DISCHARGE OF STORMWATER TO HIGH ORDER STREAMS

Determining Exempt Reaches

Prepared for

Washington State Department of Transportation
310 Maple Park Avenue SE
PO Box 7329, MS 7329
Olympia, WA
98504-7329

April 2004 Final

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April 13, 2004 Final

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List of Abbreviations

WSDOT	Washington State Department of Transportation
LiDAR	Light Detection and Ranging
CO-Ops	Center for Operational Oceanographic Products and Services
USGS	United States Geological Survey
Q_t	tidal discharge
V_t	volume of tidal prism
T_{dd}	time of tidal drawdown, in hours
Q_r	river discharge
MHHW	Mean Higher High Water
NOAA	National Oceanic and Atmospheric Association
w	channel width, in feet
Δh	change in water surface elevation during falling tide, in feet
h_{max}	water surface elevation at high tide, in feet
h_{base}	water surface elevation at low tide, in feet
RM_x	river mile of river gauge
s_t	slope of water surface at high tide
cfs	cubic feet per second
Qr(10%)	average daily river discharge exceeded by 10 percent of historical values
Qr(max)	maximum daily average river discharge
GIS	Geographic Information System
WA-DNR	Washington State Department of Natural Resources
DEM	Digital Elevation Models
DLG	Digital Line Graph
EROS	Earth Resources Observation Systems
NHD	National Hydrography Dataset
HUC	Hydrologic Unit Code
WDFW	Washington Department of Fish and Wildlife
BCMSRM	British Columbia Ministry of Sustainable Resource Management
DRG	digital raster graphics
UGA	urban growth area
USFS	United States Forest Service
NPS	National Park Service
IRA	inventoried roadless area
SDA	special designated area
NWI	National Wetlands Inventory
TIA	total impervious area
EIA	effective impervious area
UTM	Universal Transverse Mercator
NAD	North American Datum
DOQQ	Digital Ortho Quarter-Quadrangle
WRIA	Water Resource Inventory Areas
AG	pasture or other agricultural land

WSDOT	Washington State Department of Transportation
WAU	watershed administrative units
LCC	land cover criterion
OHW	ordinary high water
mi^2	square miles
X-S	cross section
PDDA	potential direct discharge area

Executive Summary

The Washington State Department of Transportation (WSDOT), working in consultation with the Washington State Department of Ecology (DOE), is in the process of developing a list of high order stream reaches in western Washington which may be exempted from stormwater flow control requirements. This complex and innovative study is being conducted using a three-phase approach. During Phase 1, a position paper was prepared that presented the theory and justification for stormwater exemptions in large river systems and synthesized the relevant literature supporting the development of a methodology to exempt river reaches from stormwater flow control based on stream order, cumulative changes in watershed vegetative cover, percent impervious area, stream gradient, and tidal influence. During Phase 2, the methodologies for analysis of streams to be exempted was developed. During Phase 3, the methodology developed under Phase 2 will be applied to western Washington to define stream reaches that are exempt from stormwater flow control regulations.

This report documents the methodologies and results obtained under Phase 2. The position paper which was developed under Phase 1 is also included as an appendix to this report. The remainder of this summary provides a brief description of each section of this report.

Section 1

This section provides an introduction for the report.

Section 2

One of the key attributes of stream reaches that are suitable to receive discharge from areas exempted from flow control requirements is that they be sufficiently large watercourses to accept a limited amount of undetained storm water discharge without sustaining significant environmental damage. Initially, project participants agreed that *stream order* should be the indicator of stream size. Consequently, methodologies and data applicable to assignment of stream order were investigated, and GIS coverage of stream order for all of western Washington was developed for this project. Subsequently, it was found that *drainage area* would be a more convenient and more easily defined parameter than stream order to indicate stream size. In western Washington, a drainage area of 100 square miles was found to correlate approximately with 5^{th} order stream segments when stream order is estimated from 1:24,000 scale maps. A minimum drainage area of 100 square miles is recommended as a necessary if not necessarily sufficient criterion for defining an *exempt* stream segment, one that is suitable to receive discharge from areas exempted from flow control requirements.

Key Results or Conclusions:

- A GIS coverage of stream order in western Washington was developed.
- 100-square miles of drainage area was adopted as a replacement for 5th order to designate streams large enough to be exempt.

Section 3

In addition to stream size, a limit to the amount of undetained stormwater that would be contributed to a stream segment was needed. Previous work reported in the literature had related this limit in western Washington to an allowable level of land cover change at future buildout. This allowable level is represented by an index consisting of a weighted combination of the percent effective impervious area (EIA) and percent forest converted to urban pervious cover (FCONV) within a drainage basin contributing runoff to a stream segment. A review of planning, zoning, and land use mapping data from counties, cities, the state, and federal agencies demonstrated that the land cover change index could be determined from available data that are generally in GIS form. Methods for processing and analyzing land use data in order to compute the index were based on standard GIS methods and assumptions regarding the relationship of land cover to land use as documented in the literature.

Key Results or Conclusions:

- Sufficient data are currently available from public agencies to evaluate land cover status at future buildout in western Washington
- Procedures for GIS processing of data to determine future land cover were developed and documented

Section 4

The Nooksack River watershed was selected as a pilot watershed to demonstrate the analysis methods and implement the stream size and land cover change criteria. To this end municipal, county, state, and federal land use data were collected and processed using GIS. The results of this pilot effort indicate portions of the north and south forks of the river as well as its entire mainstem of the river downstream of the confluence of the forks should be exempt reaches based on the combined criteria of minimum drainage area and maximum allowable land cover change. However, it was noted that a third consideration in implementing flow control exemptions for these and all other river segments in western Washington should be addressed. This relates to the need to prevent major disruptions to natural drainage patterns of smaller tributary streams because of diversions of water to exempt river reaches. To answer this concern, areas qualifying for flow control exemptions should satisfy a *proximity* requirement that limits the distance from which direct discharges may be made to exempt stream reaches. Two methods for defining reasonable proximity are described; one requiring exempted project areas to be within a specified distance on either side of an exempt stream reach, and the other requiring discharge locations from project areas that have been exempted from flow control to be within a specified distance of exempt reaches.

Key Results or Conclusions:

- Lower portions of the North Fork, South Fork, and all of the mainstem Nooksack qualify as exempt reaches based on future land cover and stream size.
- Proximity requirements must be implemented in addition to stream size and future land cover condition in order to protect small streams from excessive diversion.

Section 5

Stream size, land cover change, and proximity criteria were found to provide a conservative basis on which to define exempt stream reaches and the land areas from which undetained stormwater might be delivered to those reaches; however, the benefits of requiring flow control to larger streams that failed the land cover change criteria are not well understood. Hydrologic modeling was used to investigate two questions in an effort to address this lack of understanding. Specifically, 1) for large streams or rivers, what differences in hydrologic regime occur with the presence or absence of stream protection detention ponds in areas adjacent to a river, and, 2) how do those hydrologic differences compare with the differences associated with the presence or absence of detention ponds in headwater areas draining to small streams? Modeling results showed that the answer to both questions are “small” but to some extent dependent on the intensity of land cover change in areas adjacent to large streams. However, regardless of land cover change intensity, the relative benefits of stream protection detention ponds near large streams were found to be miniscule compared to the benefits in the headwater areas of small streams. These results suggest that large streams and rivers that fail the future land cover criterion might still be considered for exemption if future development adjacent to them is not excessively intense. Alternatively, areas adjacent to such large stream and river reaches might be reasonably exempted from flow control requirements based on the flatness of their energy gradient or the dominance of tidal influences on their flow regime- two additional criteria investigated in this study.

Key Results or Conclusions:

- Protection provided by detention ponds in areas adjacent to large stream segments are very small and tiny in comparison to protection provided by ponds in headwater areas of smaller streams.

- Most rivers segments in western Washington that drain more than 100 square miles will qualify as exempt reaches.

- The minority of rivers draining more than 100 square miles that do not meet future land cover criteria may possibly be exempted based on tidal or gradient criteria

Section 6

Hydraulic modeling was performed in order to quantify the importance of stream gradient in determining whether undetained stormwater inputs to large streams would significantly affect potential for erosion or loss of salmonid spawning habitat. The study focused on high order streams, which were defined as streams with catchment areas greater than 100 mi^2. The analysis examined the relationships between key hydraulic and geomorphic variables believed to dictate the ability of large streams to buffer the geomorphic impacts of undetained stormwater inputs. These variables include channel gradient, channel cross-section complexity, and magnitude of backwater effects. The sensitivity of shear stress and velocity as a function of multiple combinations of these channel-defining variables was examined. Results from the sensitivity analysis were used as input to evaluate gradient-based thresholds for incipient motion for spawning gravels.

Key Results or Conclusions:

- Multi-thread channels with nominal gradients of 0.05% or less could adequately buffer undetained stormwater inputs with respect to mobilization of coarse gravels (>16 mm)

- Exemptions recommended only for high order streams with unconfined channels

- Receiving channels should be unconfined not only at the location of stormwater input, but also for the entire reach downstream from this point to the mouth of the stream or river. Stormwater inputs should not occur in small isolated threads within multi-threaded channels

Section 7

The relative magnitude of stream discharge and tidewater discharge was investigated to assess the effect of tidal fluctuation on the geomorphology of low-gradient, tidally-influenced streams. The relationship between tidal and stream effects was investigated by analyzing the ratio of tidal discharge to stream discharge over ranges of stream discharge values. This relationship was evaluated to determine under what conditions and in which systems the ratio suggests dominance of tidal effects. Three river systems were analyzed, including the Green River, Snohomish River, and Chehalis River, in order to evaluate tidal influence for large streams in western Washington using available data. Hypothetical channel configurations were also analyzed in order to investigate the relative influence of tide under a more diverse set of conditions.

Key Results or Conclusions:

- Exemption not appropriate for large systems based on tidal influence
- Evaluate exemption for smaller systems case-by-case when tidal discharge is greater than or equal to two times the river discharge associated with a 2-year recurrence interval.

Section 1
Introduction

The Washington State Department of Transportation (WSDOT), working in consultation with the Washington State Department of Ecology (DOE), is in the process of developing a list of high order stream reaches in western Washington which may be exempted from stormwater flow control requirements. This complex and innovative study is being conducted using a three-phase approach. During Phase 1, a position paper was prepared that presented the theory and justification for stormwater exemptions in large river systems and synthesized the relevant literature supporting the development of a methodology to exempt river reaches from stormwater flow control based on stream order, cumulative changes in watershed vegetative cover, percent impervious area, stream gradient, and tidal influence. During Phase 2, the methodologies for analysis of streams to be exempted was developed. During Phase 3, the methodology developed under Phase 2 will be applied to western Washington to define stream reaches that are exempt from stormwater flow control regulations.

This report documents the methodologies and results obtained under Phase 2. Work tasks performed under Phase 2 included:

- Task AN-4 – Definition of Stream Order and Alternative Metrics to Stream Order
- Tasks AN-5 and AN-6 – Determine Methodology for Defining and Calculating Percent Impervious Area and Cumulative Vegetative Land Cover Changes within a Watershed
- Task AN-7 – Application of Land-Cover Change Methodologies to Nooksack River Pilot Watershed
- Task AN-8 – Hydrologic Modeling to Simulate Effects of Stormwater Runoff on Channels
- Task AN-9 – Assessment of the Effects of Channel Gradient on Potential Geomorphic Alteration Induced by Stormwater Runoff
- Task AN-10 – Assessment of the Effects of Tidal Influence on Potential Geomorphic Alteration Induced by Stormwater Runoff
-

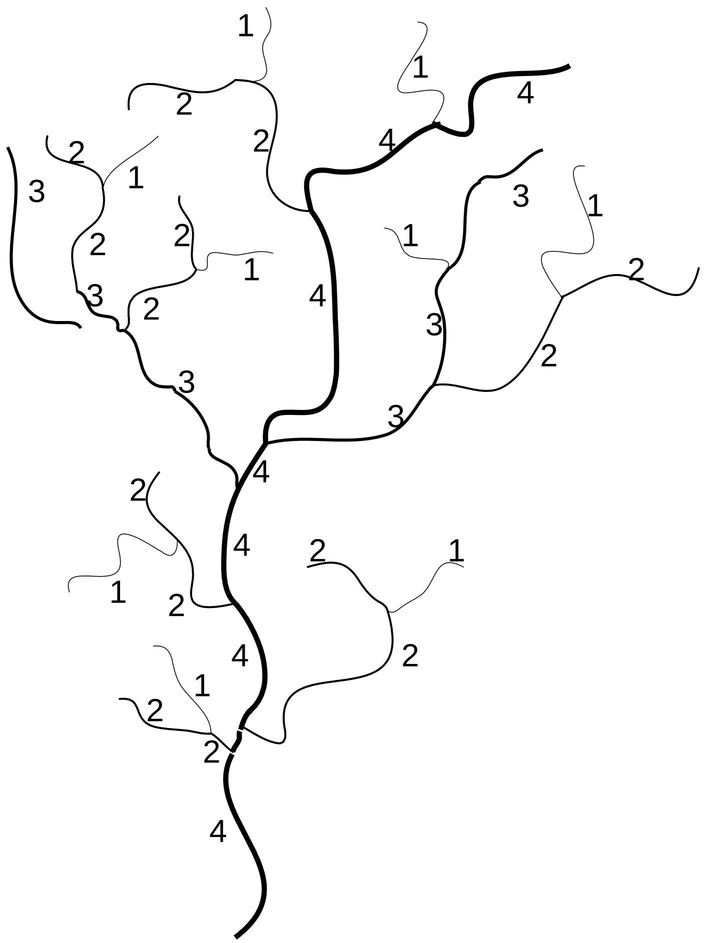
The position paper which was developed under Phase 1 is also included as an appendix to this report.

Section 2
Task AN-4 – Definition of Stream Order and Alternative Metrics to Stream Order

For this task Northwest Hydraulic Consultants (NHC) conducted a literature review and interview of several agencies (Washington Department of Natural Resources, U.S. Geological Survey, and King County) on stream ordering systems and methods relevant to the purpose of establishing a recommendation for the definition of first order streams and a methodology for mapping these streams. A functional approach to defining first order streams was taken in which the definition was closely linked to a practical identification methodology. Additionally, the utility of stream order as a means of identifying streams large enough to be considered for direct discharge was assessed in relation to Geographic Information System (GIS) data availability, map scale, drainage area, topography, and mean annual flow. Based on the results of this assessment, alternative metrics to stream order were considered and a recommendation has been made on a practical method for defining streams in western Washington that are potentially large enough to receive discharge from areas exempted from storm water quantity control.

2.1 Definition of Stream Order

Stream order is a numerical rank assigned to stream segments of a drainage network. Stream segments are defined either as headwater reaches bounded by the stream head and the first downstream tributary junction, or downstream reaches between two consecutive junctions. The original concept of stream order was presented by Robert Horton (1945) and later modified by Strahler (1957). Leopold (1994) provides a good discussion of the pros and cons of each of the two methods. A comparison of stream order numbering resulting from the Horton and the Horton-Strahler methods is shown in Figure 2-1. In Horton's original scheme, segments that form a junction never have the same order. The larger stream with higher drainage area takes on the same order as the segment below the confluence. As a result, in the original Horton methodology, a continuous series of stream segments from the lowest point of interest all the way to a watershed head above the highest confluence of branches is assigned the maximum stream order (Order 4 in Figure 2-1a). In Horton's original system, the maximum stream order number in a topographic drainage area depends upon how far downstream an observer or analyst wishes to define the lowest point of interest in the drainage network. Thus, the mainstem of the drainage network in Figure 2-1a which is assigned Order 4 would conceivably have a higher number if the frame of reference shifted to a larger watershed in which the network shown in Figure 2-1a was a subwatershed. One way around this subjectivity would be to require that the mouth always be defined at the point where a river meets the sea or a closed depression; however this would make the assignment of stream order for the purpose of describing and studying smaller, upstream basins very onerous. The modification to Horton's system proposed by Strahler avoids this difficulty by incrementing stream order number only downstream of segments of equal rank. Thus, two headwater segments that join together are both assigned



a. Stream Order Using the Horton Method

b. Stream Order Using the Horton-Strahler Method

Figure 2-1. Original and Modified Stream Ordering Scheme.

order 1 and the downstream segment formed by their confluence is assigned order 2 as shown in Figure 2-1b. Although, according to Leopold, Strahler's modification of Horton's method has some drawbacks, it is by far simpler to apply and has been the more widely accepted methodology by practicing geomorphologists and hydrologists. In fact, Strahler's modification to Horton's method has become so common, that some texts refer to it simply as "Horton's method of stream order" (see, for example, Linsley, Kohler, and Paulhus, 1982). For purposes of this study, the term "stream order" will refer to the commonly accepted, modified Horton's method as presented by Strahler (1952) as shown in Figure 2-1b.

2.2 Review of Available Statewide GIS Stream Segment Data

To aide in the evaluation of stream order and its applicability to western Washington a review of GIS datasets that covered the entire project area was performed. The review included both state and federal data sources and assessed whether datasets were readily available to the public, consistent throughout western Washington, accurate, and at a sufficient level of detail (adequately large map scale) for the project.

2.2.1 Washington State Department of Natural Resources (WA-DNR)

The existing WA-DNR stream typing dataset is the most comprehensive state-wide stream dataset currently available. In the early 1990s the DNR digitized (or collected) all of the 1:24,000 (7.5 minute) USGS quads for the entire state and developed a statewide stream layer. Since completion of that effort in 1996, stream positions, connectivity, and local spatial resolution have been modified by various agencies. The problem with this dataset is that these changes have made the dataset very inconsistent, especially with regard to spatial resolution, making it a poor choice for applying a standard stream order methodology. This modified dataset is available at <http://www.dnr.wa.gov/base/publications.html>; the original dataset is not readily available.

Currently the WA-DNR Forest Practices division is developing a rule-based method called the "Water Typing Model" to define stream type and where streams begin in watersheds. The new method is intended to replace the DNR's current 24k USGS based dataset. The new stream dataset will be based on 10-meter DEMs with the "type" of each stream segment determined as a combination of precipitation, slope, basin area and elevation. Following the specified rules, each segment will be labeled with type (I – V), habitat (shoreline, fish habitat and non-fish), and intermittency (perennial vs. non-perennial). The project has been underway for 5-years and data should be available for public review by July, 2004 (Per. Comm. Dennis McDonald; February, 2004).

2.2.2 United States Geological Survey (USGS)

USGS has DLGs (Digital Line Graphs) of hydrography for all of Washington State based on 1:100,000 (15-minute) quad maps. They also have DLGs based on 1:24,000 quad maps, but the coverage is incomplete and does not include large sections of western Washington including much of King and Snohomish Counties. Status (resolution, coverage) of USGS data sets for Washington can be checked at <http://mcmcweb.er.usgs.gov/status/wmc/wa/>. The original 100k USGS DLGs are available via the EROS Data Center <http://edc.usgs.gov/geodata> or in a modified format as part of the National Hydrography Dataset (NHD) <http://nhd.usgs.gov>. The NHD dataset also has the drawback of having been modified inconsistently from area to area.

2.2.3 Washington State Department of Fish and Wildlife (WDFW)

The current WDFW stream layer is based on the USGS 1:100,000 DLGs. **NHC** downloaded the USGS DLG hydrography data, projected the datasets to a common coordinate system and made a visual comparison of the result with the WDFW stream layer in the Nooksack watershed. The resultant GIS layers are very similar, but not identical since the USGS DLG shows outlines of wide rivers and lakeshores while the WDFW layer appears to be oriented toward the center line of channels. Additionally, the WDFW dataset has been sub-divided into 8-digit Hydrologic Unit Codes (HUCs) (also known as cataloging units), and includes useful stream name attributes that are absent from the USGS data layer. A discussion of the HUC watershed system is presented in Seaber et al. (1987). The WDFW Data is available at <http://www.streamnet.org/pnwr/PNWNAR.html>.

2.2.4 British Columbia Ministry of Sustainable Resource Management (BCMSRM)

All of the available Washington State stream segment GIS data is unfortunately cut off at the U.S. – Canada border. The BCMSRM has 1:50,000 scale stream data freely available and 1:20,000 data in progress. Both datasets can be found at <http://www.bcfisheries.gov.bc.ca/fishinv/basemaps.html>. The 1:50,000 scale dataset has stream order included as an attribute. The only two watersheds within western Washington State that have headwaters in Canada are the Nooksack and Skagit.

Consistent spatial resolution is a key attribute of a stream network dataset because spatial resolution clearly affects stream order. If the protocol for flow control exemption is based on stream order, it needs to be generated uniformly across the state or at least throughout western Washington. Arguably the most consistent datasets are those created numerically from Digital Elevation Models (DEMs). The drawback to these datasets is that they have very low accuracy in lowlands and urban areas where the data is most likely to be needed. As discussed later in Section 4.3 the USGS quad maps have rules for defining streams but there are inherently some inconsistencies that result from varying levels of leaf cover during mapping flights as well as operator error or subjectivity. The most accurate dataset available is the existing WA-DNR stream typing dataset but the level of inconsistency is far too high to be useful for this application. The best available dataset for application in this study is the WDFW 1:100,000 dataset as it is consistent, topologically correct (line segments intersect at end points and are drawn in the downhill direction), reasonably accurate and at a useful scale.

In addition to being a quality dataset, the WDFW dataset was also selected for this study because its packaging format was most suited to an automated calculation of Strahler Stream Order. The dataset is broken up into 8-digit HUC components for the entire State. These manageable watershed components allowed an Arc-View, GIS, AVENUE script to be used to calculate Strahler Stream Order in western Washington. Some of the component watershed stream networks had to be modified slightly to correct problems created by aqueducts and other non-stream features that exist in 1:100,000 USGS quad maps and are also present in the WDFW dataset. After stream order was calculated for all of the HUCs they were merged to generate a complete coverage of western Washington.

2.3 Effect of Map Scale

Stream order numbers are generally determined from topographic maps that show channel networks with varying levels of detail depending on map scale. As noted by Linsley, Kohler, and Paulhus (1982), "Order is extremely sensitive to the map scaled used. A careful study of aerial photographs will often show three or four orders of streams (mostly ephemeral rills and channels) not indicated on a 1:24,000 scale topographic map. The 1:24,000 scale topographic map will show one or two orders more than a 1:62,500 scale map. Even standard maps are not consistent in delineation of streams".

Leopold (1994) states that standard, 1:24,000 scale topographic maps with 10-foot contour intervals generally allow detection of first order channels that are typically approximately 0.7 square miles of drainage area and 1500 feet of channel length. He cites instructions to USGS cartographic technicians to extend stream segments no closer than 1000 feet from basin divides. Additionally, he cites a study in which a small portion of a basin designated as Order 1 using a 1:24,000 map was found to include four more orders of channel based on field observations and measurements of every discernable depression considered to contain concentrated storm runoff. Thus, what appeared to be an Order 1 channel at 1:24,000 scale was found to be an Order 5 channel at the much enlarged scale associated with the field mapping. Additionally, first order channel length and drainage area were reduced by a factor of approximately thirty compared to the network defined using the 1:24,000 scale topographic map.

Trainor and North (2002) performed an analysis of stream network characteristics in two different watersheds, one in northwest and the other in southeast British Columbia. They compared stream network parameters including drainage density, stream order, and bifurcation ratios based on watershed maps of three different scales: 1:20,000, 1:50,000, and 1:250,000. With regard to the influence of map scale on stream order, their study bears out the observation made by Leopold that stream order is strongly dependent on map scale and that larger map scale results in the identification of more stream orders within a drainage basin. Some of the relevant findings of this study can be summarized as follows: the majority of fifth order stream segments identified using 1:20,000 scale maps appear to be fourth order stream segments on 1:50,000 scale maps and can appear as either second or third order streams on 1:250,000 scale maps. While the trend of increasing stream order with increasing map scale is generally evident, the degree of increase in stream order is variable.

This study examined the effect of map scale on stream order specifically in the Nooksack watershed and in general in western Washington. Figure 2-2 presents a sub-basin in the Nooksack watershed that exhibits an increase of one order between the WDFW 1:100,000 hydrography coverage and 1:24000 USGS DRGs (Digital Raster Graphics) which are images of USGS quad maps. This example appears to typify differences in stream order at these two map scales throughout western Washington. This was verified by making a visual comparison of stream order using these datasets at USGS river gage locations as shown in Table 2-1. In most cases fifth order streams based on 1:24,000 maps appear as fourth streams on maps of 1:100,000 scale.

2.4 Alternative to Stream Order Threshold

As discussed in previous sections, stream order is highly dependent on map scale. In this section, the relationship of stream order to drainage area and discharge is discussed and an alternative to stream order as a threshold criterion is proposed.

Figures 2-3 and 2-4 show the relationship of mean annual discharge and drainage area to stream order at 156 current and discontinued USGS gaging station locations in selected watersheds of western Washington. The sampled watersheds include the major streams within the following WRIAs:

- 1–Nooksack
- 8–Cedar-Sammamish
- 9–Duwamish-Green
- 18–Elwha-Dungeness
- 19–Lyre-Hoko
- 20–Soleduk-Hoh
- 21–Queets-Quinalt

From these graphs it is clear that only a very approximate relationship exists between either drainage area or mean annual discharge and stream order within the sampled western Washington watersheds. Based on the 1:100,000 hydrography data, mean annual discharge of 4th and 5th order stream segments vary by nearly one whole log scale. This variability is not unexpected, given differences in drainage area, elevation, topography, geology, and most importantly precipitation that govern annual runoff at the different locations represented by the plotted data.

The primary function of minimum stream order in the context of this project is as a safety factor to be applied in combination with limits on land cover changes at buildout. It is based on the premise that predictions of land cover change from zoning would be more accurate over larger areas and that larger streams would experience less of an increase in peak flow than smaller streams as a result of flow control exemptions. Given both the map scale dependence of stream order and the lack of precision in its correlation with basic hydrologic parameters such as mean

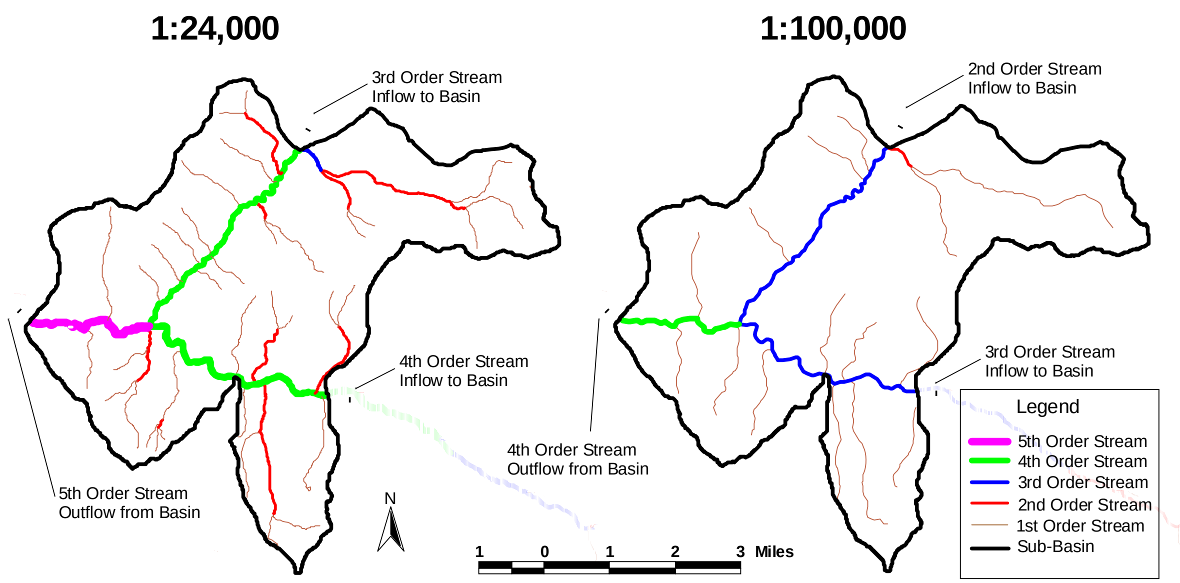


Figure 2-2. Strahler Stream Order at 1:24000 and 1:100,000 Scales.

Table 2-1. Comparison of Strahler Stream Order at selected western Washington locations (1:100,000 and 24:000:1 USGS map scales).

USGS Gage ID	USGS Gage Name	Mean Annual Discharge (cfs)	Drainage Area (miles^2)	Strahler Order 1:100,000	Strahler Order 1:24000
12040000	Clearwater River Near Clearwater, WA	1151	140	3	5
12040700	Hoh River Below Mt Tom Creek Near Forks, WA	864	98	3	5
12040900	South Fork Hoh River Near Forks, WA	537	50	3	4
12043080	East Fork Dickey River Near La Push, WA	267	40	3	4
12043300	Hoko River Near Sekiu, WA	400	51	3	4
12043430	East Twin River Near Pysht, WA	63	14	3	4
12044000	Lyre River At Piedmont, WA	217	49	3	4
12103400	Green River Below Intake Creek Near Lester, WA	132	35	3	4
12103500	Snow Creek Near Lester, WA	69	12	3	4
12105000	Smay Creek Near Lester, WA	51	9	3	3
12105500	Charley Creek Near Eagle Gorge, WA	71	11	3	3
12105700	North Fork Green River Near Palmer, WA	89	17	3	3
12105710	North Fork Green River Near Lemolo, WA	86	17	3	3
12110000	Big Soos Creek Above Jenkins Creek Near Auburn, WA	19	21	3	3
12112500	Big Soos Creek Near Auburn, WA	125	63	3	4
12112550	Soosette Creek Near Auburn, WA	6	6	3	3
12113500	North Fork Cedar River Near Lester, WA	71	9	3	4
12114500	Cedar River Below Bear Creek Near Cedar Falls, WA	163	25	3	4
12115000	Cedar River Near Cedar Falls, WA	259	41	3	4
12115500	Rex River Near Cedar Falls, WA	101	13	3	4
12117000	Taylor Creek Near Selleck, WA	97	17	3	4
12121600	Issaquah Creek Near Mouth Near Issaquah, WA	133	57	3	4
12122010	Sammamish River Above Bear Creek Near Redmond, WA	176	102	3	4
12124500	Bear Creek At Redmond, WA	74	48	3	4
12207850	Clearwater Creek Near Welcome, WA	120	19	3	4
12208500	Canyon Creek At Kulshan, WA	50	9	3	3
12209000	Sf Nooksack River Near Wickersham, WA	746	103	3	5
12210000	Sf Nooksack River At Saxon Bridge, WA	1135	129	3	5
12039300	North Fork Quinault River Near Amanda Park, WA	869	74	4	4
12039520	Raft River Below Rainy Creek Near Queets, WA	555	76	4	5
12040500	Queets River Near Clearwater, WA	4388	445	4	6
12041000	Hoh River Near Forks, WA	2020	208	4	5
12041200	Hoh River At Us Highway 101 Near Forks, WA	2542	253	4	5
12041500	Soleduck River Near Fairholm, WA	613	84	4	4
12042000	Soleduck River Near Beaver, WA	704	116	4	4

Table 2-1. Comparison of Strahler Stream Order at selected western Washington locations (1:100,000 and 24:000:1 USGS map scales) (continued).

USGS Gage ID	USGS Gage Name	Mean Annual Discharge (cfs)	Drainage Area (miles^2)	Strahler Order 1:100,000	Strahler Order 1:24000
12042500	Soleduck River Near Quillayute, WA	1348	219	4	5
12043000	Calawah River Near Forks, WA	1041	129	4	5
12043100	Dickey River Near La Push, WA	543	86	4	5
12044900	Elwha River Above Lake Mills Nr Port Angeles, WA	1532	198	4	5
12044910	Elwha River Site 1 At Lk Mills Nr Port Angeles, WA	732		4	5
12045500	Elwha River At Mcdonald Br Near Port Angeles, WA	1508	269	4	5
12046100	Elwha River Below Elwha Dam Near Port Angeles, WA	1841		4	5
12046500	Elwha River Below Diversion Near Port Angeles, WA	1967	318	4	5
12048000	Dungeness River Near Sequim, WA	384	156	4	5
12048650	Dungeness River At Rr Bridge Near Sequim, WA	201		4	5
12049000	Dungeness River At Dungeness, WA	466	197	4	5
12104500	Green River Near Lester, WA	382	96	4	5
12112600	Big Soos Creek Above Hatchery Near Auburn, WA	123	67	4	4
12116500	Cedar River At Cedar Falls, WA	321	84	4	5
12117500	Cedar River Near Landsburg, WA	685	121	4	5
12117600	Cedar River Below Diversion Near Landsburg, WA	511	124	4	5
12119000	Cedar River At Renton, WA	665	184	4	5
12125000	Sammamish River Near Redmond, WA	288	150	4	5
12125200	Sammamish River Near Woodinville, WA	311	159	4	5
12126500	Sammamish River At Bothell, WA	369	212	4	5
12205000	Nf Nooksack River Bl Cascade Creek Nr Glacier, WA	781	105	4	5
12205500	Nf Nooksack River Near Glacier, WA	1057	195	4	5
12207200	Nf Nooksack River Near Deming, WA	1668	282	4	5
12208000	Mf Nooksack River Near Deming, WA	475	73	4	5
12105900	Green River Below Howard A Hanson Dam, WA	999	221	5	5
12106500	Green River Near Palmer, WA	1098	230	5	5
12106700	Green River At Purification Plant Near Palmer, WA	956	231	5	5
12107000	Green River At Kanaskat, WA	700	240	5	5
12107500	Green River Near Black Diamond, WA	991	285	5	5
12113000	Green River Near Auburn, WA	1340	399	5	5
12113350	Green River At Tukwila, WA	1489	440	5	5
12113390	Duwamish River At Golf Course At Tukwila, WA	1938	461	5	5
12210500	Nooksack River At Deming, WA	3348	584	5	6
12211500	Nooksack River Near Lynden, WA	3705	648	5	6
12213100	Nooksack River At Ferndale, WA	3804	786	5	6

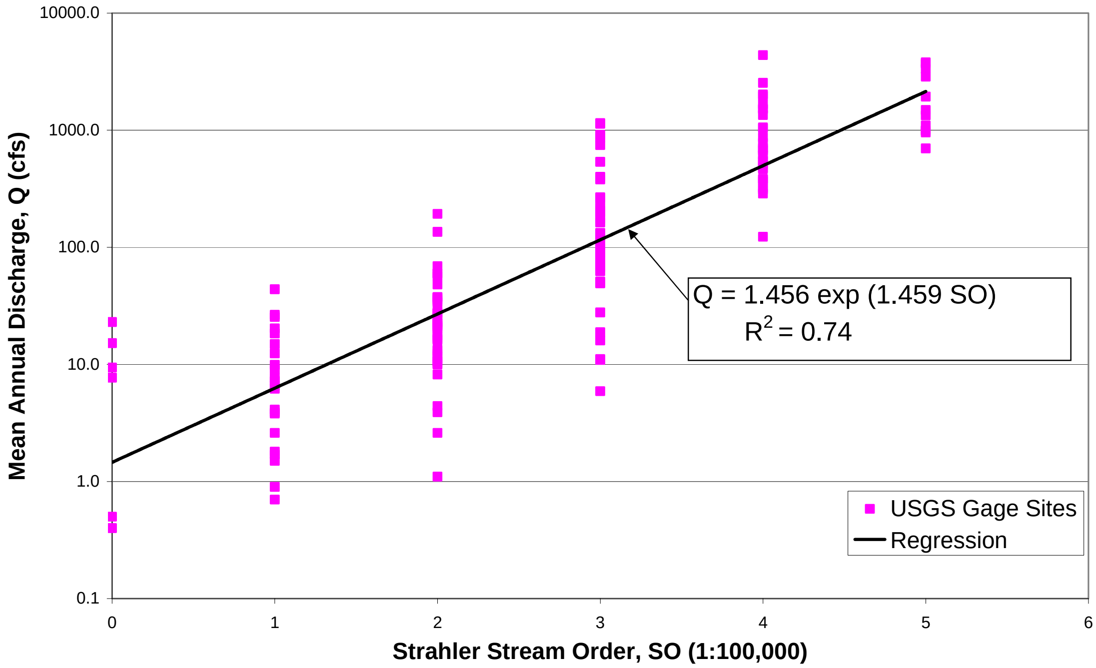


Figure 2-3. Strahler Stream Order (1:100,000) vs. Mean Annual Discharge.

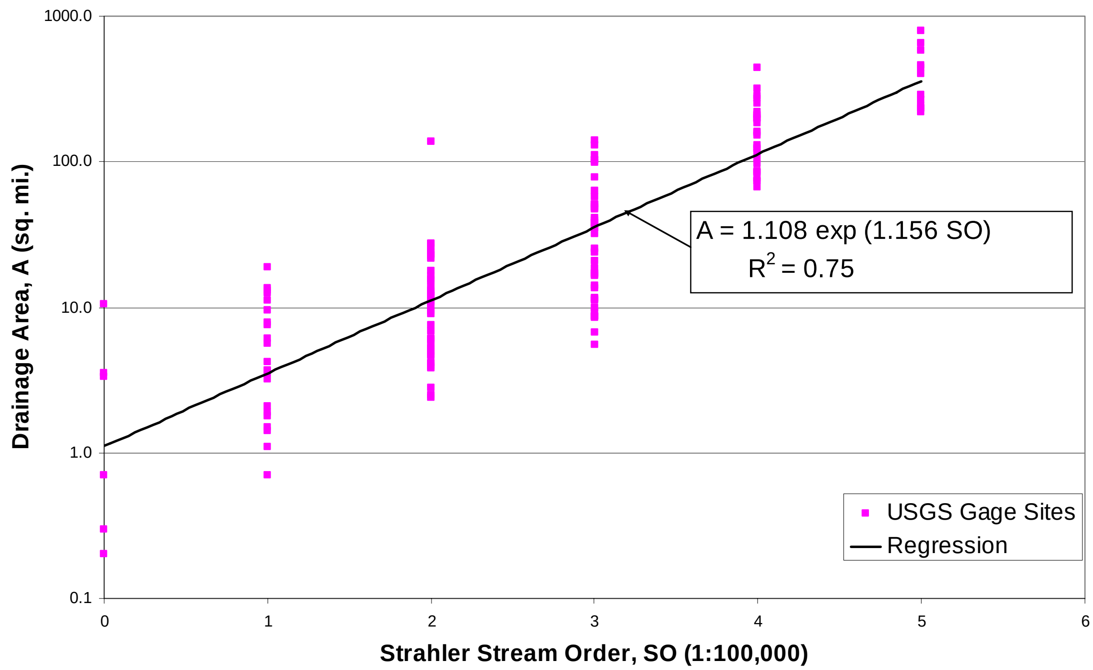


Figure 2-4. Strahler Stream Order (1:100,000) vs. Drainage Area.

annual discharge, an alternative threshold that will still provide the desired safety factor seems advisable. For this purpose, drainage area seems the most likely candidate as it is readily estimated with relative consistency. A minimum drainage area of 100 square miles is proposed as an alternative criterion to 5th order and higher streams. This area corresponds to the approximate value correlated with 4th order streams derived from 1:100,000 scale maps as shown in Figure 2-4. For stream networks derived from 1:24000 maps, this would be a typical if not precise drainage area in western Washington associated with 5th order streams. Some examples of the upstream end of river locations that would qualify for further consideration as direct discharge areas under this proposal threshold include: Cedar River below Taylor Creek at Selleck, Green River below Lester, Lake Sammamish and the Sammamish River, Middle Fork Snoqualmie River below Pratt River, North Fork Nooksack above Glacier, and South Fork Nooksack above Skookum Creek. Drainage area is also a metric that is easily reproducible using GIS tools and existing drainage basin maps. Mean annual discharge could also be used for this criterion as its correlation with Stream Order is equal to that of drainage area. Of concern with the use of discharge is that it is also dependent on land-cover, which is accounted for elsewhere in the criteria. It is also more difficult to provide an accurate estimate of mean annual discharge at any given location in the stream network.

2.5 Recommendations

The dependence of stream order on map scale, topography, and variable cartographic procedures make it less desirable as a measure of stream size than other parameters for purposes of identifying exempt stream reaches. As an alternative, drainage area is recommended as an easily and consistently determined indicator of stream size. Based on correlations with stream order at USGS gaging stations in western Washington, a drainage area of at least 100 square miles is recommended as one of the requirements for determining exempt stream reaches. This minimum drainage area is based on data in western Washington as is not recommended for the eastern portion of the state. The minimum drainage area criterion is to be applied in combination with land cover change criteria discussed in the memorandum associated with Tasks AN-5 and AN-6.

Section 3
Tasks AN-5 and AN-6 – Determine Methodology for Defining and Calculating Percent Impervious Area and Cumulative Vegetative Land Cover Changes within a Watershed

In the preceding phase of this project (Herrera and **NHC**, 2003), the project team developed a set of conditions which were determined to provide an ecologically conservative basis for allowing discharges from areas exempted from storm water quantity control requirements. One of the criteria specified a minimum stream size (stream order) and has been discussed at length in the preceding technical memorandum entitled “Task AN-4 – Definition of Stream Order and Alternative Metrics to Stream Order.” The second criterion specified a maximum amount of landuse change at planned buildout within the drainage basin of the stream reaches meeting the aforementioned size criterion. Landuse change was represented by a metric which made up of weighted values of effective impervious area and developed pervious area within a drainage basin. This technical memorandum outlines a methodology that uses zoning and Comprehensive Landuse Plan maps to estimate changes in landuse and the associated changes in land cover that are used to calculate the change metric. The key components of this metric are effective impervious area and total suburban grass or agricultural area at planned buildout.

3.1 Zoning/Planning Landuse GIS Data Assessment

A single zoning/planning landuse dataset that includes all of western Washington does not exist so data must be collected from a variety of sources. The majority of western Washington is covered by county zoning and planning maps which typically include all unincorporated and non-Urban Growth Area (UGA) portions of the counties. A review of the availability of hardcopy and GIS format zoning in western Washington’s 19 counties found that the data is generally available in digital form although the amounts charged by jurisdictions to provide these data were generally not available at the time of this writing. In some cases, data are available free of charge or would cost less than $100 (see Table 3-1). The only exceptions to this are Wahkiakum County which reported having no zoning data and Skamania County which only had a hardcopy map. In addition to county zoning data, the UGAs for cities and towns can include significant areas that overlap current county-zoned areas. Where future UGA zoning projected by a city differs from current county zoning, the future city zoning should take precedence as it is more likely to reflect the ultimate buildout condition of the area in question. Data are generally readily available from cities and towns and most medium to large towns have the data available in a digital GIS format, but datasets from some small towns will need to be digitized from raster images or hardcopy maps.

Table 3-1. County GIS comprehensive plan/zoning data availability and contact list.

County	Data Availability	Format	Cost	Contact Info
Clallam	Yes	GIS	?	Department of Community Development http://www.clallam.net/dcd/ Phone: 360-417-2321
Clark	Yes	GIS	?	Community Development http://www.co.clark.wa.us/ComDev/Default.asp Phone: 360-397-2375
Cowlitz	Yes	GIS	?	Geographic Information Systems Department http://www.co.cowlitz.wa.us/gis/index.html Terry McLaughlin, Manager 360-577-3065
Grays Harbor	Yes	GIS	$100/CD	Geographic Information Systems Department http://www.co.grays-harbor.wa.us/info/ GIS Phone: 360-379-5071
Island	Yes	GIS	?	Public Works Department http://www.islandcounty.net/publicworks/ Phone: 360-678-5111
Jefferson	Yes	GIS	?	Department of Community Development http://www.co.jefferson.wa.us/commdevelopment Phone: 360-379-4450
King	Yes	GIS	$93/CD	Geographic Information Systems Department http://www.metrokc.gov/gis/index.htm Phone: 206-263-4801
Kitsap	Yes	GIS	?	Community Development http://www.kitsapgov.com/dcd/#PLAN John James 360-337-7121
Lewis	Yes	GIS	$50/CD	Public Works-GIS Division http://www.co.lewis.wa.us/publicworks/lewisgis.htm Phone: 360-740-1182
Mason	Yes	GIS	?	Public Works http://www.co.mason.wa.us/default.shtml Alan Borden (sp?), 360-427-9670 x365
Pacific	Yes	GIS	?	Community Development http://www.co.pacific.wa.us/dcd/PLANNING.htm Phone: Mike, 360-642-9382
Pierce	Yes	GIS	?	Planning and Land Services http://www.co.pierce.wa.us/text/services/home/property/pals/other/maps.htm GIS Contact, Karen Truman, 253-798-7166
San Juan	Yes	GIS	?	Central Services http://www.co.san-juan.wa.us/gis/gislib.asp Phone: 360-378-8205
Skagit	Yes	GIS	?	Geographic Information Services http://www.skagitcounty.net GIS Contact, Geoff Almvig, 360-336-9368

Table 3-1. County GIS comprehensive plan/zoning data availability and contact list (continued).

County	Data Availability	Format	Cost	Contact Info
Skamania [a]	Yes	1977 Hardcopy N/A	?	Planning Department http://www.skamaniacounty.org/ Karen Witherspoon, 509-427-9458
Snohomish	Yes	GIS	?	GIS Department http://www.co.snohomish.wa.us/gis/ Phone: 425-388-3349
Thurston	Yes	GIS	$100/CD	Thurston GeoData Center http://www.geodata.org/ Phone: 360-754-4594
Wahkiakum [b]	No	No	?	Public Works Department http://www.cwcog.org/publicworks.html Chuck Bar(sp?), 360-795-3067
Whatcom	Yes	GIS	?	Planning and Development Services http://www.co.whatcom.wa.us/pds/planning/gis Phone: 360-676-6907

[a] Oversized, color hardcopies of zoning maps unavailable for reproduction
[b] Additional information may be obtained from Cowlitz-Wahkiakum Council of Government or City of Cathlamet

Large areas of western Washington include United States Forest Service (USFS) and National Park Service (NPS) lands which have landuse GIS data available that is more detailed than the county zoning data. The USFS has a dataset for their Inventoried Roadless Areas (IRAs) that designates which areas are planned to remain IRAs and a Special Designated Areas (SDAs) dataset that designates National Wilderness and other restricted areas. These USFS datasets help distinguished roaded and non-roaded areas and allow an estimate of the future level of imperviousness within forest areas associated with roads. The National Park Service dataset only specifies park boundaries.

Two watersheds in western Washington overlap the border with British Columbia. In both of these watersheds, the Nooksack and the Skagit, the landuses are generally rural and can be completed with existing area maps and zoning datasets from Canadian cites.

For use in land-cover change analysis, existing wetlands and lakes are preserved as future landuses. The National Wetlands Inventory (NWI) dataset is available digitally by quadrangle within all of western Washington. This GIS dataset designates which areas are upland versus wetland and the specific classification of each wetland area. British Columbia also has a similar wetlands dataset but its coverage is coarser than the U.S. dataset. The Washington State Department of Ecology (WA-Ecology) has a “major lakes” dataset that covers the entire state and is available digitally in a GIS format.

3.2 Landuse Data Analysis by Watershed Subbasin

The estimation of total impervious area (TIA), effective impervious area (EIA), and amount of forest converted to developed pervious areas at future buildout within a watershed is a stepwise process that relies on GIS databases and processing. The first major task in this process is to develop a GIS coverage of future landuses that is specific to subbasins of the watershed of interest. The basic steps applied by **NHC** to accomplish this task in the pilot watershed and recommended for application to other watersheds in western Washington is as follows:

1. **Select GIS Mapping Parameters.** The zoning and planning datasets discussed in Section 5.1 come in a variety of units, projections and datums and must be properly registered to a common coordinate system. **NHC** selected Universal Transverse Mercator (UTM) Zone-10, the North American Datum of 1927 (NAD27) with units of meters for this project. This projection was selected because of its spatial accuracy throughout western Washington and because Digital Raster Graphics (DRGs) of the USGS quadrangle maps and Digital Ortho Quarter-Quadrangle (DOQQ) photographs are freely available for the entire state in this projection and datum.

2. **Unify and Merge Zoning Maps.** Planning and zoning map units from all sources are converted into a common set of future landuse categories and then merged into a single watershed-wide coverage. In this coverage, comprehensive plan designations for urban growth areas (UGAs) made by cities and Federal landuse designations take precedence over county planning zones. See Table 3-2 for guidance on mapping different zones into a set of aggregated future landuse categories.

3. **Overlay Lake and Wetland Coverages.** GIS coverages of major lakes from WA-Ecology and of wetlands from the National Wetlands inventory (NWI) are overlayed on the merged coverage from step 2. In this process, lake areas take precedence over wetlands and both take precedence over any underlying zoning or landuse designation. In this study, lakes and designated wetland areas will be assumed to be conserved at future buildout, while full use consistent with planning and zoning categories will be assumed for all remaining areas.

4. **Develop Subbasin Delineation**. Acquire the most detailed GIS map delineating watershed subbasins available. The best map may be available from WRIA planning groups. If necessary, topographic maps should be used in combination with WA-DNR Watershed Administrative Unit (WAU) GIS maps to achieve the desired level of subbasin detail. The subbasin data set should be no coarser than the WAU which is 2 orders of sub-divisions beyond the WRIA watershed system. Additionally, subbasins that include 4th or higher order (based on 1:100,000 scale-based stream maps) stream segments should be partitioned as necessary

immediately downstream of each 2nd order or higher stream junctions with the higher order stream. Performance of this step assures a reasonable level of spatial precision in the calculation of land cover composition and total drainage area along the larger streams within the watershed. An example of this partition is shown in Figure 3-1.

5. **Intersect Subbasin and Landuse Coverages.** Perform an intersection of subbasins with the future landuse coverage. This will allow the aggregated landuse categories in Table 3-2 to be summarized for each subbasin.

3.3 Percent Forest Converted and EIA from Landuse Data Analysis

The hydrologic conditions at any point in a river system include the cumulative effects of the landuse changes that have occurred upstream of that location. The hydrologic impact from different levels of development can be characterized by assigning equivalent land-cover percentages to each landuse category. The assignments used in this study including forest, agriculture/pasture, grass, EIA, TIA, wetland and open-water are shown in Table 3-2.

Two key land-cover parameters are Effective Impervious Area (EIA) and Total Impervious Area (TIA). EIA only includes impervious areas that are hydrologically "connected" to the drainage system while TIA includes all impervious areas. The basis for the percentages of TIA and EIA in urban areas is based values published by King County (1998) and studies of urbanizing stream basins (e.g., Alley and Veenhuis, 1983 and Dinicola, 1989). Total impervious area (TIA) in industrial forest areas was assumed to be 1 percent (Jones, 2000). This is consistent with results of a field study of the White Creek watershed conducted for the Yakama Nation Fisheries Department (**NHC**, 2003) which determined similar TIA percentages and estimated EIA at approximately 50 percent of TIA. Reserve Forest landuse areas were assumed to have 0 percent EIA and TIA. For agricultural areas an EIA percentage of 1.0 was estimated from road densities in the Nooksack watershed where agricultural land tended to be divided by county roads located on quarter section lines.

A GIS tool was developed that allows cumulative land-cover change to be calculated from the landuse overlay analysis described in Section 3-2. The GIS tool is an **AVENUE** script that converts the landuse overlay analysis results to land-cover areas for each subbasin and then calculates the accumulation of those land-covers for all subbasins upstream of each stream segment in the watershed. The conversion from landuse to land-cover is performed following the ratios provided to the script in a lookup table similar to Table 3-2. The script's calculations allows the user to query the cumulative land-cover for any mainstem stream segment in the watershed and use those results to calculate the buildout land-cover change metric, LCC:

$$LCC = \%\text{Forest Converted} + 5.75 * \%EIA \qquad (5.1)$$

Table 3-2. Mapping of planning landuse data to aggregated future landuse categories and associated land cover percentages.

Zone or Planned Landuse	Aggregated Future Landuse Category	Data Source	Land Cover Percentages of Aggregated Landuse Categories						
			Forest	Agriculture or Pasture	Grass	EIA	TIA	Wetland	Open Water
Lakes	Open Water (OPEN WATER)	WA-Ecology Lake Coverage	0.0	0.0	0.0	0.0	0.0	0.0	100
Designated Wetlands	Wetland (WET)	National Wetland Inventory coverage	0.0	0.0	0.0	0.0	0.0	100.0	0.0
Designated roadless forest areas, national parks, wilderness areas	Reserve Forest (RES FOR)	National Forest coverage of Inventoried Roadless Areas (IRA), Special Designated Areas (SDA), and National Park boundaries	100.0	0.0	0.0	0.0	0.0	0.0	0.0
Roaded forest areas managed for timber production on private, state, and federal land	Industrial Forest (IND FOR)	County zoning and National Forest Administrative Boundary	99.5	0.0	0.0	0.5	1.0	0.0	0.0
Parks and recreational space	Open Grass (OPEN GRASS)	County and municipal zoning and comprehensive plans	0.0	0.0	100.0	0.0	0.0	0.0	0.0
Quarries and mining areas	Mineral Resource Lands (MRL)	County and municipal zoning and comprehensive plans	0.0	0.0	50.0	50.0	50.0	0.0	0.0
Agricultural lands	Agriculture (AG)	County and municipal zoning and comprehensive plans	0.0	99.0	0.0	1.0	1.3	0.0	0.0
Residential zones with <1 d.u. per acre	Low Density Residential (LDR)	County and municipal zoning and comprehensive plans	0.0	48.0	48.0	4.0	10.0	0.0	0.0
Residential zones with 1-3 d.u. per acre	Medium Density Residential (MDR)	County and municipal zoning and comprehensive plans	0.0	0.0	86.0	14.0	25.0	0.0	0.0
Residential zones with 4-7 d.u. per acre	High Density Residential (HDR)	County and municipal zoning and comprehensive plans	0.0	0.0	64.0	36.0	49.0	0.0	0.0
Residential zones with >7 d.u. per acre	Multi-Family Residential (MF)	County and municipal zoning and comprehensive plans	0.0	0.0	52.0	48.0	60.0	0.0	0.0
All commercial, industrial, airport, and transportation corridor zones	Commercial (COM)	County and municipal zoning and comprehensive plans	0.0	0.0	14.0	86.0	90.0	0.0	0.0

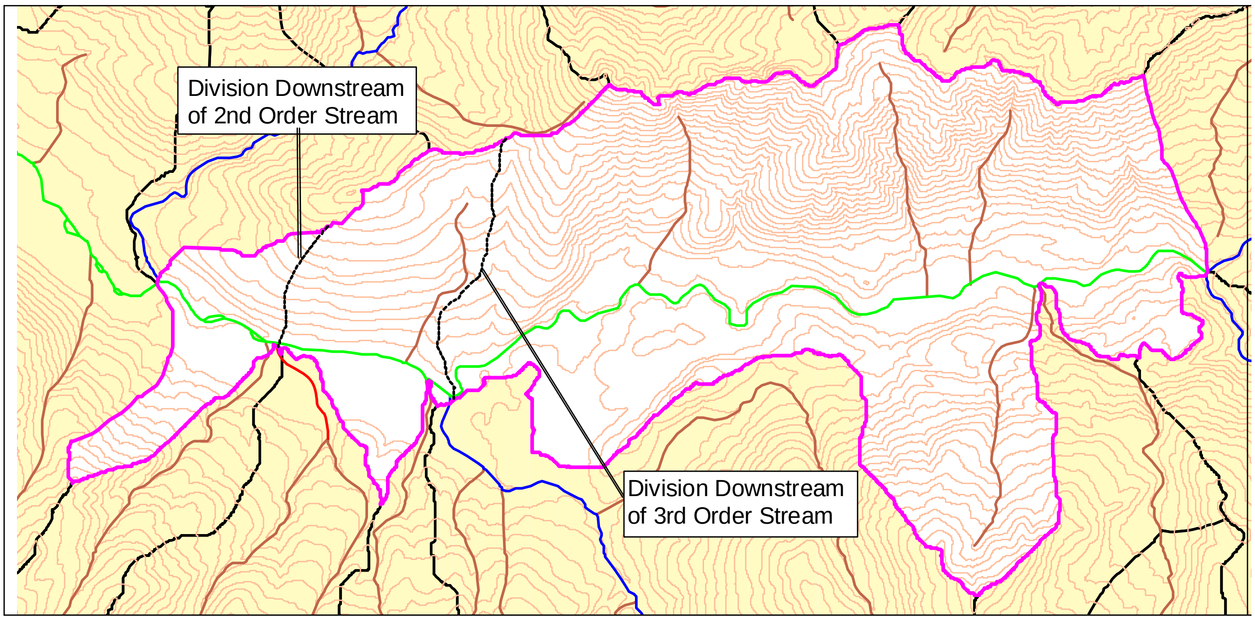


Figure 3-1. An example of partitioning subbasins immediately downstream of each junction of a 2nd order or higher stream that is tributary to a 4th or higher order stream.

Based on the recommendation presented in position paper developed in Phase 1 of this study (Herrera and NHC, 2003), segments of larger streams that drain basin areas with LCC values of less than 55.4 (see Figure 3-2) would be suitable for direct discharge from qualifying land areas in the vicinity of the stream. In addition to land-cover, the **AVENUE** script also reports cumulative drainage area to the nearest subbasin and can be used to determine locations in the watershed where the 100 square mile threshold determining the upstream limit of a nominal 5th order stream. The script and details about its logic are included in Appendix 3-1.

Note that '%Forest Converted' is the percentage of drainage area converted from forest to developed pervious land cover, a function of grass and agriculture land area calculated:

$$\text{'\%Forest Converted'} = \%Grass + 0.5 * \%AG \qquad (5.2)$$

in which "Grass" represents suburban or urban landscape and "AG" represents pasture or other agricultural land. As indicated by Equation 5.2, agricultural land has half the weight of grass because agricultural areas generally have not been graded or compacted as much as urban land and exhibits storm runoff behavior that is intermediate between that of forested and urban grass areas.

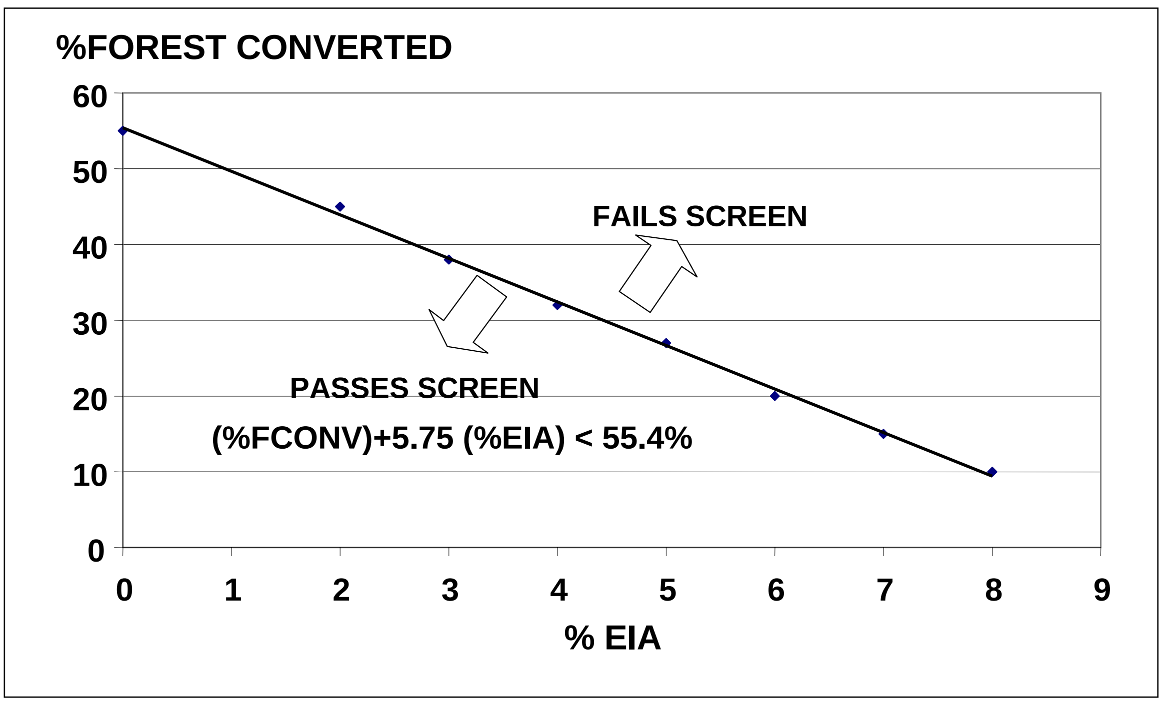


Figure 3-2. Flow Control Exemption Criterion for Landuse.

Section 4
Task AN-7 – Application of Land-Cover Change Methodologies to Nooksack River Pilot Watershed

For this task, the methodologies and results from Tasks AN-4, AN-5, and AN-6 were applied to the Nooksack River watershed which has been designated as a pilot watershed by WSDOT for this project. The Nooksack River watershed is located at the northern boundary of Washington State and drains to Bellingham Bay on Puget Sound. Aside from relatively small urban areas in the communities of Bellingham, Ferndale, Everson, Nooksack, and Lynden and a portion of Abbotsford on the Canadian side of the border, the watershed is largely undeveloped with large very areas devoted to forestry and agricultural landuse.

4.1 Watershed Landuse Analysis

4.1.1 Future Zoning Data Collection and Review

A review of the availability and format of future zoning and planning data was performed for all municipalities and governing agencies within the Nooksack River watershed. These included federal agencies (U.S. Forest Service and U.S. National Park Service), counties (Whatcom and Skagit Counties), five U.S. cities (Bellingham, Ferndale, Everson, Nooksack, and Lynden), and two Canadian jurisdictions (City of Abbotsford and Province of British Columbia). Of these, by far the most significant in terms of land use management are Whatcom County comprising 52 percent and the U. S. Forest Service (USFS) comprising 32 percent of the total 806 square mile Nooksack watershed area.

4.1.2 Ancillary Data Sets

Table 4-1 summarizes the sources and formats of data used to develop a watershed-wide land use coverage for the Nooksack. In addition to the data sets collected from the jurisdictions within the watershed, three other data sets were employed in the analysis of future watershed land use and land cover, these included GIS coverages of watershed lakes from WA-DOE lakes, U.S. wetlands from the National Wetlands Inventory (NWI), and Canadian wetlands from the British Columbia Wetlands Atlas. A rule that was followed in projecting future land use was that existing lakes and wetlands would be preserved in the future even though these areas may lie within areas zoned for development by different jurisdictions. Despite these zoning anomalies, these areas are almost always protected from development by regulations that supercede any zoning anomalies. These ancillary datasets allowed existing lakes and wetlands to be masked out when quantifying land use and cover at future buildout.

4.1.3 GIS Processing of Land Use Layer

As shown in Table 4-1, most of the land use and ancillary data was available in GIS format and were provided to **NHC** via email. However, for three towns, the City of Bellingham, the City of Nooksack and the City of Abbotsford, the effort to acquire digital data was determined to be more difficult or costly than digitizing digital raster images that were readily available via the internet. One town, the City of Everson, only had hard copy zoning information available which was also digitized into GIS format. A very small area of the watershed within British Columbia lies outside of the City of Abbotsford. For this area NHC digitized existing 1:50,000 quadrangle maps, noted existing landuses, and assumed they would apply to future, buildout conditions.

Table 4-1. Land use data sources, formats and contact information for Nooksack Basin.

Data Sources	Data Format	Contact Information [a]
WA-Ecology Lakes	GIS	http://www.ecy.wa.gov/services/gis
National Wetlands Inventory and British Columbia Wetlands Atlas	GIS	http://www.nwi.fws.gov/downloads.htm and http://www.shim.bc.ca/wetlands/main.htm
Forest Service Roadless Areas	GIS	http://roadless.fs.fed.us/documents/feis/data
Forest Service Special Designated Areas (Wilderness)	GIS	http://roadless.fs.fed.us/documents/feis/data
Forest Service Administrative Areas	GIS	http://roadless.fs.fed.us/documents/feis/data
National Parks Service Boundary	GIS	http://www.nps.gov/gis
City of Lynden UGA	GIS	http://www.lyndenwa.org/
City of Bellingham UGA	GIS Available but Digitized from Digital Image	http://www.cob.org
City of Everson UGA	Digitized from Hardcopy Map	(360) 966-3411
City of Ferndale UGA	GIS	http://www.ci.ferndale.wa.us
City of Nooksack UGA	GIS Available but Digitized from Digital Image	http://www.cityofnooksack.com
Future City of Kendall UGA	None	None
Whatcom County Zoning/UGA	GIS	http://www.co.whatcom.wa.us
Skagit County UGA	GIS	http://www.skagitcounty.net
British Columbia Current Landuse	Digitized from 50k Map	N/A
City of Abbotsford UGA	GIS Available but Digitized from Digital Image	http://www.city.abbotsford.bc.ca

[a] URLs for City and County Data Sources can be found at http://wagda.lib.washington.edu and http://www.mrsc.org.

Once GIS data sets of zoning or future land uses covering the entire watershed were collected or digitized, the following steps were taken to create a single future, land use coverage:

1. The attribute table of each dataset was expanded to include a common land use description field using rules described previously in section 5.1 and summarized in Table 5.1.

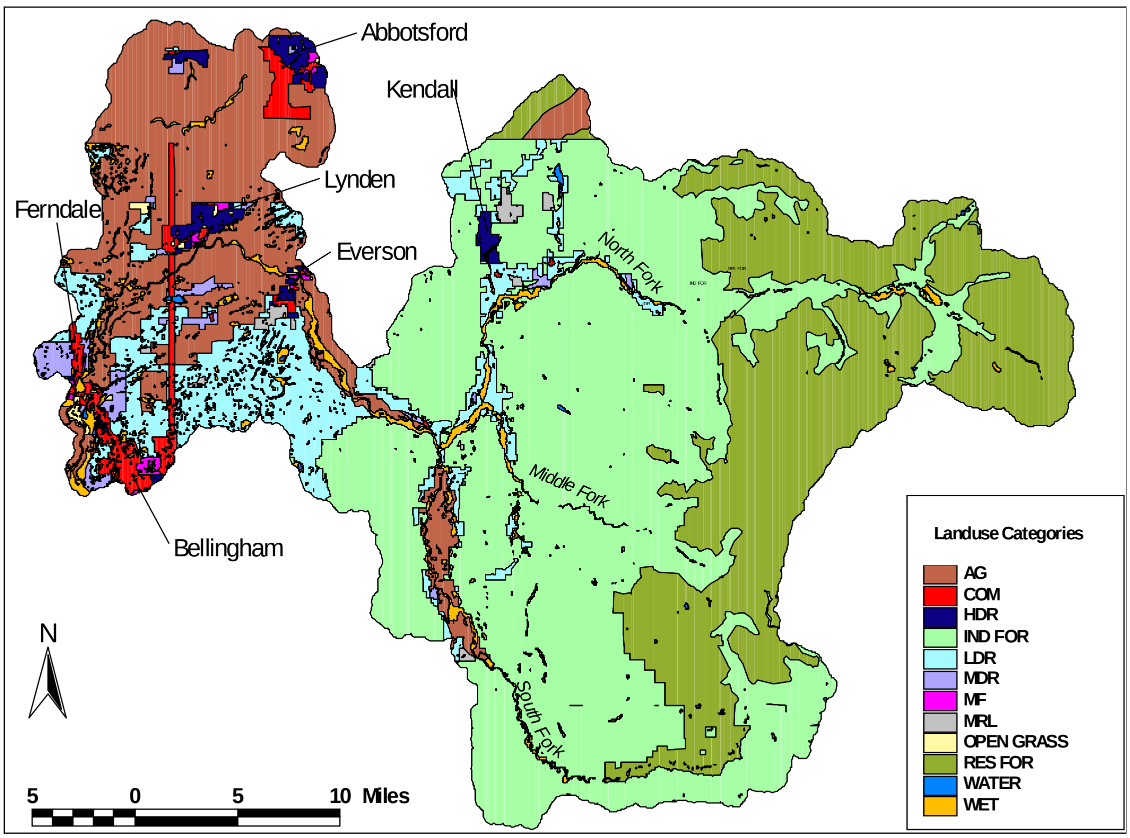


Figure 4-1. Aggregated future landuse categories in the Nooksack Watershed.

2. All data sets were reprojected to Mercator (UTM) Zone-10, North American Datum of 1927 (NAD27) with units of meters as described in Section 5.2.

3. Data sets were merged following certain rules related to areas of overlapping spatial coverage as follows:

   - Where Whatcom and Skagit County zoning maps overlapped USFS and NPS lands, the federal data sets were used because they were capable of distinguishing industrial forest from reserve forest areas as discussed in Section 5.1

   - Where urban growth areas (UGAs) of cities and counties overlapped, city zoning was assumed to reflect future conditions more accurately.

   - WA-DOE lake boundaries were assumed to take precedence over wetlands, and both lakes and wetland coverages were assumed to take precedence over zoning.

4. The merged GIS coverage of future land use was clipped to the Nooksack watershed boundary.

4.1.4 Watershed Subbasin Dataset Development

A GIS coverage of Nooksack River watershed subbasins being used in WRIA 1 planning was provided to this project by Whatcom County Department of Planning and Development Services. This subbasin coverage was selected over the WA-DNR Watershed Administrative Units (WAU) coverage because it provided a more detailed subbasin breakdown. As described in Section 5.2, the WRIA 1 subbasin coverage was edited in ArcView to create subbasin boundaries at each 2^{nd} order stream confluence to a 4^{th} order or higher stream, creating 120 unique subbasins. A consistently projected image of a USGS 1:24000 topographic map was used to help guide the partitioning of these subbasins. Note that stream order attributes had been assigned to the WDFW 1:100,000 stream segments as described in Section 4.

4.1.5 Landuse/Subbasin Overlay Analysis

The landuse and subbasin coverages were intersected to create a subbasin specific landuse coverage. Figure 4-2 displays an example of the output from this intersection which consists of a subbasin landuse summary.

4.2 Land-Cover Change Analysis

The GIS Tool discussed in Section 5.3 was applied to the Nooksack River to determine the percent change in land-cover at several locations within the watershed. The lookup table imported to ArcView for determining land-cover from landuse using relationships summarized in Table 5.2. Using this table, the WDFW 1:100,000 stream layer, the subbasin layer, and the subbasin-landuse layer described above, the script generated a stream segment dataset that includes the total drainage area and land-cover data stream segments in the watershed that receive drainage from more than a single subbasin. Figure 4-3 shows an example of these data at 4 locations within the Nooksack watershed. The two locations on the north and south forks of the river denote the upstream limits of contributing drainage area that exceeds 100 square miles on these branches of the river.

4.3 Conclusion Regarding Nooksack River Exemption

Four sample locations in the Nooksack drainage basins were used to illustrate application of the GIS tool described in Section 5.3 to calculation of the land cover based index defined by Equation 5.1. As shown in Figure 4-3, these locations include two points on the north and south forks of the Nooksack River marking the upstream limits of the 100 square mile minimum drainage area criterion, one point midway between the confluence of the forks and the mouth, and finally the mouth of the river itself. As shown in Table 4-2, while values of the land cover criterion (LCC) continuously increase in the downstream direction, they never come close to exceeding the threshold value of 55.4.

Table 4-2. Results from the Nooksack Watershed.

Location	Total Area	Percent Land-Cover							Percent Forest Converted	LCC
		Forest	Ag. or Pasture	Grass	EIA	TIA	Wetland	Water		
South Fork	104	98.6	0.0	0.0	0.4	0.7	1.0	0.05	0	2.3
North Fork	116	98.6	0.0	0.0	0.1	0.2	1.3	0.07	0	0.6
Upstream of Everson	631	89.4	4.8	2.8	0.9	1.5	2	0.08	5.2	10.4
Mouth	787	71.7	17.6	5.5	2.5	3.5	2.7	0.1	14.3	28.7

Results for the Nooksack River watershed reflect the dominance of forest and agricultural land uses at future buildout. In this regard, the Nooksack is similar to many other watersheds in western Washington, suggesting that they will also pass the land-cover criteria throughout their drainage systems. In these cases, like the Nooksack, the 100 square mile drainage area threshold will determine stream segments and nearby areas suitable for exemption from flow control requirements.

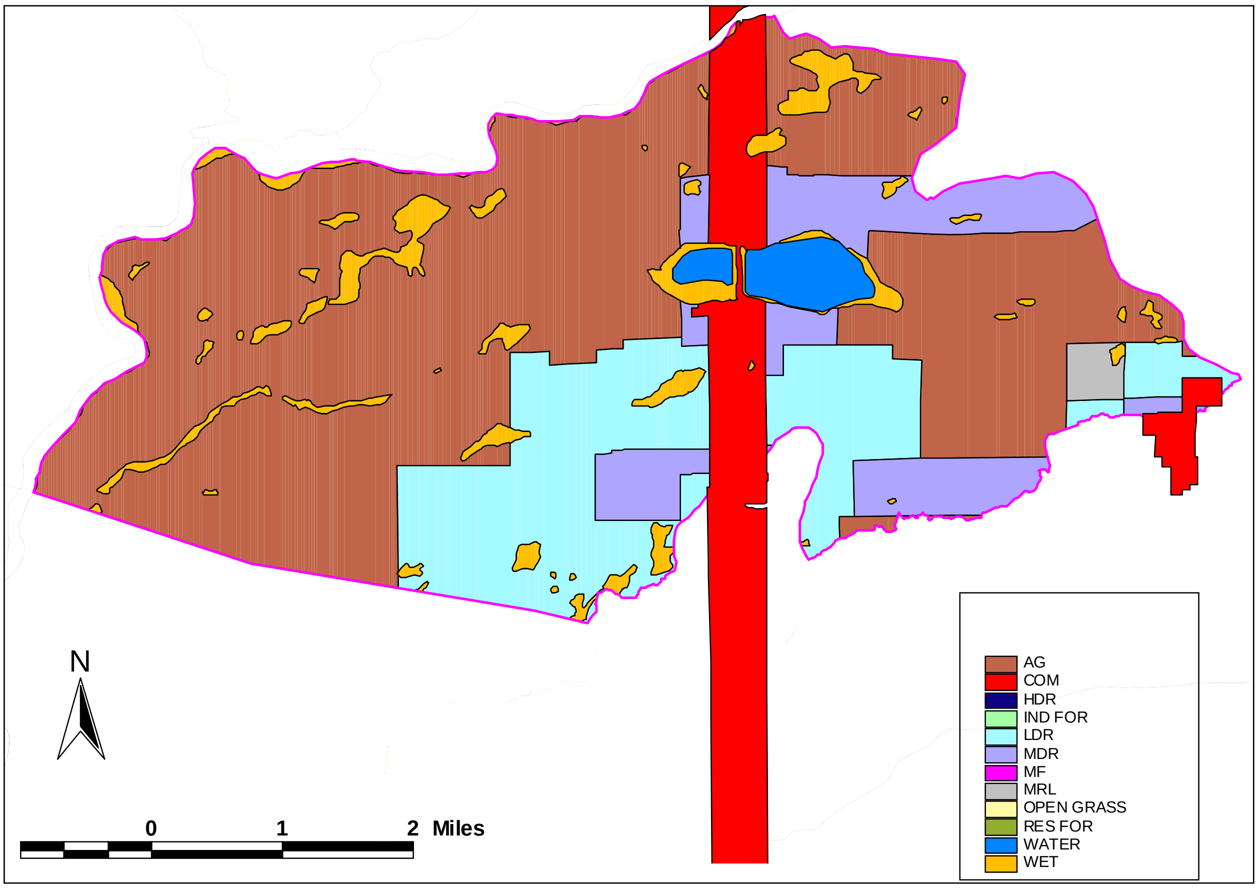


Figure 4-2. Example of landuse overlay results for subbasin in Nooksack River watershed near the Town of Lynden.

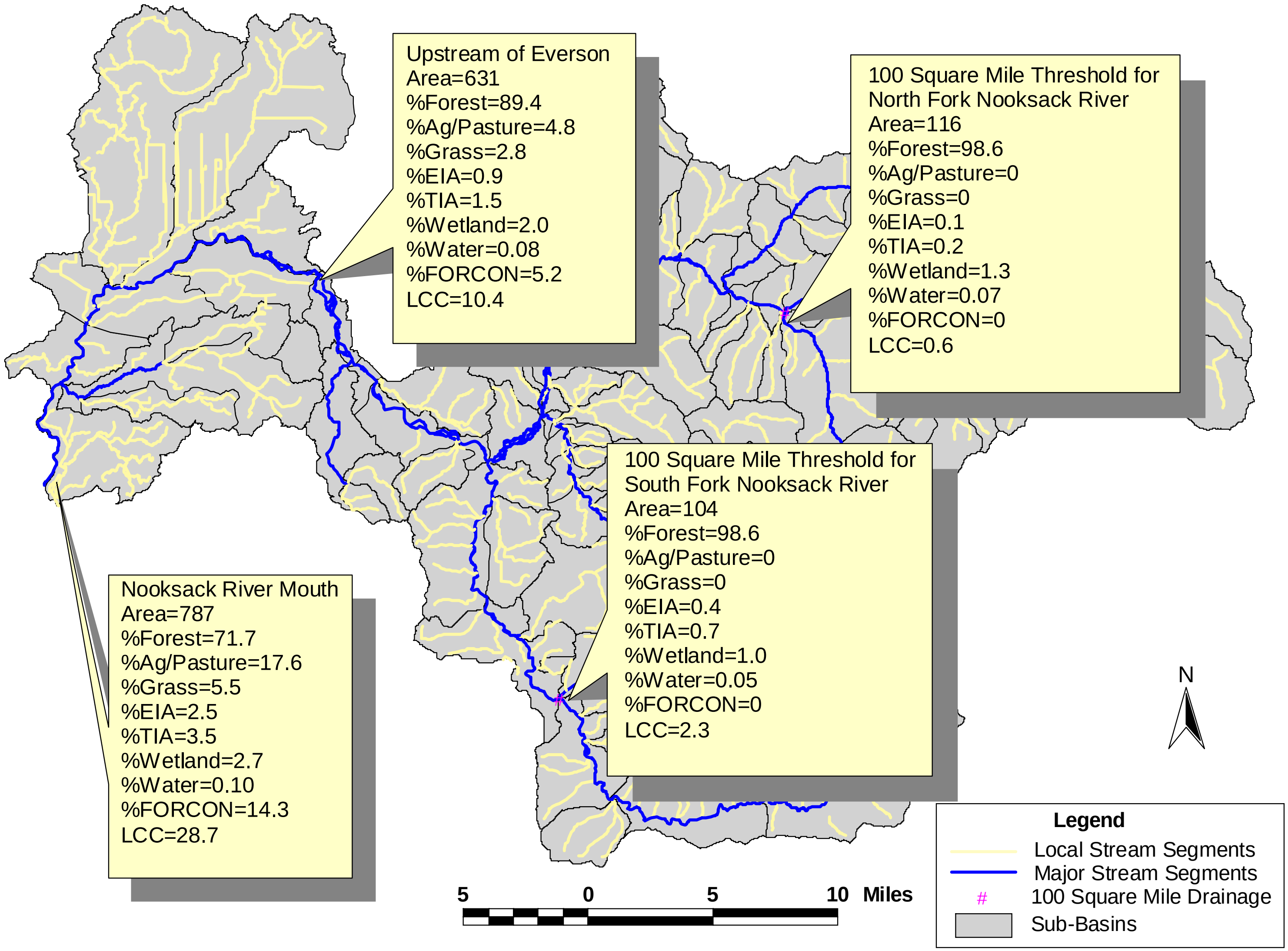


Figure 4-3. Results from GIS cumulative land-cover summation tool for the Nooksack River watershed.

4.4 Proximity Requirements for Flow Control Exemption

The land use and cover analysis described above suggest that portions of the North and South Fork Nooksack River and its entire mainstem would not be impacted by receiving runoff from projects that have been exempted from storm water flow control requirements. A further consideration in implementing flow control exemptions for these river segments is specification of land areas that qualify to send direct drainage (without flow control) to the segments. The primary issue to be addressed in this regard is the prevention of major disruptions to natural drainage patterns such as the significant depletion of flows from a tributary stream. One approach to this issue taken by King County (1998) is to require that the discharge location from an exempted project site be within one-quarter mile of the 100-year floodplain boundary of the receiving waterbody. This requirement is combined with several other provisions to assure protection of adjacent land owners and of smaller streams and wetlands that may be affected by flow exemption and conveyance of the direct discharge to the receiving waterbody.

A second approach that could be taken is to require than the total project area or any portion of the project area that would qualify for a flow control exemption would lie within a specified distance of the ordinary high water (OHW) line of a river or lake. Definition of this distance is a matter of judgment. A discussion of this question among the consult team and representatives of WSDOT and WADOE took place at a project meeting on January 24, 2004, and led to a consensus recommendation of 0.5 miles on either side of the river. This latter approach has the advantage of providing for a fairly simple, rapid and unambiguous GIS mapping of allowable direct drainage sending areas. King County's approach may be more difficult to administer but may have advantages in the protecting smaller aquatic resource features from potential damage. Regardless of the approach taken, some method is required to limit the spatial extent of sending areas and limit the short circuiting of drainage around wetlands and tributary stream segments.

4.5 Recommendations

Based on the combined criteria of drainage area (stream size), future land cover composition, and proximity to the receiving segment of the river, the following areas should be exempted from storm water flow control in the Nooksack watershed:

- Areas with sufficient proximity to the North Fork Nooksack River downstream from the confluence with Glacier Creek.
- Areas with sufficient proximity to the South Fork Nooksack River downstream from the confluence with Skookum Creek.
- Areas with sufficient proximity to the entire length of the Nooksack River downstream from the confluence of the North and South Forks.

Section 5
Task AN-8 Hydrologic Modeling to Simulate Effects of Stormwater Runoff on Channels

5.1 Introduction

For this task NHC applied hydrologic modeling to investigate the benefits of mitigating land development with stream protection detention ponds in potential direct discharge areas (PDDAs). As described in the previous memorandum, the working definition of PDDAs being used here are areas within one-half mile of a stream that drains at least 100 square miles of basin area. For comparison purposes, the hydrologic benefits (or avoided impacts) on the receiving stream resulting installation of ponds in PDDAs are compared with the benefits that of ponds in headwater basin areas that drain to smaller streams. The purpose of this exercise is to shed light on the question of whether a stream segment’s failure to meet the land cover criterion (LCC <55.4) discussed in Section 5 should or should not automatically trigger a requirement for flow control within PDDAs that could discharge to that stream segment. In order to illuminate this question, NHC modeled land use scenarios that sought to answer two questions:

1. For stream or river segments draining at least 100 square miles (nominal 5^{th} order at 1:24,000 scale), what differences in hydrologic regime occur with the presence or absence of stream protection flow control systems in the PDDAs?

2. How do the flow regime differences mentioned above compare with the differences associated with the presence or absence of detention in the same flow control systems in smaller, headwater basins?

5.2 Modeling Methods

The Hydrologic Simulation Program FORTRAN (HSPF) (Bicknell et al. 1997) was used to model a series of hypothetical scenarios in a watershed in western Washington. As noted in an earlier memorandum documenting work performed under Task AN-7, even at maximum, future buildout consistent with existing land use plans, the Nooksack watershed will be dominated primarily by forest cover and secondarily by agricultural land. Consequently, it was determined that PDDAs throughout the length of the Nooksack River from the 100-square mile threshold locations to the mouth would easily comply with the land cover-based criterion allowing flow control exemption. As a result, it was decided to select another watershed with higher current and future land use intensity to use as a case study for the modeling performed under this task. The Cedar River basin was selected for this task because it includes more intense land use than the Nooksack and because previous basin planning and modeling work conducted by King County (1993) provides some basic data to facilitate the current modeling.

5.2.1 Cedar River Basin Plan Data

In the early 1990s, King County conducted a basin planning study of the lower Cedar River basin. As part of that effort, streams, drainage subbasins, surficial geology, and land use were mapped based on 1:24,000 USGS quad maps augmented and corrected by stream walks, local drainage studies, and aerial photos. From these maps and data, HSPF models representing the lower Cedar River basin were developed. The lower Cedar River basin was defined as the developable portion of the basin that is west of the Seattle Watershed and is drained by the Cedar River downstream of the Landsburg Diversion at river mile 21.6. It includes approximately 66 square miles of the total 188 square miles of the entire Cedar River. The remaining approximately 122 square miles lies within the City of Seattle Watershed. This area is primarily mountainous, forest land that is carefully managed to protect fish and terrestrial wildlife habitat and water quality of Seattle's major water supply reservoir. King County's hydrologic models calculate continuous stream flow in the tributary streams and mainstem Cedar River below Landsburg based on 41 years of hourly precipitation data. Data and information from the county's modeling applied in this study include:

- Hourly Cedar River flows below the Landsburg diversion representing discharge from the Seattle Watershed into the downstream, developable portion of basin. This database spans the 41 year period from water year 1949 to water year 1989.

- Hourly precipitation amounts at Seatac Airport and at Landsburg and daily pan evaporation amounts based on NWS data collected at Puyallup. These datasets span the same time period as the flow record described above. Together these form the necessary inputs for long term simulations of the lower, developable portion of the Cedar River basin.

- Fourteen HSPF models of subbasins and one of the Cedar River mainstem from Landsburg to the mouth of the river representing pristine, forested land cover conditions and current channel hydraulics. Modifying and linking these fifteen models allows detailed, long term simulation of the hydrologic regime of the river resulting from different levels of urbanization (see Figure 5-1).

5.2.2 Modeling Assumptions

Period of Record

It was assumed that modeling hourly flows for different land use scenarios applying the basin plan's meteorological records spanning 41 years is more than sufficient to compare the effects of the presence and absence of detention ponds on significant aspects of the hydrologic regime.

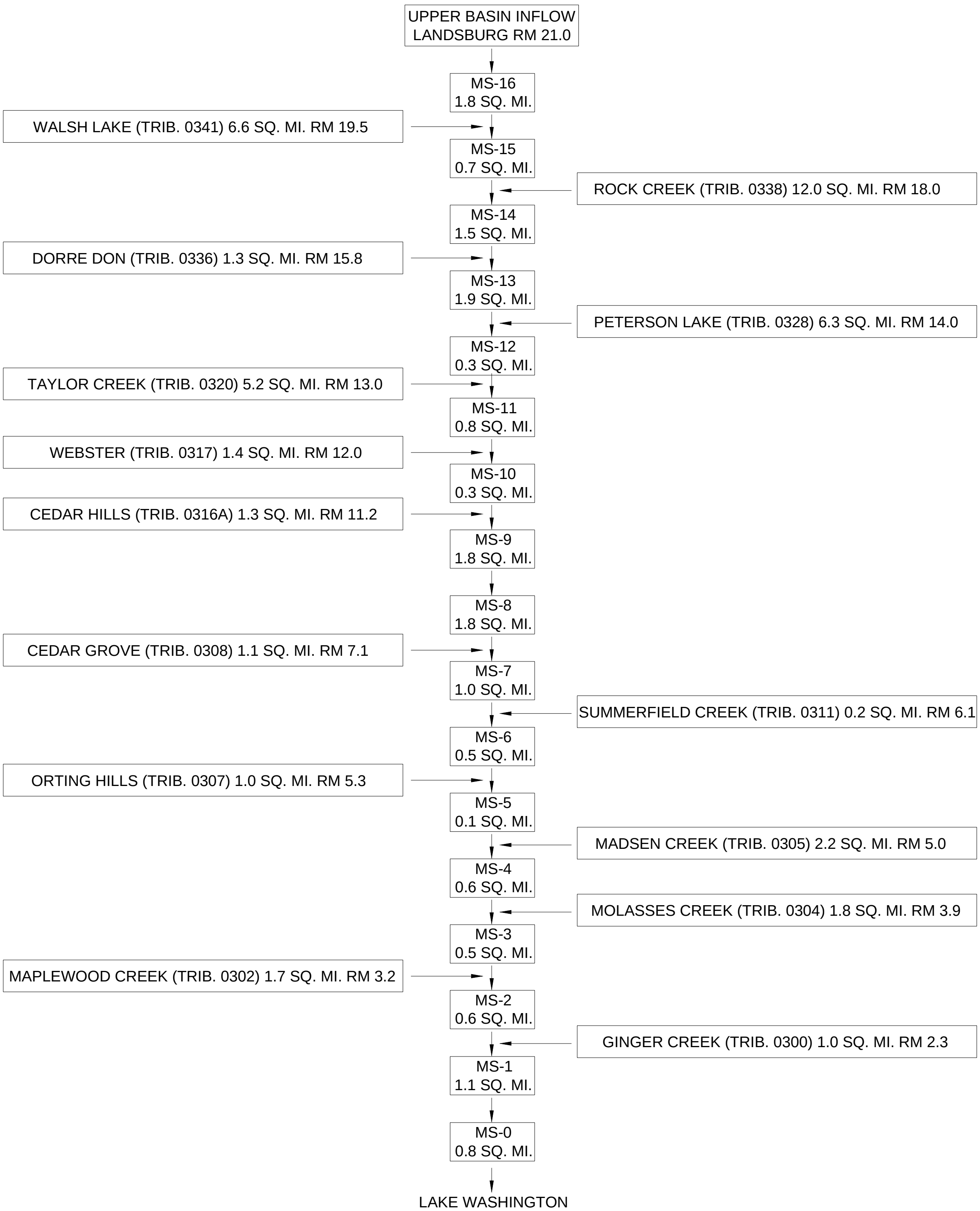


Figure 5-1. Schematic of HSPF Model of Lower Cedar River Basin.

Hydrologic Statistics

Two hydrologic statistics were chosen to compare the effectiveness of detention facilities under different land use scenarios: 1) the 2-year peak annual flow and 2) the average annual duration of flows than exceed 50 percent of the pristine, 2-year peak flow. The first statistic was selected because it is a peak flow indicator that is generally sensitive to the effects of unmitigated land use change. The second statistic is considered to be more significant for this study because it is used in the Puget Sound region as a gross indicator of aggregate sediment transport capacity and stream stability (Booth 1997)

Representation of Stream Protection Ponds

For expediency, it is assumed that the presence of stream protection detention ponds fully mitigates the hydrologic impact of development. Thus, land development scenarios with ponds are assumed to result in the same peak flow and duration values as undeveloped conditions. This avoids the time and effort necessary to actually design and simulate detention ponds for a given scenario with mitigation. It also has the advantage of being conservative from the viewpoint of showing the maximum benefit accruing from the presence of the ponds in comparison to the same land use scenario with no ponds present.

Upstream Boundary Condition

Upstream hydrographs flowing into the lower Cedar River from the Seattle Watershed at Landsburg were assumed to be the same regardless of land use scenario. This reflects the expectation that land use and cover in the upper basin will remain unchanged and confines the analysis to the effects of land use and detention in the treatment areas. A time series of hourly flows of the Cedar at Landsburg were simulated for the Cedar River Basin plan studies using the City of Seattle's SEAFM model and reflect upper basin meteorological conditions during the simulation period as well as standard rule-curve-based operations of Masonry Dam during floods.

5.2.3 Land Use Scenarios and Analysis Locations

For purposes of hydrologic simulations in this study, the Cedar River Basin may be conceptualized as three distinct areas, The Seattle Watershed, the Lower Cedar River mainstem subbasins, and the Lower Cedar River tributary subbasins. The Seattle Watershed represents approximately 66 percent (121 square miles) of predominantly forested, mountainous land that drains to tributaries and the mainstem river above river mile 21.6 (Landsburg). Based on Seattle's policies, this area is expected to remain forested. For all modeled scenarios, land cover in this area is constant and river flow at Landsburg is represented by the same time series. The lower Cedar River mainstem subbasins represent land areas adjacent to the mainstem Cedar River that include mainstem river valley and portions of the valley walls and uplands that do not drain to designated tributaries. These subbasins include 17.5 square miles or approximately 10 percent of the total basin area. In modeling a range of land use scenarios within these subbasins, development is assumed to occur only within PDDAs which are required to be within 0.5 miles of the river. This assumption is consistent with the approach of specifying areas within a certain distance of a qualifying receiving waterbody as discussed in a previous memorandum related to Task AN-7. It is also considered to be a reasonable estimate of the upper limit of areas that would be exempted from flow control using the King County approach of specifying a one quarter mile maximum distance between a project's discharge point and the river. This approach is also discussed and referenced in the Task AN-7 memorandum. PDDAs are shown as the cross-hatched area in Figure 5-2.

The lower Cedar River tributary subbasins consist of the remaining developable portion of the basin that drains to tributaries entering the Cedar River downstream of Landsburg. These tributary subbasins make up 24 percent of the total basin area. For purposes of estimating the hydrologic benefit of stream protection detention ponds in PDDAs, pristine forest land cover was assumed in tributary subbasins. Additionally, one tributary subbasin, Ginger Creek, was also used as to simulate different land use scenarios and explore the effect of stream protection detention ponds on a local tributary flow regime.

Land Use Scenarios

Four land use conditions were modeled reflecting different levels of development intensity ranging from undeveloped forest land, to moderately developed residential, mixed residential and commercial, and entirely commercial development. The land cover composition associated with these scenarios is shown in Table 5-1. These land use scenarios were modeled along the mainstem of the Cedar River. As shown in Figure 5-1, the mainstem drainage areas are composed of seventeen Cedar River valley subbasins. The total land area within the mainstem subbasins delineated for the Cedar River Basin Plan is 17.5 square miles and is approximately equal to the area of the PDDAs defined by half-mile buffer distances on either side of the river between the mouth of the river in Renton and the boundary of the Seattle Watershed near Landsburg (see Figure 5-2).

Table 5-1. Land cover composition of land use scenarios.

Land Use Scenario	% Forest and Wetland Cover	% Pervious Urban Cover (grass)	% Effective Impervious Area
1. Pristine, Forest	100	0	0
2. Mixed Residential and Open	30	55	15
3. Mixed High Density Residential and Commercial	0	60	40
4. Commercial	0	20	80

Four model runs were made corresponding to the land use scenarios in Table 5-1 to simulate the effect of land use change in PDDAs along the mainstem Cedar River. For a given HSPF model run, one land development intensity was assumed to occur in all of the mainstem subbasins, however; the maximum developable area within any one subbasin was limited to an acreage equivalent to a 1.0-mile band along the length of the river running through the subbasin. The purpose of this limitation was to approximate the effect of a rule that requires areas exempted from flow control to be within 0.5 miles of the receiving water. For all four of these model runs, pristine forested conditions (or fully mitigated conditions based on our study's assumptions) were modeled in the 14 tributary subbasins.

In order to compare the effects of land use change and the presence or absence of stream protection ponds in mainstem Cedar River PDDAs with the presence or absence of these ponds in a tributary subbasin, flows in Ginger Creek were simulated assuming each of the four land use scenarios in Table 5-1. Ginger Creek is a small stream basin with approximately 1.0 square miles of drainage area that enters the south side of the Cedar River at river mile 2.4.

Analysis Location

Simulated hourly discharges over the 41 year time span of the meteorological record were saved in a binary database at two locations along the mainstem Cedar River and at the outlet to Ginger Creek. The two mainstem locations were the mouth of the Cedar River at Renton and at an upstream point approximately midway between the mouth and Landsburg at the outlet to subbasin MS-11. Data for these three locations were then analyzed using a post processing program.

5.3 HSPF Modeling Results and Discussion

As mentioned, modeling results are presented in terms of two hydrologic statistics, the 2-year peak annual flow and the average annual duration of flows exceeding 50 percent of the 2-year peak annual, forest condition flow.

5.3.1 Peak Annual Flow

Peak flow results for each analysis location are shown in Table 5-2. Results in Table 5-2 indicate that without stream protection flow control, a conversion of 70 percent of forested land to 55 percent grass and 15 percent effective impervious area would cause an increase in 2-year, peak annual flow of approximately 3 percent at either the midpoint location or the mouth of the Cedar River. By comparison, the same kind of land cover change in a small headwater basin would increase the 2-year flow by 198 percent as shown by the Ginger Creek results. For the more intense land development scenarios, the increase in mainstem Cedar River peak annual flows is between 6 percent and 10 percent for mixed residential development and between 10 percent and 19 percent for commercial development. By contrast, the corresponding increases at the mouth of Ginger Creek are 410 percent and 676 percent. If we assume that stream protection ponds fully mitigate these increases, the contrast in benefits of the detention ponds in the two situations is very clear. In a small stream basin, where a high proportion of developable drainage area can potentially be mitigated by detention ponds, very large potential increases in peak flows can be prevented. On a mainstem river with a proportionally large inflow from a drainage area that is either not going to be developed or is not subject to flow control requirements, the benefits of detention in the PDDAs is relatively small. In the case of the Cedar River, the benefit is

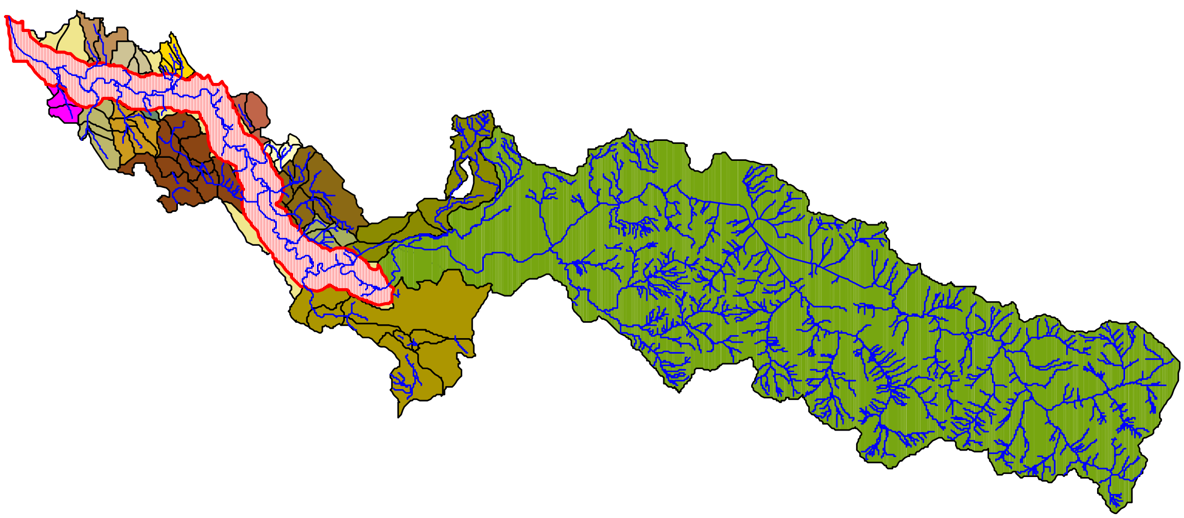


Figure 5-2. Cedar River Basin PDDAs.

between 1/36 and 1/70 the benefit of detention in headwaters basins. In the case of peak flow, the absolute and relative benefit of stream protection ponds increases with increasingly intense land use change in the PDDA. However; it appears that a change in peak flow of more than 5 percent would require a very significant change in land cover that would convert more than 15 percent of forest land to effective impervious area.

Table 5-2. Comparison of 2-year peak annual flow.

Analysis Location	Pristine or Fully Mitigated (cfs)	Mixed Res/Open (cfs)	Mixed Res/Open Percent Change	Mixed High Density Res/Com. (cfs)	Mixed High Density Res/Com. Percent Change	Com. (cfs)	Com. Percent Change
Cedar @ Renton	3427	3523	3	3776	10	4068	19
Cedar @ R.M. 12.6	3351	3463	3	3552	6	3757	12
Ginger Ck Outlet	17	51	198	87	410	133	676

5.3.2 Peak Flow Duration

The duration of peak flows above 50 percent of the 2-year flow is probably more significant from an ecological perspective than peak annual flow because high flow durations are more closely associated with sediment transport and channel stability. Additionally, in the case of the Cedar River, there is evidence to show that the ratio of outmigrating salmon fry to the number of eggs layed in salmon redds declines when discharge in the lower Cedar river exceeds a threshold that is between 1600 and 2000 cfs (Seiler and Kishimoto 1997), or a value that is similar to 50 percent of the 2-year peak annual flow. This is attributed to scour of salmon redds located in higher velocity regions of the river. The sensitivity of mainstem flow durations to the presence or absence of detention ponds in PDDAs is even smaller than the sensitivity of peak annual flows. Results for flow durations are summarized in Table 5-3. The maximum estimated increase in flow durations above the threshold discharge is 4 percent at Renton and 2 percent at river mile 12.6 under an assumption of commercial development throughout the mainstem areas adjacent to the river (PDDAs). These are very small increases that are approximately 200 times less than the increases that would occur in smaller, headwater subbasins if development were not mitigated.

The low sensitivity of high (>50 percent of the 2-year peak) flow durations to development within PDDAs of the Cedar River basin are probably most influenced by the fact that these areas account for less than 10 percent of the total drainage area contributing to the flow of the river at its mouth in Renton. Yet, the narrow, elongated shape of the Cedar River basin would tend to raise the ratio of PDDAs to total basin area compared to other watersheds. Consequently, it is expected that PDDAs in other basins with a less elongated shape would make up less than 10 percent of the basin area have even less impact on mainstem peak flows and high flow durations than were simulated for the Cedar. For example, in the Nooksack basin which has a different shape than the Cedar, PDDAs would make up less than 8 percent of the total basin area. Additionally, the extreme development intensity represented by conversion of PDDAs to commercial land use represents a worst case scenario.

Table 5-3. Comparison of average annual time exceeding 50 percent of 2-yr peak flow.

Analysis Location	Pristine or Fully Mitigated (hr/yr)	Mixed Res/Open		Mixed High Density Res/ Comm.		Comm.	
		(hr/yr)	Percent change [a]	(hr/yr)	Percent Change [a]	(hr/yr)	Percent Change [a]
Cedar @ Renton	629	637	1	645	3	654	4
Cedar @ R.M. 12.6	608	613	1	616	1	620	2
Ginger Ck Outlet	112	294	163	486	334	616	451

[a] Percentage increase over pristine or fully mitigated condition.

5.3.3 Basin Plan Current and Future Land Use

According to King County's 1992 assessment of current land cover using air photo analysis, the mainstem subbasins between Landsburg and Renton were comprised of 10 percent EIA, 34 percent grass, and 56 percent forest and wetland. At future buildout, the county projected EIA to increase to 17 percent of mainstem area, and total forest and wetland area to decrease from 56 percent to 31 percent. These increases in land use intensity are less than half the increases associated with the change from pristine, forested conditions to the Mixed Residential and Open land use scenario that was simulated in this study. This suggests that the actual increase in mainstem flow durations associated with direct discharge to the Cedar River from development projects in mainstem subbasins built between 1992 and future, full buildout conditions would be substantially less than 1 percent if those projects did not install detention ponds.

It is also interesting to note that although the Cedar River basin was selected for this modeling with the expectation that it would provide a more realistic case study than the highly rural and forested Nooksack River basin, like the Nooksack, the Cedar River passes the accumulated cover criterion throughout the nominal 5th order reach which stretches from the confluence of Taylor Creek near Selleck at river mile 29.3 to the mouth of the Cedar in Renton. Figure 5.3 shows the increase in the cover index along the portion of the river that receives drainage from developable land. Although the level of urbanization within the cumulative drainage area increases steadily in the downstream direction, the failure threshold of 55.4 is never crossed. This is primarily attributed to the protected forest land within the City of Seattle Watershed which comprises two thirds of the watershed area and secondarily to preservation of rural and forest lands by zoning in the lower part of the basin by King County.

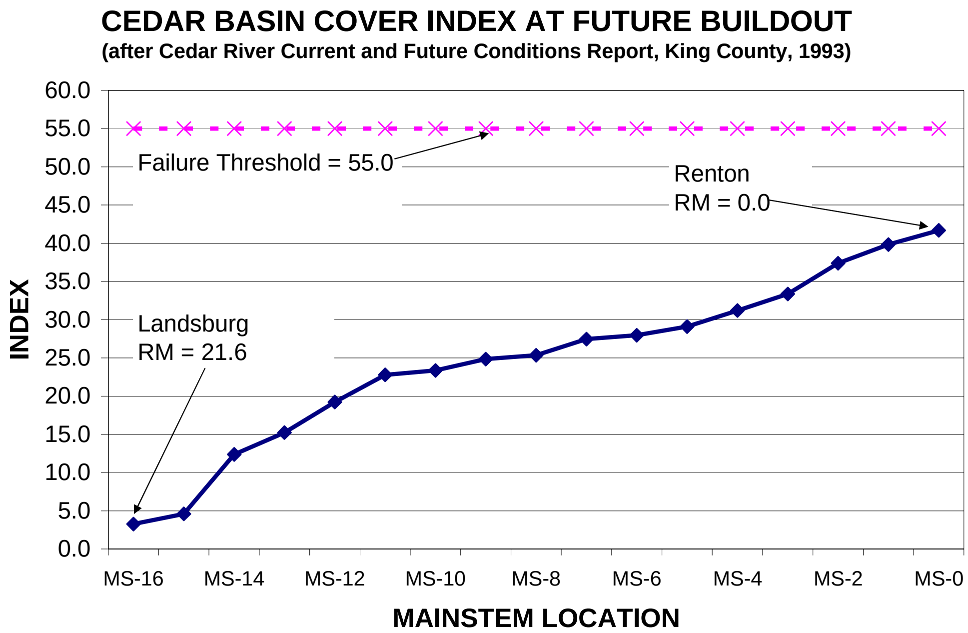


Figure 5-3. Variation in cover index from Landsburg to Renton at buildout condition.

5.4 Summary and Conclusions

HSPF continuous hydrologic modeling was employed to assess the benefits of installing stream protection ponds in PDDAs. Based on the analysis presented here, the installation of stream protection ponds in PDDAs will protect against very small increases in 2-year peak annual flows in the river. Perhaps more significantly, reductions in geomorphically significant flow durations will be much smaller than for peak flows and would range from less than 1 percent for mixed residential and open to up to 5 percent for commercial development in the PDDA. The relatively small benefit of the ponds in PDDAs is primarily a function of their limited drainage area and flow contribution compared to mainstem flow from the undeveloped portion of the basin upstream of the PDDA reaches. Given the elongated shape of the Cedar River basin, the potential impact of direct discharge from PDDAs in other watersheds would be expect to be even smaller than noted here. Based on this experience with the Cedar, it would appear that relatively few of larger streams and rivers in western Washington will fail the cover criteria. The much larger benefits of detention ponds in smaller tributary basins arises from their ability to protect lower order streams from land cover changes that can affect a high percentage of the stream's total drainage area.

5.5 Recommendations

Complete western Washington Cover Analysis. Future land cover and drainage area can form the basis for flow control exemptions on most mainstem rivers in western Washington. WSDOT should proceed with this analysis and establish a list of exempt areas along river segments.

Establish LCC-based tolerance for PDDAs. For the relatively few western Washington river segments draining more than 100 square miles that fail the cover criteria and do not satisfy gradient or tidal criteria (see Sections 9 and 10), WSDOT in concert with WSDOE should consider Development of a PDDA land cover change tolerance. This tolerance would apply results discussed in this section to assure that increments to geomorphically significant flow durations would be very small. Results from this study suggest that an LCC value of less than 141 (equivalent to the Mixed Residential/Open Scenario modeled in this section) within PDDAs would result in less than a 1 percent increase in high flow durations. This LCC value seems like a reasonable tolerance to consider.

Section 6
Task AN-9 Assessment of the Effects of Channel Gradient on Potential Geomorphic Alteration Induced by Stormwater Runoff

6.1 Introduction

This report describes the analysis performed for Task AN-9 – Assessment of the Effects of Channel Gradient on Potential Geomorphic Alteration Induced by Stormwater Runoff. The primary objective of this study was to quantify the importance of stream gradient in determining whether undetained stormwater inputs to large streams would significantly affect potential for erosion or loss of salmonid spawning habitat. The study focused on high order streams, which were defined earlier in this report as streams with catchment areas greater than 100 mi^2 (Task AN-4 Definition of First Order Streams).

Hydraulic modeling and spreadsheet analysis were performed to examine the relationships between key hydraulic and geomorphic variables, which were believed to dictate the ability of large streams to buffer the geomorphic impacts of undetained stormwater inputs. These variables include:

- Channel gradient
- Channel cross-section complexity
- Magnitude of backwater effects

The sensitivity of shear stress and velocity as a function of multiple combinations of these channel-defining variables was examined in order to evaluate thresholds for incipient motion for gravel based on published values of critical shear stress and velocity.

The remainder of this report presents detailed information on the methods, sources of information, and results from this study. Recommendations are made regarding the suitability of using stream gradient in combination with stream order as a possible basis for flow control exemptions. Recommendations detailing how to apply the methodologies and results from this study to watersheds throughout western Washington are also presented.

6.2 Approach

The sensitivity of shear stress and velocity to various combinations of channel gradient, cross-section complexity, and backwater effects was analyzed. The analysis was based on hydraulic modeling using an existing HEC-RAS model of the Nooksack River, which extends from Interstate 5 (I-5) upstream to Everson (River Mile 6.7 to River Mile 23.92). Model outputs were analyzed and plotted in off-line spreadsheets to quantify thresholds for incipient motion of coarse gravel (>16 mm) based on shear stress criteria. This grain size was selected as the basis of the incipient motion analysis because it represents a reasonable lower bound of median salmonid spawning gravel sizes for streams in Washington (Kondolf and Wolman, 1993). Larger salmonid spawning gravels would be less likely to mobilize under the threshold conditions evaluated herein.

The HEC-RAS model was modified to create a total of four scenarios for the sensitivity analysis. Each scenario represented different combinations of channel thalweg profile and backwater conditions. Within each scenario, ten flow profiles were modeled in order to represent the range of flows expected in large rivers in western Washington. More detailed information on the existing HEC-RAS model and how the sensitivity analysis was developed is provided below.

6.2.1 Description of Existing Model

The existing HEC-RAS model of the Nooksack River was developed by TetraTech/ KCM (1997) as part of the "Lower Nooksack River Comprehensive Flood Hazards Management Plan". Based on a conversation with Paula Cooper of the Whatcom County Engineering Division (March 2004), the HEC-RAS model was ultimately superseded by an unsteady two-dimensional model for the final flood hazard analysis. Since the HEC-RAS model was used as the basis for a sensitivity analysis in this flow control exemptions analysis, rather than to simulate historical or future water surface elevations in the Nooksack River floodplain, the model was considered appropriate for this application.

HEC-RAS is a one-dimensional model that uses inputs of topographic and flow data to simulate water surface elevation and velocity. Topographic data input to the model were based on 1993 aerial photographs and topographic maps provided by Walker & Associates. These data were used to estimate hydraulic roughness within the channel and floodplain areas and to develop a total of 91 floodplain cross-sections.

The model was calibrated for the flood of November 1990. As part of the calibration process, steady flow inputs at various locations along the model reach were modified until simulated water surface elevations matched documented flood conditions reasonably well. The locations along the reach where flow inputs were modified generally represent tributary inflows, or inflows and outflows from floodplain storage areas. Negative flow changes occurring in the downstream direction generally represent the effects of floodplain storage, which can be particularly significant for flood events in this portion of the Nooksack River (personal communication with Paula Cooper, February 2004). Since flood storage is not a variable being investigated for this study, the steady flow changes in the original model were deleted. Flows were input for a single location only for this application, corresponding to the upstream model boundary cross-section at River Mile 23.92. More discussion of alterations to the existing model for purposes of the sensitivity analysis is provided below.

6.2.2 Alterations to Existing Model

The model was modified in several ways to better meet the objectives of this study. These modifications include:

1. Flow changes at River Mile 23.8 and downstream were deleted so that the relationship between the key variables being studied could be more easily understood. This change resulted in a single steady flow input for the upstream boundary cross-section at River Mile 23.92.

2. Additional flow scenarios were created so modeled shear stress and velocity could be evaluated over a range of flows expected for high order streams in western Washington.

3. Three copies of the revised model were made. For each copy of the revised model, the channel thalweg profile was modified to represent the following channel gradients:

   - 0.025%
   - 0.05%
   - 0.07% (original model)
   - 0.1%

The channel gradients listed above represent nominal values only. This is because channel gradient is actually highly variable throughout the modeled reach, with some portions of the model reach being steep and other portions being relatively flat. Nominal gradient was defined for this application as the vertical drop over horizontal distance for the upstream- and downstream-most cross sections, or cross section 23.92 and 6.7, respectively. Figure 6-1 shows the thalweg profile for each of the modeled nominal gradients. The lowest gradient, 0.025%, was chosen to avoid creating artificial pools or dips in the profile, which were not of interest for this study. The steepest gradient, 0.1%, was chosen as the upper bound based on a review of channel profiles for high order streams in western Washington.

6.3 Methods

This section provides a detailed description of the hydraulic modeling performed with HEC-RAS and the spreadsheet analysis of model results.

6.3.1 Hydraulic Modeling in HEC-RAS

As described above, four scenarios were modeled corresponding to nominal channel gradients of 0.025%, 0.05%, 0.07% (original model), and 0.10%. For each scenario, a range of steady flows was input at the upstream boundary location. The steady flows modeled ranged between 5,000 cfs and 51,900 cubic feet per second (cfs). The highest flow modeled represents the 100-year flow estimate for the upstream end of the reach based on the modeling performed by TetraTech/KCM (1997). The 100-year flow estimate has since been revised to 60,000 cfs in the approximate vicinity of the upstream end of the model reach (personal communication with Paula Cooper, February 2004). However, the results obtained for this study indicate that the upper bound of 51,900 cfs that was used is sufficient to represent the sensitivities being investigated. The results are discussed further below.

Table 1 provides a summary of the multiple flow profiles modeled for each gradient scenario.

Table 6-1. Summary of steady flows modeled for each channel gradient scenario.

Flow (cfs)	5,000	10,000	15,000	20,000	25,000	30,000	35,000	40,000	47,000[a]	51,900[b]

Notes:
Peak flow estimate for the November 1990 based on original HEC-RAS model for CFHMP (KCM, 1997).
Estimate of 100-year flow input to original HEC-RAS model for CFHMP (KCM, 1997). This estimate has since been revised to 60,000 cfs (personal communication with Paula Cooper, February 2004).

HEC-RAS allows the user to define a custom list of variables for output reports. For the purposes of evaluating sensitivities in channel stability and erosion potential as a function of flow rate and channel gradient, the output variables analyzed included:

- Water surface elevation
- Hydraulic radius
- Shear stress in channel, left overbank, right overbank, and cross-sectional total
- Velocity in channel, left overbank, right overbank, and cross-sectional total

These variables were reported for all cross-sections, flow rates, and channel gradients modeled. The output reports from HEC-RAS were imported into an EXCEL spreadsheet for further analysis, as described below.

6.3.2 Spreadsheet Analysis of HEC-RAS Results

Results from several cross-sections were analyzed in detail in order to investigate the relationships between channel cross-section complexity, flow rate, channel gradient, shear stress, and velocity. Channel complexity was categorized on the basis of cross-sectional shape. Cross-sections with a single confined channel with no overbank floodplain areas, or cross-sections for which the floodplains were blocked by levees or other control structures, were categorized as single-thread. Cross-sections with multiple threads and/or with access to floodplain storage and

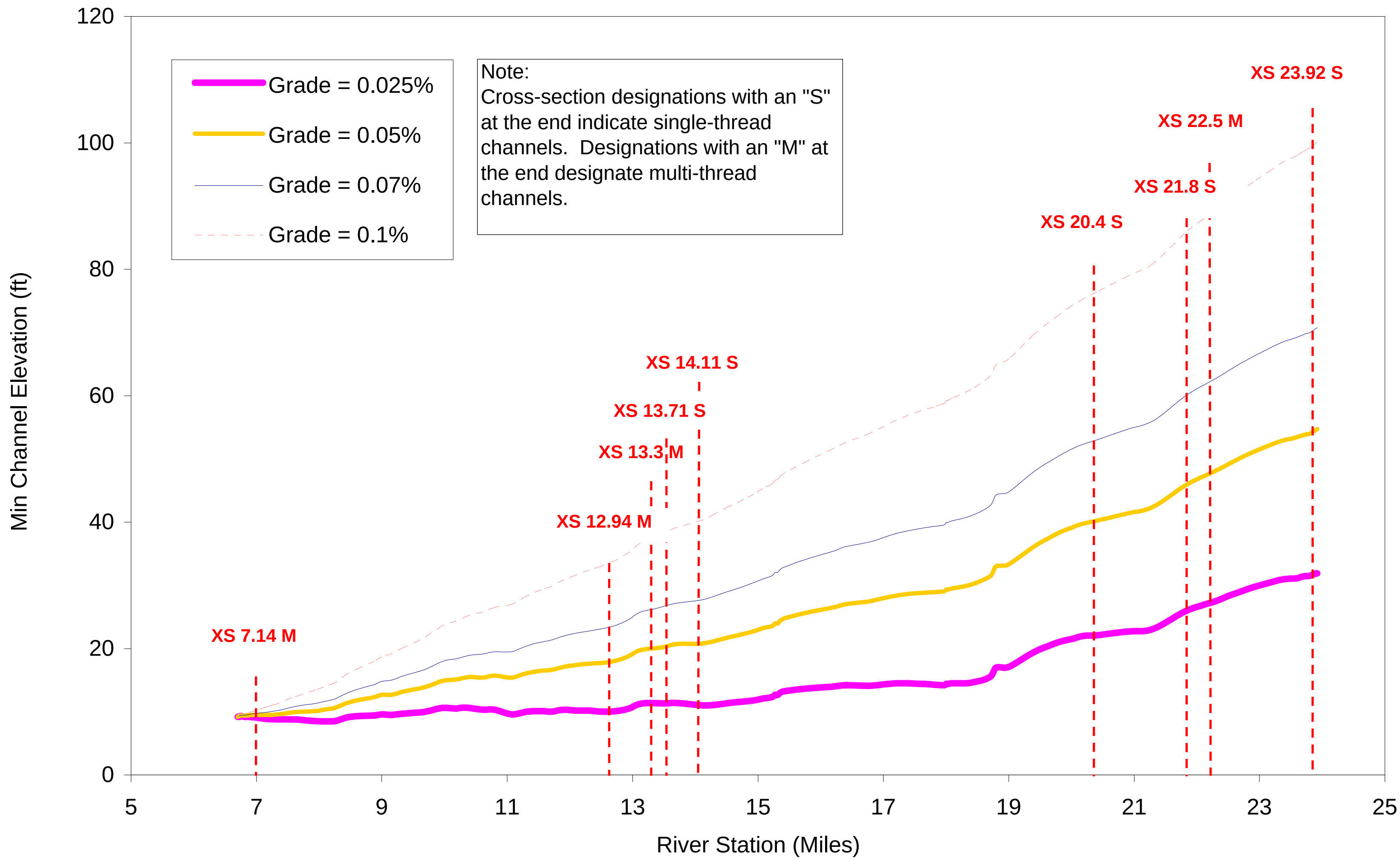


Figure 6-1 - Channel gradient scenarios modeled in HEC-RAS and cross-sections for which additional analysis was performed

conveyance were categorized as multi-thread, or complex. A total of nine cross-sections, including 5 single-thread and 4 multi-thread, were selected for this analysis. For both single- and multi-thread cases, an effort was made to select cross-sections spread throughout the model reach. In this way, the results reflect varying degrees of backwater effects and a wide range of width to depth ratios and hydraulic radii. Figure 1 shows the location of each cross-section analyzed.

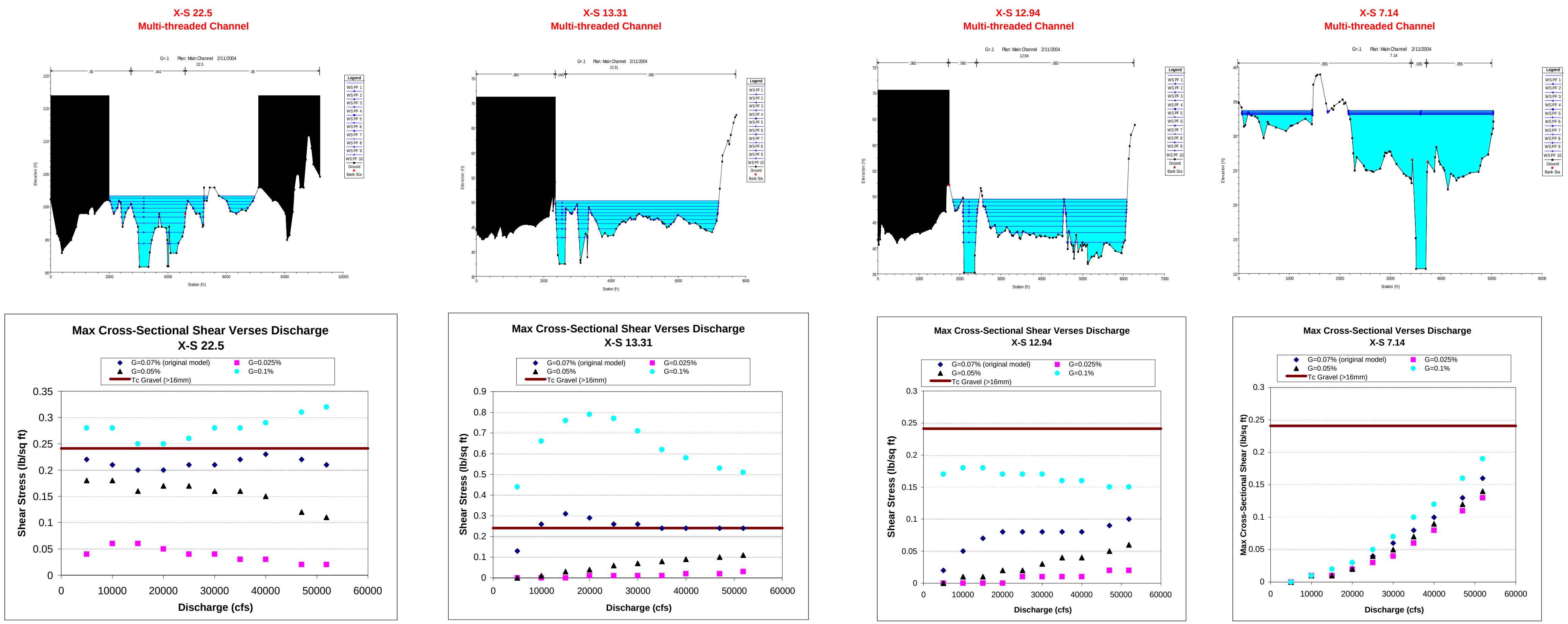
A plot of maximum cross-sectional shear stress versus discharge was developed for each cross-section. Results from each channel gradient scenario were plotted on the same graph, creating a family of curves. The critical shear stress required to mobilize coarse gravel (>16 mm), which is 0.3 lb/ft^2 (Julien, 1998), was then plotted as a horizontal line on each graph. Figure 2 shows the results for all multi-thread cross-sections. Figure 3 shows the results for all single-thread cross-sections.

6.4 Results

This section provides a discussion of the modeling results and interpretations of the meaning of those results. The HEC-RAS results were analyzed in an EXCEL spreadsheet in order to quantify the relationships between key output variables and to determine flow and channel gradient thresholds for which coarse gravel may be mobilized.

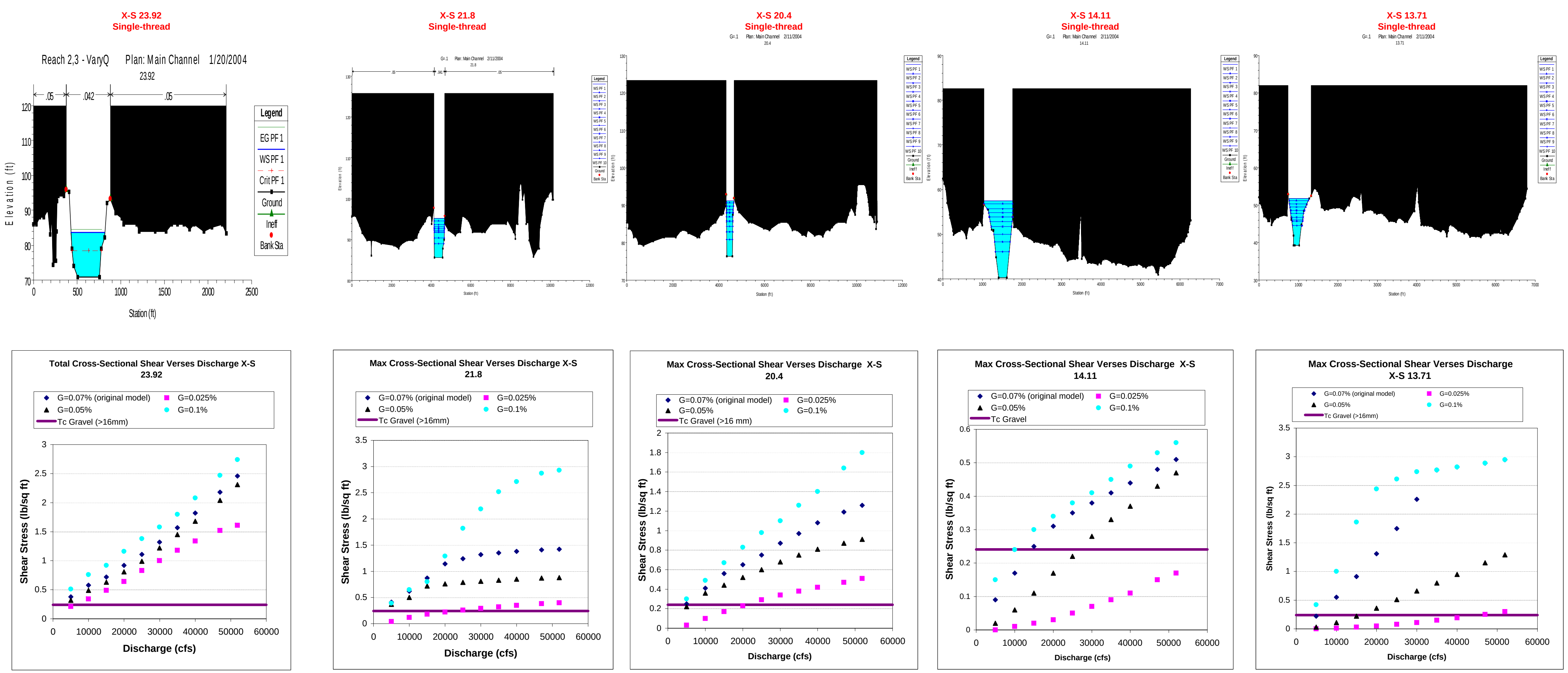
Figure 6-2 provides graphical results showing the modeled relationship between channel gradient, flow rate, and maximum cross-section shear stress for several multi-thread cross-sections. The multi-threaded cross-sections (X-S) analyzed include sections X-S 22.5, X-S 13.31, X-S 12.94, and X-S 7.14. For X-S 22.5 and 13.31, the maximum shear stress modeled for the cross-sections were below the critical shear stress threshold for coarse gravel for nominal channel gradients of 0.025% and 0.5%, regardless of flow rate. For both locations, results for the 0.07% nominal gradient scenario showed greater sensitivity of critical shear stresses to flow rate. For the 0.1% nominal gradient scenario at these locations, modeled shear stresses exceeded the critical threshold for all flows. For multi-thread X-S 12.94 and 7.14, modeled shear stresses were significantly lower than the critical shear stress for all channel gradient scenarios and for all flow rates.

Figure 6-3 provides similar graphical results as Figure 2, but for single-thread channels. The single-threaded cross-sections (X-S) analyzed include sections X-S 23.92, X-S 21.8, X-S 20.4, X-S 14.11, and X-S 13.71. Although the results differ slightly from location to location, the predominant result is that the modeled shear stresses exceed the critical shear stress for coarse gravel regardless of channel gradient and flow rate. That shear stresses would be generally higher and closer to critical threshold values in single-thread channels as compared to multi-thread channels is somewhat intuitive, since water does not access a floodplain surface through the single-thread sections. Deeper flows result in these confined cross-sections, which exert a greater pressure on the channel bottom.



Note: Cross-section plots were copied from HEC-RAS for the 0.1% gradient scenario. The water surface elevations shown represent the modeled water surface elevations for each flow input, but only for the 0.1% gradient scenario.

Figure 6-2 - Shear stress versus discharge for multiple channel gradients for selected multi-thread cross-sections



Note: Cross-section plots were copied from HEC-RAS for the 0.1% gradient scenario. The water surface elevations shown represent the modeled water surface elevations for each flow input, but only for the 0.1% gradient scenario.

Figure 6-3 - Shear stress versus discharge for multiple channel gradients for selected single-thread cross-sections

6.5 Summary and Conclusions

Hydraulic modeling using HEC-RAS was performed in order to investigate the viability of using channel gradient as a possible indicator for stormwater flow control exemptions in high order streams in western Washington. An existing HEC-RAS model of the lower Nooksack River between River Miles 6.7 and 23.92 was modified for use in this study. Modifications to the model included mainly changing the steady flow input locations, adding multiple flow profiles, and changing the thalweg profile in order to represent several theoretical channel gradient scenarios. Selected outputs from the model were imported into an EXCEL spreadsheet for further analysis.

Modeled shear stress was plotted for several multi- and single-thread cross-sections. Shear stress was plotted versus flow for all nominal channel gradient scenarios, thereby creating a family of curves for each cross-section.

The results from the analysis indicate that single-thread channels, which are laterally confined and, as such, have flows that do not access floodplain terraces and reduce the effective flow depths and velocities, tend to have shear stresses and velocities which would be capable of mobilizing coarse gravel. Therefore, the effects of undetained stormwater may be expected to accelerate erosion for such confined cross-sections.

For multi-thread channels, the results indicate that high order streams with nominal gradients of 0.05% or less may be expected to have capacity to buffer the effects of undetained stormwater inputs based on a shear stress criterion. Note that this recommended threshold value of 0.05% is conservative, since the analysis results for the 0.07% nominal channel gradient scenario showed very few instances of modeled shear stress exceeding the critical value for coarse gravel at the various locations analyzed and for most flow rates.

6.6 Recommendations

Based on the analysis performed for this study, we conclude that channel gradient may provide a reasonable basis for stormwater flow control exemptions. A stormwater flow control exemption should be allowed for direct discharge from PDDA's to rivers with a gradient of 0.05% or less. It is recommended that such exemptions be considered only for high order streams with unconfined and multi-threaded channels. The channel should be unconfined not only at the location of stormwater input, but also for the entire reach downstream from this point to the mouth of the stream or river, so that the undetained stormwater has less chance to accelerate erosion at any point in the system. Another important consideration is the location of stormwater discharge to the stream. If stormwater were discharged into a small, isolated side channel within a multi-threaded reach, that side channel would behave much like the single-thread channels analyzed and accelerated erosion might occur as described above. Stormwater discharge locations should be selected with this concept in mind.

Section 7
AN10

7.1 Introduction

This technical report investigates the effect of tidal inundation on the geomorphology of low gradient streams, and how uncontrolled stormwater discharge might affect systems where tidal influence is strong. This investigation is a part of a larger study being conducted by the Washington State Department of Transportation (WSDOT) intending to provide scientific support for stormwater flow control exemptions based on various potential criteria. This investigation of tidal influence as a potential criterion for flow control exemption is intended to test the validity and applicability of a hypothesis, not to provide an exhaustive or detailed development of tidal thresholds.

The general approach is presented first in this report, followed by a description of the data sources used in the tidal analysis. Detailed methods and results are then presented, followed by a discussion of conclusions and recommendations for further study.

7.2 General Approach

The relative magnitude of stream discharge and tidewater discharge was investigated to assess the effect of tidal fluctuation on the geomorphology of low-gradient, tidally-influenced streams. The hypothesis tested in this analysis is that channel-forming processes are dominated by the flow of tidewater through the channel rather than by upstream flows. That is, the discharge rates generated by tidewaters flushing in and out of the stream channel have a greater effect on bed and channel shear stresses than typical stream flows in these systems.

The relationship between tidal and stream effects was investigated by analyzing the ratio of tidal discharge to stream discharge over ranges of stream discharge values. This relationship was evaluated to determine under what conditions, and in which systems, the ratio suggests dominance of tidal effects.

To provide results based on real parameters, three case study systems were analyzed using available data. Hypothetical channel configurations were also analyzed to investigate a wider range of conditions.

7.3 Data Sources

Data used in the tidal influence evaluation include tide gauge data, river gauge data (stage and discharge), and LiDAR (Light Detection and Ranging) imaging data. Table 7-1 summarizes the tide and river gauge data collected for this analysis. Tide stage data were obtained for two stations from the National Oceanic and Atmospheric Administration ‘CO-OPs’ web site (NOAA 2004). River gauge data were obtained for six stations in three river systems from the U.S. Geological Survey (USGS 2004). LiDAR imaging was obtained for the Chehalis River system from the Puget Sound LiDAR Consortium web site (University of Washington 2004).

Table 7-1. Tide and river data sources.

Station Name	Station Number	River Mile	Latitude	Longitude
NOAA Tide Gauges				
Toke Point (Willapa Bay)	9440910	n.a.	46°42’30”	123°57’54”
Seattle	9447130	n.a.	47°36’18”	122°20’18”
USGS River Gauges				
Chehalis near Satsop	12035002	19.5	46°57’53”	123°31’15”
Chehalis at Porter	12031000	33.3	46°56’17”	123°18’45”
Green at Tukwila	12113350	12.4	47°27’55”	122°14’48”
Green near Auburn	12113000	32.0	47°18’45”	122°12’10”
Snohomish at Snohomish	12155500	12.4	47°54’45”	122°06’30”
Snohomish near Monroe	12150800	20.4	47°49’52”	122°02’50”

Additional data were pursued, but ultimately not used in the tidal influence evaluation. A search was conducted for river stage, velocity, and discharge data in tidally influenced locations. It was hoped that this data would provide detailed parameter data for systems during extreme tidal fluctuations and during high streamflow conditions. Three potential sources of this type of information were found in the Pacific Northwest. Gauges on the Columbia River (USGS Station 14246900 at Beaver Army Terminal), the Willamette River (Portland Harbor station), and the Chehalis River (USGS Station 12035002 near Satsop) currently use the acoustic velocity meter method of measuring discharge (USGS undated). Using a stage/area relationship, a discharge rate could be calculated in the system based on measured velocity. These stations did not provide useful data, however, for various reasons. The Columbia River station represents a system much larger than those of interest for this analysis, and estimates of river flow from upstream stations would be very rough estimates due to the distance between gauges and flow rate controls (Bonneville Dam). The Willamette River station does not yet have a stage/area relationship developed for it, and only a limited amount of velocity and discharge data are available for the Chehalis River near Satsop gauge.

7.4 Methods

To evaluate the effect of tidal flows on river channels, a critical discharge value associated with tidal flow, tidal discharge (Q_t), must be determined. Tidal discharge is associated with conditions in which river stage is decreasing rapidly during falling tide. This value can be developed by dividing an estimate of the volume of the tidal prism (V_t) by the period of tidal drawdown (t_{dd}). The volume of the tidal prism is the volume of water in the channel above ambient river conditions at a given high tide.

$$Q_t = \frac{V_t}{t_{dd}}$$

A critical value of river discharge (Q_r) must also be developed for comparison to the tidal discharge value. This value should reflect a flow rate associated with channel-forming conditions. For analysis of the case study reaches, Q_r values between the daily average 10 percent exceedance discharge and the maximum daily average discharge are evaluated. Because of tidal influence at the locations of interest in the case study systems, Q_r values were estimated from upstream gauge data by scaling in direct proportion to watershed area.

To evaluate the effect of tidal flow on stream channel geomorphology, three methods (described below) were employed to estimate the volume of the tidal prism. The first and second methods were performed on case study streams, and the third was applied to hypothetical channel configurations.

7.4.1 Tidal Prism Volume Estimation Method #1 – LiDAR Imaging

The first method used LiDAR imaging to estimate the water surface elevation of the Chehalis River at a time when tidal influence of the system was minimal. LiDAR provides topographic data for land areas, and can be used to estimate water surface elevations. These elevations are estimated by projecting elevation data across a water surface from the edges of adjacent land areas. The volume of the tidal prism was estimated by calculating the depth between MHHW, as measured at the Toke Point tide gauge, and the estimated water surface for each pixel of LiDAR data. This provides an estimate of water volume from the mouth of the Chehalis River to the estimated upstream point of tidal influence (assumed as the location where the river water surface elevation is equal to MHHW).

7.4.2 Tidal Prism Volume Estimation Method #2 – Gauge Data

Simplified models were created for each of the three case study systems (Chehalis River, Green River, and Snohomish River) using river stage data. Stage at each river mouth was assumed to be equivalent to the stage measured at the nearest NOAA tide gauge. The Toke Point tide gauge was used in the Chehalis River analysis, and the Seattle tide gauge was used in the Green and Snohomish River analyses. In each case study system, river gauges at an intermediate station (where tidal influence is observed) and an upstream station (where no influence is observed) were used in the model. To estimate the tidal prism volume, stage data were evaluated for the month of August 2003. This period was selected because river flow was presumed to be low and did not vary substantially over short periods of time. The greatest negative stage fluctuation during this period was selected for estimation of V_t. Once a specific falling tide was selected, tide prism volumes were estimated at the intermediate river stations by the following equation (see Figure 7-1 for a schematic diagram):

$$V_{t(\text{int})} = w * \frac{\Delta h}{2} * \frac{\Delta h}{(s_r - s_t)}$$

where:
w = channel width (ft)
Δh = change in water surface elevation during falling tide (ft), calculated by:

$$\Delta h = h_{\max} - h_{base}$$

where:
h_{max} = water surface elevation at high tide (ft NAVD 88)
h_{base} = water surface elevation at low tide (ft NAVD 88)

s_r = slope of water surface at low tide (ft/ft), calculated by:

$$s_r = \frac{h_{base(\text{int})} - h_{base(upst)}}{(RM_{upst} - RM_{\text{int}}) * 5{,}280}$$

where:
RM_x = river mile of river gauge (mi)

s_t = slope of water surface at high tide (ft/ft), calculated by:

$$s_t = \frac{h_{\max(\text{int})} - h_{\max(mouth)}}{(RM_{\text{int}} - RM_{mouth}) * 5{,}280}$$

Volume of the tidal prism at the mouth of the case study rivers is calculated using the following equation:

$$V_{t(mouth)} = V_{t(\text{int})} + \frac{(w_{\text{int}} + w_{mouth})}{2} * \frac{(\Delta h_{\text{int}} + \Delta h_{mouth})}{2} * RM_{\text{int}} * 5{,}280$$

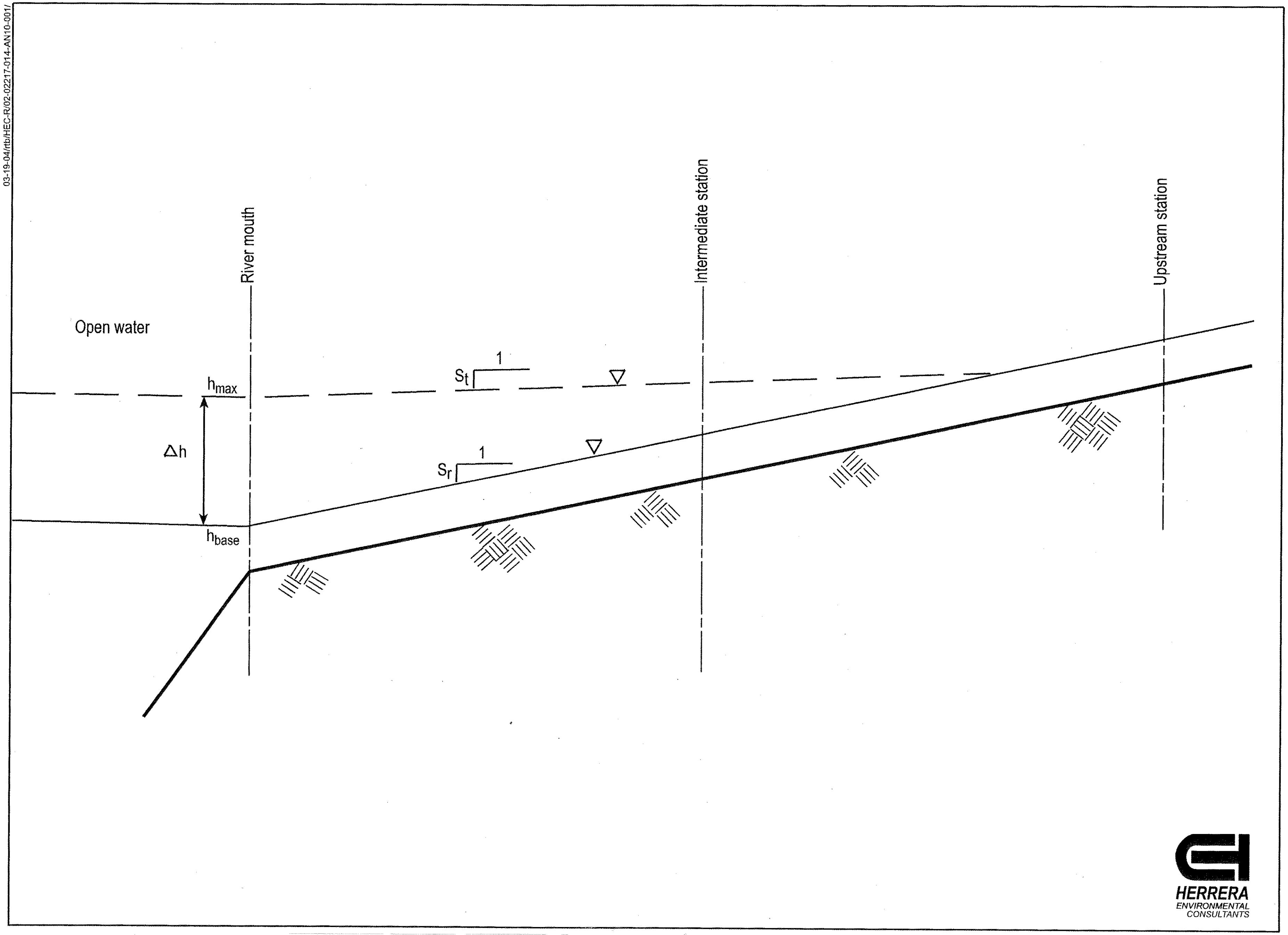


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Figure 7-1. Schematic diagram of tide analysis model for case study rivers.

Table 7-2 summarizes the input data used to calculate V_t for each of the case study systems.

Table 7-2. Input parameters for the Chehalis, Green, and Snohomish River case studies.

Location	River Mile	h_{base} (ft)	h_{max} (ft)	Δh (ft)	s_r (ft/ft)	s_t (ft/ft)	w (ft)
Chehalis River							
Mouth	0	-10.31	1.01	11.32	1.30e-4	4.80e-5	570
Satsop	19.5	3.06	5.96	2.90	2.88e-4	4.80e-5	273
Porter	33.3	23.60	23.60	0.00	2.88e-4	n.a.	260
Green River							
Mouth (Duwamish)	0	-9.59	1.17	10.76	1.13e-4	3.19e-5	440
Tukwila	12.4	-1.73	3.39	5.12	2.75e-4	3.19e-5	185
Auburn	32.0	9.90	9.90	0.00	2.75e-4	n.a.	135
Snohomish River							
Mouth	0	-9.59	1.17	10.76	3.27e-5	3.35e-5	370
Snohomish	12.4	-7.45	3.36	10.81	4.29e-4	3.35e-5	285
Monroe	20.4	10.67	10.67	0.00	4.29e-4	n.a.	250

7.4.3 Tidal Prism Volume Estimation Method #3 – Hypothetical Channel Conditions

Several hypothetical channel configurations were developed to estimate potential relationships in smaller systems. Channel widths and water surface slopes were applied, and a constant maximum tide elevation was assumed. The volume of the tide prism was calculated using the following equation:

$$V_t = \frac{1}{2} * w * \Delta h * \frac{\Delta h}{s_r}$$

These hypothetical channel configurations were analyzed over a wide range of river discharge (Q_r) values. Table 7-3 summarizes the input parameters applied for each hypothetical channel configuration.

Table 7-3. Input parameters for hypothetical channel configurations.

Configuration	w (ft)	Δh (ft)	s_r (ft/ft)
1	50	10	0.0001
2	50	10	0.001
3	100	10	0.0001
4	100	10	0.001
5	150	10	0.0001
6	150	10	0.001

7.5 Results

Using Method #1, a tide prism volume (V_t) of 11,226,000 cubic feet (cf) was estimated from the Chehalis River mouth, leading to a tide discharge (Q_t) value of 520 cubic feet per second (cfs), assuming a 6-hour drawdown period. A graphic illustrating the tide prism depths (greater depths are represented by darker grey areas) estimated using LiDAR imaging is presented in Figure 7-2. The resulting relationship of this tide discharge estimate with river discharge values is displayed in Figure 7-3 along with the results of Method #2.

Several sources of uncertainty associated with Method #1 are listed below:

- Variability in land elevations measured near water surfaces lead to inaccurate water surface elevation estimates
- Analysis can only be conducted for the flow/tide conditions occurring at the time of LiDAR imaging
- Variability in timing of LiDAR imaging of different portions of the area of interest results in discontinuous water surface elevations

Tide prism volume (V_t) and tide discharge (Q_t) estimates are presented in Table 7-4 for the three case study systems. Figure 7-3 displays the relationship of Q_t with river discharge values. Q_t/Q_r values greater than 1.0 represent conditions in which tide flows are estimated to dominate channel-forming processes.

Table 7-4. Tide prism volume and discharge estimates for the Chehalis, Green, and Snohomish River case studies.

Location	V_t (cf)	T_{dd} (hr)	Q_t (cfs)	$Q_{r(10\%)}$ (cfs)	$Q_{r(max)}$ (cfs)
Chehalis River					
Mouth	313,337,000	6	14,500	21,030	107,110
Satsop	4,780,000	6	220	14,690	74,810
Green River					
Mouth (Duwamish)	181,547,000	6	8,400	3,250	13,950
Tukwila	9,960,000	6	460	2,980	12,790
Snohomish River					
Mouth	270,771,000	6	12,540	23,550	169,870
Snohomish	42,103,000	6	1,950	20,410	147,200

$Q_{r(10\%)}$ = average daily river discharge exceeded by 10 percent of historical values
$Q_{r(max)}$ = maximum daily average river discharge

Tide prism volume and tide discharge estimates are presented in Table 7-5 for the six hypothetical channel conditions investigated using Method #3. Figure 7-4 displays the relationship of Q_t with river discharge values. Q_t/Q_r values greater than 1.0 represent conditions in which tide flows are estimated to dominate channel-forming processes.

Table 7-5. Tide prism volume and discharge estimates for hypothetical channel configurations.

Configuration	V_t (cf)	T_{dd} (hr)	Q_t (cfs)
1	25,000,000	6	1,158
2	2,500,000	6	116
3	50,000,000	6	2,315
4	5,000,000	6	232
5	75,000,000	6	3,472
6	7,500,000	6	347

7.6 Conclusions

Tidewater discharges within the river channels analyzed in this study do not appear to represent the dominant channel-forming processes. The relationship between tide flows and river flows in these systems (Figure 7-3) shows that tide discharge estimates do not exceed higher river discharge rates of concern, except in the case of the Green River. Tidal dominance is suggested at the mouth of the Green River system only, due to much lower river discharge rates than occur in the other case study systems.

The relationships between tide and river flows in the hypothetical stream channel configurations analyzed suggest that water surface slope is a primary factor. Depending upon the profile of a smaller stream system within the zone of tidal influence, tidal flows may be the dominant channel-forming factor. More detailed study of smaller systems, perhaps on a site-by-site basis, is necessary to determine if and where these conditions might occur.

The LiDAR water surface analysis method (Method #1) is not a useful tool for estimation of tide prism volumes due to the sources of uncertainty discussed above.

7.7 Recommendations

Based on the results of this analysis, a blanket exemption from flow control requirements based on tidal influence is not appropriate. Results of analyses conducted under Tasks AN-7 and AN-8 suggest that flow control exemptions will likely apply to larger river systems based on other criteria, such as basin size and land use changes. For this reason, any further study regarding potential exemptions due to tidal influence should focus on smaller streams and rivers. It is

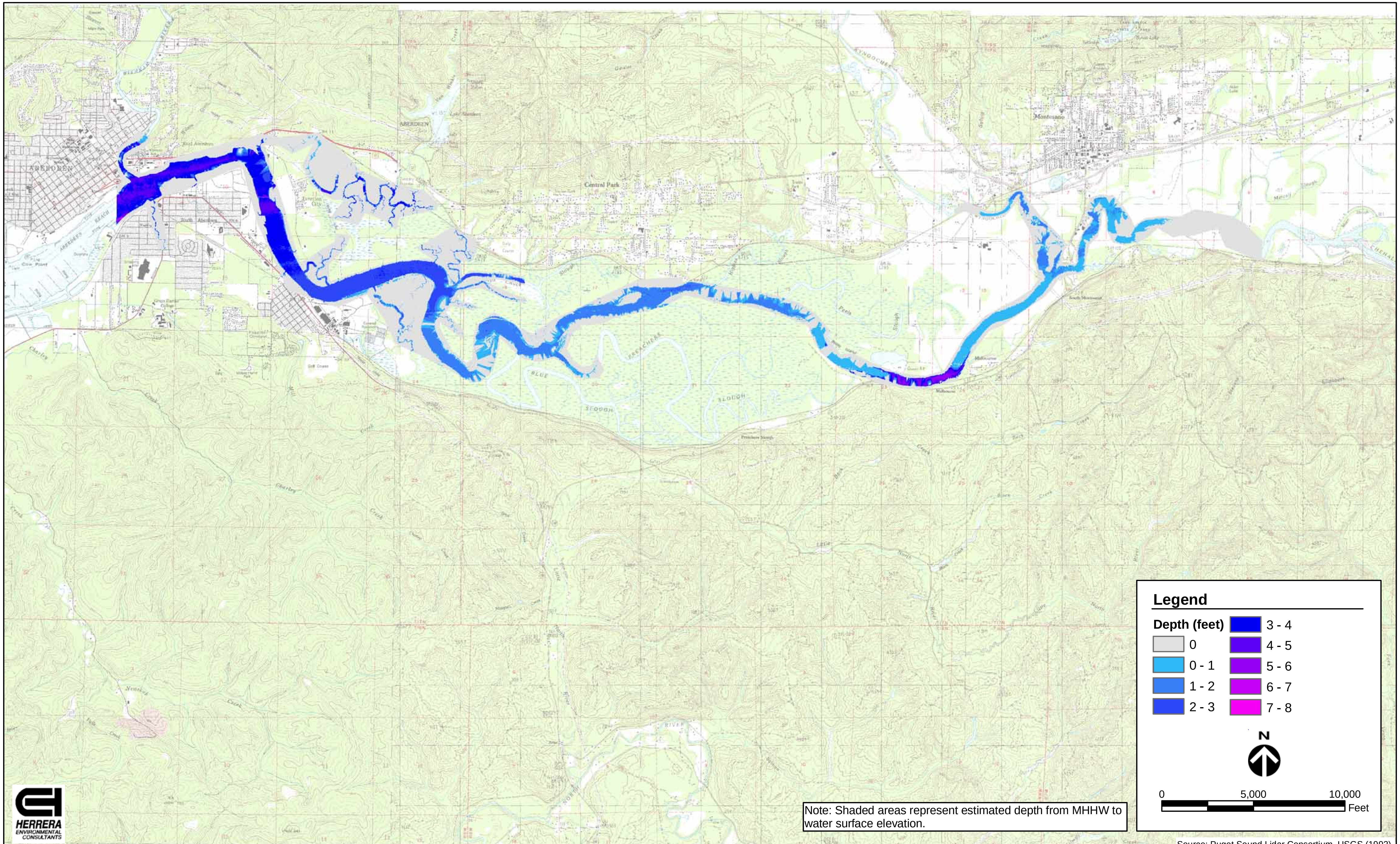


Figure 7-2. Tide prism depth using Lidar Data.

Figure 7- 3 (Task AN-10). Estimated flow relationships for tidally influenced channels

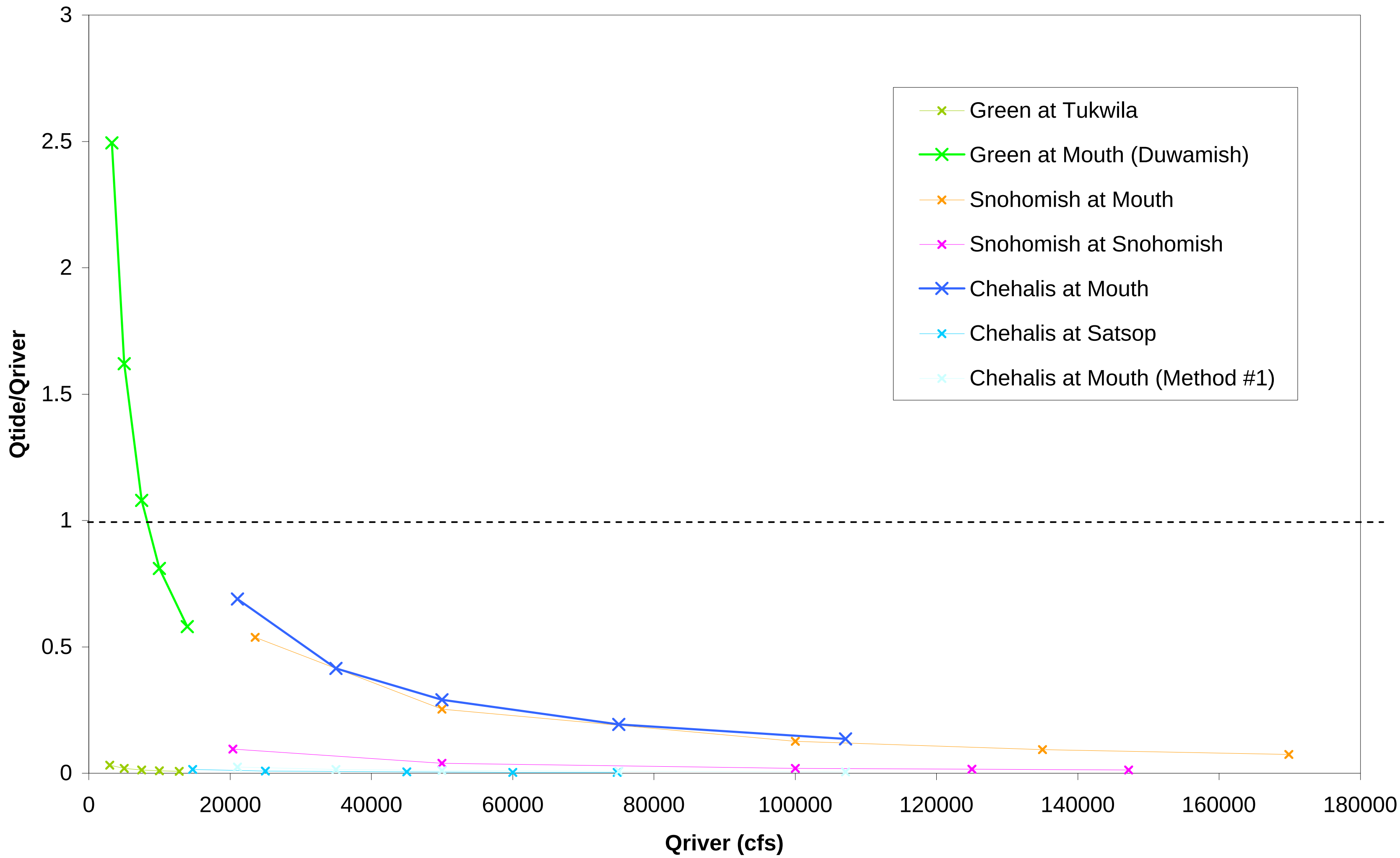
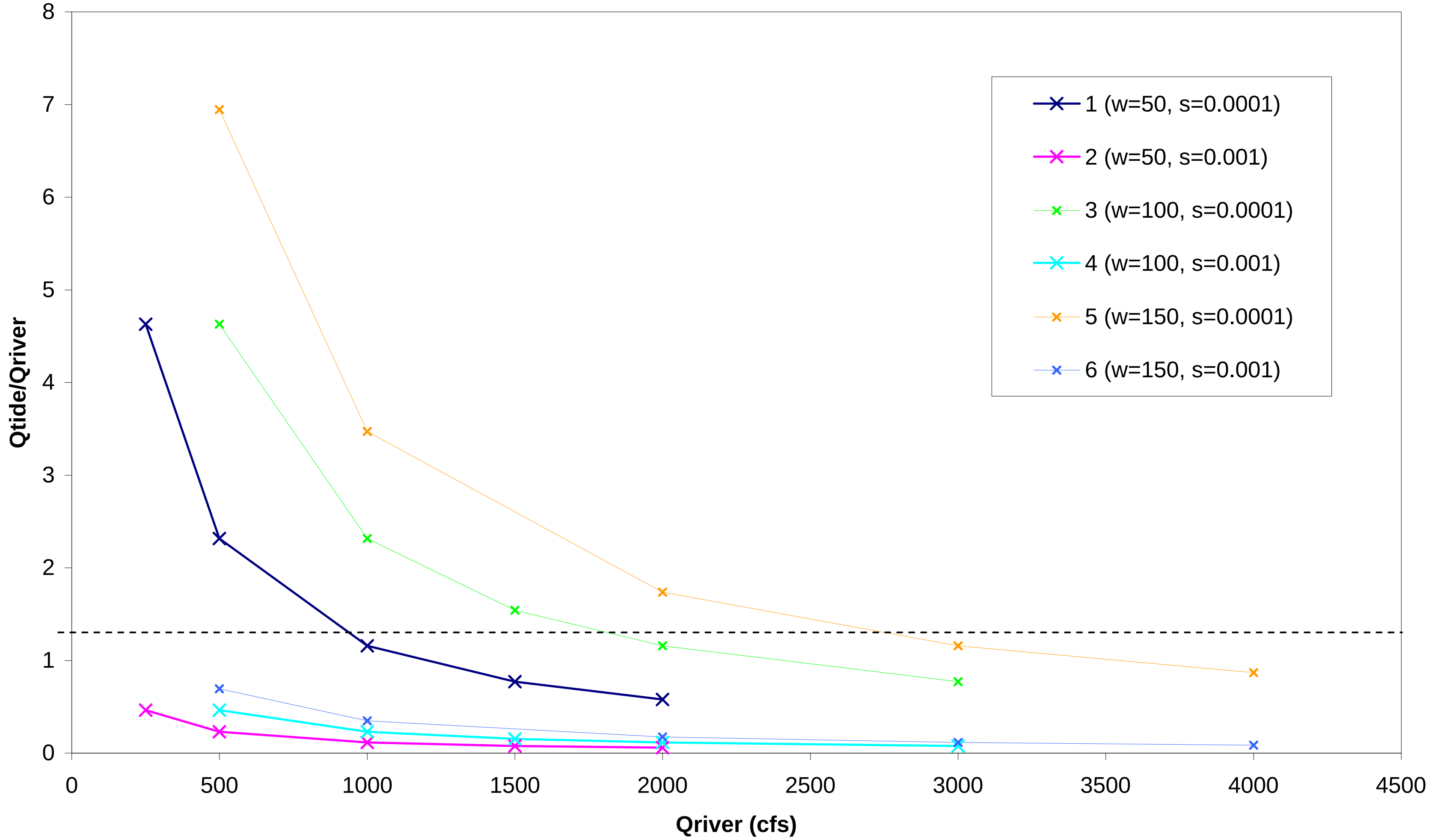


Figure 7-4 (Task AN-10). Estimated flow relationships for hypothetical tidally influenced channel configurations.



recommended, however, that these systems be analyzed on a case-by-case basis rather than as a further part of this effort. It is unlikely that a simplified criterion or set of criteria could be developed that would preclude site-specific analysis because of variability in the physical (slope, channel geometry), hydrologic (peak discharge rates), and geomorphologic (substrate composition) characteristics of stream channels within tidally-influenced reaches. For this reason, it is recommended that these systems be analyzed in detail on a case-by-case basis.

Our recommended approach for site-specific evaluation is to compare the estimated tidal discharge to the 2-year, 24-hour stream discharge in the system of interest. If the estimated tidal discharge is greater than twice the 2-year stream discharge (including stormwater discharges), it is recommended that a flow control exemption be granted due to tidal dominance in the system. The 2-year stream discharge is used as a criterion because it represents a channel-forming discharge rate in non-tidally influenced systems. The threshold described above includes a factor of safety of two to account for uncertainties inherent in the analytical method.

It is recommended that Tidal Prism Volume Estimation Method #2 be used for site-specific evaluations. If stage data is unavailable for the system of interest, a field study should be conducted to measure tidal fluctuation in the channel at multiple locations using staff and crest gauges. This field study should also include the measurement of physical channel dimensions, such as width, average depth, and slope. With this information, an accurate estimate of tidal prism volume and discharge can be determined. .

Section 8
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APPENDIX A

Notes on Application of Avenue Script

Notes on Application of Avenue Script

Cumulative Upstream Landcover Calculation Extension
Version 1.0, March 2004

Prepared for Washington State Department of Transportation
Prepared by Northwest Hydraulic Consultants

Input Data Requirements

- Polygon Theme showing a single polygon for each subbasin, with attribute data giving the unique numeric identifier for each polygon.
- Polygon Theme showing subbasin polygons split up by landuse type, with attributes giving the unique numeric identifier for each subbasin and the future landuse text code for each polygon.
- Line Theme showing stream line segments, with topology already built and checked, with a numeric attribute indicating stream order. Topology requirements: there must be a node at every intersection of three or more lines, and lines must be digitized in the direction of flow.
- Table that gives the percent landcover for each landuse type in the subbasin-landuse Theme. Landcover categories must be: Pasture/Agriculture, Grass, Forest, EIA, TIA, Wetland and Water.
- All spatial data must be in a projected coordinate system (e.g., State Plane, UTM, etc.), not in unprojected latitude and longitude coordinates.

Directions

1. Ensure that the required Themes are loaded into the current View, and that the required landuse-landcover lookup table is loaded into the Project.
2. Make the View active.
3. From the 'Landcover' menu, select 'Calculate Total Landcover Per Subbasin'. Follow the prompts. This will build a table of landcover values for each subbasin, to be used in the next step.
4. From the 'Landcover' menu, select 'Calculate Upstream Landcover Per Stream'. Follow the prompts. This will calculate the cumulative upstream landcover value for each major stream segment. A new stream segment Theme will be created, with attribute values attached.

APPENDIX B

Phase I Report

Position Paper:

Analysis of Geographic Areas Suitable for Exemptions from Stormwater Runoff Flow Control Requirements in Western Washington

Prepared for

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Prepared by

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October 6, 2003

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Introduction

Purpose of This Paper

This position paper represents an assessment of available information that can be used to evaluate the effects of direct discharges of stormwater runoff from development sites into large rivers and lakes in western Washington. This paper is intended to facilitate discussion between the Washington State Departments of Transportation and Ecology on the merits of stormwater flow control exemptions in certain areas of western Washington that drain to large water bodies nearby, and is not all inclusive of the processes that affect flooding and ecologic functions in riparian environments. This paper focuses on hydrologic and geomorphic effects of stormwater runoff on large receiving water bodies. It does not seek to address many aspects of stormwater discharges that must be carefully addressed to avoid adverse effects on groundwater and riparian environments, regardless of whether flow control (detention) is provided at a development site, such as sustenance of ground water recharge, flow dispersion and energy dissipation at stormwater outfalls, and replication of natural discharge locations.

Study Objectives

As part of the effort to revise the 1995 Washington State Department of Transportation (WSDOT) Highway Runoff Manual (HRM), the appropriateness of using stream order in combination with other watershed and hydraulic/geomorphic conditions to exempt some areas in western Washington from flow control requirements is being evaluated. The general impression is that there is some drainage area within the watershed of a larger flowing waterbody that could be exempted from the flow control requirements set forth by the Washington State Department of Ecology (Ecology). This is because the cumulative changes to the hydrology (especially surface water runoff rates and shallow subsurface ground water flow) that could occur with development of those areas do not significantly affect the dynamics of bed load movement and channel geomorphology. However, a hydrologic and geomorphic justification for that impression and a basis for limits to the use of such an exemption (e.g., maximum increase in background stream power, or total hydraulic work) has not been clearly provided for western Washington.

The ultimate goal of this study is to develop methodologies or “rules-of-thumb” for exempting certain areas from stormwater flow control requirements and thereby avoiding extensive analysis on a project-by-project basis. By investigating stream order, watershed conditions such as percent imperviousness and cumulative vegetative land cover changes, and hydraulic/geomorphic conditions such as stream channel gradient and tidal influence, these rules would be developed and applied to western Washington.

WSDOT is by no means seeking to avoid stormwater flow control requirements on all of its projects and roadways in western Washington. Stormwater flow control should be implemented in conjunction with many projects where WSDOT constructs and improves its infrastructure, to prevent worsening of flooding problems and/or to protect a receiving water from potentially damaging high flows. This study seeks to determine those areas where it can be justified that stormwater flow control would have no effect on the receiving water, absent other conditions that necessitate flow control.

Contents of This Paper

This position paper summarizes available information that supports analysis of geographic areas where stormwater detention systems are not warranted, and presents a scope of work for the next phase of study that details how the flow control exemption methodologies will be developed. This paper was developed as the first phase (Phase I) of a three-phase investigation to facilitate review and discussion of a proposed study approach between WSDOT and Ecology. The second phase (Phase II) will consist of the full development of the methodology followed by a second occasion for agency review and approval. In the final phase (Phase III), the methodology developed in Phase II will be applied to western Washington to define stream reaches exempt to flow control regulations.

This position paper is organized into the following sections:

- **Background**—A brief discussion of the background of this study and previous study efforts in eastern Washington.
- **Methodologies for Evaluating Stormwater Flow Control Exemptions—**A discussion of the basis for determining flow control exemptions that may apply in different locations, available literature supporting this analysis, and potential methodologies that can be employed in situations that are not supported by a strong literature base.
- **Available Data Sources—**A review of available data with respect to the data needs of the potential methodologies developed in the previous section,
- **Summary and Conclusions—**A summary of the findings of this position paper and conclusions regarding the feasibility of deriving scientifically-based flow control exemptions in western Washington.
- **Recommended Scope of Work—**A detailed scope of work for the next phase of study based on the methodologies described in this position paper and availability of data.

Background Information

Recent reviews by Inter-Fluve (2003) and Booth, Hartley, and Jackson (2002) document and discuss the available literature associated with the impacts and mitigation of urbanization on streams and aquatic eco-systems. The purpose of the Inter-Fluve report was to provide a "scientific" rationale for stormwater flow control to protect eastern Washington streams. Additionally, the report provided an interim recommendation to exempt 5th order streams in eastern Washington from stormwater flow control (e.g. detention) requirements. Although the Inter-Fluve report focused its attention on eastern Washington, neither the literature reviewed, nor the logical basis for its conclusions and recommendations were derived from regional data or analysis. On the contrary, the geographical scope of the reviewed literature and studies cited by Inter-Fluve was national, with a fairly strong representation of urban hydro-ecological studies from western Washington (e.g., Booth 1991; Booth 1997; Finkenbine et al. 2000; Hachmoller et al. 1991; May et al. 1997; Scott et al. 1986), Maryland (Arnold et al. 1982; Cappuccitti and Page 2000; Prestegaard et al. 2000; Schueler 1994), and the Midwest (Doyle et al. 2000; Wang et al. 2000; Poff and Allen 1995). Given the generality of the literature review conducted by Inter-Fluve and their rationale for exemptions from stormwater detention requirements, the report provides a good departure point for the purposes of this study.

Initial Definition of Stream Order

For purposes of discussion in this position paper, an initial working definition of stream order is employed that applies the term "4th order" to generally describe streams that drain greater than 30 square miles in the Puget Lowland. Examples of 4th order streams under this definition include Issaquah Creek and Bear Creek in King County. It follows under this definition that examples of 5th order or greater streams would include the Sammamish River, the Cedar River below Landsburg, the Green River below Palmer, and the Snoqualmie River below Snoqualmie Falls.

Rationale for Detention Requirements Set by Ecology

The rationale for requiring stormwater detention in eastern Washington developed by Inter-Fluve (2003) is geomorphologically based. The primary objective of stormwater detention requirements in eastern Washington (currently proposed in the draft *Stormwater Management Manual for Eastern Washington* (Ecology 2003) based on the work of Inter-Fluve [2003]) is prevention of stream destabilization by channel incision and widening associated with increased urban runoff. The design criteria in that manual focus on the prevention of the increased duration of erosive, channel-forming flows associated with runoff from newly developed areas above the natural, background level of the stream. The basis for these criteria are consistent with the rationale and design standards for flow control (detention) design criteria in the *Stormwater Management Manual for Western Washington* (Ecology 2001). Stream channel incision and widening results in loss of riparian habitat, damage to aquatic biota, downstream sedimentation, and impaired water quality. By preventing damage to the stream channel, these valuable ecosystem functions are preserved.

Definition of Potential Direct Discharge Areas (PDDAs)

In addressing the questions of flow control effectiveness and flow control exemptions associated with higher order streams, it is important to recognize the limited overall drainage basin areas to which such exemptions would potentially apply. Marsh (1998) defines “nonbasin” drainage areas as lands that drain directly into higher order streams without first flowing through lower order basins, and states that typically 15 percent to 20 percent of runoff within a large watershed drains directly into its highest-order stream or water body (see Figure 1). This definition is directly applicable to the purposes of this position paper. However, we propose the term “potential direct discharge areas” to describe those “nonbasin” areas that drain directly to 5th or higher order streams.

Two key points are that potential direct discharge areas are typically limited portions of the overall contributing drainage basin, and that the runoff from these areas must not drain through any lower order streams prior to entering the higher order stream. An example of the direct discharge concept is provided here:

For many years King County has authorized stormwater flow control exemptions for certain areas that are in close proximity to large receiving water bodies. Specifically, King County (1998) currently requires that the discharge point for an exempted drainage area must lie within 0.25 miles of the higher order receiving stream or lake, except for discharges to Lake Sammamish, Lake Washington, and Puget Sound. In recent years King County has granted flow control exemptions for discharges to the Cedar, Snoqualmie, Sammamish, and Green Rivers (excluding the reach of the Green River between State Route 18 and River Mile 6), and to Lake Washington and Lake Sammamish (Foley personal communication 2003).

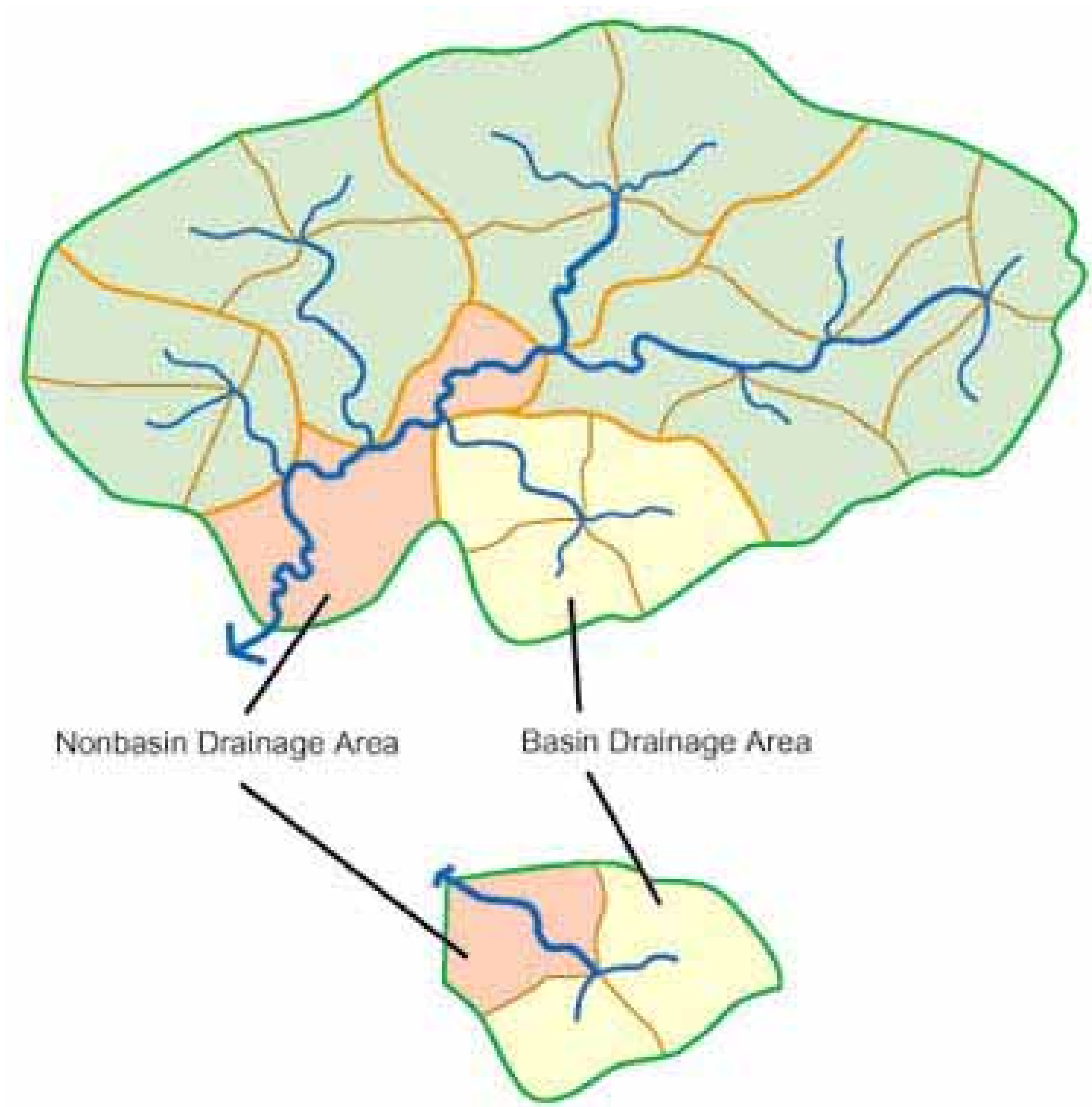

Figure 1. Illustration of nonbasin drainage areas that drain directly to higher order streams, lakes, or marine waters.

Methodologies for Evaluating Stormwater Flow Control Exemption Areas

Overview

The watersheds of western Washington vary considerably in terms of size, topography, forest cover, extent of urbanization, and flood management features (such as dams, floodplain levees, and flood water pump stations). Additionally, the rivers in these watersheds have a wide variety of channel substrates, channel depths, channel widths, and connectivity to their floodplains. In many cases the receiving water for a particular watershed is not a flowing body of water, but is instead a large lake or a saltwater body. Thus, there is no single prescriptive methodology that can be applied to assess stormwater flow control exemptions. To enable derivation of geographic areas suitable for flow control exemptions across all of western Washington, several methodologies are needed to adequately address the range of watershed and channel conditions. The following sections describe applicable research findings supporting several different approaches to developing methodologies for determining areas that are suitable for stormwater flow control exemptions.

In general, there is considerable literature available on the following subjects:

- Effects of urbanization on watershed hydrology
- Comparison of local-scale hydrographs versus basin-scale hydrographs
- Thresholds of hydrologic change that trigger geomorphic and ecologic changes in streams.

This position paper presents detailed discussion of this literature and how it relates to derivation of flow control exemptions in direct discharge areas. Watershed land use and basin-scale hydrology are grouped together as the phenomena that affect delivery of flow to a receiving water and are analyzed in the first part of this section.

The discussion of methodologies based on stream geomorphology is presented in the later part of this section. The methodologies based on stream geomorphology address the related, but analytically different, issues regarding the effects of hydrologic alterations once the watershed runoff is in a large river channel. There is very little literature available on the subjects of geomorphic change (or lack thereof) in higher order streams or tidally-influenced reaches of streams resulting from alterations of watershed hydrology. There is, however, some literature available on geomorphic effects of hydrologic alterations on streams of varying channel gradients.

Flow Control Exemptions Based on Watershed Land Use and Basin-Scale Hydrologic Conditions

This section describes the basis for analyzing stormwater flow control exemptions as a function of watershed land uses, particularly impervious surface area and vegetative cover, and analyzing flow control exemptions based on the hydrologic effects of small-scale flow control on flow peaks in higher order stream reaches.

Definition of Impervious Surface Areas

Both total impervious area (TIA) and effective impervious area (EIA) are important parameters in urban hydrology. Total impervious area refers to the sum of all nonpervious surface area within a drainage basin including all rooftops, roads, parking lots, sidewalks, driveways, etc. Effective impervious area (EIA) is the portion of TIA that does not drain via dispersion onto surrounding pervious surfaces, and that rapidly delivers storm runoff to the basin drainage system. EIA is always less than or equal to TIA. Alley and Veenhuis (1983) presented an empirical relationship based on urban neighborhoods in the Denver area that correlated TIA with EIA has follows:

$$EIA = 0.15\ TIA^{1.41} \qquad (1)$$

in which the variables are expressed as percentages.

Although the general trend described by this relationship tracks the data closely ($R^2 = 0.98$), it has some scale dependencies that could cause an underestimation of EIA in situations where clumps of commercial development are located in otherwise rural or forested drainage basins. Dinicola (1989) reviewed earlier studies and proposed a land use-based mapping of TIA to EIA that agrees with Equation 1, but avoids some of its scale-based pitfalls (see Table 1).

Table 1. TIA, EIA, and land use.

Land Use	TIA (%)	EIA (%)
Low density residential (1 dwelling unit per 2-5 acres)	10	4
Medium density residential (1-2 dwelling units per acres)	20	10
High density residential (3-7 dwelling units per acre)	35	24
Very high density or multi-family residential (more than 8 dwelling units per acre)	60	48
Commercial or industrial	90	86

Importance of Forest Cover Conversion

The linkage between urbanization and a wide spectrum of negative effects on small streams and aquatic ecosystems is well established and has been extensively reviewed (Inter-Fluve 2003;

Booth, Hartley, and Jackson 2002). In many past studies, basin imperviousness was viewed and used as a master driver of aquatic degradation effects from geomorphic instability (bed and bank erosion), to increased temperatures and pollutant loads, to loss of aquatic biotic abundance and diversity. Imperviousness has a well-known direct effect on peak discharges and storm flow durations, but historically it has also been accompanied by, and in some studies masked, the effect of other aspects of urbanization such as removal of riparian vegetation, piping of streams through culverts, physical intrusion of people, pets and livestock on stream banks and beds, introduction of toxic chemicals and nutrients associated with residential and business activity, and replacement of a drainage basin's natural soil and vegetation by lawn-dominated urban landscaping. Of all these additional aspects of urbanization, only change of pervious land cover is relevant in a discussion of storm water quantity control by detention systems.

Based on hydrologic modeling performed during development of the Issaquah Creek Basin Plan, King County (1994) found that conversion of forest land to rural residential land use could potentially result in a doubling of the 2-year recurrence interval peak discharge, but that only approximately 15 percent of the increase would be attributable to the small (4 percent) increase in effective imperviousness. The remaining 85 percent of the projected peak flow increase was attributable to forest conversion to lawns on 96 percent of the area of rural development projected. Forest clearing and conversion to lawns substantially outweighs the increase in peak flow associated with rural impervious area mainly because of the potential to convert 16 times more forest area to grass than to effective impervious area in rural zones. Although the hydrologic modeling conducted for the Issaquah Creek Basin Plan indicated that conversion of an acre of forest to impervious area increased 2-year peak flows by more than four times the increase attributable to an equal area of grass, rural land development typically converts far more forest acreage to grass than to impervious area, resulting in a larger net effect on streamflow related to the grass conversion.

Booth, Hartley, and Jackson (2002) presented a nomograph estimating stable, unstable, and uncertain geomorphic conditions associated with the ground cover conversion to different combinations of impervious area and suburban grasss cover. They based the nomograph on observations of the stability condition of 2nd and 3rd order streams in rural basins dominated by glacial till soil that were not downstream of lakes or large wetlands (Booth and Jackson 1997). The investigators found that streams observed to be stable or unstable could be distinguished by the magnitude of shifts in flood frequency going from forested to current, developed conditions. Specifically, stable streams were observed in rural basins where current 2-year peak discharge had not exceeded the undisturbed, 10-year forested peak discharge. With the assistance of hydrologic modeling, this empirically based criterion was used to create the stream stability-forest retention-impervious area nomograph. The results of this analysis indicated that a range of mature forest needs to be retained in order to maintain stability of small (up to 3rd order) streams depending on how much effective impervious area (EIA) is present in the drainage basin under consideration. A typical rural value of 4 percent EIA would require an accompanying forest cover of approximately 65 percent to provide reasonable assurance of stable stream conditions in the absence of any stormwater detention facilities to control runoff from developed areas. Note once again that EIA denotes the portion of total impervious area (TIA) that drains directly and rapidly to the stream system.

King County's experience confirms that in western Washington, basin impervious area is not the sole driver of increases in magnitude and duration of downstream peak flows and associated channel stability problems. This raises the question of whether TIA or its closely related parameter EIA might be an adequate predictor of overall forest conversion, such that considering them separately is practically unnecessary for the present purposes. Booth, Hartley, and Jackson (2002) presented data from first and second order catchments that show an expected inverse relationship between EIA and forest cover within several King County basins. While a trend is evident in the data, there is substantial dispersion about the line of central tendency. For example, at 5 percent EIA, forest retention ranged from approximately 30 percent to 85 percent. While it is likely that this level of dispersion is a scale effect resulting from small catchments containing parks and ball fields with both low impervious area and low forest cover, a determination of the tightening of the relationship for larger 4th or 5th order basins would be useful. However, at this point the available data suggest that both impervious area and forest cover loss need to be assessed.

Discussion of Flow Control Exemption in Eastern Washington Based on Watershed Land Use

Inter-Fluve (2003) proposed an interim flow control exemption for 5th order and larger streams in eastern Washington. In making this recommendation they cited research in Maryland that defined a threshold above which land development does not affect relevant stream processes and therefore flow control would not be required. (*"Research completed in Maryland has found this cutoff normally occurs around a 4th order channel"*.) Unfortunately, the specific research or literature supporting this "cutoff" is not cited or discussed. Indeed, acknowledging the lack of research in eastern Washington related to the sensitivity of streams of different order to land development, the Inter-Fluve (2003) report shifts to a rationale for flow control exemptions based on research showing that streams are typically stable when total basin impervious area is less than 5 percent. In an effort to be conservative in the face of uncertainty and lack of regionally specific research, the Inter-Fluve report finally recommends the apparently conservative flow control exemption by applying this 5 percent TIA limit to 5th order and larger streams.

The combination of these two provisos, stream order and total impervious area, appears to be very conservative since total impervious area (TIA) is always greater than effective impervious area (EIA). A 5 percent TIA limit implies an EIA limit of only 1.5 percent. The 5 percent TIA limit cited by Inter-Fluve is based predominantly on observations of 4th order and smaller streams. In these studies TIA was used as a catch-all surrogate variable (May et al. 1997) representing some urban effects such as buffer encroachment that are not germane to the issue of urban flow control by detention systems. For these reasons, it may be more appropriate to use the combined EIA and forest cover criteria presented by Booth, Hartley, and Jackson (2002). Specifically, that EIA should be limited to a range of from 0 percent to 8 percent paired with limited conversion of forest to non-forest cover ranging from 55 percent to 9 percent. This relationship is shown in Figure 2 and can be expressed in equation form as:

$$\%FCONV + 5.75\ \%EIA < 55.4\% \qquad (2)$$

> in which %FCONV is the percentage of drainage area converted from forest to developed pervious land cover and %EIA is the percentage of drainage area converted to impervious surfaces that create rapid storm runoff to the drainage system.

Compared to a single TIA limit, this criterion would be more properly aimed at changes in hydrology and channel stability, but would also be conservative in that it is based on observations of the geomorphic stability status of lower order streams.

Effect of Stream Order and Basin Scale

The *goal* of stormwater detention facilities in western Washington as established by Ecology is apparently not stream scale dependent. In developing a recommendation for a threshold discharge defining the lower limit of stream protection flow duration matching, Booth (1997) reviewed studies of both small streams and medium sized rivers. The selection of 50 percent of the 2-year, natural discharge was a pragmatic and conservative choice for a threshold that was admittedly based on variable data related to the threshold of bedload movement in predominantly gravel bedded streams. In larger streams of higher order, the range of bed sediment sizes often widens and includes increasing percentages of finer sand sized particles. In these larger streams, the selected threshold of concern may be more difficult to justify, but the principle of controlling or precluding the acceleration of erosive channel processes through limiting increases in the duration of sediment transporting flows remains valid. Further, application of the same threshold (50 percent of the pristine condition 2-year flow) is probably still valid for higher order streams that have not already been irrevocably altered geomorphologically by direct floodplain management actions, large scale manipulations of flow regime by dams, or combinations of these and other human actions.

In spite of the relevance of established flow energy criteria for higher order streams, it is generally accepted in hydrologic science that watershed perturbations affecting stream flow regime and especially peak flows are dissipative in the downstream direction. This concept may best be illustrated by a hypothetical example:

> Assume that a well-gauged, pristine watershed is subject to development that results in 10 percent of forest cover being converted to impervious surfaces, and this development is evenly distributed throughout the watershed’s catchments. A comparative analysis of pre- and post-development flow records will show that the ratio of peak discharge increases resulting from the development will be less dramatic at gage sites on higher order streams. This effect results from two factors: 1) attenuation due to storage in floodplains, lakes and reservoirs, and 2) attenuation due to variable hydrograph timing. Variable timing of component hydrographs occurs because of spatially variable runoff production rates, stream lengths, stream gradients, and hydraulic roughness that combine to cause

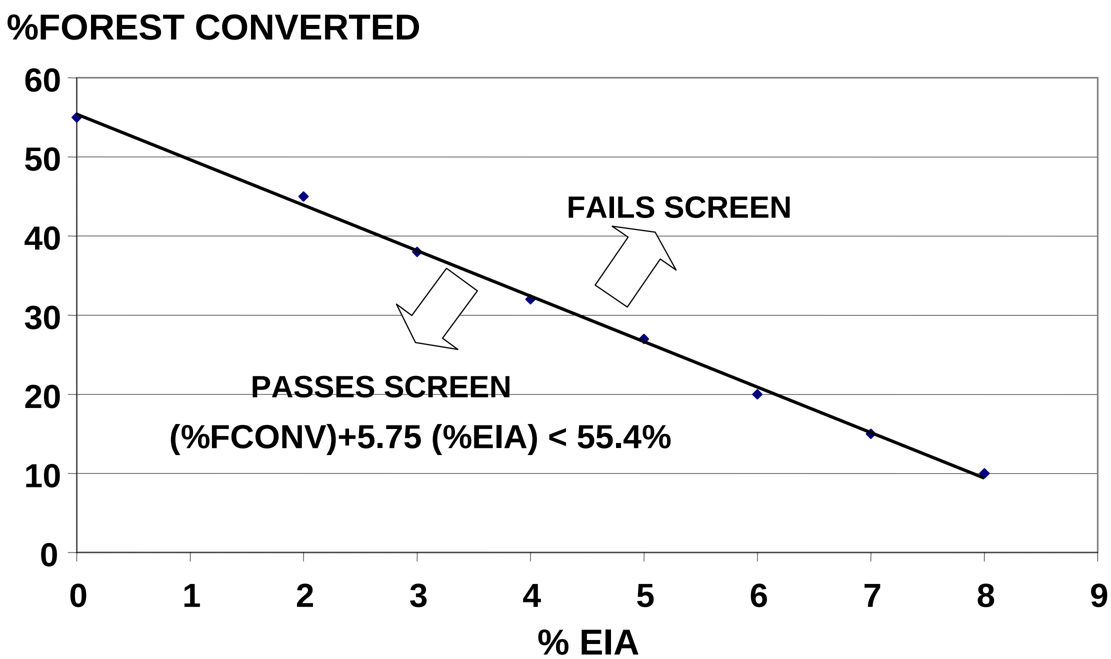

Figure 2. Proposed flow control exemption based on land use for drainage basins associated with 5th and higher order streams.

hydrograph peaks from lower order tributaries within a watershed to travel at different rates through the drainage network and arrive at higher order tributaries at different times. The temporal decoupling and attenuation of upstream peaks will generally abate the increases in peak discharges of lower order streams compared to higher order ones. This downstream, peak discharge buffering effect may be either accentuated or muted by the spatial distribution of urbanization within a watershed. Additionally, this effect will be less pronounced in a given watershed for stream flow parameters such as maximum daily flows or flood durations that integrate or average discharge rates over time because temporal decoupling and attenuation effects are less pronounced over longer sampling periods that tend to measure flood volumes rather than peaks.

Does Stormwater Detention Do Any Good for Higher Order Streams?

In a previous section it was argued that the research, logic, and rationale of the proposed flow control exemption for eastern Washington could be translated to western Washington with an additional proviso related to forest cover loss as expressed in Figure 2 and Equation 2. In this section, the issue of flow control effects on higher order streams is approached from a different angle by posing the question: is there any evidence that requiring stormwater detention systems for development in the vicinity of higher order streams is useful, and if so for what?

King County is probably one of the few entities to have examined the utility of detention systems for controlling flows of higher order streams in western Washington. Hydrologic modeling studies including stormwater detention scenarios were routine components of the King County basin planning program of the mid-1980s to mid-1990s. The largest stream considered during this program was the lower Cedar River, a 5^{th} order stream with a drainage basin of 188 square miles at the river's mouth at Lake Washington in the city of Renton. The Cedar River Basin Current and Future Conditions Report (King County 1993) looked at the effect of conveyance-level detention facilities (matching of pre-developed 2-year through 10-year peaks) on the lower Cedar River under future buildout conditions. Results for the 10-year flood were roughly typical of the range between the 2-year and the 25-year flood on the river. The County found that current urbanization (circa 1990) had raised mainstem river peaks by approximately 5 percent and that future urbanization either with detention or without detention would increase peaks by another 6 percent for a total of 11 percent over forested conditions.

Flow durations above a 2,000 cfs threshold in the mainstem of the river (slightly above a threshold of concern for the scour of salmon redds) were estimated to have increased by 7 percent under 1990 land use conditions and were expected to increase by another 6 percent under watershed buildout conditions. Again, the detention facilities were predicted to have no effect on the 5^{th} order, mainstem river. On their face, these results tend to support the view that detention facilities are not useful to control changes in the flow regime of a 5^{th} order stream in western Washington. However, such a conclusion needs to be tempered by several considerations associated with the particular basin and river conditions. These include the following:

1. Only the lower third of the Cedar River watershed was considered subject to future urbanization. The remaining two-thirds of the basin lies within the City of Seattle Watershed (for municipal water supply) which is closed to land development and remains in forest cover. Mainstem river flows at the boundary of the City of Seattle Watershed were assumed to remain constant with all future modeling scenarios.

2. The detention ponds that were tested were smaller by as much as 50 percent and less hydraulically restrictive than those currently required by Ecology. The ponds that were included in the hydrologic modeling were designed to control local runoff peaks, not runoff flow durations.

3. In modeling future buildout in the lower watershed with detention ponds, the ponds were assumed to be installed only on land zoned for urban development. This was consistent with regulatory practice exempting the small development projects typical of rural zones from flow control requirements.

King County completed several other basin studies on 4^{th} order streams during its basin planning period. In work conducted for the Bear Creek Basin Current and Future Conditions Report (King County 1989), King County applied continuous hydrologic modeling to estimate the effect of future land development that would convert a 50 square mile basin from 70 percent forest cover with 3 percent effective impervious area to 15 percent forest cover and 14 percent effective impervious area. Modeling results showed that even small detention ponds designed to control increases in 2-year peak flows would make a significant difference in the increase in peak flows at the 4^{th} order stream reach near the basin outlet. Modeling results indicated that 2-year peak flows would increase by 39 percent in the absence of these small on-site detention ponds, compared to 25 percent with the ponds. However, the modeling based on hydrologic data available in 1985 indicated that small ponds would have no impact on the durations of flow exceeding either the 1.5-year peak or 50 percent of the 2-year peak near the basin outlet. Clearly, the ponds tested were not effective at reducing erosive flow durations in the higher order stream reaches in the system.

These two case studies from King County do not clearly answer the question regarding the general efficacy of detention systems to control either peak flows or channel-forming flows in 4^{th} or higher order streams. Logically, the answer to such a question depends on the size and design of the detention systems in question. Neither of the watershed modeling studies described above involved testing the effects of stormwater detention systems of the same magnitude as now required by Ecology in western Washington.

Limits of Detention Pond Effectiveness

Both Ecology (2001) and King County ("Level 2" flow control criteria, 1998) require that stormwater detention systems accomplish matching of predeveloped flow durations up to the 50-year event. Some increase in channel-forming flow durations in extreme runoff events will not be controlled by detention facilities designed according to these criteria. The purpose of stating this here is not to expose a significant deficiency in the achievement of the goals of detention facilities. In reality, a very high percentage of the effective flow energy is controlled by such facilities. This point is included here to highlight that a judgment has indeed been made and accepted that something less than "perfect" flow control performance is sufficient.

Additionally, these detention facilities should not be viewed as providing comprehensive ecological protection to a stream. This point may be more significant. Obviously, detention facilities are not designed to provide water quality treatment or preserve summer base flows. And in PDDAs, the processes of rainfall infiltration, shallow groundwater recharge, and base flow may have particular ecological significance because of their relationship with alluvial hyporheic flows (see for example, Clinton, Edwards, and Naiman 2002). Stormwater infiltration, rather than controlled releases from detention ponds, may be the preferred stormwater management technique for protecting these processes although engineered infiltration has severe practical limitations in intensely developed areas where the ratio of impervious to pervious areas is high or where soils have naturally or human-induced low rates of permeability.

Not so obviously, detention facilities designed to the Ecology standard for western Washington will not replicate the pre-developed *storm* response of the basin. The Ecology (2001) design threshold requires matching post-developed flow durations to predeveloped (typically forested) flow durations for all events between 50 percent of the 2-year storm and the 50-year storm. In smaller storm events below the 50 percent of 2-year storm threshold, peak flows and flow durations will increase at the development site because the detention system outlet control cannot match predeveloped conditions in those storms. Small storms occurring in the summer or early fall in western Washington which previously produced nothing but a gentle, extended rise in stream base flows will result in rapid rises in stream flows under an urbanized condition in spite of the presence of detention facilities that are installed for the purposes of stream protection. While discharge from the stormwater detention systems may hold stream flow peaks below a level that would cause movement of streambed substrate and accelerate geomorphic change, more flow peaks nevertheless occur during many times of the year than occurred under natural conditions.

Stream biota are not necessarily adapted to these changes and are likely to suffer damage even though a stream may remain geomorphically stable. Thus, "state of the art" stormwater detention facilities (per Ecology) in western Washington, while dealing with significant problems of peak flow magnitude and duration, are far from comprehensive in protecting all ecological values of a natural flow regime. A recent response to historically narrowly focused techniques for managing river flows is offered by ecologically based approaches like the Indicators of Hydrologic Alteration (IHA) and Range of Variability (RVA) methods (Richter et al. 1996, 1997). These methods address conservation of a broad spectrum of flow metrics and their natural range of inter-annual variability. However, the investigators have not promulgated general rules on allowable deformations of natural flow characteristics and patterns, nor are they likely to because of their appreciation of the impracticality of generic rules for rivers that have unique ecological and socio-political contexts.

Methodologies for Analyzing Flow Control Exemptions in Watersheds That Do Not Meet Land Use Thresholds

Failure of a higher order stream to meet drainage basin cover criteria presented in Figure 2 and equation 2 does not necessarily demonstrate that any significant improvement or ecological benefit would result from installation of stormwater detention facilities in these potential direct discharge areas (PDDAs). It merely indicates that absent any other intervening effects such as dams or existing storm water detention facilities, a plausibly conservative threshold assuring stable stream conditions has been crossed in the basin. The question remains unanswered as to whether stormwater detention facilities in these PDDAs enables protection or restoration of a more functional or normative flow regime.

Prior to preparation of this position paper, the authors were not aware of any studies or literature that have addressed this question to date. As discussed above, a previous King County study of flow changes along the mainstem Cedar River, although related, was not conclusive for the present purposes. Additional literature research was conducted in an effort to find previous studies that evaluated effects of stormwater runoff on higher order streams, on streams with low gradients, and stream reaches influenced by tides.

Literature Review of Links Between Hydraulic and Geomorphic Conditions and Effects of Stormwater Runoff

A literature review was conducted to determine what scientific information is available relating to the effect of hydraulic and geomorphic conditions in a receiving water body on the degree of impact of stormwater discharges to large streams. Specifically, a search was conducted to determine if studies have already addressed the issue of stormwater and flow control in areas discharging to large rivers.

Methods of Literature Review

The literature search conducted for this first phase of the WSDOT flow control exemptions study began with review of the citations referenced in the Inter-Fluve (2003) report for the eastern Washington stormwater manual project. As noted previously, the Inter-Fluve (2003) report was fairly comprehensive in its inclusion of available literature relevant to the topic of stormwater discharges to higher order streams. The Web of Science was searched to enable review of the references cited by Inter-Fluve. The bibliographies of those reference papers were reviewed in effort to determine additional literature of relevance. From this extended list of references, literature deemed relevant was searched and, when found, reviewed. This search of literature linked to the citations in the Inter-Fluve (2003) report resulted in only a few papers with somewhat applicable information to this study, beyond the technical information presented earlier in this paper related to effects of watershed changes on streams.

Additional literature research was conducted using the keywords listed below:

- "Tidal influence(s)" and "river" (29 results)
- "Low gradient" and "sediment transport" (16 results)
- "Flow control" and "river" (13 results)
- "Low gradient" and "flow control" (0 results)
- "Tidal Influence" (118 results)
- "Imperviousness" and "river" (33 results).

While a substantial amount of literature relating to hydraulics and geomorphology of rivers was identified, no studies were found that specifically address the questions to be investigated in this study. The literature review identified a number of papers addressing the impacts of urbanization on sediment transport, channel erosion, and channel stability. Relevant findings from this literature search effort are summarized below.

Findings of Relevant Literature

The most promising findings in this literature search that embellish the information presented earlier in this paper are from work conducted at Colorado State University. Based on a study of 270 streams and rivers, Bledsoe and Watson (2001) found that logistic regression models can predict unstable channel forms with reasonable accuracy using a "mobility index" that is based on channel bed slope or valley slope (S), estimated channel-forming discharge rate (Q), and median bed material size (d_{50}). This relationship is presented as equation 3.

$$\text{Mobility index} = S(Q/d_{50})^{0.5} \qquad (3)$$

A higher mobility index correlates with greater potential for geomorphic change. In their analysis of 270 streams and rivers, Bledsoe and Watson (2000) found, with greater than 80 percent accuracy, that channel sinuosity tends to decline abruptly with mobility index values greater than approximately 0.5 $m/s^{0.5}$ in sand bedded rivers and 0.2 $m/s^{0.5}$ in gravel bedded rivers. The authors suggest that channels with sand beds with cohesive banks may be particularly susceptible to modest increases in specific stream power.

This index supports the notion that lower channel gradient correlates with less potential for geomorphic change for a given discharge rate. According to this mobility index and the authors' findings, lower channel gradient (such as typically prevails in 5^{th} and higher order stream reaches in western Washington) affords a cushion for an increase in channel-forming discharge (Q) without exceeding a threshold at which channel sinuosity would be affected.

Bledsoe and Watson (2001) also explain that a key determinant of channel response to increased discharge is the shape of the channel and its connectivity to a floodplain. Specifically, an entrenched channel with minimal connection to an adjacent floodplain will likely be more susceptible to changes in discharge in comparison to a channel that often spreads flow over a broad floodplain area. This is quite relevant to the present study. The lower reaches of many rivers in western Washington have broad alluvial floodplains that can dampen the effects of minor increases discharge. However, several rivers in western Washington have minimal floodplain areas in their lower reaches. Increased discharges in these confined river reaches have greater potential for geomorphic alterations, all other influences on the channel and flood flow being equal.

Use of Hydrologic Modeling to Simulate Effects of Stormwater Runoff on Channels

The limited findings of the literature research described above were not unexpected. Because there is a limited scientific basis upon which to derive stormwater flow control exemptions linked to channel geomorphologic characteristics and/or tidal influences, alternative means of deriving exemptions for some urbanized watersheds is needed. Hydrologic modeling can be applied to an analysis of the benefits of stormwater detention facilities by providing simulated data from which seasonal and annual flood frequency and durational analyses may be extracted. Such hydrologic analyses could be conducted for a limited number of case studies representative of western Washington streams and basins that fail the land use screening criterion discussed above. These simulation studies would be most informative if they were designed to answer two questions:

1. What differences of hydrologic regime do the presence or absence of stream protection detention systems in the PDDAs make compared to current conditions of a given higher order stream?

2. How do those differences compare with the differences between detained and undetained conditions on smaller, lower order streams?

If the answer to both questions is “small” over some range of basin land cover, drainage pattern, and geomorphic conditions, then it seems reasonable to conclude that a requirement for stormwater detention facilities in these PDDAs is ineffectual.

This type of modeling analysis would rely on data developed from the watershed land use screening process described above. The primary challenge in making a flow control exemption recommendation for these stream reaches will be in establishing an adequate consensus on what the maximum allowable difference in hydrologic parameter values with and without stormwater detention facilities in the PDDAs should be. This tolerance cannot be generally or precisely defined based on scientific literature or criteria and is likely to require a stakeholder process to determine. However, this process will most likely be more functional if informed with the range of results from the modeling study than it would be in advance of undertaking the study.

Assessment of the Effects of Channel Gradient on Potential Geomorphic Alteration Induced by Stormwater Runoff

As discussed in relation to the work by Bledsoe and Watson (2000), gradient may strongly influence the geomorphic character of a channel subjected to increases in discharge. Their findings support the basic equations that describe channel-forming processes such as sediment transport and the initiation of particle motion. The capacity of these processes to affect a channel’s morphology is typically evaluated in terms of stream power or excess shear stress and is proportional to the channel's gradient. It is therefore possible that, within basins that fail to meet the criteria in Figure 2 and Equation 2, PDDAs can be identified on high-order streams based on channel gradient.

Methodologies based on this approach, using threshold discharges associated with incipient particle motion, have been employed locally in smaller streams. Utilizing the onset of streambed motion, however, does not appear directly transferable to larger systems where the transport of smaller particles occurs at more frequent intervals. Another approach, evaluating the relationship between discharge and channel forming processes, yet designed for 4^{th} or higher order streams, is worth investigating.

A numerical model of channel forming process would provide insight into the usefulness of channel gradient as an identifying characteristic for PDDAs. Such a model, based on hydrologic data and stream geometry of selected western Washington rivers, would evaluate the effect of channel gradient on sediment transport dynamics and shear stress conditions. The results of this analysis could provide threshold gradients, for various scale reaches, below which the effect of excess discharge on channel forming process is expected to be negligible.

The effects of tidal influences could be investigated using similar principles. An evaluation of channel forming processes in reaches that are influenced by tides may show that, due to the low gradients that are typical in these reaches in possible combination with backwater effects, increases in discharge are insignificant to the process that control channel morphology. This determination could allow for a downstream delineation of PDDAs based on the distance up a given river that is affected by tides.

Available Data Sources for Flow Control Exemption Analysis

Data Availability for EIA/Forest Cover/Stream Order Criteria

Stream Order

The analysis will be based on definition and identification of 5th and higher order streams. This task is not expected to present serious difficulties and will likely be based on existing Washington State Department of Natural Resources (WDNR) or U.S. Geological Survey (USGS) databases using a working definition of stream order that is cognizant of scale dependencies.

Basin Delineation

Basin delineation is not expected to present substantial difficulties as larger scale basins have already been delineated. These basin data are available through the U.S. Environmental Protection Agency, Ecology, USGS, state WRIA planning groups, and local jurisdictions. In areas with data gaps, GIS analysis of USGS digital elevation models can be applied.

Watershed Land Use Analysis

It is proposed that the screening of western Washington watersheds to identify flow control exempt stream reaches be based on "buildout" conditions as indicated by county and city zoning maps and Growth Management Act planning data, augmented by ancillary data sets such as tax parcels. A limited survey of data sources indicates that there is no single GIS coverage with consistent zoning designations that can be applied to this task. Therefore, a coverage will have to be constructed from available maps from the Washington State Department of Community, Trade and Economic Development (CTED), county GIS layers, and in some cases hardcopy maps.

A check of the CTED web site indicates that all western Washington counties with exception of Grays Harbor, Skamania, Cowlitz, and Wahkiakum counties are engaged in full planning under GMA. The latter counties are pursuing partial planning for critical and natural resource areas. Many, if not all counties have GIS or CAD-based databases of planning, zoning, and parcel information including but not necessarily confined to Clark, Skagit, King, Pierce, Snohomish, Kitsap, Thurston, and Jefferson counties.

Other sources of watershed land use information include Regional Councils of Government, WSDOT, WDNR, the U.S. Forest Service, the U.S. National Park Service, the Puget Sound Regional Council, and the U.S. Bureau of Census.

The objective of stream basin land cover analysis will be to estimate EIA and forest cover conversion at buildout conditions along 5th and higher order streams, not to create a comprehensive, unified data layer of land cover at buildout that is accurate at smaller scales. Approximate methods could be used to accomplish any needed data filling or integration to achieve an analysis for each 5th and higher order western Washington watershed. One example of such methods would be an extrapolation of current or recent past land cover composition to future buildout using the GMA UGB coverage for Washington State that is available from the state CTED (Wentz personal communication 2003).

Land Cover Based on LANDSAT Images

The buildout analysis can be checked with LANDSAT based land cover analysis. GIS coverages for all of western Washington dated 1992 are available from the USGS NLCD program (<http://landcover.usgs.gov/nationallandcover.html>). A more recent analysis based on 2001 images is expected in 2004. The National Oceanic and Atmospheric Administration (NOAA) is cooperating with the USGS program in their analysis of land cover change in coastal areas that include many counties in western Washington.

The 1992 USGS dataset can be applied to screen out higher order stream reaches which would have failed the proposed screening criteria in 1992. Additionally, it can provide a check on the buildout coverage by assuming effectively irreversible shifts to less forest cover and more effective impervious area with time.

Data Availability for Geomorphic Analyses

Flood studies and flood models have been prepared for numerous rivers in western Washington, creating data that should be useful for analyses of geomorphic effects of varying flow conditions. Specifically, the channel cross-section and bed slope data generated for flood models in the lower reaches of river systems can be drawn upon for these types of geomorphic analyses. Specific data sets of this nature were not reviewed for the purposes of this position paper.

Summary and Recommendations

Evaluation of Stormwater Flow Control Exemptions Based on Watershed Land Use

From the viewpoint of channel stability, a recommendation for flow control exemptions based on paired EIA and forest cover conversion limits with a minimum stream order appears to be adequately conservative for western Washington for the following reasons:

1. Such a combined impervious area and forest conversion limit is based on observations for smaller stream systems (mainly 2nd and 3rd and some fourth order streams) where on-site stormwater detention was virtually absent. It is generally expected that higher order streams would be more robust than smaller streams.

2. The application of such a flow control exemption for higher order streams is clearly not a basin-wide exemption since it does not apply to locations within the basin that discharge to lower order tributaries where regulatory thresholds may require on-site stormwater detention to be applied.

3. The exemption would be based on the protection of pristine or near pristine higher order streams from channel instability. In some systems, there are more effective drivers of channel morphology than marginal increases in impervious area or loss of forest cover. These include such features as flood control dams, dikes, levees, or revetments that have greatly modified flow regimes and geomorphic processes of many higher order streams in western Washington. As a result the criterion may be overly restrictive and lack relevance for many higher order streams that exceed EIA and forest conversion limits.

Implementation of the proposed method combining stream order, effective impervious area, and forest cover is feasible. The most difficult step is the data integration and filling needed to create future buildout coverages for mixed land use areas undergoing land use change in some western Washington watersheds.

Evaluation of Stormwater Flow Control Exemptions for Watersheds That Do Not Meet Land Use Thresholds

Many watersheds in western Washington exceed the impervious surface and forest conversion thresholds that enable relatively conservative stormwater flow control exemptions based on the literature. For these watersheds a different approach is needed to examine areas where direct discharge of stormwater to the receiving water will not cause adverse hydrologic or geomorphic impacts. It is recommended that hydrologic modeling coupled with simplified modeling of channel forming processes be conducted using representative data sets to support this type of analysis.

A set of hydrologic simulation studies of up to three drainage basins considered to be representative of those basins that fail the cover criteria described by Equation 1 should be undertaken to assess the effectiveness of stream protection detention standards in PDDAs with respect to peak annual flow, seasonal peak flow, and flow durations from 50 percent of the 2-year flow through the 50-year flow. Simulation scenarios should include current, buildout, and restored conditions. To suit the needs of this study, the selected river reaches should contain a range of channel gradients. The simulation results should be used as the basis for calculating the effects of estimated flow rates and flow velocities on channel bedload movement using standard equations for incipient motion of particles and shear stress.

Based on the results of the hydrologic simulation and analysis, a recommendation can be made as to whether a subset of PDDAs that fail to satisfy equation 2 should be exempted from flow control requirements.

Modeling of channel forming processes should be performed for up to three western Washington rivers, depending on available data. This modeling would evaluate the effects of a range of channel gradients on sediment transport dynamics and shear stress conditions.

While the appropriate lower threshold of concern for stormwater discharges is open to judgment for higher order streams, especially when significant amounts of sand are present in the channel, the concept of limiting increases in sediment-moving flows in order to maintain channel stability still makes sense, especially when dealing with pristine or near-pristine stream systems. However, when protecting an existing urban stream or a river, the channel's current geomorphic state and trajectory as well as the goals of management should be considered prior to taking flow control actions. For example, King County (1996) determined that the flow threshold appropriate for stream stability analysis of urbanized Des Moines Creek should be determined by current channel cross-section and sediment properties as opposed to a pristine, forested reference condition.

Unique Issues to be Considered in Developing Flow Control Exemptions

In addition to channel stability issues, there may be other reasons for requiring stormwater flow control in areas capable of discharging to higher order streams. One example is the Green River in King County where the Green River Flood Control Zone District (1992) applies a detention standard for areas that can discharge directly to the river that is designed to protect the river's levee system from failing or overtopping during large, extended floods. This example is cited to point out the need to consider local conditions and associated drainage regulations requiring stormwater flow control in potential direct discharge areas for different reasons than those discussed in this paper.

Recommendation for Lakes

Lakes are effectively zero velocity waterbodies with respect to flow conveyance. Additionally, lakes provide natural attenuation of inflows that reduce perturbations of flow in downstream channels. On the other hand, lake and associated wetland biota are highly sensitive to shifts in hydro-period (Azous and Horner 2000) and flow attenuation by lakes is far from complete. Based on these considerations, it seems reasonable to apply a similar set of criteria to lakes but to slightly relax the order criterion from 5^{th} and higher order lakes to include lakes that receive inflow from at least one 4^{th} or higher order stream. In King County, such a relaxed order criterion would include Lake Sammamish, which receives inflow from Issaquah Creek, but no other 4^{th} order stream. Direct discharges to similar lakes in western Washington would likewise result in minimal effects.

Recommendation for Tidally Influenced River Reaches

Similar to large lakes, tidally influenced reaches of many large rivers in western Washington are effectively low velocity receiving waters that are not dominated geomorphologically by the forces of freshwater flow, particularly near the river mouth at the ocean or estuary. It is recommended that a sufficiently conservative rule of thumb be developed for PDDAs in tidally influenced reaches of 5th and higher order rivers where it is understood that the floodplain and channel are unaffected by stormwater discharges. This rule of thumb would not apply if unique flooding concerns or governing discharge limits apply to the river reach of concern. The point in a tidally influenced river where a direct stormwater discharge exemption should not result in adverse geomorphic impacts is likely downstream of the upper limits of tidal influence.

Recommended Scope of Work

A recommended scope of work for the studies described above is provided in an attachment to this position paper.

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