Clarks Creek Sediment Study Watershed Model Report

Prepared for

Puyallup Tribe of Indians

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1 Introduction

1.1 CLARKS CREEK

The Clarks Creek watershed is located in the lower Puyallup River Basin, not far from Commencement Bay (southern end of Puget Sound) and the northwest corner of Pierce County, WA (Figure 1-1). It is within Washington Department of Ecology's Water Resources Inventory Area (WRIA) 10. The Clarks Creek watershed area is divided between the City of Puyallup and unincorporated areas of Pierce County. The most northern portion of the watershed is within the Puyallup Tribal Reservation.

The surface drainage occupies an area of 10.4 square miles of glacial deposits, foothill ridges, and flat valley land along the Puyallup River. Additional groundwater flow in Clarks Creek is derived from portions of an internally drained area to the south and east of the surface drainage network, known as the Potholes region. The headwaters of the Clarks Creek surface drainage network start approximately one-third of a mile south of Maplewood Springs and flow 3.6 miles through Pierce County, the City of Puyallup, and Puyallup Tribal lands before discharging into the Puyallup River.

The surficial geology of the Clarks Creek area is a product of glaciations and subsequent alluvial processes (Jones et al., 1999). The headwaters of the Clarks Creek drainage are primarily in the Vashon recessional till. From there, the creek descends for a few miles through the upper aquifer unit before transitioning to alluvial soils in the Puyallup River valley.

The highly permeable surface aquifers of upper Clarks Creek result in substantial exchanges between the surface and ground water systems (Savoca et al., 2010). Groundwater movement in the surface aquifer (Vashon recessional till or A1 aquifer) generally follows the land surface gradient, with seeps and springs where this layer thins out, as at Maplewood Springs, which forms the headwaters of Clarks Creek. The USGS is in the process of creating a regional groundwater model, and the initial framework report (Savoca et al., 2010) suggests that water in the A1 aquifer may flow to Maplewood Springs from a distance of up to five miles or more from the south and east.

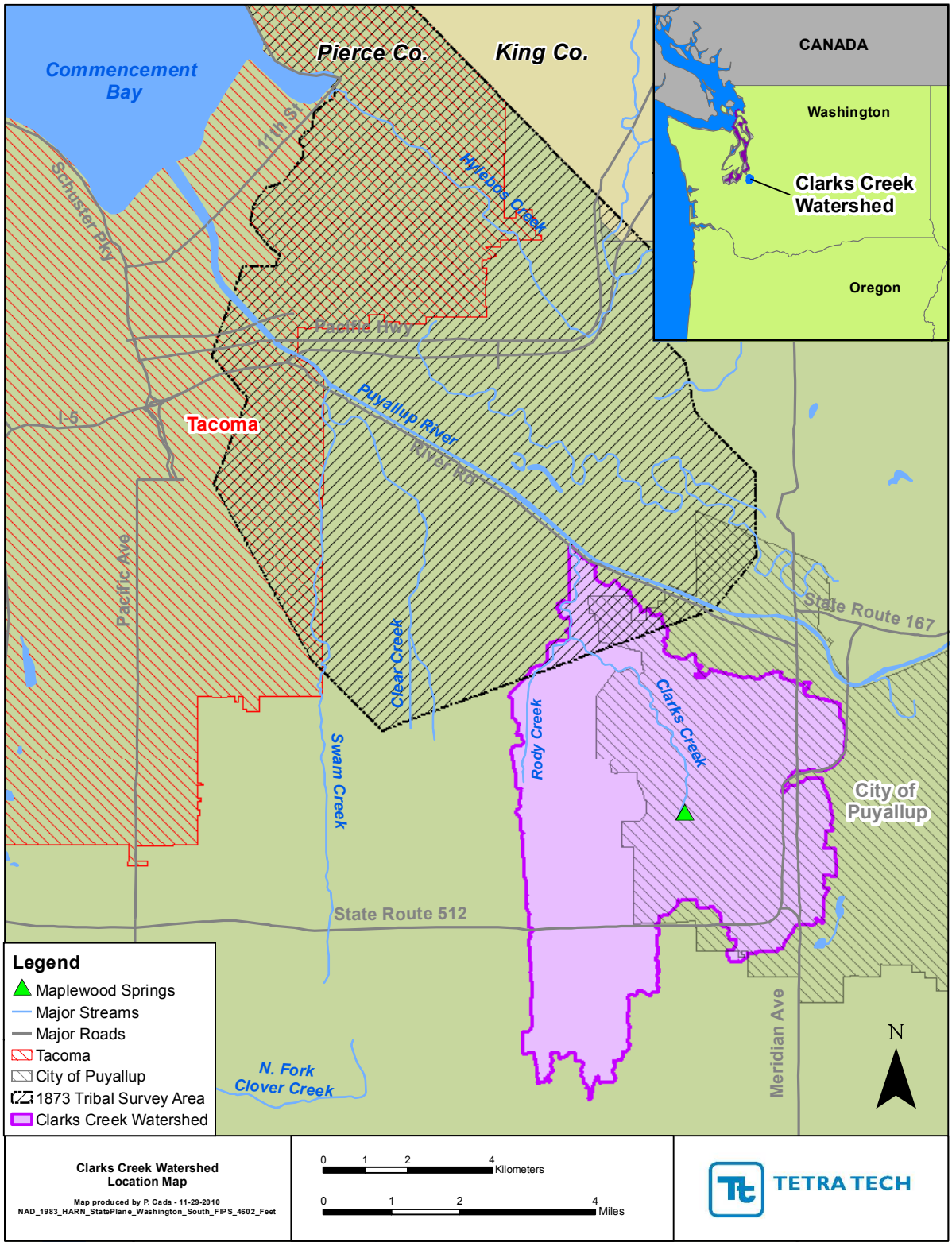

Figure 1-1. Clarks Creek Watershed Location Map

1.2 SCOPE OF THIS REPORT

The Puyallup Tribe of Indians (PTI) has been working for many years to improve water quality in Clarks Creek. As part of this effort, PTI received an EPA-funded grant entitled "Reducing Effective Impervious Surfaces in a Small Urban Catchment Using LID Practices." The overall contract to support work under this grant was issued to Brown and Caldwell, while Tetra Tech was issued a companion work assignment to support watershed modeling.

The watershed model focuses on flow and sediment loading in the watershed. Excess sediment loading contributes to a variety of water quality problems in Clarks Creek. Notably, fine sediment accumulation is an important factor in promoting dense growths of the nuisance waterweed elodea that adversely impact DO concentrations, in turn threatening salmonid success, and clog the Tribe's hatchery intakes. Sediment loads may also contain elevated nutrient concentrations that promote macrophyte growth, as well as elevated fecal coliform bacteria concentrations that can contribute to impairment of uses.

The overall goal of the project is to improve water quality in Clarks Creek by reducing sediment load. To accomplish this, the following objectives must be met:

1. Sediment sources must be identified and characterized.
2. Sediment pathways to Clarks Creek must be understood.
3. Anthropogenic elements of sediment load must be understood.
4. Methods to reduce the anthropogenic sediment load must be developed and implemented.

The Clarks Creek watershed model is a tool to assist in evaluating the relationship between sediment sources, urban stormwater, and conditions within Clarks Creek. This report documents the development, calibration, and validation of the watershed model. Following review and approval of the model, the tool can be used to aid in the selection of management efforts to protect and restore Clarks Creek.

1.3 PROJECT QUALITY OBJECTIVES

Environmental simulation models are simplified mathematical representations of complex real world systems. Models cannot accurately depict every one of the multitude of processes occurring at all physical and temporal scales in a watershed. Models can, however, make use of known interrelationships among variables to predict how a given quantity or variable would change in response to a change in an interdependent variable or forcing function. In this way, models can be useful frameworks for investigations of how a system would likely respond to a perturbation from its current state. To provide a credible basis for prediction and the evaluation of mitigation options, the ability of the model to represent real world conditions should be demonstrated through a process of model calibration and corroboration or validation.

USEPA (2002) recommends following a systematic planning process to define quality objectives and performance criteria. For modeling projects, systematic planning identifies the expected outcome of the modeling, its technical goals, cost and schedule, and the criteria for determining whether the inputs and outputs of the various intermediate stages of the project, as well as the project's final product, are acceptable. The systematic planning approach begins with identifying Principal Study Questions, and designs the modeling effort to answer these questions. This process is described in the modeling Quality Assurance Project Plan (QAPP; Tetra Tech, 2011).

Principal Study Questions

A detailed description of water quality and use assessment in Clarks Creek by Washington Department of Ecology, along with information on land use, geology, vegetation, and other watershed characteristics is provided in the Clarks Creek Data Review (Tetra Tech, 2010) conducted for USEPA Region 10 in

support of the Clarks Creek Dissolved Oxygen (DO) TMDL. Depressed DO in Clarks Creek occurs as the net result of a series of complex processes. Excess sediment loading contributes in a variety of ways to the DO problems in Clarks Creek. Notably, fine sediment accumulation is an important factor in promoting dense growths of elodea that adversely impact DO concentrations both directly, through diurnal respiration, and indirectly through contributions to SOD. Elodea growth in turn slows flows in the creek, which reinforces sediment deposition and accumulation and leads to flooding problems. Sediment loads may also contain elevated nutrient concentrations that promote macrophyte growth, as well as elevated bacterial concentrations.

In addition to use assessments conducted by Ecology, fisheries stakeholders (including the Puyallup Tribe) have an interest in reducing geomorphically significant flows that could result in salmon redd scour or burial and reduced juvenile salmon survival. The Puyallup Tribe is also interested in reducing downstream channel erosion.

In sum, the Principal Study Questions to be addressed by modeling in this project are:

1. What are the principal sources of sediment load in the Clarks Creek watershed?
2. How are sediment loads in the watershed transported to Clarks Creek?
3. What is the significance of sources of instream generation of sediment load due to scour and bank failure and what factors control these loads?
4. What is the optimal selection of management measures to reduce both the anthropogenic sediment load and excess flows that promote instream generation of sediment load via channel degradation?

Identify the Decision

The intended end product of this work is the development of a sediment management plan for Clarks Creek. The watershed simulation model should provide the ability to evaluate the relative benefit of different management alternatives that may control upland sediment loads and the occurrence of flows that cause channel scour with subsequent deposition in the lower reaches of Clarks Creek.

Identify the Inputs to the Decision

The watershed model developed as a result of this TO will be used to evaluate a variety of potential management scenarios (to be developed by Brown and Caldwell). The model provides decision-related inputs on the impacts of these scenarios on total sediment load to Clarks Creek from both upland and instream sources and anticipated rates of sediment deposition within Clarks Creek.

Develop a Decision Rule for Information Synthesis

The purpose of a decision rule is to integrate the outputs from the study into a single statement that describes the logical basis for choosing among alternative actions. Output from the previous steps will be used to guide decision makers in efforts to choose from alternative actions. The model is applied in the context of a larger stakeholder process and management scenario development being conducted by Brown and Caldwell for PTI. The overall decision rule relative to the watershed model is:

> To support uses in Clarks Creek it is necessary to control a variety of factors that contribute – directly or indirectly – to elevated sedimentation in the creek. A watershed model that is capable of evaluating flow, upland sediment sources, and instream sediment processes will be used to evaluate the contributions of different sources to current sedimentation conditions and to determine load reductions necessary to achieve standards. The evaluation of the sensitivity and importance of different stressor sources will be used to identify, evaluate, and test potential implementation strategies to reduce sedimentation in Clarks Creek. The modeling will be used to provide evaluations of the potential benefits of candidate management strategies that will be developed by Brown and Caldwell in consultation with PTI and other stakeholders.

Specify Tolerance Limits on Decision Errors

To help guide the interpretation of the technical information provided by the water quality model, general performance targets for the modeling are described in Section 5. The performance targets are based on generally accepted values from the literature and experience with previous projects. Specific numeric acceptance criteria cutoffs are not specified for the model.

1.4 MODEL SELECTION

Addressing the principal study questions requires a modeling framework that can provide a dynamic simulation of flow, upland sediment loading, and instream sediment transport processes. The Hydrologic Simulation Program – FORTRAN (HSPF) model (Bicknell et al., 2005) was selected for this purpose for several reasons:

1. HSPF provides dynamic simulation of water and sediment, including both upland and instream sediment processes at a user-specified level of detail and complexity, and is thus suitable for addressing the principle study questions.
2. HSPF models have previously been developed to address storm flows in Clarks Creek (Mastin, 1995, CH2MHill, 2003, Pierce Co., 2009). While these models are not fully calibrated for hydrology and have not yet been developed for water quality simulation, they provide a basis for additional development of the current HSPF model.
3. HSPF is supported by EPA with open source code and has a long history of well-documented applications for addressing hydrology and sediment management applications. It also provides a platform for full simulation of nutrients, bacteria, and other endpoints of potential interest.

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2 Meteorology

HSPF requires input time series of precipitation and potential evapotranspiration (PET) at a minimum. For the simulation of water and sediment only other meteorological series such as solar radiation and humidity are not required. Air temperature is needed for hydrologic simulations only if snowmelt is simulated. As snowfall is rare in Clarks Creek watershed temperature was not needed.

Meteorological time series for Clarks Creek have been assembled over time for a variety of projects. A long period of record is desirable for evaluation of a wide range of potential conditions, and data series assembled for October 1948 through March 2010 were provided by Brown and Caldwell in an HSPF water data management (WDM) file.

As described by Doten (2011) these data came from a variety of sources. Data through September 1999 were previously assembled for the City of Puyallup State Highway Basin Plan simulation modeling conducted by Brown and Caldwell and originally assembled by NHC for the Clear and Canyon Creeks Flood Insurance Mapping Study in 2003. Brown and Caldwell extended these data through March of 2010 primarily through use of data collected at the AgNet weather station at Washington State University, Puyallup Campus. This station, located in the center of the Clarks Creek watershed, commenced operation in 1995 but has many data gaps prior to September 1999. Tetra Tech subsequently extended the time series through December of 2010, using data obtained directly from the AgNet site.

Prior to the WSU AgNet site coming online, much of the precipitation data was obtained from McMillin Reservoir (Cooperate ID 455224), which reports both hourly and 15-minute precipitation. The precipitation data sources are shown in Table 2-1.

Table 2-1. Cited Precipitation Data Sources

Time Period	Source
Oct. 1949 – Sept. 1961	Seattle-Tacoma International Airport
Oct. 1961 – Nov. 1980	McMillin Reservoir
Dec. 1980 – Nov. 1985	Seattle-Tacoma International Airport
Dec. 1985 – Sept. 1989	McMillin Reservoir
Oct. 1989 – Sept. 1992	Canyon Road
Oct. 1992 – Sept. 1999	McMillin Reservoir
Oct. 1999 – Dec. 2010	WSU Puyallup AgNet

Doten (2011) notes certain problems with the earlier data assembled by NHC (2003). Most of the data are reported at intervals of hundredths of an inch, but the data from 3/31/1977 – 11/30/1980 and 11/30/1985 – 9/30/1989 are at a much coarser resolution of tenths of an inch. It is also believed that NHC replaced some of the McMillin Reservoir data for 1990-1994 due to poor quality. Further, only summary of the day results are available from McMillin for October 1996 to April 1998, and data from this period were likely disaggregated, although this is not explained in the modeling documentation.

Data commencing in October 1999 are believed to be much more accurate, and also are from within the watershed. Doten (2011) documents filling 11 brief periods of missing data using King County rain gauges.

For evapotranspiration, the WSU Puyallup station reports daily actual evapotranspiration (ETr) from alfalfa grown under controlled conditions. The NHC weather data set through 1999 purports to include PET derived from pan evaporation data from Puyallup multiplied by a factor of 0.75 (a standard factor to relate pan evaporation, which is influenced by heating of the exposed sides and bottom of the pan, to potential evaporation from crops) – although it appears that the full set of data may be derived from multiple sources and estimation methods. For the period beginning in October 1999, Brown and Caldwell created daily PET series from the Puyallup reported ETr, divided by 0.85 to get pan evaporation, and then multiplied by 0.75 to get PET. Doten (2011) demonstrates that the resulting PET estimates are generally consistent with the historical data, although it appears that monthly average PET for August – December is slightly lower for the estimates based on ETr from WSU.

It is important to note that meteorological data through Sept. 1999 have been accepted from earlier work without revision or detailed quality checks. The data from 1999 on clearly have a higher degree of internal consistency and reliability.

3 Hydrologic Response Unit Representation

This section describes the representation of upland land areas in the HSPF model for the Clarks Creek sediment reduction project.

HSPF is a lumped model. That is, the land surface is not simulated as an explicit grid. Rather, similar components of the land surface are simulated on a unit-area basis, and the unit-area results are then multiplied by the relevant area to estimate the outflow from a subbasin to a stream reach. These land surface components should be defined in a way that facilitates both parameter identification and the evaluation of management alternatives. In general, this is best accomplished by using a Hydrologic Response Unit (HRU) approach, in which upland model areas are defined on the basis of an overlay and unique combination of soil characteristics, slope, and land use/land cover.

The previous HSPF models that cover part or all of Clarks Creek use an HRU approach that was developed for the original USGS model of the Clover Creek and Clear-Clarks Creek basins (Mastin, 1996). This employed a fairly simple classification in which an HRU represented a soil group (till, outwash, or saturated area), a land cover group (forest or grass only for pervious areas), and a slope class (flat, medium, or steep). The steepness classification was applied only to the till areas, while the saturated areas are not subdivided by either land cover or slope.

Significant amounts of additional spatial data have become available since the USGS model was developed, allowing refinement of the USGS approach. In addition, the simplified representation of land cover used by Mastin for evaluating sediment sources to Clarks Creek did not consider land use (as opposed to cover), which can be an important factor in determining sediment load. For instance, agricultural land uses typically have higher sediment loading rates than lawns on similar soils and slopes. For these reasons, it is appropriate to develop a revised HRU approach. The following sections describe the key inputs (geology and soils, land use/land cover, slopes), followed by the final HRU definition (Section 3.4).

3.1 Soils and Geology

The soil series in the watershed largely reflect the surficial geology. Both are important to the model: the soils largely control infiltration rates and erodibility, while the underlying hydrogeology controls groundwater interactions. A dominant feature of the watershed is the presence of headwater springs on the Clarks Creek mainstem which occur where the overlying Vashon recessional till and outwash tails out onto lower lying alluvial soils.

Two recent USGS reports build a picture of the hydrogeology of the watershed that can be used to complement the soil surveys. Jones et al. (1999) provide an initial account. This has been superseded by Savoca et al. (2010). Savoca et al. use a rather different nomenclature, but maintain the basic distinction between the glacial uplands and lower outwash/alluvial plain. The hydrogeological conceptual framework of Savoca et al. is shown in Figure 3-1.

The surface hydrogeology of the higher elevation areas of the Clarks Creek watershed is referred to by Savoca et al. as the A1 aquifer (Jones' Qvr; the Vashon recessional outwash) and the lower permeability A2 unit (Jones' Qvt; the Vashon recessional till), both of which are underlain by the C or sea-level sand and gravel aquifer (Jones' Qc1), while the downstream, lower elevations of the stream are atop the AL alluvial aquifer (corresponds to Jones' Qc1 aquifer and Qf1 semi-confining unit).

The soil series boundaries conform to the major division of till versus alluvial hydrogeologic units. Soil data were obtained from the NRCS's SSURGO database via the USDA Data Gateway. As shown in Figure 3-2 and Figure 3-3, soils in the watershed are dominated by Alderwood gravelly sandy loam, Kitsap silt loam, Kapowsin gravelly loam, and Puyallup fine sandy loam. Most of these soils were

formed in consolidated glacial till (hardpan) and typically yield lower infiltration rates, although they may include an overlay of well-drained outwash sands and gravel.

NRCS (2001) has defined four Hydrologic Soil Groups (HSGs; Table 3-1). The hydrologic soil group classification provides a means for grouping soils by similar infiltration and runoff characteristics for model parameterization. Typically, clay soils that are poorly drained have lower infiltration rates, while well-drained sandy soils have the greatest infiltration rates. The dominant HSG in the watershed is group C, soils with slow infiltration rates, which covers half of the watershed area.

Table 3-1 NRCS Hydrologic Soil Groups in Clarks Creek Watershed

Hydrologic Soil Group	Description	Percentage of Clarks Creek Watershed
A	Soils with high infiltrations rates. Usually deep, well-drained sands or gravels. Little runoff.	7%
B	Soils with moderate infiltration rates. Usually moderately deep, moderately well-drained soils.	22%
C	Soils with slow infiltration rates. Soils with finer textures and slow water movement.	50%
D	Soils with very slow infiltration rates. Soils with high clay content and poor drainage. High amounts of runoff.	21%

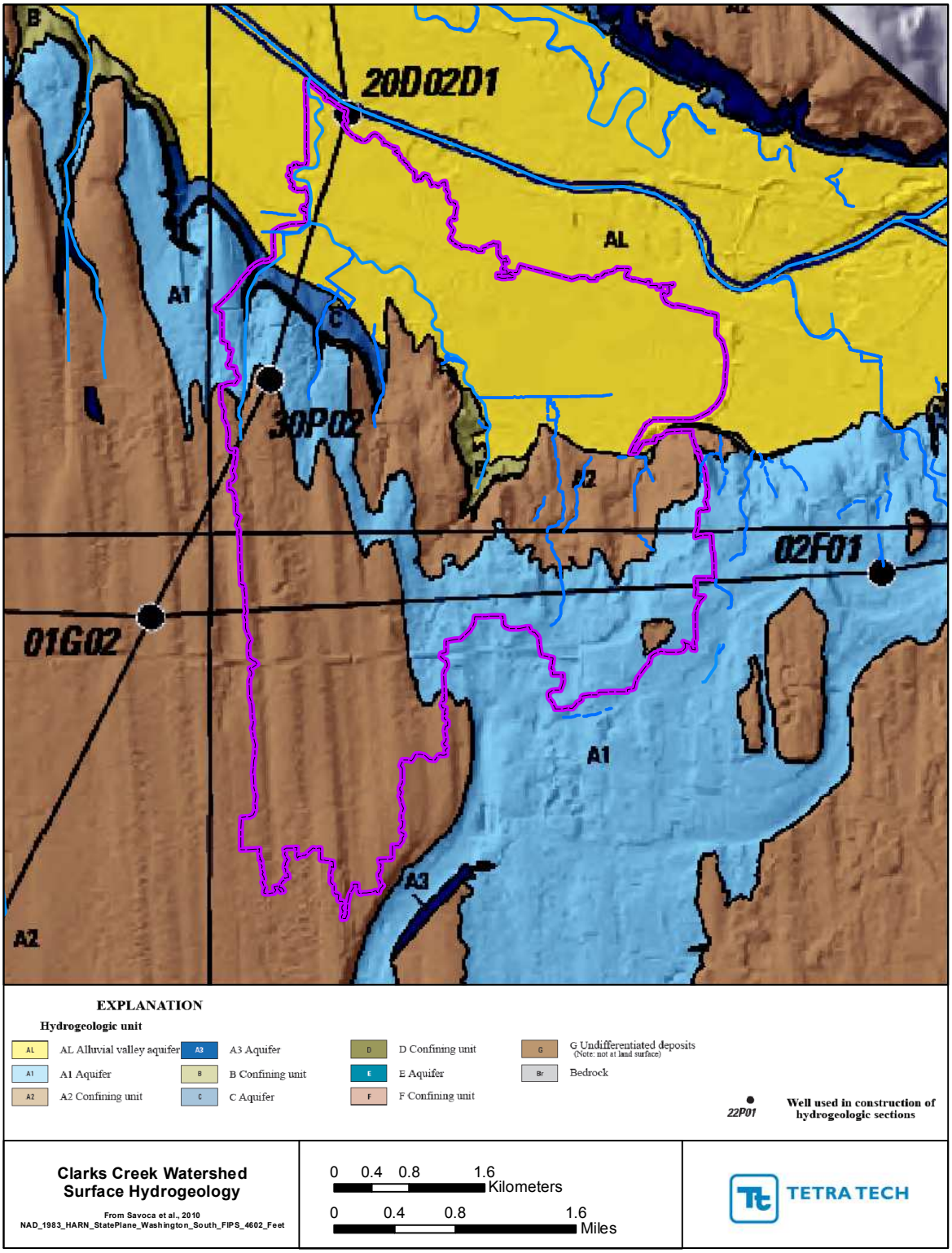

Figure 3-1. Surface Hydrogeology of the Clarks Creek Watershed (Savoca et al., 2010)

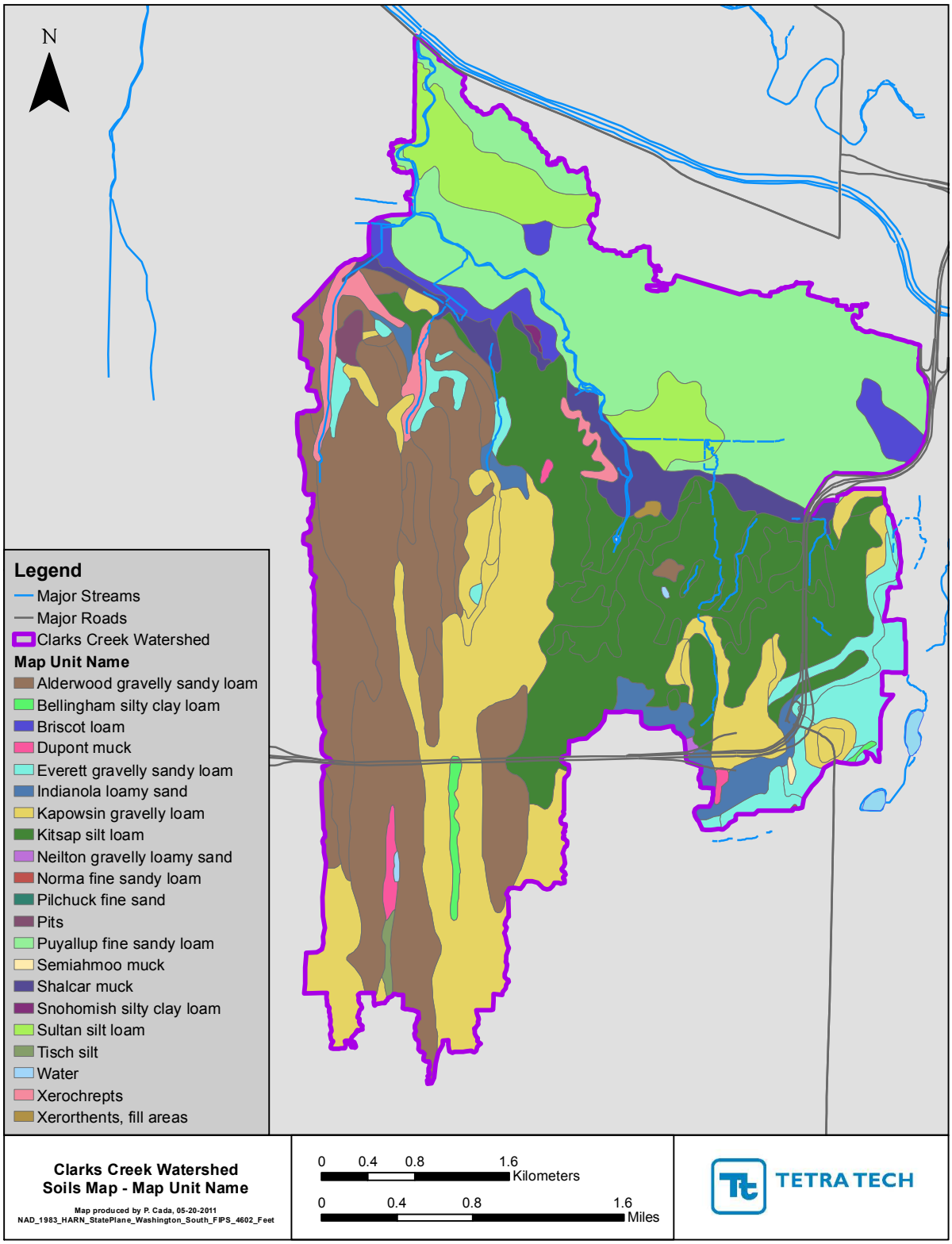

Figure 3-2 Soil Series in the Clarks Creek Watershed

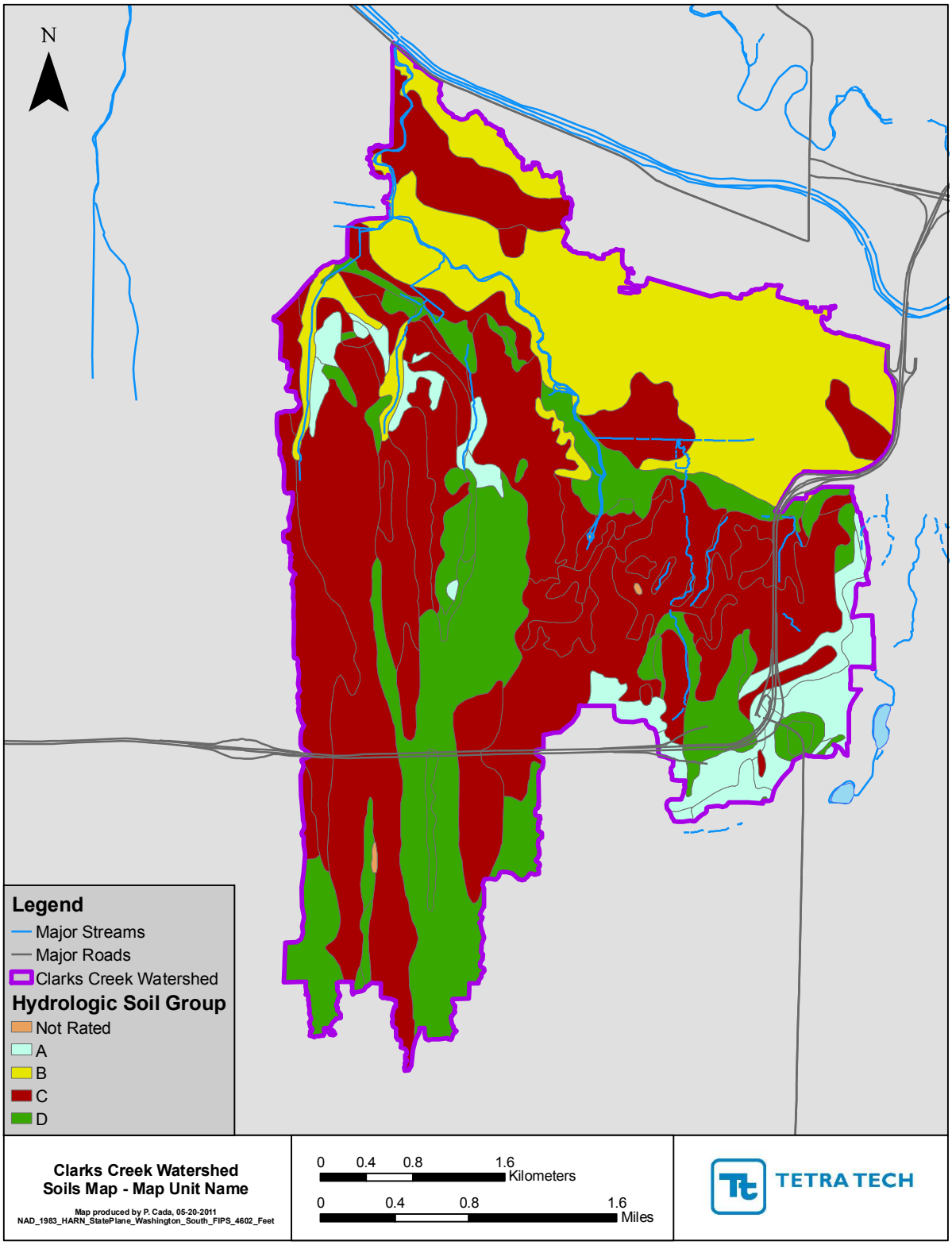

Figure 3-3 Hydrologic Soil Groups in the Clarks Creek Watershed

The Kapowsin-type soils have the lowest infiltration rates in the watershed (HSG D), while the Alderwood and Kitsap soils are more moderately drained (HSG C; see Table 3-2). The Puyallup loam, which was formed in alluvium and located along the Puyallup River Basin valley portion of the watershed, is classified as well-drained (HSG B). Several wetland areas exist in the southern headwaters of the watershed due to perched water tables and poor soil infiltration rates common in that area.

Table 3-2. Soil Series in the Clarks Creek Watershed

HSG	Soil Series	Area (acres)	Percentage
Water		4.6	0.07%
A	Everett gravelly sandy loam	287.4	4.32%
	Indianola loamy sand	135.4	2.03%
	Neilton gravelly loamy sand	3.1	0.05%
	Pits	19.5	0.29%
B	Puyallup fine sandy loam	1,346.60	20.22%
	Xerochrepts	107.7	1.62%
C	Alderwood gravelly sandy loam	1,552.30	23.31%
	Briscot loam	132.7	1.99%
	Kitsap silt loam	1,332.50	20.01%
	Pilchuck fine sand	0.3	0.00%
	Semiahmoo muck	2.7	0.04%
	Sultan silt loam	317.6	4.77%
D	Bellingham silty clay loam	25.8	0.39%
	Dupont muck	26.9	0.40%
	Kapowsin gravelly loam	1,141.10	17.14%
	Norma fine sandy loam	0.5	0.01%
	Shalcar muck	202	3.03%
	Snohomish silty clay loam	3.7	0.06%
	Tisch silt	11	0.17%
	Xerorthents, fill areas	5.4	0.08%
Grand Total		**6,658.7**	

The Mastin (1996) model separately identified saturated areas based on soil characteristics – although the category was not restricted to specifically hydric soils. These delineations do not seem to be strongly correlated with the extent of wetland areas and may be of limited use due to extensive alteration of the watershed by development and drainage. Therefore, it is more useful to identify as a separate class extant wetlands based on the Pierce County wetlands coverage.

In sum, the soils/geology component of the revised HRU classification of pervious area is as follows:

1. Till, high permeability (HSG A with some B)
2. Till, moderate permeability (HSG C)
3. Till, low permeability (HSG D)
4. Alluvial outwash soils (HSG A,B – predominantly B)
5. Alluvial outwash soils (HSG C,D – predominantly C)
0. Wetlands

3.2 LAND USE / LAND COVER

The Clarks Creek watershed (as defined by the surface drainage) occupies an area of 6,631 acres, much of which is developed land in and adjacent to the City of Puyallup, WA. Hydrologic and pollutant generating characteristics of pervious lands are determined by both the land use and the vegetative land cover. While the two categories are highly correlated (e.g., a land cover of pumpkins is likely to be an agricultural land use) they convey different information (e.g., grass on the edge of a highway is more likely to be subject to disturbance by vehicles and less likely to be fertilized than grass on a residential lawn).

In general, satellite coverages yield land cover, while parcel and tax data yield additional information on land use. Many new sources are available for both land cover and land use in the Clarks Creek watershed. Satellite-based land cover is available from the National Land Cover Dataset (NLCD; available for 1991, 2001, and 2006); the Crop Data Layer (CDL) from U.S. Department of Agriculture - National Agricultural Statistics Service, Research and Development Division (available from 2006-2007, and 2009-2010 for Washington); and the LANDFIRE coverage from USFS (2001 and 2008) (Figure 3-4 through Figure 3-6). Parcel-based land use is available in a spatial coverage from Pierce County (Figure 3-7).

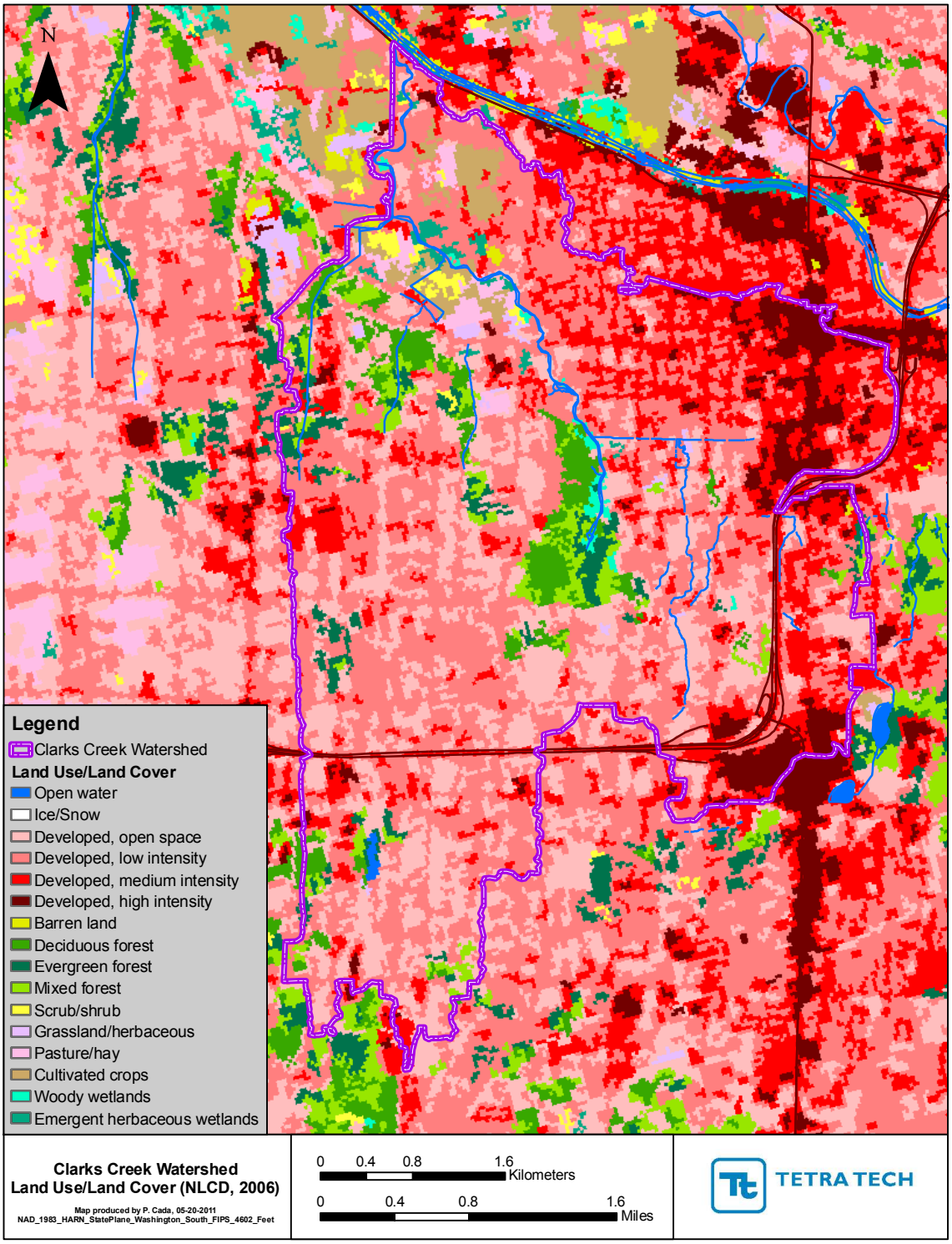

Figure 3-4. NLCD Land Use/Land Cover for the Clarks Creek Watershed

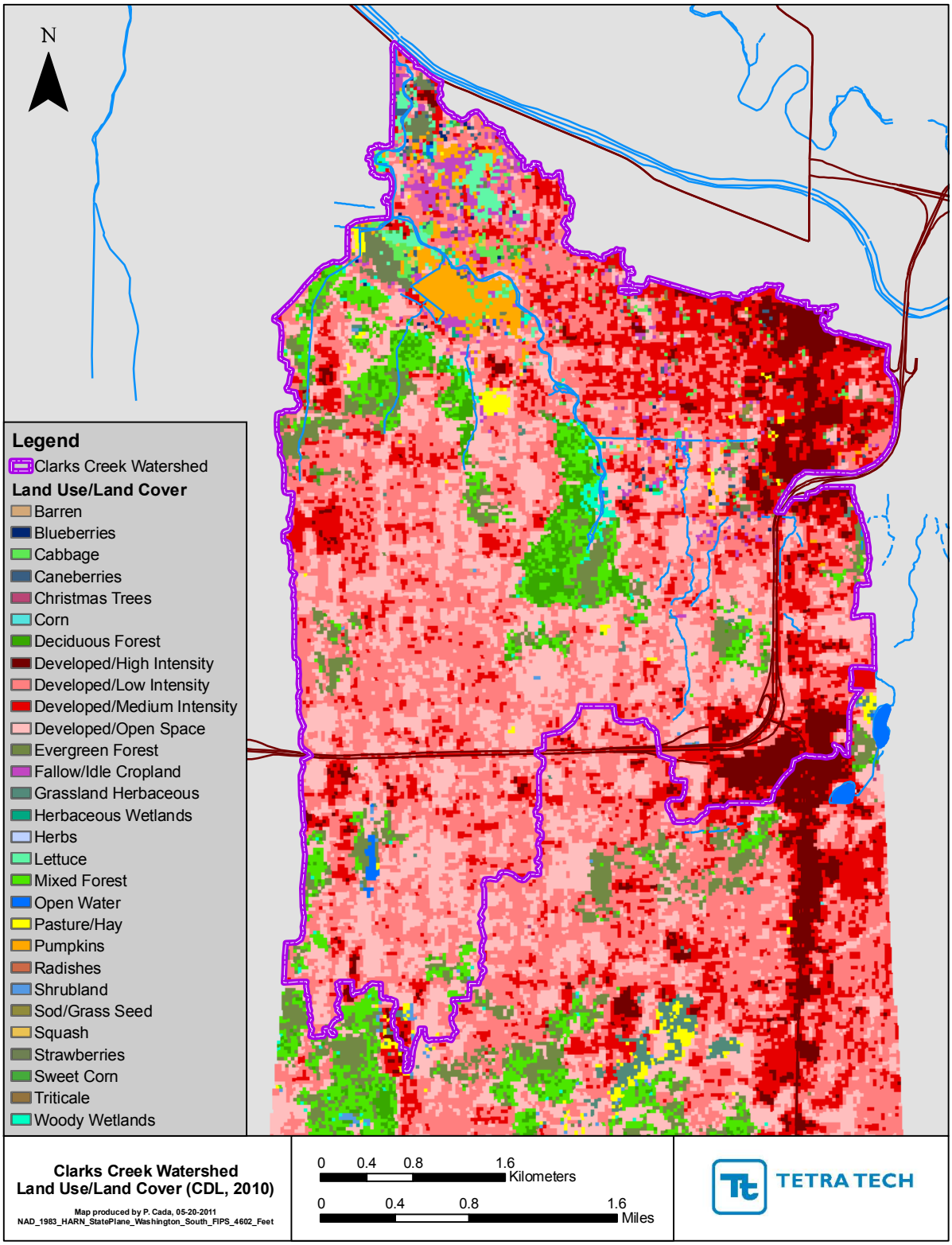

Figure 3-5. Crop Data Layer for the Clarks Creek Watershed

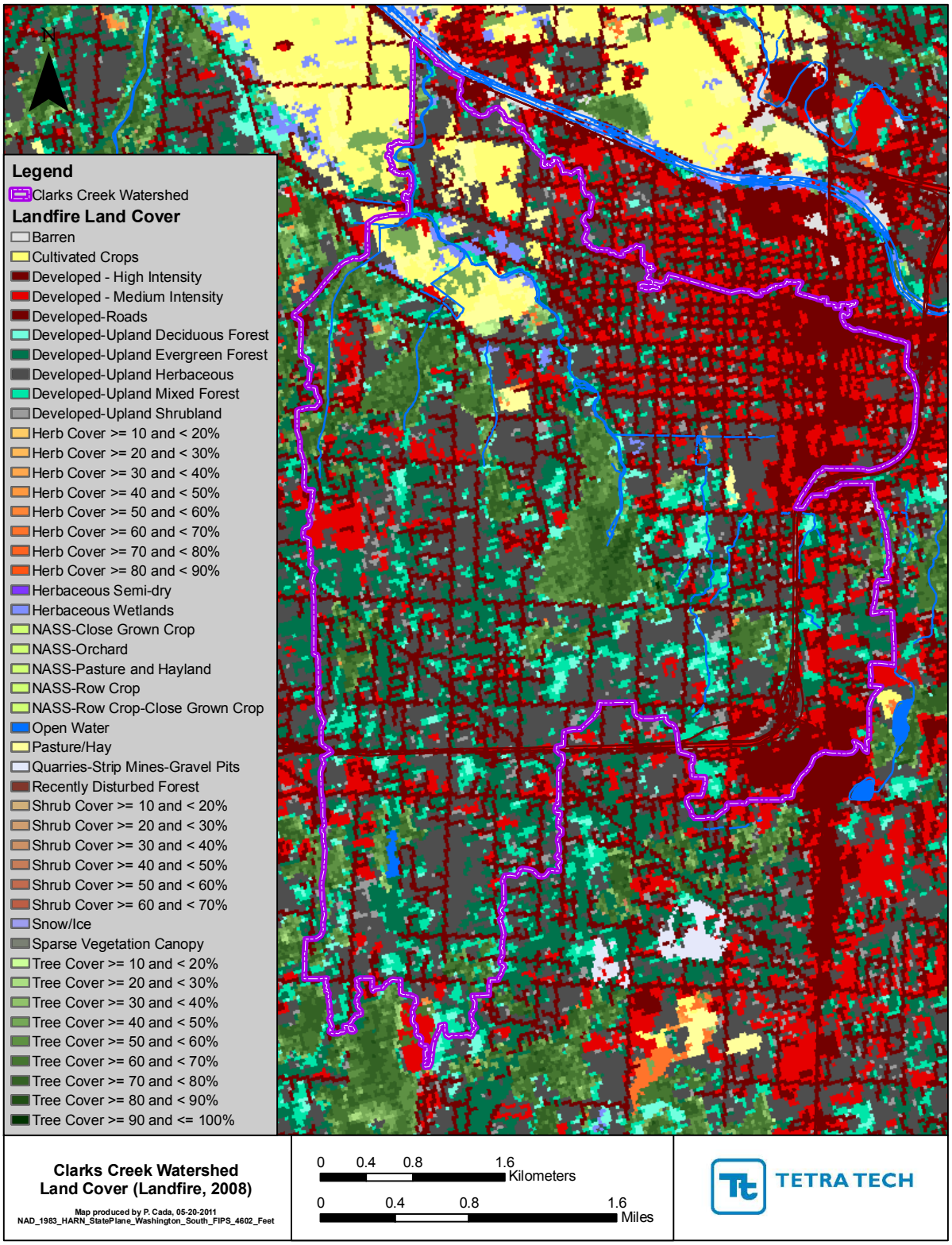

Figure 3-6. LANDFIRE Land Cover for the Clarks Creek Watershed

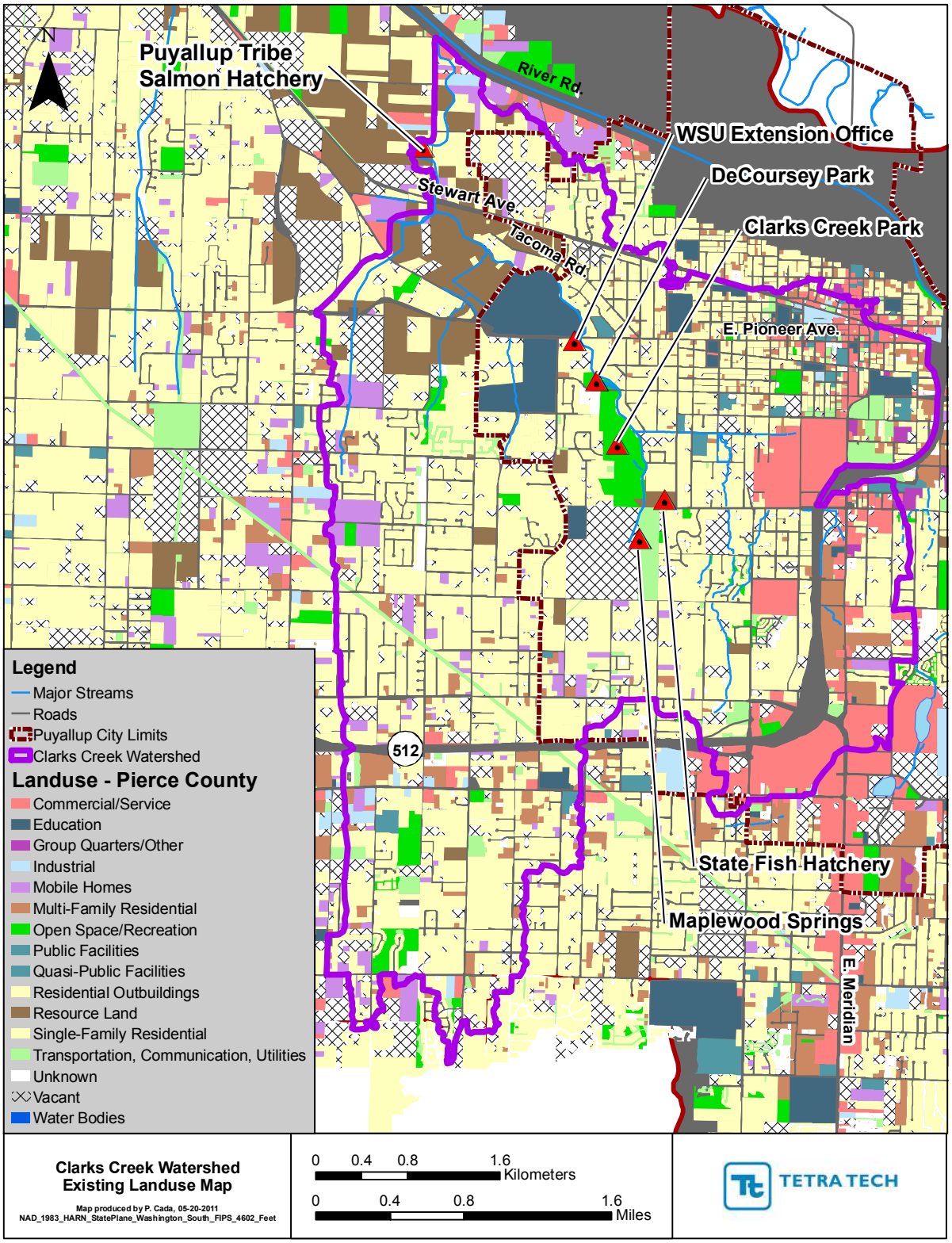

Figure 3-7 Existing Land Use from Pierce County Tax Parcel Data (3/08)

Each of these coverages was created for different purposes, and each has its advantages and disadvantages. For instance, the CDL is available yearly and gives high resolution on crop type, but does not separately distinguish roads. LANDFIRE identifies roads and gives details on tree canopy coverage (important to erosion estimation; see Figure 3-8), but does not identify specific agricultural or developed land uses, which are revealed more clearly by the Pierce County parcel-based coverage (Figure 3-7).

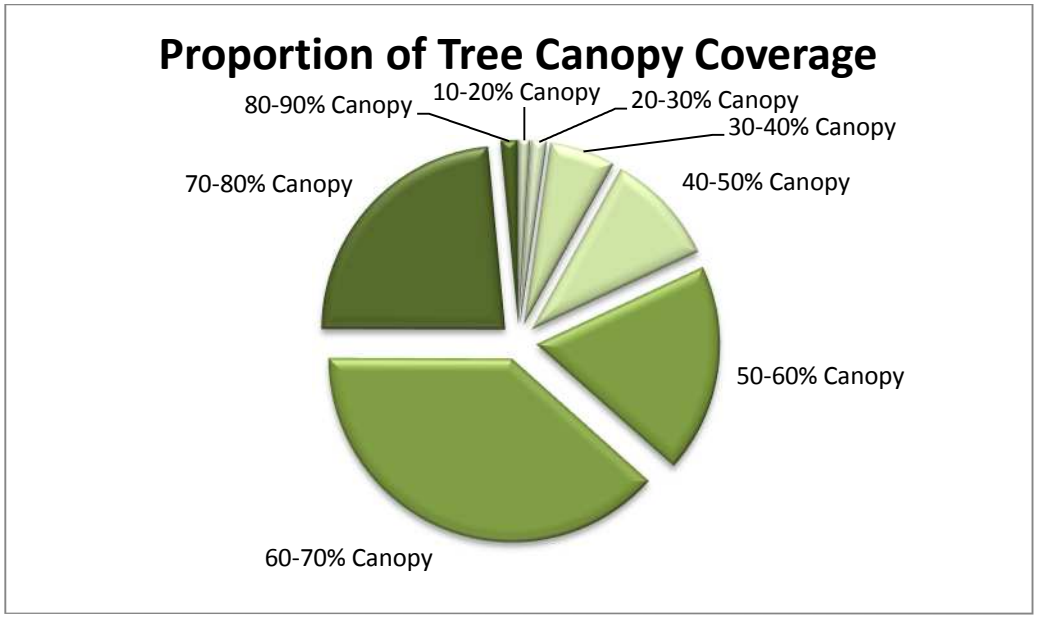

Figure 3-8. Distribution of LANDFIRE Canopy Coverage in Forest Areas of Clarks Creek

Combining the various sources of land use and land cover data provides the most useful basis for HRU determination. These data sources have been selected to account for potentially significant differences in hydrologic behavior and/or sediment load generation. The land categories developed from combining the land use and land cover data are as follows (with the numbering reflecting the scheme for pervious surfaces):

1. Forest (Tree canopy coverage > 70 percent and not within developed parcels < 1 ac)
2. Forest (Tree canopy coverage 40 – 70 percent, and not within developed parcels < 1 ac)
3. Agriculture – row crop
4. Pasture, hay, close grown crops
5. High density development (commercial, industrial, multi-family)
6. Medium density residential (1/8 - 1 ac/DU)
7. Low density single family residential (> 1 ac/DU)
8. Roads (right of way not contained within tax parcels)
9. Park and institutional land (exclusive of forest cover in categories 1 and 2, but including any miscellaneous land that does not fit into categories 1 through 8).

As noted above, wetlands are separately defined as a unique HRU category as well (with LULC code 0).

Extent of canopy coverage is included in the HRU definitions because canopy protection from rainfall impact is an important factor in determining soil erosion, as well as affecting hydrology. The 70 percent breakpoint approximates the cover factor breakpoint of 75 percent for high cover in woodlands used in the Universal Soil Loss Equation (USLE). Below 40 percent canopy cover, the USLE cover factor for forest becomes similar to that for pasture and idle land.

Forest cover is separated out of larger residential lots (> 1 ac/DU) to account for the protection of forest cover against erosion. Separating forest is not feasible for smaller lots, as the 30-m resolution of the LANDFIRE coverage cannot effectively distinguish land cover fractions within a lot size of 1 acre or less. Pervious land use within residential land use categories having lot sizes of 1 acre or less and within the non-forest portion of larger residential lots are represented as having a typical land cover of grass with shrubs and scattered trees.

The methods developed by Tetra Tech for combining the LANDFIRE, NLCD, CDL, and Pierce Co. parcel datasets into the 9 land use categories in the model are illustrated in Figure 9. LANDFIRE serves as the base coverage for areas that are classified as forest, agriculture, or pasture/hay, including fragments within residential lots greater than 1 acre in size. Residential, commercial, industrial, institutional, and park lands are classified primarily by the county land use data, after subtracting areas identified as forest, agricultural, or pasture/hay in larger parcels.

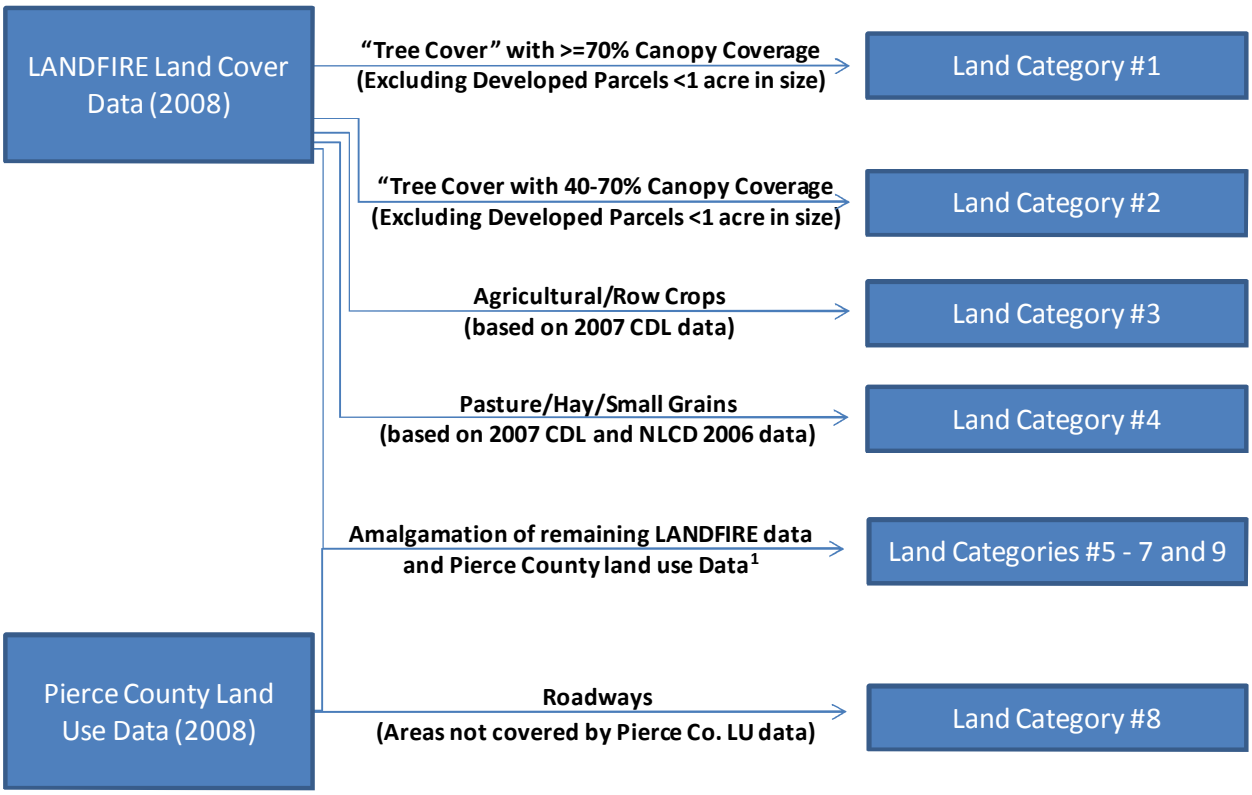

Figure 9. Methods for Combining LANDFIRE, NLCD and CDL Data Sets for Land Use/Land Cover Definition of HRUs

The remaining step of land use/land cover development for the model is the separation of impervious and pervious surfaces. HSPF models pervious areas (PERLNDs) and impervious areas (IMPLNDs) separately because of their different hydrologic behavior. Properly, the area assigned to IMPLNDs should be the directly connected (or *effective*) impervious area; impervious areas that drain onto pervious lands are typically incorporated within the PERLND representation.

Impervious surface planimetrics are not available for Pierce County (and would not show the directly connected impervious area in any case). Therefore, impervious area contained within land categories 5 through 9 are assigned on a percentage basis. The proportioning of roads (Category 8) into pervious and impervious surfaces was also adjusted by inspection of recent aerial imagery throughout the watershed. Details of the determination of directly connected impervious area are addressed in a separate

memorandum included as Appendix A. Overall, about 25 percent of the watershed is occupied by directly connected impervious area.

IMPLNDs are numbered separately from PERLNDs in HSPF. Nonetheless, the same numbering scheme is retained for IMPLNDs as is used for PERLNDs for ease in reassembling total flow and loads from specific land uses. Thus, PERLND 611 and IMPLND 611 refer to the pervious and impervious portions, respectively, of medium density development on A or B till soils on low slopes.

3.3 SLOPE

Subdivision of HRUs by slope is useful for sediment simulation as slope is a factor that determines the velocity of flow, its kinetic energy, and the associated transport of detached sediment and/or initiation of gully formation. Mastin's (1996) approach of identifying three slope classes that correspond to the soil-slope associations is adequate, but can be refined through a DEM-based analysis of slope. The higher slope classes are found primarily on the till portion of the watershed. The three classes are:

1. Low slope (0-6%)
2. Medium slope (6-12%)
3. High slope (>12%)

3.4 HRU NUMBERING

The soil, land/use cover, and slope components of the pervious land HRUs each have less than nine classes. For Clarks Creek a single weather station is used and the PERLND HRUs can be numbered in a straightforward fashion as *abc*, a three-digit number, where

a is the land use category,

b is the soil category, and

c is the slope category.

The land use category is given first so that all members of a given land use are grouped together, which is advantageous for the development of management scenarios. HRUs can be sorted on the second digit (*b*) for specification of hydrologic parameters that are primarily dependent on soil characteristics.

There are a total of 9 land use x 4 soil groups x 3 slope potential HRU categories (plus the unique wetland category). However, wetlands are not distinguished by soil or slope and only low slopes coincide with the alluvial soils, leaving a total of 122 PERLND HRUs that are actually simulated in the model.

As noted above, the numbering scheme for IMPLND HRUs is matched to that of the corresponding PERLND HRU, allowing ready reconstruction of total pervious and impervious surface flows and loads from a single parent land use. This applies to categories 511 and higher.

4 Routing Network and Segmentation

The HSPF model consists of upland subbasins and waterbody reaches. In most cases there is a one-to-one match between reach segments and subbasins. Model segmentation first should accurately reflect the surface drainage network. Additional considerations for model segmentation include the following:

- Reach segment breaks should coincide with gage and monitoring locations
- Significant inflows should coincide with breaks in the reach segments
- Different upland subbasins are used to define areas associated with different weather records
- Upland subbasin should be sufficiently small to allow for appropriate spatial targeting of management opportunities
- Segment and subbasin boundaries should reflect major changes in topography and soils to the extent practicable

For many HSPF applications, segments are designed to provide a consistent relationship to individual weather stations. For Clarks Creek a single weather station is used, and the major decision is thus the appropriate subbasin size for building management scenarios. There is a tradeoff between model resolution, model run times, and level of effort in model setup. An appropriate scale for the development, calibration, and application of a computationally efficient sediment model is one that isolates the major urban storm drainages, but does not require more than 100 or so total subbasins to simulate the entire basin. For Clarks Creek this results in subbasins on the scale of approximately 100 acres.

4.1 Surface Drainage Segmentation

The available data for completing the segmentation are a fine-scale digital elevation model (DEM) obtained from 6-foot resolution LiDAR, hydrographic coverage from the National Hydrography Dataset (NHD), detailed stormwater system mapping from both the City of Puyallup and Pierce County, and jurisdictional boundaries.

Subbasins were delineated consistent with the DEM, NHD, and stormwater system information. Subbasins are generally arranged so that tributaries and major storm sewer inputs enter at the upstream end, and subbasin boundaries are set to correspond to critical water quality and flow monitoring points (Figure 4-1). The final subbasin segmentation is shown in Figure 4-2.

Two areas of special interest are highlighted on Figure 4-2. The area in light red (subbasins 201 – 203) represents storm drainage along Pioneer Way that is being considered for diversion to the Puyallup River at 15th Street. The area in blue (subbasin 301) represents a subwatershed that is controlled by a flow splitter owned by WSDOT. The flow splitter directs most of the flow to the Puyallup River, but does allow some overflow into the Clarks Creek watershed (see Section 4.2.4).

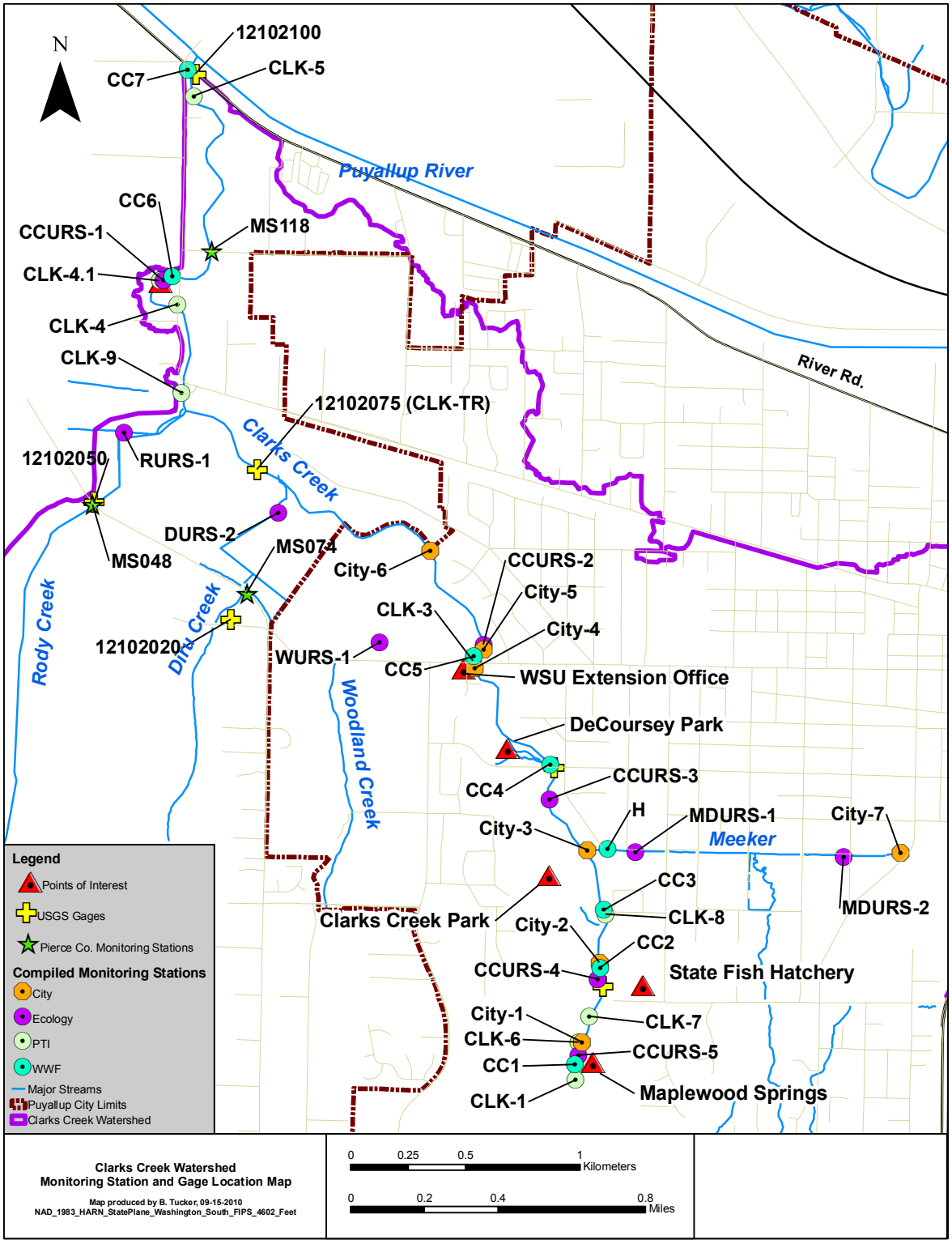

Figure 4-1. Monitoring and Gage Locations in Clarks Creek

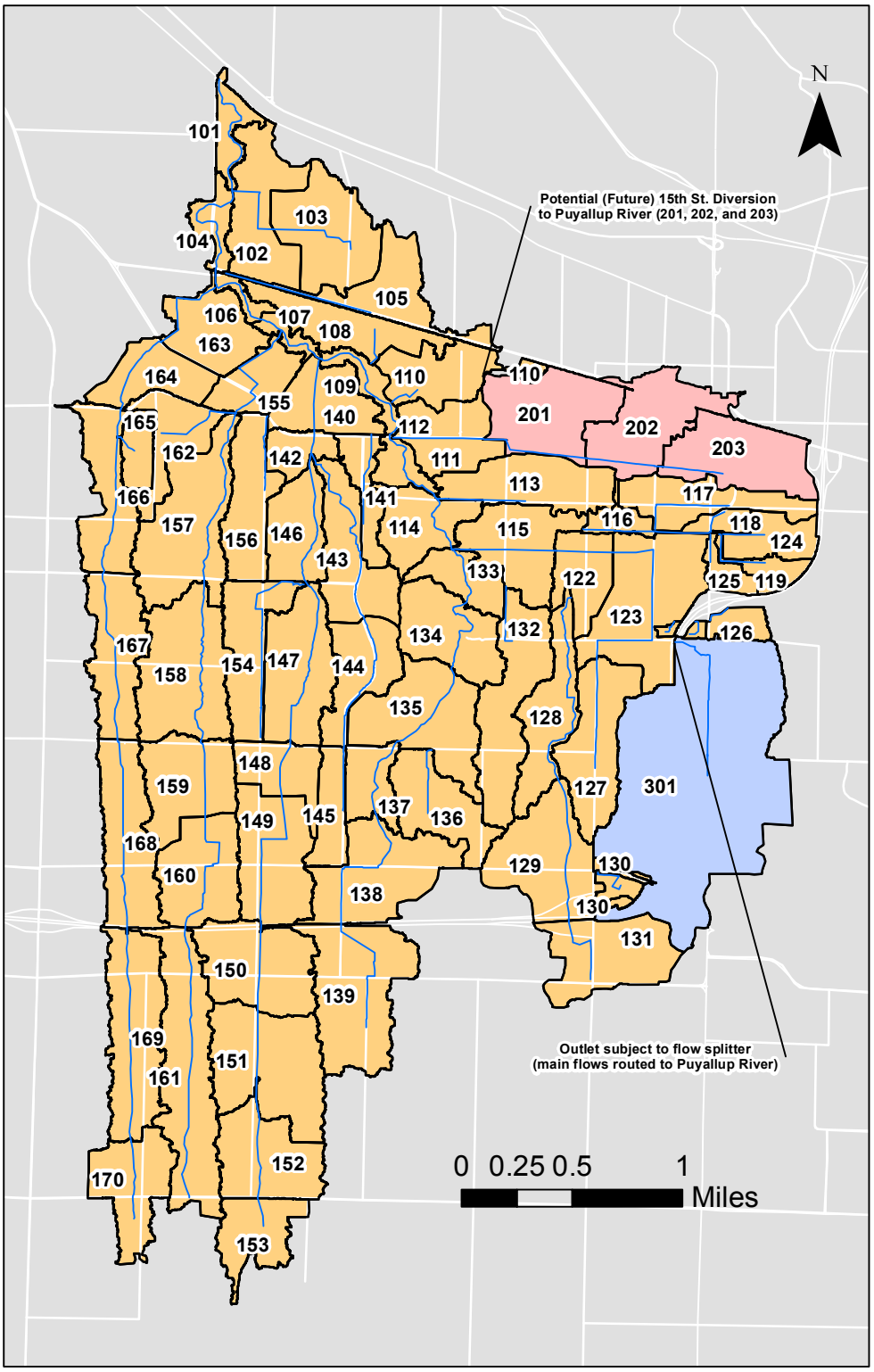

Figure 4-2. Subbasin Delineation for Clarks Creek HSPF Model

4.2 REACH HYDRAULICS

HSPF models hydrology, but does not directly simulate hydraulics. That is, the model is based on the principal of conservation of mass, but not the conservation of momentum. Hydraulic details, such as the speed of propagation of flood waves, have little impact on the water balance at time steps of a day or longer; however, hydraulics have important impacts on the energy exerted by flow, which is crucial to the examination of sediment scour and deposition. Therefore, it is important to incorporate a strong hydraulic representation in HSPF models that are designed for simulation of sediment transport.

In HSPF, the hydraulic behavior of stream reaches is specified externally through use of Functional Tables (FTables) that define stage-storage-discharge relationships. This is essentially a lookup table that enables the program to determine via interpolation, given an instantaneous value of storage in the reach, what is the corresponding depth, surface area, wetted perimeter, outflow, and flow velocity. Where available, this information can be developed directly from a hydraulic model, such as HEC-RAS or SWMM. Both models are available for portions of the Clarks Creek drainage network. Simpler methods are used for other areas where hydraulic models have not been developed.

4.2.1 HEC-RAS Modeling

HEC-RAS (Brunner, 2010) is a one-dimensional hydraulic model of water flowing through open channels. Capable of modeling complex stream networks, hydraulic structures, dendritic systems or a single river reach, HEC-RAS is typically used for channel flow analysis and floodplain determination. HEC-RAS applications provide an excellent basis for creating the FTables at selected points within a stream network. The accuracy of the generated FTable is dependent upon the spacing and number of HEC-RAS cross sections throughout a stream network, as well as the accuracy of the measured flows used to correlate river stage to discharge. Starting with the design flow profiles provided with a HEC-RAS model (e.g., flows from the 10-, 50-, 100-, 500-year return periods), the HSPF modeler can interpolate additional flow profiles to complete a model FTable.

For Clarks Creek, a HEC-RAS model of the mainstem and a part of Meeker Creek was developed as part of the Flood Insurance Study (NHC, 2005). Additional cross sections were collected and the model expanded by Brown and Caldwell as part of this sediment study (Figure 4-3). The resulting model extends from mile zero (the confluence with the Puyallup River) to mile 4.502 (in subbasin 135 in Clarks Creek Park). It also covers the lower 0.9 miles of Meeker Creek.

Tetra Tech added additional flow profiles to the HEC-RAS model. For each flow profile, HEC-RAS provides the following outputs that can be used for FTable generation:

- Q Total – total flow in cross section (cfs)
- Length Wt – weighted cross section reach length based on flow distribution (ft)
- Max Chl Dpth – maximum main channel depth (ft)
- SA Total – cumulative surface area for entire cross section from the bottom of the reach (acres)
- Volume – cumulative volume of water in the direction of computation (acre-ft)

Each point (or flow profile) representing the discharge-storage-surface area relationship by computed FTable is thus a weighted average of channel stage and discharge that is based on the weighted cross section reach length within the entire modeled reach. Also included for each flow profile in the FTable are the cumulative surface area and water volume between the reaches' upstream and downstream cross section. The HEC-RAS model provides FTables for HSPF reaches 101, 104, 106, 107, 109, 112, 114, 115, 122, 123, 133, 134, and 135.

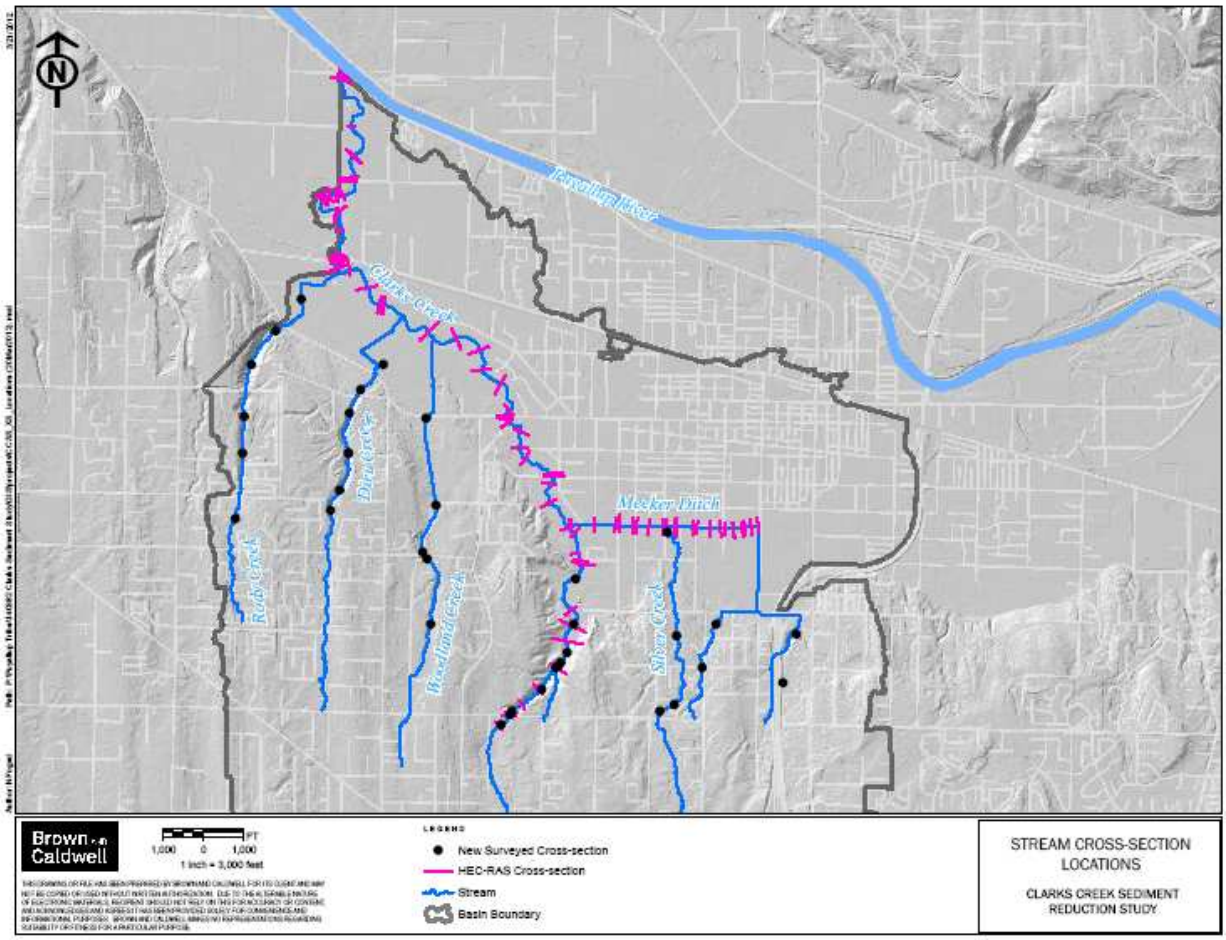

Figure 4-3. HEC-RAS Model and Additional Stream Cross-Section Locations for Clarks Creek

Figure courtesy of Brown and Caldwell.

4.2.2 SWMM Modeling

The Storm Water Management Model (SWMM; Rossman, 2010) is a hydraulic model that can simulate both open channel and piped flow, including pressurized flow. Brown and Caldwell developed a SWMM application for the Pioneer Avenue drainages in downtown Puyallup (Figure 4-4). Stormwater in this area is primarily conveyed in closed pipes, so the existence of a SWMM model is particularly useful. Output from SWMM can be used in a manner similar to output from HEC-RAS to develop FTables. This was done using custom VBA scripts to retrieve output from the SWMM binary output file. This yields FTables for subbasins 111, 201, 202, and 203 in the HSPF model.

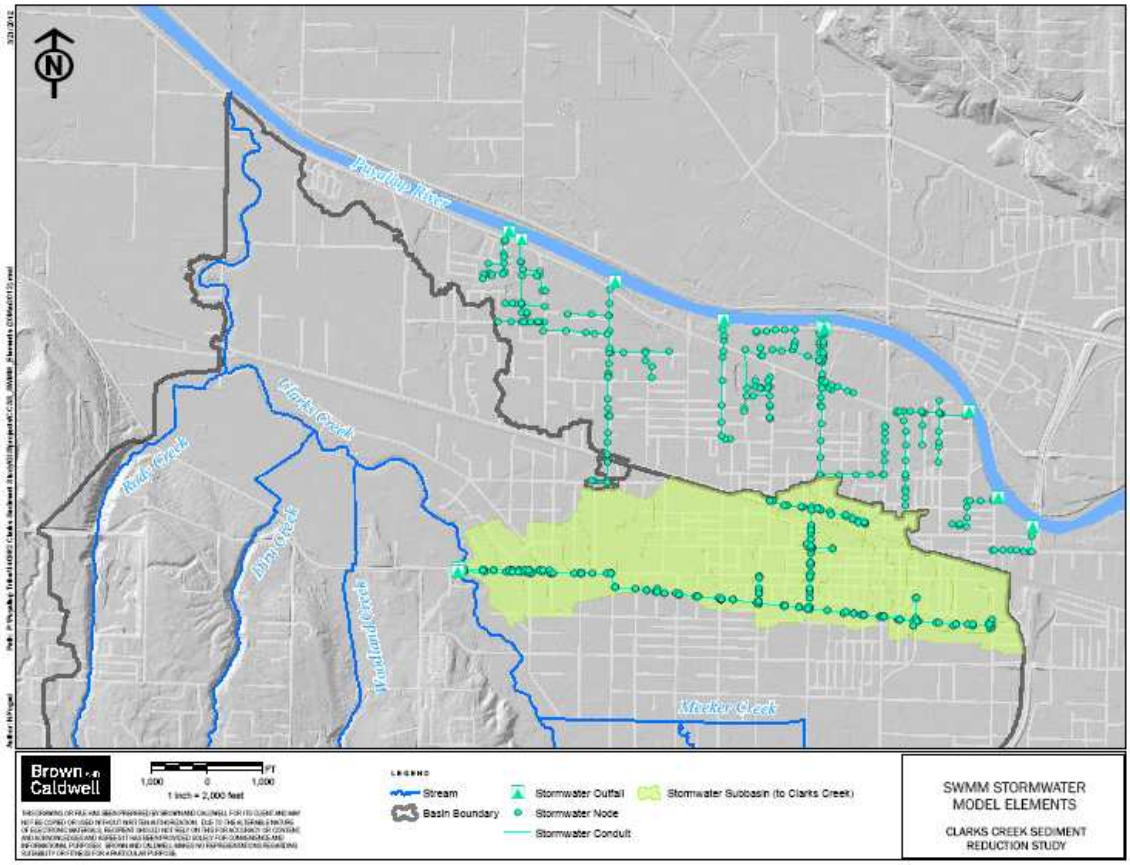

Figure 4-4. SWMM Model Incorporating Pioneer Avenue Drainage to Clarks Creek

Figure courtesy of Brown and Caldwell

4.2.3 Other Cross Sections

Brown and Caldwell also collected cross-section data for a number of locations outside the HEC-RAS model (shown by black dots in Figure 4-3). Flow at these cross sections was analyzed using a normal depth approximation in the WinXSPro™ software by Brown and Caldwell. These results were aggregated in a manner similar to the output from the HEC-RAS models to produce FTables for reaches 127, 128, 142, 146, 147, 155, 157, 163, 164, and 166.

In the remaining (mostly smaller, headwater) reaches in the model for which hydraulic models are not available, FTables were generated by the same method used in the BASINS system for HSPF model development (Moore, 2007). This approach is based on trapezoidal channel assumptions and simplified regression relationships for channel form and will have reduced accuracy relative to the FTables developed from site-specific hydraulic models. Of particular note, no hydraulic models were available for the piped stormwater conveyance systems at 7th Avenue.

4.2.4 WSDOT Flow Splitter

Reach 301 is a special case due to the presence of a flow splitter at Highway 512. As build plans from WSDOT show a concrete weir was constructed at this location in 1993 to divert flows into a 30” diameter PCCP stormwater pipe that proceeds along Highway 512 and drains to the Puyallup River. Excess flows

that exceed the weir crest overflow into a 6' x 4' box culvert that proceeds under Highway 512 toward Clarks Creek. Flow starts topping the weir at about 26.2 cfs total outflow, but the pipe flow increases with increased head to a maximum of about 48 cfs. The weir was designed to also have a low flow orifice leading to the culvert, but that is reported to be plugged with sediment based on personal inspection by the Brown and Caldwell team. An FTable was therefore created for this reach that conforms to the as-built plans and has two exits, with only the weir overflow routed into the next segment of the Clarks Creek model.

4.3 GROUNDWATER INTERACTIONS

As noted above, an important feature of the watershed is the presence of headwater springs on the Clarks Creek mainstem. A detailed north-south conceptual representation of the hydrogeology just west of the Clarks Creek mainstem (according to Savoca et al., 2010) is shown in Figure 4-5, while the plan view extent of the various aquifers is summarized in Figure 4-6. Under Savoca's conceptualization, the springs at the headwaters of Clarks Creek (which also occur to a lesser extent on its major tributaries) are due to a combination of discharges from the A1, A3, and C aquifers, the first two of which tail out at the point where Clarks Creek and its tributaries enter the lower alluvial valley, and all of which have hydraulic heads higher than ground surface in the alluvial valley (Figure 4-6).

The preliminary evaluation of flow directions in each aquifer provided by Savoca et al. (Figure 4-6) suggests that flow to the Clarks Creek springs may derive from a considerable distance to the south and southeast. This finding appears to be confirmed by recent groundwater modeling of the aquifers (Johnson et al., 2011). However, the exact contributing area to the springs (and the groundwater divide with the Clover Creek drainage) does not appear to be firmly established – although it is likely that that the Clarks Creek groundwatershed includes some of the internally drained pothole regions to the south and east of the surface drainage network.

Because the surface area contributing flow to the Clarks Creek springs is not fully known, an empirical approach was developed to simulate the till groundwater balance on a unit area basis with the applicable area determined during calibration. The development of this representation is described in Section 6.2.

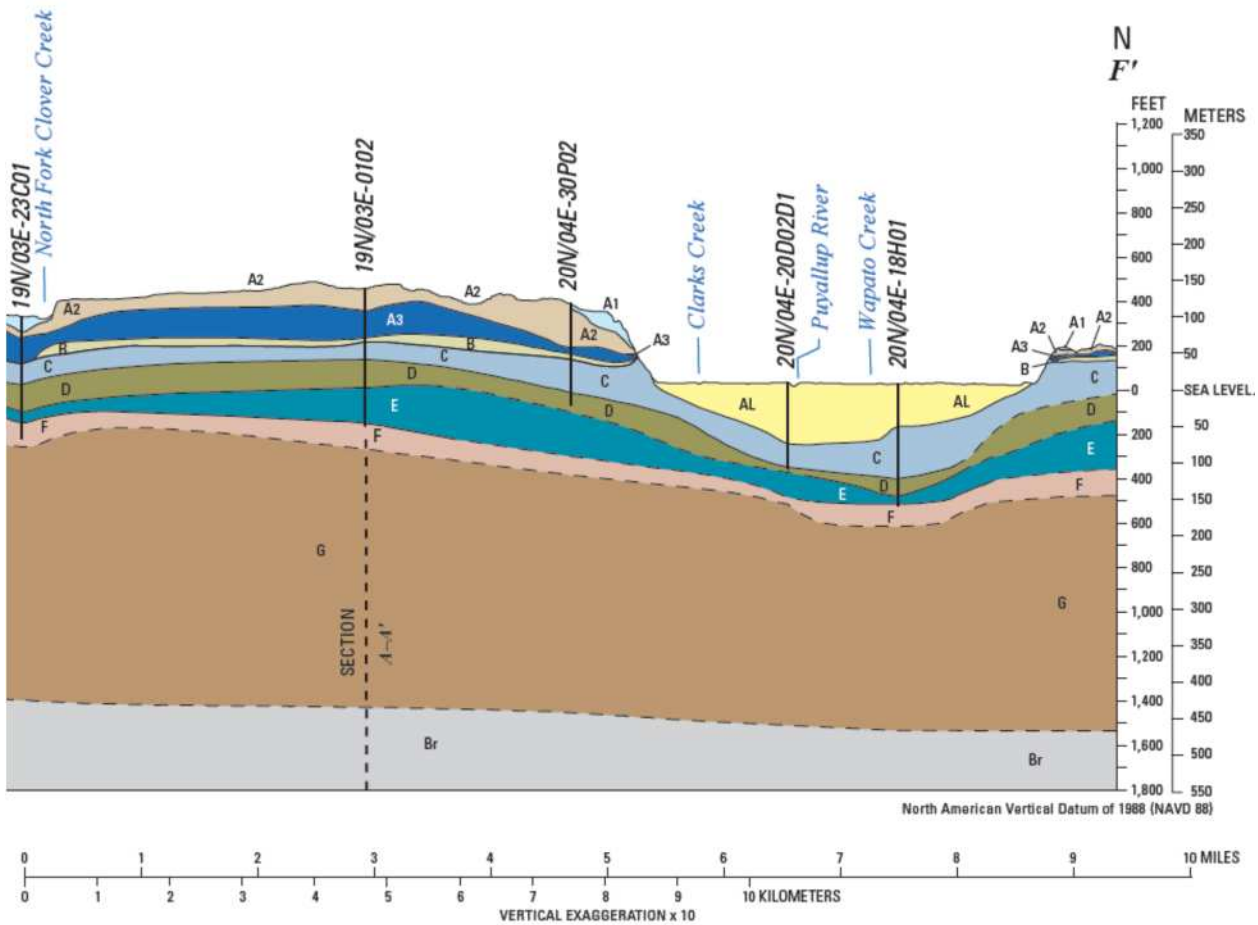

Figure 4-5. Detail of North-South Section West of Clarks Creek Headwaters (from Savoca et al., 2010, Plate 2)

4.4 STORMWATER PONDS

Many developments in the Clarks Creek watershed were built with stormwater detention ponds to control peak flows. These were mostly built under older rules that were focused on flooding issues and not on water quality or protection of channel morphology and are thus designed to achieve only short-term retention of storm flows. Nonetheless, these ponds do provide some flow-control and water quality benefits.

Unfortunately, the exact details on existing private stormwater infrastructure in the watershed are not well established. Pierce County has an inventory and GIS coverage of private stormwater ponds within its jurisdictional area, but this does not include complete information on pond size or drainage area. There are also anecdotally many private stormwater ponds within the City of Puyallup, but no comprehensive database on these ponds has been assembled. Therefore, an approximation approach is needed to address the role of private stormwater ponds in the watershed.

It is assumed that most of the stormwater ponds in the watershed receive primarily runoff from impervious surfaces that is temporarily detained but not infiltrated. This behavior is approximated as surface detention storage in the impervious land simulation. In HSPF, precipitation onto impervious areas is first subject to retention (on overhanging trees, flat roofs, etc.) that is subject to evaporation. Once this store is filled, supply is routed to surface storage. The surface storage (which is not subject to evaporation) runs off in accordance with a simple Chezy-Manning representation that considers surface

roughness (Manning's n) and path length. The surface storage routine can be used to represent temporary detention by decreasing the value of the routing variable, SRC, which is calculated internally as

$$SRC = 1020 \cdot \frac{\sqrt{SLSUR}}{NSUR \cdot LSUR},$$

where *SLSUR* is the slope, *NSUR* is the Manning's roughness coefficient, and *LSUR* is the slope length (ft). Increasing the value of the product *NSUR·LSUR* will effectively decrease the routing variable, approximating stormwater detention. The program does not allow *NSUR* to exceed 1; however, *LSUR* has no prescribed upper limit. Therefore, artificially high values of *LSUR* are used to approximate detention.

The appropriate value of *LSUR* in this representation is a calibration parameter because the fraction of stormwater that is subject to such detention is not known. The product *NSUR·LSUR* was set to 4,950 for high density residential impervious surfaces and 2,475 for medium density residential impervious surfaces in the final model. Other impervious surfaces were assumed, on average, to not be subject to significant amounts of stormwater detention.

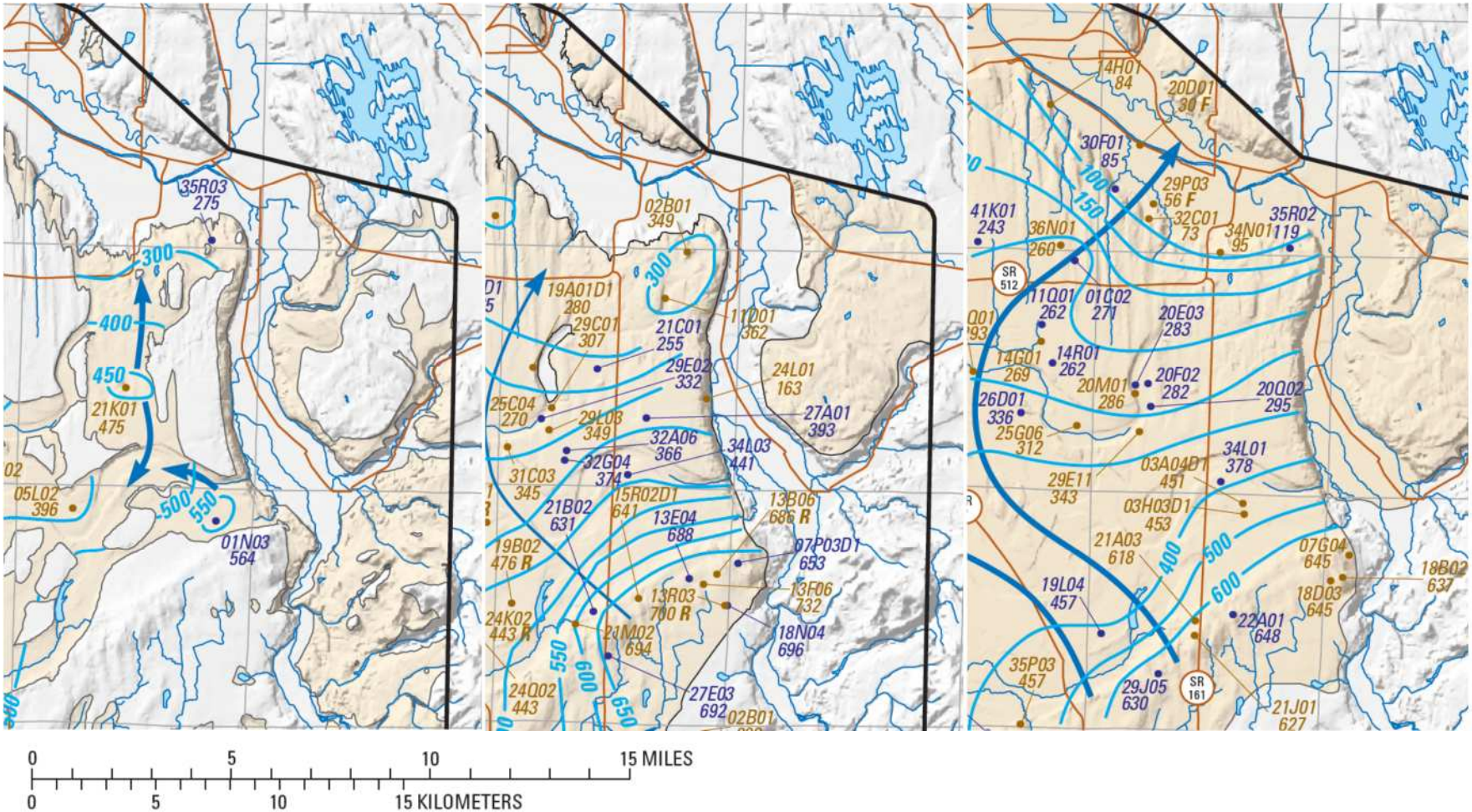

Figure 4-6. Interpreted Groundwater Flow in the A1, A3, and C Aquifers in the Vicinity of Clarks Creek (details from Savoca et al., 2010, figures 17-19)

Note: Clarks Creek shown in upper left of each figure.

The original USGS model (Mastin, 1996) covered Clear, Swan, and Canyon Creeks, but only Rody (West Fork Clarks Creek) and Diru Creek in the Clarks Creek watershed. This model was later expanded to include all of Clarks Creek as part of the 2003 basin plan. When the model was expanded, the original approach taken by Mastin to represent groundwater interactions was retained. Specifically, each creek is represented as having a losing reach that contributes to a common groundwater reservoir (represented in the model as a stream reach segment). The groundwater reservoir in turn yields flow back to downstream segments of various reaches, including Rody, Diru, and Clarks Creek, but not Woodland Creek. In the case of the Clarks Creek mainstem, losses to groundwater are represented as occurring between the State Hatchery and Meeker Ditch, while discharges from groundwater to the stream are represented as occurring at the confluence with Diru Creek. Similarly, Rody and Diru Creek have losses to groundwater in the upper reaches and gains from groundwater in the reach immediately above the confluence with Clarks Creek.

The representation of groundwater interactions in the existing model is now known to be inconsistent with the hydrogeology of the area. Specifically, significant discharges from groundwater to stream occur along the slope face where the outwash merges into the alluvial valley. Estimates of stream gain or loss presented by Savoca et al. (2010) suggest there may be minor losses from the stream in the general vicinity of Meeker Ditch, and perhaps small inflows between Tacoma Road and the mouth (both interactions with the AL aquifer), as is also shown by flow estimates during the 2002-2003 field sampling effort analyzed by Tetra Tech as part of the dissolved oxygen TMDL effort. The interactions with the AL aquifer correspond to the general longitudinal profile of Clarks Creek (Figure 4-7), as the groundwater elevation along lower Clarks Creek is about 25 m (Savoca et al., 2010). However, inflow from groundwater below Tacoma Road is likely derived from upstream portions of the Puyallup River, rather than from a local groundwater reservoir derived from losing reaches of Clarks Creek and its tributaries.

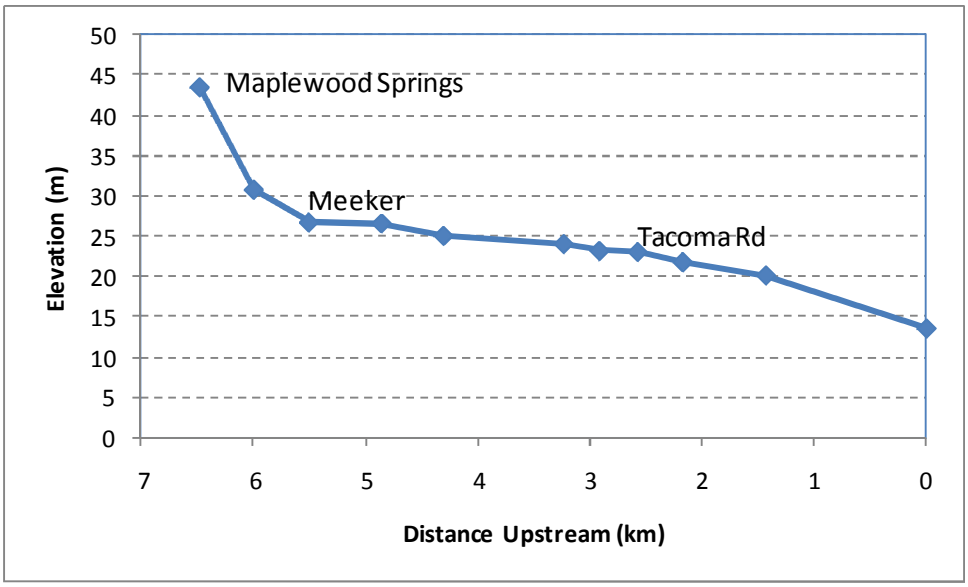

Figure 4-7. Longitudinal Profile of Clarks Creek

The additional insights on hydrogeology of the system suggested it was appropriate to refine the approach in the original USGS model. Simulation of a groundwater reservoir is still useful to represent the springs at the edge of the glacial outwash, such as Maplewood Springs. However, this reservoir is filled not by losses from the streams but rather by infiltration to the aquifers in an upstream area that includes pothole regions not connected by surface drainage to Clarks Creek. The groundwater reservoir, representing the A1 and A3 aquifers, should thus be simulated as receiving water from pervious upland segments with an areal extent greater than the local drainage area. The revised method is described in Section 6.2.

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5 Model Calibration and Validation Approach

Calibration consists of the process of adjusting model parameters to provide a match to observed conditions. Calibration is necessary because of the semi-empirical nature of water quality models. Although these models are formulated from mass balance principles, most of the kinetic descriptions in the models are empirically derived. These empirical derivations contain a number of coefficients that are usually determined by calibration to data collected in the waterbody of interest.

Calibration tunes the models to represent conditions appropriate to the waterbody and watershed under study. However, calibration alone is not sufficient to assess the predictive capability of the model, or to determine whether the model developed via calibration contains a valid representation of cause and effect relationships, especially those associated with the principal study questions. To help determine the adequacy of the calibration and to evaluate the uncertainty associated with the calibration, the model is subjected to a corroboration or validation step. In the corroboration step, the model is typically applied to a set of data independent from that used in calibration. This helps to ensure that the calibration is robust, and that the quality of the calibration is not an artifact of over-fitting to a specific set of observations. Corroboration or validation tests can also provide a direct estimate of the magnitude of uncertainty that may be expected when the model is applied to conditions outside of the calibration series.

5.1 Acceptance Criteria for Model Calibration

The quality of model calibration and validation is evaluated relative to acceptance criteria and performance targets specified in the QAPP (Tetra Tech, 2011).

The intended uses of the model focus on the effectiveness and cost-effectiveness of different implementation strategies relative to management of sediment in Clarks Creek. As such, the ability of the models to represent the relative contributions of different source areas and the relative performance of different management measures is of greatest importance, while obtaining a precise estimate of loading time series is of less direct interest. Ideally, the models should attain tight calibration to observed data; however, a less precise calibration can still provide useful information.

In light of these uses of the models, it is most informative to specify performance target ranges of precision that characterize the model results as “very good,” “good,” “fair,” or “poor.” These characterizations inform appropriate uses of the model: Where a model achieves an excellent fit it can assume a strong role in evaluating management options. Conversely, where a model achieves only a fair or poor fit it should assume a much less prominent role in the overall weight-of-evidence evaluation of management options.

The general acceptance criterion for models to be applied in this project is to achieve a quality of fit of “good” or better. In the event that this level of quality is not achieved on some or all measures the model may still be useful; however, a detailed description of its potential range of applicability should be provided.

5.2 Performance Targets for HSPF

For HSPF, a variety of performance targets have been specified, including Donigian et al. (1984), Lumb et al. (1994), and Donigian (2000). Based on these references and previous experience with the model, the HSPF performance targets for simulation of the water balance components are summarized in Table 5-1.

Table 5-1. Performance Targets for HSPF Hydrologic Simulation (Magnitude of Annual and Seasonal Relative Mean Error (*RE*); Daily and Monthly R^2)

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	≤ 15%	15 - 30%	30 - 50%	> 50%
6. Spring volume error	≤ 15%	15 - 30%	30 - 50%	> 50%
7. Summer volume error	≤ 15%	15 - 30%	30 - 50%	> 50%
8. Fall volume error	≤ 15%	15 - 30%	30 - 50%	> 50%
9. R^2 daily values	> 0.80	> 0.70	> 0.60	≤ 0.60
10. R^2 monthly values	> 0.85	> 0.75	> 0.65	≤ 0.65

It is important to clarify that the tolerance ranges are intended to be applied to mean values, and that individual events or observations may show larger differences and still be acceptable (Donigian, 2000).

In addition, the Nash-Sutcliffe coefficient of model fit efficiency (E) is reported for all calibration and validation runs – although no specific acceptance criteria were proposed in the QAPP. This is calculated as

$$E = 1 - \frac{\sum [O_i - P_i]^2}{\sum [O_i - \overline{O}]^2},$$

where O_i indicates an observed value, P_i a predicted value, and the overbar indicates an average. An E value of 1 indicates a perfect fit between measured and predicted values for all events. The resulting index can range from negative infinity to 1, with higher values indicating better fit. A value of zero indicates that the calibrated model is no better than using the average value of all the measured data to predict individual measurements.

General performance targets for water quality simulation with HSPF are also provided by Donigian (2000) and are shown in Table 5-2. These are calculated from observed and simulated daily values, and should only be applied in cases where there are a minimum of 20 observations

Table 5-2. Performance Targets for HSPF Water Quality Simulation (Magnitude of Relative Error (*RE*) on Daily Values)

Model Component	Very Good	Good	Fair	Poor
1. Suspended Sediment	≤ 20%	20 - 30%	30 - 45%	> 45%
2. Nutrients	≤ 15%	15 - 25%	25 - 35%	> 35%

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6 Hydrologic Calibration and Validation

The hydrology model is calibrated to observed flow gaging data. The primary source of flow data for calibration is the USGS gage on Clarks Creek at Tacoma Road (Station 12102075; see Figure 4-1). Gage records at this station are available for 3/1/1995 through 11/25/2008. Figure 6-1 compares recorded flows on Clarks Creek to those on nearby Clover Creek. Clarks Creek immediately stands out as having a near constant baseflow, and also being somewhat less responsive to winter storm events

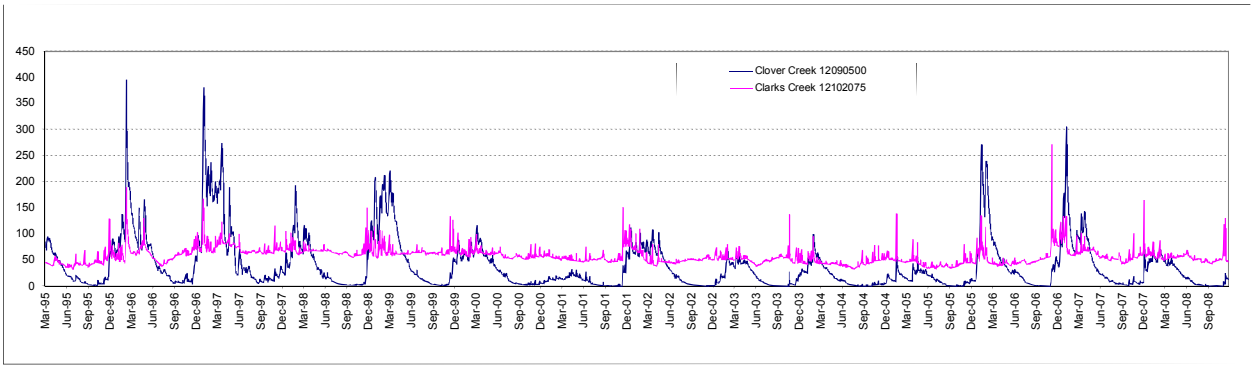


Figure 6-1. Comparison of Flow Gaging on Clarks Creek and Clover Creek, 1995-2008

To provide for model validation, flow calibration was undertaken on the gage data for 2000 – 2008, while the data for 1995 – 1999 were used for a validation test.

Scattered flow measurements exist for other locations, but are not sufficient for formal calibration. The comparison of the model to these records is discussed in Section 6.5.

6.1 Parameter Selection

The existing HSPF model of the area (Mastin, 1996) was used as a starting point for parameter values used in calibration; however, a need for significant modification was expected due to the more refined analysis of HRUs in the current model. From this starting point, parameters were varied in accordance with recommended ranges and other guidance for the HSPF model (USEPA, 2000).

Model parameters are assigned in a spreadsheet to individual HRUs based on the intersection of soil group, land use, and slope. Table 6-1 shows key hydrologic parameters that are assigned by soil group. One of the most important is INFILT, which is HSPF's index to mean soil infiltration rate (in/hr; the actual infiltration rate depends on soil moisture storage). Mastin used values for INFILT that were not divided by HSG. The revised model fits well with values that are within or near the recommended ranges for each HSG.

Table 6-1. Hydrologic Parameter Assignment by Soil Group

<table>
<tr><th rowspan="2">Soil</th><th colspan="3">INFILT (in/hr)</th><th colspan="3">LZSN (in)</th></tr>
<tr><th>This Model</th><th>Mastin (1996)</th><th>Recommended (USEPA, 2000)</th><th>This Model</th><th>Mastin (1996)</th><th>Recommended (USEPA, 2000)</th></tr>
<tr><td>Till AB</td><td>0.4</td><td rowspan="3">0.08 (forest)
0.3 (other)</td><td>0.1 – 1.0</td><td>13</td><td>6</td><td rowspan="5">3.0 – 8.0 (typical)
2.0 – 15.0 (possible)</td></tr>
<tr><td>Till C</td><td>0.12
(0.09 ag.)</td><td>0.05 – 0.1</td><td>12</td><td>6</td></tr>
<tr><td>Till D</td><td>0.05</td><td>0.01 – 0.05</td><td>12</td><td>6</td></tr>
<tr><td>Alluvial A</td><td>0.6</td><td rowspan="2">2.0 (forest)
0.8 (other)</td><td>0.4 – 1.0</td><td>12</td><td>5</td></tr>
<tr><td>Alluvial CD</td><td>0.10
(0.15 forest)</td><td>0.01 – 0.10</td><td>11</td><td>5</td></tr>
<tr><th></th><th colspan="3">AGWRC</th><th colspan="3">DEEPFR</th></tr>
<tr><td>Till AB</td><td rowspan="3">0.980
0.993 (forest)</td><td rowspan="3">0.800</td><td rowspan="5">0.92 – 0.99 (typical)
0.85 – 0.999 (possible)</td><td>0.20</td><td rowspan="3">0.25</td><td rowspan="5">0 – 0.20 (typical)
0 – 0.50 (possible)</td></tr>
<tr><td>Till C</td><td>0.20</td></tr>
<tr><td>Till D</td><td>0.15</td></tr>
<tr><td>Alluvial A</td><td rowspan="2">0.996</td><td rowspan="2">0.996</td><td rowspan="2">0</td><td rowspan="2">0</td></tr>
<tr><td>Alluvial CD</td></tr>
</table>

A parameter of particular interest is LZSN, the lower zone nominal soil storage (in). LZSN is an index of the amount of water that soil can hold within the root zone and subject to evapotranspiration by plants and is independent of infiltration rates. We found that model calibration statistics improved markedly with higher values of LZSN, and this was increased greatly from the values proposed by Mastin (1996) to a value of 11 - 13 inches, near the top of the typical range cited in USEPA (2000). Attempts to find alternate model fits with lower values of LZSN by modifying other parameters such as INFILT and INTFW uniformly yielded poorer fits to the observed gage records. The choice of a high value of LZSN means that, even where infiltration rates are low, the ultimate infiltration capacity of the soil is large, resulting in greater fractions of the total flow proceeding by interflow and groundwater pathways. This results in much of the direct stormflow in the Clarks Creek basin being simulated as derived from impervious surfaces.

The other parameters in Table 6-1 are the active groundwater recession coefficient (AGWRC) and the fraction of active groundwater storage that is lost to deep pathways (DEEPFR). A relatively large value is appropriate for DEEPFR on the till due to the recharge that feeds springs throughout the area.

Parameters that control interflow are varied by soil and slope (Table 6-2). Mastin fit very high values of the interflow inflow parameter, INTFW, for the till and these were retained after demonstrating that reduced values provided a poorer fit. Interflow was also activated for the alluvial soils. On the other hand, Mastin's values for the interflow recession coefficient (IRC) appear far too low and were revised to more typical values (USEPA, 2000).

Monthly parameter values were assigned to the lower zone ET factor (LZETP) and forest interception (CEPSC) consistent with past experience with HSPF models in the Northwest. These parameters are primarily determined by plant growth stage and are summarized in Table 6-3. Retention on impervious surfaces is also varied by month and shown in Table 6-3.

Table 6-2. Hydrologic Parameter Assignments by Slope and Soil

Slope	INTFW			IRC		
	This Model	Mastin (1996)	Recommended (USEPA, 2000)	This Model	Mastin (1996)	Recommended (USEPA, 2000)
0 – 6%	6 (till) 2 (alluvial)	6 (till) 0 (alluvial)	1 – 3 (typical) 1 – 10 (possible)	0.7 (A-B) 0.8 (C-D)	0.15 (till)	0.5 – 0.7 (typical) 0.3 – 0.85 (possible)
6 – 12%	9 (till) 2 (alluvial)	9 (till) 0 (alluvial)		0.65 (A-B) 0.76 (C-D)	0.12 (till)	
> 12%	11 (till) 2 (alluvial)	11 (till) 0 (alluvial)		0.6 (A-B) 0.7 (C-D)	0.10 (till)	

Table 6-3. Hydrologic Parameter Assignments by Month

	LU	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
LZETP	Forest	0.4	0.5	0.55	0.65	0.65	0.65	0.6	0.55	0.35	0.35	0.3	0.3
	Agriculture	0.16	0.19	0.2	0.25	0.35	0.65	0.8	0.8	0.56	0.18	0.14	0.14
	Pasture	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45
	Residential Pervious	0.45	0.45	0.45	0.45	0.45	0.5	0.45	0.4	0.35	0.35	0.35	0.4
	Road Pervious	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45
	Park	0.4	0.5	0.6	0.6	0.6	0.6	0.6	0.55	0.4	0.4	0.4	0.4
CEPSC	Forest > 70%	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.2	0.15	0.15	0.15
	Forest < 70%	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15
	Agriculture	0.04	0.04	0.04	0.04	0.05	0.06	0.12	0.143	0.15	0.105	0.07	0.05
	Pasture	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10
	Residential Pervious	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10
	Road Pervious	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10
	Park	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15
RETN (in)	MD – HD Residential Impervious	0.1	0.15	0.15	0.1	0.1	0.1	0.1	0.1	0.05	0.05	0.05	0.05
	LD Residential Impervious	0.25	0.25	0.25	0.1	0.1	0.1	0.1	0.05	0.05	0.05	0.05	0.1
	Road Impervious	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05
	Park Impervious	0.25	0.25	0.25	0.1	0.1	0.1	0.1	0.05	0.05	0.05	0.05	0.1

6.2 GROUNDWATER MODEL SETUP FOR SPRING DISCHARGE

One of the biggest challenges for simulating the hydrology of Clarks Creek is representing the incremental groundwater inflow from the Vashon Till. As described in Section 4.3, this flow originates from an area that is significantly larger than the surface drainage network of Clarks Creek – but, at this time, the extent of the contributing area is not exactly known. Flow recorded at the USGS gage on Clarks Creek at Tacoma Road shows a persistent baseflow component ranging between 40 and 60 cfs that is associated with these springs. This baseflow is always present, but does respond to climate, declining after dry periods and increasing after wet periods.

Given that no groundwater model is currently available and the size of the contributing area for baseflow is unknown an iterative approach was taken to simulating the spring flow entering the system. In essence, this approach involved simulating a representative pervious land segment (on a per-acre basis) and optimizing a fit to estimated spring flow based on the pervious land segment contributions to active groundwater. The target for the optimization is a smoothed lower bound estimate of spring flow obtained by applying a sliding window baseflow separation routine to observed flows at Tacoma Road, then identifying the objective function as the smoothed 3-month average of the 25th percentile of the monthly baseflow sums.

Aquifer outflows to the surface water model were calculated separately in a spreadsheet. The aquifer mass balance is represented at a monthly scale by a storage (S_t) and an outflow (O_t) term (both in/mo). In addition, there is assumed to be leakage to lower aquifers that do not reemerge in Clarks Creek. The monthly aquifer storage is:

$$S_t = S_{t-1} + I_t - k\,S_{t-1}{}^2 - O_t\,,$$

where k is a leakage coefficient. The outflow term (in/mo) is then given as a central difference on previous and partially updated storage terms:

$$O_t = \frac{\left[a\,S_{t-1}{}^b + a\,MAX(S_{t-1} - O_{t-1}, 0)^b\right]}{2} \cdot m_t\,,$$

where a and b are parameters and m is a monthly adjustment factor. Finally, the outflow in in/mo can be converted to an outflow in cfs (Q) by multiplying by an area factor, r, which has units of cfs/(in-mo) but is essentially a calibration factor to relate the unit area outflow term to the unknown contributing area:

$$Q = r \cdot O_t\,.$$

This model has four constants (a, b, k, and r), plus a set of monthly factors (m).

For fitting purposes, inflow to the aquifer was assumed to occur from a forested land segment on low slopes with A soils, characterized by the parameters assumed for the Mastin (1996) model. The A soils assumption is appropriate given the assumption that the majority of the recharge occurs over more pervious sand deposits. Fit was based on minimizing squared differences on the smoothed objective function over the period of gaging at Tacoma Road (1995-2008), using a model run that started in 1960 with an assumed storage of 34 in (a value selected to maintain an approximately stable groundwater storage over the 50-year simulation period). Optimized parameter values are shown in Table 6-4. Note that the value obtained for r suggests that there is an additional drainage area of approximately 1 ½ square miles contributing to the groundwater flow that discharges to Clarks Creek through springs at the base of the Vashon Till.

Table 6-4. Groundwater Model Parameter Estimates for Clarks Creek

Parameter	Estimate
a	$2.09 \cdot 10^{-11}$ in
b	5.611
k	$2.26 \cdot 10^{-4}$ (in-mo)$^{-1}$
r	6,980 cfs/(in-mo)

These parameters provide a reasonable match to the lower bound estimates of spring-fed baseflow for 1995-2008 over long term simulations started in 1960 (Figure 6-2). The match is not, however, exact, and appears to introduce discrepancies in some years.

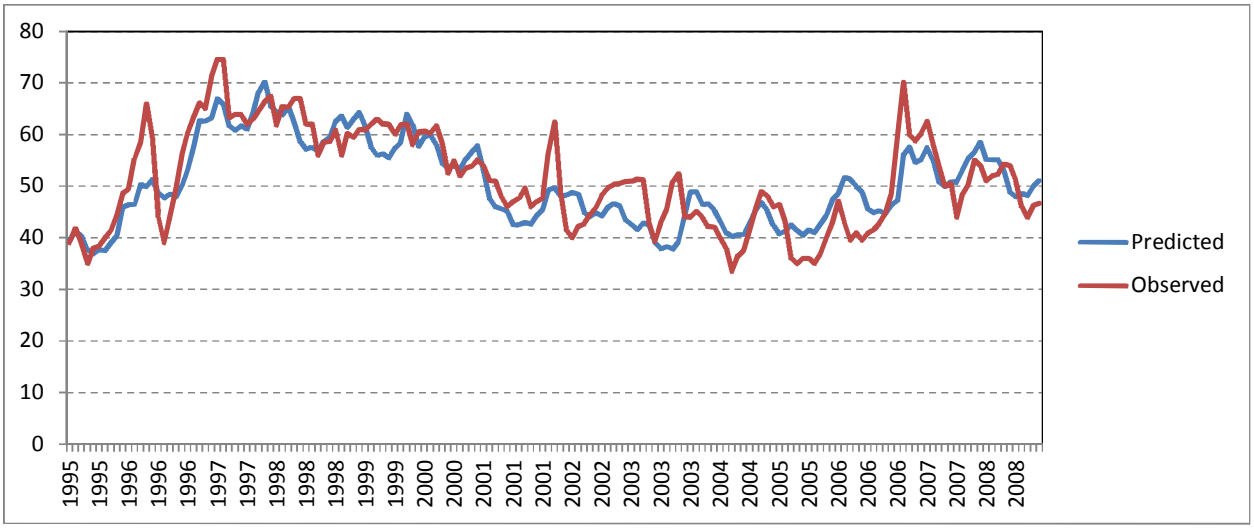


Figure 6-2. Calibrated Fit to Inferred Spring Contribution to Clarks Creek Flow

The outflow from the groundwater springs upstream of the Tacoma Road gage was assigned 77% to Reach 133, 17 % to reach 134, and 6% to reach 135 based on limited flow monitoring at various points in the system conducted in 2002-2003. In addition, small amounts of spring outflow were assigned to Rody Creek (1.85% of the flow to the mainstem) and Diru Creek (1.06% of the flow to the mainstem).

6.3 Hydrology Model Calibration

The hydrology model calibration (2000 – 2008) is summarized below in Figure 6-3 through Figure 6-10, Table 6-5, and Table 6-6. At certain points during this period the uncertainties introduced by the spring discharge model are evident (e.g., the second half of 2003, during which baseflow steadily increased despite the absence of significant rain). Nonetheless, the overall model fit is rated as good.

As shown in Table 6-6, all of the annual and seasonal relative mean error statistics are in the "very good" range (refer to the performance targets in Table 5-1). The uncertainties introduced by the spring simulation, which has some difficulties in representing the short-term variations in baseflow discharge, are, however, evident in the relatively low daily *E* value of 0.54. The coefficient of determination (R^2) for daily discharges is 0.70 (Figure 6-5), which is in the good range. The coefficient of determination for monthly discharges is, however, poor (Figure 6-6). This is largely due to two periods in which the model under-predicts observed flow (Nov.-Dec. 2002 and Nov.-Dec. 2006). Despite this, the monthly *E* (0.95) is very high. Therefore, the model calibration is deemed acceptable.

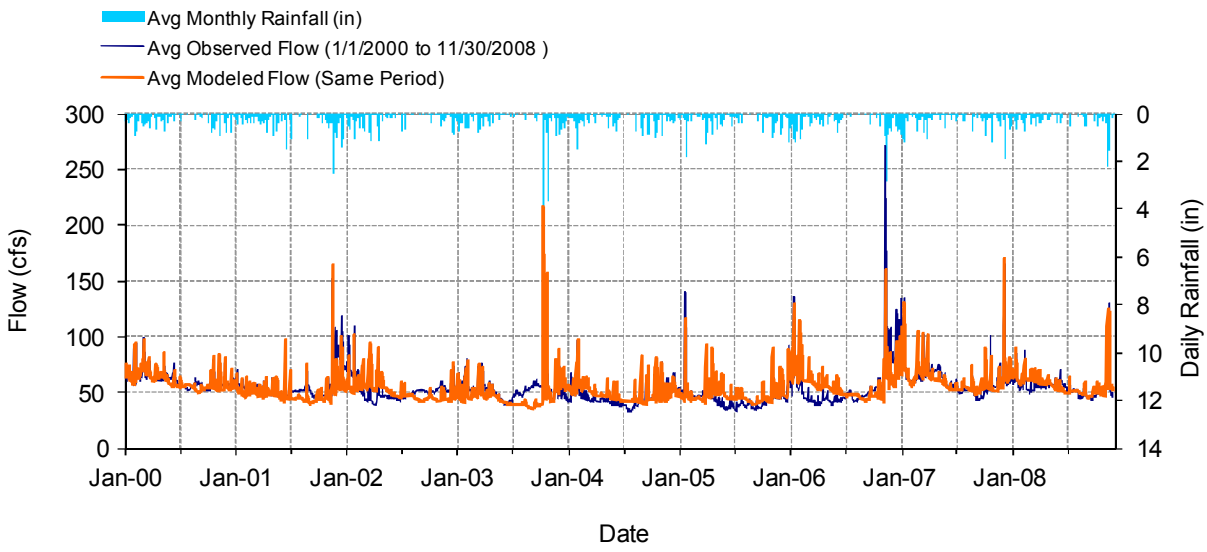


Figure 6-3. Mean Daily Flow: Model vs. USGS 12102075 Clarks Creek at Tacoma Road near Puyallup, WA, Calibration Period

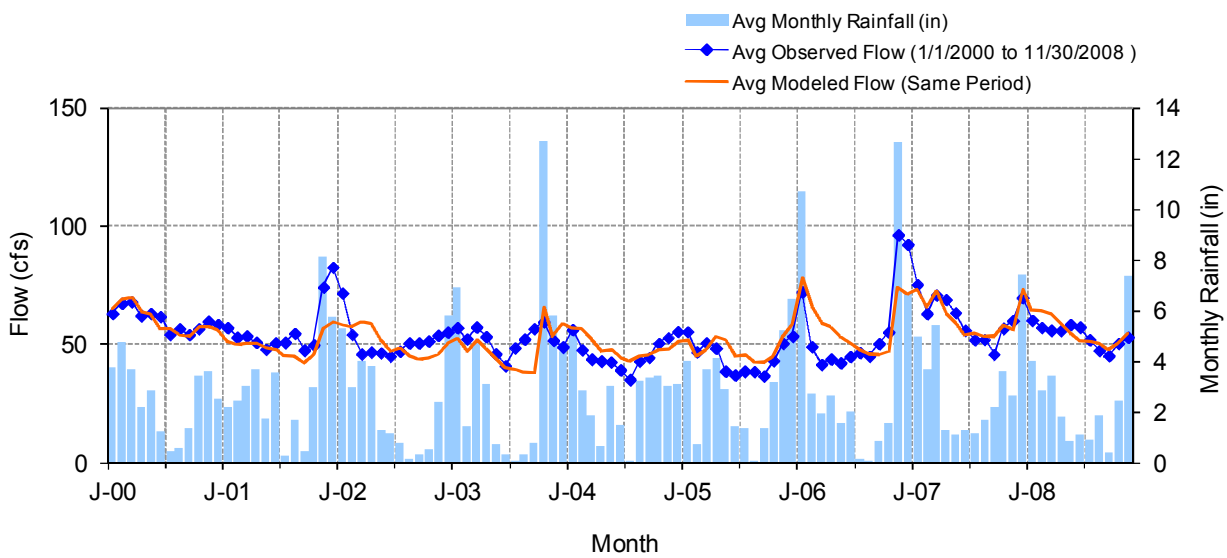


Figure 6-4. Mean Monthly Flow: Model vs. USGS 12102075 Clarks Creek at Tacoma Road near Puyallup, WA, Calibration Period

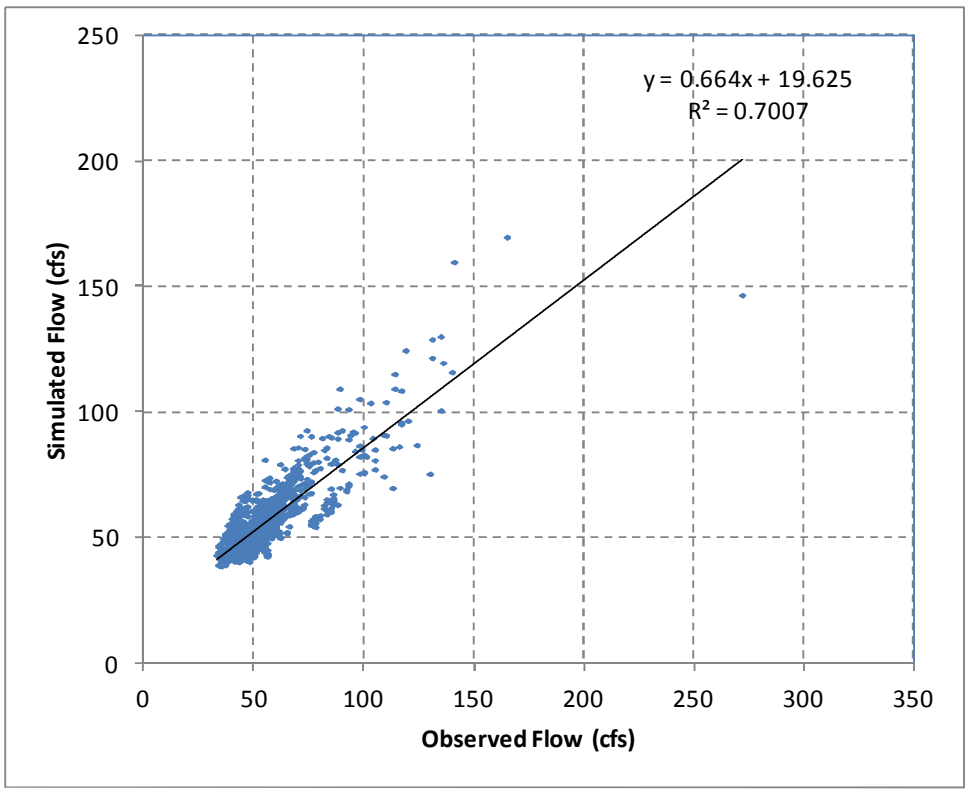


Figure 6-5. Daily Flow Regression: Model vs. USGS 12102075 Clarks Creek at Tacoma Road near Puyallup, WA, Calibration Period

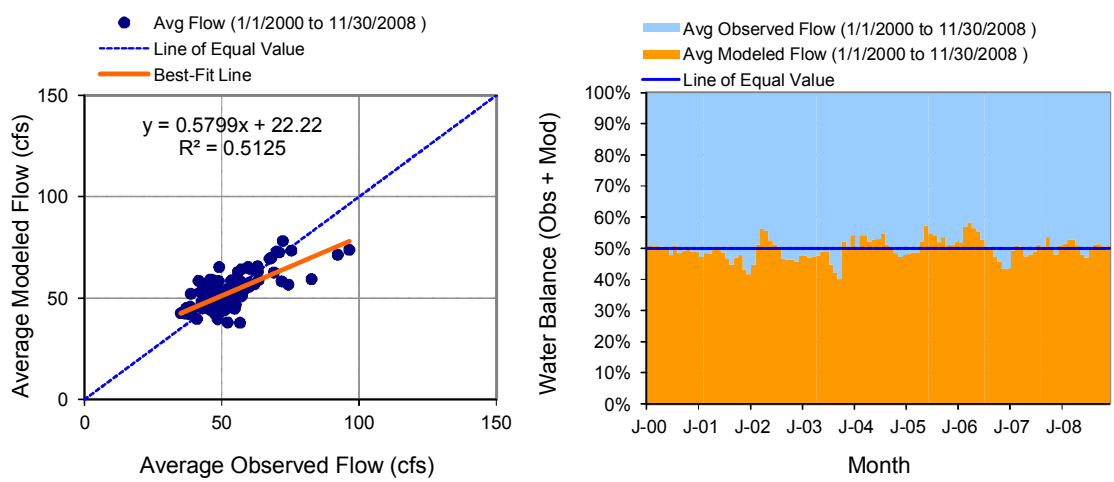


Figure 6-6. Monthly Flow Regression and Temporal Variation: Model vs. USGS 12102075 Clarks Creek at Tacoma Road near Puyallup, WA, Calibration Period

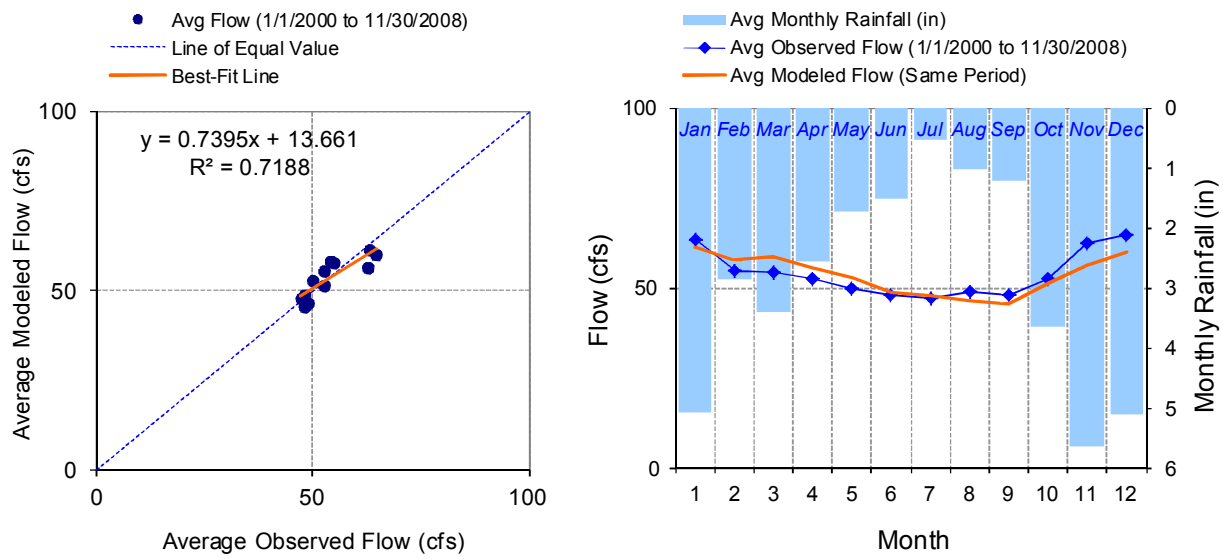


Figure 6-7. Seasonal Regression and Temporal Aggregate: Model vs. USGS 12102075 Clarks Creek at Tacoma Road near Puyallup, WA, Calibration Period

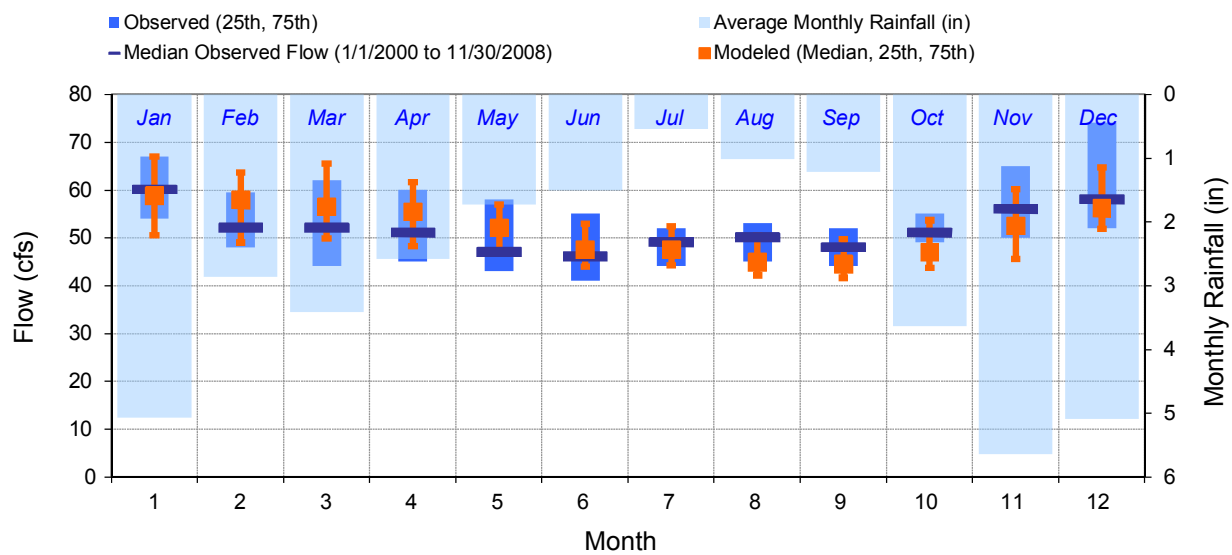


Figure 6-8. Seasonal Medians and Ranges: Model vs. USGS 12102075 Clarks Creek at Tacoma Road near Puyallup, WA, Calibration Period

Table 6-5 Seasonal Summary: Model vs. USGS 12102075 Clarks Creek at Tacoma Road near Puyallup, WA, Calibration Period

MONTH	OBSERVED FLOW (CFS)				MODELED FLOW (CFS)			
	MEAN	MEDIAN	25TH	75TH	MEAN	MEDIAN	25TH	75TH
Jan	63.17	60.00	54.00	67.00	61.33	58.73	50.54	66.92
Feb	54.58	52.00	48.00	59.50	57.88	57.88	48.94	63.65
Mar	54.19	52.00	44.00	62.00	58.37	56.49	49.86	65.51
Apr	52.56	51.00	45.00	60.00	55.60	55.41	48.26	61.58
May	49.89	47.00	43.00	58.00	52.69	52.04	47.32	56.92
Jun	48.09	46.00	41.00	55.00	48.54	47.48	43.91	52.90
Jul	47.21	49.00	44.00	52.00	47.91	47.47	44.23	52.34
Aug	48.91	50.00	45.00	53.00	46.39	44.88	42.13	50.50
Sep	47.96	48.00	44.00	52.00	45.69	44.43	41.61	49.69
Oct	52.59	51.00	49.00	55.00	51.31	46.95	43.73	53.62
Nov	62.54	56.00	50.00	65.00	56.34	52.46	45.54	60.11
Dec	64.54	58.00	52.00	74.00	59.80	56.16	51.87	64.65

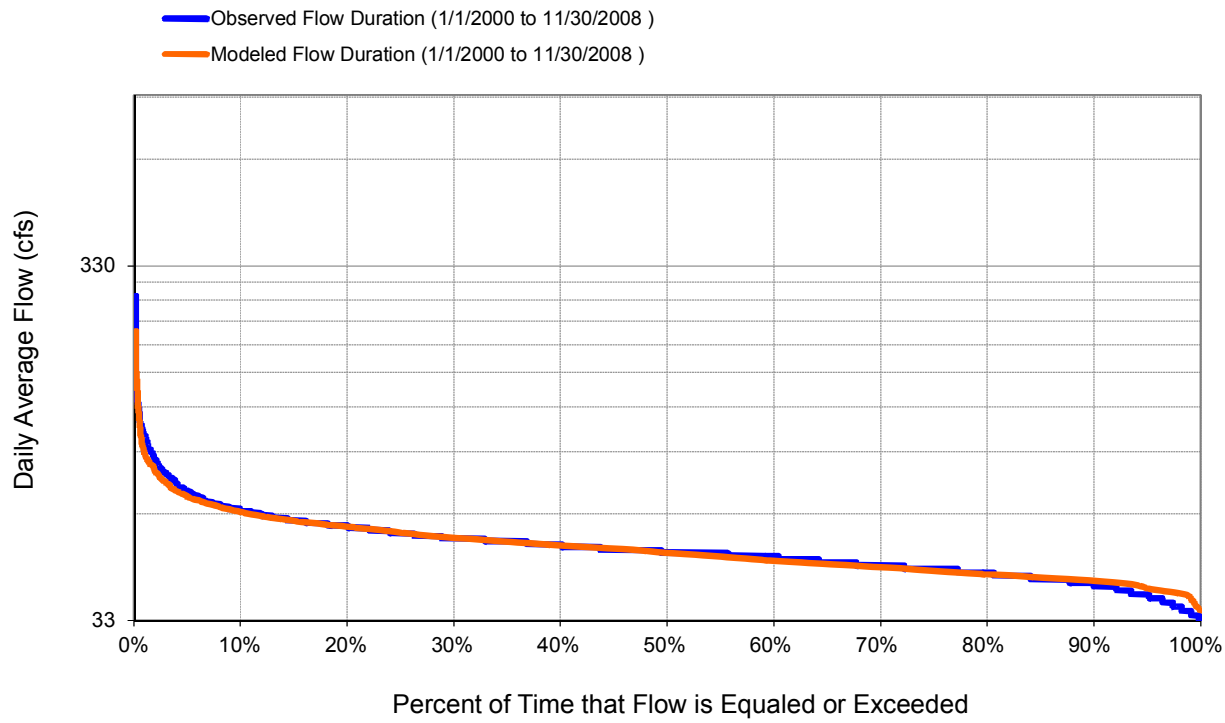


Figure 6-9. Flow Exceedence: Model vs. USGS 12102075 Clarks Creek at Tacoma Road near Puyallup, WA, Calibration Period

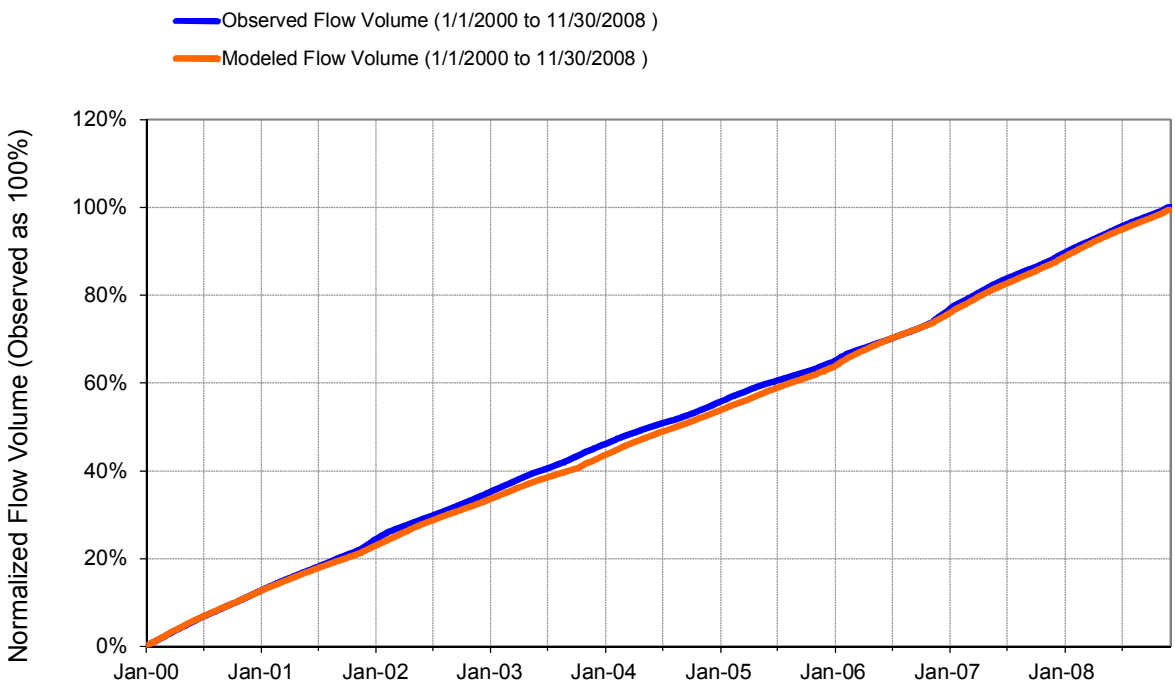


Figure 6-10 . Flow Accumulation: Model vs. USGS 12102075 Clarks Creek at Tacoma Road near Puyallup, WA, Calibration Period

Table 6-6. Summary Statistics: Model vs. USGS 12102075 Clarks Creek at Tacoma Road near Puyallup, WA, Calibration Period

HSPF Simulated Flow		Observed Flow Gage		
REACH OUTFLOW FROM DSN 103 8.92-Year Analysis Period: 1/1/2000 - 11/30/2008 Flow volumes are (inches/year) for upstream drainage area This version has fix to hydrograph separation		USGS 12102075 CLARKS CREEK AT TACOMA ROAD NEAR PUYALLUP, WA Hydrologic Unit Code: 17110014 Latitude: 47.19760016 Longitude: -122.337343 Drainage Area (sq-mi): 13		
Total Simulated In-stream Flow:	**55.72**	Total Observed In-stream Flow:		**56.07**
Total of simulated highest 10% flows:	**8.30**	Total of Observed highest 10% flows:		**8.64**
Total of Simulated lowest 50% flows:	**23.64**	Total of Observed Lowest 50% flows:		**23.61**
Simulated Summer Flow Volume (months 7-9):	**12.40**	Observed Summer Flow Volume (7-9):		**12.76**
Simulated Fall Flow Volume (months 10-12):	**14.14**	Observed Fall Flow Volume (10-12):		**15.16**
Simulated Winter Flow Volume (months 1-3):	**15.45**	Observed Winter Flow Volume (1-3):		**14.97**
Simulated Spring Flow Volume (months 4-6):	**13.74**	Observed Spring Flow Volume (4-6):		**13.18**
Total Simulated Storm Volume:	**2.60**	Total Observed Storm Volume:		**2.38**
Simulated Summer Storm Volume (7-9):	**0.21**	Observed Summer Storm Volume (7-9):		**0.23**
Errors (Simulated-Observed)	*Error Statistics*	*Recommended Criteria*	*Run (n-1)*	*Prev Cal*
Error in total volume:	-0.62	10	-0.75	-0.41
Error in 50% lowest flows:	0.14	10	0.11	0.41
Error in 10% highest flows:	-3.94	15	-4.39	-3.93
Seasonal volume error - Summer:	-2.82	30	-2.78	-2.58
Seasonal volume error - Fall:	-6.72	30	-6.75	-6.67
Seasonal volume error - Winter:	3.20	30	2.79	3.43
Seasonal volume error - Spring:	4.19	30	4.10	4.54
Error in storm volumes:	9.10	20	8.47	8.80
Error in summer storm volumes:	-8.83	50	-8.79	-8.83
Nash-Sutcliffe Coefficient of Efficiency, E:	0.539	Model accuracy increases	0.540	0.538
Monthly NSE	0.950	as E approaches 1.0	0.950	0.950

6.4 HYDROLOGY MODEL VALIDATION

The hydrology validation was conducted for 1995-1999 and confirms the performance of the calibrated model (Figure 6-11 through Figure 6-18, Table 6-6, and Table 6-7). The relative mean error statistics (Table 6-7) are all "very good", with the exception of the storm volume error, which is only "good". Reassuringly, the validation period statistics show an increase in the daily Nash-Sutcliffe *E* to 0.699 and the coefficients of determination (R^2) are 0.744 for daily flows and 0.817 for monthly flows, both in the "good" range.

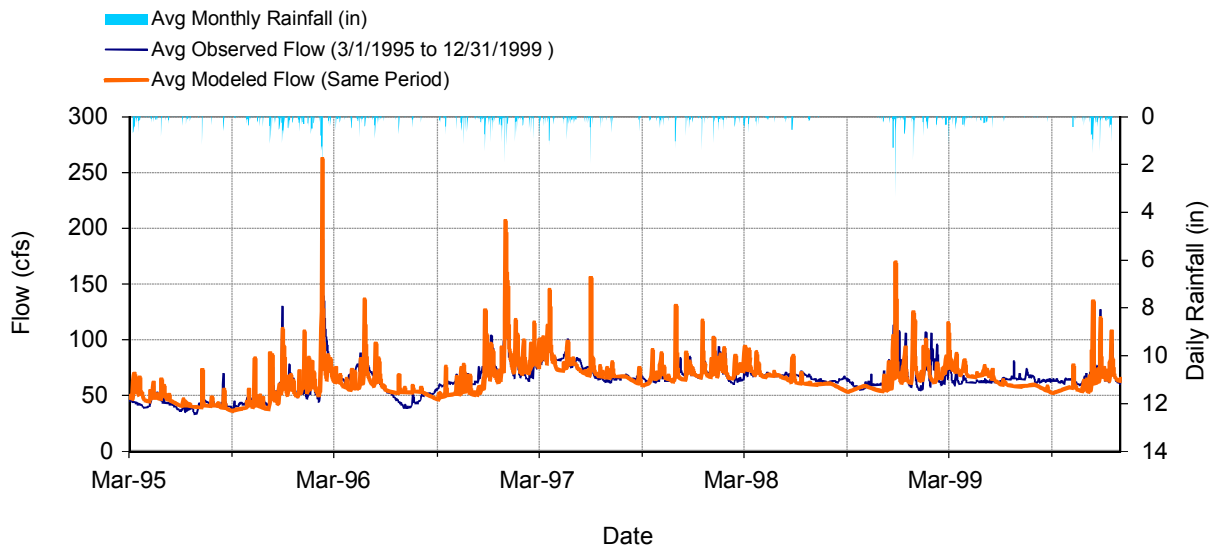


Figure 6-11. Mean Daily Flow: Model vs. USGS 12102075 Clarks Creek at Tacoma Road near Puyallup, WA, Validation Period

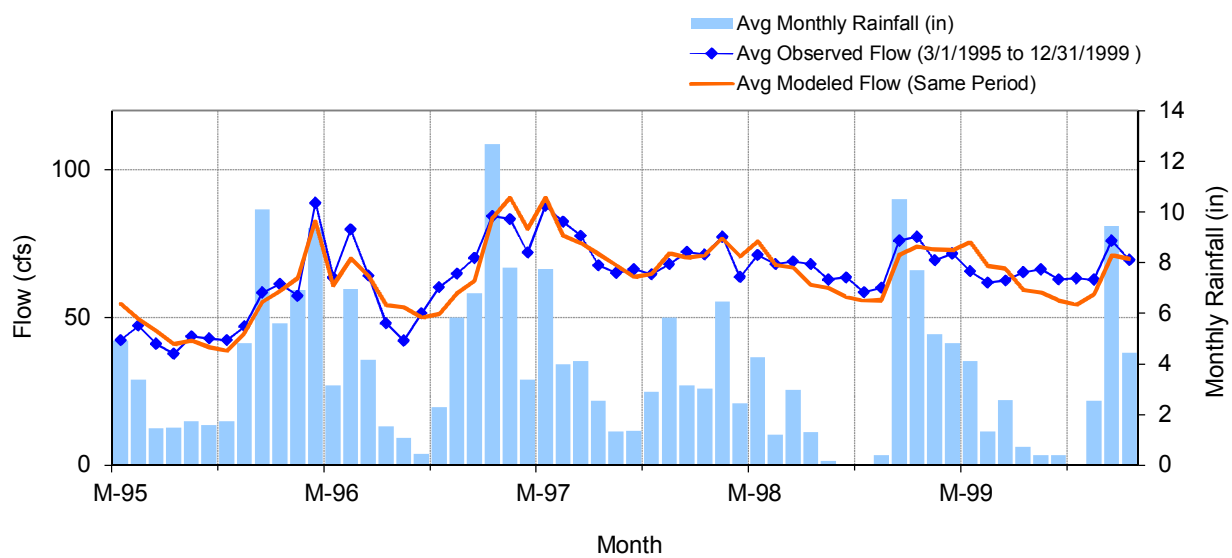


Figure 6-12. Mean Monthly Flow: Model vs. USGS 12102075 Clarks Creek at Tacoma Road near Puyallup, WA, Validation Period

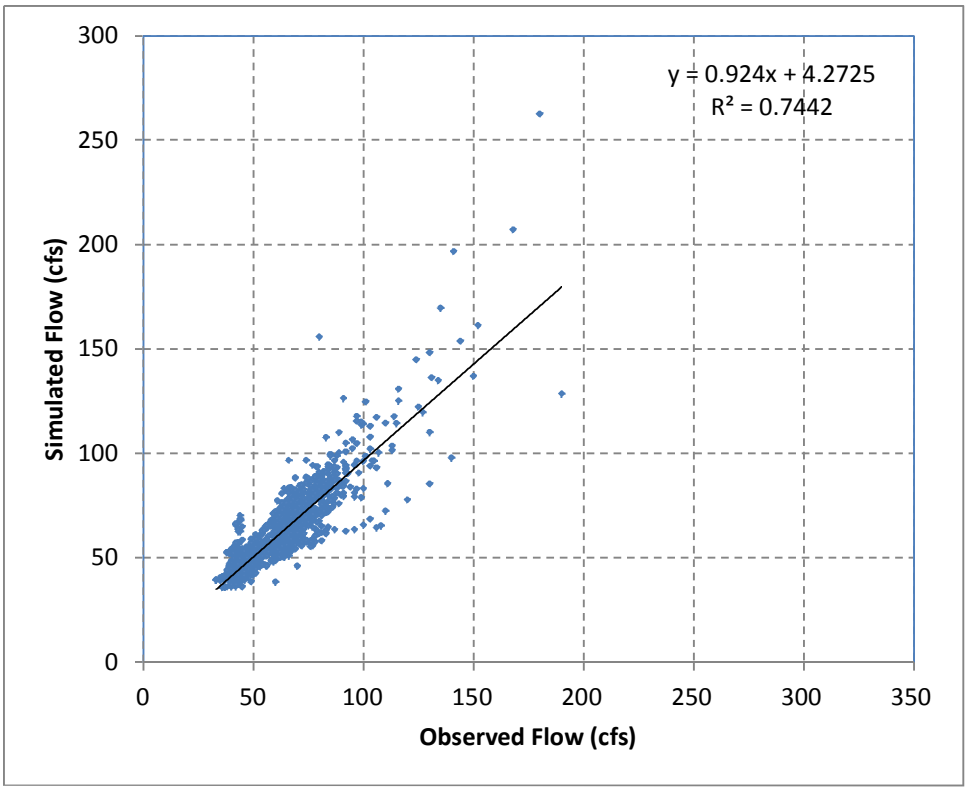


Figure 6-13. Daily Flow Regression: Model vs. USGS 12102075 Clarks Creek at Tacoma Road near Puyallup, WA, Validation Period

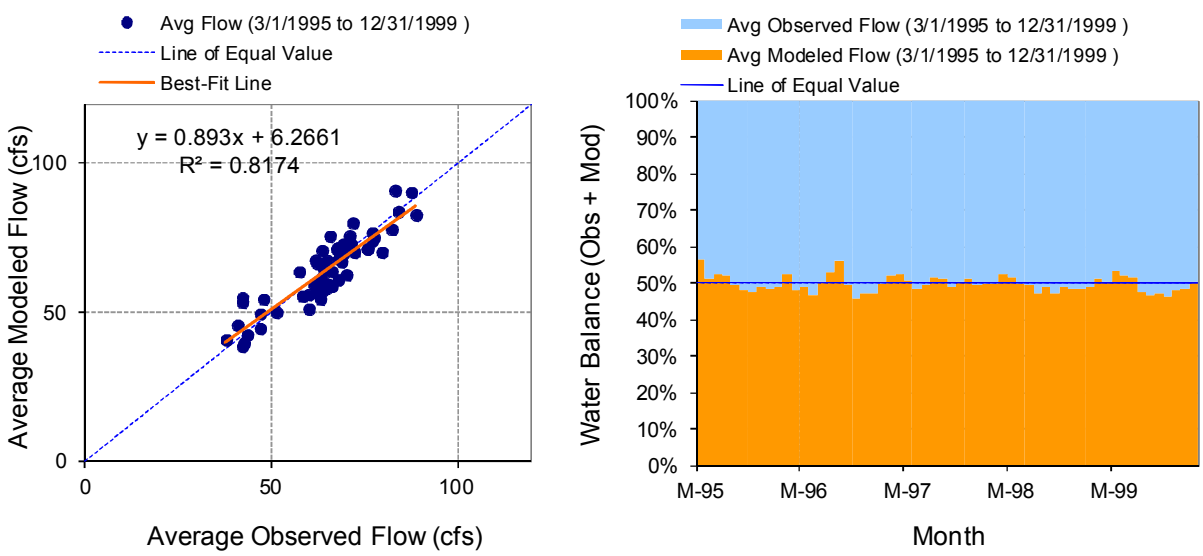
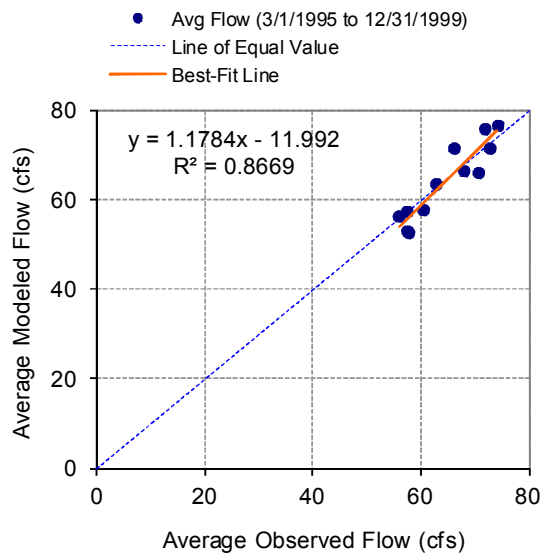


Figure 6-14. Monthly Flow Regression and Temporal Variation: Model vs. USGS 12102075 Clarks Creek at Tacoma Road near Puyallup, WA, Validation Period

Figure 6-15. Seasonal Regression and Temporal Aggregate: Model vs. USGS 12102075 Clarks Creek at Tacoma Road near Puyallup, WA, Validation Period



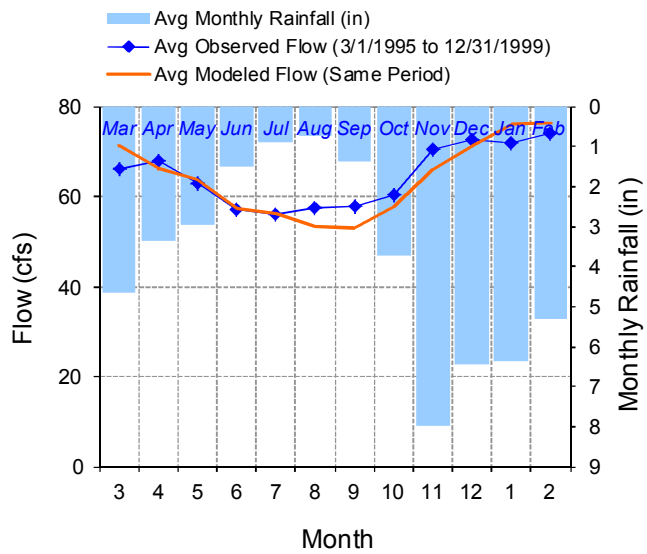


Figure 6-16. Seasonal Medians and Ranges: Model vs. USGS 12102075 Clarks Creek at Tacoma Road near Puyallup, WA, Validation Period

Table 6-7. Seasonal Summary: Model vs. USGS 12102075 Clarks Creek at Tacoma Road near Puyallup, WA, Validation Period

MONTH	OBSERVED FLOW (CFS)				MODELED FLOW (CFS)			
	MEAN	MEDIAN	25TH	75TH	MEAN	MEDIAN	25TH	75TH
Mar	66.01	65.00	60.00	77.50	71.42	70.92	61.21	80.40
Apr	67.78	67.50	61.00	78.00	66.40	67.33	59.35	71.77
May	62.79	65.00	60.00	71.00	63.61	65.01	59.10	70.11
Jun	57.25	64.00	44.25	66.75	57.31	59.11	52.39	61.82
Jul	55.89	62.00	43.50	65.00	56.27	58.47	52.40	60.32
Aug	57.35	62.00	51.00	64.00	53.16	54.47	48.14	59.06
Sep	57.72	61.00	56.00	63.00	52.84	53.80	49.37	57.09
Oct	60.45	62.00	59.00	64.00	57.61	56.30	52.54	63.29
Nov	70.48	69.00	62.00	73.00	66.01	63.79	54.20	70.89
Dec	72.68	68.00	63.00	77.50	71.43	66.82	63.28	72.89
Jan	71.77	69.00	58.75	81.00	75.91	71.26	65.37	83.17
Feb	74.07	67.00	63.00	76.00	76.52	72.60	65.66	78.77

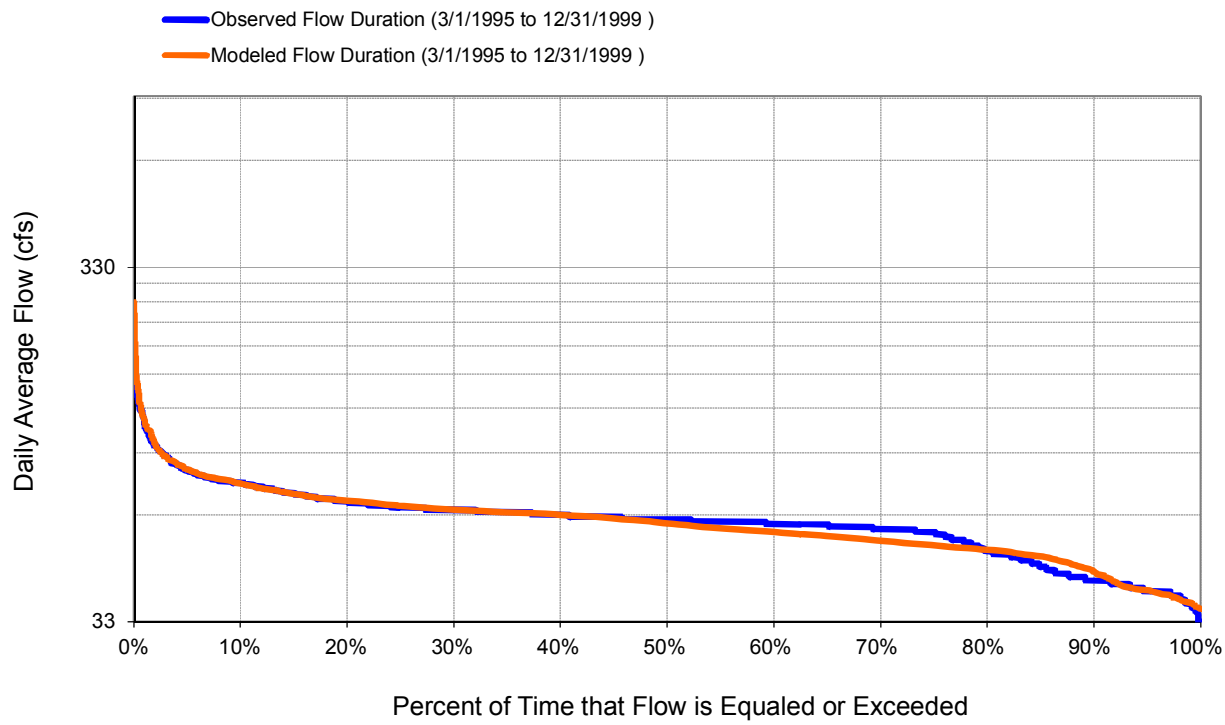


Figure 6-17. Flow Exceedence: Model vs. USGS 12102075 Clarks Creek at Tacoma Road near Puyallup, WA, Validation Period

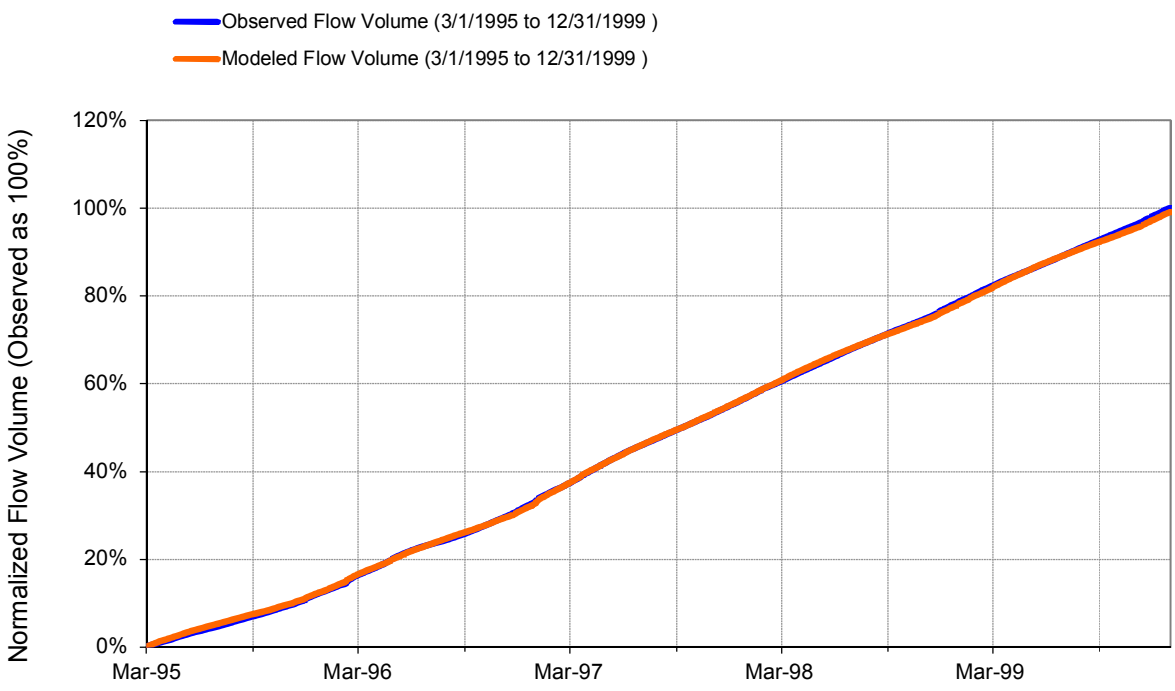


Figure 6-18. Flow Accumulation: Model vs. USGS 12102075 Clarks Creek at Tacoma Road near Puyallup, WA, Validation Period

Table 6-8. Summary Statistics: Model vs. USGS 12102075 Clarks Creek at Tacoma Road near Puyallup, WA, Validation Period

HSPF Simulated Flow		Observed Flow Gage	
REACH OUTFLOW FROM DSN 103 4.84-Year Analysis Period: 3/1/1995 - 12/31/1999 Flow volumes are (inches/year) for upstream drainage area This version has fix to hydrograph separation		USGS 12102075 CLARKS CREEK AT TACOMA ROAD NEAR PUYALLUP, WA Hydrologic Unit Code: 17110014 Latitude: 47.19760016 Longitude: -122.337343 Drainage Area (sq-mi): 13	
Total Simulated In-stream Flow:	**66.43**	Total Observed In-stream Flow:	**67.06**
Total of simulated highest 10% flows:	**10.21**	Total of Observed highest 10% flows:	**10.01**
Total of Simulated lowest 50% flows:	**27.42**	Total of Observed Lowest 50% flows:	**28.25**
Simulated Summer Flow Volume (months 7-9):	**14.72**	Observed Summer Flow Volume (7-9):	**15.50**
Simulated Fall Flow Volume (months 10-12):	**17.68**	Observed Fall Flow Volume (10-12):	**18.45**
Simulated Winter Flow Volume (months 1-3):	**17.22**	Observed Winter Flow Volume (1-3):	**16.26**
Simulated Spring Flow Volume (months 4-6):	**16.80**	Observed Spring Flow Volume (4-6):	**16.85**
Total Simulated Storm Volume:	**3.30**	Total Observed Storm Volume:	**2.79**
Simulated Summer Storm Volume (7-9):	**0.20**	Observed Summer Storm Volume (7-9):	**0.26**
Errors (Simulated-Observed)	*Error Statistics*	*Recommended Criteria*	
Error in total volume:	-0.94	10	
Error in 50% lowest flows:	-2.94	10	
Error in 10% highest flows:	1.95	15	
Seasonal volume error - Summer:	-5.05	30	
Seasonal volume error - Fall:	-4.18	30	
Seasonal volume error - Winter:	5.92	30	
Seasonal volume error - Spring:	-0.25	30	
Error in storm volumes:	18.52	20	
Error in summer storm volumes:	-21.90	50	
Nash-Sutcliffe Coefficient of Efficiency, E:	0.699	Model accuracy increases	
Monthly NSE	0.950	as E approaches 1.0	

6.5 Simulation of Hourly Flows

The USGS NWIS system provides access to 15-minute raw flow estimates from the Tacoma Road gage for the period 3/28/1995 – 9/30/2008 (with gaps). These can be used to evaluate model performance at its native hourly time step. Typical results for fall 2007 are shown in Figure 6-19. In general, the model simulation appears accurate, with good representation of storm hydrograph timing and shape for most events. There is one period on November 4, 2007 when gaged flow increased above 100 cfs with no recorded rainfall. Subdaily gage data are missing for December 16 to December 17, 2007.

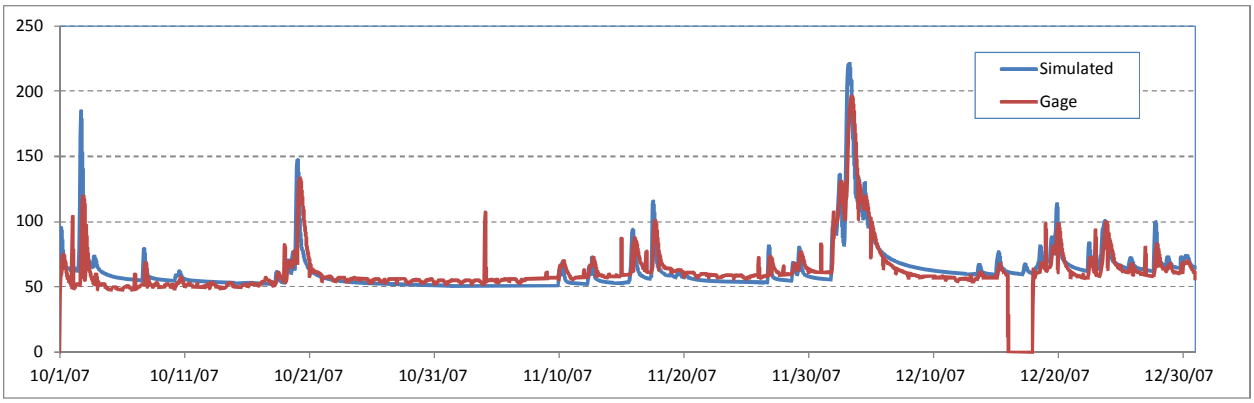


Figure 6-19. Hourly Flow Prediction for Clarks Creek at Tacoma Rd., Fall 2007

In contrast, results for fall 2003 are shown in Figure 6-20 and reveal several anomalies. Most notably, an extremely large flow is predicted for October 8, 2003, whereas the gage shows almost no response on that date. The large predicted flow is due to the precipitation record, as the WSU Puyallup station reported 4.85 inches total rainfall for this date. If correct, this would be an extraordinarily large rainfall event for the area. However, the reported data are suspect: On this date, the Seatac airport station reported only 0.27 inches, while the McMillin Reservoir gage reported about 0.3 inches. Thus, the WSU record for this day may be incorrect.

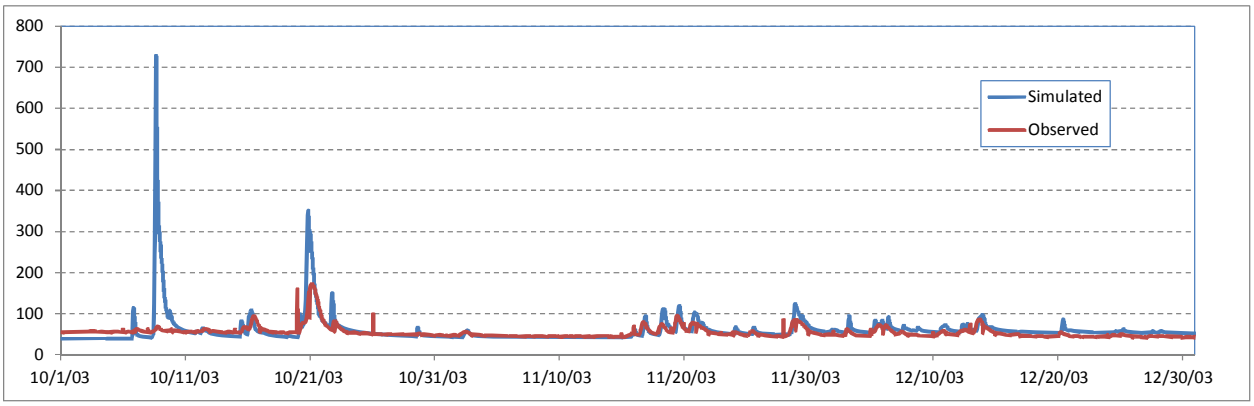


Figure 6-20. Hourly Flow Prediction for Clarks Creek at Tacoma Rd., Fall 2003

Note: Precipitation data appear to be incorrect for 10/8/2003.

Figure 6-20 also shows an actual major event on October 20 – October 21, 2003. This storm caused approximately $800,000 damage and set record daily rainfall totals at Seatac Airport, Olympia, and other locations according to NOAA event record details (http://www4.ncdc.noaa.gov/cgi-win/wwcgi.dll?wwevent~ShowEvent~521417). In Pierce County, 5.7 inches of precipitation was recorded at McMillin Reservoir on this date and 3.7 inches at WSU, with approximately another 0.5 inches on the following day. The model appears to overpredict the results from the gage, which had a daily average flow of only 138 cfs and a peak of 165 cfs on 10/21. However, instantaneous flow measurements made downstream at 56th Street during water quality sampling reported 279 cfs on this day, in line with the model predictions. If both gage records are accurate this storm may have been spatially heterogeneous, with more intense rainfall on the downstream portions of Clarks Creek.

6.6 Comparison to Additional Flow Information

Limited instantaneous flow measurements are available at locations other than Tacoma Road. Between 1981 and 1997, 41 field measurements of flow are reported by USGS for Clarks Creek at the mouth (gage 12102100). For the period 2006-2008, USGS has also taken 9 field measurements on Clarks Creek at Puyallup (gage 12102000, located at the upstream end of Clarks Creek Park; this was also monitored continuously from March 1946 to May 1948) and two field measurements from Clarks Creek at 7th Ave. SW (gage 12102010). USGS also reports 12 measurements at the mouth of Rody Creek (12102050). Additional instantaneous flow measurements at multiple locations on Clarks Creek and tributaries were taken during the 2002-2003 water quality sampling used to develop the fecal coliform TMDL (WA ECY, 2008), including measurements on several of the tributaries.

The USGS flow measurements were obtained using standard, quality assured methods, and are mostly rated by USGS as of only fair accuracy. The additional 2002-2003 flow data are based on rating curves developed from a limited number of measurements and no detailed quality assessments are available. These data should be considered as of unknown accuracy.

The most extensive and likely most reliable of these additional series are those associated with the USGS stations at the mouth of Clarks Creek and Rody Creek (Figure 6-21), although these are instantaneous

rather than daily average measurements. Note that the non-USGS measurements on Rody were not obtained at exactly the same location as the USGS measurements.

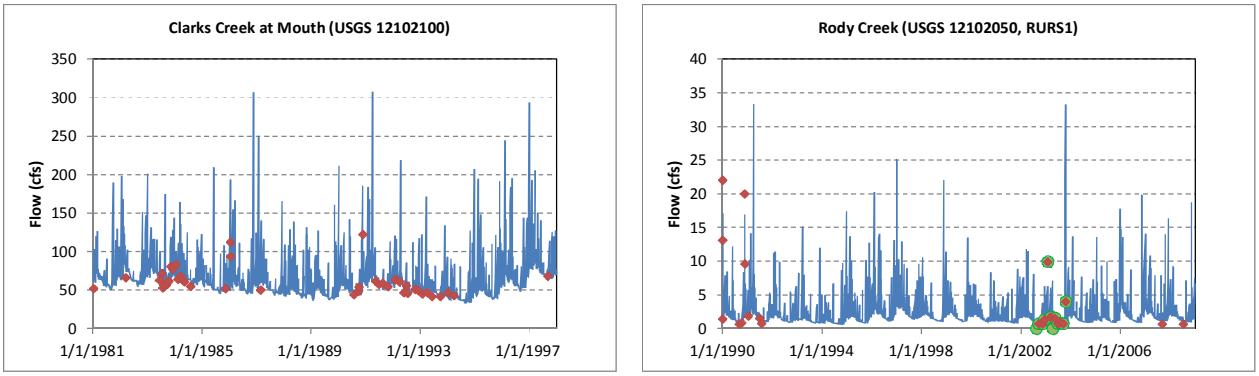


Figure 6-21. Comparison of Observed and Simulated Flows for Clarks Creek at Mouth and Rody Creek (cfs)

Note: Non-USGS measurements are shown with a green halo; simulated flows are daily averages, observed flows are instantaneous measurements.

The agreement between observations and predictions appears reasonable, particularly given that the observations are instantaneous. The average error at the mouth is 8.03 percent, while that on Rody Creek is 15.35 percent.

Comparisons at eight additional stations are shown in Figure 6-22. The model appears reasonable. Some individual events appear to be under-predicted, but this is likely due to the 2002-2003 instantaneous measurements targeting peak storm flows.

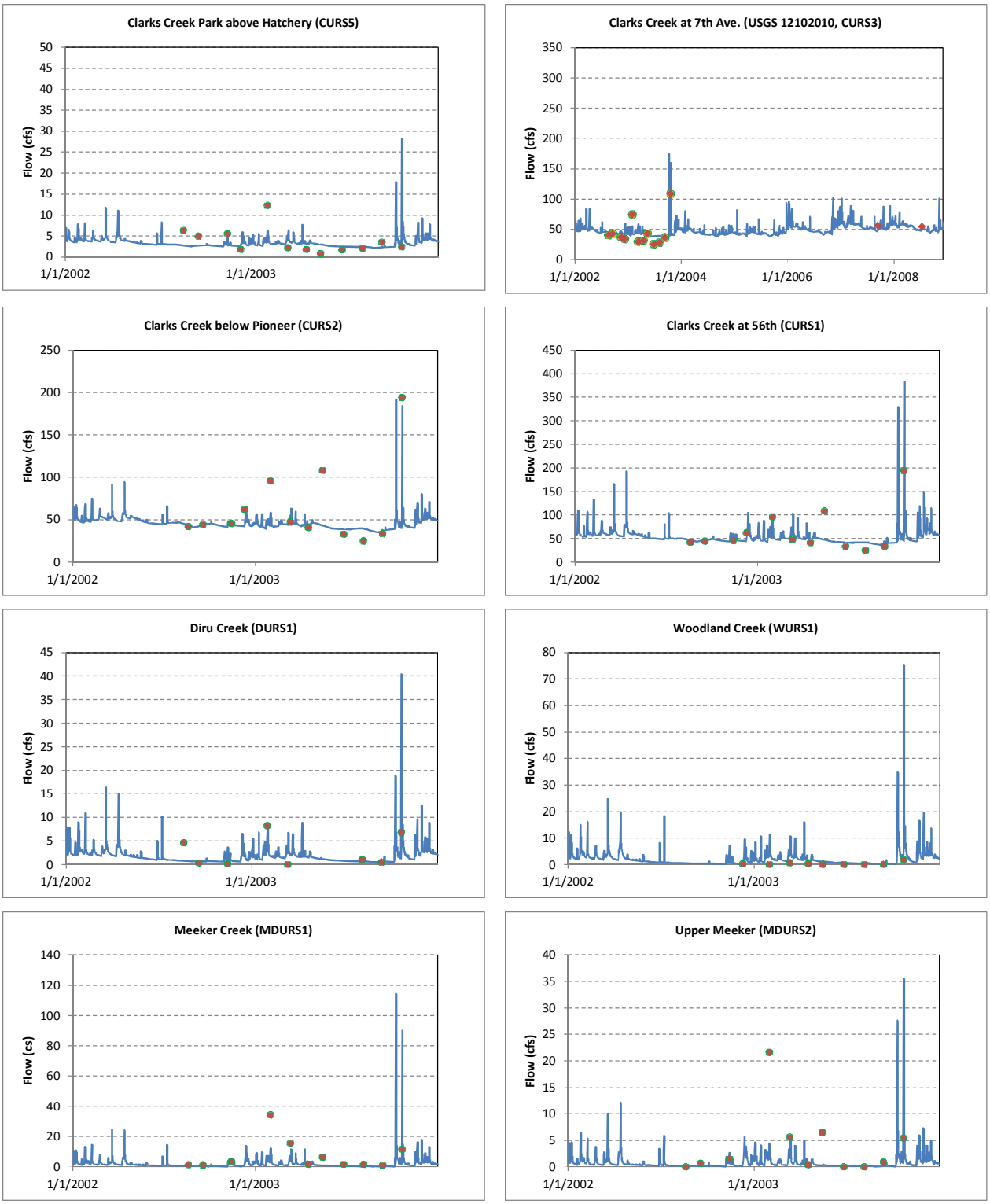


Figure 6-22. Comparison of Observed and Simulated Flows for Miscellaneous Clarks Creek Measurements (cfs)

Note: Non-USGS measurements are shown with a green halo; simulated flows are daily averages, observed flows are instantaneous measurements.

Additional flow observations are available in the area of the State Hatchery (USGS 12102000 and CURS4). The stations appear to be not exactly coincident, although the location given for the 2002-2003 station (CURS4) is uncertain as the coordinates do not fall on the streamline. Both are in the general neighborhood of the overflow releases from Maplewood Springs and the return flow from the hatchery, but the exact spatial relationship is unclear. This is also an area where significant amounts of spring flow enter the stream from the foot of the Vashon Till. The two gages are in the middle of HSPF reach 135, so also are not exactly matched to the model. USGS measurements at this location fall slightly below model predictions, while the 2002-2003 measurements at CURS4 tend to be higher (Figure 6-23). These discrepancies are likely related to the location of the gage sites relative to the complex inflows in this reach.

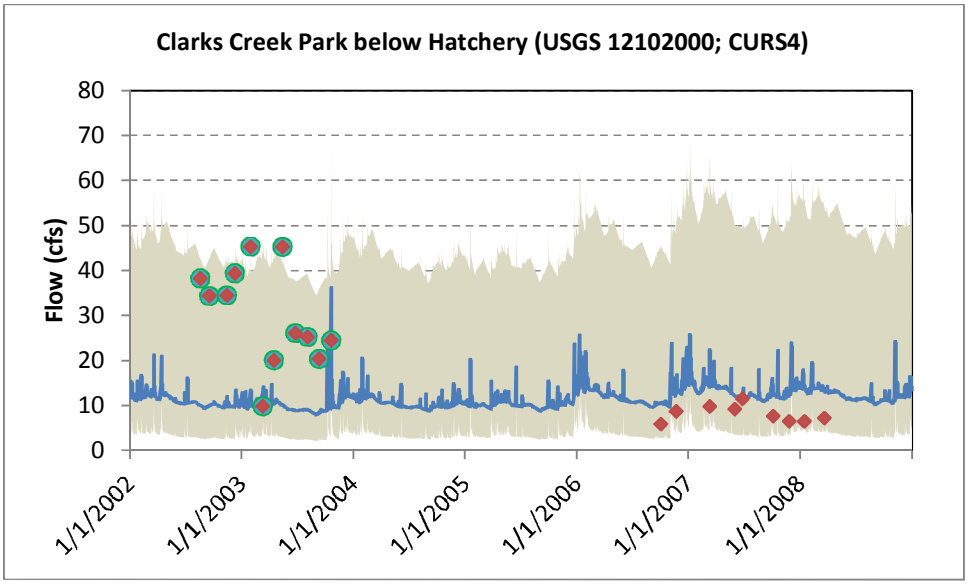


Figure 6-23. Flow Measurements in Vicinity of State Hatchery

Note: Blue line shows model predictions for Reach 134. Grey area shows range from upstream Reach 135 to downstream reach 133. Non-USGS measurements are shown with a green halo; simulated flows are daily averages, observed flows are instantaneous measurements.

7 Sediment Calibration and Validation

The HSPF model has the capability to simulate a variety of processes related to sediment and solids transport. On pervious and impervious upland areas the model simulates a single bulk solids class, subject to some or all of the following processes:

- Detachment of sediment from pervious surfaces by rainfall splash or human influences (as a function of rainfall intensity, cover, soil characteristics, and management practices).
- Accumulation of solids on impervious surfaces.
- Wind deposition of solids on pervious and impervious surfaces.
- Reattachment of solids into the soil matrix or removal of solids from impervious surfaces by wind, street cleaning, or other mechanisms.
- Washoff of detached solids to receiving streams as a function of surface flow depth.
- Scour of the soil matrix by concentrated flow (gully formation).

The bulk solids simulated on the uplands are converted to three size fractions (sand, silt, clay) when load enters the receiving water. This is a user specification: the model does not compute size fractions on the upland or calculate enrichment of fines during transport.

Within the stream network, the model simulates the three size classes separately, performing mass balances in both the water column and stream bed. Solids in the stream are subject to the following processes:

- Advective transport.
- Settling and deposition to the stream bed at lower flows as a function of flow velocity (for non-cohesive sand) or shear stress (for cohesive silt and clay).
- Scour from the stream bed and bank at higher flows as a function of flow velocity (for non-cohesive sand) or shear stress (for cohesive silt and clay).
- Point source load additions.

A stream reach is represented as a fully mixed segment and the model does not contain detailed geometry of the channel at the within-reach scale, so the resolution of processes is limited to the scale of reach. The model thus simulates aggradation and degradation of stream reaches in an approximate, summary manner that is appropriate to a watershed scale mass balance, but does not identify the exact location of aggradation and degradation processes in specific stream reaches.

7.1 Sediment Calibration Approach

Calibration of watershed sediment models is complex because instream observations of TSS are the net result of a variety of complex processes, including sediment detachment on the uplands, transport of detached sediment from the land surface to streams, and bank erosion, scour, and deposition within the streams. In addition, data for calibration are often limited – certainly the case for Clarks Creek. As a result, there is often not a unique solution to model calibration, as, for example, high concentrations observed in stream could result from elevated upland loads and/or sediment scour within the channel. These two sources are not readily distinguished through observations unless auxiliary information (such as radionuclide data) is collected to identify the fraction of stream sediment that has been in recent contact with the atmosphere.

An additional challenge for sediment calibration is that sediment concentrations often vary rapidly over short time intervals. For instance, the first flush phenomenon can result in TSS concentrations that spike up in the rising limb of the storm hydrograph, then decline. Instantaneous grab samples may provide little

information on the daily average sediment concentration, while sub-daily model predictions and observations for the same time interval may show large discrepancies if there are small differences in the timing of predicted and observed flows. Flow-weighted composites over the storm hydrograph are most informative. For Clarks Creek, most available TSS samples are grab samples – and the time of collection is not available for most of the samples. The recourse is to compare these point-in-time samples to daily average concentrations produced by the model and attempt to obtain a representation that is unbiased over the long term, recognizing that there will be significant discrepancies between some individual observations and model predictions.

The approach undertaken for sediment calibration follows the guidance of USEPA (2006) and Donigian and Love (2003).

The general strategy for sediment calibration of the Clarks Creek model, following Donigian and Love (2003), consists of the following steps:

- Specify initial upland parameter values for soil erodibility (detachment rates) on pervious land and soil accumulation rates on impervious surfaces based on external information (e.g., soils data, literature).
- Adjust upland sediment transport rates from individual land uses to achieve general consistency with annual sediment loading rates reported in the literature (preferably from local studies).
- Analyze the instream sediment mass balance on a reach by reach basis to ensure reasonable representation of areas of scour and deposition.
- Adjust instream/channel parameters to match observed total suspended solids (TSS) concentrations and loads.

Each of these steps is described below.

7.2 UPLAND PARAMETER SPECIFICATION

Parameters controlling the erodibility of the soil are specified based on soil properties. The HSPF model does not use the Universal Soil Loss Equation (USLE) for sediment simulation; however, some of the parameters used in HSPF are similar to those in the USLE. The USDA State Soils (SSURGO) database provides a number of USLE parameter estimates by soil type, and these can be used to set initial parameter values – ensuring relative consistency between the HSPF and USLE approaches.

HSPF erosion parameters for pervious land uses were estimated based on a theoretical relationship between HSPF algorithms and documented soil parameters, ensuring consistency in relative estimates of erosion based on soil type and cover. Sediment is available for transport once it is detached from the soil matrix. HSPF calculates the detachment rate of sediment by rainfall energy (in tons/acre) as

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

where DET is the detachment rate (tons/acre), COVER is the dimensionless factor accounting for the effects of cover on the detachment of soil particles, SMPF is the dimensionless management practice factor, KRER is the coefficient in the soil detachment equation, JRER is the exponent in the soil detachment equation, which is recommended to be set to 1.81, and P is precipitation in inches. Actual sediment storage available for transport (*DETS*) is a function of accumulation over time and the reincorporation rate, *AFFIX*. The equation for *DET* is formally similar to the USLE equation (Wischmeier and Smith, 1978) where RE is the rainfall erosivity, K is the soil erodibility factor, LS is the length-slope factor, C is the cover factor, and P is the practice factor,

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

USLE predicts sediment loss from one or a series of events at the field scale, and thus incorporates local transport as well as sediment detachment. For a large event with a significant antecedent dry period, it is reasonable to assume that *DET*≈*DETS* if *AFFIX* is greater than zero. Further, during a large runoff event, sediment yield at the field scale is assumed to be limited by supply, rather than transport capacity. Under those conditions, the USLE yield from an event should approximate *DET* in HSPF.

With these assumptions, the HSPF variable *SMPF* may be taken as fully analogous to the USLE P factor. The complement of *COVER* is equivalent to the USLE C factor (i.e., (1 - *COVER*) = C). This leaves the following equivalence (given JRER = 1.81):

$$KRER \cdot P^{JRER} \quad = \quad RE \cdot K \cdot LS \text{, or}$$

$$KRER = {RE \cdot K \cdot LS}/{P^{1.81}}$$

The empirical equation of Richardson et al. (1983) as further tested by Haith and Merrill (1987) gives an expression for RE (in units of MJ-mm/ha-h) in terms of precipitation:

$$RE \quad = \quad 64.6 \cdot a_t \cdot R^{1.81}$$

where R is precipitation in cm and a_t is an empirical factor that varies by location and season. As shown in Haith et al. (1992), the expression for RE can be re-expressed in units of metric tons/ha as:

$$RE \quad = \quad 0.132 \cdot 64.6 \cdot a_t \cdot R^{1.81}$$

This relationship suggests that the HSPF exponent on precipitation, *JRER*, should be set to 1.81.

The remainder of the terms in the calculation of *RE* must be subsumed into the *KRER* term of HSPF, with a units conversion. Writing *RE* in terms of tons/acre and using precipitation in inches:

$$RE\,(tons/ac) \quad = \quad \left[0.132 \cdot 64.6 \cdot a_t\right] \cdot P\,(in)^{1.81} \cdot (2.54\ cm/in)^{1.81} \cdot (1\ ton/ac)/(2.24\ tonnes/ha)$$

The average value for a_t for this part of Washington is about 0.18 (Selker et al., 1990), yielding

$$RE = 3.7032 \cdot P^{1.81}$$

The power term for precipitation can then be eliminated from the equation for *KRER*, leaving the following expression (English units) in terms of the USLE K factor:

$$KRER \quad = \quad 3.7032 \cdot K \cdot LS$$

The K factor is available directly from soil surveys, while the LS factor can be estimated from slope, using the expression of Wischmeier and Smith (1978):

$$LS = \left(0.045\,L\right)^b \cdot \left(65.41 \sin^2 \theta_k + 4.56 \sin \theta_k + 0.065\right) \text{, where}$$

$\theta = \tan^{-1}(S/100)$, *S* is the slope in percent, *L* is the slope length, and *b* takes the following values: 0.5 for S ≥ 5, 0.4 for 3.5 ≤ S < 5, 0.3 for 1 ≤ S < 3, and 0.2 for S < 1.

This approach establishes initial values for *KRER* that are consistent with USLE information. It should be noted that Donigian and Love (2003) recommend setting *KRER* directly equal to the USLE *K* factor. As can be seen from the discussion above, this is theoretically incorrect, although *KRER* will be proportional to *K*, depending on slope.

Other soil erosion parameters were assigned based on land use. The *SMPF* factor is typically used to describe row crop agricultural management practices, and was left at 1 for all land uses in the watershed except agriculture, where a value of 0.75 was assigned, representing approximately 50 percent adoption

of erosion reduction BMPs. *COVER* was assigned to PERLND as the complement of the USLE *C* factor, estimated on a monthly basis. Basic *C* factors were assigned according to Novotny and Chesters (1981).

Evidence was not available to support a detailed analysis of gully formation outside the stream network, although this can be a significant source of sediment load. The gully routines were turned on for the highest-sloped forest land segments.

For impervious surfaces (including roads), availability of solids is simulated with a buildup-washoff formulation, which requires an accumulation rate (ACCSD) and a removal rate (REMSDP). The asymptotic steady-state limit of storage mass (under conditions of no washoff) is equal to the accumulation rate divided by the removal rate. Initial values were set based on literature and experience (Table 7-1). Accumulation rates are set to vary within a relatively narrow range from 0.01 tons/ac/day to 0.02 tons/ac/day, with higher rates for high density urban land uses, consistent with studies summarized in USEPA (2006) and Novotny and Olem (1994). Removal rates for most land uses are set at 0.04 per day, in the typical range recommended by USEPA (2006). Higher removal rates are set for roads. On transportation arteries significant removal is caused by wind turbulence caused by passing cars, while many urban streets are subject to mechanical street cleaning. While empirical relationships have been developed to describe the effect of traffic density, curb height, and street cleaning frequency on removal rates for solids (Novotny and Olem, 1994), such data were not readily available for the Clarks Creek watershed.

Table 7-1. Sediment Buildup Parameters for Impervious Lands

Impervious Land Use	Accumulation (ACCSDP, t/ac/day)	Removal (REMSDP; day^{-1})
High density developed	0.020	0.040
Medium density developed	0.015	0.040
Low density developed	0.015	0.040
Road (till area)	0.012	0.100
Road (alluvial areas)	0.012	0.100
Park	0.010	0.040

Washoff of sediment from high and medium density impervious areas was simulated with sediment option SDOP=0, which calculates transport capacity as a function of depth of flow, not depth of flow plus surface storage. Use of this option is essential for impervious surfaces in Clarks Creek because surface storage is being used to approximate partial stormwater detention, as described in Section 4.4, and this storage should not be included in transport capacity.

7.3 SEDIMENT TRANSPORT TO STREAM

HSPF simulates transport of detached sediment as a function of overland flow depth, controlled by a coefficient (KSER) and an exponent (JSER) on flow depth. The exponent, JSER, was set to the recommended value of 1.67, while the coefficient, KSER, was adjusted to obtain a reasonable representation of average annual solids loading by land use (as a function of hydrology) while also providing an amount of suspended solids load consistent with instream observations. One useful reference from western Washington is the Green-Duwamish study in King Co. (Herrera, 2007). This reports average annual loading rates from low-to-medium-density development of 0.07 tons/ac/yr and from high density development of 0.077 tons/ac/yr. Herrera also reports suspended solids load from agriculture that seem low (0.0215 t/ac/yr) and from forest that seem high (0.0489 t/ac/yr), but may reflect the specific circumstances of their monitoring watersheds. Intact forest can often have much lower loading rates, whereas agriculture with poorer management practices can have significantly higher loads.

Notably, Herrera's forest tributaries were about 90 percent forest, with the remainder including roads, grass, and some development, which could account for a majority of the load. The Clarks Creek model separates intact forest from these other land uses and is expected to have low unit area loading rates.

National data on solids loads from roads provide averages mostly in the range of 0.14 to 2 t/ac/yr (Driscoll et al., 1990), with the higher loads tending to occur in areas that combine high traffic with high amounts of wind-blown dust deposition. The average simulated loading rates for the Clarks Creek watershed are thus expected to fall at the lower end of this range.

A reasonable representation of sediment yield by land use was obtained by setting a uniform value of the pervious land sediment transport coefficient KSER at 10.0 while varying the impervious land transport coefficient KEIM from 0.054 to 0.065, with the higher values specified for roads, which are generally designed for efficient water removal. The resulting upland sediment yield rates are summarized in Figure 7-1.

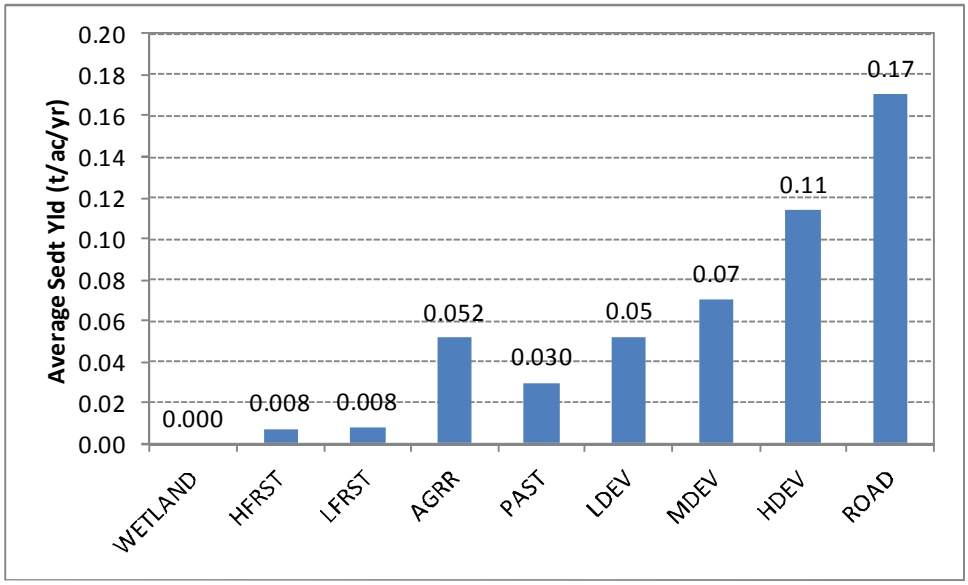


Figure 7-1. Average Annual Sediment Yield by Land Use

Note: Unweighted averages across all soils and slopes are shown for comparison to literature values. Impervious area percentages are assumed to be 5% for low density development (LDEV), 20% for medium density development (MDEV), 45% for high density development (HDEV), and 67% for roads for purposes of comparison.

HSPF simulates total sediment on the uplands, but represents sand, silt, and clay separately in the stream reaches. Assignment to these classes is made in the MASS-LINK block, which routes the upland load to the stream. Across the whole watershed, the area-weighted composition of surficial sediment is 48 percent sand, 40 percent silt, and 11 percent clay based on the SSURGO soil survey coverage. Sediment detachment and transport processes, however, result in a progressive enrichment of the finer fractions and proportionately less transport of the heavier sand fraction. Because the probability of redeposition of clays during overland transport is very small, Walling (1983) showed that the enrichment ratio for clay is approximately equal to the inverse of the delivery ratio (and thus should vary by subbasin size). For the small subbasins in the Clarks Creek model, an initial estimate of a delivery ratio as a function of area of around 30 percent is reasonable based on Roehl (1962); thus the clay fraction was increased from 11 to 37 percent and the silt fraction from 40 to 45 percent, leaving 18 percent sand. Note that even though loading may be enriched in fines much of the sediment bed is made up of sand. This occurs because the clay and much of the silt wash through the stream without settling out.

7.4 REACH SEDIMENT SETUP

Complex cycles of deposition and scour occur in stream reaches, determined by the shear stress exerted on the bed material and the external sediment supply. The model simulates deposition and scour (aggradation and deposition) of silt and clay in stream reaches based on exerted shear stress relative to critical shear stresses for deposition and scour (τ_{CD} and τ_{CS}) for each sediment size class, particle deposition velocities, and a limiting maximum potential rate of scour (W, lb/ft^2/d). The parameters τ_{CD}, τ_{CS}, and W are site-specific and vary by reach. (HSPF is a spatially lumped model, with stream reaches represented as fully mixed, and the simulated boundary shear stress represents reach-averaged conditions, while actual shear varies continuously based on local characteristics of the channel. As the processes are non-linear, a single set of parameters will not adequately represent the behavior of bed sediment in all reaches; instead, these should be set on a reach-by-reach basis.)

For the non-cohesive, sand fraction of sediment, HSPF provides several options, including the Toffaletti method, the Colby method, and a simplified exponential relationship to flow. The Toffaletti and Colby methods are most appropriate for wide sand-bed rivers and additionally can cause stability problems in the model, so the third (exponential equation) approach is used for Clarks Creek. In this approach sand transport capacity is a function of KSAND · AVVELE ^{EXPSND}, where AVVELE is the average velocity and KSAND and EXPSND are user-specified parameters.

Following the advice of Donigian and Love (2003) and USEPA (2006), critical shear stresses for cohesive sediments were initially set to percentiles of the overall shear (Tau) distribution, which is closely tied to flow (Figure 7-2). Specifically, τ_{CD} was set at the 25th and 20th percentiles of the distribution, for silt and clay, respectively, while τ_{CS} was set at the 95th and 90th percentiles for silt and clay. This allows scour to occur only at higher flows, with clay scouring prior to silt. Model predictions of scour at high flows are sensitive to these values; however, sufficient monitoring data of extreme events is not available to refine these values further.

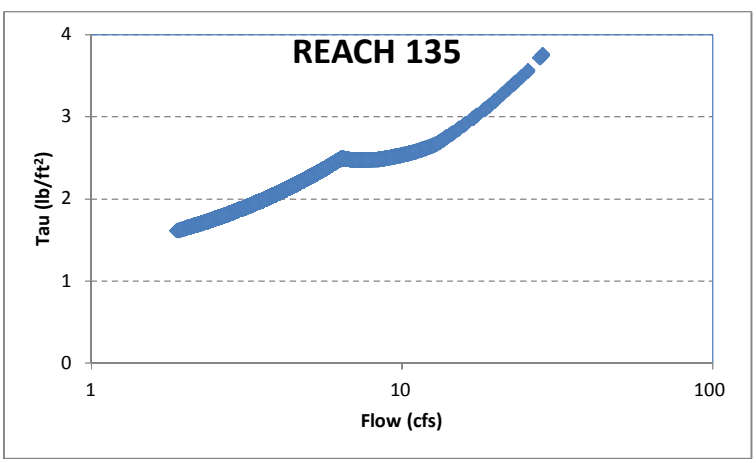


Figure 7-2. Example Relationship between Tau and Flow, Reach 135

Simulation of channel scour and deposition must provide a reasonable mass balance in the stream reaches in addition to matching observed TSS concentrations. The total change in simulated nominal bed depth over the 51-year simulation period is summarized by reach in Figure 7-3. (This is a "nominal" rather than actual change because HSPF represents the reaches in a simplified, one-dimensional manner). As seen in this figure, most stream reaches remain approximately stable over time. Degradation (decrease in bed depth) is simulated primarily in reaches that intersect the face of the Vashon Till (134 on the mainstem, 128 on Silver Creek, 147 on Woodland Creek, 157 on Diru Creek, and 166 on Rody Creek), while aggradation is simulated in the most downstream reaches of Woodland, Diru, and Rody, and in the mainstem after in enters the alluvial plain of the Puyallup River.

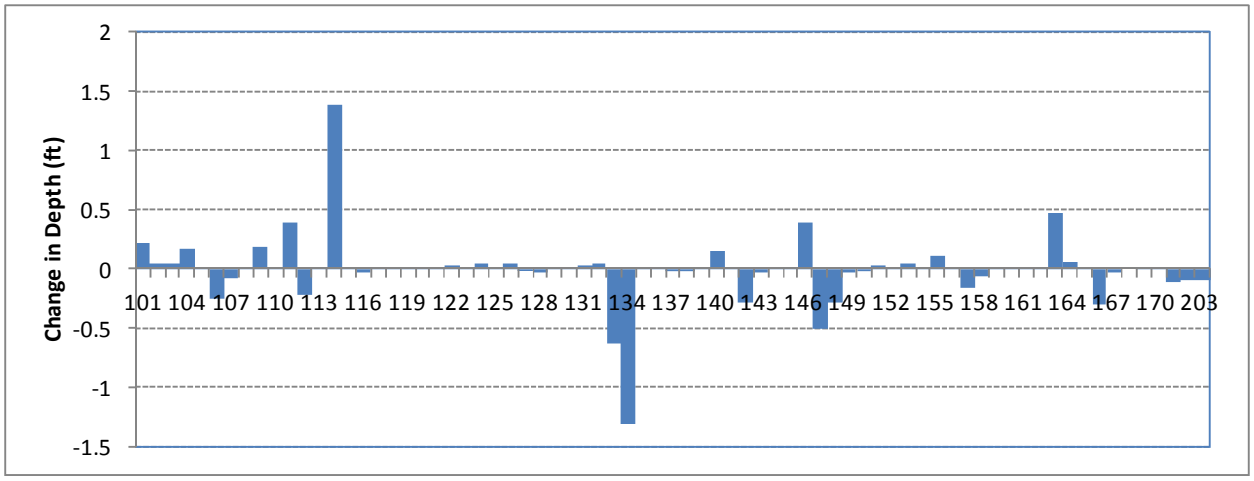


Figure 7-3. Simulated Change in Bed Depth by Model Reach, 1960-2010

Note: Depth changes are relative measures of scour/deposition in a one-dimensional reach model,

7.5 INSTREAM SEDIMENT CALIBRATION

The full sediment model is calibrated through comparison to observed total suspended solids concentrations by adjusting the parameters that control the scour and deposition of sand, silt, and clay (as well as by adjusting the upland transport simulation.) Suspended solids observations are available at multiple stations, but the number of samples at individual stations is limited. The calibration period was selected as the more data rich period of 2002 – 2010, while earlier data were used for validation. Unfortunately, the desired minimum sample size of 20 observations is attained at only a few of the stations. Accordingly, a weight of evidence approach was used, for which model fit statistics are supplemented with a variety of graphical comparisons.

It should be noted that a technical limitation of the HSPF model creates potential problems for fitting to observed concentrations in very small streams. Specifically, HSPF subroutine BDEXCH turns off the simulation of cohesive sediment scour and deposition when reach average depth falls below 0.17 ft (2 inches), where average depth is defined as the reach volume divided by the surface area. This is designed to prevent model instability. With the exception of the mainstem of Clarks Creek downstream of Maplewood Springs, most reaches in the model experience average depths that are less than 0.17 ft at least some of the time. During these periods settling of silt and clay is not simulated; instead, both are transported through the reach unchanged, whereas in fact significant settling is likely to occur during such low flow conditions. This limits the model's ability to reproduce low flow observations, including observations in the mainstem that are affected by simulated concentrations in smaller tributaries. This is not a significant problem, however, as the load transported at low flows will be small and will not contribute significantly to solids concentrations and loads in the Clarks Creek mainstem.

Figure 7-4 through Figure 7-7 show sediment calibration results at four stations on Clarks Creek mainstem, arranged in downstream order. For each of these observation points the model predicts the range of TSS observations reasonably well, although not all individual observations are matched. The lowest observations (less than 2 mg/L) are over-estimated at 7th Street and 12th Street primarily due to an assumption that low levels of fines are associated with the baseflow from springs in the upper reaches of the creek (1 mg/L above the State Hatchery and 2 mg/L below). These constant concentration assumptions (which represent a typical background condition due to factors such as animal activity as well as any fine sediment actually discharged or eroded at the spring outfalls) fit the majority of the data, but over-predict some individual low-flow measurements.

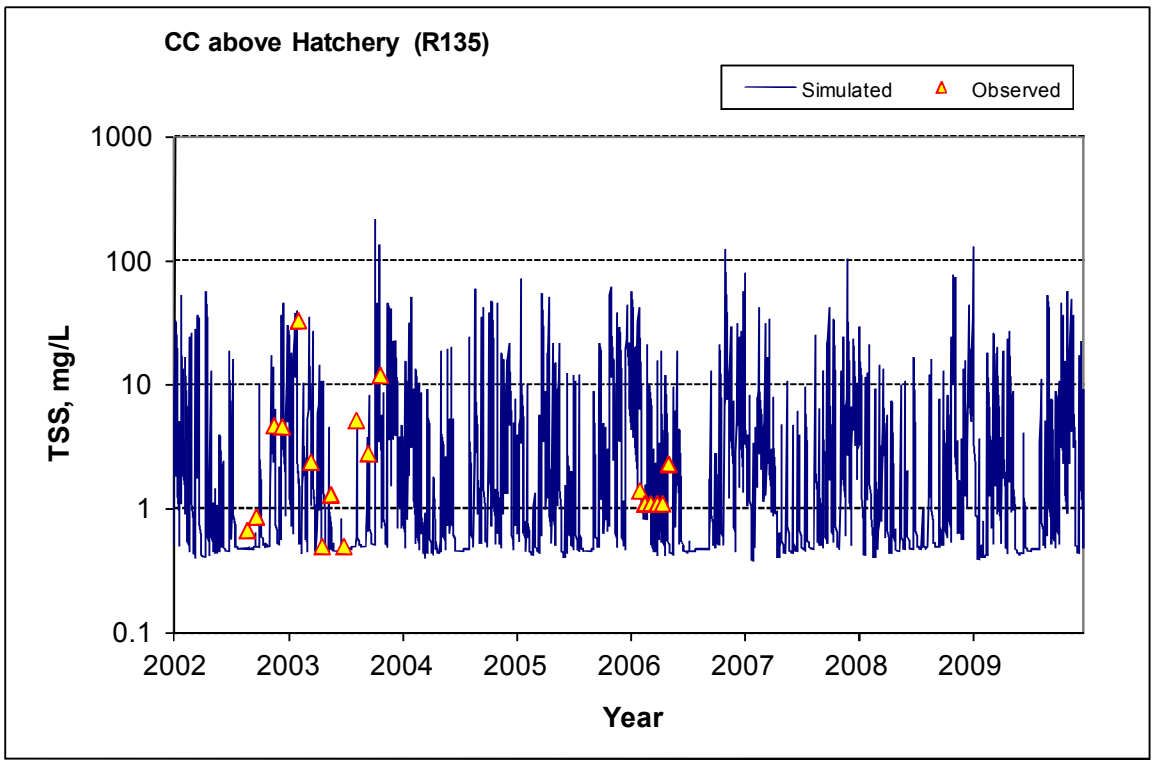


Figure 7-4. Time Series Comparison for TSS, Clarks Creek above State Hatchery, 2002-2010

Note: Data shown are for stations CCURS-5 and Clk-4

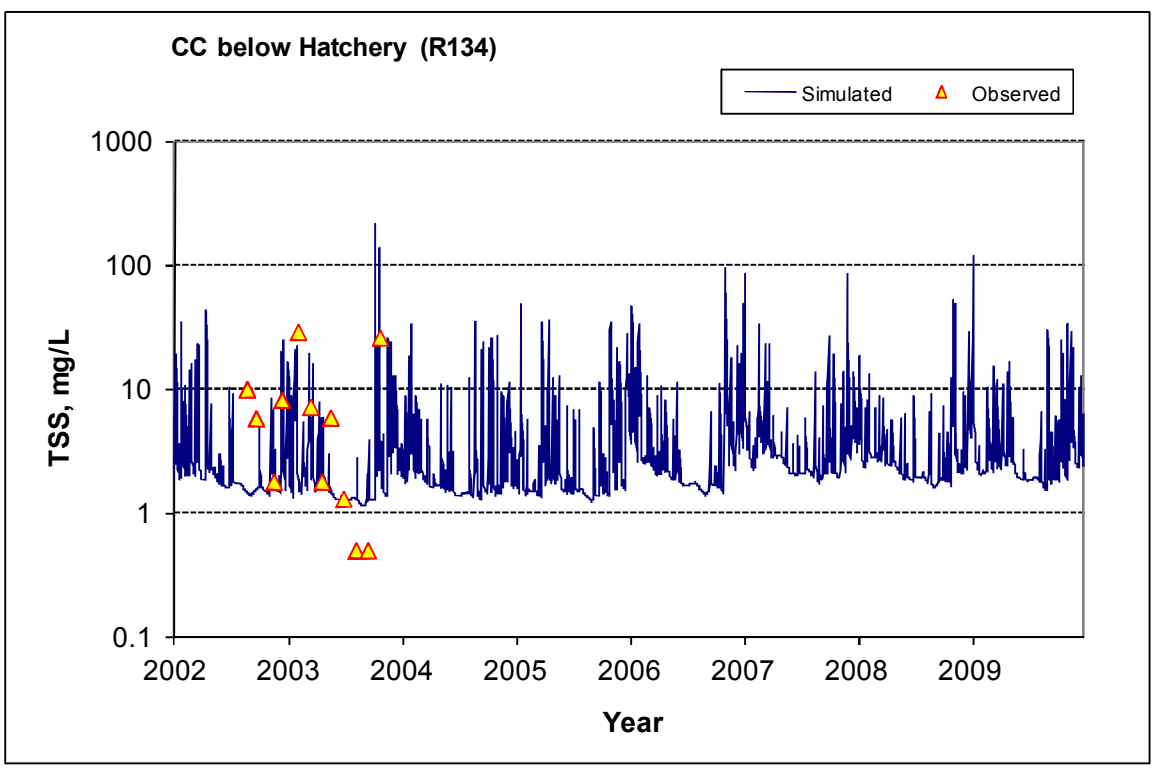


Figure 7-5. Time Series Comparison for TSS, Clarks Creek below State Hatchery, 2002-2010

Note: Data shown are for station CCURS-2

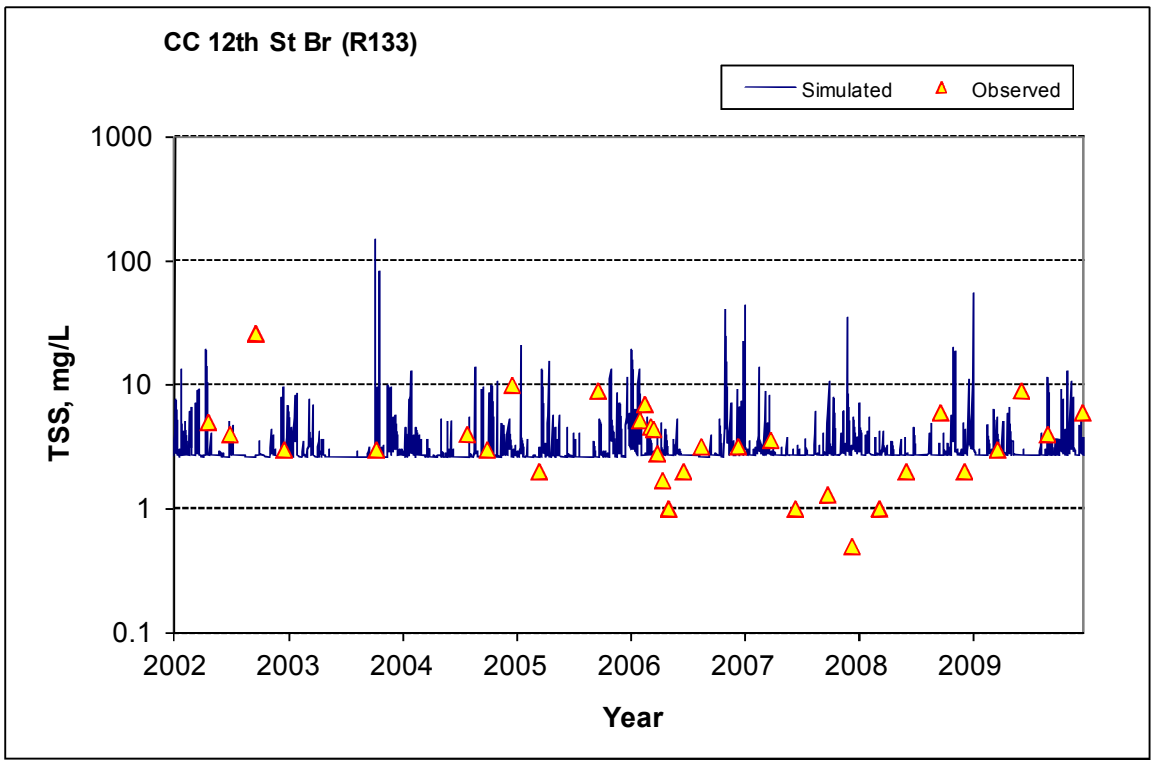


Figure 7-6. Time Series Comparison for TSS, Clarks Creek at 12th St. Bridge, 2002-2010

Note: Data shown are for station Clk-8

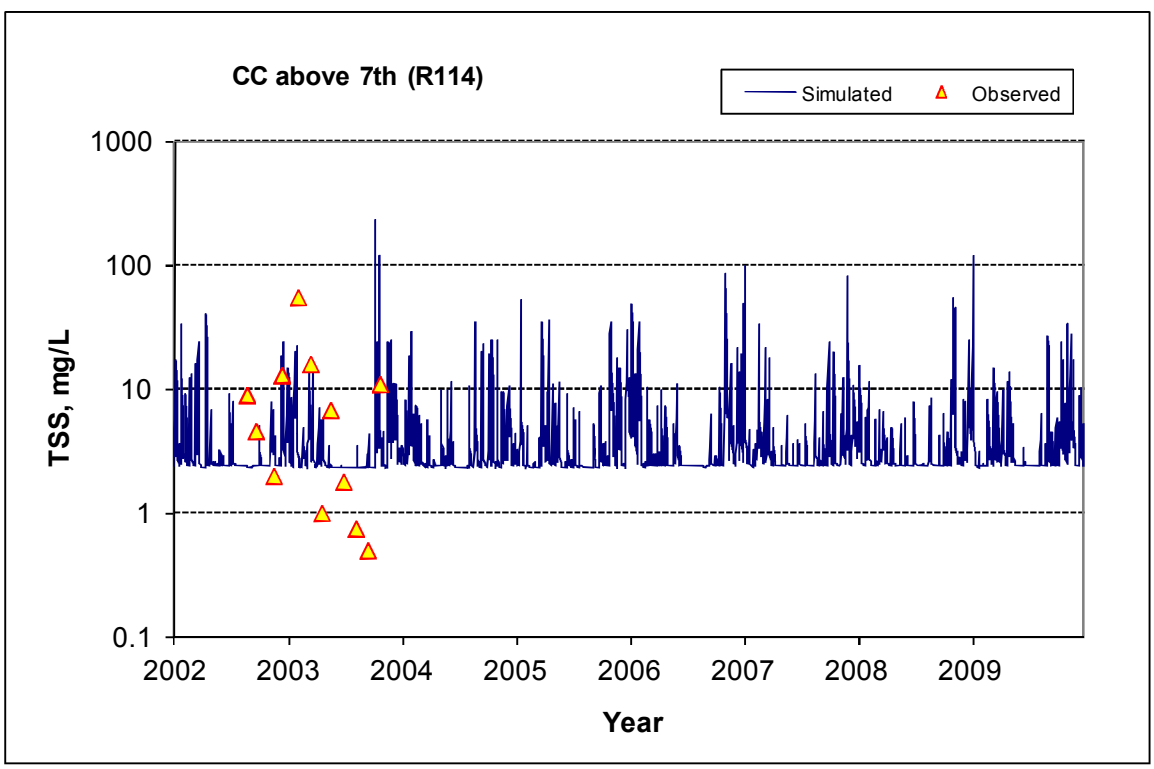


Figure 7-7. Time Series Comparison for TSS, Clarks Creek above 7th Street, 2002-2010

Note: Data shown are for station CCURS-3

The calibration procedure is illustrated in more detail for the downstream station on Clarks Creek at 66th Street. In addition to standard time series plots (Figure 7-8), power plots of load and concentration versus flow were used to ensure that the model and data show similar relationships (Figure 7-9). Plots of prediction error versus month and flow are used to check whether there are significant trends with season or flow magnitude, recognizing that considerable variability is expected from the comparison of grab samples to daily averages. For this station (Figure 7-10 and Figure 7-11), the errors are relatively evenly distributed against month (it could be contended that December TSS is over-estimated, but the sample size is small). Distribution of errors versus flow also does not show any strong bias. Observations appear to be somewhat over-predicted at high flows, but this may be a result of small differences in timing and the comparison of model daily averages to grab samples. In addition, the HSPF representation of reaches cannot distinguish between bedload and suspended load and will thus overpredict observations of TSS if a significant fraction of solids is moving as bedload and is not represented in water column grab samples.

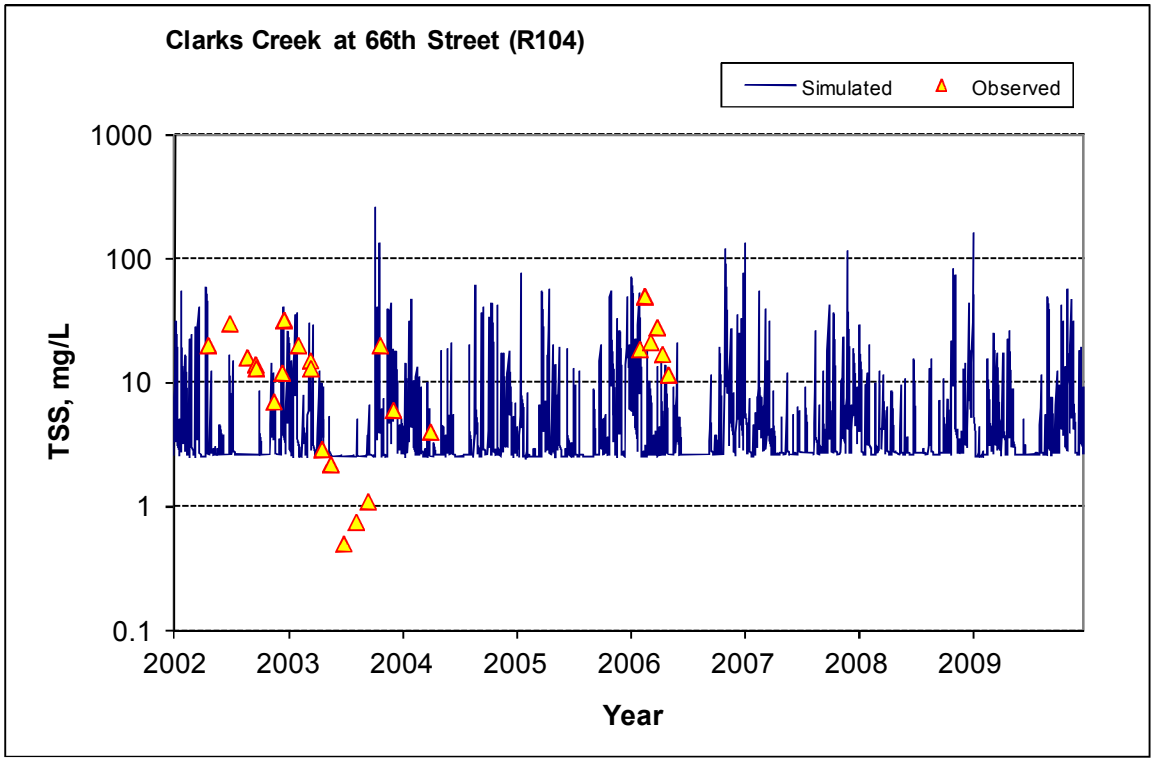


Figure 7-8. Time Series Comparison for TSS Calibration, Clarks Creek at 66th Street, 2002-2010

Note: Data shown are for stations CLK-4.1, Clk-4, and CCURS-1.

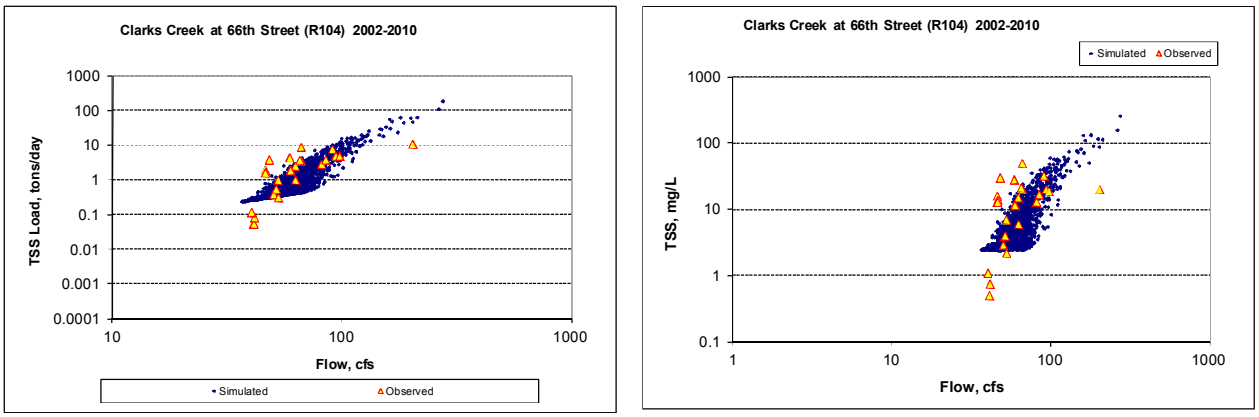


Figure 7-9. Power Plots of TSS Load and Concentration versus Flow, Clarks Creek at 66th Street, 2002-2010

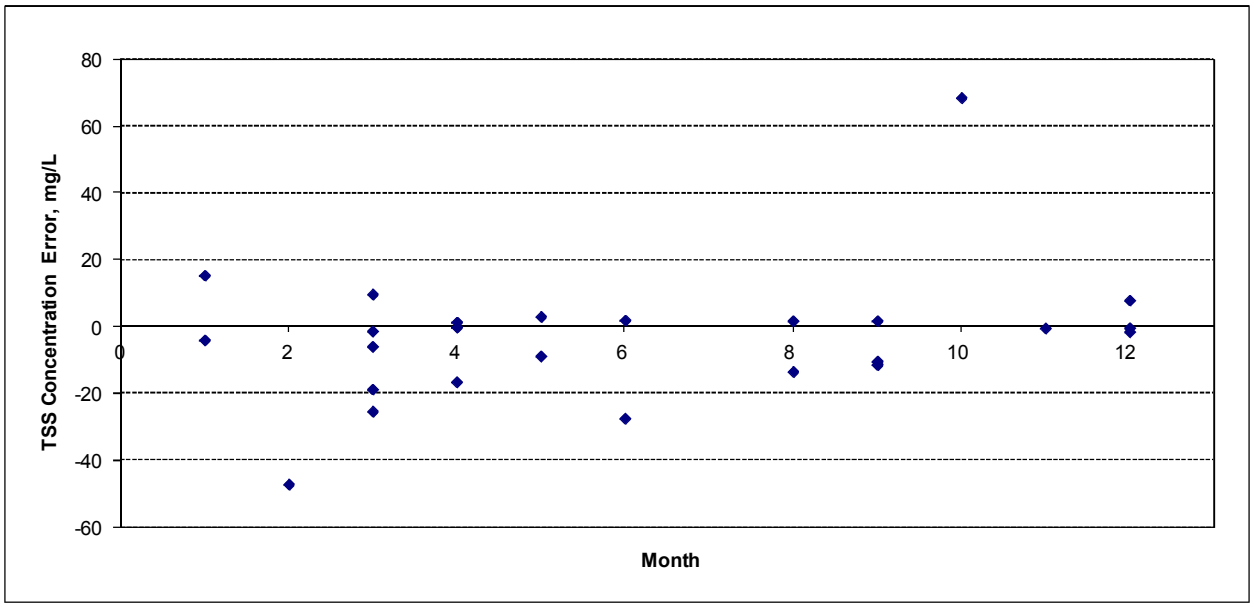


Figure 7-10. TSS Prediction Error versus Month, Clarks Creek at 66th Street, 2002-2010

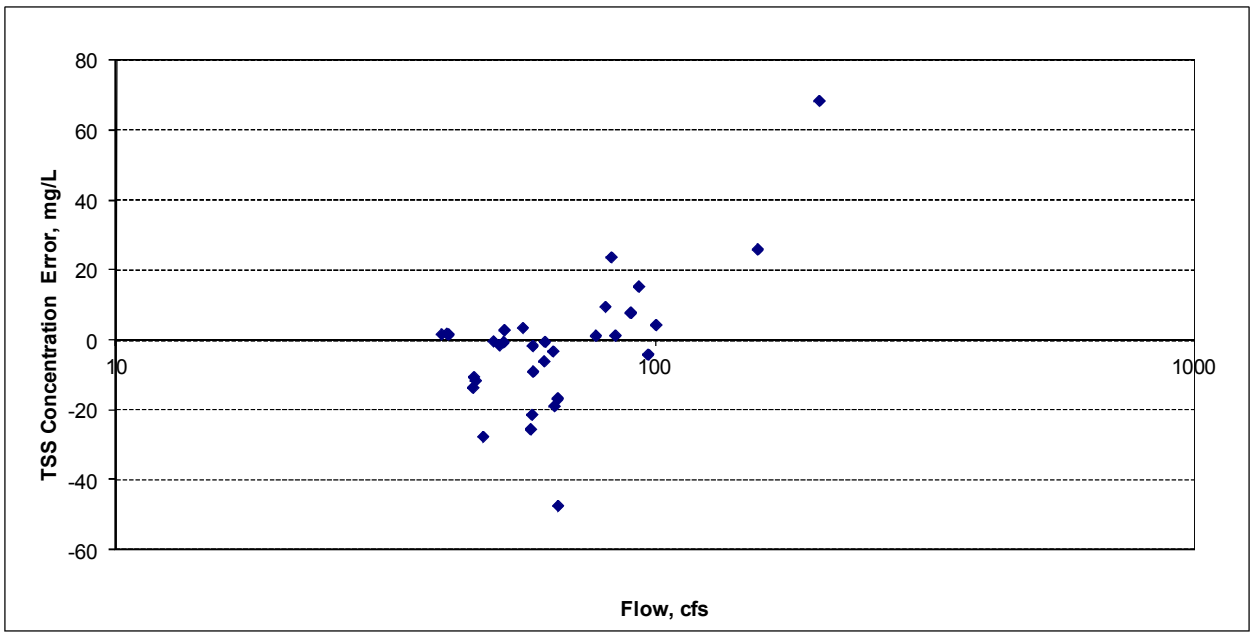


Figure 7-11. TSS Prediction Error versus Flow, Clarks Creek at 66th Street, 2002-2010

Further examination of TSS prediction errors at 66th Street suggest that much of the uncertainty in storm flow concentration predictions could be due to small errors in timing. The observations are point-in-time grab samples that are likely to vary rapidly in time due to pulses from the nearby storm drains. Comparison is shown above to daily average model output as the majority of data do not show time of sample collection. Even if time of collection is available, small shifts in phase between the model and data due to reliance on a single weather station are likely to lead to relatively large discrepancies between the model and individual observations. The strong intra-day variability in predicted sediment concentrations at this station is shown in a detailed examination of December 2002 results (Figure 7-12).

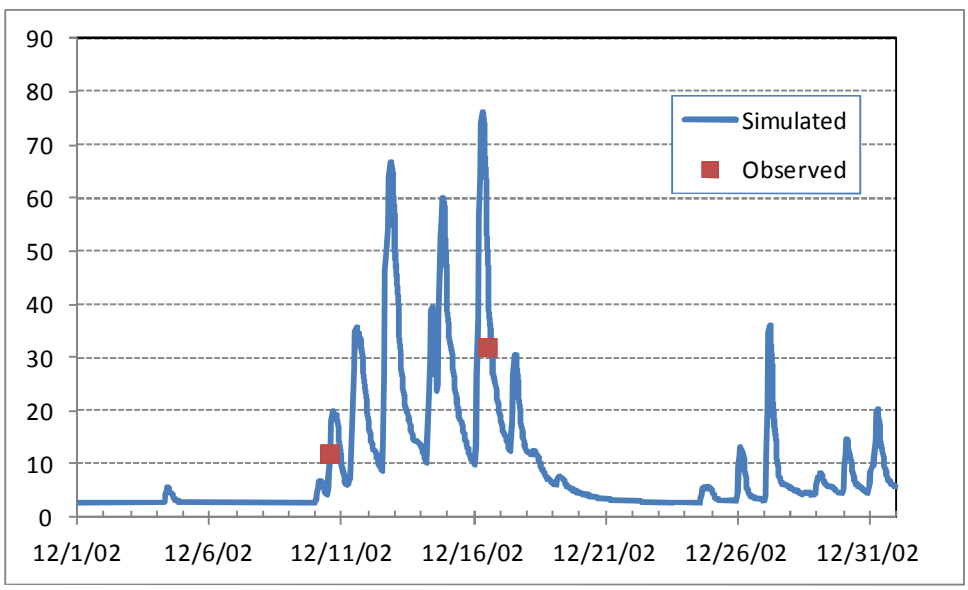


Figure 7-12. Hourly Variability in Predicted Sediment Concentration, Clarks Creek at 66th Street, December 2002

Additional data, mostly from 2002-2003, are available at the mouths of Meeker, Rody, and Diru Creeks. Calibration statistics for TSS are presented in Table 7-2. Most of the stations either do not meet the

minimum data requirement for quantitative analysis of 20 samples (see Section 5.2), or exceed it by a small amount. This leaves the results open to undue influence by outliers. This can be mitigated by examining median rather than average relative errors. Good or very good results are obtained for most stations and high average relative errors are mostly attributable to outliers. For example, at the 12th Street monitoring site, the large average relative error is mostly due to a large error associated with the event of 10/8/2003 when the model predicted a daily average of 145 mg/L, but the observation showed only 3 mg/L. As was noted in Section 6.5, the extreme precipitation recorded for this day may be in error.

Results for Clarks Creek above the State Hatchery should be viewed in light of the observation that flow is often under-predicted at this site due to uncertainty as to exactly where the spring-fed baseflow enters the stream (see Figure 6-23). Therefore, the over-estimation, on average, of TSS at this location is not unexpected.

The limited sampling at the mouths of Meeker, Rody, and Diru Creeks and upstream on Meeker Creek is also affected by occasional outliers and mistiming of event peaks, although the overall results appear consistent with the observations. Further, the simulated concentrations in Meeker, Rody, and Diru are consistent with the observed concentrations just downstream in Clarks Creek at 66th Street.

Table 7-2. Calibration Statistics for Total Suspended Sediment, 2002 – 2010

Station	Observation Count	Mean Observed (mg/L)	Average Relative Error	Median Relative Error
Clarks Creek at 66th Street	25	15.03	-21.7%	-8.6%
Clarks Creek above 7th Street	12	9.00	6.9%	-7.6%
Clarks Creek at 12th Street	32	4.48	70.4%	-7.2%
Clarks Creek below State Hatchery	12	8.17	17.4%	-0.8%
Clarks Creek above State Hatchery	18	4.26	152.3%	3.7%
Meeker Creek mouth	12	28.61	1.7%	-6.8%
Meeker at Reach 123	11	43.98	-27.0%	5.6%
Rody Creek mouth	11	30.67	-6.1%	-2.1%
Diru Creek mouth	11	14.02	51.3%	4.0%

Note: Relative errors are calculated as simulated minus observed normalized to the observed mean.

In sum, data for model calibration to TSS are limited; however, the model appears to perform adequately in predicting the available data. Sample sizes are small and easily influenced by a few outliers. The model does represent both the temporal and spatial trends in observed TSS.

7.6 SEDIMENT MODEL TESTING

The greatest amount of data is for 2002-2003, so observations from 2002 on were used for model calibration. Data from the period prior to 2002 was not used for calibration but reserved for additional testing of the sediment model. Ordinarily, this would be termed a validation test. Unfortunately, sample

sizes for this period are small, with the maximum number of available samples at a single station being nine. Therefore, examination of model predictions for this period is treated as a more qualitative corroboration test. Nonetheless, the general performance of the model for this period appears reasonable. Note that some of the samples collected at 66th Street prior to 2002 were apparently downstream of the Tribal hatchery rearing pond discharge, whereas later samples were upstream, which may help explain the results at that station.

Table 7-3. Validation Statistics for Total Suspended Sediment, 1996 – 2001

Station	Observation Count	Mean Observed (mg/L)	Average Relative Error	Median Relative Error
Clarks Creek at 66th Street	7	8.36	60.0%	43.4%
Clarks Creek above 7th Street	0	ND	ND	ND
Clarks Creek at 12th Street	3	4.63	47.7%	32.1%
Clarks Creek below State Hatchery	8	11.21	-28.2%	-8.5%
Clarks Creek above State Hatchery	9	34.6	-72.2%	1.8%
Meeker Creek mouth	5	123.78	-84.4%	-6.4%
Meeker at Reach 123	3	2.30	267.0%	348.7%
Rody Creek mouth	0	ND	ND	ND
Diru Creek mouth	0	ND	ND	ND

7.7 SEDIMENT LOAD SOURCES

The Clarks Creek model simulation indicates that most flow from pervious surfaces proceeds by interflow and groundwater pathways, rather than direct surface runoff. As a result, the majority of sediment load is simulated as coming from impervious surfaces (although much of this load will actually arise at the interface between impervious and pervious surfaces). The presence of some sediment load coming from interflow through macropores or soil "tubes" is in part accounted for by assigning a small sediment concentration to the spring discharges.

The overall sediment balance for the 51-year simulation period is summarized in Table 7-4. Over the entire stream network there is a net flux to the water column from the stream bank and bed (scour minus deposition) of 5 tons/yr. This obscures the fact that reaches at the face of the Vashon till are simulated as having substantial degradation. Degrading reaches are estimated to export a total of 103 tons/yr of sediment to the system, on average.

Table 7-4. Clarks Creek Sediment Balance for 1960-2010 Simulation

Source	Sediment Load (tons/yr)
Upland Sources (load to stream network)	471.4
Baseflow Sources (assigned to spring inflows)	102.9
Net Channel Processes	5.0
Outflow to Puyallup River	579.3

Over the whole watershed (excluding reach 301, where most flow and load is diverted to the Puyallup River by the WSDOT flow splitter), the largest source of sediment is runoff from the uplands. Details of the source of this load are shown in Table 7-5. These reflect generally low loading rates for pervious surfaces (and small areas associated with the agriculture and pasture land uses). High density development (which accounts for 13.3 percent of the land area in the watershed) is estimated to provide 30 percent of the total upland sediment load – largely because it contains 40 percent of the impervious area in the watershed. This suggests that strategies to reduce sediment load could focus on areas of more dense development. However, the mainstem of Clarks Creek is also strongly influenced by channel degradation in the area near and above the State Hatchery, estimated by the model to contribute about 42 tons/yr on average. Analysis of tributary contributions to the Clarks Creek mainstem (Table 7-6) suggests that Meeker Creek is the largest tributary contributor of sediment load. The high rates of load suggested by Table 7-6 for Woodland Creek may be an over-estimate as filtering in the wetland reported to be present at the confluence of Woodland Creek and Clarks Creek is not explicitly accounted for in the model.

Table 7-5. Upland Sediment Load Sources for 1960-2010 Simulation

Land Use	Average Total Load to Streams (tons/yr)
Forest	6.6
Agriculture and Pasture	6.7
High Density Development	140.4
Medium Density Development	53.8
Low Density Development	40.3
Roads	156.4
Parks	67.1

Table 7-6. Major Tributary Contributions to Sediment Load to Clarks Creek Mainstem

Tributary	Average Annual Load to Mainstem (tons/yr)
Clarks Creek Mainstem above Meeker Creek	180.8
Meeker Creek	107.2
7th Street Storm Drains	28.8
Pioneer Way Storm Drains	54.2
Woodland Creek	101.8
Diru Creek	51.1
Rody Creek	46.4

7.8 EFFECTIVE WORK ANALYSIS

An effective work analysis based on HSPF model simulated shear stress and geomorphic field work was conducted to estimate potential scour and depositional zones in the Clarks Creek mainstem channel. This is accomplished by combining flow and bed shear stress estimates from Tetra Tech's HSPF hydrology model with estimates of critical shear stress for incipient motion based on bed particle characteristics of individual stream reaches provided by Brown and Caldwell[1].

In physics, "work" is the product of a force times the distance through which it acts and is equivalent to a measure of energy – for example, the energy required to lift a bucket of water 10 feet, or to move a ton of sand 100 yards. The rate of movement of sediment is a function of stream power, which is the product of velocity and boundary shear stress (ft/s · lb/ft^2 in English units). If velocity is high but boundary shear is low, few particles will be eroded from the bed. Conversely, if shear is high but velocity is low, particles will be eroded, but little transport will occur. The sum or integral of power over time has units of work, and measures the total amount of sediment transport potential affecting a stream reach. Leopold et al. (1964) recognized that much of the total work done in erosion and transport of sediment occurs through the accumulation of events that have moderate to low power, but occur frequently. It is partly for this reason that bankfull flows (typically with a recurrence interval from 1.3 to 1.7 years) determine the cross-sectional shape of natural channels, rather than larger, more extreme events that may exhibit more power, but occur infrequently. Therefore, an analysis of the effective work done on a channel is an important indicator of channel stability – particularly for the evaluation of impacts of potential changes in hydrology.

It should be noted that the available data are not sufficient to produce quantitative estimates of total erosion. Critical shear stress is based on characteristic particle size (d_{50}) and does not reflect the full range of particles present in the bed, while shear stress time series are calculated from a one-dimensional model in which channel dimensions represent averages over model reaches. Instead, the analysis is most useful for relative evaluation.

[1] Critical Shear Stress Values for Use in Effective Work Analysis, Clarks Creek Sediment Study. Memorandum from Nathan Foged, Brown and Caldwell, December 15, 2011.

The effective work index, *W*, is an integrated measure of the magnitude of work done by flows that exceed a specified critical value for the streambed. The effective work index (in work units of ft-lb/ft^2) is calculated as

$$W = C \sum_{i=1}^{n} (\tau_i - \tau_c)^e V_i \, \Delta t \text{, for } \tau_i > \tau_c,$$

where *C* is a units conversion constant dependent on the exponent *e*, *n* is the number of flow records, τ_i is the exerted boundary shear stress (lb/ft^2) determined using the central channel conditions, τ_c is the critical shear stress that initiates bed mobility (lb/ft^2), *e* is an exponent that captures the rise in stream power with flow (range 1.0 to 2.5), *V* is the mid-channel velocity (ft/s), and Δt is the duration of each flow record (s). Note that the resulting index depends on both the frequency at which τ_c is exceeded and the degree of skew in the flow histogram.

For the Clarks Creek analysis, *e* is assumed to be 1.5 (consistent with theoretical analyses of bedload transport such as Meyer-Peter-Muller), and *C* is ignored, as a relative comparison is the main object. Sixty years of hourly model output are available (529,960 records). To simplify the analysis, this record was sub-sampled to extract one (hourly) record per day. Results for the mainstem model segments (outlined in blue in Figure 7-13) are shown in Table 7-7.

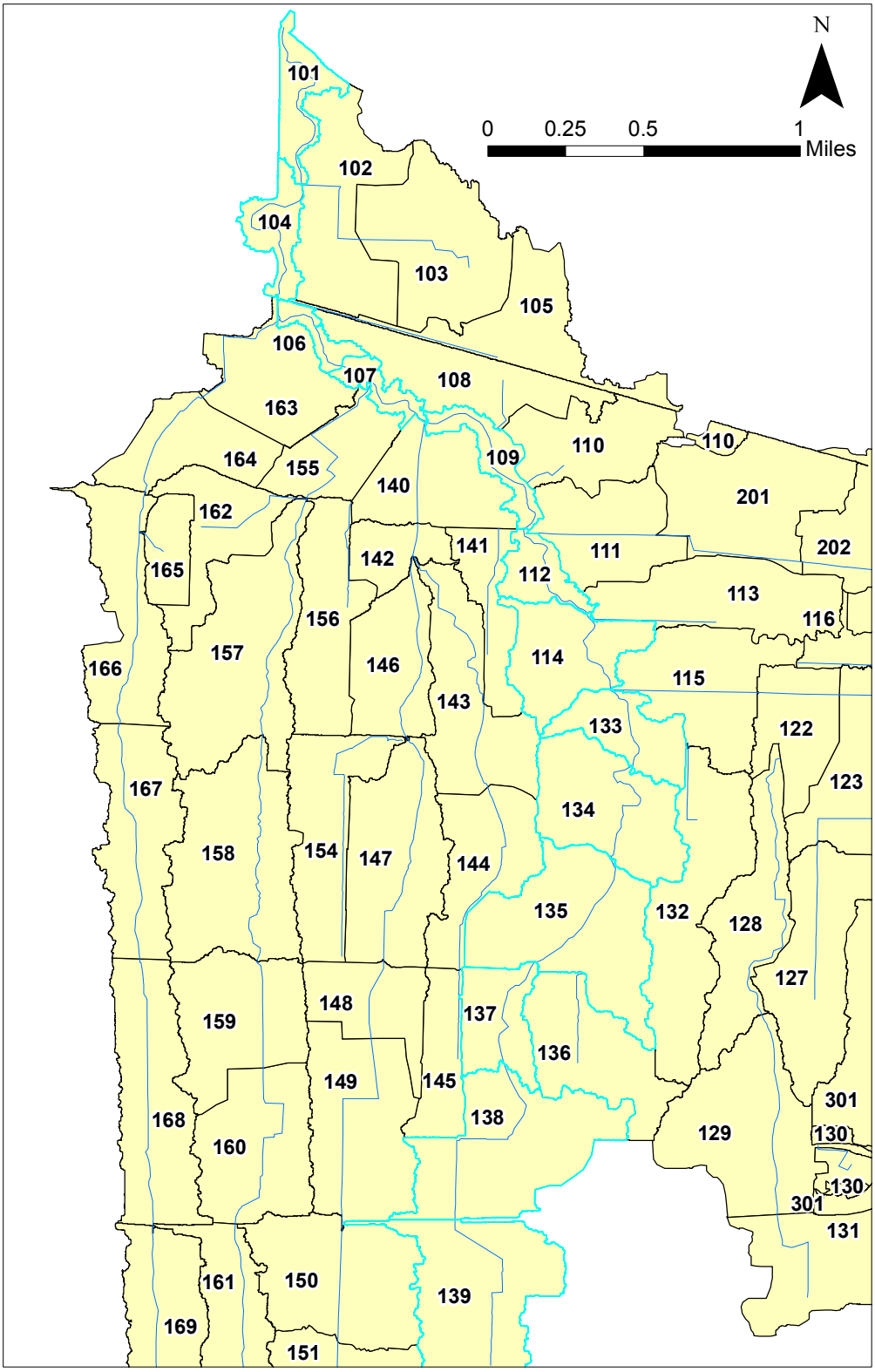


Figure 7-13. Mainstem Reaches, Clarks Creek

Reaches 104, 106, 107, 109, 112, 114, 133, 134,135,137, 138, and 139 constitute the Clarks Creek mainstem.

Table 7-7. Effective Work Analysis for Clarks Creek Mainstem

HSPF Reach	Particle Diameter (d_{50}, mm)	Classification for d_{50}	Critical Shear Stress, τ_c (lb/ft^2)	Average Velocity (ft/s)	Effective Work Index, W (60-year sum)
101	5.97	Fine gravel	0.0818	1.65	$5.12 \cdot 10^8$
104	5.97	Fine gravel	0.0818	1.10	$1.36 \cdot 10^8$
106	0.10	Very fine sand	0.0024	1.20	$2.46 \cdot 10^8$
107	0.09	Very find sand	0.0023	1.81	$1.47 \cdot 10^8$
109	0.09	Very fine sand	0.0023	1.67	$1.10 \cdot 10^8$
112	0.29	Medium sand	0.0043	0.96	$4.77 \cdot 10^7$
114	0.22	Fine sand	0.0036	0.70	$6.49 \cdot 10^7$
133	0.14	Fine sand	0.0028	0.73	$2.52 \cdot 10^7$
134	4.28	Fine gravel	0.0555	1.12	$3.76 \cdot 10^9$
135	13.57	Medium gravel	0.2034	2.08	$8.77 \cdot 10^9$
137	4.84	Fine gravel	0.0642	14.98	$3.80 \cdot 10^9$
138	4.84	Fine gravel	0.0642	10.80	$6.53 \cdot 10^8$
139	4.84	Fine gravel	0.0642	8.48	$1.92 \cdot 10^8$

The longitudinal profile of the effective work index is shown in Figure 7-14. The effective work index reaches a maximum in reach 135, the steep reach upstream of the State Hatchery in Clarks Creek Park. This is consistent with the coarse nature of the sediment in this reach which reflects the impact of cumulative work removing fines. Active scouring is likely occurring in this reach. As the stream emerges from the face of the Vashon Till onto the alluvial plain the gradient, effective work, and the diameter all decrease dramatically, suggesting areas that are primarily depositional. Effective work increases again in the most downstream reaches, consistent with a coarsening of the sediment.

Effective work curves (plotting the summed work index versus flow range bins) are most useful for examining potential channel response to changes in conditions (e.g., pre- and post-development). Portions of the curve in which work increases dramatically provide an indication of the flow range that may need to be controlled to promote channel stability. Figure 7-15 shows effective work curves for existing conditions in the till area. When natural condition and full buildout runs are completed these can be used to examine potential changes in channel stability. Pre and post-development conditions can also be summarized by the Erosion Potential (MacRae, 1992), E_p, calculated as W_{post}/W_{pre}. An E_p value greater than about 1.5 is typically a strong indicator of potential channel instability.

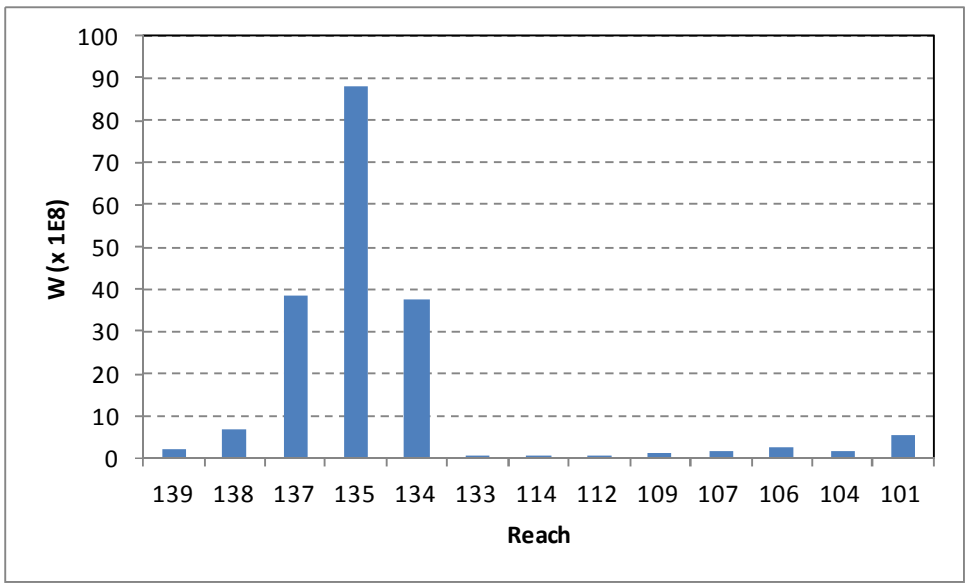


Figure 7-14. Longitudinal Profile of Effective Work Index (W)

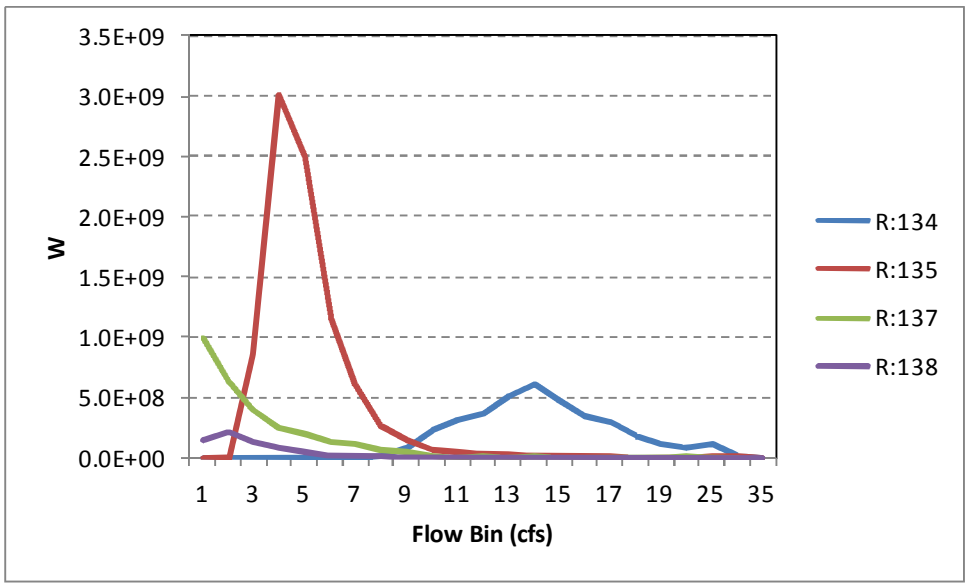


Figure 7-15. Effective Work (W) Curves for Reaches in the Till Area, Existing Conditions

Note: Flow bins show the high value of the flow interval summarized in the graph, using 1 cfs increments up to 20 cfs.

The effective work analysis shows the potential for work to be done (movement of sediment over distance) relative to the current median sediment diameter. The peak value in Reach 135 suggests that ongoing degradation of the channel is likely occurring in this reach.

7.9 SENSITIVITY OF SEDIMENT MODEL RESULTS

Sufficient data are not available to strongly constrain a unique solution to the simulation of sediment in Clarks Creek. Nonetheless, the model provides a reasonable description of the processes contributing to sediment load and transport within the creek, based on multiple lines of evidence. The model is useful, but not necessarily always correct. In particular, attribution of loads to specific sources is uncertain given the relatively small amount of local monitoring data. Model predictions are especially sensitive to the following assumptions:

- The relative importance of loads from pervious surfaces is in large part determined by the amount of overland flow simulated from such surfaces. Flow at the only continuous stream gage in Clarks Creek (Tacoma Road) is strongly influenced by spring discharges, so the fit of model partitioning between surface and subsurface flows is subject to some uncertainty.
- Loads from pervious surfaces appear to be more strongly controlled by transport capacity than by detached sediment availability. The current model is consistent with studies from the Green-Duwamish watershed in King Co.; however, detailed local monitoring could refine and improve the fit.
- The majority of land area in the Clarks Creek watershed is occupied by medium density residential land uses and roads. Total sediment load predictions are thus sensitive to the loads predicted for residential and road impervious surfaces. Unlike pervious surfaces, load from impervious surfaces is more strongly controlled by solids availability than transport capacity. Thus, the model predictions are particularly sensitive to the ratio of solids accumulation to solids removal on impervious surfaces (ACCSDP/REMSDP), which determines the limiting concentration of solids available for transport to the stream.

The current model is based on limited observations of flow and TSS. No small-scale monitoring has been conducted to estimate loads from individual land use areas. As additional data are collected it is likely that the Clarks Creek model can be improved. However, the existing model, despite uncertainties, is believed to provide a strong basis for the initial evaluation of potential sediment control options.

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8 Other Water Quality Parameters

Clarks Creek is impaired due to excessive concentrations of fecal coliform bacteria and due to low dissolved oxygen concentrations that appear to be related to nutrient enrichment and overgrowth of the invasive macroalgae *Elodea nuttalli*. Therefore, estimates of both bacterial and nutrient/organic matter loads to the creek are of considerable importance.

8.1 WATER QUALITY MODEL SETUP

Unfortunately, resources were not available to undertake full calibration of the watershed model to bacteria and nutrients at this time. As an alternative, information on land use and model simulated surface and subsurface flows by land use were combined with event mean concentrations (EMCs) obtained from a nearby watershed to estimate likely bacterial and nutrient loading. The concentrations were obtained from the Green-Duwamish watershed in King County, where detailed monitoring and analysis of concentrations and loads by land use has been conducted (Herrera, 2007).

This report (Table 5-12) gives pollutant loads for different land cover types (high density developed, low-to-medium density developed, agriculture, and forest – see Table 8-1) and reports flow and loading rates separately for baseflow and event runoff conditions.

Table 8-1. Green-Duwamish Loading Rates by Land Use (Herrera, 2007)

Constituent	Flow Component	High Density Developed	Low-Medium Density	Agriculture	Forest
Inorganic N (lb/ac/yr)	Baseflow	2.85	2.41	6.69	4.73
	Runoff	4.82	3.03	5.00	2.23
Inorganic P (lb/ac/yr)	Baseflow	0.04	0.04	0.06	0.10
	Runoff	0.11	0.05	0.49	0.02
Organic P (lb/ac/yr)	Baseflow	0.12	0.04	0.11	0.04
	Runoff	0.32	0.15	0.21	0.11
Fecal Coliform (#/ac/yr)	Baseflow	2.76E+10	6.60E+09	1.20E+09	1.40E+09
	Runoff	1.12E+11	6.25E+10	4.71E+10	4.60E+09

The information in Table 8-1 was converted to event mean concentrations (EMCs) to allow portability to a slightly different precipitation-runoff regime. For calculating EMCs for developed lands, the flow attributable to impervious surfaces was estimated as

$$Q_I = \frac{Q_{tot} - Q_P \cdot (1 - I)}{I},$$

where Q_{tot} is the total unit area runoff (volume per area per year), I is the impervious fraction, Q_I is the unit area runoff from impervious surfaces, and Q_P is the unit area runoff from developed pervious surfaces, assumed to be equivalent to the runoff rate cited for agriculture (0.12 ML/ha/yr). Low-to-medium density developed land was assumed to have an effective imperviousness of 25 percent, and high density developed land was assumed to have an effective imperviousness of 75 percent. Baseflow EMCs

are assumed to apply to groundwater discharge, while storm event EMCs are assumed to apply to surface runoff and interflow (as most of the storm event volume simulated for Clarks Creek occurs as rapid interflow.) Finally, EMCs for pervious runoff from developed land use categories are assumed to be similar to forest, although the load is scaled up to agricultural runoff rates. The resulting EMCs are shown in Table 8-2. Note that Herrera (2007) does not provide results for total N or organic N, so only the inorganic N components (nitrate, nitrite, and ammonia nitrogen) are shown.

Table 8-2. Green-Duwamish EMCs for Nutrients and Bacteria

Constituent	Flow Component	High Density Developed	Low-Medium Density	Agriculture	Forest
Inorganic N (mg/L)	Pervious Runoff	22.727	22.727	46.667	22.727
	Baseflow	16.842	13.500	41.667	9.464
	Impervious Runoff	10.485	15.051	NA	NA
Inorganic P (mg/L)	Pervious Runoff	0.182	0.182	4.583	0.182
	Baseflow	0.263	0.250	0.389	0.196
	Impervious Runoff	0.255	0.485	NA	NA
Organic P (mg/L)	Pervious Runoff	1.091	1.091	1.917	1.091
	Baseflow	0.684	0.250	0.667	0.089
	Impervious Runoff	0.727	0.798	NA	NA
Fecal Coliform Bacteria (#/L)	Pervious Runoff	4.182E+04	4.182E+04	3.925E+05	4.182E+04
	Baseflow	1.453E+05	3.300E+04	6.667E+03	2.500E+03
	Impervious Runoff	2.461E+05	6.526E+05	NA	NA

Note: "Pervious Runoff" includes both surface flow and interflow. EMCs are calculated from Table 5-12 in Herrera (2007).

In addition to runoff from the land surface, a nitrate concentration of 2 mg/L is assigned to the spring outflows that feed Clarks Creek, based on data summarized by Jones et al. (1999). No pollutant loads are assigned to the two hatchery discharges: these loads are believed to be small and very little data are available.

8.2 WATER QUALITY MODEL RESULTS

The EMC approach provides reasonable estimates of loading to the Clarks Creek system. It does not provide reliable concentration estimates because (1) actual concentrations in runoff will vary with event, (2) processes within the stream channel, such as uptake of nutrients by macrophytes or losses to the sediment are not simulated, and (3) the water quality simulation is not calibrated.

Table 8-4 shows the average annual distribution of upland load sources by land use. Of note here is the large inorganic N load attributed to "springs". This represents the 2 mg/L nitrate-N concentration assigned to the spring-fed baseflow in Clarks Creek, as documented by Jones et al. (1999). As the flow from the springs is on the order of 40-50 cfs this represents 37 percent of the total inorganic N load.

Table 8-3. Upland Nutrient and Bacteria Load Sources for 1960-2010 Simulation

Land Use	Inorganic N (lb/yr)	Inorganic P (lb/yr)	Organic P (lb/yr)	Fecal Coliform (#/yr)
Forest	22,244	391	424	1.5E+07
Agriculture and Pasture	29,450	523	541	4.7E+12
High Density Development	58,657	1,322	3,785	5.5E+14
Medium Density Development	83,706	1,609	2,566	3.9E+14
Low Density Development	52,808	896	1,605	1.6E+14
Roads	62,859	1,388	3,985	5.7E+14
Parks	47,523	1,001	1,599	3.2E+14
Springs	209,058	0	0	0

The distribution of loads by tributary is provided in Table 8-4 and Figure 8-1. Note that these are summations of upland loads to a tributary, not actual loads within the tributary, which will be subject to various uptake and transformation processes.

Table 8-4. Major Tributary Contributions of Nutrient and Bacteria Load to Clarks Creek

Tributary	Inorganic N (lb/yr)	Inorganic P (lb/yr)	Organic P (lb/yr)	Fecal Coliform (#/yr)
Clarks Creek Mainstem above Meeker	243,300	653	1,290	1.59E+14
Meeker Creek	61,418	1,308	2,937	4.44E+14
7th Street Storm Drains	16,048	360	760	1.27E+14
Pioneer Way Storm Drains	28,377	666	1,404	2.56E+14
Woodland Creek	77,196	1,457	3,042	3.94E+14
Diru Creek	47,070	870	1,704	2.14E+14
Rody Creek	43,242	753	1,523	1.90E+14

Note: Loads do not reflect any instream losses or retention.

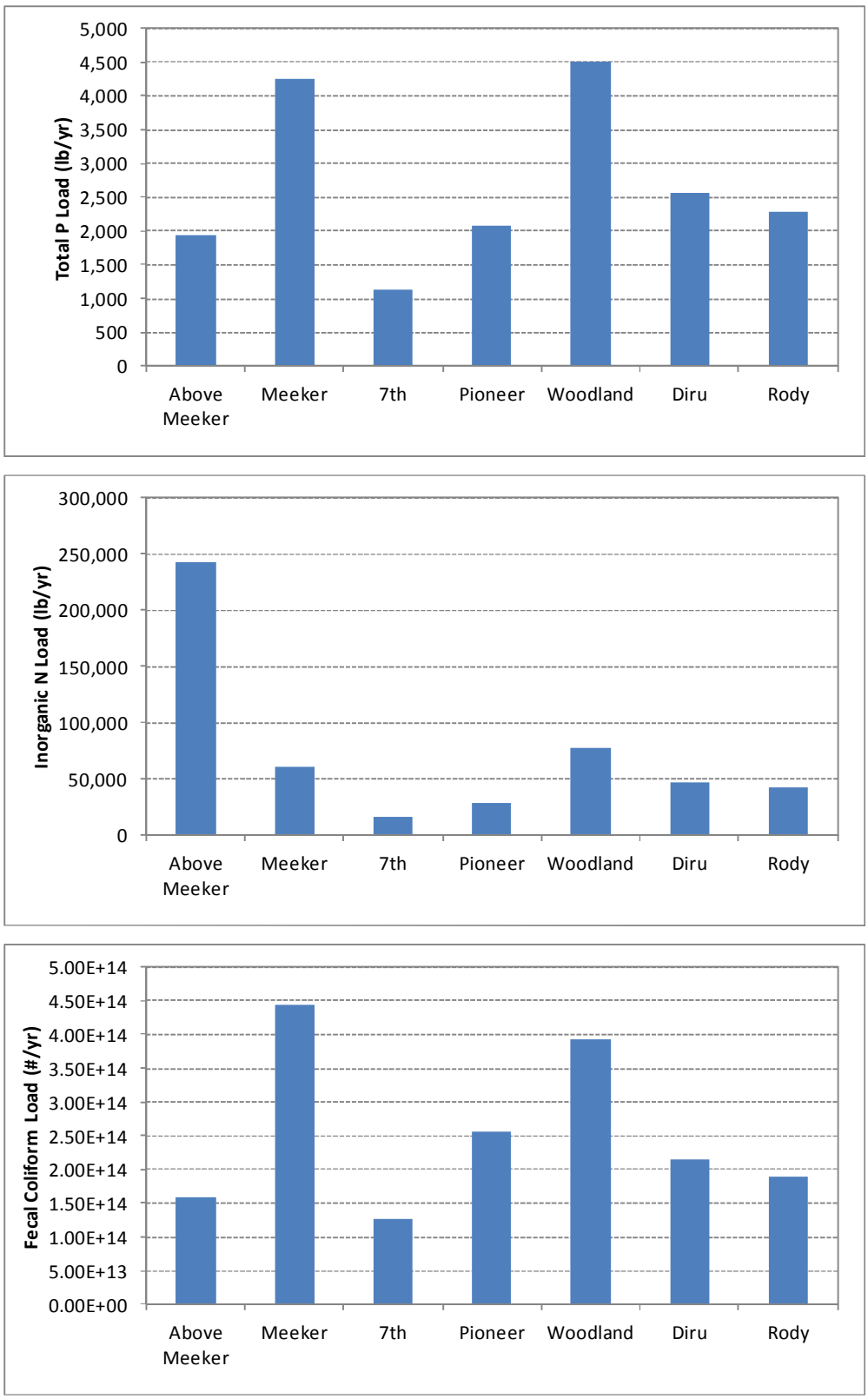

Figure 8-1. Nutrient and Bacterial Loads by Tributary to Clarks Creek Mainstem

9 Natural Condition and Buildout Scenarios

9.1 Natural Conditions Scenario

The natural conditions scenario is intended to evaluate flows and sediment loads in Clarks Creek in the absence of anthropogenic development. To do this, land use in the model was reverted to a representation of presumed natural conditions, eliminating all developed land use classes (including roads) and converting non-wetland areas back to mature forest. Note that the drainage network and channel characteristics were generally *not* modified for this scenario as their pre-development conditions are not well documented. The major exception is that the flow splitter that currently routes most of the flow from subbasin 301 to the Puyallup River was removed from the model.

9.2 Buildout Scenario

The buildout scenario examines the potential impacts of full buildout in the watershed. The land use for this case is obtained by converting existing undeveloped land uses to zoned land uses except where protected from development (e.g., parks). This reveals the maximum amount of development and impervious surfaces that could occur in the watershed under current land use plans. The buildout land use changes the amount of directly connected impervious area in the watershed from 25 percent to 31 percent. Comparison of existing to future buildout land uses in the watersheds (Figure 9-1) shows that this scenario involves a significant amount of redevelopment from low density to medium density developed land uses.

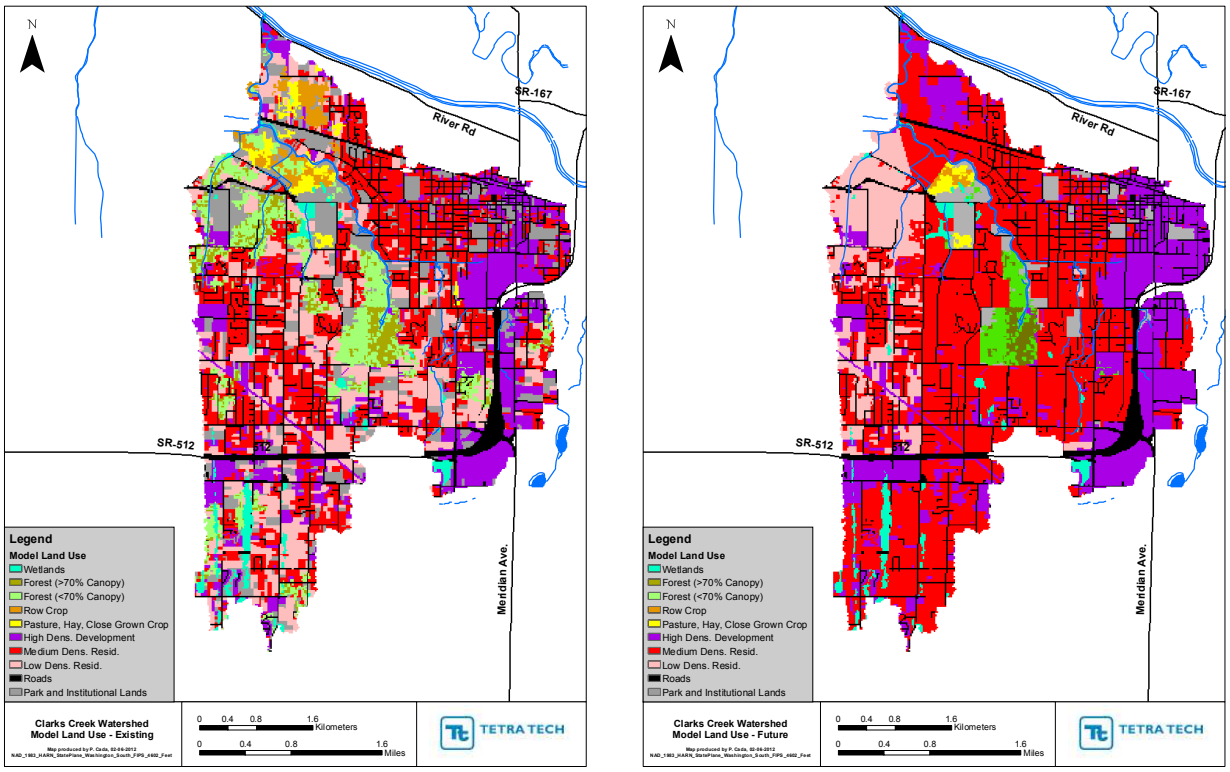

Figure 9-1. Current and Future Buildout Land Uses in Clarks Creek Watershed

Ecology's draft Phase II Municipal Stormwater Permit, Minimum Requirement #5, "On-site Stormwater Management," specifies Low Impact Design (LID) requirements that would apply to development

projects that result in greater than 2,000 square feet of new plus replaced hard surfaces. Specifically, this says "Stormwater discharges shall match developed discharge durations to pre-developed durations for the range of pre-developed discharge rates from 8% of the 2-year peak flow to 50% of the 2-year peak flow." If more than 5,000 square feet of hard surface is created, then Minimum Requirement #7 also applies, which requires stormwater BMPs to control flow duration from one half of the 2-year peak flow up to the 50-year peak flow.

The type of stormwater controls that can be expected for future development thus depends in part on the size of projects: smaller projects would need to meet Minimum Requirement #5, while larger requirements would need to meet both Minimum Requirement #5 and Minimum Requirement #7. The intent of the buildout simulation is to provide a future baseline that represents a realistic worse case that is still consistent with the regulations. Some unknown portion of the new development would occur in smaller projects so that Minimum Requirement #7 would not apply. Therefore, the buildout scenario is constructed under the assumption that all new development will meet Minimum Requirement #5 (but not #7) to provide a reasonable worst-case baseline against which to evaluate additional BMP requirements.

The majority of peak runoff comes from impervious surfaces, and the difference in peak flows between developed pervious and undeveloped pervious will be much less than the difference between impervious and undeveloped pervious lands. Therefore, Minimum Requirement #5 is approximated by designing a BMP representation that controls runoff from impervious surfaces to not exceed pre-development pervious surface runoff from 8 percent of the 2-year peak flow to 50 percent of the 2-year peak flow. The BMP is represented in HSPF as a "stream reach" on a unit area basis, the hydraulic behavior of which is described in an FTable relating storage to outflow. This unit area simulation is multiplied by the area in new impervious surfaces draining to each stream reach to represent the impacts of new development constructed in accordance with Minimum Requirement #5.

To construct the analysis, the pre-development condition was assumed to be dense forest on C soils - essentially the median soil type for the watershed. Analysis of 51 years of simulated runoff events using the BASINS Synoptic Analysis tool gives a 2-year peak flow of 0.00623 in/hr, so the control requirements apply from 0.000498 to 0.00311 in/hr.

The generic BMP (which could, for instance, be bioretention) is represented as having a treated outflow, Q_{Treat} and a bypass outflow, Q_{Bypass}, so the total outflow is $Q_{Out} = Q_{Treat} + Q_{Bypass}$, all in units of in/hr. The treated outflow is simulated as following a first-order recession curve, similar to groundwater discharge. A continuous mass balance of the BMP behavior relative to an input series (Q_{In}) from simulation of one acre of impervious cover (without any extra surface storage) can then be constructed as follows:

$$Q_{Treat} = \text{Min}\ \{K_{GW} \cdot V_{t-1}, Q_{Max}\},$$

where V_{t-1} is the storage volume at the end of the previous time step, Q_{Max} is the maximum allowed outflow rate, and $K_{GW} = 1 - A_{GWRC}^{1/24}$, where A_{GWRC} is a daily recession parameter, with the same functional interpretation as the recession parameter in HSPF. Bypass flow occurs when the storage volume exceeds the maximum storage capacity of the BMP:

$$Q_{Bypass} = \text{Max}\ \{0, V_{t-1} + Q_{In} - V_{Max}\},$$

where Q_{In} is the inflow for the time step and V_{Max} is the maximum storage capacity. Finally, the new volume at time t is updated as

$$V_t = \text{Min}\ \{V_{t-1} - Q_{Treat} + Q_{In} - Q_{Bypass} - Q_{Seep}, V_{Max}\},$$

where Q_{Seep} represents net losses that may include seepage to groundwater or evapotranspiration.

Iterative application of this model reveals a set of parameters that satisfies the control requirements of Minimum Requirement #5, with $A_{GWRC} = 0.985$, $Q_{Max} = 0.0023$ in/hr, $V_{Max} = 3.6$ in, and $Q_{Seep} = 0.003$ in/hr. (V_{Max} would be applied on the basis of acres of impervious area; if the BMP had a depth of 3 ft this would work out to a requirement of 4,356 ft^2 of BMP per each acre of imperviousness.) Application

results to the 1960-2010 simulation are shown in Figure 9-2. The green line shows unmitigated conditions for runoff from impervious surfaces, while the red line represents natural conditions flow, obtained from model simulation of undisturbed forest. The blue line shows mitigated flow, with the BMP representing Minimum Requirement #5 in place, and remains below the natural condition curve across the control range of 0.000498 to 0.00311 in/hr.

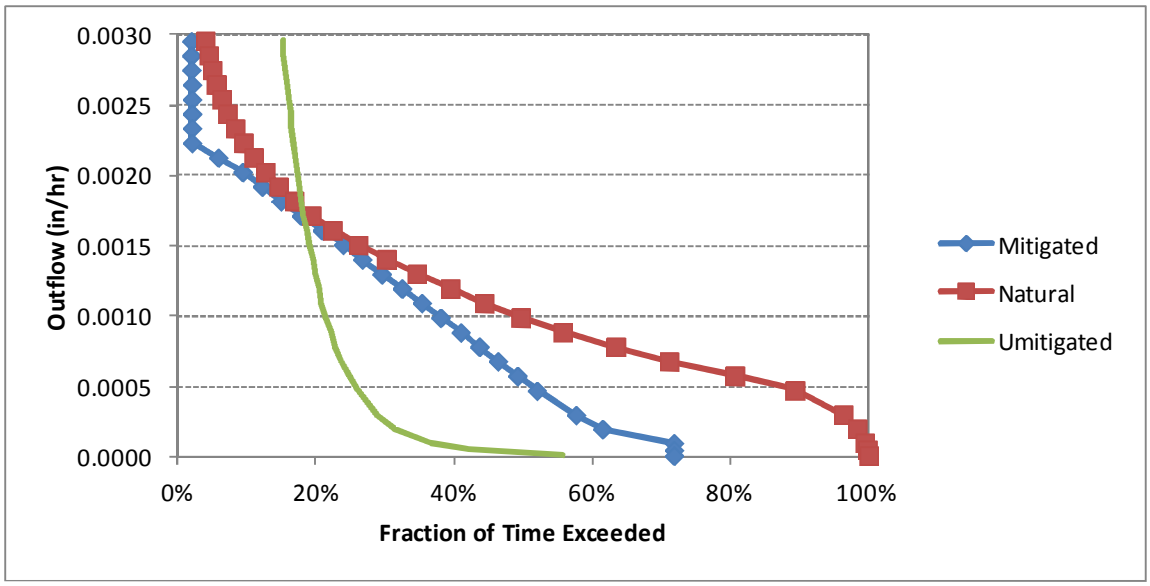

Figure 9-2. BMP Representation of LID Performance Standard for New Development

To implement this generic BMP in the HSPF model via a reach FTable, the output must be represented in units of cfs (per acre, as this is on a unit basis). A factor of 1.008333 converts outflow in ac-in/hr to cfs. The resulting FTable is shown in Table 9-1. Output from this FTable is multiplied by the appropriate area of new impervious surfaces (and the conversion from inches to feet) to link this "reach" to each receiving stream segment.

Table 9-1. HSPF FTable for Representing LID BMP on a Unit Area Basis

```
  FTABLE    100
Future Imperv LID Standard, in/ac        ***
 rows cols                               ***
   11    6
     DEPTH      AREA    VOLUME  treated   bypass    loss    ***
       in        ac     ac-in   ----- cfs/ac-in-hr -------- ***
     00.000  00.0000  00.00000  00.00000  00.00000  0.000000
     00.003  00.0972  00.00300  00.00000  00.00000  0.003025
     00.010  00.0972  00.01000  00.00000  00.00000  0.003025
     00.167  00.0972  00.16650  00.00010  00.00000  0.003025
     00.500  00.0972  00.50000  00.00032  00.00000  0.003025
     01.000  00.0972  01.00000  00.00063  00.00000  0.003025
     02.000  00.0972  02.00000  00.00127  00.00000  0.003025
     03.000  00.0972  03.00000  00.00190  00.00000  0.003025
     03.600  00.0972  03.50000  00.00222  00.00000  0.003025
     04.000  00.0972  04.00000  00.00222  04.02809  0.003025
     10.000  00.0972  10.00000  00.00222  10.07809  0.003025
  END FTABLE100
```

Flow into the BMP that is not bypassed is assumed to achieve a significant degree of sediment retention as the treated water will likely be filtered through the LID planting medium. Specifically, trapping of 100 percent of sand, 90 percent of silt, and 80 percent of clay is assumed.

9.3 SCENARIO RESULTS

Buildout conditions result in an increase in impervious area; however, the extent of directly connected impervious area is already high under current conditions. Therefore, the difference between current conditions and natural conditions is more dramatic than the difference between current and buildout conditions.

Scenario statistics for flow at a variety of key locations in the watershed are provided in Table 9-2. There are only small differences between scenarios for median and average flows. For the mainstem, the majority of the flow is provided by spring discharges which are assumed to remain unchanged under the three scenarios. In contrast, large differences are seen for the 2-year and 10-year recurrence daily flows. For the 2-year event, flows under current conditions are much greater than estimated for natural conditions both in the tributaries and at the downstream station on Clarks Creek at 66th Street. In contrast, 2-year and 10-year flows in Clarks Creek at 12th Street are predicted to have increased only slightly relative to natural conditions, mostly because a large portion of the upstream drainage area is protected by Clarks Creek Park.

Table 9-2. Scenario Results for Flow

Parameter	Scenario	Clarks Creek at 66th St.	Meeker Creek Mouth	Clarks Creek at 12th St.	Diru Creek Mouth	Rody Creek Mouth
Median Flow (cfs)	Current	63.8	1.4	54.5	1.7	1.8
	Natural	62.2	1.7	54.2	1.5	1.6
	Buildout	63.9	1.3	54.5	1.7	1.8
Average Flow (cfs)	Current	66.8	2.4	54.4	2.3	2.3
	Natural	63.1	2.1	54.0	1.7	1.8
	Buildout	67.3	2.5	54.4	2.3	2.3
2-year Daily Flow (cfs)	Current	182.5	27.0	86.5	16.6	14.3
	Natural	116.0	11.8	85.7	8.2	6.6
	Buildout	195.0	30.3	86.6	18.2	15.2
10-year Daily Flow (cfs)	Current	256.0	46.6	88.9	25.5	21.6
	Natural	147.8	19.6	87.1	13.4	10.5
	Buildout	279.9	54.6	88.9	28.0	23.3

Figure 9-3 displays flow-duration curves for Clarks Creek at 66th Street in two different ways. The top panel plots daily flow for each scenario versus the percent of time that flow is exceeded, which emphasizes the middle range of flows. The bottom panel plots flows versus empirical recurrence

frequency in the 51-year model simulation, which emphasizes the extreme flows. The top panel emphasizes that there is little difference between scenarios for median and small flows, which are largely determined by spring discharges, although the current and buildout scenarios diverge from natural conditions for flows that are exceeded less than 20 percent of the time – i.e., during wet weather runoff events. The bottom panel shows, in contrast, that there are large differences for larger storm flows that occur with a return frequency of two years or more.

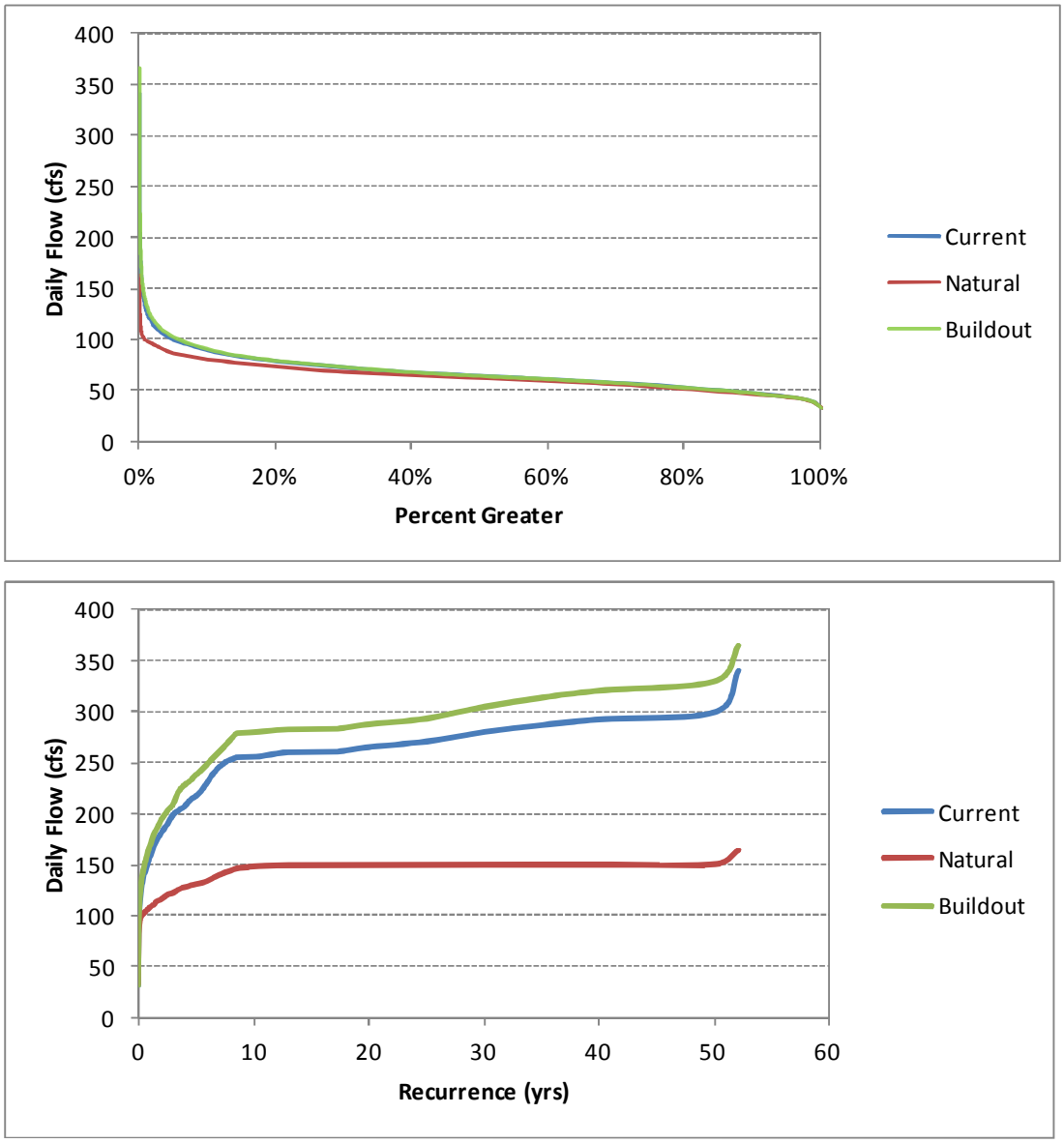

Figure 9-3. Flow Durations for Clarks Creek at 66th St. under Current, Natural, and Buildout Conditions

Scenario results for sediment (Table 9-3) generally follow the results for flow: There is only a small difference between current conditions and predicted conditions at buildout, but both the current and buildout scenarios have much higher TSS concentrations and sediment loads than are predicted for forested natural conditions. Interestingly, the predicted loads are somewhat lower under buildout conditions than under current conditions. This is due to the sediment removal simulated in the BMPs required under the proposed general permit, which includes lands that are predicted to be re-developed to higher density developed land uses. The simulation of sediment deposition at 12th Street on Upper Clarks

Creek suggests that there may have been significant deposition at this location even under natural conditions, due primarily to erosion in the steep reaches immediately upstream. If correct, this result suggests that this portion of Clarks Creek had not reached a dynamic equilibrium under natural conditions, but was instead still actively adjusting to conditions following the conclusion of the last glaciation.

Table 9-3. Scenario Results for Sediment

Parameter	Scenario	Clarks Creek at 66th St.	Meeker Creek Mouth	Clarks Creek at 12th St.	Diru Creek Mouth	Rody Creek Mouth
Median TSS (mg/L)	Current	2.9	5.9	2.8	2.8	2.8
	Natural	1.7	0.5	1.8	1.9	2.9
	Buildout	2.9	6.1	2.8	2.9	2.8
Average TSS (mg/L)	Current	6.1	14.8	3.3	9.0	11.0
	Natural	2.1	2.4	1.9	3.2	1.9
	Buildout	6.5	16.2	3.4	9.7	11.7
Average Annual Sediment Load (tons/yr)	Current	578.7	107.2	180.8	51.1	56.8
	Natural	138.5	9.9	99.5	7.6	5.7
	Buildout	637.6	124.0	186.8	59.4	63.8
Sediment Deposition (tons/yr)	Current	10.1	0.1	-11.7	2.6	3.1
	Natural	0.8	-0.2	-16.2	-2.3	-1.1
	Buildout	10.8	0.1	-10.8	3.7	3.9

The model simulates the most active channel degradation as occurring in reach 134 (one reach above 13th Street), with an average of 30.0 tons/yr of scour under current conditions. The natural condition simulation shows less scour, but still simulates 26.0 tons/yr. The buildout condition scenario predicts a slight increase, to 31.0 tons/yr.

Relative to natural conditions, the model suggests a large increase in average TSS concentrations and annual sediment load. This is accompanied by a large increase in sediment deposition in lower Clarks Creek at the 66th Street monitoring point.

As seen above (Figure 9-3), buildout conditions result in a noticeable increase in the magnitude of large, low-frequency storm event flows, but only small changes in the more frequent flows that do the majority of the work on the channel. An effective work analysis was also conducted for buildout conditions and compared to the results for existing conditions for the Clarks Creek mainstem reaches through the ratio of the sum of the effective work indices, E_p, calculated as $W_{buildout}/W_{existing}$ (see Section 7.8). Results are summarized in Table 9-4. While E_p is greater than one, the largest value is about 1.06, far less than the criterion of 1.5 recommended as a strong indicator of potential channel instability by MacRae (1992). Thus, the anticipated conditions at buildout (with stormwater controls equivalent to Minimum Requirement #5) do not appear likely to induce significant additional channel instability.

Table 9-4. Change in Effective Work Index from Existing to Buildout Conditions

Reach	*W* at Buildout (x 10^{-8})	*W*, Existing (x 10^{-8})	E_p
139	1.97	1.95	1.00882
138	6.89	6.64	1.03713
137	40.72	38.58	1.05560
135	88.34	87.88	1.00523
134	37.71	37.61	1.00275
133	0.25	0.25	1.00099
114	0.65	0.65	1.00208
112	0.48	0.48	1.00241
109	1.10	1.10	1.00217
107	1.48	1.47	1.00435
106	2.46	2.46	1.00132
104	1.37	1.36	1.00613
101	5.21	5.13	1.01503

In sum, the watershed model scenarios suggest that existing development has substantially altered the natural hydrology and sediment dynamics of Clarks Creek, leading to increased peak flows, increased sediment load, degradation of upland stream reaches, and aggradation of reaches in the alluvial plain. However, risks from future development appear relatively small – mostly because most of the available land has already been developed. Mitigation of sediment problems in Clarks Creek would thus require addressing flow and sediment loads from existing development.

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Appendix A. Impervious Area Determination

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TETRA TECH

Memorandum

Date:	December 1, 2011
To:	Char Naylor/PTI
c:	*Jon Butcher/Tetra Tech* *Mike Milne/B&C*
From:	Jerry Scheller/Tetra Tech, Tracy Winjum/Tetra Tech
Project No./Name:	135-64934-11001-01/Clark Creek Sediment Study
Subject:	Impervious Surfaces Analysis

This memorandum presents the approach used for estimating impervious area in the Clark Creek Basin for input into the HSPF model developed for the Clarks Creek Sediment Reduction Project.

Roadways, parking lots sidewalks, roof tops and any other hard or paved surface that prevent rainfall from infiltrating into the ground are considered to be impervious surfaces. Impervious surfaces are classified two ways, directly-connected and indirectly-connected. Directly-connected impervious areas (DCIA) are impervious surfaces that are directly connected to the receiving water through a constructed drainage system. Usually these drainage conveyance systems are comprised of curb and gutter, pipes, and ditches and speed the flow of stormwater runoff to the receiving water. For this reason, DCIA has the greatest impact on peak flow and runoff volumes in the Clarks Creek basin. Indirectly-connected impervious surfaces are those surfaces located adjacent to vegetated areas such as lawn, forest or pasture, and usually exhibit runoff characteristics similar to the adjacent land cover. Total impervious area (TIA) is the combination of the directly- and indirectly-connected impervious area. For this memo, impervious surfaces will be presented as DCIA and TIA.

Impervious surface is represented in the HSPF model with a series of Hydrologic Response Units (HRUs), referred to as IMPLNDS, that define runoff characteristics during rainfall events. Four HSPF IMPLND classifications were identified in the memorandum *HRU's for Clarks Creek Model* (Tetra Tech, 2011). The four IMPLND classifications are described below:

IMPLND 1: Impervious area of major highways.

IMPLND 2: Impervious areas of roads and driveways in residential, park and institutional areas.

IMPLND 3: Impervious area of high-density development parking lots.

IMPLND 4: Building footprints.

Pervious HRU and HSPF model development is described in a separate memorandum.

IMPLND 1 impervious area for major highways was measured directly for the aerial photography. SR512 is the only major highway in the Clarks Creek Basin. Directly measured impervious highway area is documented in Table A-1 in Attachment A.

The impervious area for IMPLND 2, 3, and 4 classifications were computed by applying a representative fraction of TIA and DCIA for roads and driveways for a variety of land covers in the Clarks Creek basin. Impervious fractions were estimated by direct measurement from aerial photos by sampling of nine locations assumed to represent a range of land covers found in the basin. Sampled represented areas are documented in Attachment B.

The impervious fractions were applied to the landuse on a parcel basis taken from the Land Use shapefile provided by Piece County. Rights-of-way were classified as commercial, residential or rural based on adjoining parcel land use. Impervious fractions were applied to each right-of-way area. Figure 1 shows the land and right-of-way use in the Clarks Creek basin. Table 1 shows the corresponding impervious area fraction for each land use.

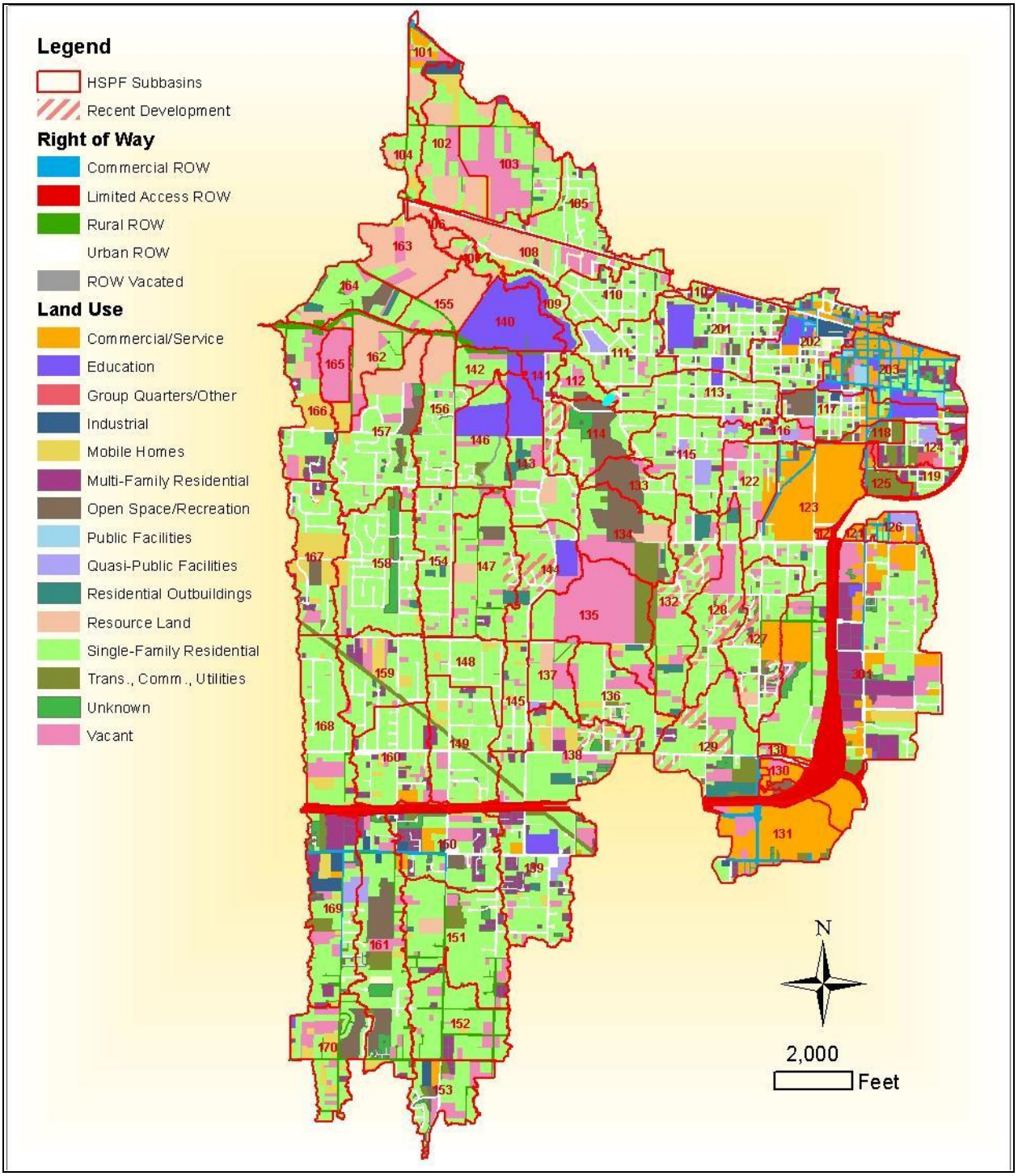


Figure 2 Land Use in the Clarks Creek Basin (Pierce County, 2011)

TABLE 1
PARCEL LAND USE ESTIMATED IMPERVIOUS AREA FRACTION

Land Use Category	TIA (%)	DCIA Fraction (%) Road-Parking	HD[a] Parking	Roof	Source
Unknown	0	0		0	
SFR (0-1/8 acre)	56	11		40	Sampled[b]
SFR (1/8-1/4 acre)	41	9		0	Sampled[b]
SFR (1/8-1/4 acre) - Recent[c]	41	9		20	Sampled[b]
SFR (1/4-1/2 acre)	39	10		0	Sampled[b]
SFR (1/4-1/2 acre) - Recent[c]	39	10		21	Sampled[b]
SFR (1/2-1 acre)	17	5		0	Sampled[b]
SFR (>1 acre)	17	5		0	Sampled[b]
MFR	75	0	48	25	Sampled[b]
MFR - Low-Density	40	10		5	By Inspection[d]
Group Quarters/Other	75	0	48	25	Assumed to be MFR
Mobile Homes	85	0	60	25	By inspection[d]
Residential Outbuildings	17	5		0	Assumed to be SFR (1/2 - 1 ac)
Commercial/Service	85	0	70	14	Sampled[b]
Industrial	90	0	45	45	By Inspection
Transportation, Communication, Utilities	90	90		0	
Education	53	0	24	26	Sampled[b]
Public Facilities	90	0	45	45	
Quasi-Public Facilities	90	0	45	45	By Inspection
Open Space/Recreation	5	5		0	
Open Space/Recreation - High-Density	86	0	70	14	By Inspection[d]
Resource Land	0	0		0	
Vacant	0	0		0	

DCIA = Directly Connected Impervious Area, TIA = Total Impervious Area, HD = High Density, SFR = Single Family Residential, MFR=Multi-Family Residential

a. High density parking associated with multi-car parking areas in commercial, MFR, etc.
b. Sampled areas documented in Attachment B.
c. Recent developments are assumed to have rooftops directly connected to storm drain system. See Figure 1 for Recent developments.
d. From aerial photography. See Table A-2 for list of parcels in this category.

The following assumptions were used to develop DCIA and TIA estimates:

- Single-family residential less than 1/8 acre assumed to have roof downspouts connected to storm drain.
- "Recent" single-family development between 1/8 and 1/2 acre assumed to have roof downspouts connected to storm drain. "Recent" developments identified by inspection of the aerial photos based on street and house patterns and are documented in Figure 1.
- Low density multi-family residential parcels identified by inspection of the aerial photo, DCIA values assumed. Parcels are listed Table A-2 in Attachment A.
- Mobile home parks identified by inspection of the aerial photos. DCIA assigned based on sampled multi-family residential values. Parcels are listed in Table A-3 in Attachment A.
- Non-park mobile homes assigned single-family residential DCIA values for older developments.
- High-density open space identified by inspection of the aerial photo. DCIA assigned based on sampled commercial values. Parcels are listed in Table A-2 in Attachment A.
- By inspection of the aerial photo, "Unknown" land use appears to cover open tracts of green space or native growth protection area. Three high-density properties identified and assigned commercial DCIA values
- Group Quarters/Other assigned multi-family residential DCIA values.
- Industrial, Transportation, Communication, Utilities, Public Facilities and Quasi-Public Facilities assigned DCIA values estimated by inspection of the aerial photo.

Estiamted DCIA and TIA for each HSPF Subbasin are shown in Figure 3 and Table 3.

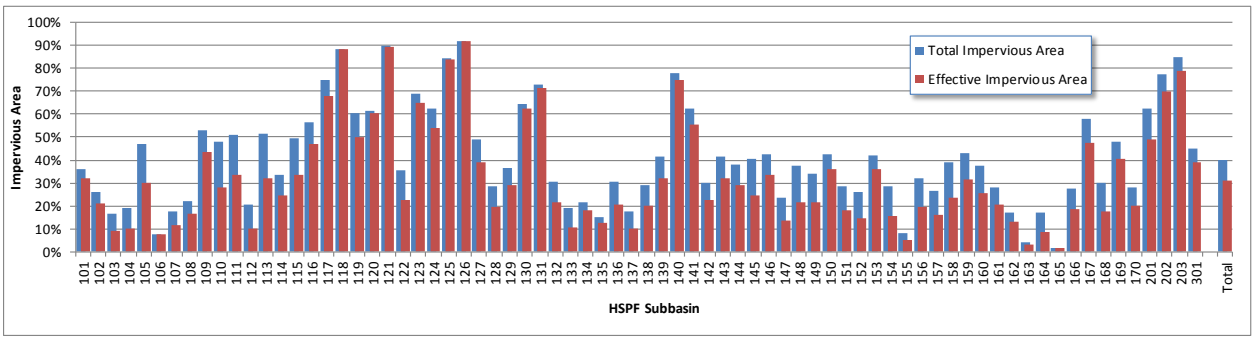


Figure 3. DCIA and TIA for Clarks Creek HSPF Subbasins

TABLE 3
HSPF IMPLND AREA

HSPF Subbasin	Area (acres)	TIA (acres)	TIA (%)	DCIA (acres) Road/Parking	Roof	HD Parking	Major Highway	Total DCIA	%DCIA
101	33.2	11.9	36%	3.7	1.7	5.1	0.0	10.6	32%
102	109.9	28.7	26%	3.5	5.6	8.4	5.6	23.0	21%
103	123.2	20.4	17%	8.1	0.8	1.4	0.8	11.1	9%
104	31.2	5.9	19%	3.1	0.0	0.0	0.0	3.1	10%
105	85.8	40.3	47%	24.0	0.4	0.8	0.4	25.7	30%
106	13.9	1.0	8%	1.0	0.0	0.0	0.0	1.0	8%
107	17.4	3.1	18%	0.6	0.3	0.7	0.3	2.0	11%
108	81.7	17.9	22%	11.0	0.7	1.3	0.7	13.5	17%
109	28.3	15.0	53%	1.6	3.7	3.4	3.7	12.4	44%
110	82.9	39.7	48%	20.7	0.6	1.1	0.6	23.1	28%
111	80.1	40.8	51%	17.0	3.0	3.8	3.0	26.9	34%
112	28.5	5.8	20%	2.5	0.1	0.2	0.1	2.9	10%
113	100.8	51.9	52%	24.5	2.3	3.1	2.3	32.2	32%
114	73.9	24.7	33%	9.3	2.5	3.6	2.5	18.0	24%
115	101.5	50.2	49%	19.1	5.0	5.1	5.0	34.3	34%
116	21.8	12.3	57%	4.5	1.8	2.1	1.8	10.2	47%
117	81.7	61.1	75%	21.7	8.1	17.5	8.1	55.4	68%
118	17.8	15.1	88%	13.6	0.4	1.3	0.4	15.7	88%
119	24.7	15.0	61%	5.8	1.6	3.1	1.9	12.3	50%
120	3.0	1.9	61%	0.0	0.3	1.4	0.1	1.8	61%
121	4.5	4.0	90%	0.5	0.5	2.5	0.5	4.0	89%
122	62.7	22.2	35%	9.1	0.7	3.6	0.7	14.1	23%
123	170.1	117.4	69%	18.7	14.9	75.2	1.9	110.6	65%
124	47.3	29.5	62%	12.3	5.1	7.5	0.6	25.5	54%
125	21.5	18.2	84%	15.0	0.6	2.0	0.6	18.1	84%
126	24.1	21.3	92%	5.1	3.6	9.9	3.6	22.2	92%
127	115.3	56.2	49%	24.5	6.1	8.2	6.1	44.9	39%
128	93.8	26.9	29%	10.4	4.0	0.0	4.0	18.4	20%
129	145.2	53.1	37%	29.4	5.6	4.6	2.2	41.8	29%
130	18.6	12.0	65%	1.6	1.4	7.2	1.4	11.6	62%
131	114.2	83.3	73%	13.8	11.5	55.2	1.2	81.7	72%
132	131.9	40.6	31%	20.9	3.7	0.0	3.7	28.3	21%
133	48.3	9.1	19%	5.0	0.0	0.0	0.0	5.0	10%

TABLE 3 (CONTINUED)
HSPF IMPLND AREA

HSPF Subbasin	Area (acres)	TIA (acres)	TIA (%)	DCIA (acres) Road/Parking	Roof	HD Parking	Major Highway	Total DCIA	%DCIA
134	100.2	21.6	22%	17.2	0.3	0.0	0.3	17.9	18%
135	139.7	20.8	15%	17.2	0.0	0.0	0.0	17.2	12%
136	91.3	27.9	31%	13.0	2.5	0.7	2.5	18.8	21%
137	49.0	8.7	18%	3.3	0.5	0.5	0.5	4.9	10%
138	138.4	39.9	29%	21.5	2.9	1.0	2.0	27.4	20%
139	167.3	69.4	41%	25.7	10.2	15.7	2.2	53.9	32%
140	80.0	62.3	78%	1.5	20.0	18.4	20.0	59.9	75%
141	46.1	28.8	62%	10.3	6.0	3.3	6.0	25.5	55%
142	34.3	10.3	30%	3.6	1.4	1.3	1.4	7.7	23%
143	103.2	42.9	42%	11.9	7.3	6.7	7.3	33.2	32%
144	80.4	30.8	38%	10.2	5.2	2.7	5.2	23.3	29%
145	46.6	18.9	41%	10.3	0.3	0.6	0.3	11.5	25%
146	78.3	33.3	42%	7.6	6.4	5.9	6.4	26.4	34%
147	123.0	28.9	24%	11.5	1.9	1.0	1.9	16.4	13%
148	61.5	23.2	38%	13.0	0.1	0.1	0.1	13.3	22%
149	125.3	42.7	34%	23.2	1.0	1.9	0.8	26.9	21%
150	128.4	54.8	43%	19.3	7.2	15.7	3.9	46.0	36%
151	161.5	46.4	29%	23.5	1.4	2.5	1.4	28.9	18%
152	106.5	27.6	26%	14.3	0.4	0.4	0.4	15.5	15%
153	68.3	28.6	42%	11.4	4.7	3.7	4.7	24.6	36%
154	93.3	26.8	29%	14.3	0.1	0.2	0.1	14.7	16%
155	56.1	4.5	8%	2.7	0.0	0.0	0.0	2.7	5%
156	94.8	30.3	32%	18.3	0.1	0.1	0.1	18.6	20%
157	163.4	43.1	26%	26.6	0.0	0.0	0.0	26.6	16%
158	155.8	60.9	39%	29.9	1.8	3.4	1.8	36.9	24%
159	104.4	44.8	43%	18.6	3.6	7.0	3.6	32.8	31%
160	106.5	40.1	38%	18.2	2.4	6.2	0.5	27.3	26%
161	184.7	51.9	28%	25.2	5.7	5.4	1.4	37.7	20%
162	68.8	11.7	17%	9.0	0.0	0.0	0.0	9.0	13%
163	80.5	3.2	4%	2.3	0.0	0.0	0.0	2.3	3%
164	69.1	11.8	17%	6.0	0.0	0.0	0.0	6.0	9%
165	31.4	0.5	1%	0.4	0.0	0.0	0.0	0.4	1%
166	97.7	27.0	28%	11.6	1.6	3.1	1.6	18.0	18%

TABLE 3 (CONTINUED)
HSPF IMPLND AREA

HSPF Subbasin	Area (acres)	TIA (acres)	TIA (%)	DCIA (acres) Road/Parking	Roof	HD Parking	Major Highway	Total DCIA	%DCIA
167	107.5	62.4	58%	16.5	8.8	17.0	8.8	51.1	48%
168	120.8	36.4	30%	18.5	0.3	0.6	1.5	21.0	17%
169	142.2	68.4	48%	22.7	14.5	19.5	0.9	57.7	41%
170	92.6	25.9	28%	11.7	3.3	0.4	3.3	18.7	20%
201	121.1	75.4	62%	29.1	10.2	10.0	10.2	59.4	49%
202	115.1	89.3	78%	35.4	11.6	21.7	11.6	80.3	70%
203	117.6	99.8	85%	36.5	13.9	28.8	13.9	93.1	79%
301	525.6	236.9	45%	55.8	29.9	93.2	25.5	204.3	39%
Total	6,717	2,675	40%	1,041	284	538	216	2,080	31%

ATTACHMENT A

TABLE A-1
DIRECTLY MEASURED SUBBASIN IMPERVIOUS AREA

Subbasin	Impervious Area (ac)
119	1.9
120	0.1
123	1.9
124	0.6
125	0.6
129	2.2
131	1.2
138	2.0
139	2.2
149	0.8
150	3.9
160	0.5
161	1.4
168	1.5
169	0.9
301	25.5

ATTACHMENT A (CONTINUED)

TABLE A-2
PARCELS WITH EXCEPTIONS TO LAND USE CLASSIFICATIONS

Mobile Home Parcels Assumed to be High Density Properties	Multi-Family Parcels assumed to be Low-Density Properties	Open-Space Parcels Assumed to be High Density Properties
0419061008	0420202009	6020120011
0420313004	7560011080	0420284126
0420317034	7560011080	
0420313071	7065000801	
0420313071	0419078034	
0420313075	0419077031	
0420313076	4315000643	
0420313076	4315000642	
3745000270	4315000641	
3745000270	0419077029	
0419065001	0419077029	
0420202088	0420331066	
0420195021	5505450082	
0420195021	0419056014	
0420191099	0419056015	
0420191100	7065000801	
0420202088	4005000023	
0420195021	4315001025	
0420195021	4315001024	
0420191099	4315001026	
0420191100	4315001027	
0420191101	0419176033	
0420292019	0419176032	
0420292019	0419181034	
0420292019	0419185010	
0420292024		
0420292024		
0420292024		
0420292024		
0420203006		
0420203006		
0420203006		

ATTACHMENT B

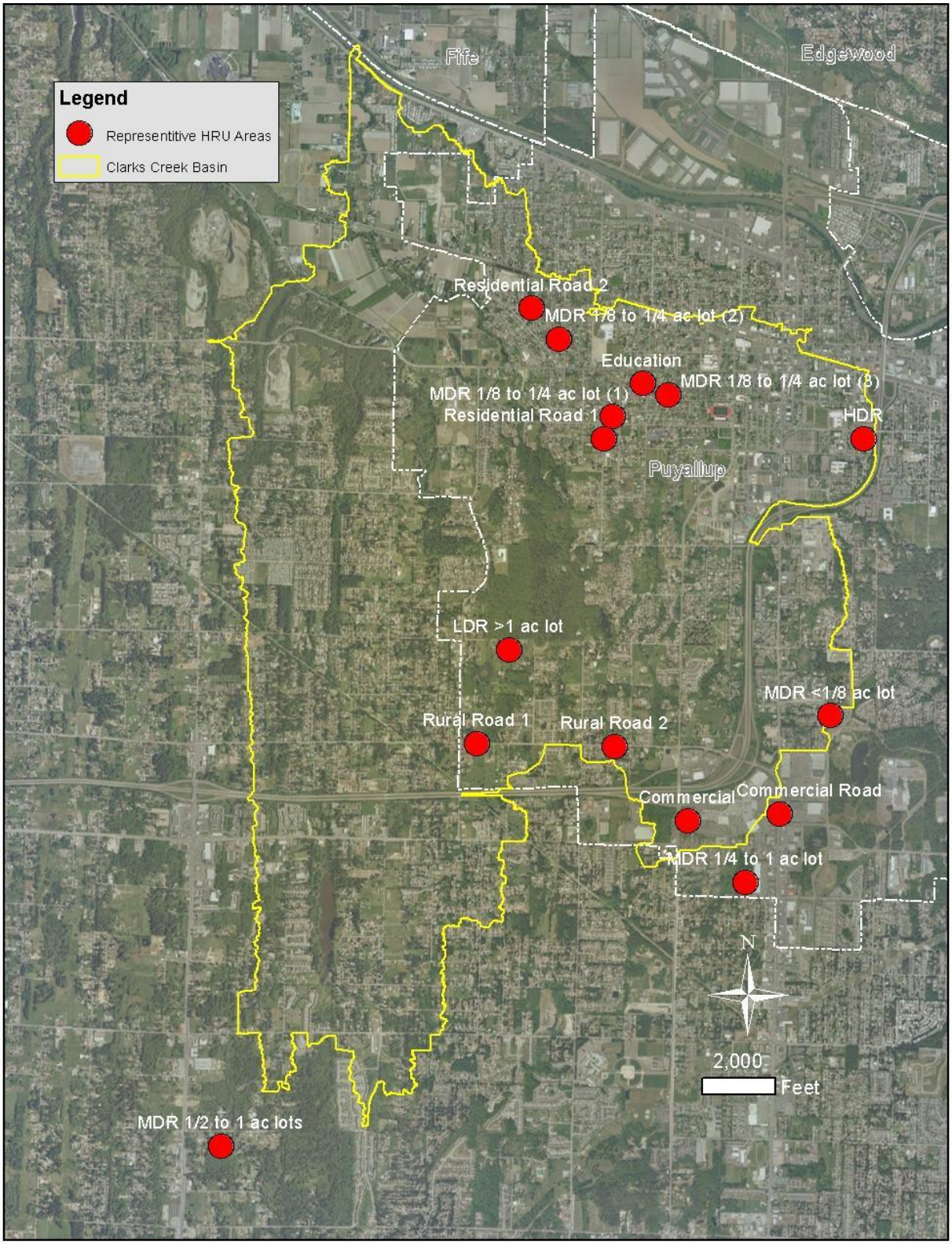


Figure B-1 Sampled Representative Impervious Areas

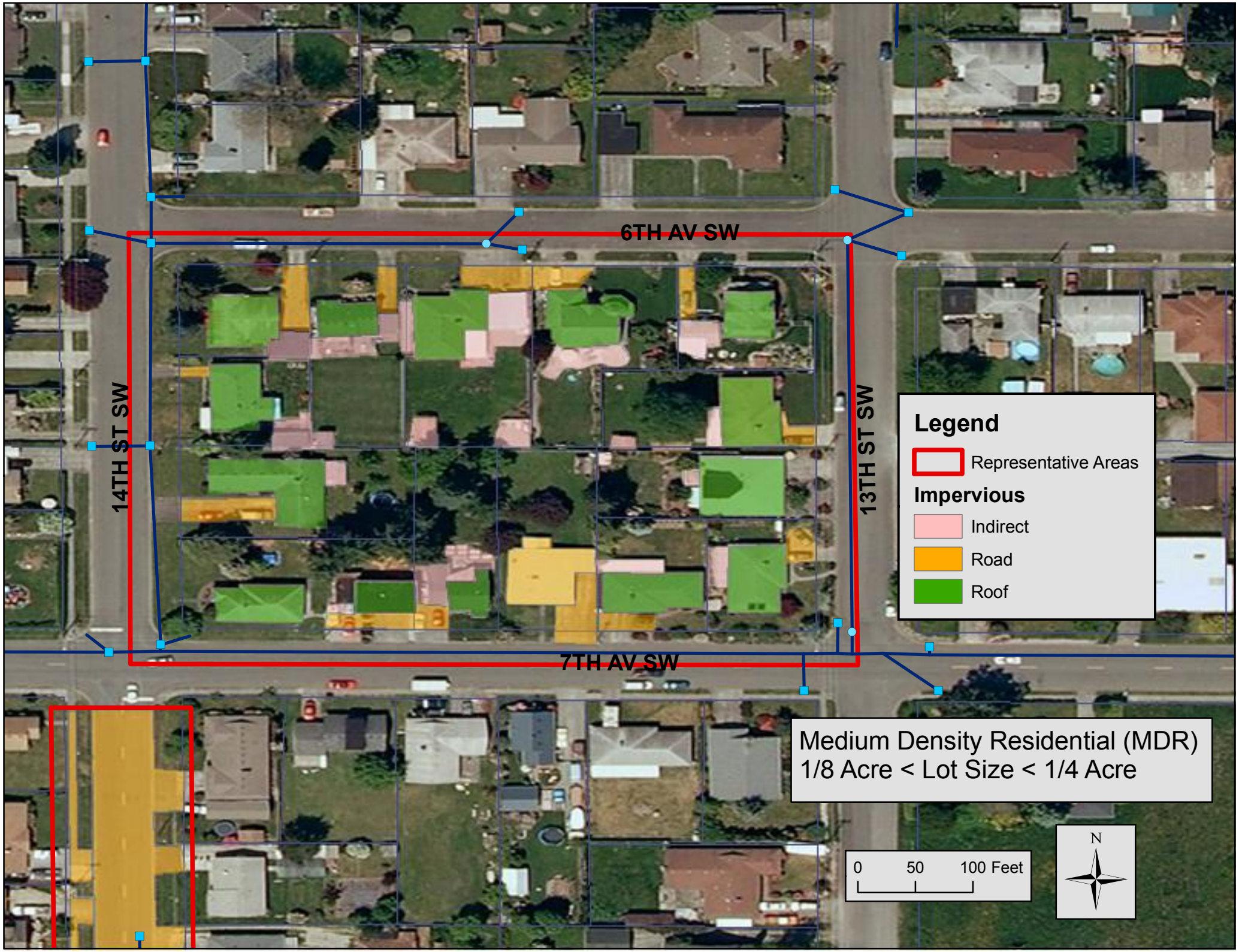
ATTACHMENT B (CONTINUED)

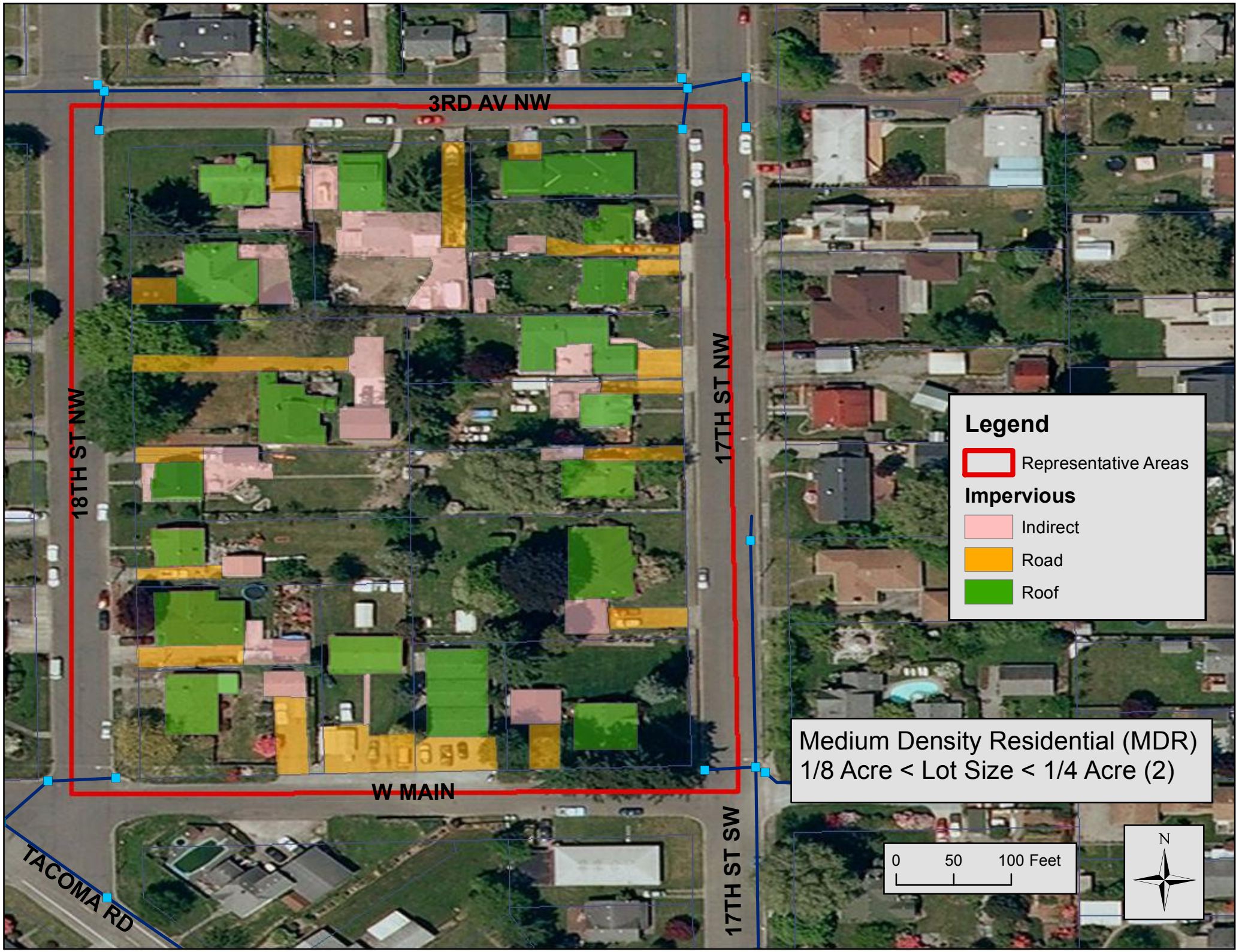
TABLE B-1
IMPERVIOUS AREA FROM REPRESENTATIVE LAND USE SAMPLING

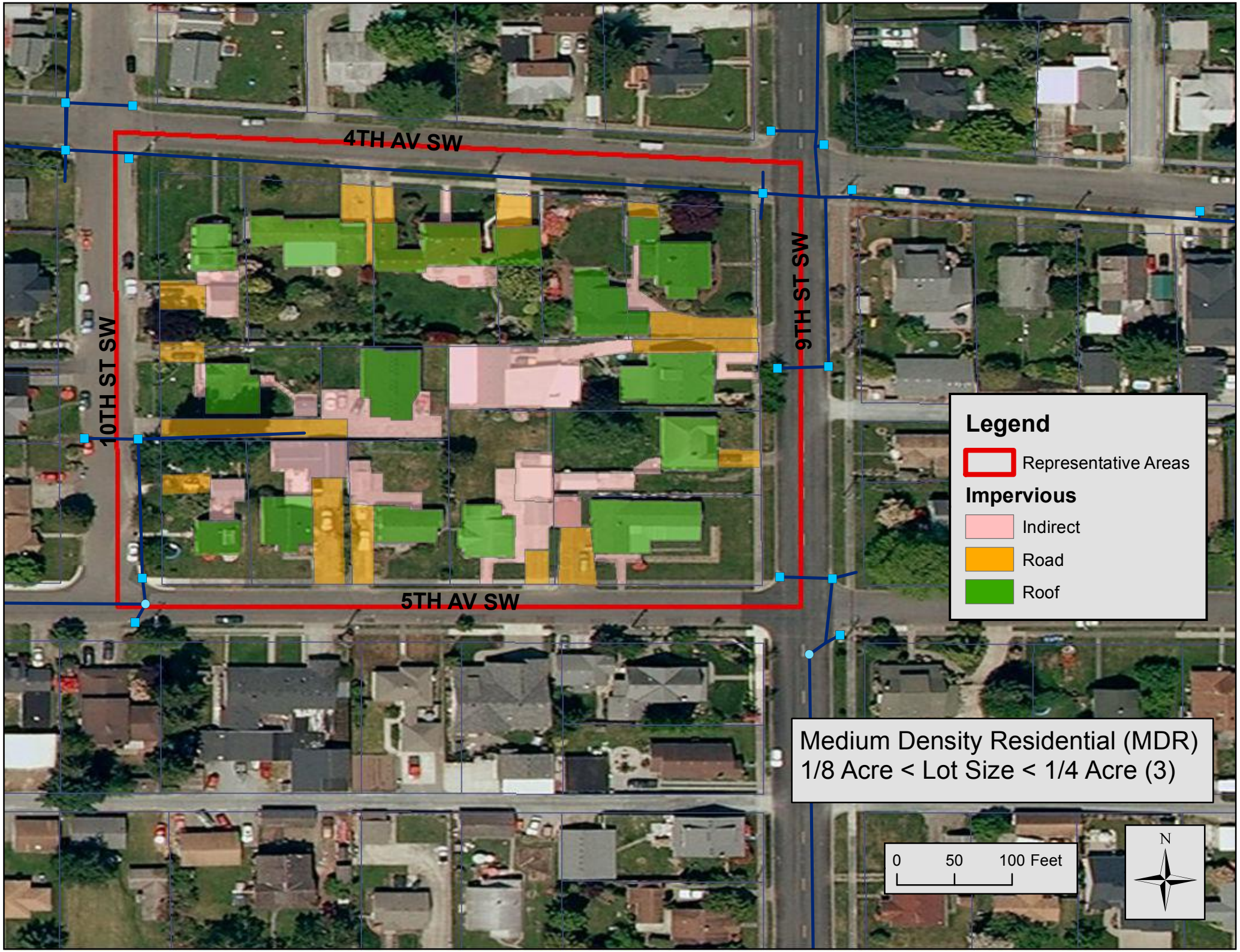
Land Use	TIA (%)	DCIA (%)	Roof Imp. (%)	Driveway/ Parking Imp. (%)
High Density/Multi-family Residential	75%	73%	25%	48%
Medium Density Residential/Single Family				
< 1/8 acre	56%	52%	40%	11%
1/8 acre to 1/4 acre (Roof Disconnected)	41%	9%		9%
Sample 1	39%	7%		7%
Sample 2	37%	10%		10%
Sample 3	45%	10%		10%
1/8 acre to 1/4 acre (Roof connected)	41%	30%	20%	9%
Sample 1	39%	30%	23%	7%
Sample 2	37%	28%	17%	10%
Sample 3	45%	31%	21%	10%
1/4 acre to 1/2 acre (Roof Disconnected)	39%	31%	21%	10%
1/4 acre to 1/2 acre (Connected)	39%	10%	0%	10%
1/2 acre to 1 acre	17%	5%	0%	5%
Low Density Residential > 1 acre	17%	5%	0%	5%
Commercial	85%	85%	14%	70%
Education	53%	50%	26%	24%
Rural Road	70%	70%		70%
Sample 1	66%	66%		66%
Sample 2	74%	74%		74%
Residential Road	78%	78%		78%
Sample 1	73%	73%		73%
Sample 2	83%	83%		83%
Commercial Road	100%	100%		100%

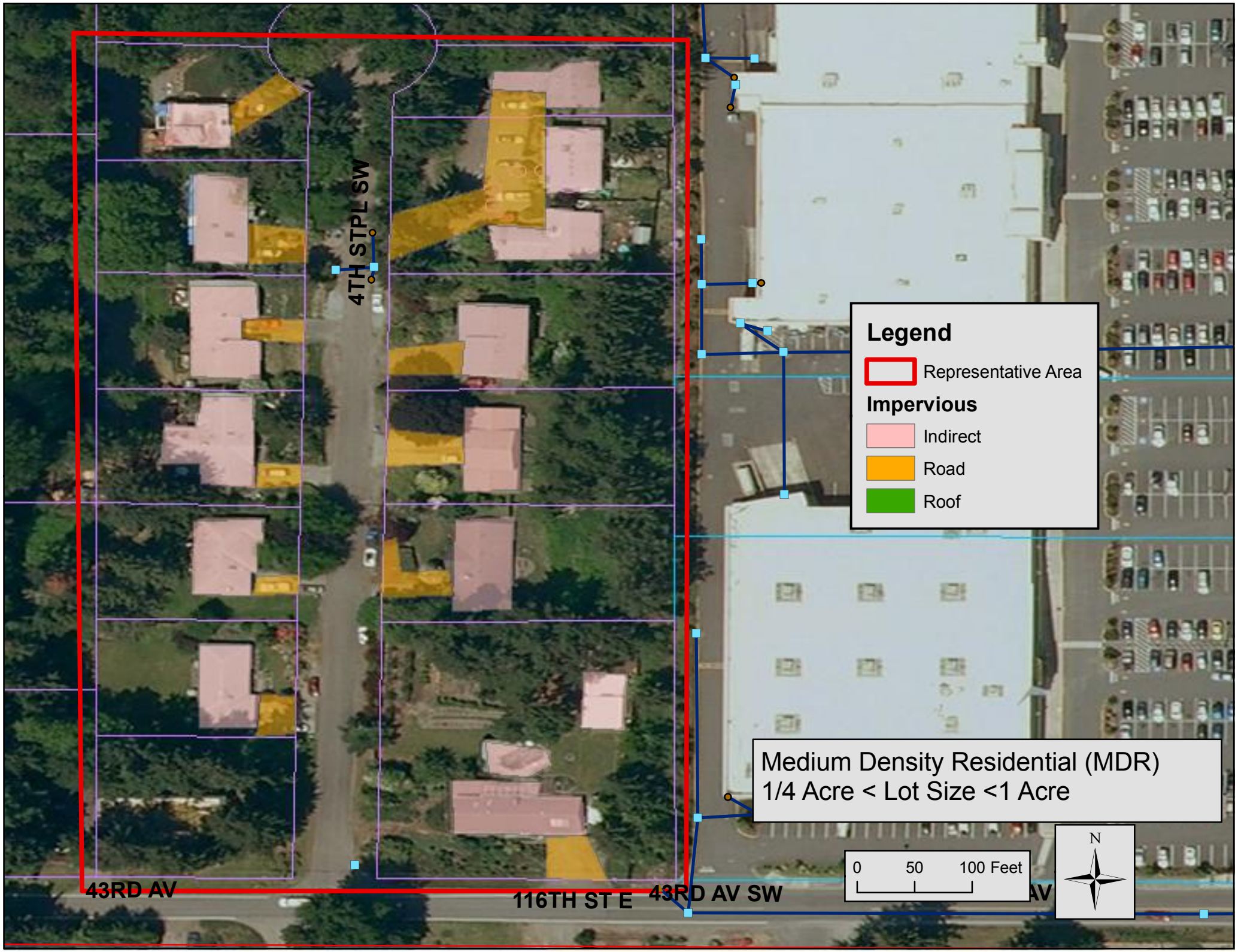
High Density Residential (HDR)
Legend
Representative Area
Impervious
Indirect
Road
Roof
7TH ST SE
9TH AV SE
8TH ST SE
RAMP SR512 RPN1 W
SR512 HWY W
SR512 HWY E
0
50
100 Feet
N

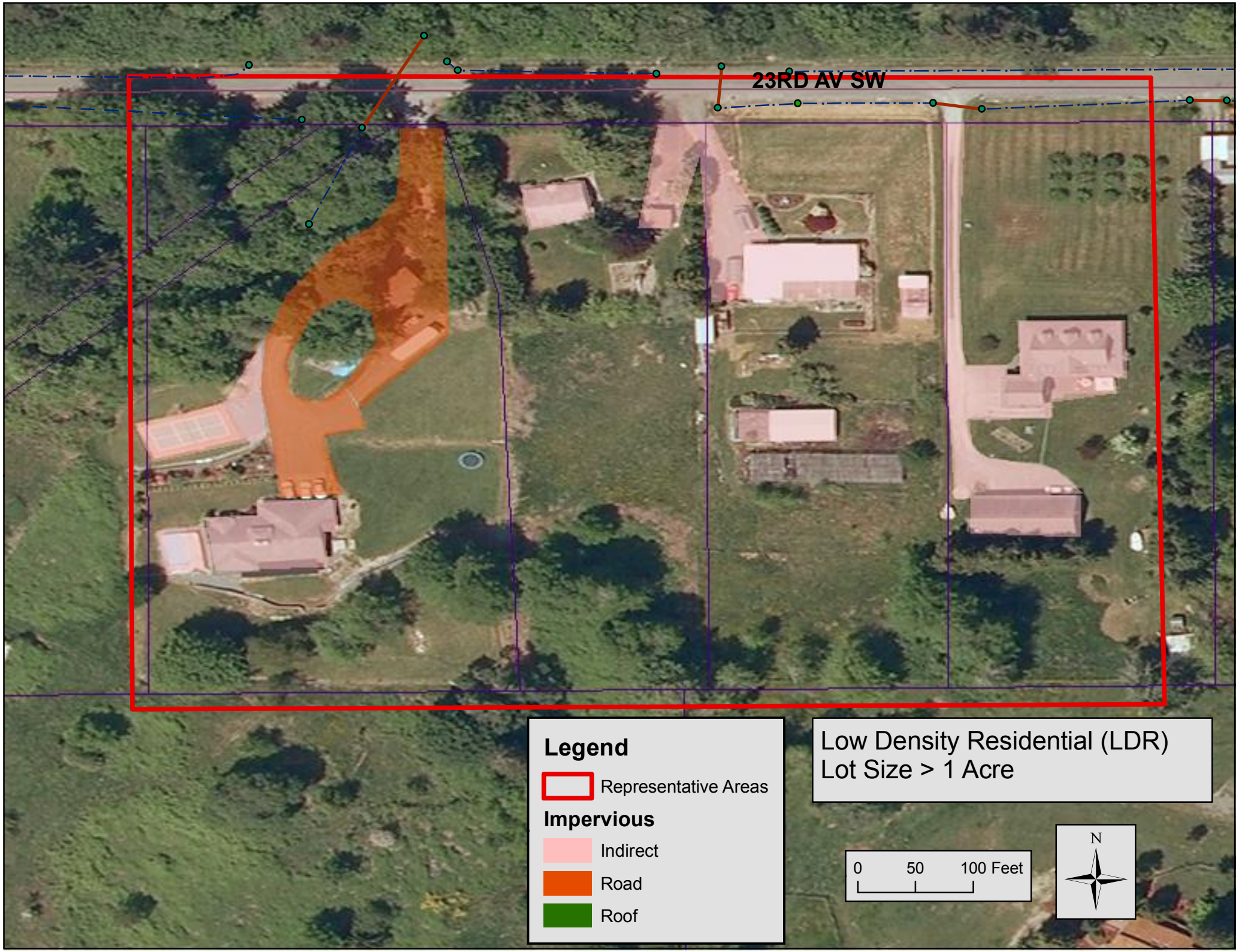
27TH AV SE
28TH AV SE
5TH ST SE
28TH AV SE
29TH AV SE
6TH ST SE
Legend
Representative Areas
Impervious
Indirect
Road
Roof
Medium Density Residential (MDR)
Lot Size < 1/8 Acre
0
50
100 Feet
N


6TH AV SW
7TH AV SW
14TH ST SW
13TH ST SW
Legend
Representative Areas
Impervious
Indirect
Road
Roof
Medium Density Residential (MDR)
1/8 Acre < Lot Size < 1/4 Acre
0
50
100 Feet
N

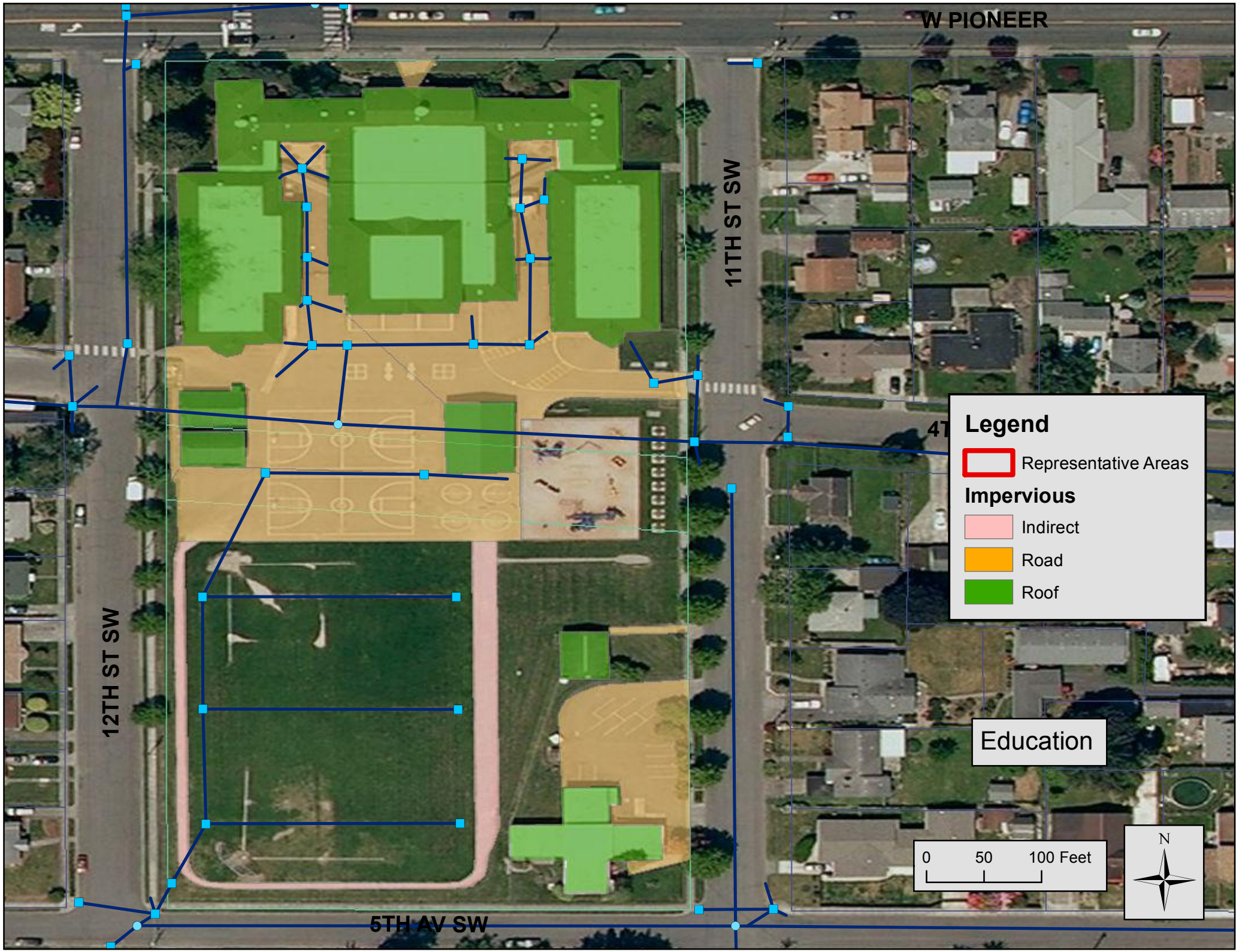

3RD AV NW
18TH ST NW
17TH ST NW
W MAIN
TACOMA RD
17TH ST SW
Legend
Representative Areas
Impervious
Indirect
Road
Roof
Medium Density Residential (MDR)
1/8 Acre < Lot Size < 1/4 Acre (2)
0
50
100 Feet
N


4TH AV SW
5TH AV SW
10TH ST SW
9TH ST SW
Legend
Representative Areas
Impervious
Indirect
Road
Roof
Medium Density Residential (MDR)
1/8 Acre < Lot Size < 1/4 Acre (3)
0
50
100 Feet
N


4TH STPL SW
43RD AV
116TH ST E
43RD AV SW
Legend
Representative Area
Impervious
Indirect
Road
Roof
Medium Density Residential (MDR)
1/4 Acre < Lot Size <1 Acre
0
50
100 Feet
N

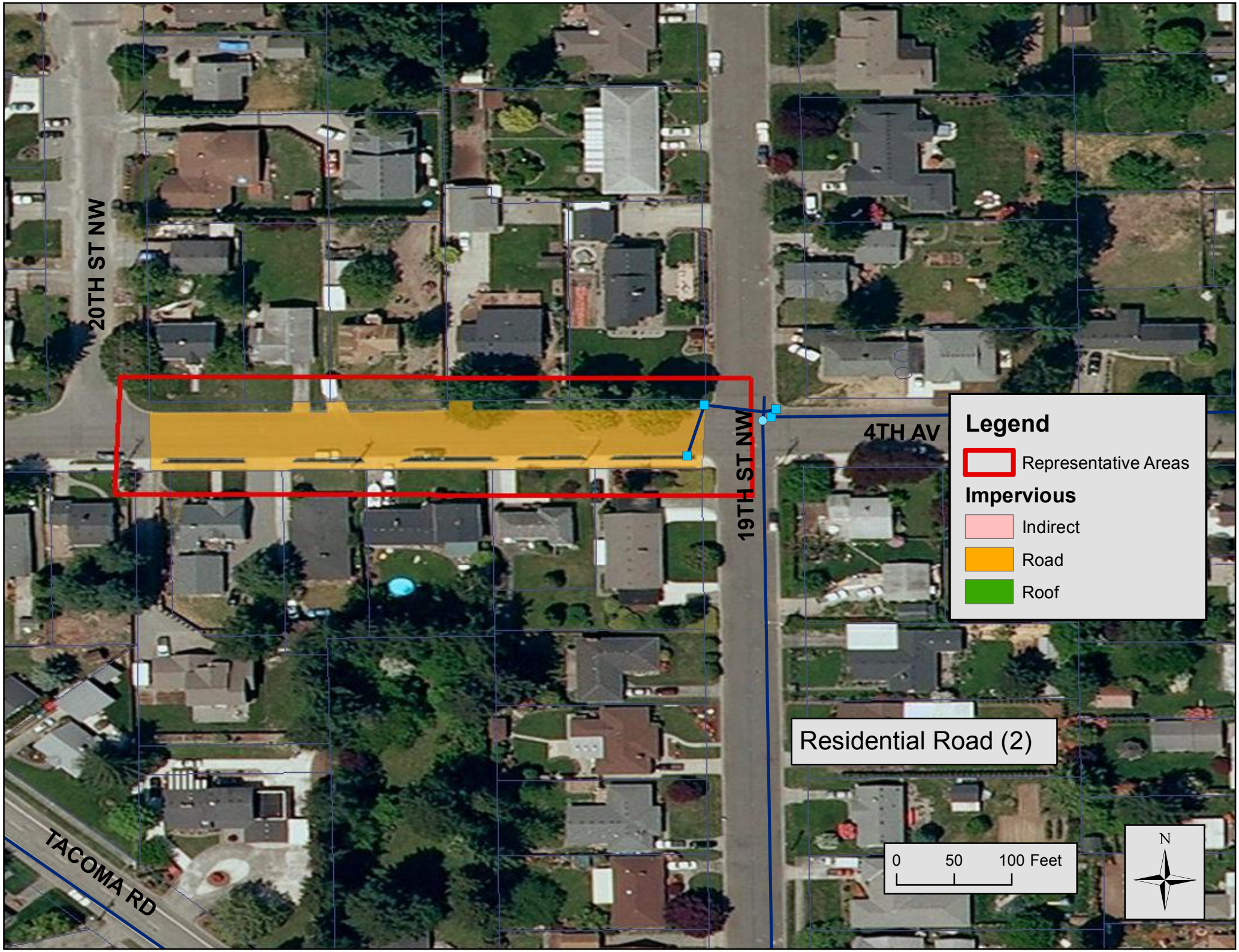

23RD AV SW
Legend
Representative Areas
Impervious
Indirect
Road
Roof
Low Density Residential (LDR)
Lot Size > 1 Acre
0
50
100 Feet
N

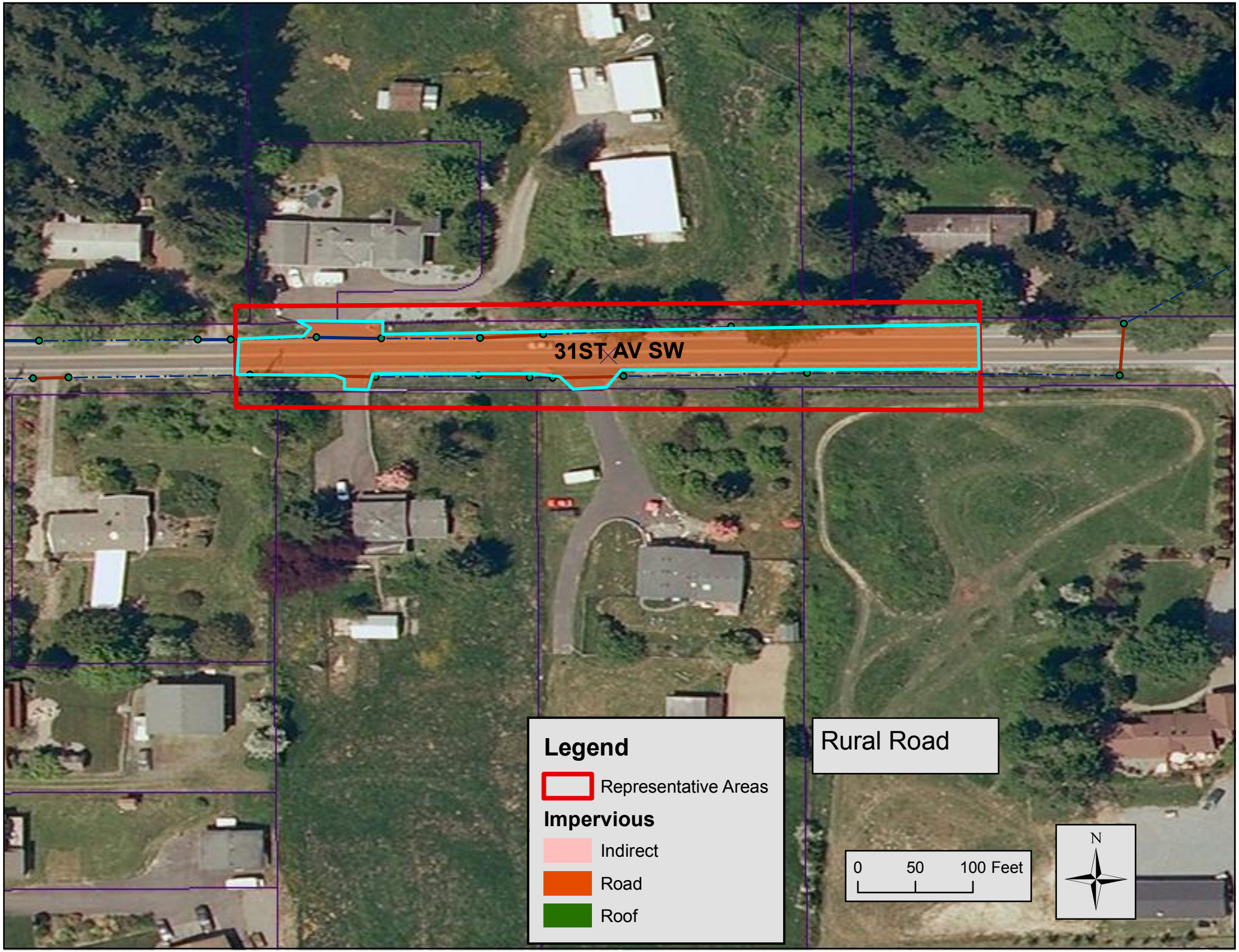
9TH ST SW
Legend
Representative Areas
Impervious
Indirect
Road
Roof
High Density Commercial
0
50
100 Feet
N


W PIONEER
11TH ST SW
12TH ST SW
5TH AV SW
Legend
Representative Areas
Impervious
Indirect
Road
Roof
Education
0
50
100 Feet
N

Legend
Representative Area
Impervious
Indirect
Road
Roof
S MERIDIAN
37TH AV SE
Commercial Road
0
50
100 Feet
N

14TH ST SW
13TH ST SW
9TH AV SW
Legend
Representative Area
Impervious
Indirect
Road
Roof
Residential Road
0
50
100 Feet
N


20TH ST NW
19TH ST NW
4TH AV
TACOMA RD
Legend
Representative Areas
Impervious
Indirect
Road
Roof
Residential Road (2)
0
50
100 Feet
N


31ST AV SW
Legend
Representative Areas
Impervious
Indirect
Road
Roof
Rural Road
0
50
100 Feet
N

31ST AV SW
Legend
Representative Areas
Impervious
Indirect
Road
Roof
Rural Road (2)
0
50
100 Feet
N