LSPC Model Development and Hydrology Calibration for the Green/Duwamish River Pollutant Load Assessment

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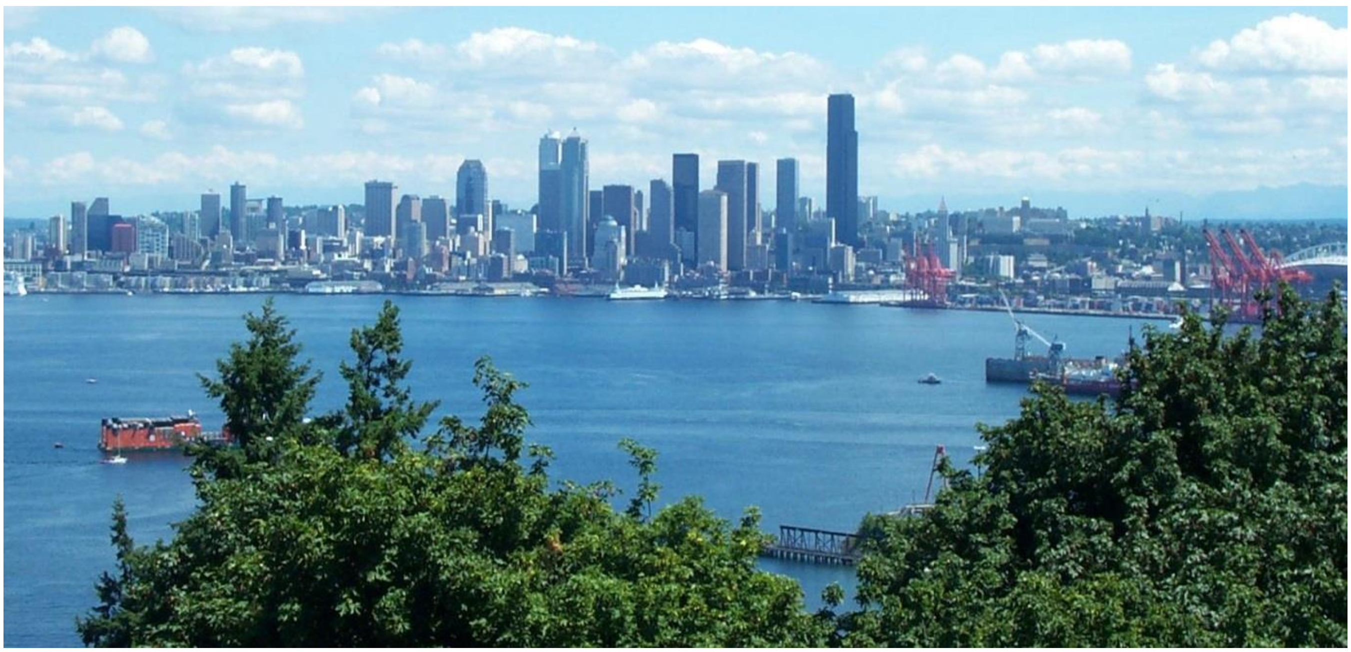

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1.0 INTRODUCTION

This report describes the development and calibration of hydrologic simulation models for the Green/Duwamish River watershed in King County, Washington. The following sections document the model setup procedures and data sources, including information on subbasin and reach delineation; development of upland hydrologic response units that describe land use, cover, slope, and soil characteristics; updated meteorology; representation of boundary conditions; development of reach hydraulic representations, and calibration of the model for hydrology. Calibration for water quality will be documented in a future report.

Washington Department of Ecology (Ecology) and the U.S. Environmental Protection Agency (EPA) are developing a Pollutant Loading Assessment (PLA) to describe 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). 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 project QAPP (Tetra Tech, 2016) describes the PLA modeling approach, which consists of a linked watershed/receiving water/food web modeling system describing hydrology, hydrodynamics, and pollutant loading in the Green/Duwamish River watershed. The PLA tool will represent sediment transport, resuspension and sedimentation, as well as the dominant processes affecting the transformations and transport of toxic pollutants throughout the watershed. Components include Loading Simulation Program - C++ (LSPC; USEPA 2009) watershed models, the Environmental Fluid Dynamics Code (EFDC; Tetra Tech, 2007) receiving water model, and the Arnot and Gobas (2004) food web model (FWM).

There are a series of existing Hydrologic Simulation Program FORTRAN (HSPF; Bicknell et al., 2014) watershed models for catchments in the Green/Duwamish River Watershed (Figure 1-1), developed by King County and its contractors and documented in King County (2013). The LSPC model is built from the same underlying code and algorithms used in HSPF. Both models provide dynamic simulations of hydrology, sediment erosion and transport, and pollutant loading, fate, and transport. LSPC implements HSPF algorithms in modernized, C++ code and provides added flexibility to address the needs of the Green/Duwamish watershed PLA study, including elimination of HSPF array size limitations, flexibility in assignment of meteorological stations, a linked database, and enhanced user interface. In addition, LSPC is tailored to interface with the EFDC model.

The general parameterization of the existing calibrated HSPF models served as the initial guide for the development of the LSPC models, and all hydrologic features represented in the HSPF models were incorporated into the LSPC models. The LSPC models extend the simulation period through 2015 and expand the spatial domain to cover the drainage area within the City of Seattle. Meteorological forcing series were also updated and modernized. Station-based weather data, which is often not representative of weather over a surrounding area, were used in the HSPF models. As discussed in Section 4.1, gridded meteorological data can better represent climatic variations across a watershed and gridded data is used for the LSPC models. Additional improvements include the representation of a major surface water appropriation, which is explicitly simulated in the Green River LSPC model (Section 6.1), as well as revisions to reach hydraulics (Section 7.0).

For ease of application and to reflect the different characteristics of the downstream area, LSPC is implemented in two linked models. As shown in Figure 1-2, areas that drain to the Green River between the Howard A. Hanson Dam and river mile 17 (the head of the EFDC model domain) are included in the Green River LSPC model along with tributaries including Soos Creek, Newaukum Creek, Deep Creek, Olson Creek and others (Figure 1-3).

The Green River merges with the Black River in the City of Tukwila, forming the Duwamish River. The downstream portion of the watershed is within Seattle city limits, where combined, separated, and partially separated sewer systems are all present. In this region, it is important to further differentiate land uses based on sewer classes. A separate, although hydrologically connected, LSPC submodel of the Duwamish River includes the Black River and Hamm Creek watersheds and all direct drainage to the Lower Duwamish Waterway.

Simulated flows are compared to flows recorded at multiple USGS and King County gages and model parameters were adjusted to optimize the representation of watershed hydrology. Hydrology calibration results, presented and discussed in Section 9.0, indicate that the LSPC models provide a strong foundation for the future simulation of sediment and pollutant fate and transport to support the PLA.

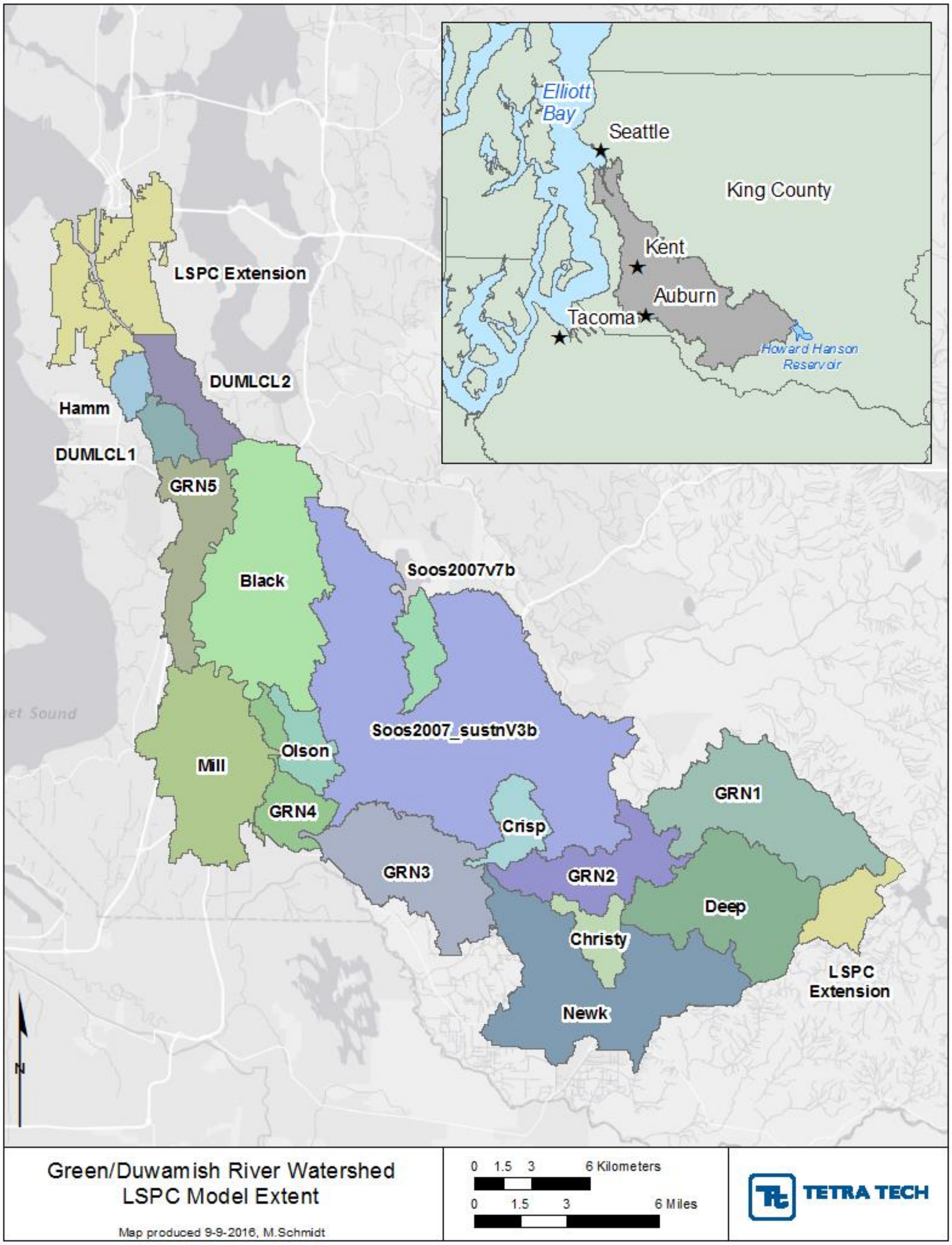

Figure 1-1. Green/Duwamish River Watershed LSPC Model Extent and Existing HSPF Models

Note: Map shows names of HSPF user control input files obtained from King Co.

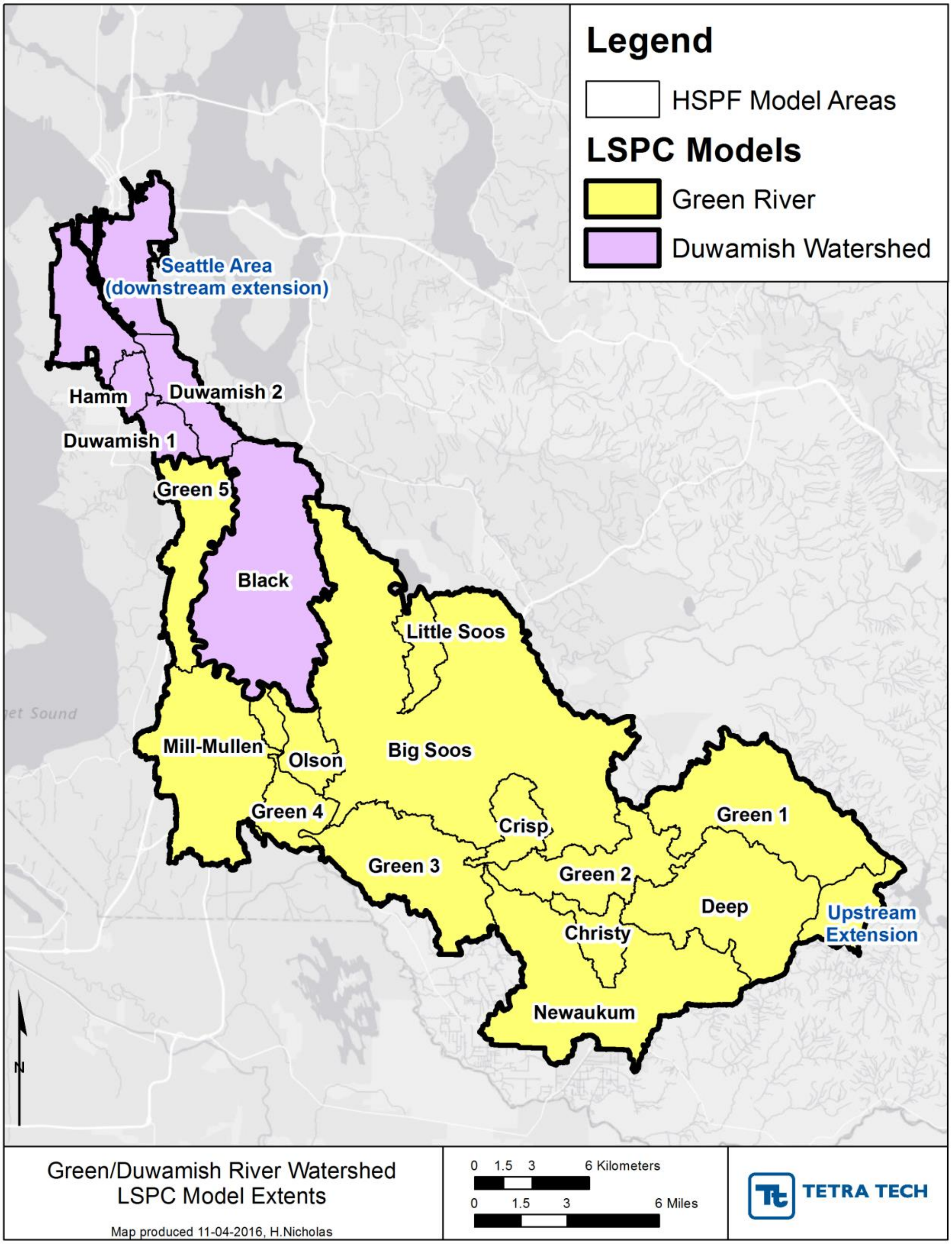

Figure 1-2. Green River and Duwamish River LSPC Model Domains

Note: Map includes boundaries of King Co. HSPF models with full watershed name.

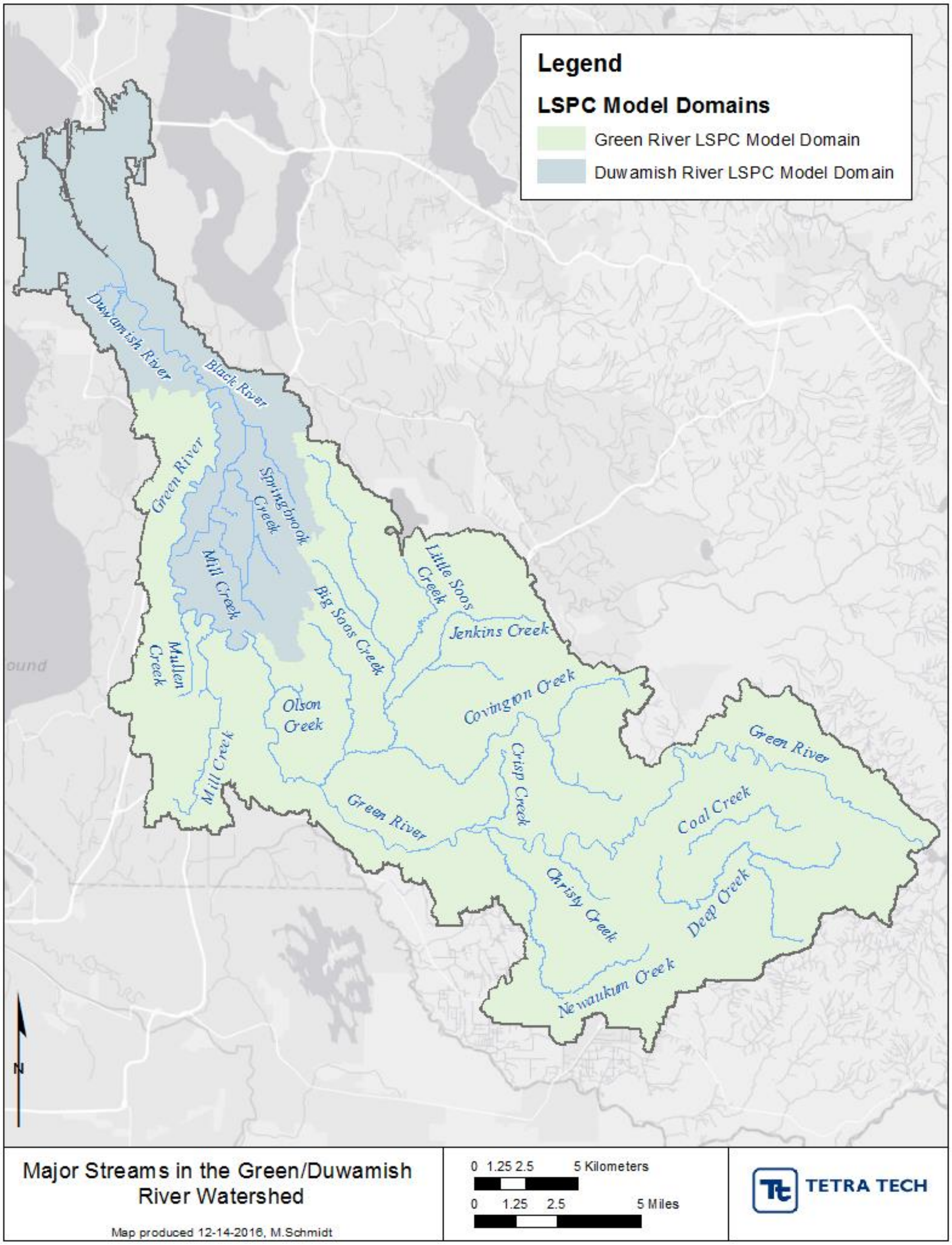

Figure 1-3. Major Streams in the Green/Duwamish River Watershed Model Domain

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2.0 SUBBASIN AND REACH DELINEATIONS

Model subbasins and corresponding reaches provide the basis for flow accumulation and routing in a watershed model. Subbasins were delineated for the LSPC watershed models and, to the extent possible, delineations used in the HSPF models were maintained in the LSPC models. The LSPC model domains include areas that drain to the Green River or Duwamish Waterway that were not represented in the HSPF models. The upstream extent of the Green River LSPC model is the outlet of the Howard A Hanson Reservoir and two additional subbasins were delineated to simulate hydrology in this portion of the watershed. The Lower Duwamish Waterway lies within the City of Seattle and discharges to Elliott Bay. The original HSPF models did not include the Seattle portion of the watershed and multiple subbasins were added to the Duwamish Waterway LSPC model to represent this region of the watershed.

2.1 HSPF MODEL DELINEATIONS

The existing HSPF models of the Green/Duwamish River Watershed are shown above in Figure 1-1, along with the portions of the LDW watershed that were not covered by these models. The LSPC models generally maintain the subbasin delineations created for HSPF, available in seventeen linked models:

1. Black River
2. Christy Creek
3. Crisp Creek
4. Deep Creek
5. Duwamish LCL1 (DUMLCL1)
6. Duwamish LCL2 (DUMLCL2)
7. Green River 1 (GRN1)
8. Green River 2 (GRN2)
9. Green River 3 (GRN3)
10. Green River 4 (GRN4)
11. Green River 5 (GRN5)
12. Mill/Mullen (Mill)
13. Hamm Creek
14. Newaukum Creek
15. Olson Creek
16. Soos Creek
17. Little Soos Creek

There are a few areas in which the LSPC model delineations differ from the HSPF model delineations for reaches and subbasins:

1. In HSPF, reaches may be modeled without being housed in a unique subbasin; however, in LSPC, all reaches must have a unique subbasin. Therefore, in the LSPC setup, all reaches have unique subbasins even if the assigned area is zero.
2. In the HSPF model called Green River 5, a small subbasin called LGR101 had been previously excluded from the model extent and included in a drainage outside of the Duwamish area. Based on advice from Jeff Burkey of King County, this subbasin has been included in the LSPC model extent.
3. Black River delineations:
    a. The HSPF model originally included a subbasin BLA310, but the land area in this subbasin was routed to reach BLA300. Subbasin and reach BLA310 were removed from the new model and combined to create a larger BLA300 subbasin.

   b. Similarly, subbasin BLA001 was merged to create a larger BLA070 because the routing reflected that relationship.
   c. Subbasin BLA260 was split into two subbasins at the location of a USGS flow gage that will be used for hydrology calibration.
4. Crisp Creek: Subbasin CRI006 had been previous excluded from the HSPF models because it was a closed basin. It has been reincorporated for the LSPC model to allow for groundwater (only) flow routing from Horseshoe Lake to Crisp Creek.
5. DUMLCL2: This model was represented as a single subbasin in the HSPF effort. For the LSPC model, this area was split into three subbasins to align with the inflows from the Hamm Creek and DUMLCL1 models.

2.2 LSPC MODEL EXTENT

The Green/Duwamish HSPF models do not cover the full extent of the watershed draining to the LDW. To capture these areas, the Green River LSPC model was extended on the upstream end, and the Duwamish River LSPC model was extended on the downstream end, covering a large area within the City of Seattle.

2.2.1 Upstream Extension

We extended the model domain upstream to the outlet of the Howard A Hanson Reservoir. This addition also includes the Bear Creek tributary immediately downstream of the reservoir (Figure 2-1). Daily flow data are available from the Howard A. Hanson Reservoir, so it serves as the upper boundary condition for the model (Section 5.1). The reach and subbasin delineation for this area was developed using NHDPlusV2 flowline and catchment shapefiles.

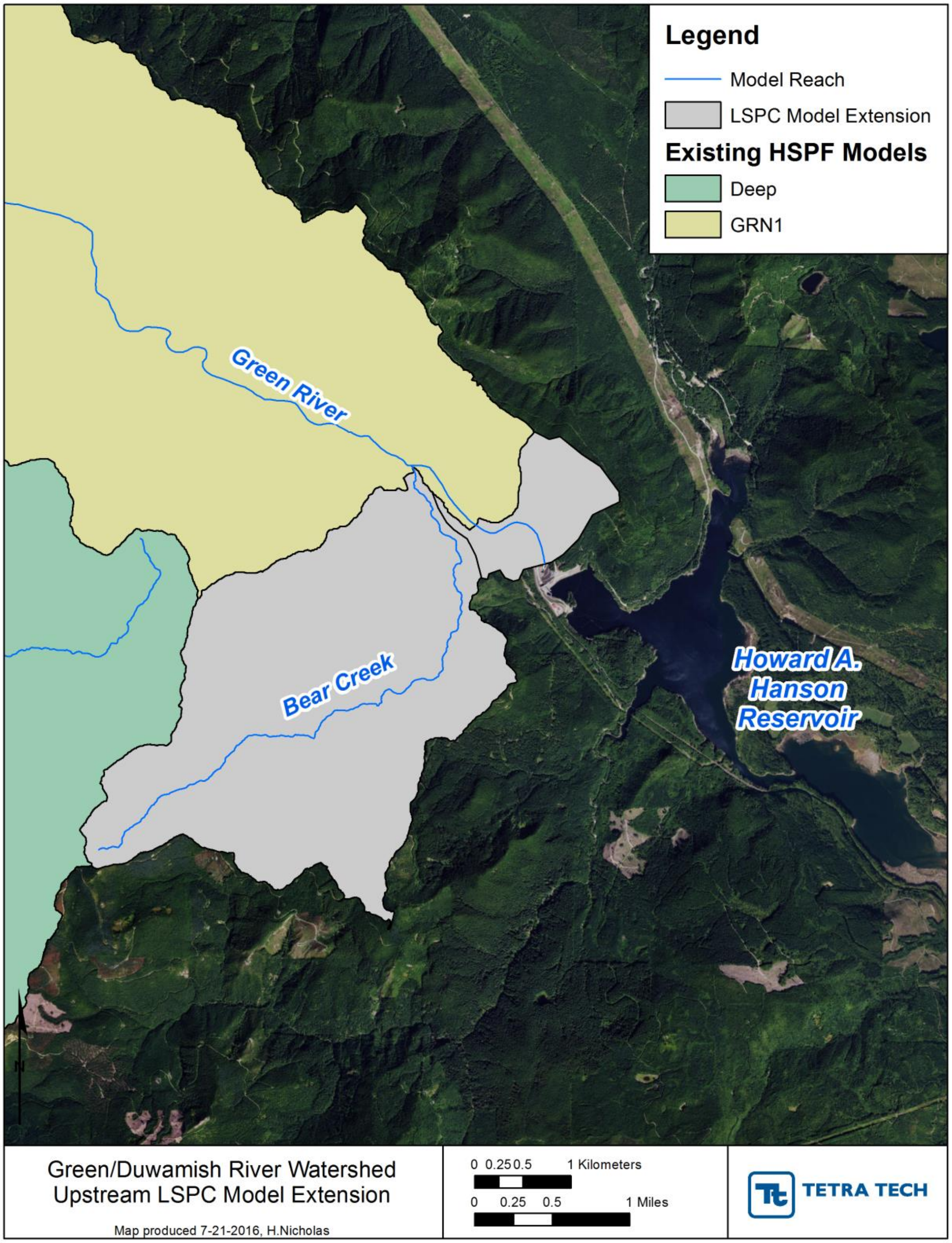

Figure 2-1. Existing HSPF Watershed Models and Upstream LSPC Model Extension

2.2.2 Downstream Extension

King County's HSPF models did not extend into the City of Seattle, which includes direct drainage to the LDW. Within the City, most drainage is engineered, with significant modifications to natural flow patterns. To extend the LSPC model to the outlet of the Lower Duwamish Waterway into Elliott Bay, we undertook an in-depth spatial analysis of the Seattle portion of the watershed. Seattle Public Utilities (SPU) supplied spatial coverages of the following items:

- Combined Sewer Overflow (CSO) drainage areas (DWW_cso_basin_plgn_pv.shp)
- Areas which drain directly to a receiving water body via outfalls (DWW_drainage_basin_plgn_pv.shp)
- Mainline sewer point features: Catch Basins, Maintenance Holes, Plugs, etc. (DWW_mainline_endpt_pv.shp)
- Sewer line features: Drainage, Combined, and Sanitary (DWW_mainline_ln_pv.shp)
- Sewer point features: outfalls for surface drainage, mainline, and non-mainline (DWW_outfall_pt_pv.shp)
- Sewer point features: outfalls related to NPDES permits (DWW_outfall_pt_pv_NPDES.shp)
- Areas which drain directly to a receiving water body via outfalls, direct drainage, or urban streams (DWW_receiving_wtrbdy_plgn_pv.shp)
- Designations of sewer classes: Combined, Separated, and Partially Separated (DWW_SEWER_CLASS_AREA_PLGN.shp)
- Urban creek drainage areas within Seattle area (DWW_urban_crk_wtrshd_plgn_pv.shp)
- Drainage areas, outlet locations, and pipeline infrastructure shapefiles for the SPU basin-scale SWMM flow modeling (DrainageModels2010.shp)

The downstream extent of the LSPC model is the outlet of the Lower Duwamish Waterway to Elliott Bay on either side of Harbor Island. Because the Lower Duwamish Waterway will be characterized using the EFDC model, the waterway itself is not included in the LSPC model. The lower LSPC model extent was based on surface drainage areas, SWMM model basins (see Section 7.2), urban creek watersheds, sewer lines, and sewer drainage classes. Direct surface drainage areas and SWMM model boundaries are key inputs to the outline of the downstream extent (Figure 2-2 and Figure 2-3). The LSPC model extent does not match the King County "natural" watershed boundaries for the Seattle area because the King County boundaries were determined using LiDAR rather than infrastructure-based routing ("sewersheds") in the Seattle area.

Major sewer class areas are used to develop land use classes within the model to ensure, for example, that only natural subsurface flows from combined sewer areas are routed downstream since surface runoff is routed with wastewater to treatment facilities (see discussion in Section 3.4 and Figure 3-8). Using these combined layers, and keeping with the basic sizes of subwatersheds delineated for the HSPF models, subbasins were delineated for the lower LSPC model extent (Figure 2-4.)

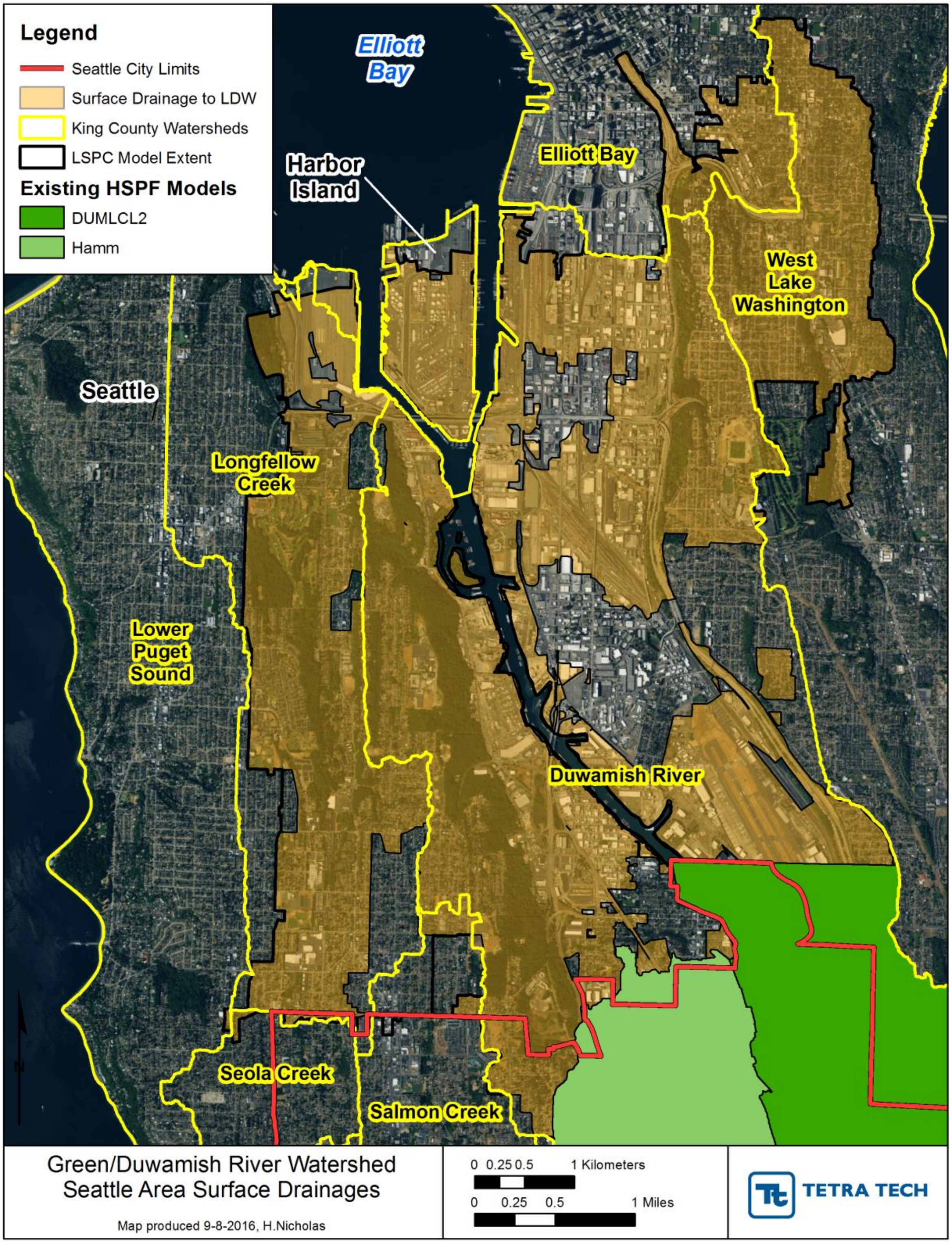

Figure 2-2. Seattle Surface Drainage Basins to the Lower Duwamish Waterway and King County Duwamish Watershed Boundary

Note: Areas served by fully combined sewers are not included in this map.

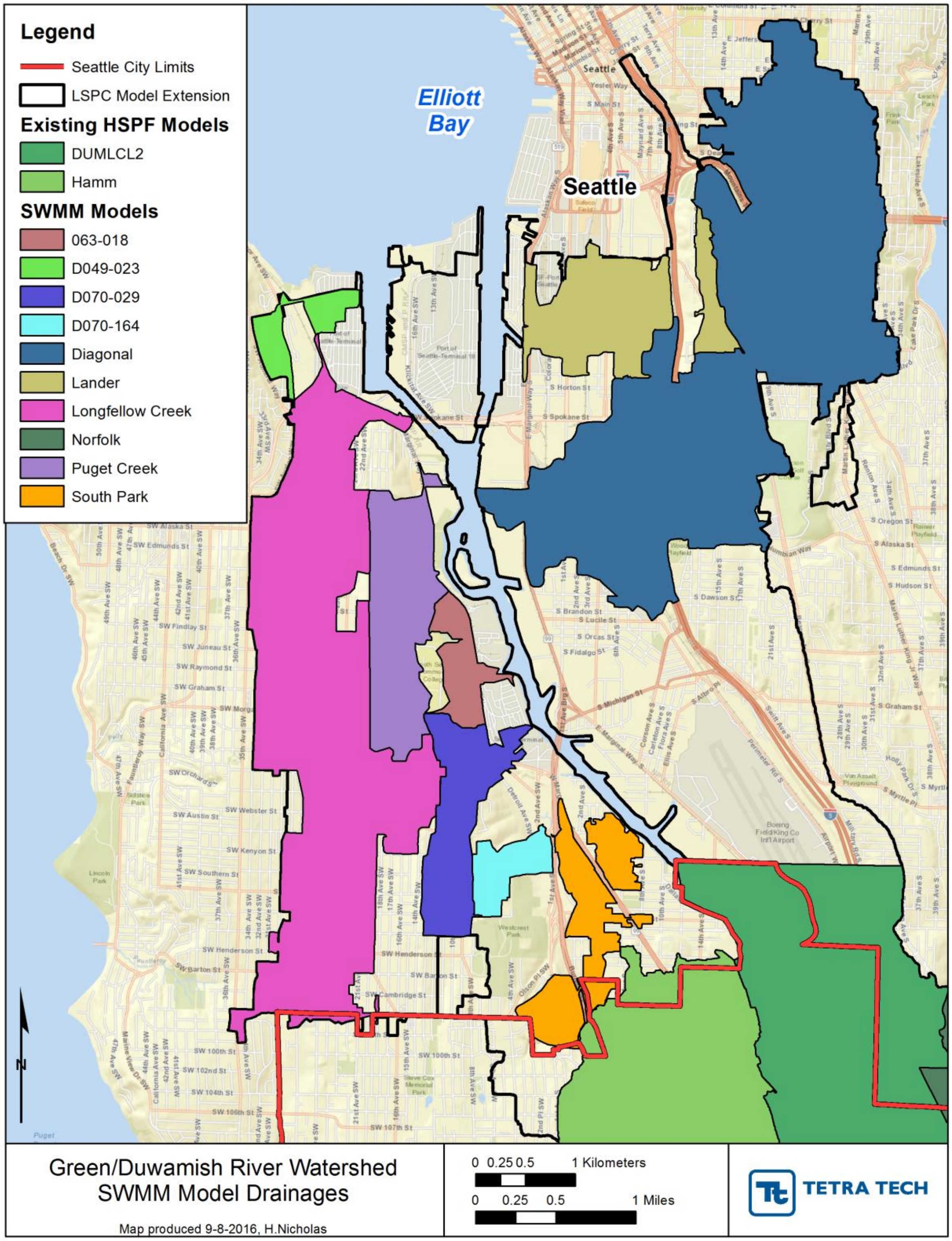

Figure 2-3. Drainage Areas for SPU SWMM Hydraulic Modeling (Seattle Public Utilities, 2010)

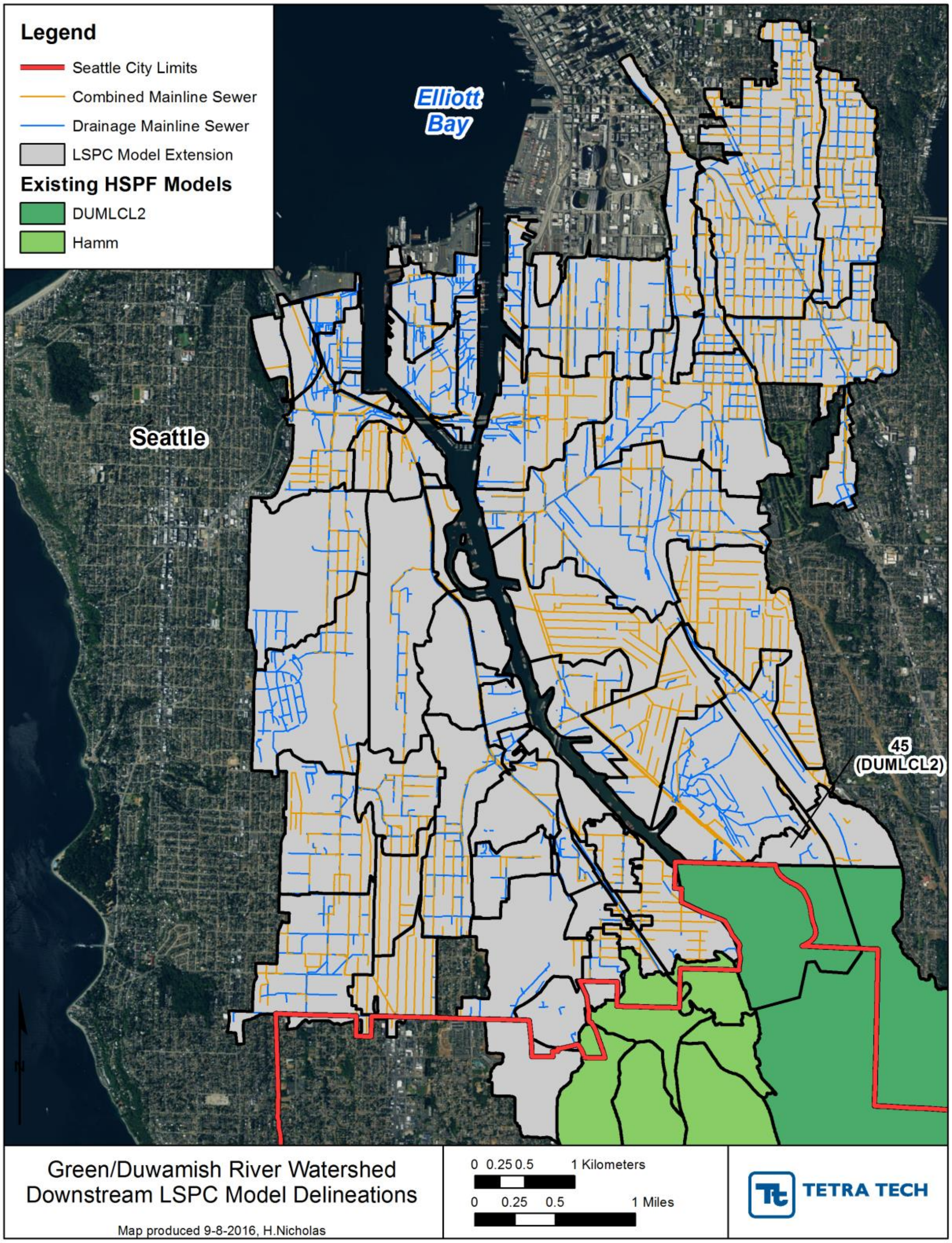

Figure 2-4. Downstream LSPC Model Extension Subbasin Delineations

2.3 DRAINAGE NETWORK

The upstream extent of the Green River LSPC model is the Howard A. Hanson Reservoir and Dam. Tributary streams including Christy Creek, Newaukum Creek, and Crisp Creek flow to the Green River as it meanders westward for about 30 miles (Figure 2-5). Surface flows from the Deep Creek and Coal Creek drainage areas are hydrologically disconnected from the Green River. These creeks terminate at Deep Lake and Fish Lake, respectively. Subsurface flows from Deep Creek and Coal Creek drainage areas, however, contribute to the Green River as baseflow. The Green River turns north, is joined by Soos Creek and Mill Creek, and merges with the Black River to form the Duwamish River. This point marks the boundary between the Green River and Duwamish River LSPC models, as shown in Figure 2-5. The Duwamish River then flows north through City of Seattle, and discharges to the Elliott Bay.

The Green River LSPC model is hydrologically connected to the Duwamish River LSPC model; simulated flows from the Green River act as a boundary condition for the Duwamish River LSPC model. The Black River and Hamm Creek drainage areas are represented in the Duwamish River LSPC model, as are regions in the City of Seattle that directly drain to the Lower Duwamish Waterway.

Model subbasins for the Green River and Duwamish River LSPC models are shown in Figure 2-6 through Figure 2-9. For most of the subbasins, the first two digits of a 5-digit subbasin number represent the originating HSPF model or indicate if it is a new model subbasin. Soos Creek watershed subbasins are designated with six digits beginning with “180.” A guide to the numbering scheme is provided in Table 2-1. The three ending digits are unique to the model subbasin and, where possible, the HSPF subbasin number was applied directly to LSPC to create the final reach designation.

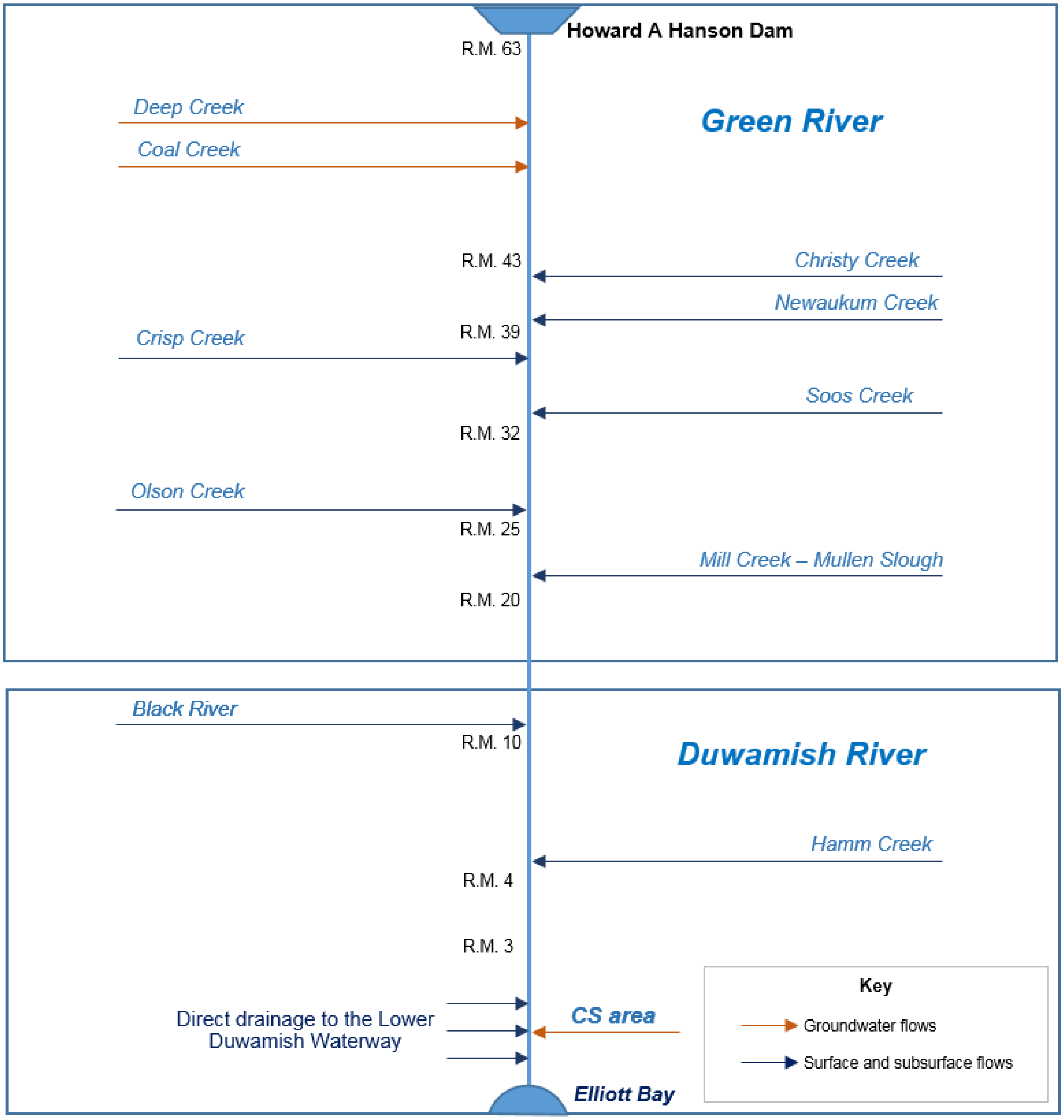

Figure 2-5. Stream Network and Connectivity of the Green River and Duwamish River LSPC Models

Notes: River Mile (R.M.) zero is defined as the southern tip of Harbor Island. The Coal Creek and Deep Creek drainage areas flow to Fish Lake and Deep Lake, respectively, which are closed surface depressions. Groundwater from Coal Creek and Deep Creek subbasins resurfaces as springs that contribute flow to the Green River. There is also some groundwater flow that may originate within the combined sewer (CS) area. Crisp Creek, Soos Creek, and Black Creek have subbasin groundwater transfers that are not represented in this schematic.

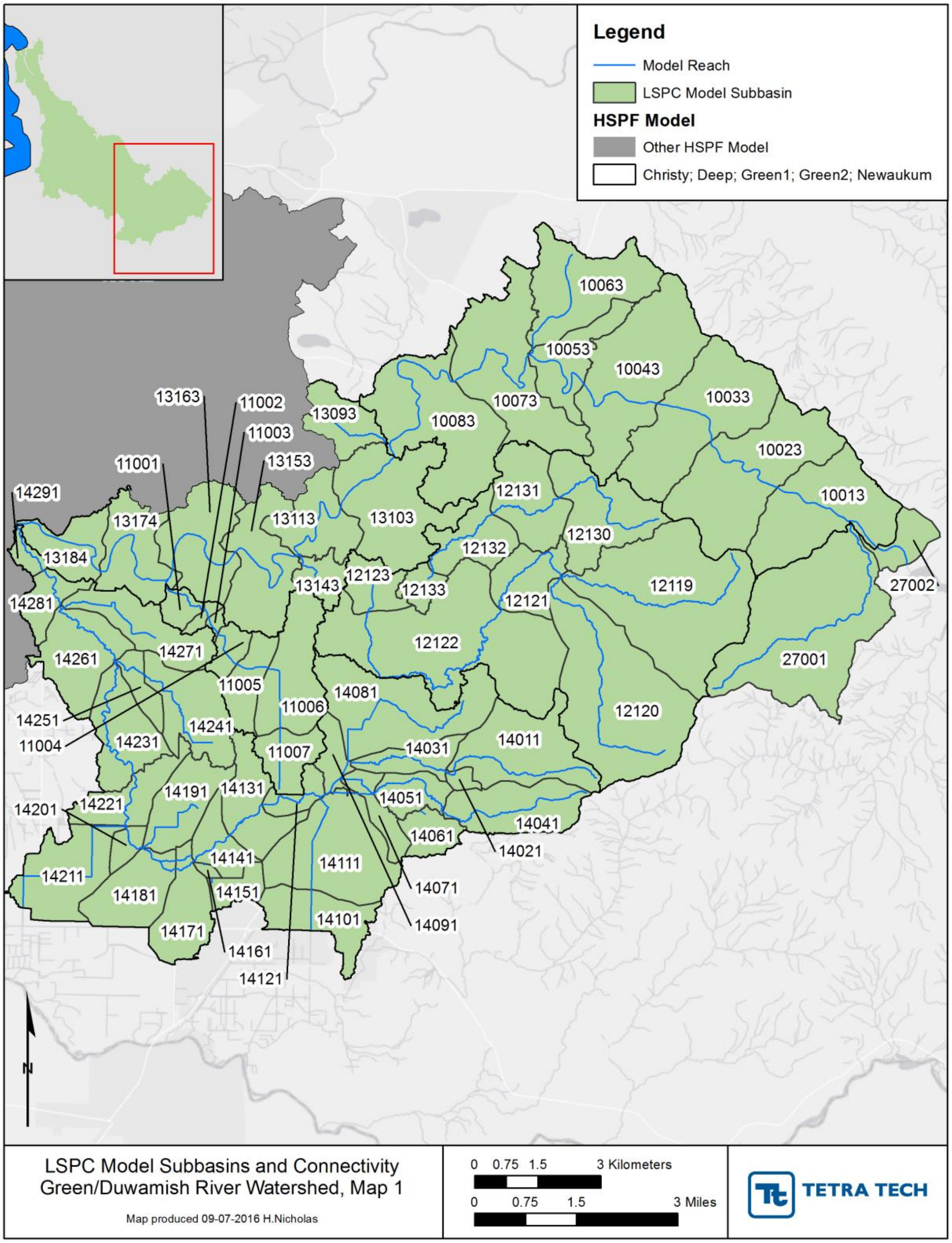

Figure 2-6. LSPC Model Subbasins for the Upper Green River Watersheds

Note: LSPC model subbasin maps are not all at the same scale.

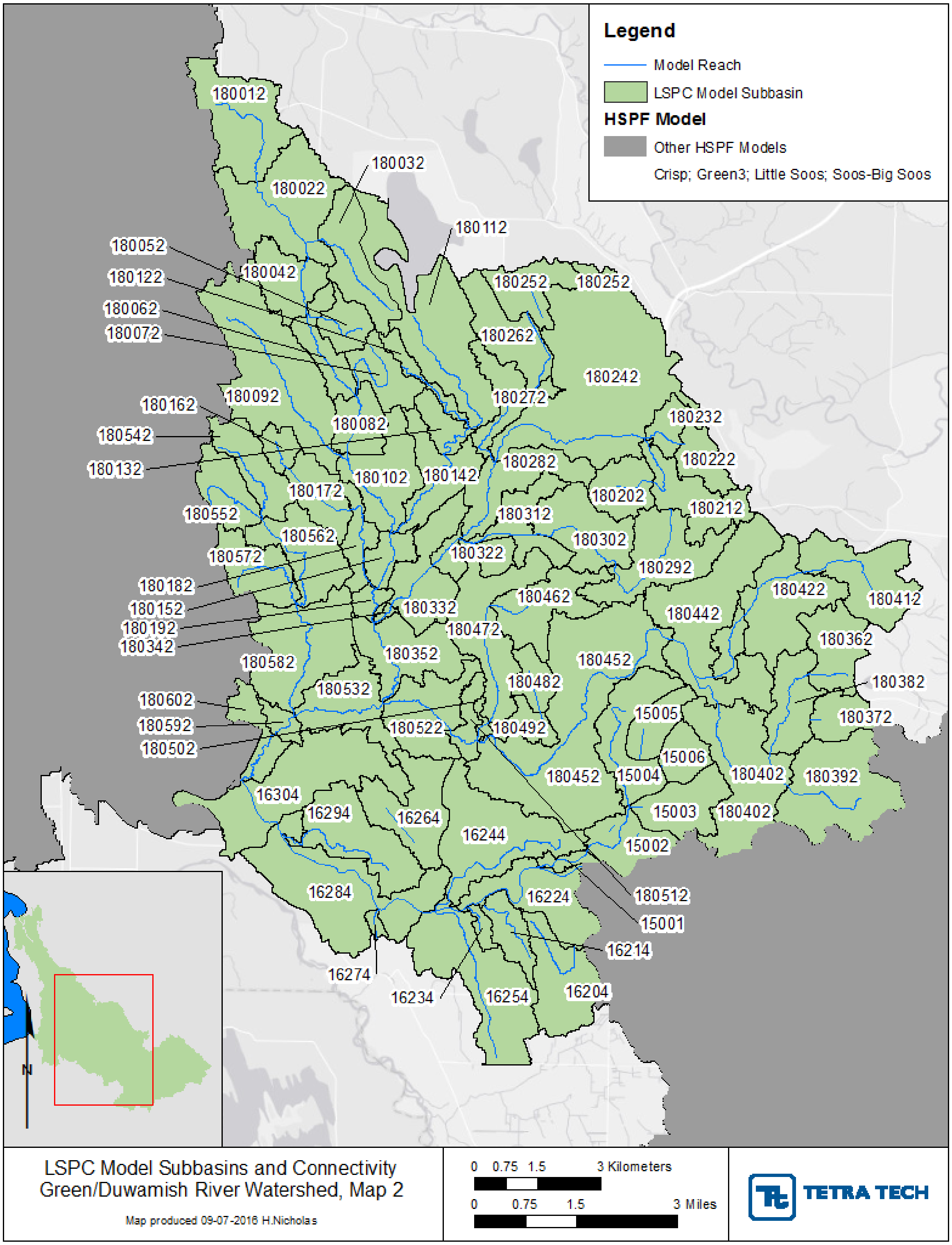

Figure 2-7. LSPC Model Subbasins for the Middle Green River and Soos Creek Drainages

Note: LSPC model subbasin maps are not all at the same scale.

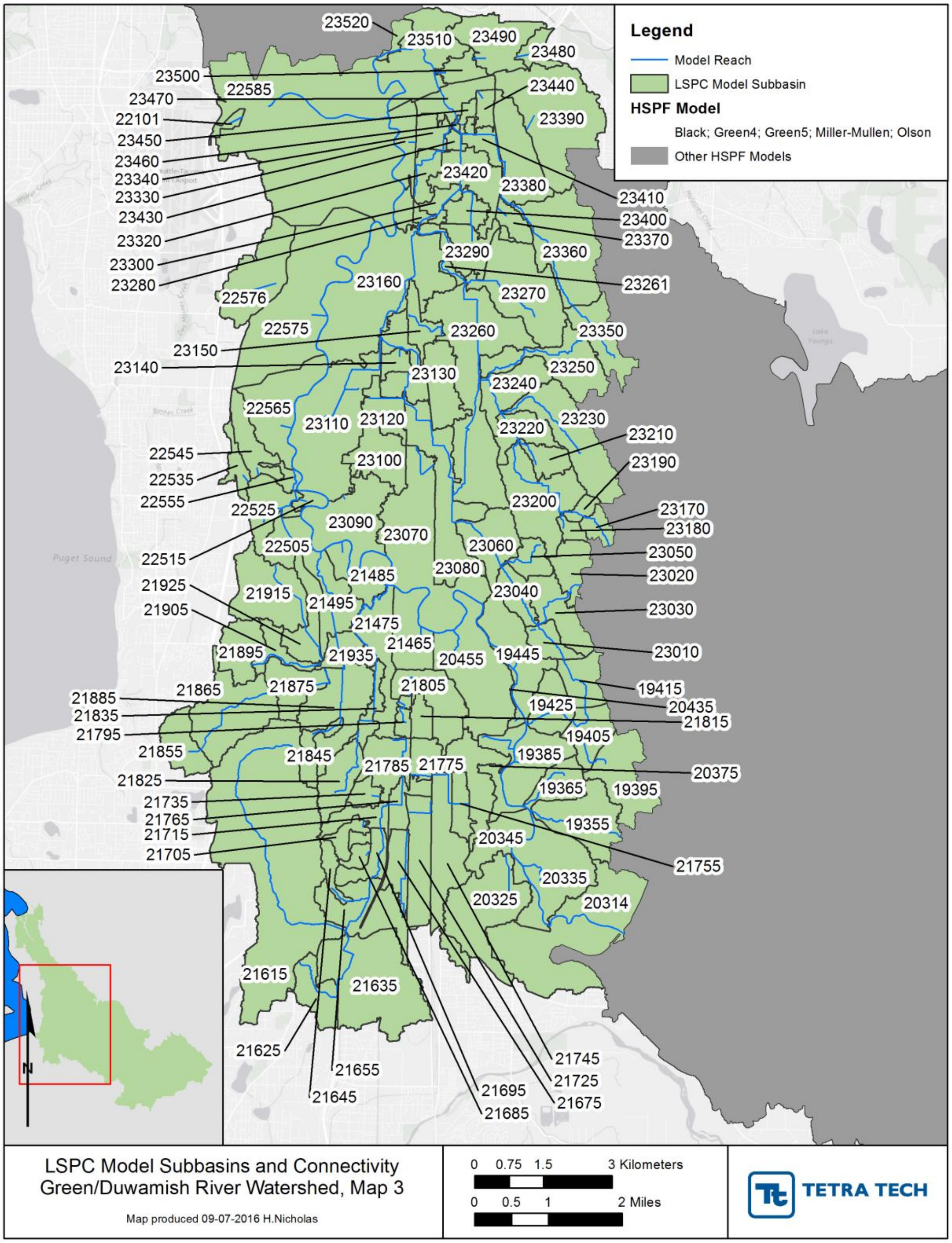

Figure 2-8. LSPC Model Subbasins for the Lower Green River and Upper Duwamish River Drainages

Note: LSPC model subbasin maps are not all at the same scale.

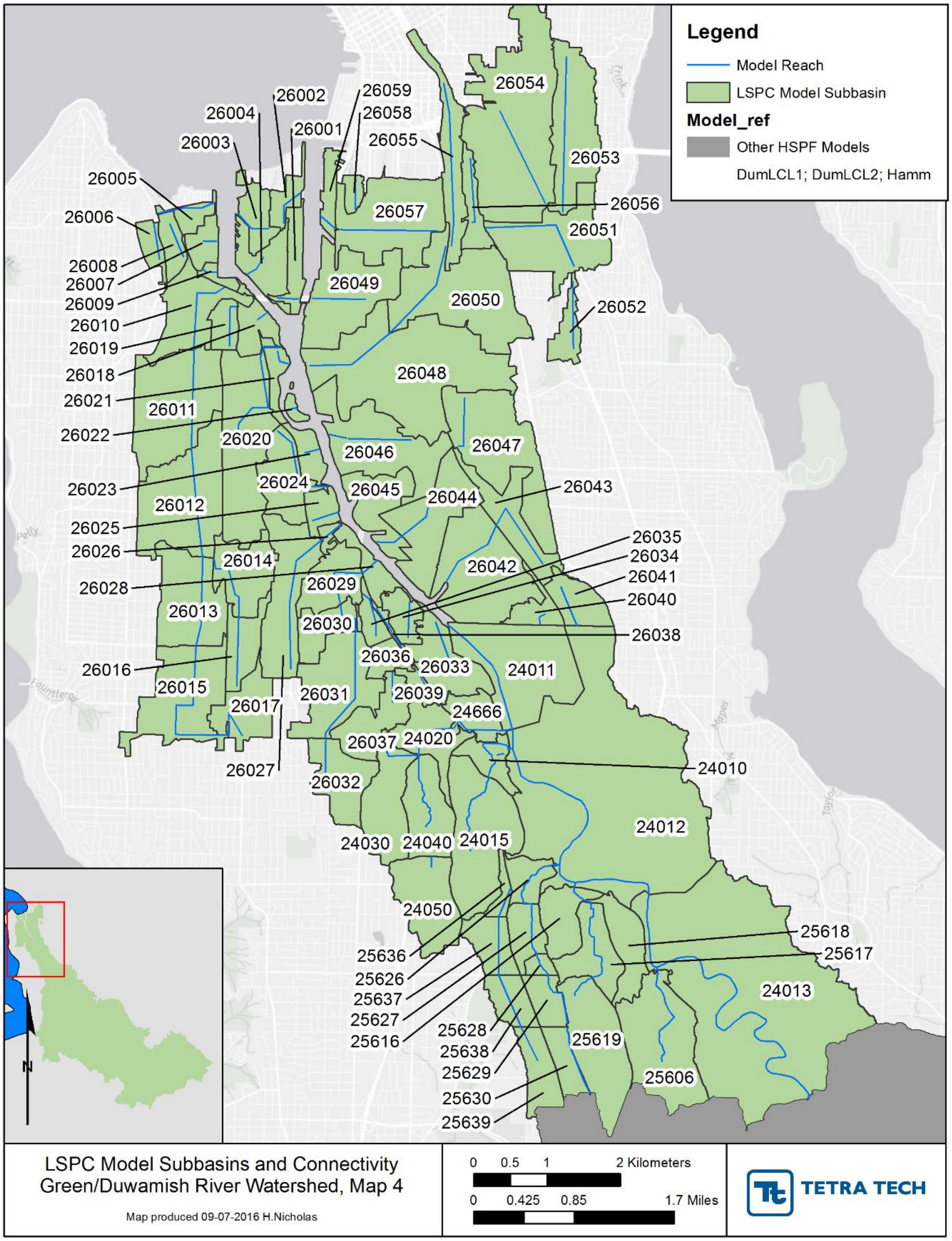

Figure 2-9. LSPC Model Subbasins for the Lower Duwamish River Drainages

Note: LSPC model subbasin maps are not all at the same scale.

Table 2-1. Subbasin Numbering Scheme in the Green/Duwamish River LSPC Models

First Digits of a Subbasin Number	Originating HSPF Model
10	GRN1
11	Christy
12	Deep
13	GRN2
14	Newaukum
15	Crisp
16	GRN3
19	Olson
20	GRN4
21	Mill
22	GRN5
23	Black
24	Hamm
25	DumLCL1
26	DuwamLCL2 and new subbasins in the Duwamish River LSPC model
27	New subbasins in the Green River LSPC model
180	Soos

3.0 UPLAND REPRESENTATION

Model development for LSPC is driven by hydrologic response units (HRUs) that identify areas of similar hydrologic properties due to similarities in land cover, soil type, and slope. For the Green/Duwamish River Watershed LSPC models, HRUs are updated for the extended model area, although classifications and parameterization are designed to capture as much of the existing HSPF model details as possible.

3.1 SOILS/GEOLOGY

Soils and surficial geology control hydraulic properties such as runoff and infiltration in conjunction with land slope and land use/ land cover. Soils information is derived from the Natural Resources Conservation Service (NRCS) Soil Survey-Geographic (SSURGO) coverage for the King County area (https://www.nrcs.usda.gov/wps/portal/nrcs/surveylist/soils/survey/state/?stateId=WA) and further refined with surficial geography information from USGS (1995) and King County (1997), as aggregated by King County for the existing HSPF models. SSURGO soils were initially binned for the HSPF model development based on hydraulic properties into the following classes: Till, Outwash, Saturated, and Bedrock (Table 3-1). These soil classes are maintained for the LSPC model development (Figure 3-1), although similarly to the HSPF model development, near-surface bedrock areas were modeled as “till” because of the limited extent of truly exposed bedrock in the watershed. The final soil groups used in the model are therefore Till, Outwash, and Saturated.

Table 3-1. Classification Bins for SSURGO Soil Map Units

Soil Type			
Till	**Outwash**	**Saturated**	**Bedrock**
Qmv	Qb	Qls	Tb
Qoal	Qal	Qw	Tdg
Qob	Qag		Teg
Qpf	Qf		Tf
Qt	Qva		Ti
Qtb	Qvi		Tmp
Qtu	Qvr		To
Qu	Qyal		Tp
Qvb			Tpr
Qvp			Tpt
Qvt			Ts
Qvu			Tsc
M			Tsg
Qom			Tv

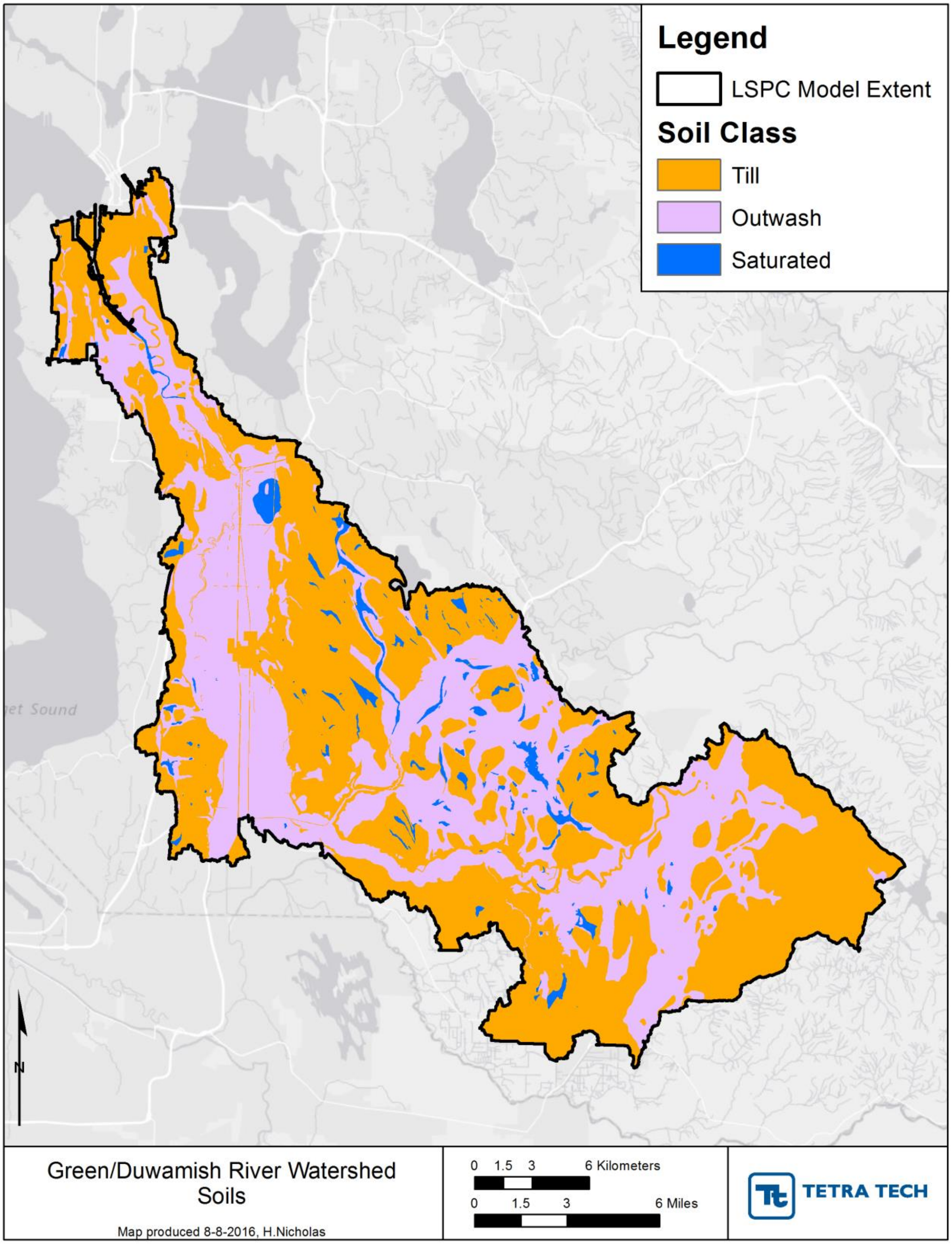

Figure 3-1. Binned Soil Classes (Till, Outwash, Saturated) for the Green/Duwamish River Model

3.2 SLOPES

King County provided a land slope raster for the model area, which is the same source layer for slopes used in the existing HSPF model development. The percent slope raster was developed from a 10-meter DEM developed from LiDAR (Light Detection And Ranging) coverage (King County, 2003). The slope raster was binned into four classes: Flat (0-5%), Low (5-10%), Medium (10-15%), and Steep (>15%). For the majority of the existing HSPF model areas, the slopes were aggregated as Flat (<5%) and Moderate (>5%), although for the Soos Watershed area, the four slope bins were maintained during more recent modeling efforts. For the LSPC model HRU development, slopes are binned as Flat and Moderate for the entirety of the watershed (including the extended areas), as shown in Figure 3-2.

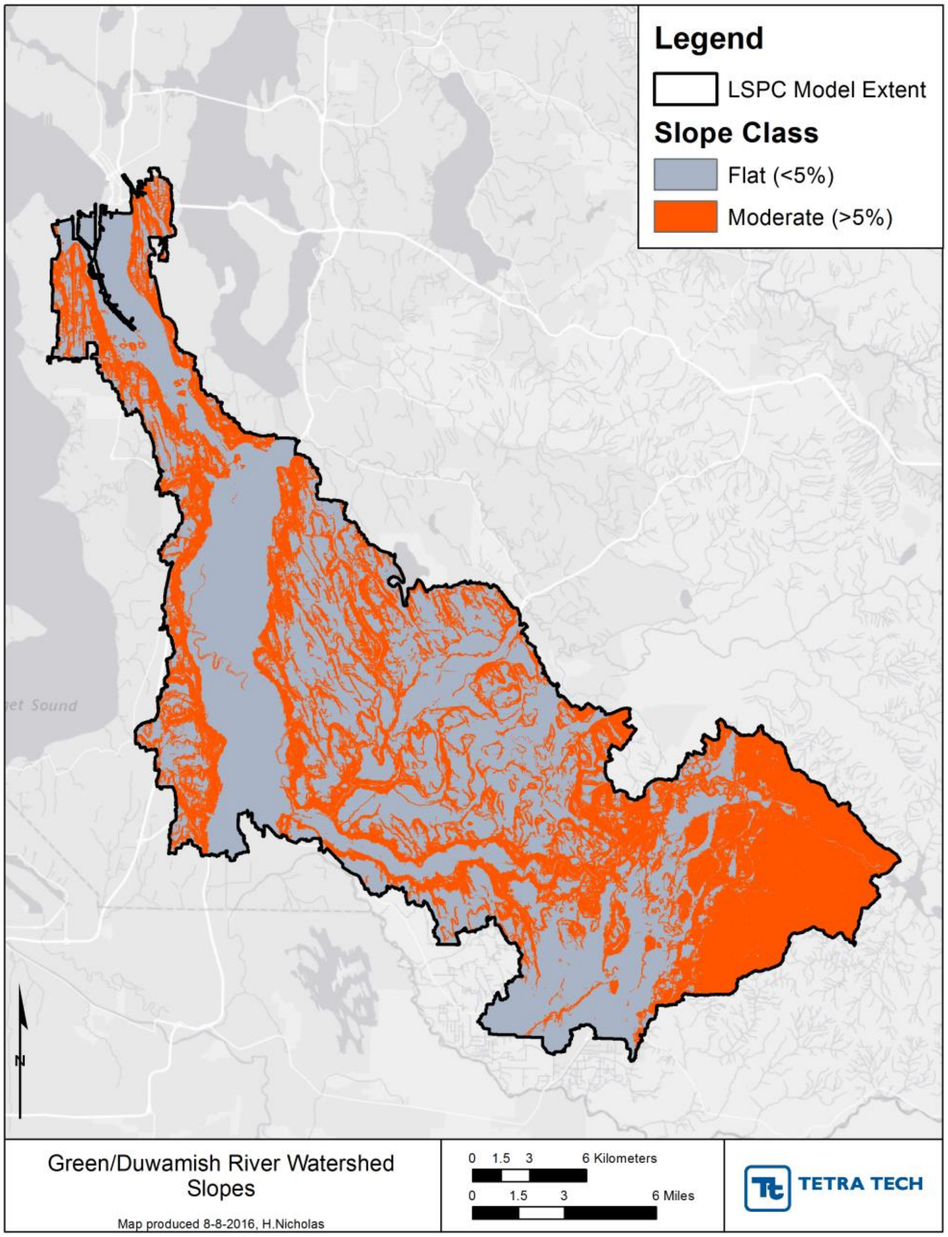

Figure 3-2. Binned Percent Slope Raster (Flat, Moderate) for the Green/Duwamish River Model

3.3 LAND USE/LAND COVER

3.3.1 Base Land Use/Land Cover

Land use and land cover information combine anthropogenic activities (e.g., residential land use) with vegetative cover (or its absence). The land use designation is also used to identify drainage types within the City of Seattle. Land cover classifications for the LSPC models are based on the National Land Cover Database (NLCD) 2006 dataset (http://www.mrlc.gov; Homer et al., 2012; Figure 3-3). These land uses classes were aggregated to reflect the HSPF model land uses that were developed from a University of Washington 2007 land use coverage. The NLCD identification of wetlands is suspect in areas with wet climates, where the reflectance of wet soils can be similar to that of wetlands. King County provided an updated coverage of the wetland areas within the watershed, which we used to reclassify the NLCD wetlands that lie outside the true wetland areas after consulting aerial imagery. Areas misclassified as woody wetlands (NLCD class 90) were reassigned to forest, and areas misclassified as emergent herbaceous wetlands (NLCD class 95) were reassigned to grassland. Table 3-2 summarizes the model land uses and their primary data sources.

Table 3-2. Land Use/Land Cover Categories and Aggregation for Duwamish/Green Watershed

Model Land Use	Source Class	Source Layer
Water	Water[1]	NLCD 2006
Barren	Barren	
Shrub	Shrub	
Grassland	Herbaceous	
	Emergent Herbaceous Wetlands	
Forest	Mixed Forest	
	Deciduous Forest	
	Coniferous Forest	
	Woody Wetlands	
Agriculture	Cultivated Crops	
	Pasture	
Low Density Residential	Open Space Development	
	Low Density Development	
High Density Residential	Medium Density Development	
Commercial/Industrial	High Density Development	
Wetlands	Wetlands	King County

[1]Reaches explicitly modeled as lakes have their area removed from this land use category in GIS post-processing

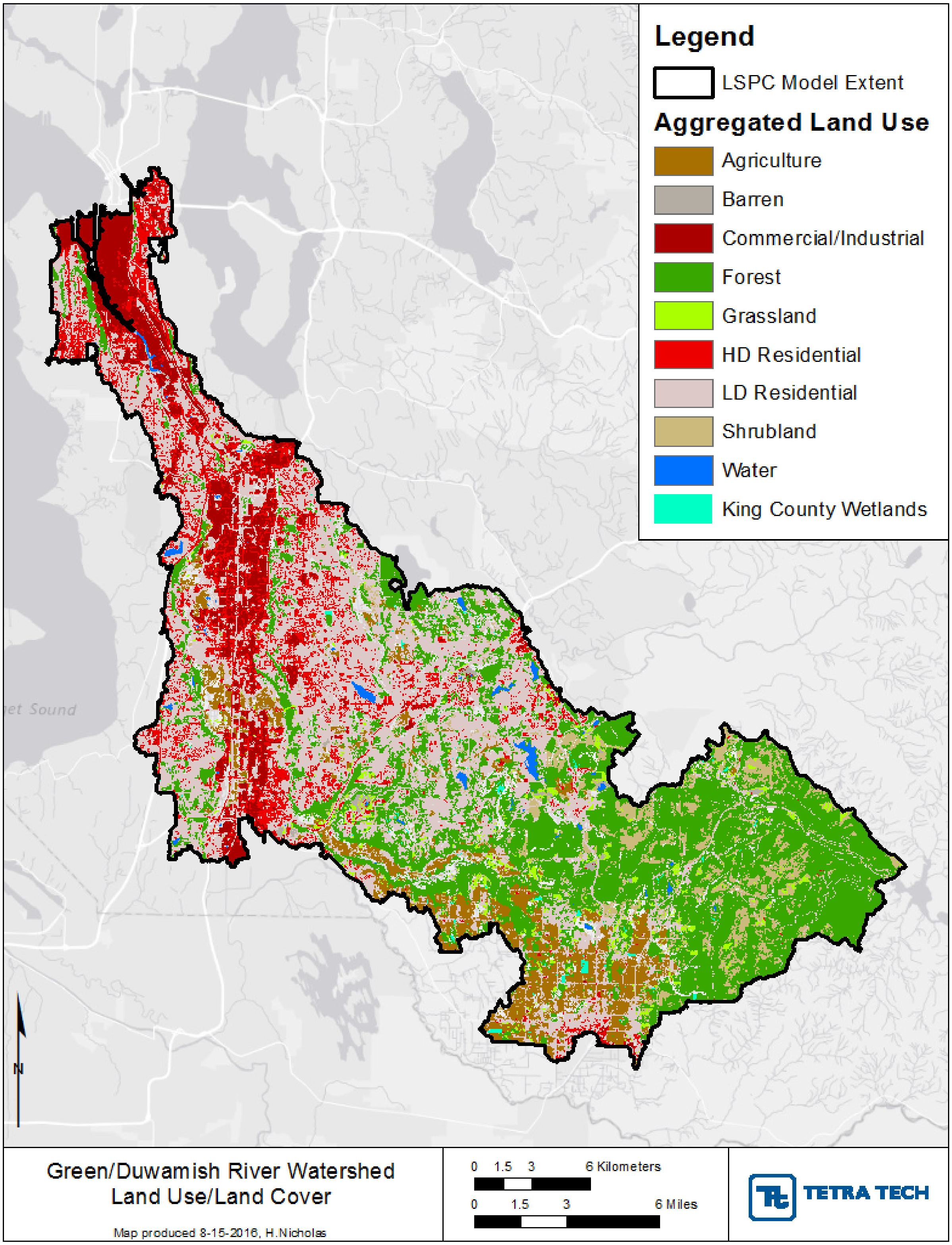

Figure 3-3. Land Use and Land Cover for the Green/Duwamish River Model (2006 NLCD)

3.3.2 Imperviousness

The presence of hard or impervious surfaces that do not infiltrate precipitation is a key factor in how water and pollutants will move through the landscape. To identify impervious area across the watershed, several key data sources not available for the original HSPF models were employed:

1. Impervious and Impacted Surfaces (King Co., 2011): tiled rasters (e.g. t20r05_09i002, 2 ft. resolution) across the Green/Duwamish watershed showing impervious/impacted surfaces generated by King County. Data sources for this layer range from 2000 Ikonos multiband imagery, 2011 transportation network shapefile, building footprints from cities within the area, and 2007 orthoimagery for King County.
2. Man Made Features Area and Height (King County, 2010a): tiled rasters (e.g. t20r05_bht006, 6 ft. resolution) across the Green/Duwamish watershed, which were generated by King County. These rasters show the height of manmade features as a continuous raster, developed using LiDAR data, and the impervious area coverage from 2009.
3. Metro Transportation Network (TNET) in King County: shapefile (trans_network.shp) of roads and railroads, classified by type.

One goal in developing the impervious coverage was to differentiate between “roof”, “road”, and “other” ground-level imperviousness (i.e. driveways, parking lots). It is anticipated that these distinctions will be useful for pollutant source representation. The Impervious/Impacted Surfaces raster was used as the base raster, but did not clearly define the roof, road, and other categories across the watershed. A filter was applied to the Manmade Features raster to pull out areas that were greater than 8 feet in height, and were surrounded by pixels greater than 8 feet tall. To ensure that roof area was appropriately represented using this methodology; the roof area feature raster was compared to fine resolution (1 m or less) satellite and aerial imagery in GIS. Roofs identified in the feature raster aligned with buildings shown in aerial imagery. These roof areas were burned into the impervious surfaces raster. Roads were also burned into the impervious surface raster by buffering from the Transportation Network polyline shapefile by road class code. The following table shows the buffer widths that were used (on either side of the centerline) based on road class, which mirrors the assumptions from the HSPF modeling effort. Once the roadways and roofs were burned into the impervious raster, the result was a raster showing roads, roofs, and other (i.e. ground level non-road imperviousness) (Figure 3-4).

Table 3-3. King County Transportation Network Buffering

Road Class Code	Road Description	Buffer Width (ft)
C	Collector Arterial	20
F	Freeway	40
L	Local Arterial	15
M	Minor Arterial	10
P	Principal Arterial	30

The impervious raster is used to identify total impervious area, although the inputs to the model are based on effective impervious area, which is discussed in Section 3.3.3.

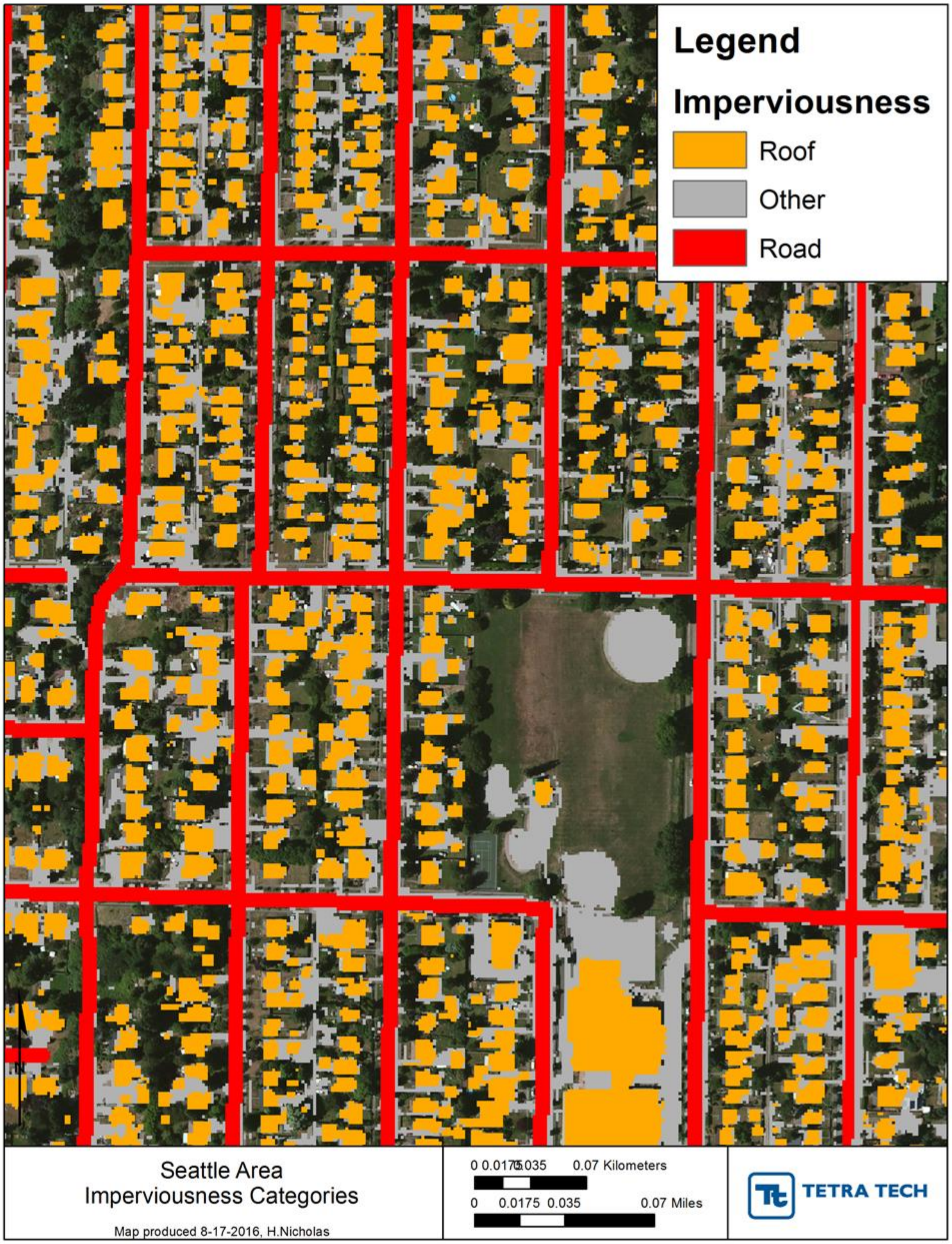

Figure 3-4. Impervious Coverage Example for the Seattle Area near Highland Park Playground

3.3.3 Effective Impervious Area

Impervious surfaces are an important source of direct runoff to streams; however, not all impervious surfaces are directly connected to the drainage network. Some definitions will be useful for the discussion of this subject:

TIA: Total impervious area calculated as a percentage (0-100) of the subbasin area.

EIA: Effective (i.e., hydraulically connected) impervious area calculated as a percentage (0-100) of the subbasin area.

Ef: The fraction of impervious area that is effective (EIA/TIA).

Particularly in less densely developed areas, substantial fractions of impervious surfaces (such as roof drains) are not directly connected to streams. The impervious area that is hydraulically connected to the stream or surface drainage network over an entirely impervious pathway is referred to as EIA (Han and Burian, 2009). Land areas simulated in the watershed model as impervious surfaces should represent only the EIA in the LSPC model, rather than the TIA. Impervious areas that are not hydraulically connected are either isolated depressions or flow onto adjacent pervious areas (where they may infiltrate or, during larger events, contribute to overland flow) and flows originating from such surfaces are best represented as having the characteristics of the receiving pervious area.

There is a subtle but important distinction between EIA and Directly Connected Impervious area (DCIA). DCIA is the portion of TIA that is directly connected to the drainage system, generally defined by field surveys or map measurements. Many earlier authors have treated EIA and DCIA as equivalent, but this is not strictly true, as was pointed out by Boyd et al. (1993). Essentially, DCIA is a map characteristic (independent of rainfall-runoff relationships) and EIA is a hydraulic characteristic. EIA can be expected to be slightly less than DCIA to factors such as interception by overhanging vegetation, infiltration through cracks in the impervious surface, blockages in gutters, etc. (Ebrahimian et al. 2016a, 2016b). Boyd et al. (1993) estimated that EIA was 86 percent of DCIA in 26 urban catchments, while Ebrahimian et al. (2016b) reanalyzed the data and obtained an estimate of 76 percent.

Boyd et al. (1993) developed linear regression methods of estimating EIA from small watershed gaging data based on a simple model that distinguishes between runoff event flows due (almost) entirely to EIA and flows that represent the combined effects of runoff from impervious and pervious surfaces. Distinguishing the EIA-only events was somewhat subjective, and the residuals of the regression were not consistent with ordinary least squares assumptions. Ebrahimian et al. (2016a, 2016b) have developed an improved method that uses a successive weighted least squares approach to resolve these issues. Unfortunately, the approach is rather complex to implement and may encounter problems where flow measurements are obtained from a channel where flows are affected by groundwater exchanges – as is the case for most gages in the Green/Duwamish watershed. Specially designed studies of this type might be appropriate for gaging on small, urban catchments within the watershed, but are not currently available.

Without detailed studies of local EIA, development of the watershed model requires estimation of EIA based on watershed studies of TIA/EIA and/or model calibration. Typically, initial estimates are drawn from available studies, and these estimates are then adjusted through watershed model calibration to measured stream gage data.

Initial Estimates of EIA

For the WRIA 9 HSPF models, King County (2013) used 2007 relatively coarse (30-m) resolution satellite imagery (plus a separate buffered line roads coverage) to identify impervious surface areas. EIA was then initially estimated based on several studies from the Puget Sound area and refined during model calibration. Since those models were created, King County (2010a, 2011) has assembled high-resolution coverages of impervious surfaces and heights throughout the watershed that enables distinction of roofs from roads and other ground-level impervious areas. As the different types of imperviousness are likely to have differing degrees of connectedness, we revisited the EIA determinations.

EIA is best determined based on detailed local drainage studies, but these are not available for the whole model area. A wide variety of simpler estimation methods is available. For the more recent SUSTAIN modeling, King County (2014) converted TIA to EIA using the locally developed regression equation of Elmer (2001):

$$Elmer\ Equation: EIA_{total} = 1.0428 \times TIA_{total} - 11.28\%$$

This equation was proposed by King County (2014) as the most appropriate approximation for estimating EIA in more highly developed areas of the County. However, the equation is likely dependent on the resolution of the TIA coverage, is not applicable below a TIA of 10.82%, and does not distinguish EIA for different types of urban cover. Even in very rural areas, EIA for roads, in particular, will not go to zero as allowed by the Elmer equation, as there will be some connected area at and near stream crossings. King County (2016, Table 3.2.2.D) contains recommended values of Ef to be used in evaluation of site designs, ranging from 0.40 for rural residential areas (< 1 dwelling unit per acre) to 0.95 for commercial, industrial, or roads with collection systems; however, these estimates include roadway imperviousness within the residential areas. They also appear to be conservative (high) estimates for use for plan review purposes.

Wright (2013) conducted a study of an urban headwater watershed of Newaukum Creek, with a TIA of 70%. Using the method of Boyd (1993), Wright estimated an EIA of 20% in this watershed, for an Ef of 0.29. No more recent detailed studies of EIA were located for King Co. or western Washington.

We reviewed and compared several other methods for estimating EIA, including the five non-linear equations proposed by Sutherland (1995) and linear methods (similar to Elmer) proposed by Roy and Shuster (2009) and Wenger et al. (2008), all of which provide slightly different results. The Roy and Shuster and Wenger et al. equations, while presented as EIA, are actually estimates of DCIA. They are based on studies in specific geographic areas (Cincinnati and Atlanta, respectively) that may not be fully relevant to King County, and, as with Elmer, do not resolve EIA for subbasins with low imperviousness. In contrast, the equations of Sutherland (1995) are based on a reanalysis of data collected by the USGS primarily from Portland, OR (Laenan, 1980; 1983), which is more climatically relevant to the Seattle area and includes estimates of EIA for subbasins with low TIA. The original work of Laenan (and also the reanalysis of Sutherland) is ultimately based on optimization using a hydrologic model and thus provides EIA (rather than DCIA) estimates.

Two equations of particular relevance from Sutherland (1995) are his Equation 1, applicable to average basins where the local drainage collection systems for the urban areas within the basin are predominantly storm sewered with curb and gutter and rooftops from single family residences are not directly connected to the storm sewer or piped directly to the street curb; and Equation 4, applicable to somewhat disconnected basins where at least 50% of the urban areas within the basin are not storm sewered but are served by grassy swales or roadside ditches, and the residential rooftops are not directly connected:

$$Sutherland\ Equation\ 1: EIA = 0.1 \times TIA^{1.5}$$

$$Sutherland\ Equation\ 4: EIA = 0.04 \times TIA^{1.7}$$

The Elmer equation is compared to Sutherland equations 1 and 4 in Figure 3-5, with the right hand side of the figure showing the results for TIA < 20. The Elmer equation gives higher EIA for TIA > 19, but the three equations appear to agree within the margin of error. Unlike the Elmer equation, the Sutherland equations do not have a cutoff point at which the EIA estimate goes to zero. This is desirable because we are evaluating EIA at the scale of relatively large subbasins that may contain small developments amidst larger amounts of rural land as well as roads that are connected where they cross streams. Based on the analysis, the Elmer equation was initially applied where TIA ≥ 18 and Sutherland Equation 1 where TIA < 18 percent.

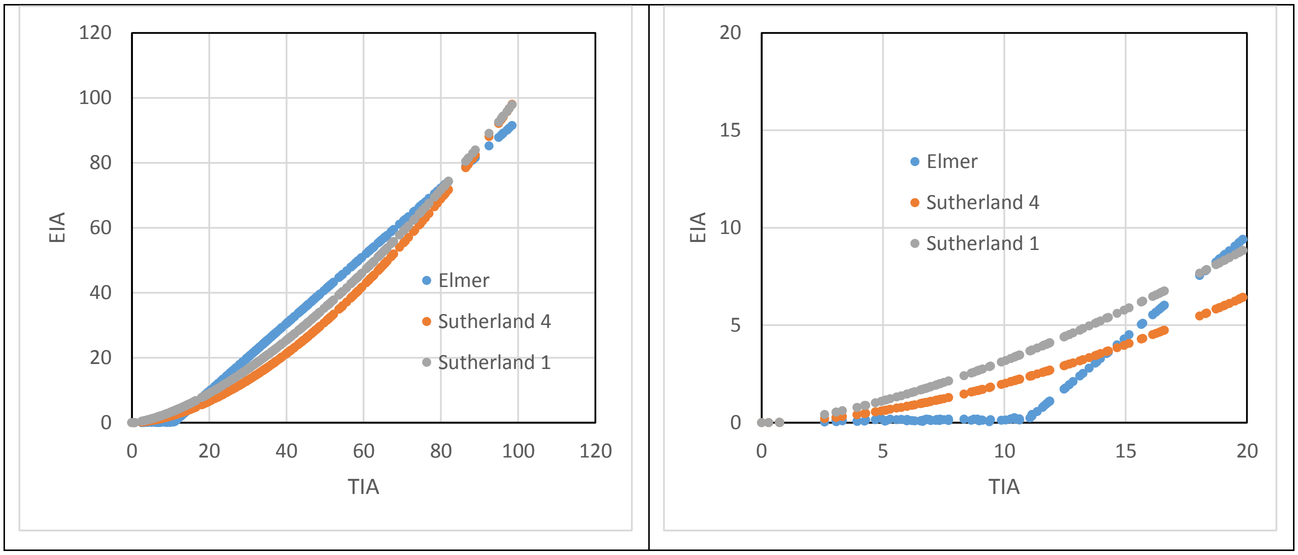

Figure 3-5. Comparison of Elmer and Sutherland EIA Equations for Full Range of TIA (left) and TIA < 20% (right) as Determined for Subbasins in the Green-Duwamish LSPC Model

The next step is separating the EIA attributable to roads and other sources through definition of Ef for road and non-road impervious surfaces. In more rural areas, EIA is predominantly derived from roads and most roads will have at least some minimal amount of EIA. Therefore, we required $0.05 \leq Ef_{road} \leq 0.95$. In addition, Ef_{road} and $Ef_{nonroad}$ must be consistent with EIA_{total} and $Ef_{nonroad}$ must be ≥ 0. This is achieved by imposing the additional constraint $Ef_{road} \leq EIA_{total} / TIA_{road}$. This constraint has the effect of reducing the EIA for roads in subbasins where the total connected area, EIA_{total} is low. Finally, given Ef_{road}, the remaining effective impervious area is derived from $TIA_{nonroad}$ by defining $Ef_{nonroad} = [EIA_{total} – Ef_{road} \times TIA_{road}] / TIA_{nonroad}$. The total EIA calculation is preserved as $EIA_{total} = Ef_{road} \times TIA_{road}/100 + Ef_{nonroad} \times TIA_{nonroad}/100$.

Ineffective impervious area (TIA – EIA) for each impervious category is assigned back to grass cover on the appropriate underlying geology, which is the same approach used by King County (2013) in developing the HSPF models. Over the entire LSPC model domain, average TIA is 21.5% (ranging from zero to 98.5% in individual subbasins) and the initial estimated EIA was 12.0% (ranging from to zero to 91.5% in individual subbasins).

Adjusted EIA

The initial EIA estimates from regional equations are approximations that do not necessarily reflect the characteristics of individual watersheds, such as the degree to which downspouts and driveways are disconnected from the stormwater drainage network. Consistent with King County's (2013) model calibration effort, we found that it was necessary to adjust EIA downward to match observed watershed responses

The impervious areas represented in the WRIA 9 HSPF models were associated with low-density residential, high density residential, commercial, and road land uses. The total impervious areas represented by these land use classes were converted to EIA by land use class and model area to capture the level of connectivity and impact of a given area. For the HSPF models, EIAs were adjusted as a calibration parameter to improve the fit for hydrology, resulting in reductions in EIA relative to the Elmer equation. In the LSPC models, there are four impervious classes that were tabulated as hydrologic response units, as described in Section **3.5**: ground-level residential (such as driveways and residential streets), ground-level commercial/industrial (such as parking lots and high density area roads and highways), ground-level non-developed (such as roads through forest, grass, and agricultural lands), and roofs (for all building types). For the HSPF model development, approximately 10,000 acres of EIA (7.5%) were estimated to be present after calibration adjustments in the area that drains to the Green River (Table 3-4). The same spatial extent within the Green River LSPC model was initially estimated to have 15,335 acres of EIA (11.6%; Table 3-5).

During the hydrology calibration for LSPC, it was apparent that simulated flows using the initial default EIA estimates peaked and receded more quickly than observed flows at calibration stations across the watershed. This suggested that EIA was initially over-estimated. EIA was thus reduced to improve the match between model output and observed data. The fraction of EIA reassigned differed by region due to variations in roof connectivity to storm sewers, presence of green infrastructure (e.g. bioretention areas), and other factors. Ground-level residential EIA and ground-level non-developed EIA are more likely to be connected to vegetated, pervious surfaces such as lawns or grassy fields. For that reason, higher fractions were applied to reassign ground-level residential EIA and ground-level non-developed EIA to pervious land compared to ground-level commercial/industrial and roofs.

Treatment of EIA as a calibration parameter is consistent with the approach of Boyd et al. (1993) and Laenan (1980, 1983), who recognized EIA (as opposed to DCIA) as an inherently hydraulic parameter. We did not, however, use the advanced regression techniques proposed by Ebrahimian et al. (2016a, 2016b) to estimate EIA because the majority of the stream gages appear to be affected by groundwater exchanges that may make them unsuitable for this purpose. We also lacked detailed information on local drainage characteristics that influence EIA, such as bioretention, small stormwater ponds, and the extent of curbs – which would provide direct information on DCIA and, indirectly, EIA. Further studies of local DCIA and applications of the methods of Ebrahimian et al. at suitable gages could be used in future to further refine this aspect of the model. The attribution of EIA for specific impervious surface types may assume greater importance when the model is developed and applied for estimation of toxics loading.

For subbasins in the Green River LSPC model that drain to Mill Creek or Mullen Creek, 80% of the initial ground-level residential EIA and 80% of the ground-level non-developed EIA were reclassified as pervious land during calibration. A lower fraction, 50%, was used to reassign ground-level commercial/industrial EIA and roof EIA in the Mill-Mullen Creek drainage area. Fractions of 60% (ground level residential and ground level non-developed) and 40% (ground-level commercial/industrial and roofs) were used to reassign EIA for all other subbasins in the Green River HSPF Model. EIA was also reduced for subbasins in the Black River and Hamm Creek drainage areas within the Duwamish River LSPC model. Ground level residential and ground level non-developed EIA were reduced by 60% for subbasins in the Black River drainage area (i.e., Springbrook Creek and Mill Creek). EIA for ground-level commercial/industrial and roofs was reduced by 20% in this region. Hamm Creek forms in a primarily residential area and lower reassignment fractions were used (30% for ground level residential and ground level non-developed; 10% for ground-level commercial/industrial and roofs). The area that drains directly to the Duwamish River and Lower Duwamish Waterway is densely developed and heavily impervious so initial EIA estimates were not reduced in this area.

EIA classes represented in the LSPC models include an impervious class for roofs and three ground-level impervious classes: residential, commercial/industrial, and non-developed, as described in Section 3.5**.** Initially classified EIA that was reassigned during this process was allotted to similar pervious classes. For example, the reassigned area from the commercial/industrial ground level EIA class was reassigned to the commercial/industrial pervious classes. Pervious classes are further differentiated by soil and slope and for the commercial/industrial class these include outwash, till on flat slopes and till on moderate slopes (Section 3.0). Soil and slope vary spatially, so an area-weighted approach was used at the subbasin level to divide the reassigned EIA area to the respective pervious groups. Subbasin drainage areas were not altered as impervious land was reduced and reclassified as pervious within the subbasin boundaries.

Initial and final EIA for the Green River and Duwamish River LSPC models are provided in Error! Reference source not found. and **Error! Reference source not found.**. The corresponding HSPF model assignments (King Co., 2013) are shown in **Error! Reference source not found.** and **Error! Reference source not found.**. The final Ef estimate for the Green River LSPC model is 0.26, while that for the Duwamish River LSPC model is 0.55.

These estimates are within the range of Ef of 0.08 to 0.97 estimated by Ebrahimian et al. (2016b) for 48 study watersheds (primarily within Minnesota and Austin, TX), while the estimate for the Duwamish River LSPC model is close to Ebrahimian et al.'s average of Ef=0.50. The value of Ef for the Green River model is close to that of Wright (2013) of Ef = 0.29 for an urban subcatchment in Newaukum Creek and similar to the Ef of 0.36 reported for a residential area in Boulder, CO by Lee and Heaney (2003).

Table 3-4. Effective Impervious Area for Impervious Classes in the Green River HSPF Models

Impervious HRU Description	Final EIA (acres)
Low and High Density Residential	3,550
Commercial	3,414
Roads	3,012
Total	**9,976**

Note: These areas were tabulated from the HSPF models that correspond with the Green River LSPC model (Figure 1-2).

Table 3-5. Effective Impervious Area for Impervious Classes in the Green River LSPC Model

Impervious HRU Description	Initial EIA (acres)	Final EIA (acres)	Final Ef
Ground-level Residential	8,780	3,131	0.22
Ground-level Commercial	1,548	852	0.45
Ground-level Non-developed	2,224	838	0.17
Roofs	2,777	1,579	0.42
Total	**15,335**	**6,400**	**0.26**

Note: EIA shown for the same region represented in **Error! Reference source not found.**.

Table 3-6. Effective Impervious Area for Impervious Classes in the Duwamish River HSPF Models

Impervious HRU Description	Final EIA (acres)
Low and High Density Residential	1,098
Commercial	3,442
Roads	773
Total	**5,314**

Note: These areas are representative of the Hamm, Black, and Duwamish River HSPF models that align with the Duwamish River LSPC model.

Table 3-7. Effective Impervious Area for Impervious Classes in the Duwamish River LSPC Model

Impervious HRU Description	Initial EIA (acres)	Final EIA (acres)	Final Ef
Ground-level Residential	5,812	2,325	0.42
Ground-level Commercial	4,369	2,146	0.71
Ground-level Non-developed	167	69	0.40
Roofs	2,943	2,344	0.63
Total	**13,290**	**6,884**	**0.55**

Note: EIA shown for the same region represented in Table 3.6.

As shown in **Error! Reference source not found.** and **Error! Reference source not found.**, calibrated EIA is lower for the Green River LSPC model (6,400 acres) compared to HSPF (9,976 acres). This could be due to alterations to the built environment (e.g., roof-to-sewer disconnections) and construction of green infrastructure to delay storm runoff. The implementation of such practices has increased in the watershed as private businesses, cities and other public entities work to counteract the impacts of development. This may explain alterations in the observed hydrograph at Mill Creek near Peasley Canyon Road (41c) from early 2007 to 2015. The peak flow following a winter precipitation event of 1.5 inches was approximately 93 cfs in 2007 (Figure 3-6). For a similar winter precipitation event (1.5 inches) in 2015, the observed peak flow was muted to 52 cfs (Figure 3-7). Furthermore, cumulated precipitation on the 7 days prior to the peak flow in the 2007 event was significantly less (2.36 inches) than the 2015 event (4.37 inches). The ground was likely less saturated for the 2007 event but peak flow was almost double that of the 2015 event. The LSPC model calibration is optimized based on the entire simulated period (minus a ramp-up year). Reducing impervious areas improved the overall performance of the model, especially for recent years.

Variations between the optimized EIA used in the HSPF and Duwamish River LSPC model may be in part due to development that has occurred in the lower part of the watershed. EIA totals 5,314 acres in the Hamm Creek, Black River, and Duwamish River HSPF models. EIA for the same extent in the Duwamish River LSPC model is higher at 6,884 acres.

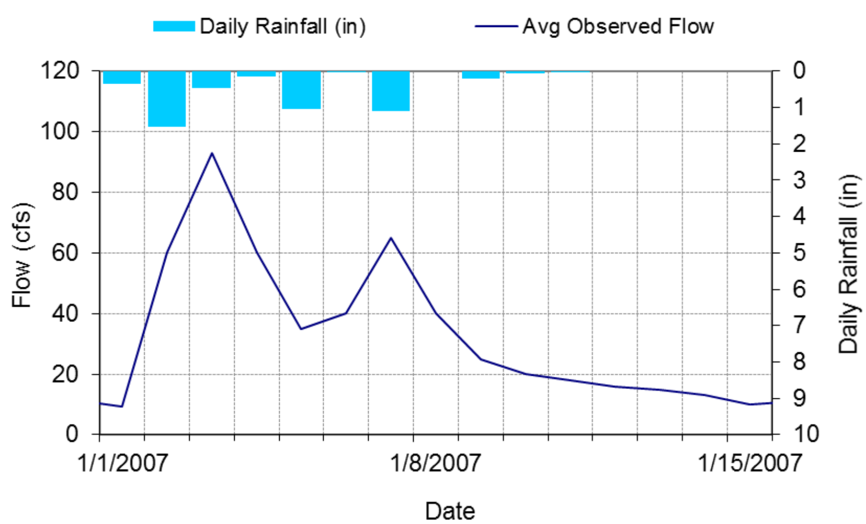

Figure 3-6. Observed Hydrograph for 2007 Winter Precipitation Event at Mill Creek near Peasley Canyon Rd (41c)

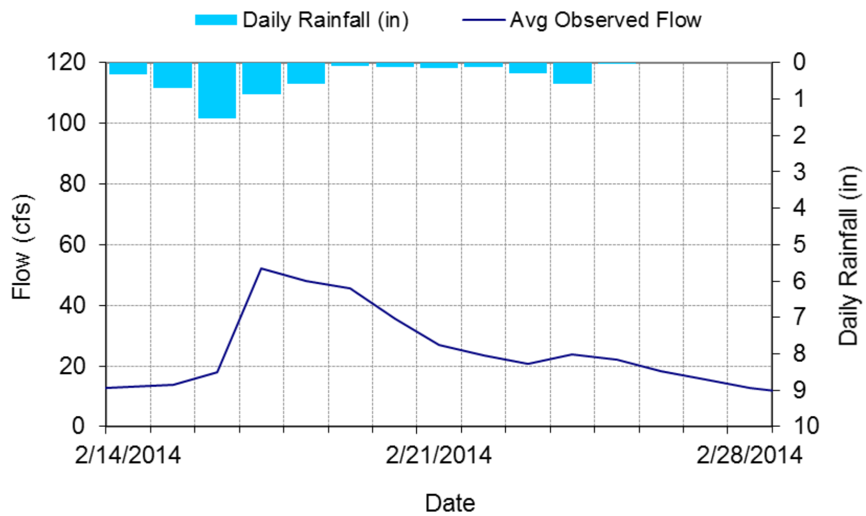

Figure 3-7. Observed Hydrograph for 2015 Winter Precipitation Event at Mill Creek near Peasley Canyon Rd (41c)

3.4 DRAINAGE CLASSES FOR SEATTLE HRUS

Modeled land uses within the area of the City of Seattle were subdivided based on whether they are physically located within the following drainage classes identified by SPU: Combined Sewer, Separated Sewer, and Partially Separated Sewer (Figure 3-8). See Section 2.2.2 for the delineation of area draining to the Lower Duwamish Waterway. Separated sewer areas are modeled such that both surface runoff and groundwater are routed to the stream network. For combined sewered areas, surface runoff is routed out of the system (in reality, to an out of basin wastewater treatment facility combined with sanitary sewer lines), and only groundwater is potentially routed downstream (with the exception of combined sewer overflows). King Co. natural drainage boundaries are used to determine combined sewer areas that are likely to contribute groundwater discharge to the Lower Duwamish Waterway. For partially separated sewer areas, runoff from roofs is routed out of the model (presumed to be connected to the sanitary sewer network), while runoff from ground level pervious and impervious surfaces (roads, parking lots, driveways) is routed to the stream network, similar to separate sewer areas. In the upstream Green River LSPC model and the portion of the Duwamish River model outside the Seattle City Limits all surface drainage is separated, and the split between the three sewer classes for HRU delineation only occurs in the Seattle jurisdiction.

Note that the sewer class shapefile depicted in Figure 3-8 is relatively coarse and captures general area patterns, not precise information on drainage for every individual parcel. SPU has begun development of a parcel-by-parcel sewer and drainage connectivity identification process for the purpose of identifying existing and potential areas of green infrastructure. This fine-scale SPU layer may be of-interest for model refinements, but is currently incomplete and there are too many unknowns to incorporate those data at the time of this report.

A conceptual model of groundwater flow in the Duwamish Industrial Area (Booth and Herman, 1998), along with a numerical model of groundwater flow (Fabritz et al., 1998) suggest that most recharge occurring within the topographic divides of the natural surface watershed of the LDW flows to the waterway. This includes flows originating from the combined sewer service area, at least where bedrock is not present at the surface.

The groundwater modeling predicts seeps where groundwater discharges to the surface. These seeps occur along Longfellow Creek and along the contact between the uplands and the valley sediments. Total discharge via these seeps was estimated at approximately 10 cfs, or 30 percent of the infiltration to the local watershed area, and could be potential pathways for pollutant transport.[1]

3.5 HRU DEVELOPMENT

HRUs are developed to capture similarities and differences in hydrologic response for combinations of land use, soil, slope, and imperviousness. The 6-foot resolution rasters for soil class, slope class, aggregated land use class, sewer class, and impervious class were combined using raster algebra. Post-processing of the resulting raster was completed in Excel to aggregate HRUs. Table 3-8 shows the HRUs developed for the Green River LSPC model.

The Duwamish River LSPC model uses similar base HRU classes (Table 3-9), but also incorporates a split for all land uses into areas with separate, combined, or partially separated storm sewer drainage. Most of the area covered by the Duwamish River model is highly developed and only small areas of some more rural land uses, such as agriculture, are present, so these were lumped across geology and slope.

[1] Unfortunately, it does not appear that the 1998 MODFLOW model is available. Ecology has subsequently worked to update and expand the Duwamish Basin Groundwater Pathways Conceptual Model, but no final report has been produced to date.

Figure 3-8. Sewer Classes in the Lower Duwamish Waterway (Seattle Public Utilities, 2016)

Table 3-8. Hydrologic Response Units (HRUs) for the Green River LSPC Model

#	Geology	Slope	Land Cover/ Impervious	Area (ac)	Data Sources
1	Commercial/Ind.: Ground Level Impervious (EIA)			852	NLCD High Density Developed, Transportation Network, Imperviousness
2	Residential: Ground Level Impervious (EIA)			3,131	NLCD Open Space, Low, and Medium Density Developed, Transportation Network, Imperviousness
3	Non-Developed: Ground Level Impervious (EIA)			838	All NLCD non-developed classes, Imperviousness
4	Impervious Roof (EIA)			1,579	Imperviousness
5	Outwash	All	Agriculture	3,063	USGS Outwash, NLCD Crop and Pasture
6	Saturated	All	Agriculture	76	USGS Saturated, NLCD Crop and Pasture
7	Till	Flat	Agriculture	6,172	USGS Till and Bedrock, NLCD Crop and Pasture, LiDAR
8	Till	Moderate	Agriculture	899	
9	All	All	Barren	247	NLCD Barren
10	Outwash	All	Commercial/Industrial	1,458	USGS Outwash and Saturated, High Density Developed
11	Till	Flat	Commercial/Industrial	589	USGS Till and Bedrock, NLCD High Density Developed, LiDAR
12	Till	Moderate	Commercial/Industrial	190	
13	Outwash	All	Forest	18,020	USGS Outwash NLCD Mixed, Deciduous, and Coniferous Forest, Woody Wetlands
14	Saturated	All	Forest	1,509	USGS Saturated, NLCD Mixed, Deciduous, and Coniferous Forest, Woody Wetlands
15	Till	Flat	Forest	6,105	USGS Till and Bedrock, NLCD Forest, Woody Wetlands, LIDAR
16	Till	Moderate	Forest	21,989	
17	Outwash	All	Grassland	6,827	USGS Outwash, NLCD Herbaceous, Emergent Herbaceous Wetlands
18	Saturated	All	Grassland	123	USGS Saturated, NLCD Herbaceous, Emergent Herbaceous Wetlands
19	Till	Flat	Grassland	6,965	USGS Till and Bedrock, NLCD Herbaceous, Emergent Herbaceous Wetlands, LiDAR
20	Till	Moderate	Grassland	657	
21	Outwash	All	HD Residential	1,994	USGS Outwash and Saturated, NLCD Medium Density Developed
22	Till	Flat	HD Residential	1,186	USGS Till and Bedrock, NLCD Medium Density Developed, LiDAR
23	Till	Moderate	HD Residential	758	
24	Outwash	All	LD Residential	15,541	USGS Outwash and Saturated, NLCD Open Space and Low Density Developed
25	Till	Flat	LD Residential	10,702	USGS Till and Bedrock, NLCD Open Space and Low Density Developed, LiDAR
26	Till	Moderate	LD Residential	8,363	
27	Outwash	All	Shrub/Scrub	2,853	USGS Outwash, NLCD Shrub/Scrub
28	Saturated	All	Shrub/Scrub	125	USGS Saturated, NLCD Shrub/Scrub
29	Till	Flat	Shrub/Scrub	758	USGS Till and Bedrock, NLCD Shrub/Scrub, LiDAR
30	Till	Moderate	Shrub/Scrub	4,243	
31	All	All	Water	950	NLCD Open Water
32	Saturated	All	Wetlands	489	King County Wetlands, NLCD/USGS Saturated Grasslands

Table 3-9. Hydrologic Response Units (HRUs) for the Duwamish River LSPC Model

#	Geology	Slope	Land Cover/Impervious	Separated Sewer Area (ac)	Combined Sewer Area (ac; see note)	Partially Separated Sewer Area (ac)
1	Commercial/Ind.: Ground Level Impervious (EIA)			2,146	583	1,679
2	Residential: Ground Level Impervious (EIA)			2,325	438	1,084
3	Non-Developed: Ground Level Impervious (EIA)			69	5	16
4	Impervious Roof (EIA)			2,344	536	1,048
5-7	Used for coding pervious areas served by combined sewers (see note)					
8	All	All	Agriculture	152	0	0
9	All	All	Barren	54	0	4
10	Outwash	All	Commercial/Industrial	1,051	42	65
11	Till	Flat	Commercial/Industrial	316	26	85
12	Till	Moderate	Commercial/Industrial	124	8	51
13	Outwash	All	Forest	472	13	55
14	Saturated	All	Forest	68	0	0
15	Till	Flat	Forest	121	8	8
16	Till	Moderate	Forest	644	83	334
17	Outwash	All	Grassland	1,235	68	72
18	Saturated	All	Grassland	100	0	2
19	Till	Flat	Grassland	1,149	188	498
20	Till	Moderate	Grassland	15	0	2
21	Outwash	All	HD Residential	1,269	160	369
22	Till	Flat	HD Residential	805	92	142
23	Till	Moderate	HD Residential	719	124	214
24	Outwash	All	LD Residential	3,225	308	527
25	Till	Flat	LD Residential	2,301	135	216
26	Till	Moderate	LD Residential	2,842	120	169
27	All	All	Shrub/Scrub	51	0	0
28	All	All	Water	102	8	18

Note: Codes 5, 6, and 7 are used for pervious areas served by combined sewers, with 5 representing commercial/industrial land, 6 representing non-developed land, and 7 representing residential land.

4.0 METEOROLOGY

Meteorological forcing series required for the hydrologic simulation are hourly precipitation and potential evapotranspiration. Weather records from King County's Hydrologic Information Center, the National Weather Service's Sea-Tac station, and Washington State University's (WSU) Puyallup station were used to create the input weather series for the existing HSPF models (Figure 4-1). An important component of the development of the LSPC models was the extension in time of the meteorological series.

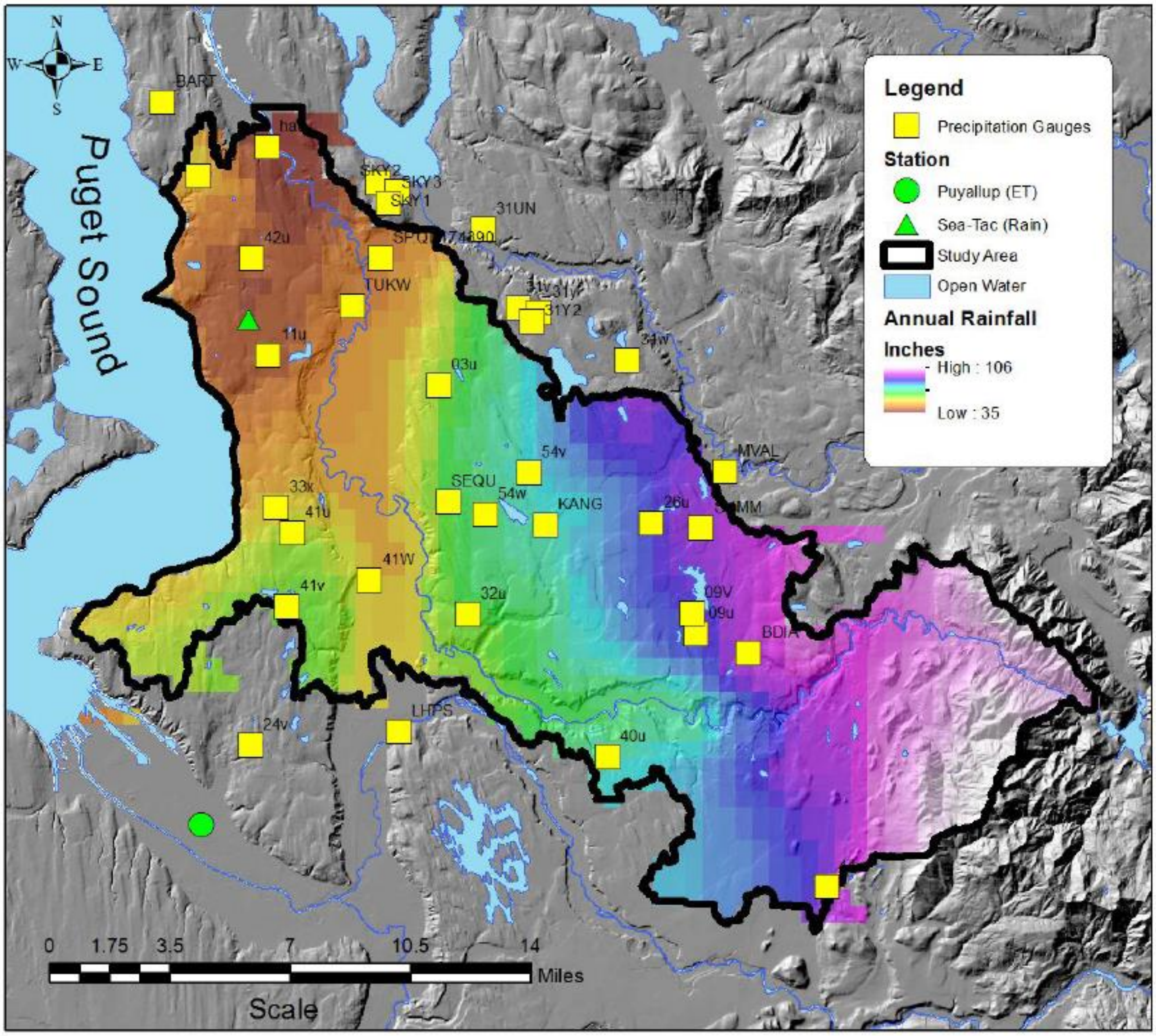

Figure 4-1. King County Precipitation Gauges, Washington State University's Puyallup Station, and the National Weather Service's Sea-Tac Station used in the HSPF Watershed Models (King County, 2013)

Point-in-space monitoring records are often not representative of integrated weather over a surrounding model area. This is likely the case for the Green/Duwamish River Watershed where annual precipitation totals vary significantly across the landscape, ranging from 35 in/yr near the Puget Sound to more than 100 in/yr near the Howard A. Hanson Dam. Gridded weather products can be used to better represent climatic variations across a diverse landscape. These products also directly provide hourly air temperature, wind, and solar radiation data as well as parameters for computing cloud cover, dew point temperature, and potential evapotranspiration, all of which are required for an LSPC model. Another benefit of gridded meteorological products is that these sources provide continuous data without gaps. This is not the case for point-in-space stations. Significant QA work is required to process station-based records and, for earlier modeling efforts, this included patching missing records and developing proximity-based composite time series. Gridded products also simplify and streamline the process of extending the spatial domain of the LSPC models and/or lengthening the simulation period.

PRISM (Parameter-elevation Relationships on Independent Slopes Model) provides annual, monthly, and daily gridded precipitation data for the conterminous United States (Daly et al., 2008, 2015; daily output was added to PRISM in 2015). PRISM calculates a climate-elevation regression function for each grid cell and the regression is used to distribute station-based precipitation data to the grid cell. Approximately 13,000 precipitation stations are used in the analysis. For each grid cell, precipitation stations are assigned weights based on location, elevation, coastal proximity, topographic facet orientation, vertical atmospheric layer, topographic position, and orographic effectiveness of the terrain; the stations are then entered into the regression function to establish the gridded precipitation product.

Another gridded product is the North American Land Data Assimilation System (NLDAS-2) meteorological time-series (Mitchell et al., 2004). NLDAS-2 (http://ldas.gsfc.nasa.gov/nldas/NLDAS2forcing.php) provides continuous hourly data from 1979 to present on a 1/8 degree grid that has been processed to fill gaps. The precipitation data in NLDAS-2 are based on interpolation of daily gauge precipitation including orographic adjustments based on PRISM and temporally disaggregated using Doppler radar and satellite data. NLDAS-2 also provides solar radiation, wind at 10 m (which can be scaled to wind at 2 m), and absolute humidity plus air pressure, from which dew point can be calculated. Cloud cover (which is needed in LSPC only to estimate long wave radiation exchange with the atmosphere) is not included in the NLDAS output, but can be back-calculated from the ratio of estimated incident solar radiation to cloud free solar radiation using the regression relationship developed by Davis (1997). Hourly potential evapotranspiration (PET) estimates are included in the NLDAS dataset, generated using a modified Penman energy-balance method. However, the NLDAS estimates of PET are included only for legacy compatibility with input requirements of the Sacramento Streamflow Accounting Model, do not incorporate subsequent corrections to NLDAS estimates of energy forcing, and have been found to overestimate ET in other modeling efforts. Potential evapotranspiration can be computed based on the NLDAS-2 corrected estimates of air temperature, wind, humidity, air pressure, and solar radiation.

The Green/Duwamish River Watershed LSPC model uses meteorological data from both PRISM and NLDAS. Hourly weather forcing series, including precipitation (PREC), air temperature (ATEM), cloud cover (CLOU), dew point temperature (DEWP), solar radiation (SOLR), wind speed (WSPD), and potential evapotranspiration (PEVT), were developed for calendar years 1996-2015. The basic overview of each meteorological input, data source, and processing notes are provided in Table 4-1 and these are discussed in more detail in the following sections. For hydrology, the energy terms (ATEM, CLOU, DEWP, SOLR, and WSPD) are required for calculation of PEVT. They will also be used directly when the model is further developed for temperature and water quality simulation.

NLDAS gridded data was retrieved for the spatial extent of the Green/Duwamish River Watershed LSPC models. Data from 12 NLDAS grid cells, which align with the modeled area, were used both directly as model inputs and to compute other, non-reported weather forcing series, such as cloud cover.

Table 4-1. Processing Details for Hourly Weather Forcing Series

LSPC Model Input	Description (units)	Parameter Source	Processing Notes
PREC	Precipitation (in)	PPT (PRISM), APCP (NLDAS)	Daily PRISM precipitation data were disaggregated based on NLDAS hourly precipitation distributions
ATEM	Air Temperature (°F)	TMP (NLDAS)	Hourly air temperature, used directly
SOLR	Solar Radiation (Ly)	DSWRF (NLDAS)	Hourly short wave radiation, used directly
CLOU	Cloud Cover (%)	DSWRF (NLDAS)	Inferred from hourly short wave radiation at 2 meters, and estimated cloudless-sky short wave radiation
DEWP	Dew Point Temperature (°F)	SPFH, PRES, TMP (NLDAS)	Function of hourly specific humidity, air pressure, and air temperature
WIND	Wind Travel (mi)	UGRD, VRGD (NLDAS)	Net wind travel from component vectors
PEVT	Potential Evapotranspiration (in)	DSWRF, TMP, WIND, SPFH, PRES (NLDAS)	Computed from solar radiation, air temperature, wind, specific humidity, air pressure, and elevation

4.1 PRECIPITATION (PREC)

PRISM has been shown to better represent precipitation than WorldClim and Daymet, which are other publicly available gridded meteorological products (Daly et al., 2008). This is especially true for regions similar to the Green/Duwamish River Watershed where coastal effects and large elevation gradients affect precipitation patterns (Daly et al., 2008). Because of this PRISM was used to generate precipitation (PREC) series for the LSPC models. A total of 71 PRISM grid cells span the model study area. These are shown in Figure 4-2 along with the local PRISM input stations used to calibrate and spatially interpolate the data. Daily precipitation data for these grid cells were retrieved from the PRISM database using Python scripts created by Tetra Tech. Daily precipitation records for each PRISM grid cell were then disaggregated to an hourly time step. To do this, sub-daily rainfall distributions were generated from NLDAS hourly precipitation records. Each PRISM grid cell was then spatially mapped to a NLDAS grid cell and the PRISM data were disaggregated to an hourly time step according to the sub-daily precipitation patterns of the overlapping NLDAS grid cell.

On a small fraction of days, a PRISM cell reports precipitation but the larger NLDAS grid cell does not. This generally occurs when the total precipitation amount reported by PRISM was very low, averaging less than 0.01 in/day and often at the beginning or end of a multi-day event. In such cases an NRCS Type 1-A 24-hour rainfall distribution pattern was used to disaggregate the non-zero PRISM precipitation. A spatial analysis was completed to assign input precipitation time series to model subbasins and reaches.

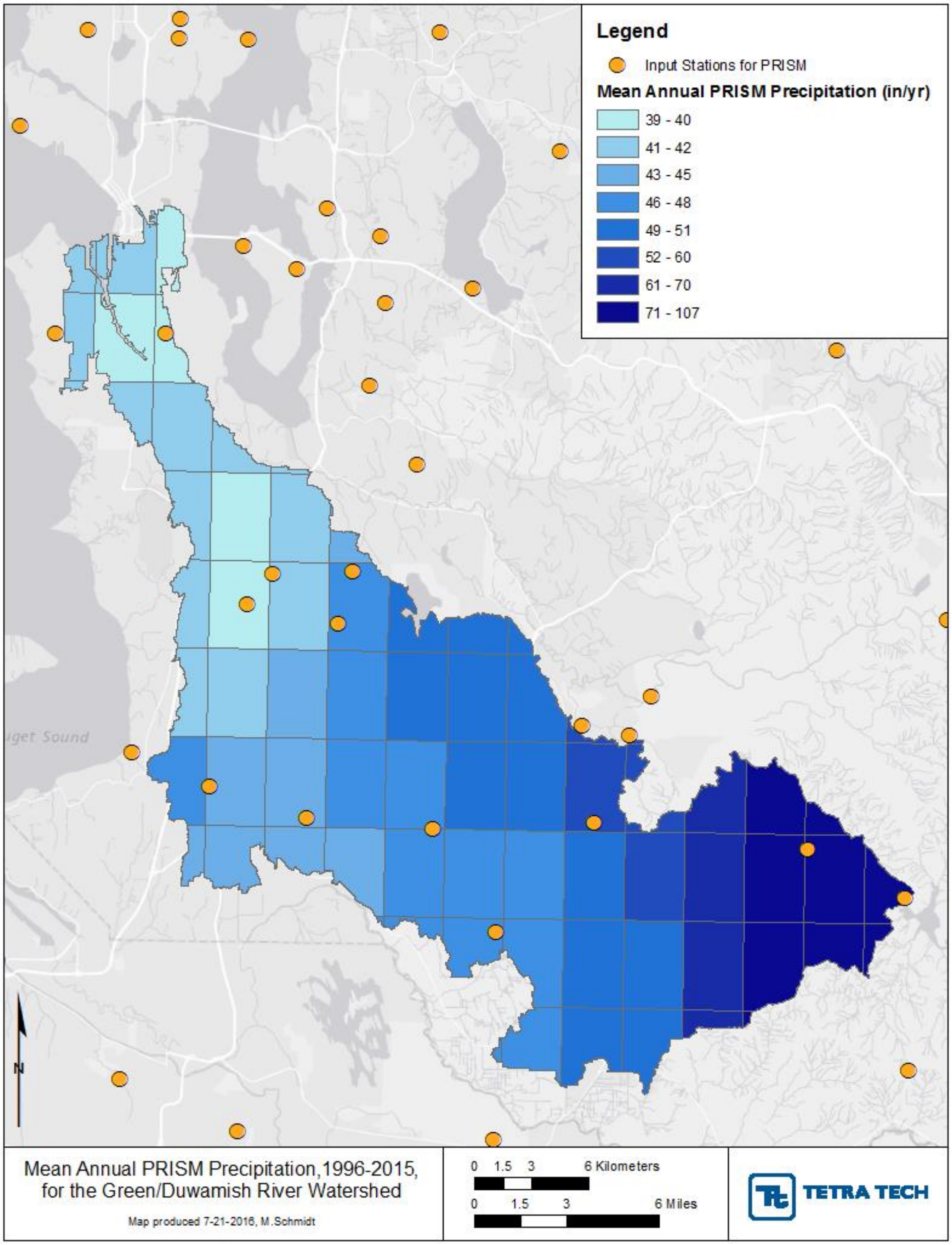

Figure 4-2. Mean Annual PRISM Precipitation (1996-2015) for the Green/Duwamish River Watershed

Note: Orange dots show the local precipitation gauges included in the PRISM spatial regression model.

Precipitation series used in the King Co. (2013) HSPF models of Crisp Creek, Deep Creek, and the lower Green River (Gren5) are compared to PRISM precipitation estimates in Figure 4-3 - Figure 4-5. These figures show cumulative precipitation for the overlapping model periods of the HSPF and LSPC models, 1/1/1996 – 11/30/2011. There are six PRISM grid cells that align with the Deep Creek subbasins, three for the Crisp River subbasins, and seven for the lower Green River subbasins (Gren5). The Deep Creek is located in the upper portion of the LSPC model extent, where mean annual precipitation totals are the highest. Cumulative PRISM precipitation across the Deep Creek watershed varies from 876 to 1,594 inches (Figure 4-3); precipitation applied in the HSPF model is much lower at a total of 639 inches. There is less variation between HSPF and PRISM in the middle portion of the Green/Duwamish River Watershed. Cumulative PRISM precipitation for Crisp Creek, for example, ranges from 730 – 800 inches and the HSPF total was 684 inches. Precipitation records in the lower Green River drainage area are similar for the seven PRISM records (625 – 657 inches) and for the input HSPF series (641 inches).

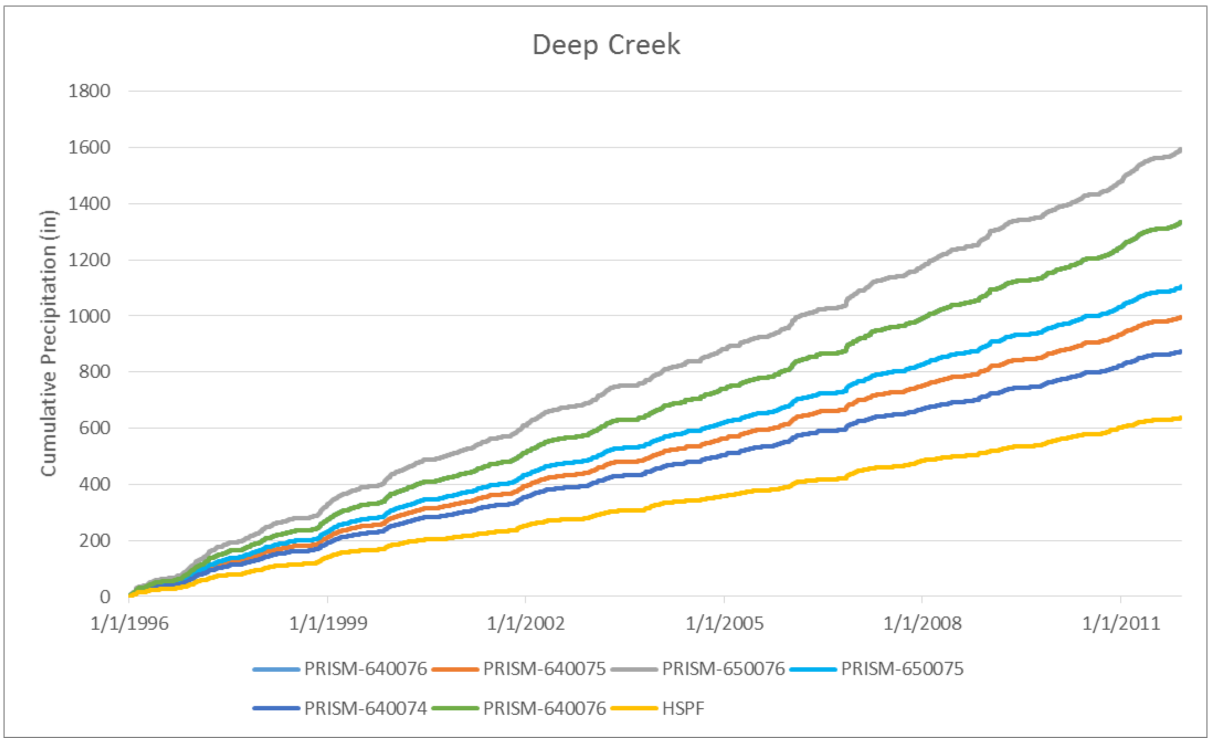

Figure 4-3. Cumulative Precipitation for the Deep Creek HSPF Model and the PRISM Grids used for Deep Creek Subbasins in the LSPC Model

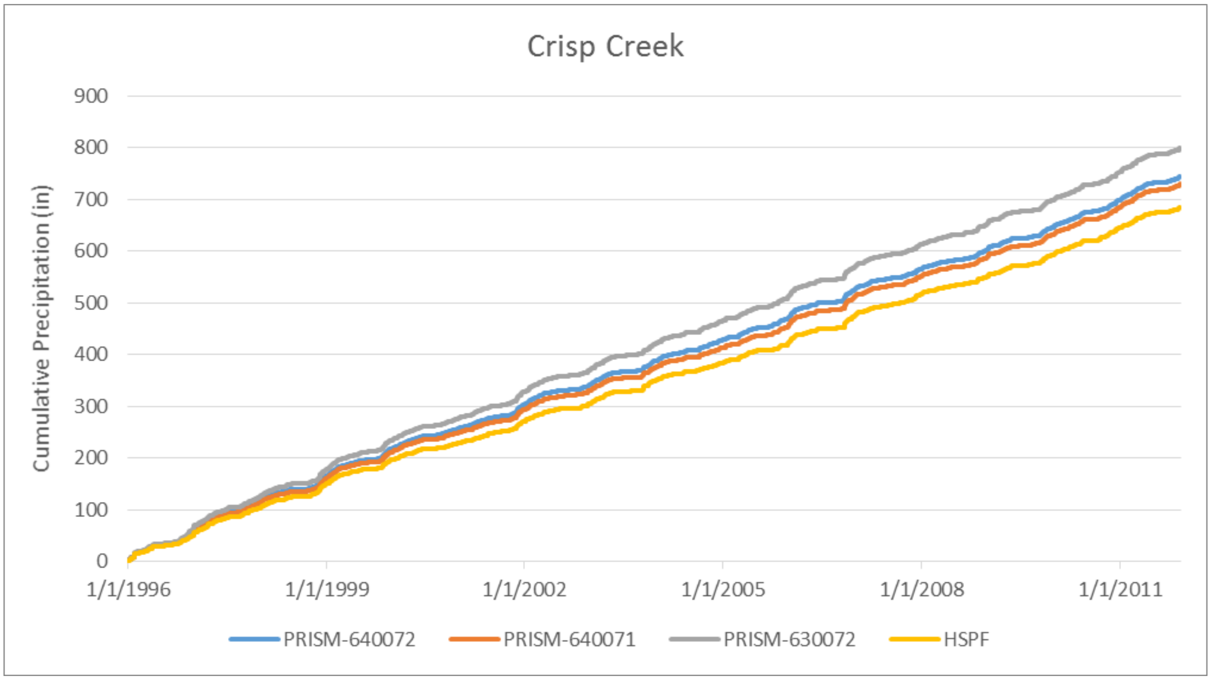

Figure 4-4. Cumulative Precipitation for the Crisp Creek HSPF Model and the PRISM Grids used for Crisp Creek Subbasins in the LSPC Model

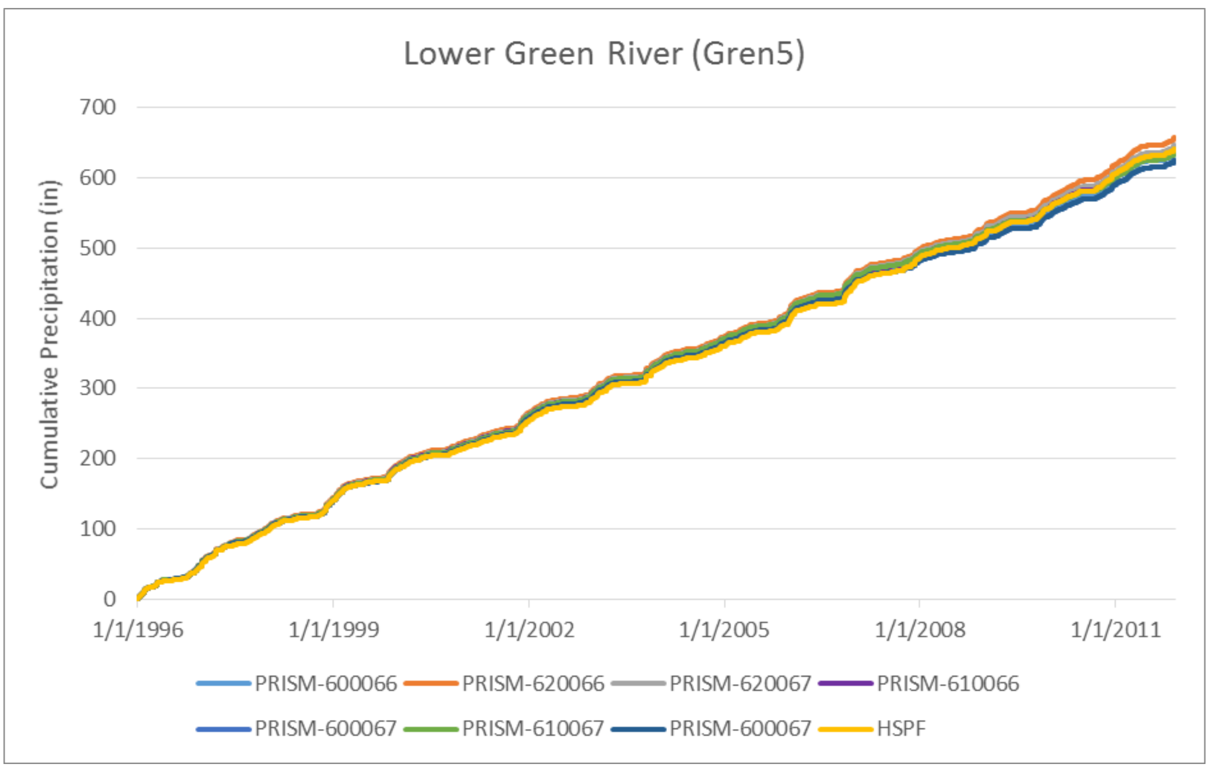

Figure 4-5. Cumulative Precipitation for the Lower Green River (Gren5) HSPF Model and the PRISM Grids used for the Lower Green River Subbasins in the LSPC Model

Records from two point-in-space gauges, *32u* and *hau*, which are respectively located in the Green River and Duwamish River drainage areas were compared to PRISM. The precipitation gauge *32u* is centrally located in the Green/Duwamish River Watershed and the spatially corresponding PRISM grid cell for gauge *32u* is 00630069. Daily precipitation records are compared for gauge *32u* and PRISM grid cell 00630069 in Figure 4-6. As shown by the line of best fit ($R^2 = 0.8737$), daily precipitation at the point-in-space station and grid cell are similar. There are discrepancies on certain days. The highest daily precipitation value during the period of 10/1/1998 – 9/30/2009 occurred on 10/20/2003. On this day, the PRISM precipitation totaled 4.51 in. whereas the gauged precipitation is about an inch more at 5.42 in. Cumulative PRISM precipitation for this period does exceed gauge 32u precipitation at 482 in. and 450 in., respectively.

The results for the gauge in the Duwamish River drainage area are similar to that of the representative Green River comparison. The overlapping PRISM grid cell for the *hau* station is 00590066 and the two datasets are highly correlated ($R^2 = 0.9075$). Cumulative precipitation (10/1/1998 – 9/30/2009) is reported as higher at the point-in-space station than the PRISM grid cell (455 in. vs. 411 in.)

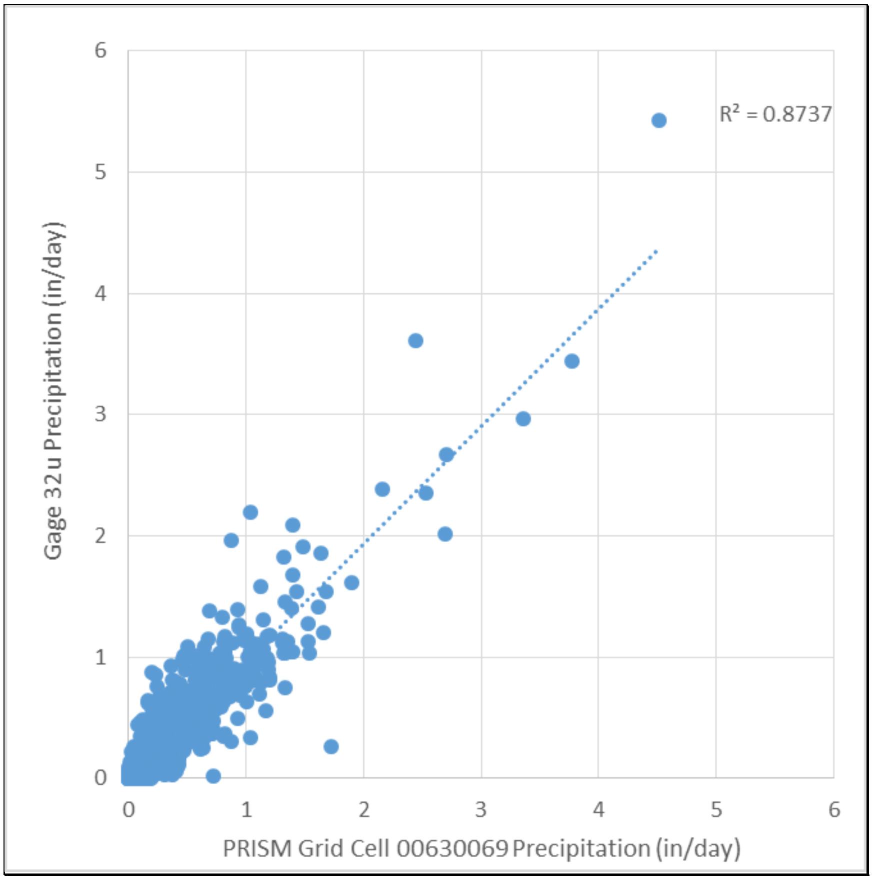

Figure 4-6. Comparison of Daily Precipitation at Gage *32u* and Corresponding PRISM Grid Cell 00630069 (10/1/1998 – 9/30/2009)

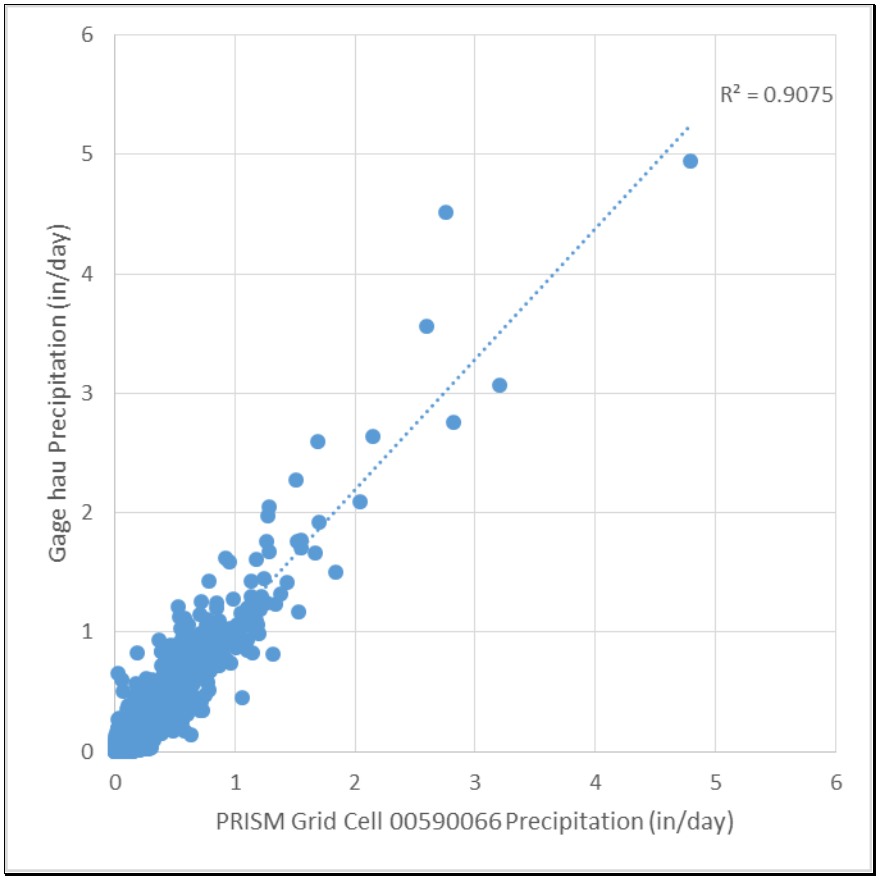

Figure 4-7. Comparison of Daily Precipitation at Gage *hau* and Corresponding PRISM Grid Cell 00590066 (10/1/1998 – 9/30/2009)

Apparent discrepancies in precipitation totals for individual events are likely primarily due to the expected greater variability for gage measurements at a point in space relative to the spatially averaged depth across a PRISM grid cell. The spatially averaged depth is believed to be the more reliable input for runoff simulation.

4.2 AIR TEMPERATURE (ATEM)

NLDAS directly provides hourly air temperature (TMP) at 2 meters above the surface. NLDAS reports temperatures in Kelvin and data retrieved for the Green/Duwamish LSPC model were converted to degrees Fahrenheit.

4.3 SOLAR RADIATION (SOLR)

NLDAS directly provides estimation of hourly shortwave solar radiation (DSWRF) at 2 meters above the surface (W/m^2) corrected for atmospheric conditions. The solar radiation data were converted to LSPC compatible units (Langleys).

4.4 WIND TRAVEL (WIND)

NLDAS provides estimation of directional hourly wind speeds (m/s) at 10 meters above land surface as northing and easting vector components (UGRD and VGRD), which are used to compute total wind travel distance for the hour ($\sqrt{UGRD^2 + VGRD^2}$) The 10-m estimate is scaled to 2 meters above the ground:

$$W_{2-meters} = 3600 \times \frac{1}{1609.34} \times 0.2^{0.143} \times W_{10-meters}$$

where, $W_{10-meters}$ is the wind travel at 10 meters above the ground in m/s and $W_{2-meters}$ is wind travel for the duration of an hour at 2 meters above the ground in miles.

4.5 CLOUD COVER (CLOU)

Cloud cover fraction is not directly reported by NLDAS; however, it can be back calculated from the relationship of Davis (1997) describing the ratio of ambient solar radiation at the surface (E_{surf}) to radiation from a cloudless sky ($E_{cloudless}$):

$$\frac{E_{surf}}{E_{cloudless}} = 1 - 0.6740\ C^{2.854}$$

where, C is the fractional cloud cover.

$E_{cloudless}$ is a function of latitude and time of year and is calculated for each NLDAS grid cell with the SARA Time Series Utility Tool (https://www.aquaterra.com/resources/downloads/saratsutility.php).

LSPC requires cloud cover inputs to be specified as tenths (0 to 10).

4.6 DEW POINT TEMPERATURE (DEWP)

NLDAS does not provide dew point temperature, but does provide specific humidity (SPFH) and atmospheric pressure (PRES). Dew point temperature was calculated using the following approach that is based on NOAA methods:

1. Calculate vapor pressure (e, mb) as a function of atmospheric pressure (p, mb) and specific humidity (q) from definition of q as a function of the mixing ratio, yielding

$$e = \frac{q\ p}{0.622 + 0.378\ q}$$

2. Use e to calculate dewpoint (Td [C], °C) by rearranging the National Weather Service Weather Calculator equation (http://www.wrh.noaa.gov/slc/projects/wxcalc/formulas/vaporPressure.pdf, accessed 11/2/16) for e (mb) as a function of Td [C]:

$$e = 6.11\ x\ 10^{\frac{7.5\,Td}{237.7+Td}}$$

$$Td[C] = Log_{10}\left(\frac{e}{6.11}\right)\ x\ \left[\frac{237.7}{7.5 - Log_{10}(e/6.11)}\right]$$

3. Convert to dew point in °F:

$$Td[F] = 32 + Td[C] x\ 9/5$$

4. Ensure consistency with local daily air temperature data minimum (T_{min}, °F). Relative humidity increases with a decrease in air temperature and reaches 100% at dew point. Since theoretically relative humidity cannot exceed 100%, dew point temperature cannot be greater than air temperature:

$$Td[F] = Max(T_{min}, Td[F])$$

4.7 POTENTIAL EVAPOTRANSPIRATION (PEVT)

The evapotranspiration data used in the WRIA9 HSPF models are primarily from estimates at an observation station operated by Washington State University in Puyallup (King County, 2013). Gaps in the Puyallup series were filled with calculated PEVT, resulting in a single, continuous record that was applied across the WRIA9 models. This approach does not represent spatial differences in PEVT across the Green/Duwamish River and additional PEVT series were developed for the LSPC models.

NLDAS provides an estimate of potential evapotranspiration (PEVAP) calculated by the modified Penman method of Mahrt and Ek (1984). However, this is not a focus of NLDAS because NLDAS is designed to run a variety of Land Surface Models (LSMs; such as the NOAH model), most of which generate their own energy-based ET estimates. PET is provided by NLDAS only because one of the LSMs (SAC-SMA, the Sacramento soil moisture accounting model) does require it as an input (http://ldas.gsfc.nasa.gov/nldas/NLDAS2forcing.php; accessed 9/2/2015). On investigation, it turns out that the PET that NLDAS reports is the PET calculated by the North American Regional Reanalysis (NARR) dataset (Mesinger, et al., 2006). NARR is documented to have a large positive bias in the estimation of shortwave radiation (Xia, et al., 2012). NLDAS solar radiation corrects the NARR shortwave radiation estimates using satellite-based estimates, but the PET estimates ported from NARR are not corrected. In addition, NARR is at a coarser spatial scale than NLDAS and the PET estimates may be off in areas with strong edge effects.

NLDAS provides variables, including air temperature, relative humidity, air pressure, solar radiation, and wind speed that are necessary to estimate PEVT using an energy balance method. A Python script that computes Penman-Monteith Reference Evapotranspiration (Waterloo, 2014) based on the FAO56 method (Allen et al. 1998) was adapted to develop the PEVT time series. Twelve PEVT series, corresponding with the twelve NLDAS grid cells that span the model extent, were generated. The mean annual NLDAS-computed PEVT ranges from 33.9 to 38.1 inches (Figure 4-8). The average across the 12 series, 35.4 inches, is similar to the mean annual PEVT used in the HSPF models (35.7 inches). There are benefits, however, of supplementing the station-based PEVT with NLDAS-computed PEVT. First, the NLDAS-computed PEVT characterizes variation in PEVT across the watershed. These differences are attributed to physical and climatic features that vary across the landscape including elevation, air temperature, and relative humidity. In addition to the spatial variations in PEVT, PEVT fluctuates throughout a 24-hour period. The existing HSPF models used PEVT specified as a daily total that is distributed equally throughout the day. Because of the spatial and temporal benefits of the gridded PEVT series, the NLDAS-computed PEVT series are used in the LSPC model (Figure 4-9).

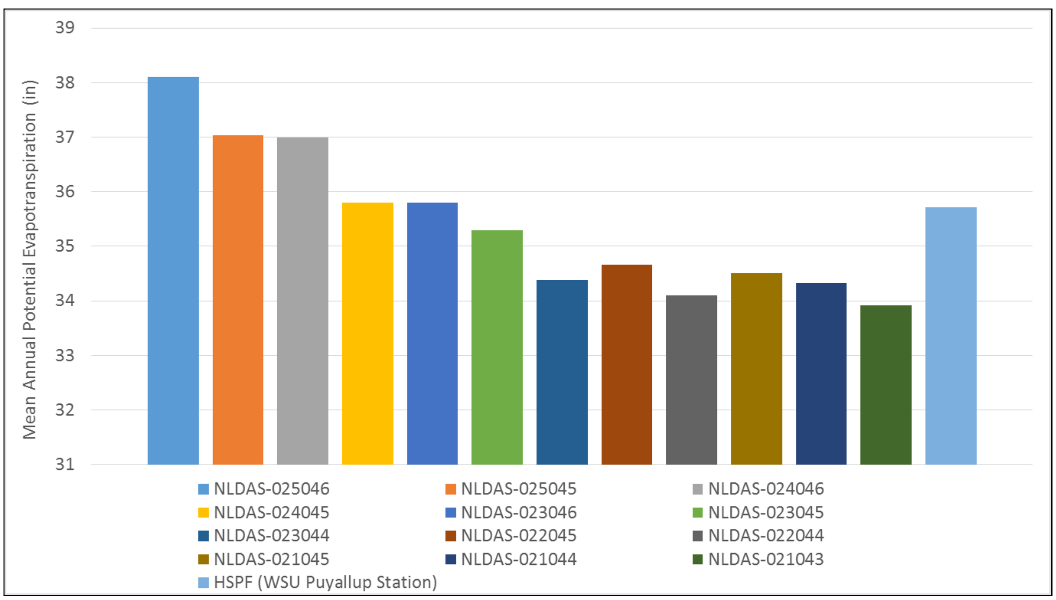

Figure 4-8. NLDAS-Computed and WSU Puyallup Mean Annual Potential Evapotranspiration, 1996-2010

Note: Potential evapotranspiration reported by NLDAS is not used for the LSPC model; rather NLDAS data, including air temperature, relative humidity, air pressure, solar radiation, and wind speed, were used to compute potential evapotranspiration forcing series that are used in the LSPC model.

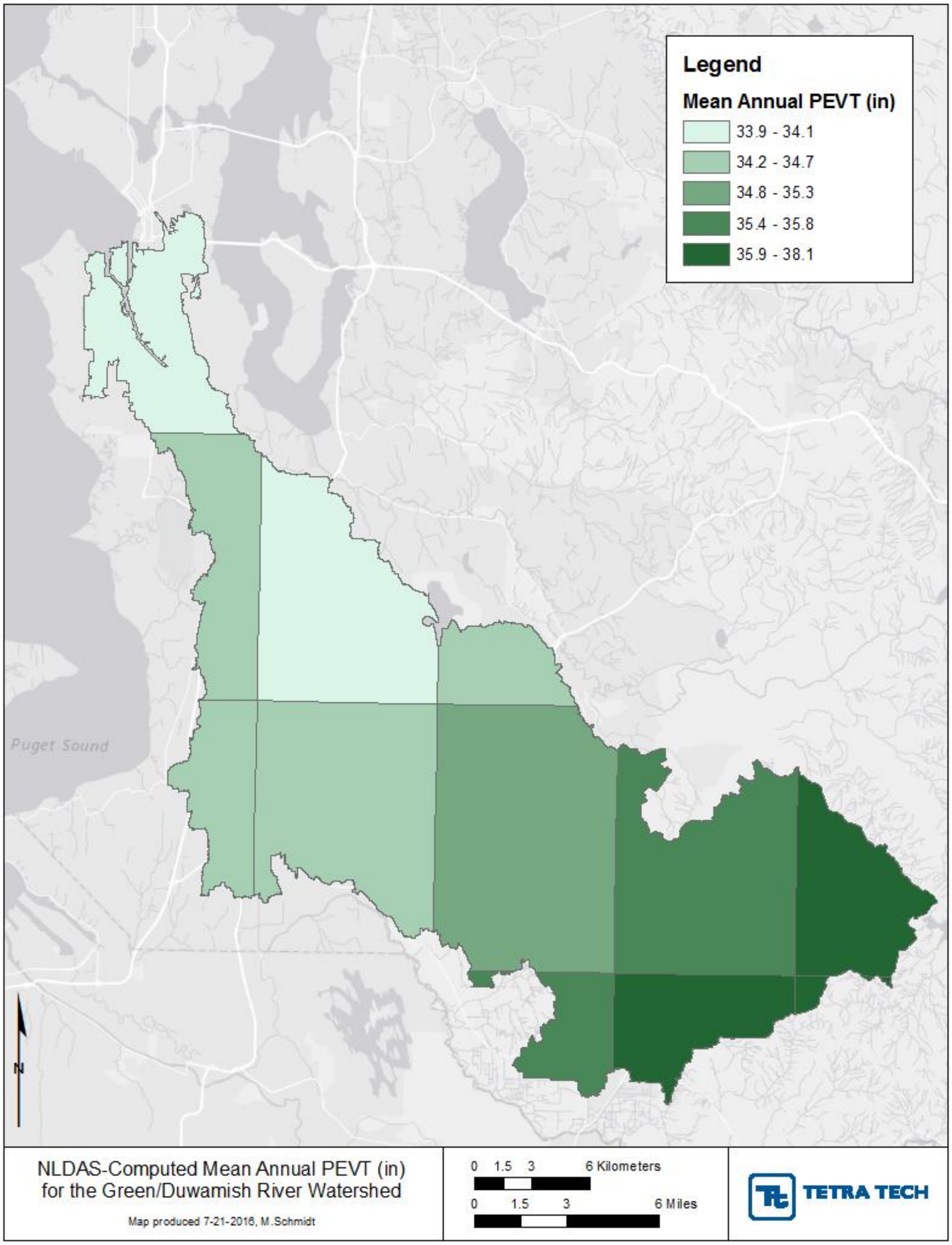

Figure 4-9. Mean Annual Potential Evapotranspiration (PEVT) Computed from NLDAS Weather Data using FAO56 Method, 1996-2010

5.0 BOUNDARY FLOWS AND GROUNDWATER TRANSFERS

5.1 SURFACE BOUNDARY FLOWS

Flooding was a frequent issue in the Green River Valley in the first half of the 20th century. To mitigate flooding in the watershed, the U.S. Army Corps of Engineers dammed the Green River in 1961 to form the Howard A. Hanson Reservoir at RM 64.5. The Corps continues to operate the Howard A. Hanson Reservoir and Dam to protect against flooding in the valley, store water supplies, and to maintain adequate flows during critical periods for native fish species. The controlled releases from the reservoir affect flows in the Green River and, therefore, outflows from the dam are represented as a boundary condition to the Green River LSPC model. A USGS gage (12105900) is located on the Green River immediately below the Howard A. Hanson Dam. Flow data from this gage are available for the entire simulation period and were used to develop a daily flow boundary condition time series. (Sub-daily data are not used because flow is affected by the Tacoma Water dam diversion just downstream [see Section 6.1] and the diversion records are available at a daily time step.) Outflows from the reservoir, which range from 157 – 8,060 cfs and average 1,004 cfs for the simulated period, are routed to reach 27002 in the Green River LSPC model.

The Lake Youngs Reservoir is operated by SPU and provides water supplies to parts of King County. The reservoir is located on the northern side of the Soos Creek watershed, external to the Green River LSPC model, but it is hydrologically connected as it feeds water to the Little Soos Creek via a siphon pipe. A constant flow of 2 cfs was used to represent the discharge from Lake Youngs in the Soos Creek HSPF model. This boundary condition was confirmed (Kevin Buckley, personal communication, 9/13/2016) and applied to reach 180112 in the Green River LSPC model. Other reservoirs, such as Lake Sawyer, are internal to and fully simulated within the LSPC model.

5.2 SUBSURFACE FLOWS

Aquifer boundaries and groundwater flow paths differ from that of the surface flow network as a result of the complex glacial geology of the watershed. Groundwater transfers are simulated in both the HSPF and LSPC models to mimic subsurface flow paths in the Green/Duwamish River watershed. Surface and subsurface flows can easily be routed to arbitrary locations in HSPF, but LSPC was not designed with this capability. In LSPC, upland routing is specified at the HRU level, so subbasins that share HRU classes must use the same upland-to-reach routing scheme. Tetra Tech revised the LSPC code to simulate groundwater transfers in the Green/Duwamish River Watershed LSPC models. This revision provides the option to bypass routing a subbasin’s groundwater to its corresponding reach (card 80), and instead route a fraction, or all, of the groundwater outflow to an alternative reach (card 700). Water quality constituents, including pollutants, heat, dissolved oxygen, and general constituents, are rerouted with the flow.

The framework for simulating subsurface flow paths in the LSPC models is similar to that of the HSPF models. Modifications were made to the framework, however, during the development and calibration of the LSPC models. Aspects of the HSPF groundwater routing scheme that are applied directly in the LSPC models and modifications that were made are first summarized and then discussed in detail.

Subbasin groundwater transfers and springs that discharge groundwater from the adjacent Cedar River watershed are simulated in both the HSPF and LSPC models. Subbasin groundwater transfers are simulated in the Deep Creek, Crisp Creek, and Black River HSPF models and the approach used to route groundwater, described in detail below, is identical in the LSPC models. The Soos Creek HSPF model also simulates groundwater transfers; many of the subbasin transfers from the HSPF model are directly implemented in the Green River LSPC model. In the Soos Creek HSPF model, there are five subbasins that route groundwater to nearby tributaries or to the mainstem Green River. These waterways are not represented within the Soos Creek

HSPF model domain. The LSPC model connects the re-routed groundwater flow from these five subbasins to the adjacent model areas. In the HSPF model, resurfacing groundwater is often divided and contributes baseflow to the local reach and to an alternative reach. Fractions used to split groundwater outflow were adjusted for the LSPC model during the hydrology calibration. In most cases, a higher fraction of resurfacing groundwater contributes to the local reach in the LSPC model compared to the HSPF model. The groundwater transfer framework for the LSPC model also includes transfers for subbasins in the Mill Creek drainage area that are not represented in the corresponding HSPF model. Spring locations in the LSPC models match those in the HSPF models. Discharge rates, however, were increased for the springs in the Black River drainage area to reduce discrepancies in simulated and observed low flow regimes in this region.

Groundwater originating from the adjacent Cedar River Watershed resurfaces as springs that feed reaches in the Soos Creek and Black River drainage areas. The Muckleshoot Indian Tribe (MIT) and Keta Waters identified and added groundwater inflows to the Soos Creek HSPF model in 2012 (Carlson and Massmann, 2012). MIT and Keta Waters utilized several descriptive studies (Woodward et al., 1995; Hart Crowser, 1990; Hart Crowser, 1995; Robinson and Noble, 1995) to characterize groundwater seep locations in the Soos Creek Watershed and to estimate the magnitude of the inflows. Steady inflows of 1 cfs were supplied to four reaches in the Soos Creek HSPF model; the model reaches with this boundary condition include a Jenkins Creek reach (180212), Wilderness Lake (180222), Shadow Lake (180252), and a tributary reach to Jenkins Creek (180262). Similarly, reaches 23060 and 23200 (LSPC numbering) receive baseflows of 0.2 and 0.3 cfs from external sources in King County's Black River HSPF model. Groundwater contours, spring locations, and estimated discharge rates discussed in a regional U.S. Geological Survey study (Woodward et al., 1995) were reviewed during the development of the LSPC models. Groundwater contours confirm the direction of subsurface flows represented in the HSPF models. Spring discharge rates, however, are difficult to measure and fluctuate with the groundwater table. Therefore, the external baseflows were initially set to the rates used in the HSPF models and these flows were recalibrated for LSPC. HSPF inflows were maintained for Soos Creek but the inflows to the two Black River subbasins were modified during the calibration. Comparison of low flows at downstream gages in the Black River Watershed revealed a discrepancy between simulated and observed baseflows as observed baseflows in this region were higher than simulated baseflows. To adjust for this, external groundwater discharge rates were increased from 0.2 to 0.4 cfs for reach 23060 and from 0.3 to 1.0 cfs for reach 23200.

There are subsurface transfers between subbasins in the Deep Creek, Crisp Creek, and Black River drainage areas. The representation of these in LSPC is identical to that of the existing HSPF models. Several large springs flow into the Green River between RM 48 and 52. These springs are likely reemerging groundwater from the nearby Deep Creek and Coal Creek drainage areas (Northwest Hydraulic Consultants, 2005). Surface flows from these creeks are disconnected from the Green River. Deep Creek flows to Deep Lake and Coal Creek flows to Fish Lake, both of which are closed depressions. Groundwater transfers for these catchments were represented in the Deep Creek HSPF model and served as a guide for incorporating these into the LSPC model. To represent these transfers in the Green River LSPC model, groundwater discharging from Coal Creek subbasins (12119-12123) is routed to Green River reach 13113. Similarly, groundwater from Deep Creek subbasins (12130-12133) is transferred to Green River reach 13174, while surface runoff is not routed out of the basin. Horseshoe Lake (15006) is located in the Crisp Creek drainage area and is also a naturally closed surface depression. Groundwater from the Horseshoe Lake catchment seeps southward and becomes baseflow for Crisp Creek. To represent this flow regime in the Green River LSPC model, groundwater from the uplands in subbasin 15006 is routed to reach 15003, which matches the approach used in the Crisp Creek HSPF model. The Green River Natural Resource Area (GRNRA) is an engineered wetland that was constructed in the Black River Watershed on the site of a retired WWTP. Groundwater flows from the GRNRA catchment (23110) and an adjacent subwatershed (23160) are thought to re-emerge as springs that feed Springbrook Creek. This groundwater movement and resurfacing was incorporated in the Black River HSPF model and is also applied in the LSPC model. This transfer is simulated in the Duwamish River LSPC model by routing discharging groundwater from these reaches to Springbrook Creek reach 23280.

The highly permeable Covington Plain is a natural recharge area. A U.S. Geological Survey study that described and quantified groundwater occurrence and water quality in the greater Southwest King County (Woodward et al., 1995). This study mapped groundwater contours in the region. The contours show that the lateral groundwater flow paths in the Soos Creek Watershed traverse from the northeast to the southwest. Because of this, water infiltrating in the Covington and Jenkins Creek drainage areas recharges aquifers that discharge directly to the Green River and Big Soos Creek (Woodward et al., 1995). Likewise, a high point in the groundwater table is centered at Lake Youngs. This promotes outward flow of groundwater in the Little Soos Creek Watershed. Groundwater contours and quantitative information from the USGS study guided the incorporation of groundwater transfers in the Soos Creek HSPF model. The Muckleshoot Indian Tribe and Keta Water identified 17 model subbasins where groundwater transfers are expected to occur. Most of the transfers represented in the HSPF model originate and discharge within the Soos Creek Watershed. Others do not; groundwater from six catchments (180392, 180402, 180412, 180452, 182572, and 180582) is discharged externally from the HSPF model of Soos Creek.

Lateral groundwater transfers simulated in the Soos Creek HSPF model were used in the LSPC model. Unlike the HSPF model, the LSPC model includes the catchments that surround the Soos Creek watershed on the south and west sides. Therefore, groundwater from subbasins 180392, 180452, 182572, and 180582 that is discharged externally in the HSPF model are routed to the Green River following paths verified using groundwater contours. The discharge reaches for these four catchments are shown in Table 5-1. On the southeast side, groundwater is transferred to a Crisp Creek subbasin from subbasin 180402. Subbasin 180412 is located near the Soos Creek and Cedar River Watershed boundary, and half of the groundwater from this catchment exits the LSPC model domain as it likely resurfaces in the Cedar River drainage area.

Groundwater seepage and discharge locations assumed in the HSPF model were reviewed, verified, and incorporated into the LSPC model. As shown in Table 5-1, fractions are applied to split resurfacing groundwater between two model reaches. Half of the discharging groundwater in subbasin 180142, for example, is routed to reach 180142 and the other half flows south and contributes to reach 180332. The flow splitting fractions were initially set to values used in the Soos Creek HSPF model. These fractions, however, are estimates as groundwater flows are difficult to quantify and field measurements are not available. The observed low flow regimes at several gages in the Soos Creek Watershed guided fraction adjustments. Fractions were only changed for four catchments in the Covington-Jenkins area because low flows were underestimated in Covington Creek and overestimated in Jenkins Creek. Groundwater from Covington Creek catchments is routed to Jenkins Creek following the HSPF scheme. The fractions were altered as described in the notes of Table 5-1 so that a higher fraction of groundwater reemerges locally in the Covington Creek area and less is transferred to Jenkins Creek. All other groundwater transfers from the Soos Creek HSPF model were maintained in the LSPC model.

Subsurface flows originating from the Auburn-Kent Valley contribute to the Green River north of Auburn (Northwest Hydraulic Consultants, 2005). A high point in the groundwater table is located east of Federal Way; this causes groundwater to flow parallel to the dried White River channel, which historically merged with the Green River before it was redirected southward in the early 1900s (Northwest Hydraulic Consultants, 2005; Woodward et. al., 1995). Groundwater transfers in this region were not simulated in the Mill Creek HSPF model. To enhance the representation of hydrology in the LSPC model, groundwater discharging from subbasins in the Mill Creek Watershed is split and contributes flow both to the local stream and direct to the Green River. Reemerging groundwater is split for all Mill Creek subbasins and the flow splitting fractions shown in Table 5-2 were established during the hydrology calibration.

Table 5-1. Groundwater Transfer Scheme for Subbasins in the Soos Creek Watershed

Soos Creek Subbasin	Discharge Reach (Groundwater Fraction)	Discharge Reach (Groundwater Fraction)
180112	180242 (1.00)	
180122	180072 (1.00)	
180132	180102 (1.00)	
180142	180142 (0.50)	180332 (0.50)
180252	180242 (1.00)	
180262	180242 (1.00)	
180272	180242 (0.50)	180282 (0.50)
180392	180392 (0.25)	13113 (0.75)
180402	180402 (0.25)	15003 (0.75)
180412	180412 (0.25)	Discharged externally (0.75)
180442	180442 (0.25)	180292 (0.75)
180452	180452 (0.45)	16244 (0.55)
180462	180462 (0.50)	180322 (0.50)
180472	180472 (0.75)	180332 (0.25)
180482	180482 (0.75)	180332 (0.25)
180572	20317 (1.00)	
180582	20316 (1.00)	

Notes: Groundwater routing fractions used in the Soos Creek HSPF model were revised for the LSPC model for some subbasins. Groundwater outflow from subbasin 180412 is routed to 180412 (0.50) and externally discharged (0.50) in the HSPF model and as shown in this table these fractions were adjusted for the LSCP model. In the HSPF model all groundwater outflow for subbasin 180442 is routed to 180292. In the LSPC model, groundwater is routed to both the local reach (180442) and transferred to subbasin 180292. All groundwater outflow from subbasin 180462 is routed to 180322 in the HSPF model. In the LSPC model, however, half of the groundwater outflow is routed locally to 180462 and half is transferred to 180322. Similar to subbasin 180462, all groundwater outflow discharges to 180332 in the HSPF model whereas local routing was also used in the LSPC model. Subbasins 180392, 180402, 180452, 180572, and 180582 discharged groundwater externally in the HSPF model and routing schemes were revised for these subbasins because adjacent area is included in the Green River LSPC model.

Table 5-2. Groundwater Transfers for Mill Creek Subbasins in the Green River LSPC Model

Mill Creek Subbasin	Discharge Reach (Groundwater Fraction)	Discharge Reach (Groundwater Fraction)
21465	21465 (0.85)	22566 (0.15)
21475	21475 (0.85)	22566 (0.15)
21485	21485 (0.85)	22566 (0.15)
21495	21495 (0.85)	22566 (0.15)
21615	21615 (0.50)	20317 (0.50)
21625	21625 (0.50)	20317 (0.50)
21635	21635 (0.50)	20317 (0.50)
21645	21645 (0.75)	20317 (0.25)
21655	21655 (0.75)	20317 (0.25)
21675	21675 (0.75)	20317 (0.25)
21685	21685 (0.75)	20317 (0.25)
21695	21695 (0.75)	20317 (0.25)
21705	21705 (0.85)	22566 (0.15)
21715	21715 (0.85)	22566 (0.15)
21725	21725 (0.85)	22566 (0.15)
21735	21735 (0.85)	22566 (0.15)
21745	21745 (0.85)	22566 (0.15)
21755	21755 (0.85)	22566 (0.15)
21765	21765 (0.85)	22566 (0.15)
21775	21775 (0.85)	22566 (0.15)
21785	21785 (0.85)	22566 (0.15)
21795	21795 (0.85)	22566 (0.15)
21805	21805 (0.85)	22566 (0.15)
21815	21815 (0.85)	22566 (0.15)

Table 5-2. Groundwater Transfers for Mill Creek Subbasins in the Green River LSPC Model (continued)

Mill Creek Subbasin	Discharge Reach (Groundwater Fraction)	Discharge Reach (Groundwater Fraction)
21825	21825 (0.85)	22566 (0.15)
21835	21835 (0.85)	22566 (0.15)
21845	21845 (0.85)	22566 (0.15)
21855	21855 (0.85)	22566 (0.15)
21865	21865 (0.85)	22566 (0.15)
21875	21875 (0.85)	22566 (0.15)
21885	21885 (0.85)	22566 (0.15)
21895	21895 (0.85)	22566 (0.15)
21905	21905 (0.85)	22566 (0.15)
21915	21915 (0.85)	22566 (0.15)
21925	21925 (0.85)	22566 (0.15)
21935	21935 (0.85)	22566 (0.15)

6.0 WATER APPROPRIATIONS

6.1 SURFACE WATER DIVERSIONS

Surface water withdrawn for municipal/domestic supply, industrial processing, or for other purposes affects watershed hydrology. Tacoma Water has historically drawn the most significant diversion in the Green/Duwamish River Watershed. In 1913, Tacoma Water constructed a gravity-fed pipeline to convey surface water supplies from the Green River to the City of Tacoma. Tacoma Water was granted a second diversion water right in 1986 for the Second Supply Project (SSP), although this was not fully implemented until 2007. Tacoma Water, the City of Kent, the Lakehaven Utility District, and the Covington Water District joined together to form the Regional Water Supply System (RWSS) and the SSP became a joint venture between these entities.

Surface water is diverted by Tacoma Public Utilities via the Tacoma Headworks Diversion Dam at RM 61, 0.7 mi downstream of the Bear Creek confluence. The dam was originally constructed in 1911, with a height of 17 ft and crest length of 152 ft, providing a maximum capacity of 72 MGD. As part of the Second Supply Project, the dam height was raised by 6.5 ft, completed in late 2005, providing a maximum capacity of 160 MGD. Diversions go to the nearby Green River Headworks water treatment facility and then to two major pipelines; Pipeline No. 1 flows southwest to Enumclaw then due west to service the City of Tacoma in Pierce County. The SSP Pipeline, also referred to as Pipeline No. 5, flows west, delivers water to the City of Kent and the Covington Water District, and then terminates at the City of Tacoma.

Tacoma's permits collectively grant it water rights to 434,344 ac-ft/yr with a maximum instantaneous diversion rate of 699 cfs as shown in Table 6-1 (D. Wood at Ecology, personal communication, August 31, 2016). Daily diversion flows for the years 2005-2015 (Table 6-2) are listed in Tacoma's publically available operation reports (Tacoma Public Utilities, 2016) and daily diversion records for earlier years (1996-2004) were provided by Tacoma Public Utilities (personal communication from Jason Moline, Tacoma Public Utilities, September 8, 2016).

Table 6-1. Permitted Surface Water Appropriations in the Green River Watershed Model

Water Right Permit ID	Owner	Maximum Instantaneous Diversion (cfs)	Maximum Annual Diversion (ac-ft/yr)
S1-*03787	Tacoma PUD	100	72,372
S1-00726	Tacoma PUD	100	72,372
S1-002298CL	City of Tacoma	499	289,600

Source: D. Wood, Ecology, personal communication, August 31, 2016.

Table 6-2. Annual Average Surface Water Diversions by Tacoma Water

Year	Annual Average Diversion (cfs)
1996	98.6
1997	96.7
1998	97.0
1999	87.6
2000	94.0
2001	88.1
2002	82.0
2003	78.9
2004	87.4
2005	85.7
2006	87.5
2007	89.5
2008	91.3
2009	85.0
2010	85.1
2011	86.7
2012	92.2
2013	92.9
2014	90.3
2015	75.7

Sources: Reported values for years 2005-2015 were retrieved from Tacoma Water's operation reports (Tacoma Public Utilities, 2016) and simulated daily diversions for years 1996-2004 is currently estimated using a non-linear regression. Tacoma Public Utilities is in the process of providing metered data for the 1996-2004 period.

6.2 GROUNDWATER PUMPING

Shallow groundwater pumping from alluvial aquifers can induce recharge and reduce stream baseflow, altering basin hydrology especially during low-flow periods. Major groundwater pumping wells that affect surface flow were identified during the Soos Creek HSPF model update (Massmann, 2012) and their withdrawals were incorporated into the model. These are all permitted Group A water systems. Group A well systems are classified as those that have more than 15 connections or systems that serve 25 or more people for 60 or more days per year. The Group A systems in the Soos Creek HSPF model include the City of Kent, the Covington Water District, and the King County Water District #111. Groundwater production or metering data was used to create withdrawal time series for the existing Soos Creek HSPF model. In general, the records spanned calendar years 2001-2008 and the remaining years were simulated with constant, estimated withdrawals of 1 cfs.

With the aid of Ecology, requests were sent to the three Group A well systems asking for pumping records for the model period (1996-2015). The City of Kent and the Covington Water District provided withdrawal data that are incorporated in the LSPC model. The Covington Water District shared monthly withdrawal records for the 222nd Place and Witte well fields. Likewise, daily pumping data for the Clark, Kent, Seven Oaks, and Armstrong wells were provided by the City of Kent. In the Soos Creek HSPF model, streamflow is reduced at reaches in the vicinity of the wells. In general, fractions were applied to estimate streamflow reductions due to nearby pumping. These fractions were estimated based on the proximity of the well field to the reach and depth of extraction (Carlson, 2012; Carlson and Massmann, 2012). The fractions applied in the HSPF model and locations of streamflow reductions caused by pumping are maintained in the LSPC model (Table 6-3).

Table 6-3. Group A Well Withdrawals Simulated in the Soos Creek Portion of the Green River LSPC Model

Group A Well System	Well Field Name	Annual Average Withdrawal for 1996-2015 (cfs)	Record Frequency	LSPC Reach	Streamflow Reduction as a Fraction of the Pumping Rate
Covington Water District	222nd Place	2.56	Monthly	180442	1.00
Covington Water District	Witte	0.64	Monthly	180212	0.25
City of Kent	Kent	3.61	Daily	180442	0.50
City of Kent	Kent	3.61	Daily	180292	0.25
City of Kent	Clark	5.62	Daily	180212	0.50
City of Kent	Clark	5.62	Daily	180292	0.25
City of Kent	Clark	5.62	Daily	180222	0.25
City of Kent	Armstrong	0.48	Daily	180322	0.50
City of Kent	Seven Oaks	0.13	Daily	180552	0.50

A majority of the Group A wells in the basin are located in the Covington Plain, which is mostly occupied by the Soos Creek watershed (Woodward et al., 1995). Other Group A wells are present in the basin outside the Soos Creek watershed, but no studies have been undertaken to determine if and to what extent they may deplete surface flows. There are also numerous individual household and irrigation wells. Lack of complete data on these interactions is deemed acceptable for the purposes of the current modeling effort in support of the PLA as the bulk of pollutant transport is expected to occur during higher flow events.

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7.0 REACH HYDRAULICS

LSPC, like HSPF, is a water balance (hydrologic) model and not a hydraulic model. LSPC represents stream reaches as one-dimensional fully mixed reactors and, while maintaining mass balance, does not explicitly conserve momentum. To simulate the details of hydrograph response to storm events LSPC 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 LSPC model platform offers various options for defining reach FTables, including explicit representation in the model input file. LSPC also has the capability to internally derive FTables based on channel geometry. A variety of quantitative approaches, such as culvert and weir analyses, was used to generate FTables in the Green/Duwamish River Watershed HSPF models.

To optimize the LSPC model performance it is important to incorporate as much hydraulic information as feasible. As a starting point, the existing HSPF FTables were incorporated into the LSPC model. FTables were revised for reaches where additional hydraulic information was available. For example, hydraulic information can be extracted from HEC-RAS flood and SWMM stormwater conveyance models, as described below.

There are model reaches that are not in an HSPF model but are represented in the Green River and Duwamish River LSPC models. In the Green River model this includes the two reaches for the upstream extension (27001 and 27002), a region that was originally represented in the Des Moines HSPF model but actually drains to the Green River (22101), and Horseshoe Lake, a closed lake in the Crisp Creek drainage area (15006). Horseshoe Lake was modeled in the Crisp Creek HSPF model but an FTable was not developed for it because this reach is not routed to a downstream reach. The stream reaches that drain directly to the Lower Duwamish Waterway in the Duwamish LSPC model are also not represented in a HSPF model. FTables were derived for many of the aforementioned reaches using information extracted from calibrated HEC-RAS and SWMM models (Section 7.1 and Section 7.2), regional hydraulic geometry (Section 7.3), and USGS and King County rating tables (Section 7.4). For most of the major stormwater conveyances within Seattle, the regional SWWM model served as the data source for reach FTables. Reach hydraulics for un-engineered reaches in the Seattle area no covered by SWMM models use LSPC default FTables.

7.1 HEC-RAS MODELS

HEC-RAS is the standard model for Federal Emergency Management Agency (FEMA) flood insurance mapping studies and typically involves a detailed analysis of stream channel and restricting structure information. HEC-RAS hydraulic models allow for direct calculation of FTables (i.e., by evaluating discharge at LSPC subbasin outflows and summing upstream storage volume and area in the reach), but are available for only limited areas. Where the HEC-RAS models are available, runs are made with a range of flow conditions to develop FTables by summing and averaging over the cross-sections within an LSPC model reach.

The lower and middle Green River HEC-RAS model (King County, 2010b) provided information for 13 reaches in the Green River LSPC model (Table 7-1 and Figure 7-1), and included various unsteady flow simulations between the 10-yr and 500-yr storm events. The 10-, 50-, 100-, and 500-yr events were run to develop relative flow change percentages at each of the major reaches in the model. Although flow in the unsteady flow simulation continuously increases at each cross-section along the river, consistent flow values were assumed within each reach to run a steady flow simulation for the FTable development. A diverse set of flow profiles, ranging from extreme low-flow events to extreme high-flow events, were modeled under steady-state conditions and used to characterize the 13 reach FTables. A HEC-RAS model of Springbrook Creek and Mill Creek (King County, 2008) and was used to generate FTables for 12 reaches in the Black River drainage area (Table 7-1 and Figure 7-1).

Table 7-1. HEC-RAS Derived FTables in the Green/Duwamish River Watershed LSPC Models

LSPC Reach ID	HEC-RAS Model
13174	Lower and Middle Green River
13184	Lower and Middle Green River
16224	Lower and Middle Green River
16284	Lower and Middle Green River
16304	Lower and Middle Green River
20314	Lower and Middle Green River
20315	Lower and Middle Green River
20316	Lower and Middle Green River
20317	Lower and Middle Green River
22566	Lower and Middle Green River
22577	Lower and Middle Green River
22586	Lower and Middle Green River
26596	Lower and Middle Green River
23080	Springbrook Creek and Mill Creek
23130	Springbrook Creek and Mill Creek
23160	Springbrook Creek and Mill Creek
23260	Springbrook Creek and Mill Creek
23261	Springbrook Creek and Mill Creek
23270	Springbrook Creek and Mill Creek
23280	Springbrook Creek and Mill Creek
23420	Springbrook Creek and Mill Creek
23430	Springbrook Creek and Mill Creek
23460	Springbrook Creek and Mill Creek
23470	Springbrook Creek and Mill Creek
23510	Springbrook Creek and Mill Creek

Note: Model reach 23085 is within the domain of the Springbrook Creek and Mill Creek HEC-RAS model. This FTable, however, was not updated based on information obtained through the HEC-RAS simulations. The HSPF FTable for this reach represents flows for the Mill Creek Diversion, and this FTable was directly applied in the LSPC model.

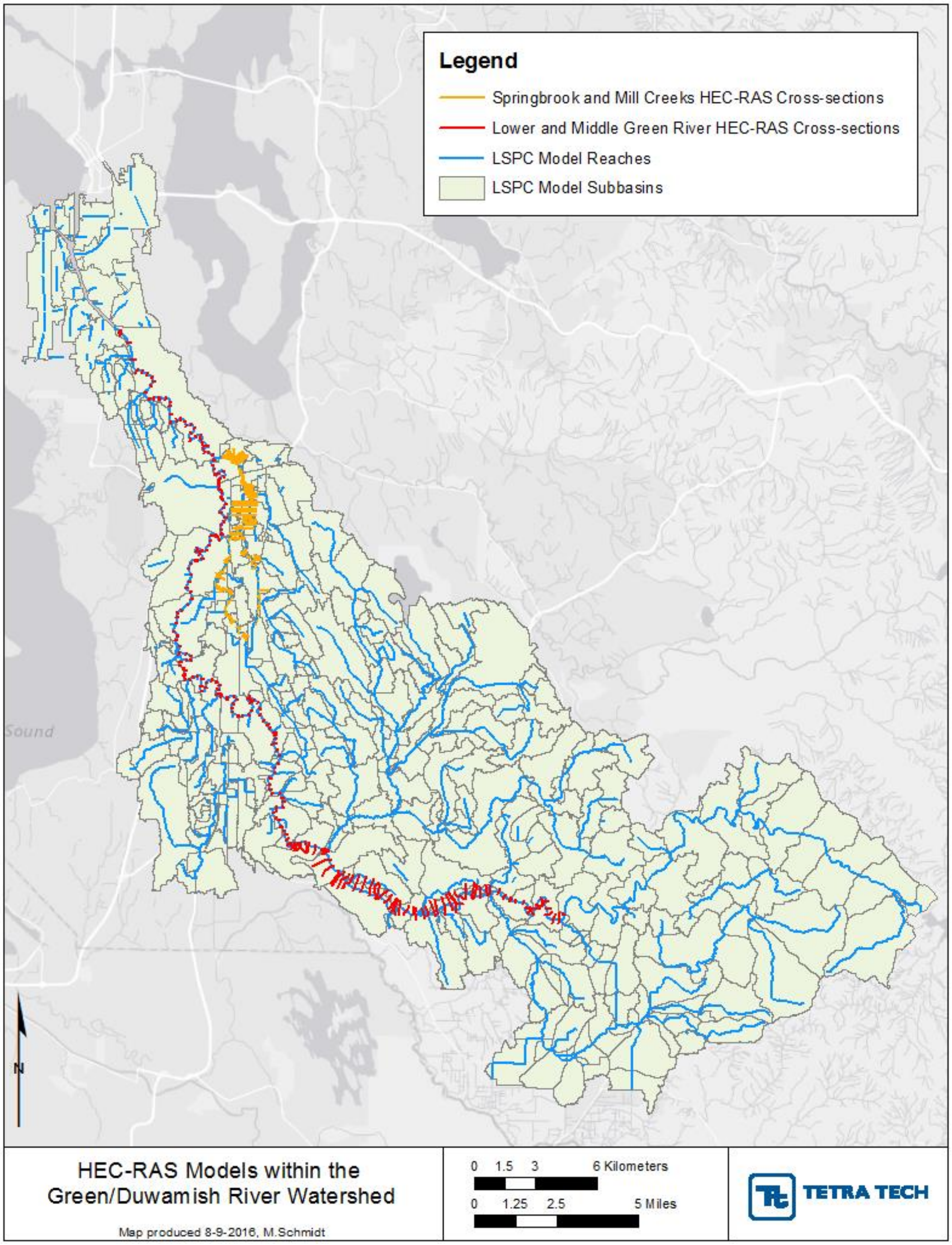

Figure 7-1. HEC-RAS Models used to Generate FTables in the Green/Duwamish River Watershed

Note: Colored lines normal to model reaches indicate cross sections used in the HEC-RAS models.

7.2 SWMM MODELS

SPU developed a series of hydraulic models for drainage basins within the Seattle area using EPA's Storm Water Management Model (SWMM) version 5 modeling platform (Seattle Public Utilities, 2010). Similar to HEC-RAS, results from the SWMM model simulations are used to create reach/conveyance information for FTables. The coverage of these SWMM models, which address storm/sewer watersheds with areas greater than 50 acres, was shown above in Figure 2-3.

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. LSPC summarizes hydraulics as a relationship between storage volume and discharge and cannot fully represent hysteresis that results from conveyance limits interior to an LSPC 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 7-2, in which the red LOESS line, based on local fit to 20 out of 1,803 points ($\alpha = 0.011$) represents the compromise relationship between total storage in the reach and discharge at the outlet. In this example, storage in excess of 9,000 ft^3 results in some surface flooding which delays discharge on the rising limb of the hydrograph.

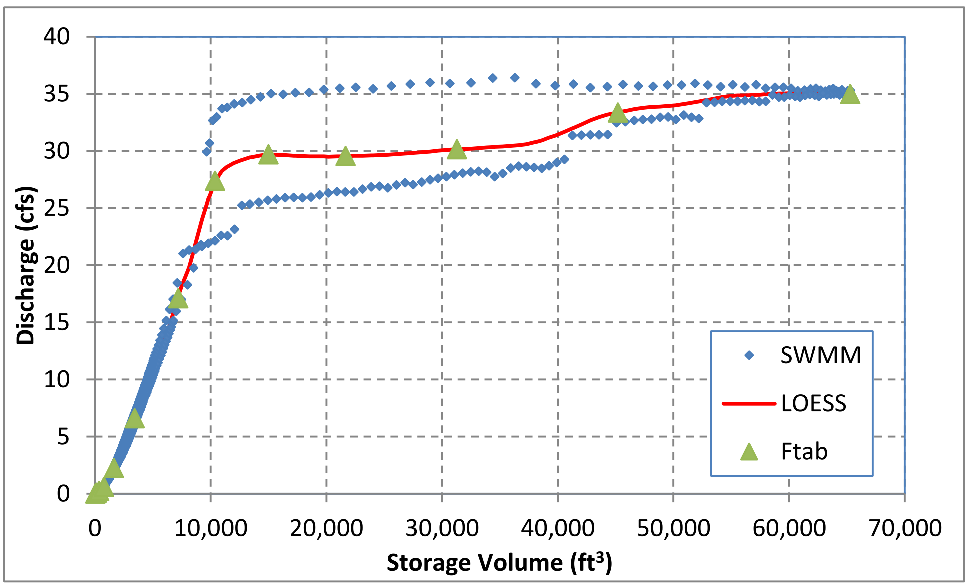

Figure 7-2. Example LOESS fit to SWMM output for LSPC Reach 26006

7.3 REGIONAL HYDRAULIC GEOMETRY

HEC-RAS models and stream cross sections are not available for the upper Green River below Howard Hanson Dam. FTables for this region are based on regional hydraulic geometry equations for the Pacific Northwest developed by Castro and Jackson (2001). However, we also recognize that the creation of this flood control dam has likely altered geomorphology in the upper Green River, although the channel adjustments since dam construction are believed to be relatively minor. Therefore, regional hydraulic geometry is applied as the best available approximation until such time as detailed channel surveys are available.

The strongest relationships for hydraulic geometry developed by Castro and Jackson were for channel dimensions (in natural channels) as a function bankfull flow, Q_{bank}. Regional equations based on drainage area provided a much poorer fit. For the Pacific maritime mountain streams region (which includes the upper Green River), Castro and Jackson developed the following relationships to Q_{bank} in cfs:

A_{bank} (cross sectional area, ft^2) = 0.454 $Q_{bank}^{0.913}$, R^2 = 81.0%

W_{bank} (bankfull width, ft) = 2.37 $Q_{bank}^{0.5}$, R^2 = 76.0%

Y_{bank} (bankfull depth, ft) = 0.15 $Q_{bank}^{0.45}$, R^2 = 61.9%

These relationships apply to natural (undammed) streams. For the reaches below Howard Hanson Dam, we assume that the regional channel bankfull geometry relationships are still appropriate in general, despite subsequent morphological changes since dam construction.

We also lack information on bankfull flows (Q_{bank}) downstream of Howard Hanson Dam. To address this, we use the relationship between bankfull depth (Y_{bank}) and mean depth (Y_{mean}) of $Y_{mean} = Y_{bank}/1.25$ (USEPA, 2007). Applying Manning's equation and assuming that slope (s) and Manning's roughness coefficient (n) do not vary with depth when the stream is within its banks, the ratio of Q_{bank} to Q_{mean} under current conditions may be expressed as:

$$\frac{Q_{bank}}{Q_{mean}} = \left\{\frac{b\ Y_{bank} + m_c\ Y_{bank}^{\ 2}}{b\ \left({Y_{bank}}/{1.25}\right) + m_c\ \left({Y_{bank}}/{1.25}\right)^2}\right\}^{5/3}\ x\ \left\{\frac{b\ 2\ \left({Y_{bsnk}}/{1.25}\right)\ (m_c^{\ 2}+1)^{0.5}}{b\ 2\ Y_{bank}\ (m_c^{\ 2}+1)^{0.5}}\right\}^{2/3}$$

Here b is the channel bottom width and m_c is the side bank slope ratio (run over rise). Both Y_{bank} and the calculated value of b vary nonlinearly as a function of Q_{bank} in the hydraulic geometry regressions; however, the rate of change relative to Q_{bank} is small (Figure 7-3).

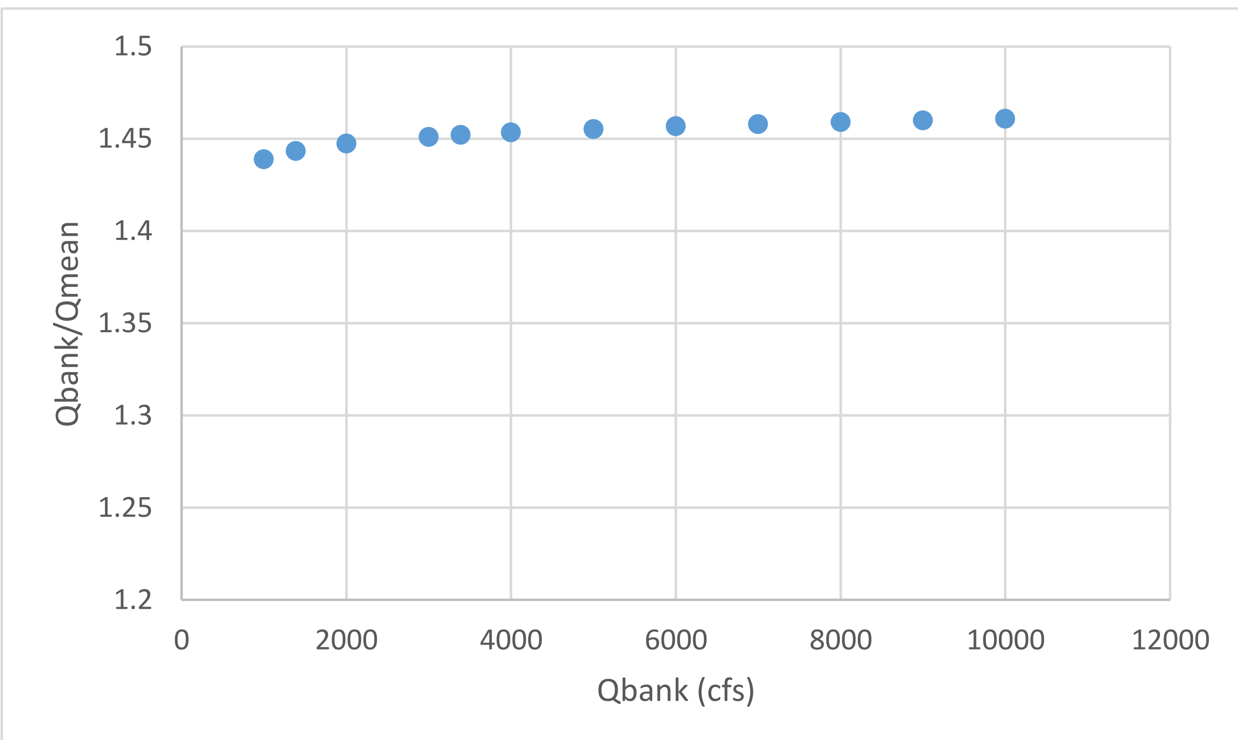

Figure 7-3. Relationship of Bankfull Flow (Q_{bank}) to Mean Flow (Q_{mean}) as a Function of Q_{bank}

In addition to Howard Hanson Dam (created in 1961), flow in the upper Green River is also affected by the Tacoma Headworks Dam, constructed in 1913 at RM 61, and its associated diversion. Flow gaging is not available prior the construction of the Tacoma Headworks. USACE (2000) reports the results of a natural flows study, which estimated the natural mean annual flow as 1,386 cfs. This is similar to the mean gaged flow below Hanson dam of 1,988 cfs for water years 1961-2015 (USGS gage 12105900 Green River below Howard A Hanson Dam, WA). In this range of the curve, the Q_{bank}/Q_{mean} ratio is approximately 1.447, leading to an estimated Q_{bank} for the natural channel of 2,878 cfs. The Castro and Jackson (2001) equations are applied at this flow (with adjustment for drainage area as necessary).

Assuming a trapezoidal channel shape (USEPA, 2007), the bottom width (b, ft), side slope ratio (m_c), and wetted perimeter at bankfull (P_{bank}, ft) can be calculated as:

$$b = 2\,\frac{A_{bank}}{Y_{bank}} - W_{bank}$$

$$m_c = \frac{W_{bank} - b}{2\,Y_{bank}}$$

$$P_{bank} = b + 2\,Y_{bank}\,(m_c{}^2 + 1)^{0.5}$$

Back-solving Manning's equation for flow then yields an estimate of the roughness coefficient (n) in English units consistent with the Castro and Jackson (2001) hydraulic geometry equations:

$$n = \frac{A_{bank}}{Q_{bank}\,x}\;x\;1.486\left(\frac{A_{bank}}{P_{bank}}\right)^{2/3}\;x\;s^{0.5},$$

where s is the energy grade, assumed equal to the average reach slope (ft/ft). Where independent estimates of Manning's coefficient are available for a reach the hydraulic geometry can be varied from the Castro and Jackson defaults to ensure consistency.

Given these assumptions, the flow (Q, cfs) at any depth (Y) up to bankfull can be estimated by applying Manning's equation:

$$Q = \frac{1.486}{n}\,A^{5/3}\,P^{-2/3}\,s^{0.5}\text{, where}$$

$$A = b\,Y + m_c\,Y^2 \text{ , and}$$

$$P = b + 2\,Y\,(m_c^2 + 1)^{0.5}$$

Storage volume at a given depth is calculated as $A \cdot L$, where L is the length of the reach.

Calculations above bankfull flow proceed as recommended by USEPA (2007), in which the side width of the active floodplain in the trapezoidal approximation is assumed to be equal to the bankfull width and the floodplain side slope (run over rise) is $m_F = 2.0$. In addition, a higher Manning's coefficient is needed for the floodplain to account for the effects of roughness and vegetation. A value of $n = 0.20$ is used, consistent with the examples in Arcement and Schneider (1989). No friction loss is assumed between the within bank and overbank portions of the flow, consistent with Hardy et al. (2005).

For reaches not on the mainstem, the natural Q_{mean} is estimated using the equation given by Castro and Jackson (2001) as 91.05 $DA^{0.67}$, where DA is the drainage area (mi^2). For reaches on the Green River mainstem downstream of Howard A. Hanson Dam, the natural Q_{mean} is estimated as the dam release times the drainage area ratio raised to the power of 0.67.

7.4 RATING TABLE ANALYSIS

A rating table is used to convert an observed measurement of stream water surface elevation (gage height) to an estimate of flow. Rating tables change over time as the channel shape changes in response to storm events. At the basin-scale of modeling, however, the details of elevation and cross-sectional area within individual stream segments are of less importance; rather, we need a reasonable representation of the stage-storage-discharge relationship. This can be obtained from recent rating tables with accompanying cross sections and will remain approximately valid for changing conditions over time (although the base level is likely to change) unless the channel form is extensively reworked. To use rating tables with cross sections, first top width, cross sectional area, and wetted perimeter are calculated directly from the cross section. Volume and surface area at each rating table depth increment are then calculated by multiplying by length of the reach within the subbasin. This essentially assumes that the gage is located at a point that controls flow within the subbasin or is at least typical of flow in the subbasin. Where the gage does not fall at the subbasin mouth, we assume depth and cross-sectional area remain constant over this relatively short distance and use the length of entire reach for calculation. We do not use rating tables from the middle of a subbasin if there is a significant proportional increase in drainage area from the gage to the subbasin pour point.

The available King County cross sections generally extend only to the water surface on the date of observation. We extended these cross sections into the overbank area using LiDAR elevation data. In most cases, the water surface elevation at the date of the cross section is not the same as the water surface elevation in LiDAR. In the case where the cross section does not reach up to the LiDAR elevation, the profile was interpolated between the two.

King County rating tables were used to create FTables for several gaged reaches in the Green River and Duwamish River LSPC models. These include Covington Creek (180512), Jenkins Creek (180332), Crisp Creek (15002), Mill Creek (21615), Little Soos (180142), Mill Creek in the Black River drainage area (23080), and Duwamish River Tributary 0003 (25626). King County also provided cross sections for these reaches, which were used to compute reach storage with respect to water depth.

USGS rating tables were available for and used to create FTables for the following reaches: Upper Green River (27002 and 10023), Newaukum (14281), Big Soos Creek (180592), Lower Green River (20315), and Mill Creek in the Black River drainage area (23060). We gathered supplementary information on channel shape from USGS channel field observations because detailed cross sections are not available for these reaches.

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8.0 FLOW GAGING DATA

King County and the USGS operate and maintain several flow gages in the Green/Duwamish River Watershed. Twelve King County and six USGS gages in the watershed have flow data for the model simulation period after omitting results of the first year to allow for model spin-up (1/1/1997-12/31/2015). We generally selected stations for model calibration where data were available for a minimum of 2 years during the modeling period. The King County gage on Olson Creek did not have 2 years of data during the calibration period. This gage was previously used to calibrate the Olson Creek HSPF model so it was selected to guide the LSPC model calibration in this portion of the watershed. The periods of record for the selected King County and USGS gages are shown in Table 8-1 and Table 8-2. Their locations are shown in Figure 8-1.

Table 8-1. King County Flow Gages for Hydrology Calibration of Green/Duwamish River LSPC Models

King County Gage ID	Gage Name	Period of Record used in Calibration	Drainage Area (mi^2)
03f	Mill Creek (Kent) above Diversion	3/15/2002 – 6/7/2004	4.81
03G	Springbrook Creek at O'Grady Way	12/3/2001 – 10/24/2011	25.6
09a	Covington Creek near mouth	1/1/1997 – 12/31/2015	21.7
40d	Crisp Creek at Green River Rd	1/1/1997 – 12/31/2015	3.59
13a	Duwamish River Tributary 0003	11/10/2010 – 12/31/2015	0.56
ha5	Hamm Creek South Fork	1/1/1997 – 8/15/2008	0.74
26a	Jenkins Creek near mouth	1/1/1997 – 12/31/2015	16.8
41a	Mill Creek at SR 181	1/1/1997 – 4/22/2006	13.4
41c	Mill Creek at Peasley Canyon Rd	4/22/2004 – 10/27/2015	4.19
mf1	Mill Creek near Peasley Canyon	2/24/1997 – 2/10/2004	5.93
32c	Olson Creek Lower Green River Tributary 0069 at Green River Rd	12/7/2010 – 10/25/2011	1.84
54i	Little Soos Creek at SE 272nd	1/1/1997 – 12/31/2015	3.69

Note: Flow gage period of record is shown only for the LSPC model calibration period (1/1/1997 -12/31/2015).

Table 8-2. USGS Flow Gages for Hydrology Calibration of Green/Duwamish River LSPC Models

USGS Gage ID	Gage Name	Period of Record used in Calibration	Drainage Area (mi^2)
12106700	Green River at Purification Plant near Palmer, WA	1/1/1997 – 12/31/2015	231
12108500	Newaukum Creek near Black Diamond, WA	1/1/1997 – 12/31/2015	27.4
12112600	Big Soos Creek above hatchery near Auburn, WA	1/1/1997 – 12/31/2015	66.7
12113000	Green River near Auburn	1/1/1997 – 12/31/2015	399
12113344	Green River at 200th St. at Kent, WA	1/1/2012 – 12/31/2015	451
12113346	Springbrook Creek at Orillia, WA	1/1/1997 – 12/31/2015	8.44
12113347	Mill Creek at Earthworks Park at Kent, WA	1/1/1997 – 12/31/2015	2.49
12113349	Mill Creek near mouth at Orillia, WA	1/1/1997 – 12/31/2015	5.63

Note: Flow gage period of record is shown only for the LSPC model calibration period (1/1/1996 -12/31/2015).

USGS gage 12105900 (Green River below Howard A. Hanson Dam) is not used for calibration because it is a boundary condition for the model. Gage 12106700 is just downstream, below the Tacoma diversion, and is not a true calibration location; it serves primarily as a check on the representation of the diversion.

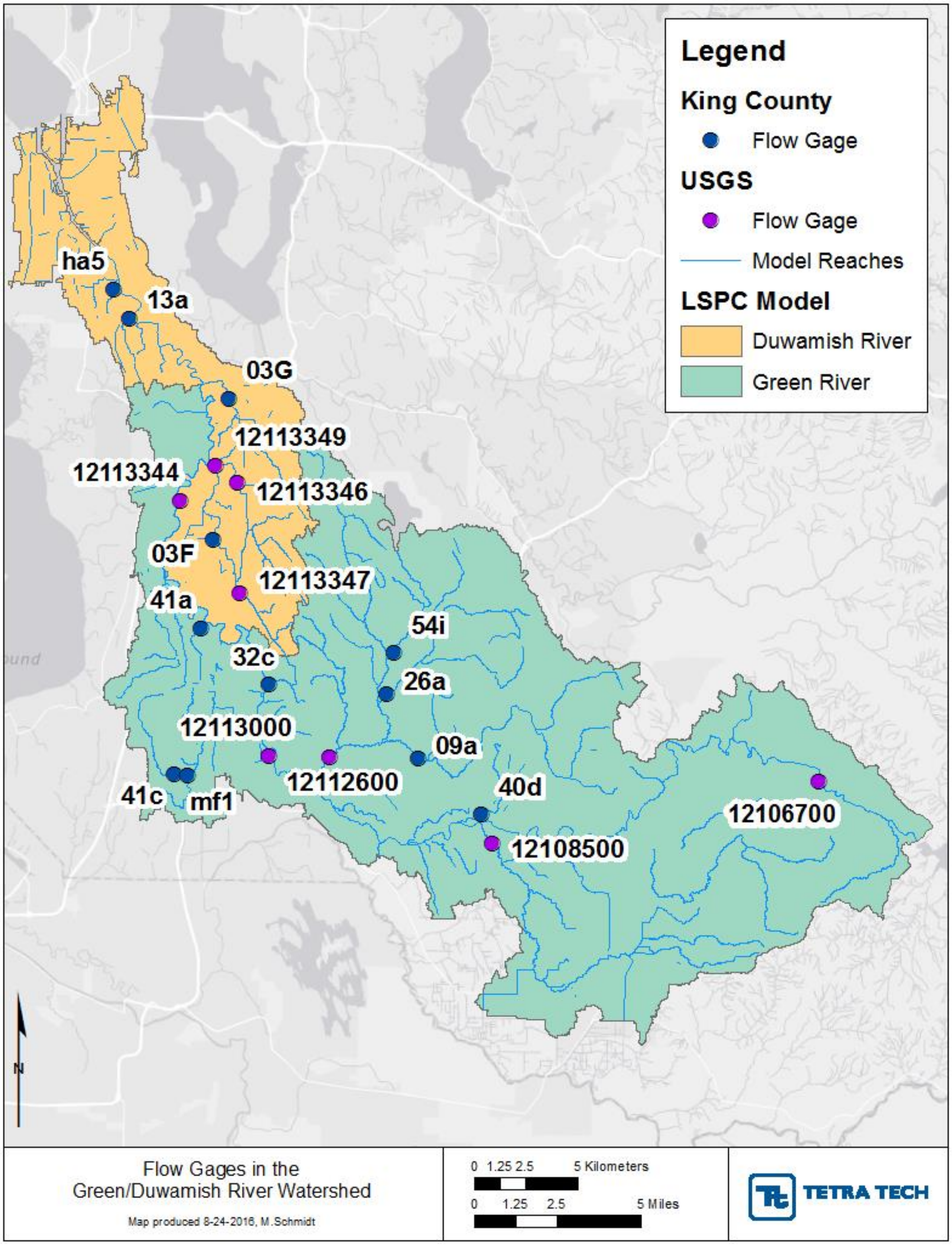

Figure 8-1. Flow Gages used for Hydrology Calibration of the Green/Duwamish River Watershed LSPC Models

It is important to note that stream gage records are not perfect. Estimates of flow depend on rating curves that relate depth in a stilling well or weir to total flow through the stream cross-section. That relationship is established using detailed surveys of depth and velocity in the cross-section. The rating curve tends to change over time, especially in sand bed streams, and must be recalibrated periodically to correct drift. For higher flows, the rating curve is often extrapolated beyond the range of measurements. In addition, flow records may be estimated during periods of gage malfunction or maintenance. For example, some daily flows were estimated for the Green River gage located near Auburn, WA, (USGS 12113000) for WY 2014. Larger numbers of estimated flows are associated with some of the King County gage records and gages with a significant number of estimated flows for the calibration period include Covington Creek (KC 09a; 405 days), Hamm Creek South Fork (KC ha5; 106 days), Jenkins Creek (KC 26a; 127 days), Mill Creek near Peasley Canyon (KC mf1; 124 days), Mill Creek at SR181 (KC 41a; 192 days), and Little Soos Creek (KC 54i; 301 days). Calibration measures reported in Section 9.0 use all available flow data, estimated or not. To determine the impact of estimated flows on the calibration, we also computed hydrology calibration measures with all estimated flows. Results from this analysis showed that including estimated flows does not degrade apparent model fit significantly.

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9.0 HYDROLOGY CALIBRATION

The initial parameter values for hydrology in the Green River and Duwamish River LSPC models were adopted from the existing calibrated HSPF models (King Co., 2013). The LSPC model period spans 1/1/1996 – 12/31/2015. The first year of simulation serves as a spin-up period during which soil moisture storages equilibrate and is omitted from calibration; the remaining period of 1997 – 2015 is used for calibration, as laid out in the Quality Assurance Project Plan (Tetra Tech, 2016)..

Model performance is evaluated based on (1) the annual water balance (Section 9.1), (2) comparison of simulated ET to satellite-based estimates (Section 9.2), and (3) detailed comparisons of simulated and observed flows at calibration gages (Section 9.3). Parameters were adjusted iteratively to improve the annual water balance, low/high flow distribution, storm event flows, and hydrograph shape. Both qualitative comparisons, such as time series plots and flow duration curves, and quantitative metrics including seasonal, high flow, and low flow errors are used.

The calibration strategy focused on development of a robust and consistent set of parameters. Specifically, we endeavored to provide consistent parameter values for each HRU (which encompasses land use, land cover, soil, and slope characteristics). We did define four large parameter group areass, each of which can have slightly different parameter values for a given HRU. These are the Soos Creek drainage, the remainder of the Green River model, the Black River plus Hamm Creek portion of the Duwamish River model, and the remainder of the Duwamish River model within Seattle. Specification of different parameter values at the local sub-basin scale could likely have improved model calibration statistics at some gages (e.g., Crisp Creek), but at the risk of potentially biasing parameters to fit or compensate for anomalies in either the flow or precipitation records. Use of a unified set of parameters that provides a reasonable fit across multiple gages ensures a more robust overall simulation.

Model parameter adjustment during hydrologic calibration followed the guidance and ranges in USEPA (2000) and AQUA TERRA (2012). LSPC contains a large number of parameters, but results have high sensitivity to only a smaller set of these parameters. Calibrated values for the most sensitive hydrologic parameters for pervious land are summarized in Table 9-1. Other important parameters, such as the monthly interception storage capacity (CEPSC) and the index to lower zone evapotranspiration (LZETP) parameters, are based primarily on seasonal leaf area development of the land cover. The full set of parameter values for the calibrated models are available in the model input file, supplied electronically upon request.

Table 9-1. Calibrated Ranges of Selected Hydrology Parameters

HRU	Land Use	Soil	LZSN (in)	INFILT (in/hr)	AGWRC	UZSN (in)
Green River Model						
5	Agriculture	Outwash	5.0-6.72	0.375	0.995-0.998	0.40
6	Agriculture	Saturated	3.67-4.00	0.225	0.995-0.997	0.40
7-9	Agriculture	Till	3.00-5.25	0.075-0.3375	0.995-0.998	0.20-0.40
10	Comm/Ind	Outwash	4.32-5.00	0.375	0.995-0.998	0.40
11-12	Comm/Ind	Till	3.00-4.32	0.075-0.0375	0.965-0.995	0.20-0.30
13	Forest	Outwash	5.00-9.60	0.375-0.5625	0.998-0.999	0.40
14	Forest	Saturated	4.00-5.18	0.225-0.3375	0.998-0.999	0.40
15-16	Forest	Till	3.00-7.56	0.0375-0.375	0.998	0.20-0.30
17	Grassland	Outwash	5.00-7.20	0.375-0.475	0.995-0.998	0.40
18	Grassland	Saturated	4.00-4.32	0.225-0.325	0.995-0.997	0.40
19-20	Grassland	Till	3.00-5.40	0.0375-0.175	0.965-0.995	0.20-0.30
21	HD Res	Outwash	5.00-7.20	0.375	0.995-0.998	0.40
22-23	HD Res	Till	3.00-4.32	0.0375-0.075	0.945-0.995	0.20-0.30
24	LD Res	Outwash	5.00-7.20	0.375-0.4125	0.995-0.998	0.40
25-26	LD Res	Till	3.00-5.40	0.075-	0.945-0.995	0.20-0.30
27	Shrub/Scrub	Outwash	5.00-8.16	0.375-0.750	0.945-0.998	0.40
28	Shrub/Scrub	Saturated	4.00-5.18	0.225	0.995-0.997	0.40
29-30	Shrub/Scrub	Till	3.00-6.48	0.0375-0.075	0.965-0.995	0.20-0.30
32	Wetland	Saturated	9.80	0.1875	0.995-0.999	2.90
Duwamish Model						
8	Agriculture	All	10.49	0.075	0.996	0.40-0.90
9	Barren	All	10.49	0.3375	0.998	0.50-1.00
10	Comm/Ind	Outwash	10.49	0.375	0.998	0.50-1.00
11-12	Comm/Ind	Till	5.25	0.0375-0.075	0.965-0.990	0.30-0.90
13	Forest	Outwash	7.95-10.49	0.5625	0.999	0.50-1.00
14	Forest	Saturated	3.11-4.11	0.3375	0.998-0.999	0.50-1.00
15-16	Forest	Till	4.47-6.89	0.112-0.188	0.998	0.30-0.90
17	Grassland	Outwash	10.49	0.475	0.998	0.50-1.00
18	Grassland	Saturated	4.11	0.325	0.997	0.50-1.00
19-20	Grassland	Till	4.47-5.46	0.1375-0.175	0.965-0.990	0.30-0.90
21	HD Res	Outwash	10.49	0.375	0.998	0.50-1.00
22-23	HD Res	Till	3.57-5.25	0.0375-0.075	0.935-0.990	0.30-0.90
24	LD Res	Outwash	10.49	0.4125	0.998	0.50-1.00
25-26	LD Res	Till	4.47-6.56	0.0375-0.075	0.935-0.990	0.30-0.90
27	Shrub/Scrub	All	4.92	0.075	0.965-0.990	0.40-0.90
28	Water	All	4.56	0.1875	0.999	3.00-3.50

Notes: Each model contains two sets of parameters for different geographical areas. In addition, parameters may be varied by slope class. Refer to Table 3-8 and Table 3-9 for HRU definitions. Variables listed are: LZSN – lower zone nominal soil moisture storage (inches), INFILT – Index to mean soil infiltration rate (in/hr), AGWRC – groundwater recession rate (dimensionless), and UZSN – nominal upper zone soil moisture storage (inches).

9.1 ANNUAL WATER BALANCE

The annual water balance summarizes the fate of precipitation on the landscape. For the Green River LSPC Model (Figure 9-1) approximately 38% of precipitation evaporates or transpires, not directly contributing to streamflow. About 38% infiltrates and becomes shallow active groundwater that feeds streams as baseflow. The remaining water becomes interflow (19%) or surface runoff (5%) that contributes to streamflow. According to a groundwater study conducted for southwestern King County, 40% of precipitation recharges groundwater, 40% evaporates/transpires, and 20% becomes overland flow (USGS, 1995). Simulated active groundwater and evapotranspiration closely aligns with these estimates. In LSPC interflow is very shallow subsurface flow that contributes to streamflow through the upper soil layer as opposed to recharging aquifers. When interflow and surface runoff are combined, these pathways align with overland flow estimates.

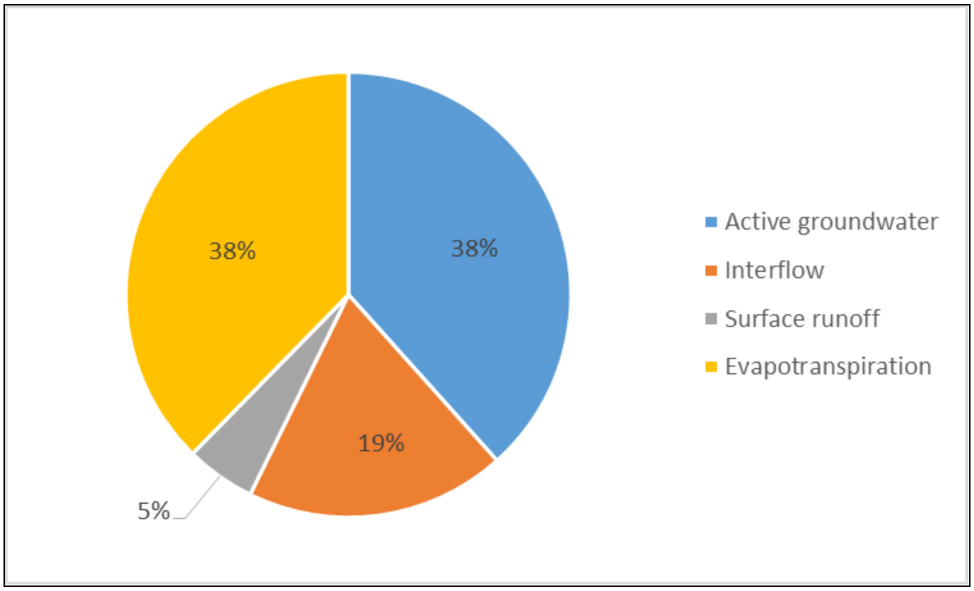

Figure 9-1. Simulated Water Balance for the Green River LSPC Model

For the Duwamish River LSPC Model evapotranspiration dominates the annual water balance (Figure 9-2). This is largely due to reduced infiltration. The high imperviousness in this region results in a higher fraction of surface runoff (18%) compared to the Green River LSPC model (5%). Subsurface flow contributions from active groundwater and interflow are lower at 24% and 13% respectively.

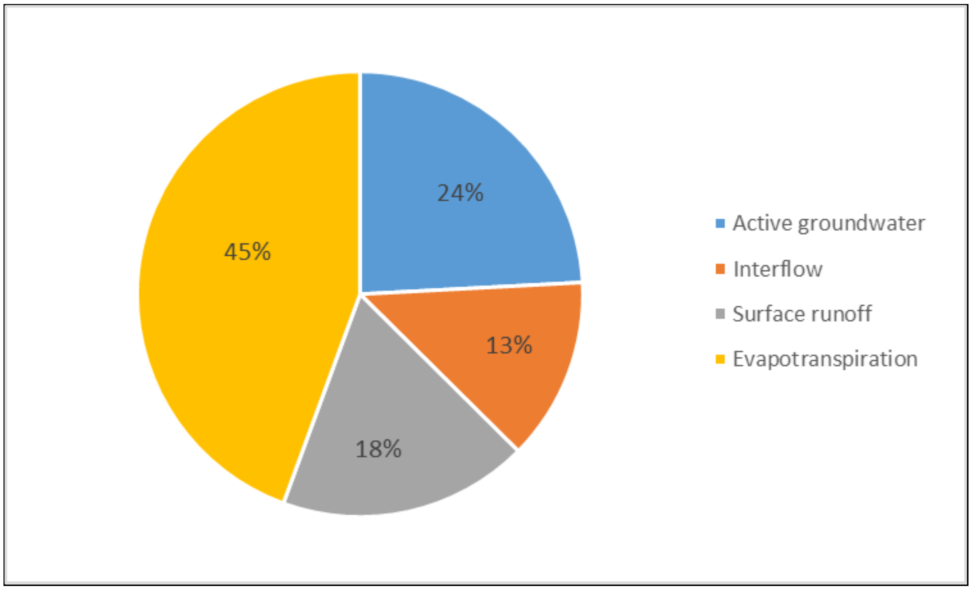

Figure 9-2. Simulated Water Balance for the Duwamish River LSPC Model

9.2 EVAPOTRANSPIRATION

Evapotranspiration (ET) is the sum of evaporation from soil, water, and leaf surfaces and transpiration of soil water by plants. ET is the largest component of the water balance and is thus crucial to hydrologic calibration, but actual ET is often unconstrained in watershed models due to a lack of observed data. This issue was addressed for the Green River and Duwamish River LSPC models through the use of remotely sensed ET data. The MODIS Global Evapotranspiration Project (MOD16) provides estimates of global terrestrial ET by using satellite remote sensing data at a spatial scale of 1 km^2 grid and at temporal scales of 8-days, months, and yearly totals from 2000 to 2010. It is important to recognize that MODIS does not directly measure evapotranspiration. Rather, an algorithm that considers MODIS land cover, albedo, leaf area index, and enhanced vegetation index is combined with daily meteorological data from NASA's Global Modeling and Assimilation Office reanalysis datasets using a Penman-Monteith type of approach (Mu et al., 2011). A validation study (Velpuri et al., 2013) showed that MODIS was able to estimate monthly ET within about 25 percent based on comparison to FLUXNET tower studies. These data are thus imprecise, but are useful to check that modeled ET patterns are realistic.

Monthly ET estimates for the Green-Duwamish River Watershed were extracted from the global MOD16 dataset. The gridded data were then aggregated to the level of the watersheds. The aggregated monthly data were compared to actual ET (TAET) simulated by the model and used to inform the pan coefficients used to convert Penman Pan PET to land surface PET in the model. Penman Pan Coefficients that were used in the model range from 0.6 in the Upper Green River drainage area to 0.7 near the Lower Duwamish Waterway. The pattern of observed monthly evapotranspiration was also used to refine the MON-INTERCEP and MON-LZETPARM blocks in the LSPC models.

Figure 9-3 shows mean monthly simulated evapotranspiration in comparison with MODIS estimates for the Green River LSPC Model. MODIS has been shown to have about a 25% error margin (Velpuri et al., 2013) so upper and lower bounds of this magnitude are also shown on the plot. The seasonal ET pattern simulated in the Green River LSPC model generally aligns with the lower MODIS ET estimates and both the simulated and MODIS ET peak in July. MODIS predicts a slower ramp up of ET in the spring and simulated ET is closer to the upper bound during the early part of the year. This may be because the MODIS algorithm relies on leaf area whereas a significant portion of the total evaporation during early periods of plant growth may come directly from the soil surface. MODIS estimates are higher than simulated ET for other months, but simulated ET for these months is in the range of uncertainty for MODIS. Overall, simulated ET matches well with MODIS ET (R^2 =0.8786) for the Green River LSPC model (Figure 9-4). Results are similar for the Duwamish River LSPC Model (Figure 9-5 and Figure 9-6).

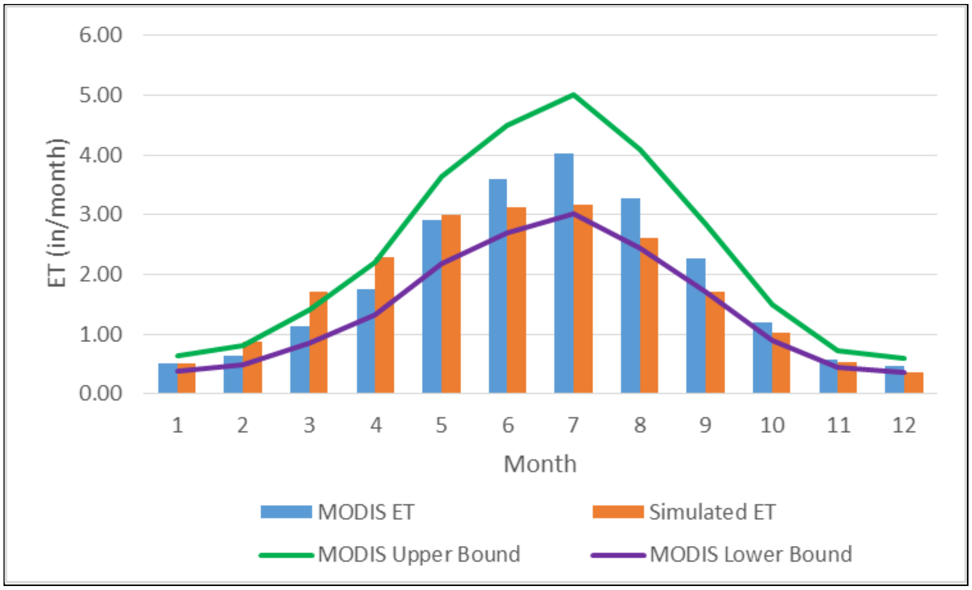

Figure 9-3. Comparison of Mean Monthly MODIS ET and Simulated Actual ET for the Green River LSPC Model (2000-2014)

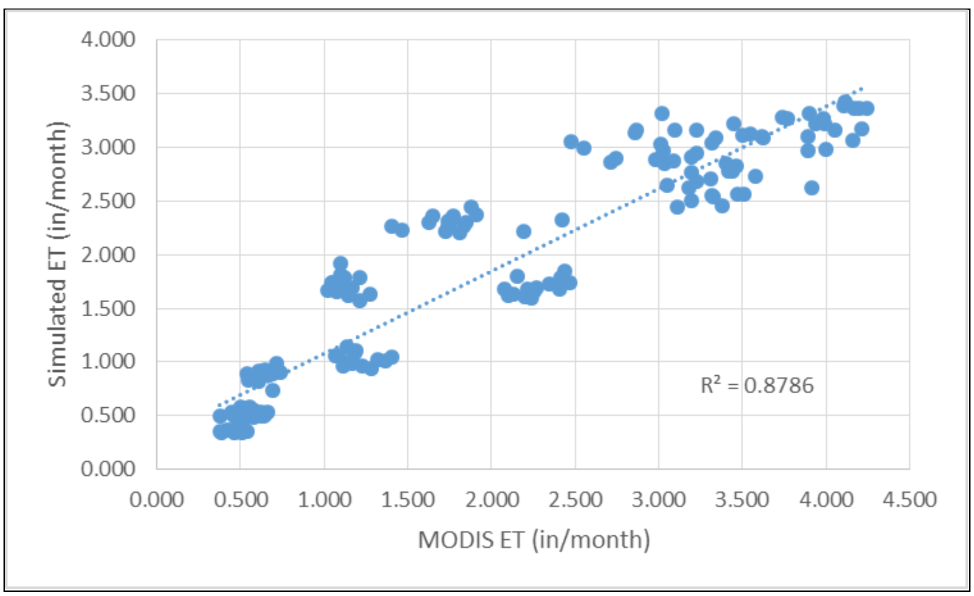

Figure 9-4. Regression of Monthly Simulated ET and MODIS ET for the Green River LSPC Model (2000-2014)

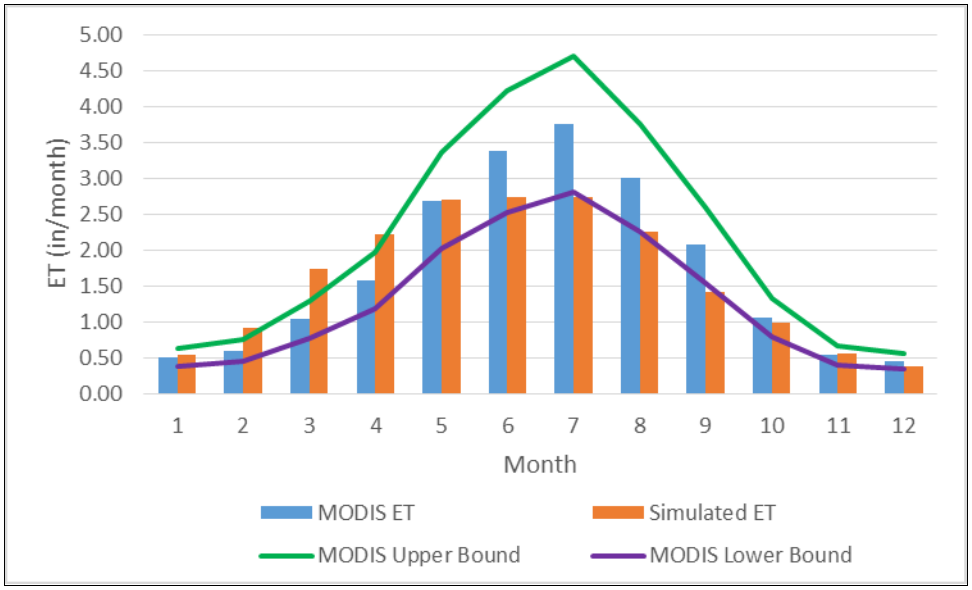

Figure 9-5. Comparison of Mean Monthly MODIS ET and Simulated Actual ET for the Duwamish River LSPC Model (2000-2014)

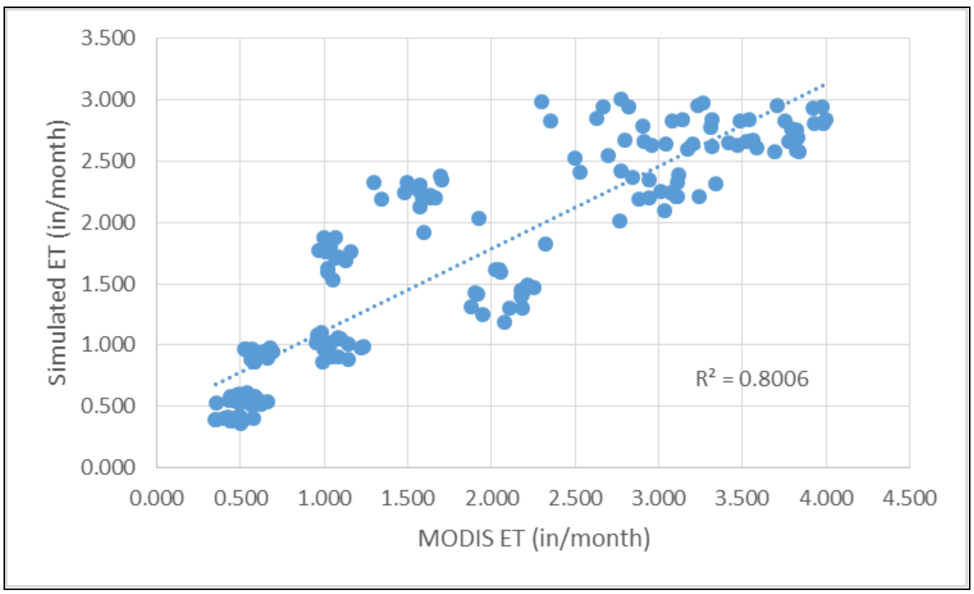

Figure 9-6. Regression of Monthly Simulated ET and MODIS ET for the Duwamish River LSPC Model (2000-2014)

9.3 FLOW CALIBRATION

After constraining evapotranspiration to a realistic range, model parameters were adjusted to achieve a match between simulated and observed flow time series. We used flow records from 20 gages operated by King County and USGS in the Green-Duwamish River watershed, as described in Section 8.0 and shown in Figure 8-1. These include three gages on the Green River mainstem and 17 gages on tributaries.

The calibration is evaluated both graphically and through model fit statistics. Statistics include measures of relative average error for a variety of aspects of the flow series, as recommended by Donigian et al. (1984) and Lumb et al. (1994) for calibration of the HSPF model, and the Nash-Sutcliffe coefficient of model fit efficiency (NSE; Nash and Sutcliffe, 1970), as recommended by Moriasi et al. (2007) for watershed models in general. The NSE statistics, which can range from minus infinity to one, index the model's ability to replicate the variance in observations, with a value of one indicating a perfect fit and a value of zero indicating that the model is no better a predictor than the long-term average. The relative error measures help ensure that the model represents seasonal patterns and both high and low flow ranges. Calibration seeks to obtain a balance between low relative errors and high NSE coefficients, supplemented by visual comparisons of simulated and observed flow series, flow-duration curves, and cumulative errors.

As stated in the Quality Assurance Project Plan (Tetra Tech, 2016), the project team did not establish quantitative statistical model acceptance targets, based on the following considerations:

1. Overall model quality cannot be fully captured in numeric error statistics.
2. Model error can vary widely depending on the system characteristics and simulated parameters, and the irreducible error cannot be predicted at the outset of the project.
3. It may not be possible to reduce error below numeric acceptance criteria without additional data collection, and this can significantly impact the project schedule, budget, and management goals. A decision to delay model acceptance for additional data collection is a major management decision that should not be pre-judged by criteria in the project planning document.
4. Model acceptance is a policy decision of regulatory agency management and should involve consideration of numerous factors and goals in model quality.

While we did not establish specific quantitative targets for model acceptance, the statistical measures can be used to examine the relative performance of different aspects of the models. The literature (e.g., Donigian, 2000; Moriasi et al., 2007; Duda et al., 2012) provides general guidance on the interpretation of statistical measures of fit for hydrology in the evaluation of LSPC and similar watershed model performance. These qualitative ranges, reflecting the consensus of the literature cited above, are shown in Table 9-2.

The categories in the two shades of green (labeled "Very Good" and "Good") suggest a high level of agreement between model and observations. Residual uncertainty in this range is expected in most watershed models due to imprecise estimates of precipitation, flow, and potential evapotranspiration, along with the approximations inherent in characterizing the land surface. The other two categories in the table suggest aspects of the calibration where additional scrutiny may need to be applied in evaluating the application of the model.

Table 9-2. Model Evaluation Components for the Green-Duwamish River LSPC Flow Calibration

Model Component	Very Good	Good	Fair	Poor
1. Error in total volume	≤ 5%	5 - 10%	10 - 15%	> 15%
2. Error in 50% lowest flow volumes	≤ 10%	10 - 15%	15 - 25%	> 25%
3. Error in 10% highest flow volumes	≤ 10%	10 - 15%	15 - 25%	> 25%
4. Error in storm volume	≤ 10%	10 - 15%	15 - 25%	> 25%
5. Winter volume error (JFM)	≤ 15%	15 - 30%	30 - 50%	> 50%
6. Spring volume error (AMJ)	≤ 15%	15 - 30%	30 - 50%	> 50%
7. Summer volume error (JAS)	≤ 15%	15 - 30%	30 - 50%	> 50%
8. Fall volume error (OND)	≤ 15%	15 - 30%	30 - 50%	> 50%
9. NSE on daily values	> 0.80	> 0.70	> 0.60	≤ 0.60
10. NSE on monthly values	> 0.85	> 0.75	> 0.65	≤ 0.65

Table 9-3 and Table 9-4 summarize the main statistical results from the model calibration for the Green River and Duwamish River LSPC models, respectively. Complete seasonal statistics and graphical analyses (daily and monthly time series, monthly ranges, flow duration curves, cumulative mass curves) are provided in the appendices. In general, the LSPC models represent watershed hydrology well, with a majority of “Good” and “Very Good” ratings. The performance of the model at major tributary and mainstem gages rates as “Good” to “Very Good”. Simulated flows deviate more from observed flows at gages for smaller drainage areas on Crisp Creek, Little Soos Creek, Olson Creek, and Hamm Creek, as indicated by higher relative errors and lower NSEs at these sites. With the exception of Crisp Creek (discussed further below), “Poor” rankings for the Green River model are seen only for relative error on flows below the median at two stations that appear to have complex interactions with groundwater and represent a small fraction of the total drainage area. In the Duwamish River LSPC model, there are “Poor” rankings for total volume error on Duwamish River Tributary 0003 and for Monthly NSE on Hamm Creek South Fork. Both of these gages drain watersheds less than 1 square mile in size that represent less than 0.5% of the total drainage area. Whether additional calibration efforts are warranted for these small watersheds will depend in part on their significance as potential sources of toxics load.

Table 9-3. Results for the Green River LSPC Model Flow Calibration (1997-2015)

Flow Gage Name (Gage Number)	Gage Area as Percent of Total Watershed	Percent Error in Total Volume	Percent Error in 50% Lowest Flow Volumes	Percent Error in 10% Highest Flow Volumes	Daily NSE	Monthly NSE
Green River at Purification Plant near Palmer, WA (USGS 12106700)	3.45%	2.42%	6.07%	0.22%	0.983	0.993
Green River nr Auburn (USGS 12113000)	67.9%	-5.47%	-3.74%	-8.53%	0.964	0.978
Green River at 200th St. at Kent, WA (USGS 12113344)	87.9%	-5.75%	-6.16%	-7.15%	0.973	0.979
Big Soos Creek nr Auburn (USGS 12112600)	25.6%	-5.77%	-9.40%	2.79%	0.870	0.910
Covington Creek nr Mouth (KC 09a)	8.33%	-5.27%	-3.62%	8.19%	0.683	0.835
Crisp Creek at Green River Rd (KC 40d)	1.38%	19.1%	-3.71%	36.1%	0.060	-0.029
Jenkins Creek nr Mouth (KC 26a)	6.45%	2.54%	-1.42%	6.55%	0.829	0.886
Little Soos Creek at SE 272 (KC 54i)	1.42%	-5.29%	6.97%	-10.9%	0.601	0.847
Mill Creek at SR181 (KC 41a)	5.14%	-11.0%	6.75%	-3.29%	0.676	0.899
Mill Creek at Peasley Canyon (KC mf1)	2.28%	-4.94%	26.5%	-5.58%	0.763	0.883
Mill Creek nr Peasley Canyon Rd (KC 41c)	1.61%	-3.66%	-3.12%	-7.20%	0.836	0.894
Newaukum Creek nr Black Diamond (USGS 12108500)	10.5%	-1.54%	12.0%	-14.5%	0.833	0.902
Olson Creek at Green River Rd (KC 32c)	0.71%	9.15%	93.9%	-8.49%	0.797	0.900

Notes: Gage area as percent of total watershed is calculated relative to the total area draining to the Lower Duwamish Watershed from Howard A. Hanson Dam to the outlet of the Lower Duwamish Watershed to Elliott Bay on either side of Harbor Island.

Table 9-4. Results for the Duwamish River LSPC Model Flow Calibration (1997-2015)

Flow Gage Name (Gage Number)	Gage Area as Percent of Total Watershed	Percent Error in Total Volume	Percent Error in 50% Lowest Flow Volumes	Percent Error in 10% Highest Flow Volumes	Daily NSE	Monthly NSE
Duwamish River Tributary 0003 (KC 13a)	0.21%	16.1%	-7.08%	-6.30%	0.841	0.923
Hamm Creek South Fork (KC ha5)	0.28%	-8.33%	-12.7%	4.50%	0.627	0.639
Mill Creek at Earthworks Park at Kent, WA (Black R.) (USGS 12113347)	0.96%	2.1%	5.06%	-8.11%	0.766	0.874
Mill Creek (Kent) above Diversion (Black R.) (KC 03F)	1.85%	-5.05%	5.75%	-11.3%	0.860	0.965
Mill Creek near mouth at Orillia (Black R.) (USGS 12113349)	2.16%	-8.93%	-8.23%	-3.93%	0.881	0.930
Springbrook Creek at O'Grady Way (Black R.) (KC 03G)	9.83%	-1.97%	-2.61%	-0.79%	0.863	0.933
Springbrook Creek at Orillia, WA (Black R.) (USGS 12113346)	3.24%	-2.00%	-8.62%	-4.59%	0.722	0.733

Notes: Gage area as percent of total watershed is calculated relative to the total area draining to the Lower Duwamish Watershed from Howard A. Hanson Dam to the outlet of the Lower Duwamish Watershed to Elliott Bay on either side of Harbor Island.

Green River Mainstem

Of the three gages on the Green River mainstem, the upper gage at the Purification Plant is not far downstream from the Howard A. Hanson Dam boundary condition, and is thus primarily a test of the adequacy of the representation of this boundary condition and the Tacoma Water diversion above this gage. The fit to observations is very close.

A key summary for runoff from the Green River watershed is the USGS gage on the Green River near Auburn, representing 67.9% of the contributing area downstream of Howard A. Hanson Dam (Table 9-3). Performance at this gage is rated "Very Good" for four of the five measures reported in Table 9-2 and as "Good" on the fifth. The appendices provide more comprehensive statistics on different aspects of the model fit. Example summary results for this station are shown in Table 9-5 and demonstrate that the model is able to achieve a "very good" level of fit across all seasons. The coefficient of determination (R^2) between daily average observed and simulated flows is 0.98.

Table 9-5. Calibration Statistics for Green River near Auburn

LSPC Simulated Flow		Observed Flow Gage	
REACH OUTFLOW FROM SWS 20314		Green River near Auburn (USGS 12113000)	
19-Year Analysis Period: 1/1/1997 - 12/31/2015 Flow volumes are (inches/year) for upstream drainage area		Drainage Area (sq-mi): 399	
Total Simulated In-stream Flow:	**44.98**	Total Observed In-stream Flow:	**47.59**
Total of simulated highest 10% flows:	**13.97**	Total of Observed highest 10% flows:	**15.28**
Total of Simulated lowest 50% flows:	**9.13**	Total of Observed Lowest 50% flows:	**9.48**
Simulated Summer Flow Volume (months 7-9):	**3.41**	Observed Summer Flow Volume (7-9):	**3.65**
Simulated Fall Flow Volume (months 10-12):	**13.04**	Observed Fall Flow Volume (10-12):	**13.03**
Simulated Winter Flow Volume (months 1-3):	**16.06**	Observed Winter Flow Volume (1-3):	**17.10**
Simulated Spring Flow Volume (months 4-6):	**12.46**	Observed Spring Flow Volume (4-6):	**13.81**
Total Simulated Storm Volume:	**10.77**	Total Observed Storm Volume:	**12.30**
Simulated Summer Storm Volume (7-9):	**0.33**	Observed Summer Storm Volume (7-9):	**0.37**
Errors (Simulated-Observed)	*Error Statistics*		
Error in total volume:	-5.47%		
Error in 50% lowest flows:	-3.74%		
Error in 10% highest flows:	-8.53%		
Seasonal volume error - Summer:	-6.38%		
Seasonal volume error - Fall:	0.05%		
Seasonal volume error - Winter:	-6.05%		
Seasonal volume error - Spring:	-9.73%		
Error in storm volumes:	-12.49%		
Error in summer storm volumes:	-9.30%		
Nash-Sutcliffe Coefficient of Efficiency, E:	0.964	Model accuracy increases	
Baseline adjusted coefficient (Garrick), E':	0.853	as E or E' approaches 1.0	
Monthly NSE	0.978		

USGS has operated a downstream mainstem gage at 200th St. at Kent since 2012, representing 87.9% of the contributing area downstream of Howard A. Hanson Dam. Although the available period of record is short, the model fit is also “Very Good” for four of five measures, and “Good” for the relative error on total volume.

Soos Creek

Four gages used in the Green River LSPC model calibration are located in the Soos Creek drainage area. These include the gages on Little Soos Creek, Jenkins Creek, Covington Creek, and Big Soos Creek. As discussed in Section 5.2, groundwater seeps and losses are prevalent in this region. Groundwater flow paths and discharge points are represented in the model with groundwater transfers. Groundwater is the primary source of streamflow during low flow periods. As shown by the relative error results for the 50% lowest flows, which are classified as “Very Good” at all four gages in the Soos Creek drainage area, groundwater activity and contributions are well represented on average. For the 10% highest flows, simulated flows are greater than observed flows at all of these gages except for Little Soos Creek. This is primarily caused by two storm events; storm flows in Little Soos Creek on 1/8/2009 and 12/9/2015 are underestimated by the model (Figure 9-7). The recorded mean daily flow on 1/8/2009 is 189 cfs and the corresponding simulated flow is 38 cfs. Precipitation on the three days prior totals 3.98 inches. A flow of 16.1 cfs occurred on 10/21/2003 and the three-day precipitation total leading up to this event was greater at 5.19 inches. King County confirmed that siphon-controlled releases from Lake Youngs are consistently around 2 cfs (Daniel Huang, personal communication, 9/13/2016) so misrepresented reservoir releases do not explain the underestimated storm flows on these days. Gage uncertainties or inaccurate precipitation estimates may explain the inconsistent precipitation-to-flow relationship at Little Soos. Little Soos Creek represents a small portion of the watershed (1.4%) so the less than ideal fit at this gage has little impact on the overall functionality of the LSPC models. The highest observed flow event is also underestimated at Big Soos Creek: The daily flow recorded at Big Soos Creek on 1/9/2009 was 1,610 cfs whereas the simulated flow on this day is significantly less at 1,110 cfs (Figure 9-8). In general, the shape of the simulated and observed flow duration curves at Big Soos Creek are similar (Figure 9-9) although discrepancies are notable for extreme high and low flows and for moderate flows in the 30% - 60% exceedance range.

Crisp Creek

Hydrology in the Crisp Creek drainage area appears to differ from that of the greater Green River Watershed. Most gages in the watershed exhibit distinct seasonality; winter flows are significantly higher than summer flows. Winter flows are about 5 times greater than summer flows at the Green River near Auburn gage and at the nearby Newaukum Creek gage, for example. There is less high-to-low flow variability at Crisp Creek. Observed flows during the winter are only double that of summer flows (Figure 9-10). Flows in Crisp Creek are thought to be controlled by surface-groundwater interactions. Losses from the stream to the shallow aquifer or additional unmodeled storage within the watershed may explain the muted high flows, which are overestimated by the model (36.1% error on the 10% highest flows). Alternatively, there could be unidentified issues in the gage rating curve estimates for high flow rates. Parameter adjustments that improved the fit at Crisp degraded the fit at several other gages and, therefore, were not retained. Simulated hydrology at the Crisp Creek gage could possibly be improved through a focused study of the area; however, this small watershed (1.38% of the total drainage area) is not a significant contributor to the overall hydrology of the Green River. Whether or not additional effort should be applied to the Crisp Creek simulation should depend in part on its significance as a contributor to toxic pollutant loads relevant to the PLA.

Mill Creek (Green River) and Olson Creek

Two gages (41c and mf1) on Mill Creek (the creek of this name within the Green River model) measure streamflow near Peasley Canyon. Gage 41c is upstream of mf1. Observed flows at these gages exhibit similar patterns; however, low flows tend to be slightly underestimated at 41c yet overestimated at mf1. A gage was operated near the mouth of Mill Creek between 2/1/2003 – 4/30/2006. The lower Mill Creek gage is subject to backwater from the Green River, as a result of which the gage was discontinued in spring 2006. Daily NSE at this gage is low (0.676), likely due to inaccurate flow readings. Generally, gages with less than two years of flow data are not used in the hydrology calibration. An exception was made for King County gage 32c so that flows in Olson Creek could be evaluated and guide model parameterization. The 50% lowest observed flows average 1.16 cfs and the corresponding simulated flows average 2.24 cfs, which results in a high error value of 93.9% for this brief observation period, although the absolute error is small (Table 9-3).

Springbrook Creek, Mill Creek (Black River), and Hamm Creek

Overall, the fit is good at the three Mill Creek (Black River basin) and two Springbrook Creek gages. The average daily and monthly NSEs for these five gages are 0.818 and 0.887. The fit at the most downstream gage, Springbrook Creek near O'Grady, is rated "Very Good" with relative errors <5% (Table 9-4). There is a break in the observed flow data from 12/18/2004 to 6/24/2010. Storm flows before June 2003 tend to be of greater magnitude compared to storm flows during later years (Figure 9-11). Expansion of the Green River Natural Resource Area, an engineered wetland, construction of detention ponds, and implementation of other green stormwater control practices during the mid-2000s may explain this trend, as progressive changes in stormwater control practices are not represented in the model. The calibrated fit for Hamm Creek South Fork, a small tributary stream representing 0.28% of the watershed area, is "Fair." Simulated flows correspond well with observed flows after 2003 but discrepancies are evident for earlier years (Figure 9-12). This may be partially due to a beaver dam that was located downstream of the gage during the simulated period (Daniel Smith, personal communication, 10/17/2016).

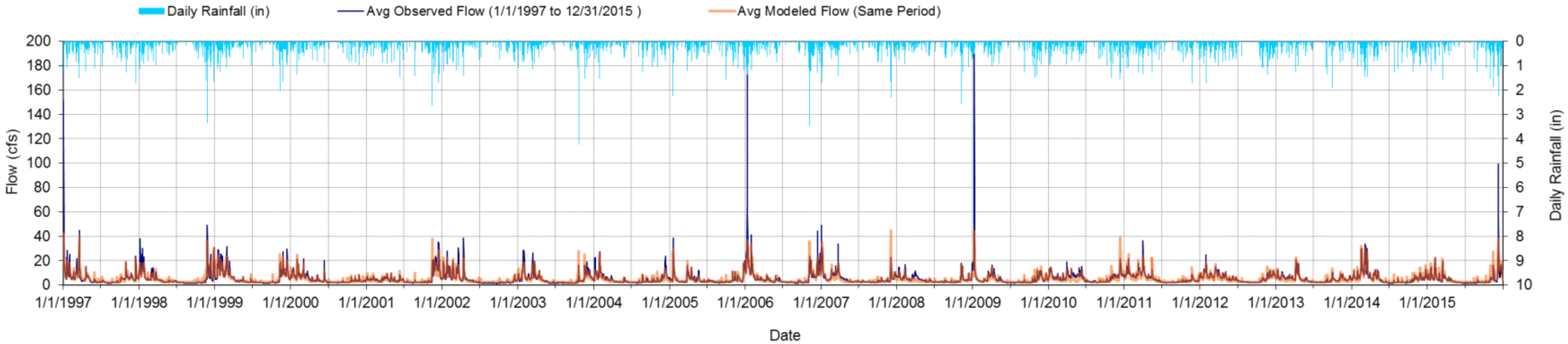

Figure 9-7. Time Series of Calibrated LSPC and Observed Flows at Little Soos Creek (King County 54i), 1997-2015

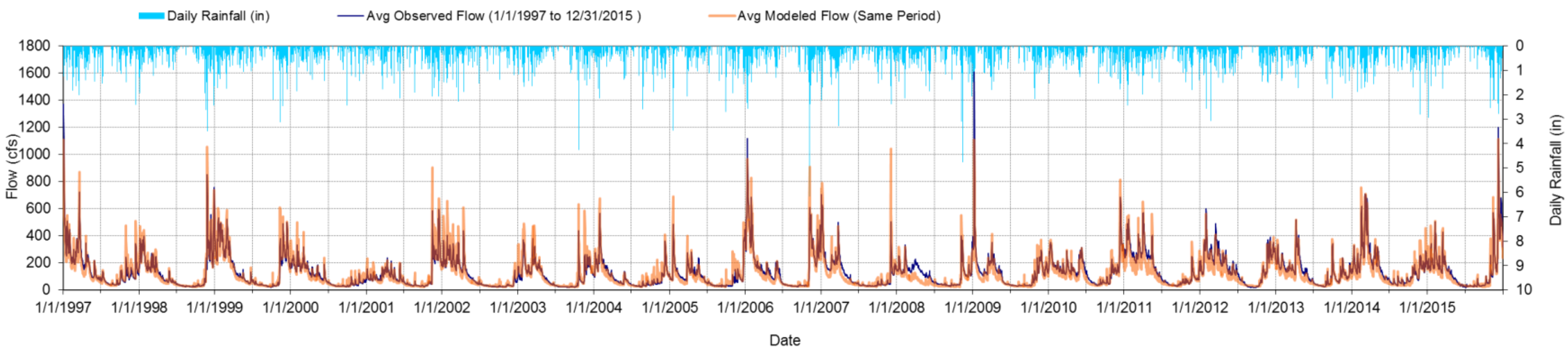

Figure 9-8. Time Series of Calibrated LSPC and Observed Flows at Big Soos Creek near Auburn (USGS 12112600), 1997-2015

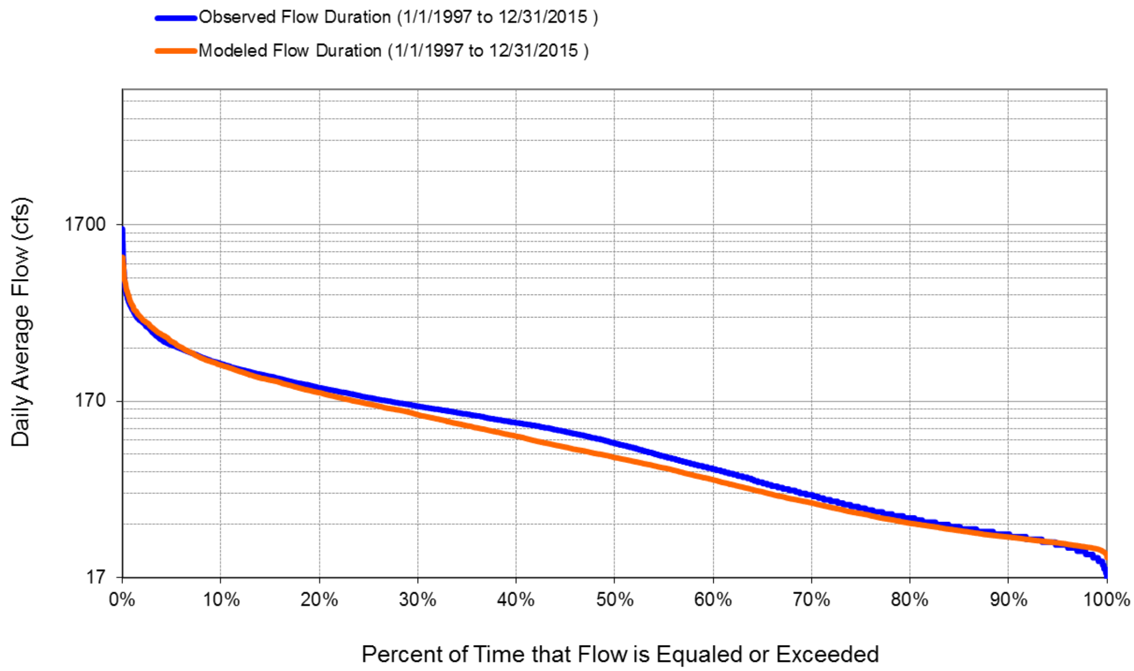

Figure 9-9. Flow Exceedance Curve for Big Soos Creek near Auburn (USGS 12112600), 1997-2015

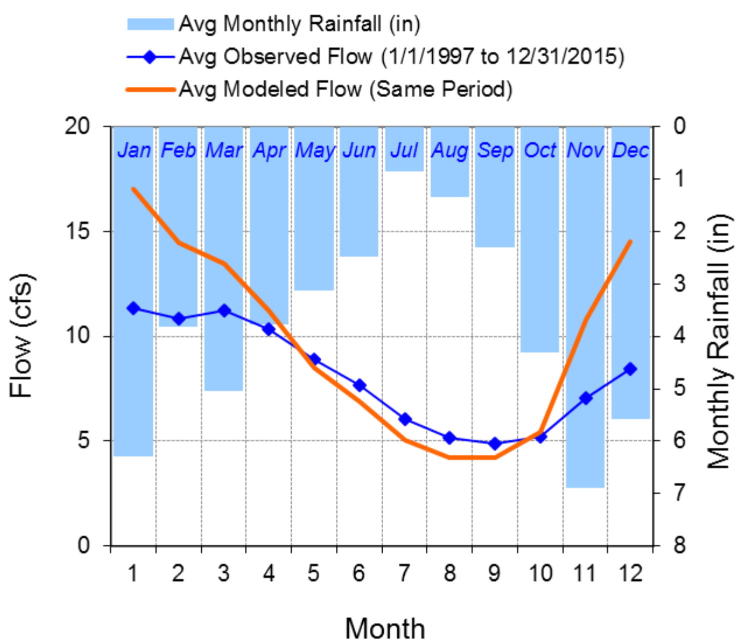

Figure 9-10. Average Monthly Observed and Simulated Flows at Crisp Creek (King County 40d), 1997-2015

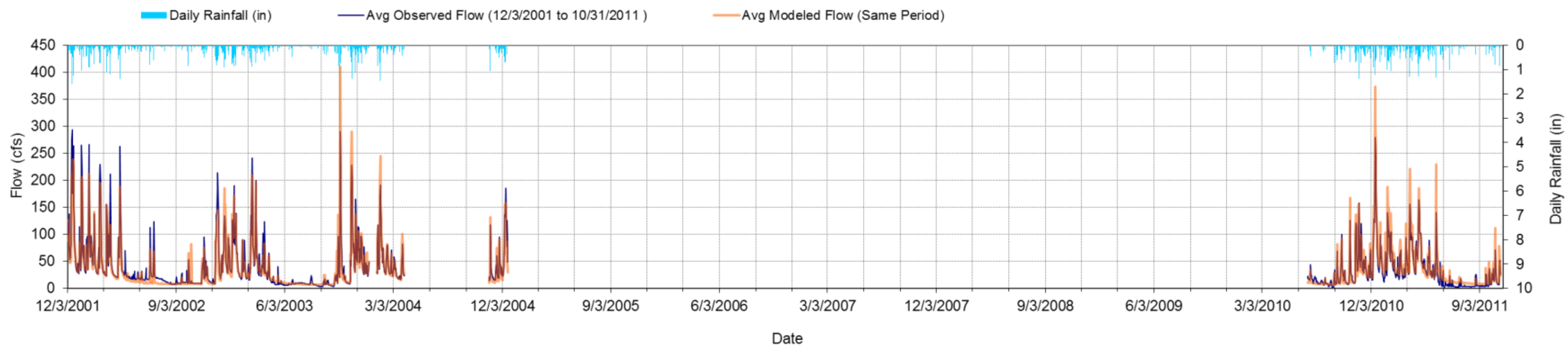

Figure 9-11. Time series of Calibrated LSPC and Observed Flows at Springbrook Creek near O'Grady Way (King County 03G), 1997-2015

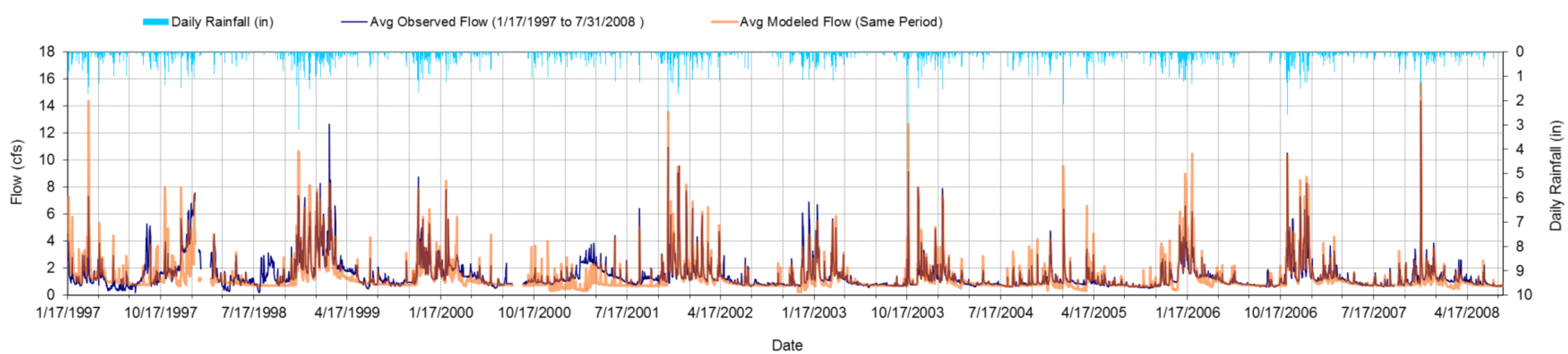

Figure 9-12. Time series of Calibrated LSPC and Observed Flows at Hamm Creek South Fork (King County ha5), 1997-2015

9.4 SUB-DAILY STORM EVENT FLOWS

The preceding sections demonstrate that the model performs well for daily hydrology. Performance on the sub-daily hydraulic details of storm events is also important, particularly in relation to the scour and transport of channel and bank sediments. Representation of sub-daily time series can be challenging as it is strongly dependent on the pattern and timing of precipitation.

Most gages in the watershed report hourly flows, which is the simulation time step used in the LSPC model. Hourly flows are compared for sample individual storm events at Big Soos Creek near Auburn, Mill Creek near Peasley, and Springbrook Creek near O'Grady in Figure 9-13, Figure 9-14, and Figure 9-15.

Big Soos Creek flows for a storm event that occurred in January 2009 are plotted in Figure 9-13. The model provides a close match to observation, although the simulated peak flow is somewhat lower than the observed peak flow and occurs earlier. Hydrographs for Mill Creek are shown for a November 1998 storm in Figure 9-14. Simulated flows align closely with observed flows for the period leading up to the peak flow. LSPC flows are prolonged on the falling limb of the hydrograph compared to observed flows during this event. The opposite is true for the Springbrook Creek October 2003 storm, where observed peak flows are muted and recede less quickly than simulated flows.

Model performance at the hourly scale can be strongly affected by the hydraulic representation in FTables. Additional information on channel geometry and further use of detailed hydraulic models to build FTables can likely further improve the sub-daily storm event simulation.

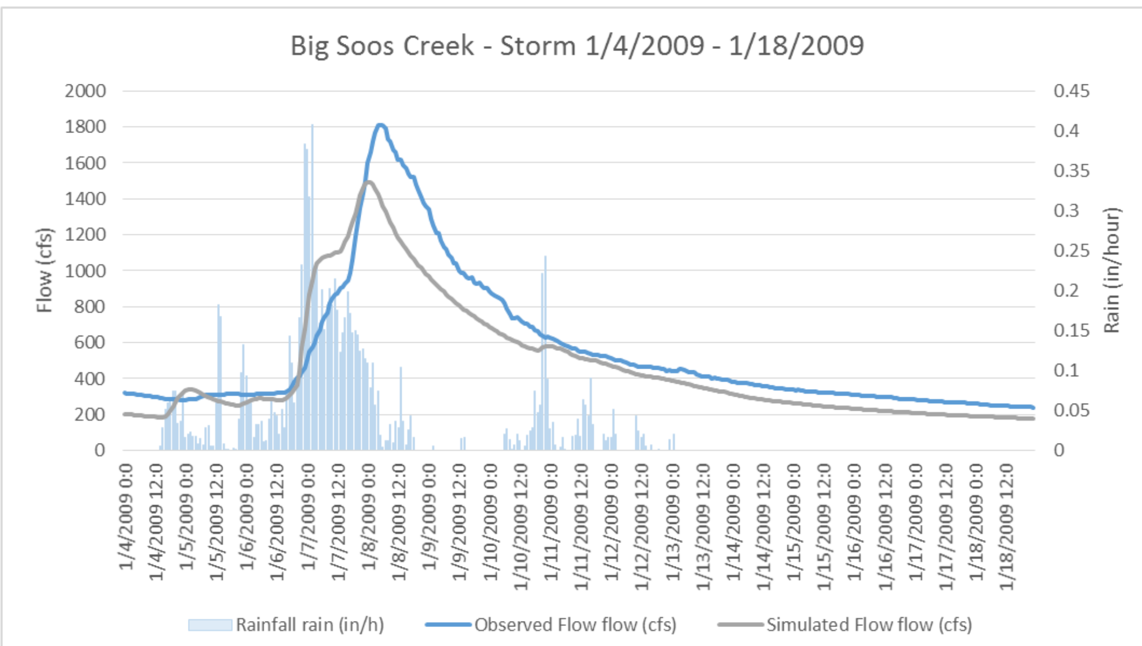

Figure 9-13. Hourly Observed and Simulated flow at Big Soos Creek near Auburn (USGS 12112600) for January 2009 Storm Event

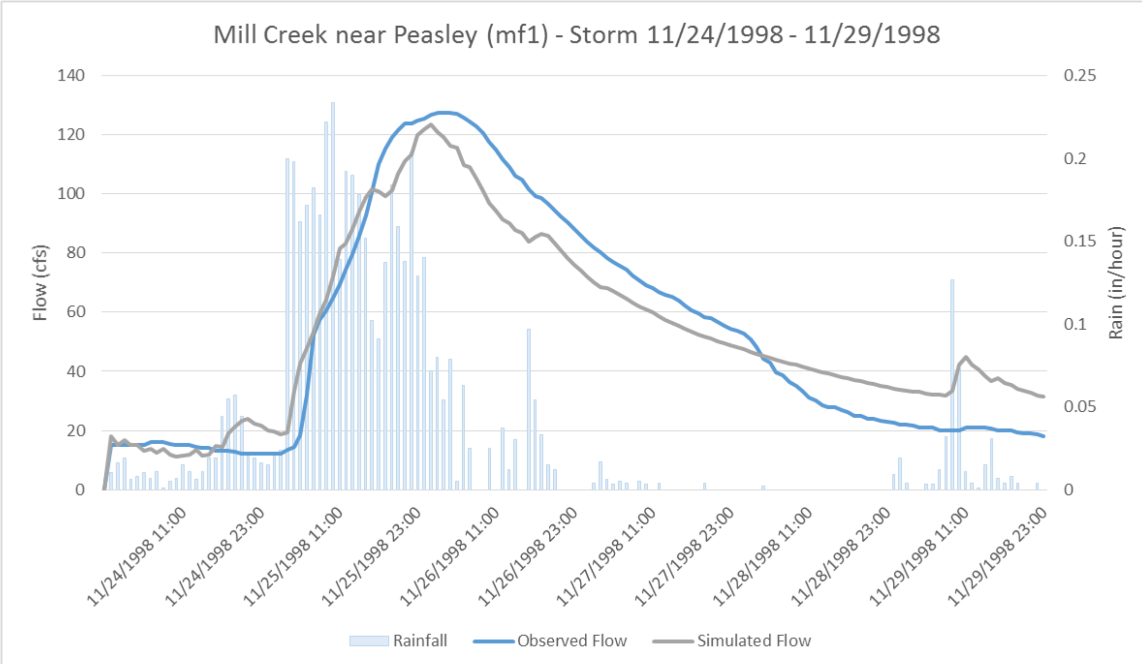

Figure 9-14. Hourly Observed and Simulated flow at Mill Creek near Peasley (King County mf1) for November 1998 Storm Event

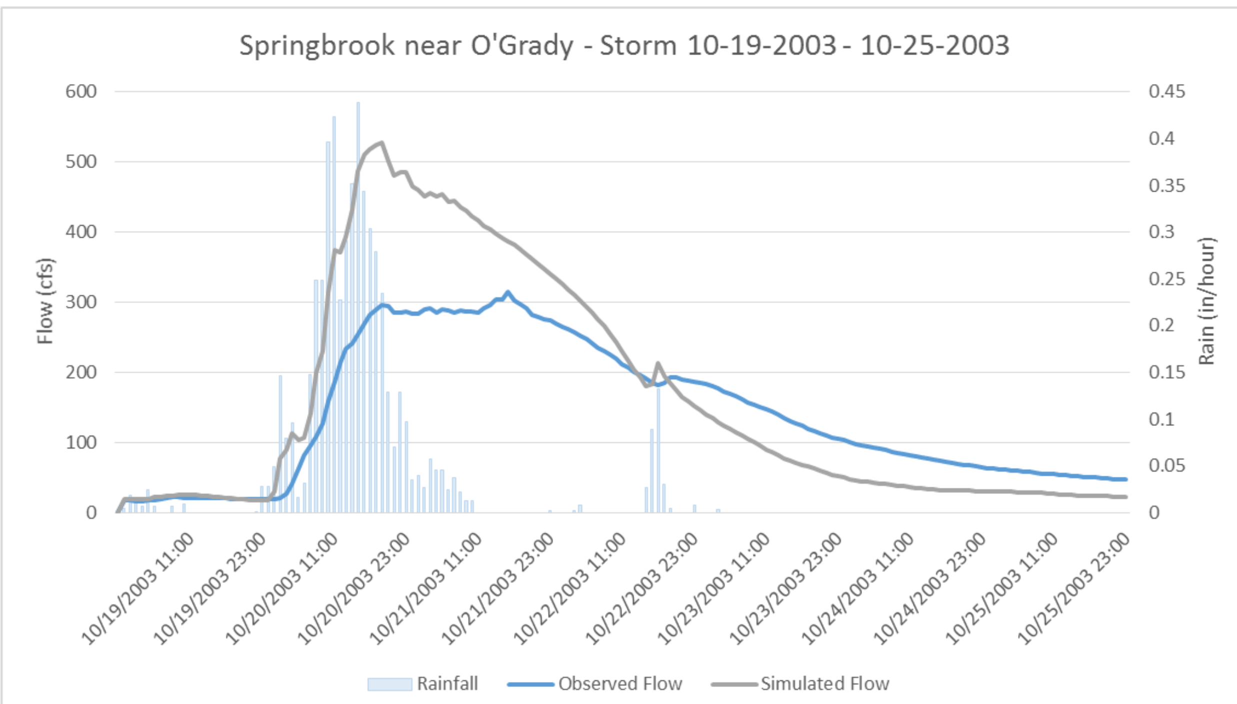

Figure 9-15. Hourly Observed and Simulated flow at Springbrook Creek near O'Grady (King County 03G) for October 2003 Storm Event

9.5 SOURCES OF MODEL UNCERTAINTY

USEPA's Council for Regulatory Environmental Modeling (CREM, 2009) defines a model as "a simplification of reality that is constructed to gain insights into select attributes of a particular physical, biological, economic, or social system." CREM acknowledges that models cannot completely replicate the complexity inherent in environmental systems, but are essential to analyze environmental questions and characterize systems that are too complex to be addressed solely through empirical means.

The purposes for which environmental simulation models are constructed fall into two general categories: (1) to diagnose and examine causes of events or observed conditions, and (2) to forecast outcomes and future conditions. The linked modeling system being developed for the Green/Duwamish River PLA will be used in both ways: to examine causes of historic and ongoing sources, fate, and transport of toxic pollutants within the watershed, receiving water, and biota, and to forecast how these aspects might change in response to future conditions, including management interventions.

The watershed model described in this report is one part of the overall proposed modeling system, and the hydrology simulation development and calibration is one aspect of the watershed model. The ultimate usefulness of the watershed model cannot be fully evaluated until it is fully developed for the simulation of the fate and transport of toxics; however, it is also the case that the representation of hydrology and hydraulics is fundamental to the toxics simulation. It is therefore important to summarize the types and sources of uncertainties in the LSPC watershed model as currently developed.

These uncertainties can be organized into five general categories:

1. Model Formulation

   The ability of a simulation model and its associated uncertainties is dependent on the process representation contained within the model code. LSPC (and its parent model, HSPF) is a well-established, general purpose watershed model that has been deemed appropriate to support the PLA, as is summarized in the QAPP (Tetra Tech, 2016). Acknowledged limitations of the model formulation include the following:
   a. The model is a lumped model, which means that properties of a given type of upland HRU are assumed to be consistent over a subbasin, as opposed to a distributed, grid-based model. If finer spatial resolution is needed in certain areas the model can be revised to use a smaller-scale segmentation.
   b. LSPC represents stream segments as one-dimensional, fully mixed segments. The model is thus limited in its ability to simulated fine-scale sediment scour and deposition processes, and does not distinguish between channel bed and bank erosion processes (see also 4.a).

2. Model Forcing

   Model forcing refers to the specification of external data that drive hydrology, including meteorological data and boundary flows.
   a. Precipitation estimates are subject to uncertainty based on the PRISM interpolation from point gauge measurements and interpretation of radar data. These uncertainties are expected to be small on average, but may bias representation of individual events.
   b. The upstream boundary condition is based on USGS gaging below Howard A. Hanson Dam. The gage records appear to have a high degree of accuracy, but are always subject to some uncertainty due to changes in channel condition.
   c. Surface water diversions are not fully known and rates of groundwater pumping and its effect on surface flows is imprecisely known.
   d. Groundwater transfers between subbasins and across the watershed boundary are not well studied. Construction of a groundwater simulation model and linkage to the watershed model would improve predictions, but would be most relevant to low flows, while most toxics transport is likely associated with high flows.

3. Land Use Representation
    a. The land use representation depends primarily on the 2006 NLCD. This is based on satellite interpretation, which is subject to some erroneous classification. Pervious land use classes are limited to those identified by NLCD. Detailed analysis using other sources of information might be warranted in areas with significant potential sources of toxics loads.
    b. The model does not represent land use change over time. On the scale of the whole watershed, this does not appear to be a significant issue; however, changes in land use may be important to results in some smaller subbasins. LSPC can represent land use change over time if needed for specific areas within the watershed.

4. Hydraulics

    Channel configuration and hydraulics determine the shear stress that is exerted on bed and bank materials as well as the energy available to move sediment and associated pollutants.
    a. Because LSPC is a one-dimensional representation of stream reaches, details of hydraulics are typically obtained from external analyses. Complete flood profile models such as HEC-RAS are preferable for this purpose, but HEC-RAS models are available only for some reaches. For many urban drainages within Seattle SWMM, models are available, but calibration data were limited for some of these models. SWMM models are available for some other municipalities in the watershed, but have not been obtained. Additional access to or refinement of flood profile and hydraulic stormwater conveyance models would improve the representation of hydraulics within LSPC. Note that this would not have much effect on the overall water balance or daily flow simulation, but could be important for refining estimates of potential for sediment (and associated pollutant) scour, deposition, and transport.
    b. A major calibration adjustment in the model that is a significant potential source of uncertainty in the hydrologic simulation is the estimation of EIA (see discussion in Section 3.3.3). The sensitivity of the model to EIA estimates is summarized further below.

5. Calibration Data

    Model parameters are adjusted and the performance of the model is evaluated by comparing simulated flows to observed flows. The quality of the calibration depends on the availability and accuracy of the gaged flows.
    a. Estimates of flow rate are obtained by converting observations of stream stage to flow, using a rating curve. The accuracy of estimated flows is limited by the accuracy of the rating curve. The rating curve is affected by changes in channel form (i.e., debris, sand bars) and requires frequent recalibration. It is also often necessary to extrapolate results for high flow events beyond the range of observed flow and to fill in for periods of equipment malfunction. It appears that some of the King County flow gages had relatively infrequent rating curve adjustments, which could result in increased uncertainty in reported flow estimates.
    b. Some tributary stations appear to be affected by backwater from the mainstem under high flow conditions, which would result in inaccurate flow estimates from stage.
    c. Many parts of the watershed have few or no gages, and several of the existing gages have operated for only short periods. Quality of the calibration cannot be directly assessed in areas without gaging.

Various other sources of uncertainty could be added to the list presented above, but these are likely to encompass the major sources. Of those on the list, the most important sources of uncertainty relative to use for pollutant load assessment for toxics primarily associated with stormwater would appear to be 4a (detailed hydraulic models for reaches of interest to toxics modeling), 5c (flow gaging that is limited in space and time), and 4b (estimation of EIA). Other sources of uncertainty are important to the overall water balance and model fit, but less significant to toxics transport – such as uncertainty in the representation of groundwater interactions that could be addressed through development of a regional groundwater flow model.

Item 4a could be addressed through both creation and calibration of additional flood elevation models and through access and use of existing municipal SWMM stormwater conveyance models. As the creation of new flood models can be expensive, we recommend, at a minimum, that the PLA Team keep track of and incorporate information from such hydraulic models as it becomes available.

Any defects in past gaging incorporated in item 5c that cannot be corrected. However, it will be important to ensure that a robust gaging program is maintained into the future, including good QA controls, and that the model calibration be evaluated and updated if necessary after several years of additional data are collected.

The role of the third major source of uncertainty (item 4b, estimation of EIA) is illuminated through sensitivity analysis. A series of runs were completed to examine hydrologic uncertainty due to the representation of effective impervious area (EIA) in the model. The upland hydrologic parameterization was held constant and the only variable altered for the sensitivity runs was EIA. Results for the EIA sensitivity analysis are presented for the most downstream flow gage in the Black River watershed, Springbrook Creek at O'Grady Way (King Co. 03G), because the contributing area is primarily residential with some commercial property and sewers are separated – conditions where the EIA estimate is most uncertain (Table 6). Initial baseline EIA scenario (obtained from the equations discussed in Section 3.3.3) results in high volume error, especially the overestimation of high flow volumes, and a poorer fit is indicated by the low NSEs. As shown by the tests presented in Table 6, adjusting EIA significantly alters simulated discharges in Springbrook Creek. EIA reassignment optimized simulated flows at several gage locations in the watershed; nevertheless, assumed EIA remains a source of model uncertainty. The representation could likely be further improved through a combination of detailed surveys of DCIA and calibration of Ef to gaging results using the statistical methods described by Ebrahimian et al. (2016a). Refinement of EIA by impervious surface type could be of more importance for toxics load simulations.

Table 6. EIA Sensitivity Analysis for Springbrook Creek near O'Grady Way (King Co. 03G; 12/1/2001-10/31/2011)

EIA Scenario	Fraction of Res-GL and NonDev-GL EIA Reassigned to Pervious Developed	Fraction of Com/Ind-GL and Roofs Reassigned to Pervious Developed	Percent Error in Total Volume	Percent Error in 50% Lowest Flow Volumes	Percent Error in 10% Highest Flow Volumes	Daily NSE	Monthly NSE
Baseline	0.00	0.00	11.4%	-17.1%	29.7%	0.652	0.833
Medium	0.45	0.15	1.37%	-6.06%	6.65%	0.840	0.927
High	0.75	0.25	-5.30%	0.42%	-8.09%	0.866	0.928
Final	0.60	0.20	-1.97%	-2.61%	-0.79%	0.863	0.931

Note: EIA was reassigned to developed pervious land for residential ground level EIA (Res-GL), non-developed ground level EIA (NonDev-GL), commercial/industrial ground-level EIA (Com/Ind-GL) and roofs.

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