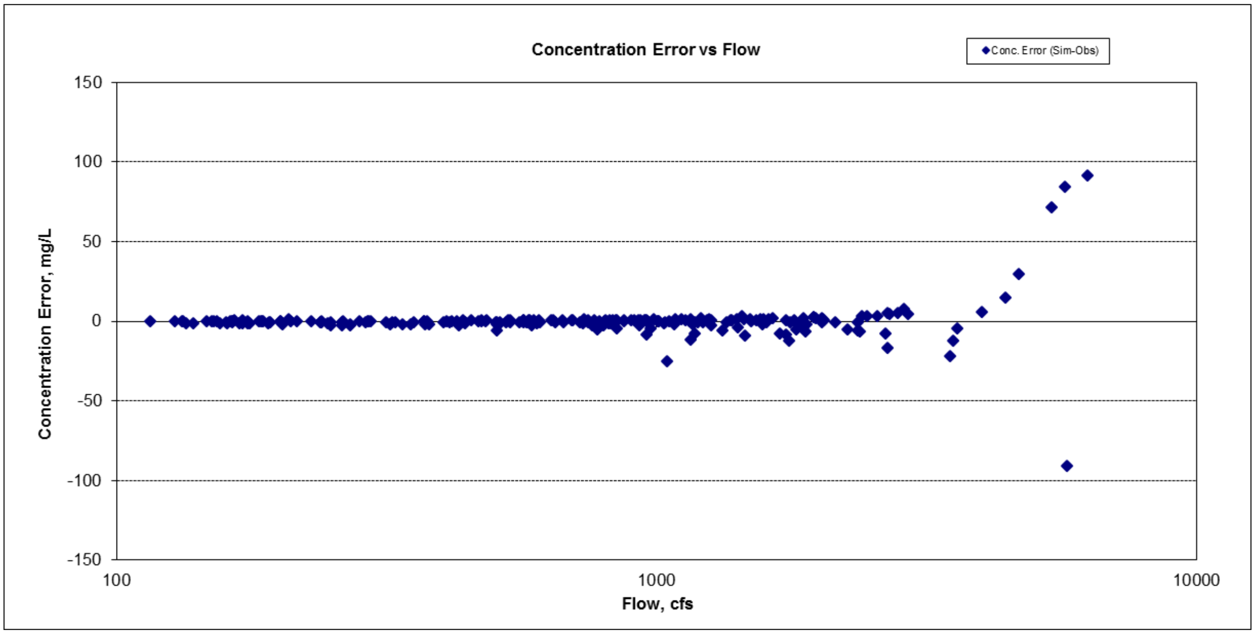


Figure 3-8. Distribution of Concentration Error versus Flow for Sediment, Green River, Reach 106

Table 3-5. Calibration/Validation statistics for Green River, reach 106

Measure	Validation 1997-2006	Calibration 2007-2017
Count	119	127
Concentration Average Error	18.83%	-13.13%
Concentration Median Error	0.36%	-3.68%
Load Average Error	62.36%	-5.59%
Load Median Error	0.02%	-0.71%

3.3.4 Initial Calibration Work

Due to limited project resources, a full sediment calibration of the HSPF models has not yet been undertaken. However, one important calibration task – the specification of low flow sediment concentrations – was performed. A review of the calibration plots revealed that at many locations the model under-predicts low flow concentrations. An example is shown in Figure 3-9. While most observed concentrations are in the range of 1 – 3 mg/L, the model predicts values as low as 0.001 mg/L. The reason is that the reach simulation allows sediment to settle out to very low concentrations at lower flows, where shear stresses are insufficient to mobilize fine sediment particles. In reality, sediment is usually present in water bodies at low but measurable concentrations due to localized turbulent flow and disturbance by animals, bottom-feeding fish, and human activities. In addition, groundwater may carry fine sediment into water bodies. To address these issue, the models were updated to represent a baseflow sediment loading background represented as associated with groundwater inflow. Sediment associated with groundwater (i.e., AGWO) was specified in the model MASS-LINK blocks using a multiplier on AGWO to represent a fixed concentration (but variable mass) of sediment entering the reach. This included groundwater transfers within and between the models. Based on a review of the calibration plots at all of the monitored locations and subsequent verification, the following concentrations were used in each model:

- Upper Green: 3 mg/L
- Soos: 2 mg/L
- Lower Green: 5 mg/L
- Duwamish: 5 mg/L

Figure 3-10 shows the resulting improvement in the low flow representation of sediment concentration. The model does over-predict some of the concentrations at this location, but matches the central tendency of the low flow concentrations well.

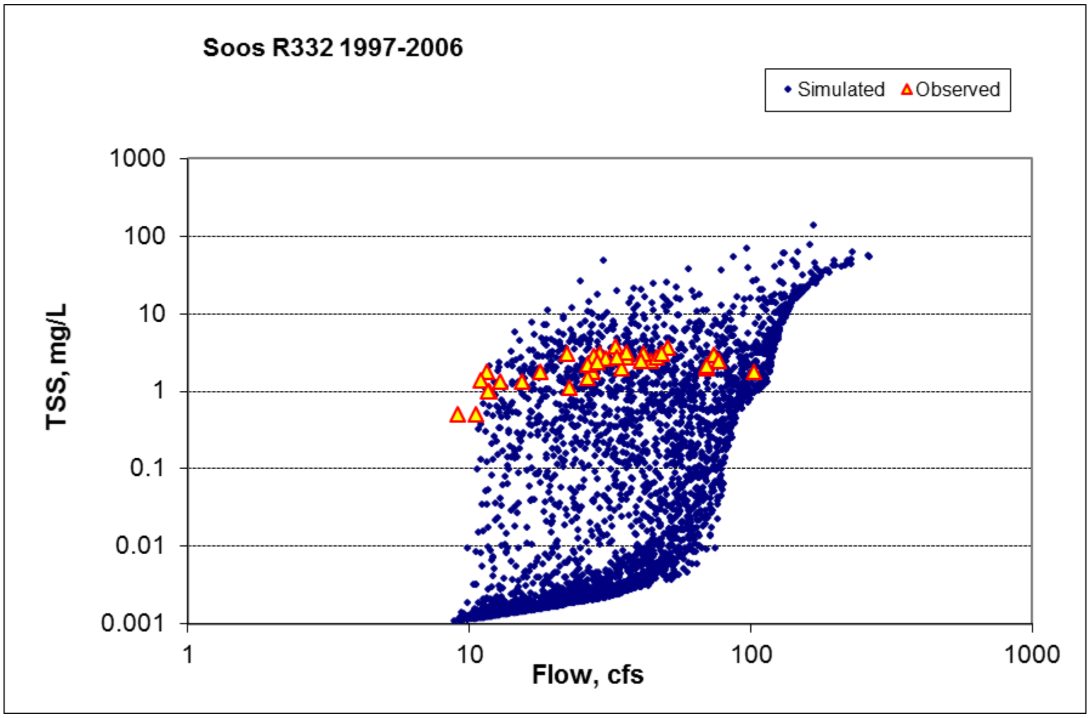


Figure 3-9. Sediment Concentration versus Flow for Jenkins Creek, Reach 332, Prior to Addition of Baseflow Sediment

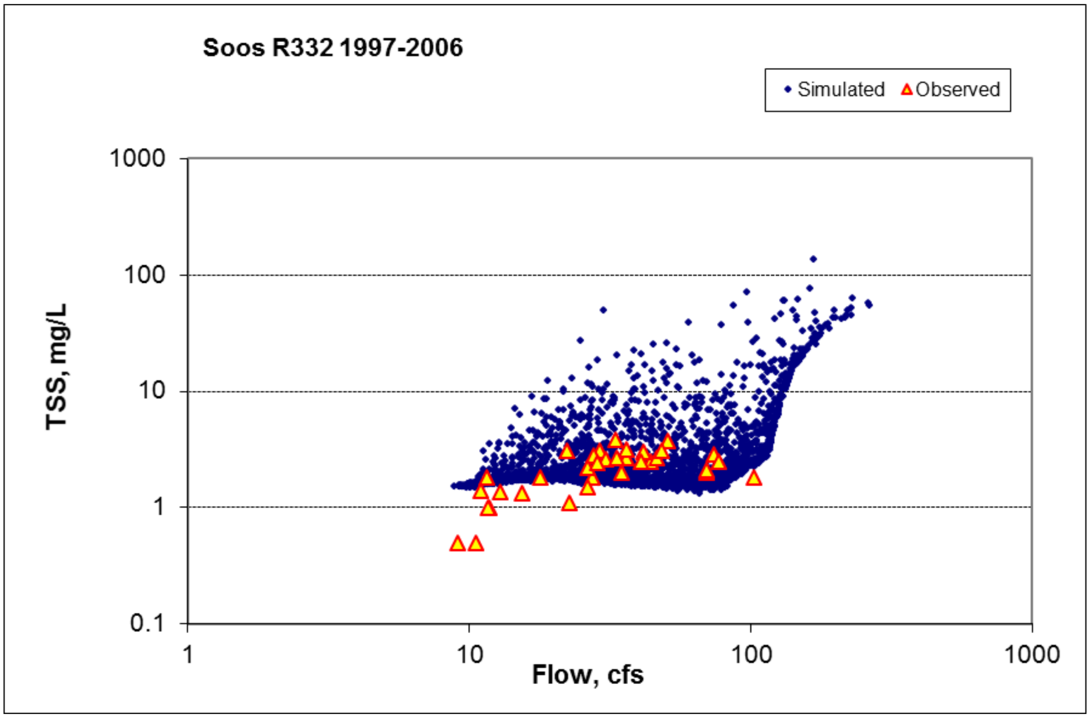


Figure 3-10. Sediment Concentration versus Flow for Jenkins Creek, Reach 332, After Addition of Baseflow Sediment

3.4 NEXT STEPS

As described in the introductory material for Section 3.0, sediment calibration should be undertaken using an iterative approach. USEPA (2006) provides a detailed discussion of the steps, which generally follow this sequence:

1. Update upland sediment simulation so that sediment yields for each land use match expectations to local and regional data.
2. Set initial shear stress scour and deposition thresholds based on an analysis of tau distributions individually for each reach.
3. Examine long term simulation of deposition and scour in each reach and tune until the behavior matches physically realistic expectation (and local information when available).
4. Calculate simulated load contributions (upland and reach) and determine whether the relative contributions of each match local data and expectations.
5. Compare instream simulated and observed sediment concentrations and loads, and refine sediment parameters as needed to achieve an acceptable fit.

During the calibration process, it may be necessary to repeat some of the steps. For example, upland sediment loads may need to be adjusted to achieve a good fit to monitoring data.

Many of the steps in the process have already been initialized. Section 3.2.2 discusses first steps taken to adjust upland sediment yields in the Upper Green River, Soos Creek, and Lower Green River models (step 1), and Section 3.2.3 provides a summary of long term deposition and scour in each reach (step 3). An analysis of tau distributions has been performed and thresholds set for each reach (step 2). To complete the sediment calibration, we recommend the following steps:

- **Set calibration and validation periods.** The example shown in Section 3.3.3 makes assumptions about calibration and validation time periods, but these can be adjusted. It is often advantageous to use more recent data for the calibration paired with the temporal representation of land use, but if more monitoring data are available for earlier time periods, it may be beneficial to use older data for calibration.
- **Complete steps 1 through 4 shown above.** If any changes are made to the hydrology simulation, the shear stress scour and deposition thresholds should be recalculated.
- **Calculate total upstream land area by land use class to each water quality monitoring station.** This helps with step 5; as an example, if the upstream area to a monitoring station is primarily forested, one might adjust upland forest parameters in the process of calibration.
- **Perform calibration step 5 from upstream to downstream.** Focus on headwater sites first, then the mainstem sites. Both upland and instream parameters may need to be adjusted to achieve the best balance of fit at all the monitoring stations.

4.0 REFERENCES

AQUA TERRA Consultants. 2003. Green River Water Quality Assessment, and Sammamish-Washington, Analysis and Modeling Program Watershed Modeling Calibration Report. Prepared for King County Watershed Modeling Services by AQUA TERRA Consultants, Everett, WA, and Mountain View, CA.

AQUA TERRA Consultants. 2012. Modeling Guidance for BASINS/HSPF Applications under the MPCA One Water Program. Prepared for Minnesota Pollution Control Agency by AQUA TERRA Consultants, Mountain View, CA.

Bicknell, B.R, J.C. Imhoff, J.L. Kittle JL, Jr., et al. 2005. HSPF Version 12.2 User's Manual. Athens, GA: U.S. Environmental Protection Agency, National Exposure Research Laboratory, Office of Research and Development.

Bieger, K., H. Rathgens, P.M. Allen, and J.G. Arnold. 2015. Development and Evaluation of Bankfull Hydraulic Geometry Relationships for the Physiographic Regions of the United States. Journal of the American Water Resources Association. 51(3): 842-858.

Brown and Caldwell. 2015. City of Auburn Comprehensive Storm Drainage Plan. Prepared for the Community Development and Public Works Department, City of Auburn, Washington.

Cleveland, W.S., and S.J. Devlin. 1988. Locally-weighted regression: an approach to regression analysis by local fitting. *Journal of the American Statistical Association*. 83 (403): 596–610.

Donigian, A.S., Jr. 2000. HSPF Training Workshop Handbook and CD. Lecture #19. Calibration and Verification Issues. Prepared for and presented to the U.S. Environmental Protection Agency, Office of Water, Office of Science and Technology, Washington, DC.

Donigian, A.S. Jr., and J.T. Love. 2003. Sediment Calibration Procedures and Guidelines for Watershed Modeling. Presented at the Water Environment Federation Total Maximum Daily Load Conference, November 16–19, 2003, Chicago, IL.

Duda, P.B., P.R. Hummel, A.S. Donigian, Jr., and J.C. Imhoff. 2012. BASINS/HSPF: Model use, calibration, and validation. *Transactions of the ASABE*, 55(4): 1523-1547.

Herrera Environmental Consultants, Inc. 2007. Water quality statistical and pollutant loadings analysis. Green-Duwamish Watershed Water Quality Assessment. Prepared for King County Water and Land Resources Division. Herrera Environmental Consultants, Seattle, WA.

King County. 2013. Watershed Model Development for Water Resource Inventory Area (WRIA) 9 Stormwater Retrofit Planning Project. King County Department of Natural Resources and Parks, Water and Land Resource Division.

King County. 2010. Lower and Middle Green River HEC-RAS Model. River and Floodplain Management Section – King County Water and Land Resources Division. Received from Kyle Comanor, July, 2016.

Rossman, L.A. 2015. Storm Water Management Model User's Manual Version 5.1. EPA- 600/R-14/413b. National Risk Management Laboratory Office of Research and Development, U.S. Environmental Protection Agency.

Tetra Tech. 2017. LSPC Model Development and Hydrology Calibration for the Green/Duwamish River Pollutant Load Assessment. Prepared for EPA Region 10 and Washington Department of Ecology. Tetra Tech, Inc., Research Triangle Park, NC.

USEPA. 2007. Two Automated Methods for Creating Hydraulic Function Tables (FTABLES). BASINS Technical Note 2. Office of Water, U.S. Environmental Protection Agency, Washington, DC.

USEPA. 2006. BASINS Technical Note 8: Sediment Parameter and Calibration Guidance for HSPF. Office of Water, U.S. Environmental Protection Agency, Washington, DC.