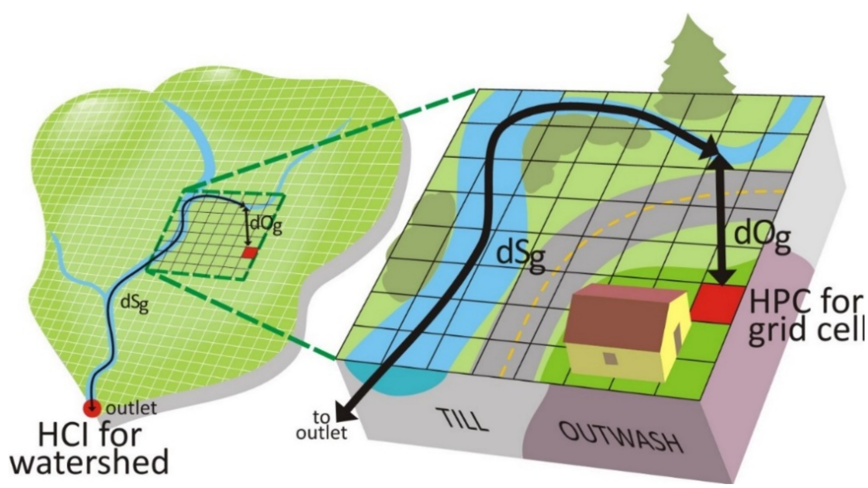
Puget Sound Watershed Characterization

Volume 4: Mid-Scale Assessment of Hydrologic Condition



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Cover page graphic adapted from Lucchetti et al. 2014. Figure 2 in this publication

Puget Sound Watershed Characterization

Volume 4: Mid-Scale Assessment of Hydrologic Condition

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Acronyms and Abbreviations

AU	Assessment Unit
B-IBI	Benthic Index of Biotic Integrity
BMPs	best management practices
CAO	Critical Areas Ordinance
CCAP	Coastal Change Analysis Program
DEM	Digital Elevation Model
dOg	distance between the grid cell and the stream channel
dSg	distance down the stream channel to the basin outlet
ESA	Environmental Science Associates
HCI	Hydrologic Condition Index
HCV	hydrologic condition value
HPC	high pulse counts
HPC_{coeff}	high pulse count coefficient
HSPF	Hydrologic Simulation Program Fortran
IDW	inverse distance weighting
LID	Low Impact Development
LULC	Land Use and Land Cover
NOAA	National Oceanic and Atmospheric Administration
PLE	Puget Lowland Ecoregion
PSWC	Puget Sound Watershed Characterization
PSWC 2.0	PSWC Update Project
QAPP	Quality Assurance Project Plan
WAG	Watershed Advisory Group
WCT	Watershed Characterization Tool
WMM	Watershed Management Matrix
WRIA	Water Resource Inventory Area

Executive Summary

The Puget Sound Watershed Characterization (PSWC) is a set of water and habitat assessments described in four volumes that compare areas within a watershed for restoration and protection value as well as identifying the best location for development. It also provides a decision-support framework that helps integrate these assessments across multiple scales for use in watershed based planning at the regional, county, and city levels.

Existing Volumes 1, 2, and 3

Volume 1 briefly describes the overall conceptual decision support framework for the PSWC and details the assessment of water resources using analyses of watershed processes. It also includes Watershed Characterization Tool (WCT) 1 which assesses the relative level of importance and degradation for watershed processes and WCT2 for assessing water quality processes.

Volume 2 compares relative fish and wildlife habitat values across multiple environments and includes a series of tools (WCT3) for assessing the habitats in those environments (freshwater habitat, terrestrial habitat, and marine shorelines).

Volume 3 explains how to synthesize the results of each preceding volume into an integrated decision support framework to support protection and restoration actions over multiple scales.

New Volume 4

For Volume 4, the Department of Ecology (Ecology) has initiated development of a new "mid-scale" assessment tool (WCT4) known as the Hydrologic Condition Index (HCI) for potential further development to be applied throughout Puget Sound watersheds.

Stream "flashiness" is the characteristic of a stream having a rapid increase in flow shortly after onset of a precipitation event, and an equally rapid return to base conditions shortly after the end of the precipitation event.

The HCI is designed to be a useful tool in helping land use planners, stakeholders, and decision makers understand the effect of existing and projected future development on stream "flashiness" and the overall hydrologic condition of a watershed. It is based on hydrologic principles and methods that show a correlation to monitored stream conditions.

The HCI method integrates what we know about the effects of land cover, geology, and distance to a stream into a single index score of hydrologic condition for a given watershed. It accomplishes this by imposing a spatial grid on a watershed to assess the combination of land cover, surficial geology, and distance to stream for the likelihood of contributing to stream flashiness (i.e. produce more high pulse counts). The index calculation uses high pulse count values derived from calibrated hydrologic models run on a series of King County watersheds (using 61 years of precipitation and climate data) to produce average HPC coefficients (see Appendix B). An HCI score is achieved by summing the grid values (HPCg) across the watershed and comparing this to the worst possible combination of land cover and surficial geology (i.e. all paved road) to produce a relative HCI score.

Decision Support Framework

How to Use PSWC Tools

Application	WRIA-wide	Sub-basin	Reach to sub-basin
Spatial Scale	**Broad-scale:** 10 to 100s of sq. miles (1000s of acres).	**Mid-scale:** 0.5 sq. mile to 10 sq. miles (100s of acres).	**Fine-scale:** 10s of acres
Toolbox	Puget Sound Watershed Characterization Broad Scale Tools (WCT): WCT1 – Water Flow Processes WCT2 – Water Quality WCT3 – Fish & Wildlife	HCI tool and Comprehensive Integration of PSWC results with HCI scores, including high pulse counts (HPC). WCT4 – HCI Tool (New) WCT5- Decision Support Framework (New)	Finer scale hydrologic models (e.g. HSPF) and local data
Application of Tools	Use PSWC broad-scale results (importance and degradation) to support landscape-level prioritization for protection, restoration, & development actions.	Use sub-basin tools such as the HCI to determine overall existing and future condition of watershed, to assist in build out analysis, and to select the best development patterns through alternative futures scenarios.	Sub-basin based alternative future scenarios. Use finer scale hydrologic models to develop specific location and design of proposed development.

To develop a mid-scale assessment tool that predicts hydrologic condition, Ecology first tested the HCI and its associated variables under different conditions of spatial resolution and surface water flow routing.

The testing addressed the following questions:

1) Do HCI scores vary significantly at different spatial scales[1] (extent and grain size)? Test at different watershed sizes and with two grid resolutions (1.8-meter & 30-meter grid resolution).
2) Do HCI scores vary significantly using either a simulated natural flow network or Euclidean[2]-based calculation (straight line distance to stream) to assess distance from an upland pixel into the stream-channel network?
3) Is the HCI a useful method for evaluating Alternative Futures scenarios that vary the type, location, and density of development?

The results of testing ten combinations of land-cover resolution, flow path, and distance variables suggested that finer scale land use data (e.g. less than 30 m), in combination with a

[1] Patterns within an ecological system or mosaic are a function of scale, which is comprised of extent and grain (Forman and Godron 1986).
[2] The Euclidean distance is the "ordinary" or straight-line distance between two points.

natural flow path grid and an overland inverse distance variable should preferentially be applied when using the HCI:

1) **Application of the HCI at the sub-basin or catchment scale (100s of acres or less) using the 1.8-meter resolution land-cover data, with natural path or euclidian flow calculation and the overland distance variable (dO_g).** This application would be on a case-by-case basis and reserved primarily for addressing the effects of reach to sub-basin scale development proposals on basin hydrology. This application would be best suited for the “Alternative Futures tool” that could eventually be designed for use on the PSWC website.

2) **Application of the HCI at the Watershed Management Unit[3] (greater than 100s of acres) scale using 30-meter resolution land-cover data, with natural flow path (Euclidean distance calculation acceptable if resources not available to created natural flow grid) and the overland distance variable (dO_g).** The products could include HCI scores for: (a) existing conditions; (b) future buildout (i.e., watershed-wide Alternative Futures scenarios) using conventional development patterns at low, medium, and high intensity; and (c) future buildout using “green infrastructure” methods for medium and high-intensity development.

Volume 4 also provides guidance for the application of the HCI within a Decision Support Framework (WCT5), which integrates the broad-scale (Volume 1) and mid-scale HCI assessment methods.

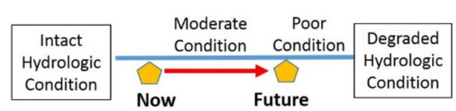
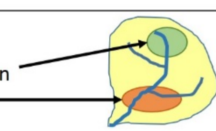
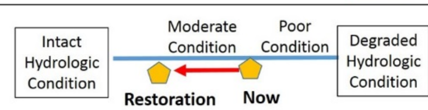
Steps	Use Tool	Examples
① What is the predominate Watershed Management Category for your watershed?	Broad scale results and local information.	
② Determine risk from future buildout. Good, moderate, or poor hydrologic condition?	HCI score for existing and full buildout.	
③ Integrate results from step 1 and 2.	Solution templates.	• For “Protection” areas and HCI < 0.21, use protection actions • For “Restoration” areas and HCI > 0.21 & < 0.44, use restoration actions. • For “Development” areas and HCI > 0.44, use LID.
④ Which areas will help maintain a healthy hydrologic condition?	HCI scores, land cover, geology, and proposed actions.	Identify areas that could improve Hydrologic condition through restoration actions or green development actions. 
⑤ Design future development alternatives and rerun HCI.	HCI score for proposed development.	

Figure above describes the five steps for integrating broad- and mid-scale tools (WCT1&4)

[3]A Watershed Management Unit (Volume 1 of PSWC) is a sub-basin within a WRIA (100s of square miles) that typically encompasses an entire “named” stream system.

Application of the HCI for Alternative Futures Scenarios in the Taylor Creek watershed demonstrates its potential usefulness to local governments in locating and designing development at the sub-basin scale so that it minimizes impacts to hydrological conditions within a watershed. Additionally, the framework provides guidance on how the range of HCI scores within a region, when coupled with biological indicators such as the Benthic Index of Biological Integrity (B-IBI), can be used to establish hydrologic condition categories that can be applied systematically throughout Puget Sound.

Introduction

Puget Sound Watershed Characterization Volumes 1-4

The Puget Sound Watershed Characterization (PSWC) is a set of water and habitat assessments described in four volumes that compare areas within a watershed for restoration and protection value as well as identify the best locations for development.

The information it provides allows local and regional governments, as well as non-governmental organizations, to base their decisions regarding land use on a systematic analytic framework that integrates this watershed information over multiple scales. The PSWC consists of four volumes, which are described below.

Volumes 1, 2, and 3

The conceptual framework for integrating watershed information over multiple scales was presented in Volume 1 of the PSWC (Stanley et al. 2016). The framework was designed to help users make watershed-based land-use decisions at a broad scale (thousands of acres), that support the protection and restoration of ecologically important lands, and to identify where development would least likely impact watershed processes and functions. It included Watershed Characterization Tool (WCT) 1 which assesses the level of importance and degradation for watershed processes, and WCT2 for assessing water quality processes.

Volume 2 covers fish and wildlife habitats across multiple environments (freshwater, terrestrial, and marine) and includes a series of tools (WCT3) for assessing the habitats in those environments.

Volume 3 explains how to synthesize the results of each preceding volume into an integrated framework to support protection and restoration actions.

Goal of Volume 4

The goal of Volume 4 is to provide information to local planners and decision makers to support continued development and implementation of a multi-scale decision support framework for all Puget Sound watersheds.

To attain this goal, the Hydrologic Condition Index (HCI) or WCT4, was developed and tested in eight watersheds (Figure 1) to assist users in understanding the effect of existing and future development on the hydrologic health of a watershed at the mid-scale.

What is the Hydrologic Condition Index Tool?

The HCI tool integrates what we know about the effects of land cover, geology, and distance down a stream into a single "score" of hydrologic condition for a given watershed. It is based on detailed hydrologic modeling (Hydrological Simulation Program – FORTRAN, or HSPF), calibrated to regional lowland watershed geology and flows, which generates scores predicting the effect of a given land cover and potential effect of land cover changes upon the "flashiness" component (i.e. High Pulse Counts) of stream hydrology within a watershed. It accomplishes this by simulating the flow of water across a watershed through individual grid cells and identifies the “high pulse” value for a given land cover and surficial geology type in each grid cell. These high pulse values are used to derive HPC coefficients (HPC_{coeff}, Appendix B), which are then summed and normalized to produce an HCI score for the watershed. The calculation includes the distance of the flow path between a grid cell and the stream, known as overland distance (dO_g) and can also include the distance down the stream to the outlet for the watershed (dS_g).

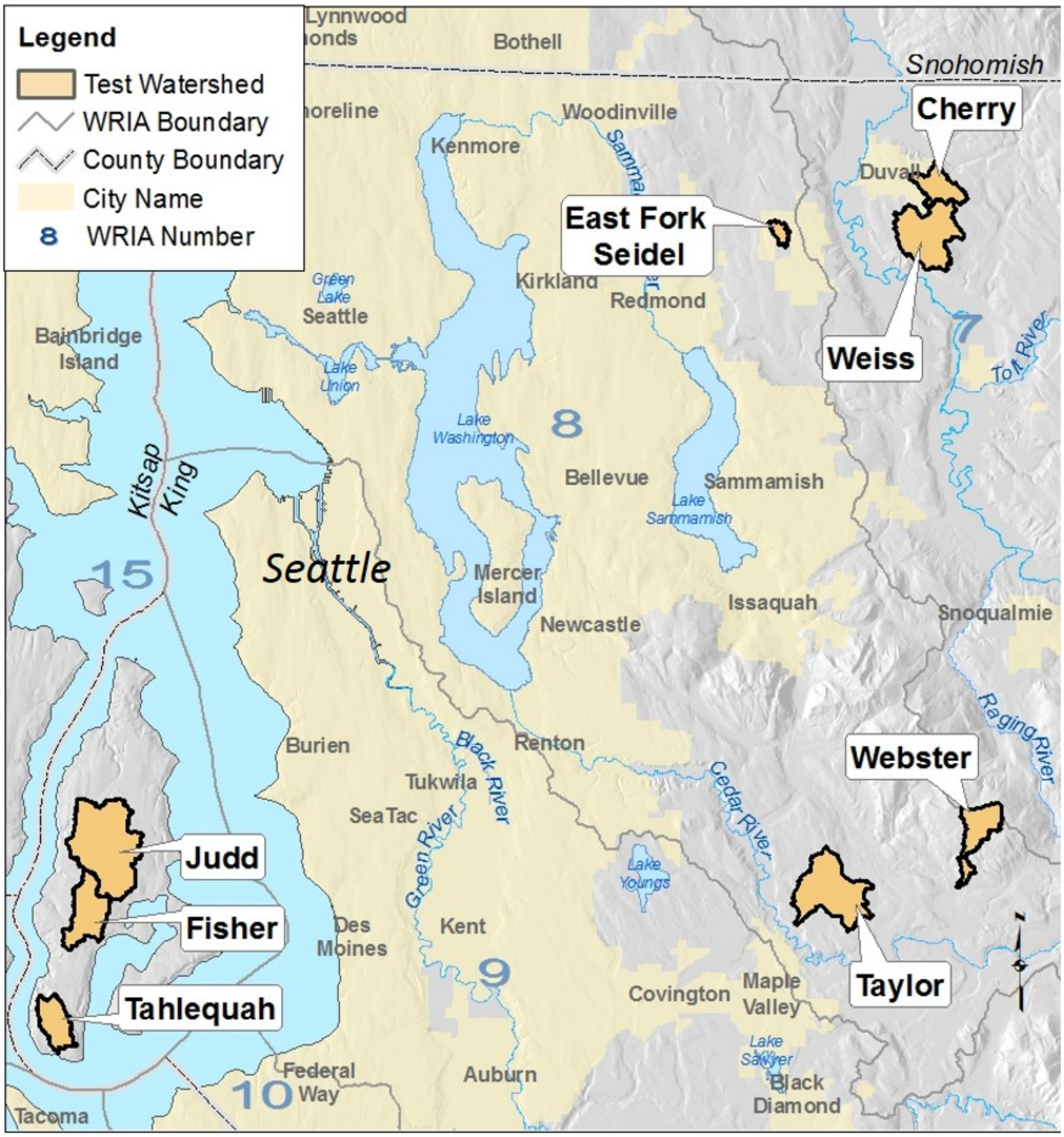


Figure 1. Eight data-rich test watersheds used by King County in developing the initial Hydrologic Condition Index method (Lucchetti et al. 2014), and used by the Department of Ecology in testing the HCI variables. Land-cover patterns in these watersheds are similar to many other developing rural and suburban watersheds in Puget Sound.

How the HCI Tool can be used

The utility of the HCI as a mid-scale tool is its ability to estimate the relative hydrologic condition of the current or potential land cover configuration for any given watershed area without having to conduct potentially expensive and time consuming stream gaging and/or complex hydrologic modelling. The HCI uses an inverse distance-weighted calculation of hydrologic response (in this case High Pulse Counts or HPCs) under best (all forest) to worst (all pavement) possible land covers.

The purpose of the HCI is to assist planners and resource managers in:

1. The rapid comparison of the impacts of different future development land cover scenarios on watershed hydrology;
2. Developing land use patterns (long range planning), land-use regulations, and development standards that sustain a healthy watershed hydrology; and
3. Identifying the most effective types and locations of watershed hydrology restoration and protection actions.

Using examples, this document demonstrates how the HCI can be applied within a decision-support framework, Watershed Characterization Tool #5 (WCT5) that also integrates the results of both the broad- and mid-scale characterization tools (Table 1). The ultimate goal is to have a consistent and comprehensive approach and an updated decision support framework throughout Puget Sound, with the results available on the PSWC website (https://ecology.wa.gov/Water-Shorelines/Puget-Sound/Watershed-characterization-project).

Table 1. Decision Support Framework illustrating both the recommended scale and application of the Puget Sound Watershed Characterization tools.

Application	WRIA-wide	Sub-basin	Reach to sub-basin
Spatial Scale	Broad-scale: 10 to 100s of sq. miles.	Mid-scale: AUs of approximately 0.5 sq. mile to 10 sq. miles.	Fine-scale: Acres
Toolbox	Puget Sound Watershed Characterization Broad Scale Tools (WCT): WCT1 – Water Flow Processes WCT2 – Water Quality WCT3 – Fish & Wildlife	HCI tool and Comprehensive Integration of PSWC results with HCI scores, including high pulse counts (HPC). WCT4 – HCI Tool (New) WCT5- Decision Support Framework (New)	Finer scale hydrologic models (e.g. HSPF) and local data
Application of Tools	Use PSWC broad-scale results (importance and degradation) to support landscape-level prioritization for development, protection, & restoration actions.	Use sub-basin tools such as the HCI to determine overall existing and future condition of a watershed and to assist in build out analysis to select the best development patterns (alternative futures).	Sub-basin-based alternative future scenarios. Use finer scale hydrologic models to develop the specific location and design of proposed development.

Testing and Development of the Mid-Scale Assessment Tools

To develop a mid-scale assessment tool that predicts hydrologic condition we tested the HCI and its associated variables under different spatial resolution and flow routing scenarios. The decision regarding preferred combination of these parameters was based on the degree of correlation of HCI scores with gage data in the test watersheds.

A technical team of watershed experts known as the Watershed Advisory Group (WAG), including the consultant team, reviewed and commented on the results of the tests and provided final peer review of this document. The WAG consisted of the following participants:

- Charlene Andrade, Washington Department of Commerce
- Derek Booth, Stillwater Sciences and University of Washington
- Aaron Booy, Environmental Science Associates
- Dan Gariepy, Washington Department of Ecology
- Paul Cereghino, National Oceanic and Atmospheric Administration
- James Gregory, Environmental Science Associates
- Susan Grigsby, Washington Department of Ecology
- Colin Hume, Washington Department of Ecology
- Gino Lucchetti, Consultant/King County (retired)
- Brad McMillan, Washington Department of Ecology
- Brad Murphy, Thurston County Planning
- Stephen Stanley, Washington Department of Ecology
- Ashley Steele, U.S. Forest Service
- Abbey Stockwell, Washington Department of Ecology
- George Wilhere, Washington Department of Fish and Wildlife
- Amy Yahnke, Washington Department of Ecology

Best Available Science

The design and output of the HCI tool was judged by technical reviewers, to be based on best available science and useful as a tool in representing an “indexed” condition of watershed processes. The HCI is a mechanistic assessment tool that assesses surface water flow routing (distance to stream) and modeled response to land cover and surficial geology conditions; it does not estimate rates, quantities, or patterns of hydrologic flow as do other more complex hydrologic models. Instead, it provides a relatively easy, quick, consistent way to assess condition of hydrologic processes based on patterns of land cover and surficial geology within a watershed.

The HCI tool was selected because it:

1) Provides a quantitative assessment of the effect of land-cover change on stream hydrological processes;
2) Can be calibrated for lowland watersheds of Puget Sound (already calibrated for WRIAs 7, 8, 9 and 15); and
3) Can be incorporated into the PSWC framework and applied throughout Puget Sound watersheds.

Previous Studies and Relevant Literature

In 2008, the EPA and King County partnered in a multiyear, comprehensive scientific study to better understand the County's stringent, new (2005) and controversial land use regulations and assess whether they would likely be effective at preventing environmental degradation from ongoing and future development (Lucchetti et al. 2014). Prior to implementation, a separate Quality Assurance Project Plan (QAPP) (Lucchetti and Latterell 2008) describing context, goals, logic, study design, and expected outcomes was produced for that project; it can be accessed here: [http://your.kingcounty.gov/dnrp/library/water-and-land/data-and-trends/monitoring/critical-areas/081119-epa-cao-qapp.pdf.](http://your.kingcounty.gov/dnrp/library/water-and-land/data-and-trends/monitoring/critical-areas/081119-epa-cao-qapp.pdf)

In part using the HCI, the Critical Areas Ordinance study concluded that the County's environmental regulations would likely be effective in minimizing hydrologic change and protecting the water flow processes for unincorporated rural areas where the large majority of the County's remaining high functioning aquatic habitat exists.

While many hydrologic metrics could have been used, Lucchetti et al (2014) based their Hydrologic Condition Index (HCI), on high pulse counts (HPC)[4] in part because HPCs seemed the most intuitive and easy metric to explain to policy makers and citizens, but also because DeGasperi et al. (2009) found that HPC met all four criteria for identifying a "useful hydrologic indicator":

1) Sensitivity to urbanization consistent with expected hydrologic response;
2) Statistically significant trends[5] in urbanizing watersheds and not in undeveloped watersheds;
3) Correlation with biological response to urbanization as measured by the Benthic Index of Biotic Integrity (B-IBI); and
4) Relative insensitivity to confounding factors such as watershed area.

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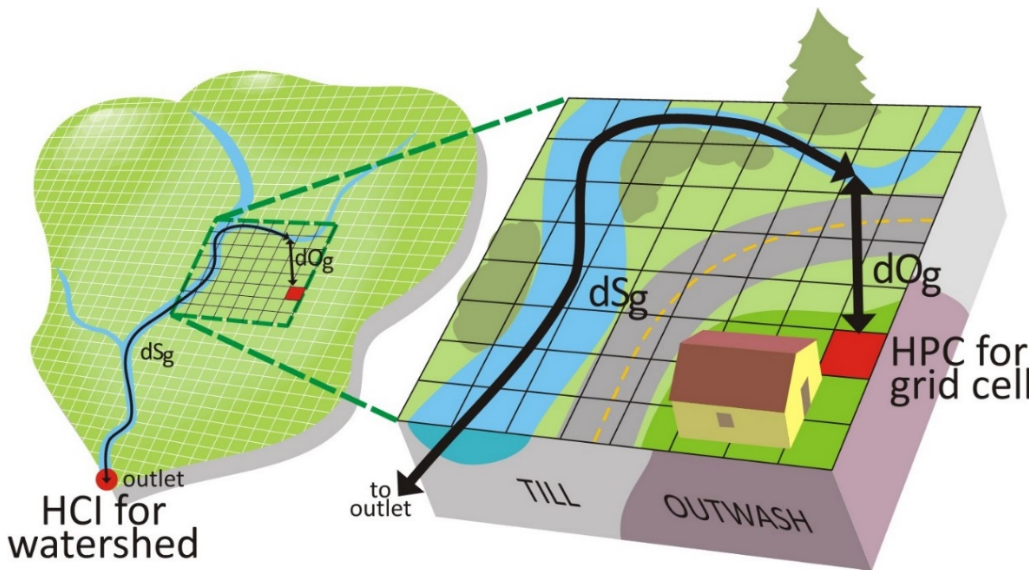
[4] A **high pulse** is defined as 2X the mean annual flow for that water year. The number of high pulses over any given 1-year period (the high pulse count, or HPC) for a specific watershed is typically lower for watersheds with greater forested cover relative to watersheds primarily covered by urban development. HPC values tend to show a strong negative correlation with biological indicators such as a B-IBI.

[5] A regression analysis was done to test the level of linear dependence or correlation between HPC (gage generated) and HCI values. If the result of the analysis (shown as "r") is closer to 1 than 0 than the correlation is higher. For this test, $r=0.88$ indicating a high correlation. A statistical significance test was also done (shown as "p") which should be less than 0.05; $p=0.01$ for the correlation results, indicating that it is statistically significant.

Description of the HCI Tool

Initial Application in King County

In their 2008 study, Lucchetti et al (2014) developed the first version of the HCI[6], to measure the effect of land-cover change resulting from development on flows in lowland streams and rivers (Figure 2). The sections below describe how the HCI is calculated using high pulse count coefficients (as defined in Figure 2 and on the next page) for different types of land cover and the use of distance from a stream to any grid cell in a watershed.



Calculation of Hydrologic Condition Index for a Watershed	This index uses **three components** to characterize each grid cell in a watershed: land cover type, geology, and distance to a stream.
Step 1. Calculate the High Pulse Count value for each grid cell (HPCg). Multiplying the average coefficient for the dominant land cover-geology combination of the grid cell, BY the inverse distance from that grid cell to the stream **(dOg)** and down to the watershed outlet **(dSg).**	$HPCg = HPC_{coeff}\left[\frac{1}{dOg + dSg}\right]$
Step 2. Calculate the Hydrologic Condition Value (HCVs) for the watershed. Sum all the HPC grid cell values within the watershed.	$HCVs = \sum^{n}_{g=1} HPCg$
Step 3. Calculate the Hydrologic Condition Index (HCI) for the watershed. Divide the hydrologic condition value BY the worst case HCV when the watershed is 100% paved.	$HCI = \left[\frac{HCVs}{HCVs\ worst}\right]$

Figure 2. Algorithm and method for applying and testing the Hydrologic Condition Index. Graphic (adapted from Lucchetti et al. 2014) illustrates a schematic of land cover and surficial geology types overlaid by grid cells, each with unique distance variables to the nearest stream and down to the watershed outlet.

[6] Ecology used the King County version of the HCI, as shown in Figure 2, for initial testing until preferred use of the distance variable was determined (dOg only).

How it Works

The HCI method identifies the "high pulse" value for any combination of twelve land covers (see Appendix B) and two surficial geologies and uses the inverse distance to assess the potential effect of water flow from a grid cell to the bottom, or "outlet" of a given watershed extent. These high pulse values, used as HPC coefficients (Appendix B) in the HCI calculation, are summed for all grid cells in the watershed, and then normalized to produce a watershed HCI score. The calculation uses flow path distance between each grid cell and the stream, known as overland distance (dO_g) and the distance down the stream to the outlet for the watershed (dS_g). The flow path for the overland portion of the watershed can involve either a natural (typically meandering) path or a direct path (i.e., Euclidean or "as the bird flies"). This information is then used in the distance variable of the HCI equation.

Summing all distance-weighted HPC_g grid cell values provides a total hydrologic condition value (HCV) for the watershed. A normalized HCI score is achieved by dividing the existing condition HCV (representing conditions in a particular year or simulated development scenario) by the worst case HCV for the same watershed (every grid cell is "fully paved").

Developing Coefficients for High Pulse Counts

Based on land cover type and surficial geology, the HCI relies on outputs (High Pulse Counts) from a calibrated hydrologic model (e.g. HSPF) to apply a set of high pulse count coefficients (HPC_{coeff}) for each grid cell in a watershed (see Figure 2). To determine HPC_{coeff} values for use in the HCI algorithm, King County used the previously calibrated hydrologic models developed in five lowland King County watersheds. Those watersheds are different than the eight being used in this document for HCI development and testing, but were selected by King County because calibrated HSPF models were already established for them (Bicknell et al. 2005). King County used these "virtual" watersheds to generate HPC values for 12 established land-cover types (ranging from forested to urban cover) on both till and outwash (for a total of 24 total HPC values) using 61 years of past precipitation data. The HPC values represent an average high pulse count across all 61 years of HSPF model runs for each combination of land-cover type and geology. This study used these five watershed derived HPC values, then averaged them to develop coefficients (HPC_{coeff}) for each land cover-geology combination (Appendix B).

Optimal Combination of Land Cover Resolution, Routing and Distance Variable

Review and testing of the HCI method (details provided in Appendix A), suggest that the most accurate results, relative to gage records, resulted from the use of higher resolution land cover data (1.8 meter vs. 30 meter), a natural flow path distance grid, and the "overland" distance variable (grid cell to stream, dO_g) only. Based on these results, it is recommended, when possible, that local governments and resource managers use this combination of land cover data, routing, and distance variable when using the HCI method. However, other combinations of variables, though likely less "accurate" in ability to predict High Pulse Counts downstream, have relevance as demonstrated by reasonable regression results. Table 2 presents the regression results for the ten combinations of land cover resolution, routing, and distance which were compared.

Table 2. Regression results for grid size and routing alternative tests, showing correlation of HCI values to stream-gage HPCs for all test watersheds.

Routing	Grid Size	Regression Analysis Result (R^2 Value)
Natural dO_g *	1.8 meter	0.806
Euclidean dO_g	1.8 meter	0.738
Natural $dO_g + dS_g$ **	30 meter	0.650
Euclidean $dO_g + dS_g$	1.8 meter	0.643
No Distance	1.8 meter	0.641
Natural dO_g	30 meter	0.614
Natural $dO_g + dS_g$	1.8 meter	0.582
Euclidian $dO_g + dS_g$	30 meter	0.540
Euclidean dO_g	30 meter	0.520
No Distance	30 meter	0.426

* Distance to stream; ** Distance to stream & outlet

Use of Distance in the Hydrologic Condition Index Tool

When King County initially developed the HCI, a key consideration for evaluating the effectiveness of County critical areas and land use standards was to weight the effect of distance. This was based on research by Van Sickle and Johnson (2008) showing that both exponential decay and inverse distance models worked better in capturing actual conditions within the stream and watershed tested. To factor in distance, grid cell distances were inverted (i.e., 1/distance), to give the shortest distances for a stream, the highest weightings.

Figure 3 and Table 3 illustrate the effect of distance on the HCI scores. For example, when development polygons (land cover changed to High Intensity Urban) are located the farthest from the stream network (polygons 1 & 2 in Figure 3), this results in a lower HCI score indicating the least impact on the stream hydrologic condition relative to those located closer (polygons 3 & 4 in Figure 3), which produce a higher HCI score (i.e. likely greater hydrologic impact).

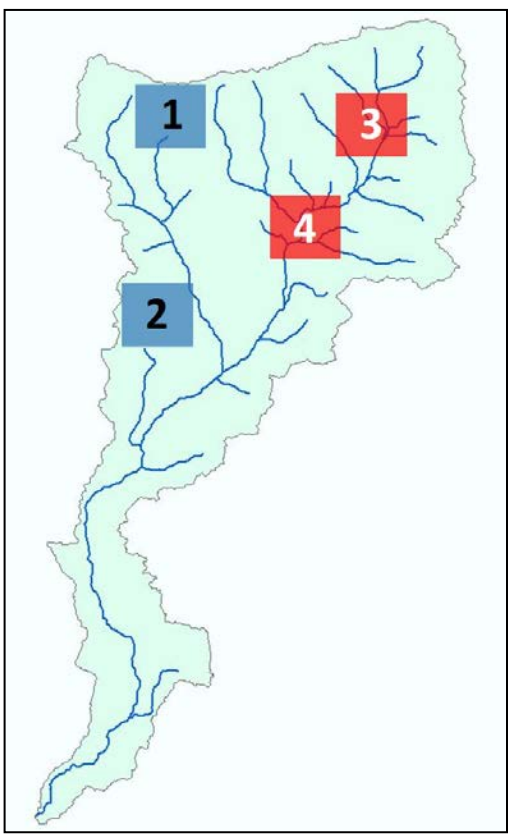


Figure 3. HCI distance factor sensitivity testing within the Webster Creek watershed.

Table 3. HCI distance factor results in the Webster Creek watershed. Development polygons referenced above in Figure 3.

Development Polygon Location	HCI Score
Development polygons farther from stream network (polygons 1 & 2)	0.130
Development polygons closer to stream network (polygons 3 & 4)	0.207

Hydrologic Condition Categories

One of the key purposes of the decision-support framework, presented later in this guidance, is to provide planners and citizens with information that can help sustain the ecological condition of a watershed's aquatic ecosystem by locating and designing development in a manner that minimizes hydrologic impacts. The HCI score can be used in conjunction with indicators such as the Benthic Index of Biotic Integrity (B-IBI) to identify specific categories of hydrologic conditions that indicate the level of degradation to water flow processes. The categories of hydrologic condition presented here are simply termed "good," "moderate," and "poor."

These hydrologic scores and hydrologic condition categories are based on generalized relationships and should be considered preliminary. Additional testing of the HCI in other watersheds will be necessary to better understand the relationship between the HCI, high pulse counts, and B-IBI relative to the actual (e.g. field based monitoring data) hydrologic condition of a watershed. The intent of this guidance is to demonstrate, using examples from one of the best-studied test watersheds, how these hydrologic condition categories can be established by users.

All examples presented below are based on HCI runs conducted at 30-meter resolution using the dO_g (grid cell to stream) and Euclidean flow path, as this will likely be the method most widely available to users given data limitations. However, because better predictive accuracy of the HCI scores is obtained when using 1.8-m resolution using the dO_g and Natural flow path, this should be applied at the sub-basin scale if land-cover data at this resolution is available[7]. Table 4 summarizes how the hydrologic condition categories were developed.

Setting Ranges for Hydrologic Condition Categories

To establish what might be different categories of hydrologic conditions for a watershed, we can use our existing data on measured high pulse counts in conjunction with B-IBI scores and associated high pulse counts for the King County area (Figure 4; data from King County B-IBI Monitoring Program for Puget Sound Lowland, DeGasperi & Gregersen 2015). Where high pulse counts exceed approximately 13 to 14, most B-IBI scores also express a significant drop below this apparent threshold. In other words, the biological data indicate that streams with

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[7] Note, that if this combination of data is used, somewhat different HCI scores and hydrologic condition categories will be obtained relative to the examples provided in this section.

degraded hydrologic conditions (i.e., high pulse counts exceeding 13 to 14) also have impaired ecological conditions. Conversely, the B-IBI data suggest that streams with HPC of less than 13 to 14 have much improved hydrological conditions, which supports, though does not guarantee, a "healthy" biological community.

This HPC "break" described above can be applied in Figure 4 to identify an approximate condition threshold for protection of stream health. There are exceptions to this HPC threshold between "good" and "poor" B-IBI scores, such as Ravine Creek on Bainbridge Island, which has a low HPC value but also a poor B-IBI score, but they are limited and do not negate the overall pattern.

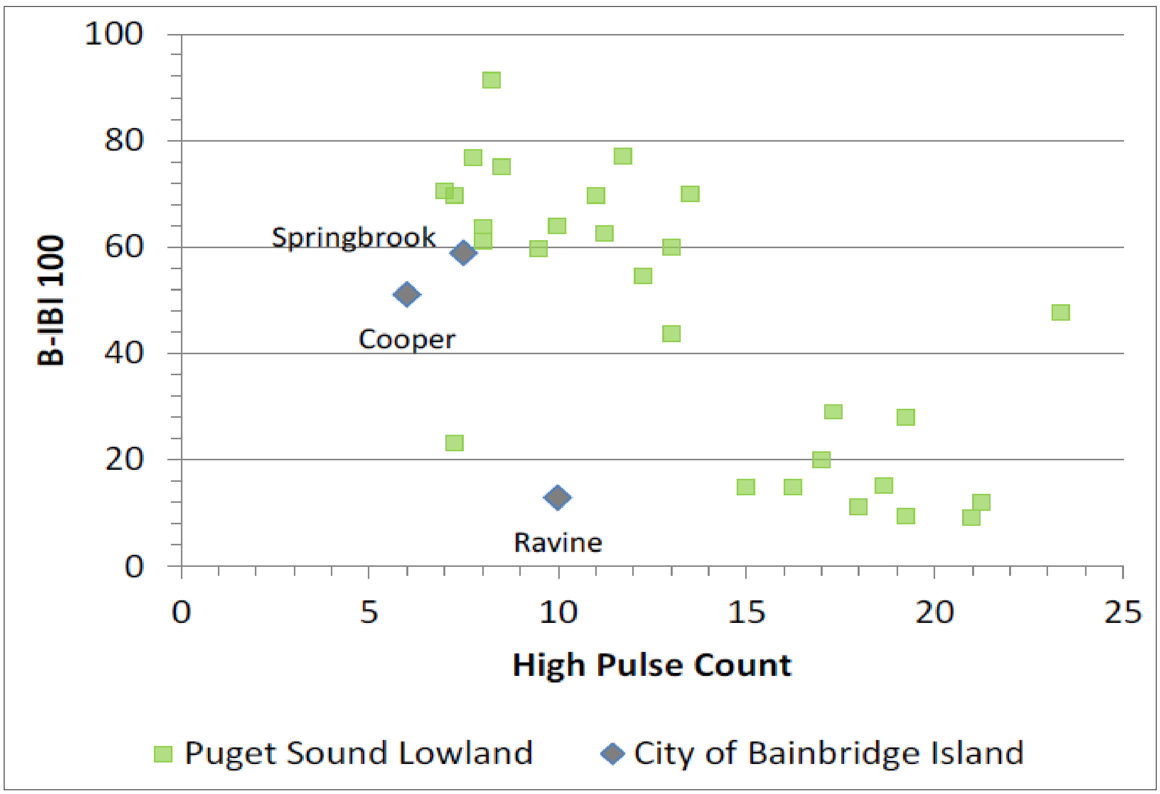

Figure 4. Plot of measured high pulse counts and Benthic Index of Biotic Integrity (B-IBI) survey points. A high pulse count of approximately 14 to 15 provides an approximate, useful discrimination between good (60-80), fair (40-60), and poor (<40) B-IBI scores. B-IBI data from DeGasperi & Gregersen (2015).

The test watersheds provide a provisional basis to predict HPC, and thus biological conditions as expressed by B-IBI, from HCI results where no gage data presently exists (Figure 5). These results suggest a good, albeit imperfect, linear relationship between HCI and HPC in those watersheds, permitting an inference of hydrologic condition on the basis of HCI alone. In predicting these categories well, however, it is important to have a wide range of developed conditions and associated gage data (high pulse counts), which is not presently available from the test watersheds used in this study. For example, to provide a stronger basis for establishing any boundary between the moderate and poor hydrologic conditions, there should be test watersheds that have gage data with HPCs exceeding 14. This would help to establish what the corresponding HCI scores are for these higher pulse counts and what the degree of correlation may be.

With the key assumption that this pattern expressed across multiple watersheds would be replicated at the same location over multiple time periods, an example of its application is provided. The Taylor Creek watershed has a high pulse count of around 12, which corresponds to an HCI of 0.21 and a good hydrologic condition. This HCI score would then be our approximate guide for evaluating whether hydrologic conditions supporting stream health would likely be sustained into the future under alternative future development scenarios.

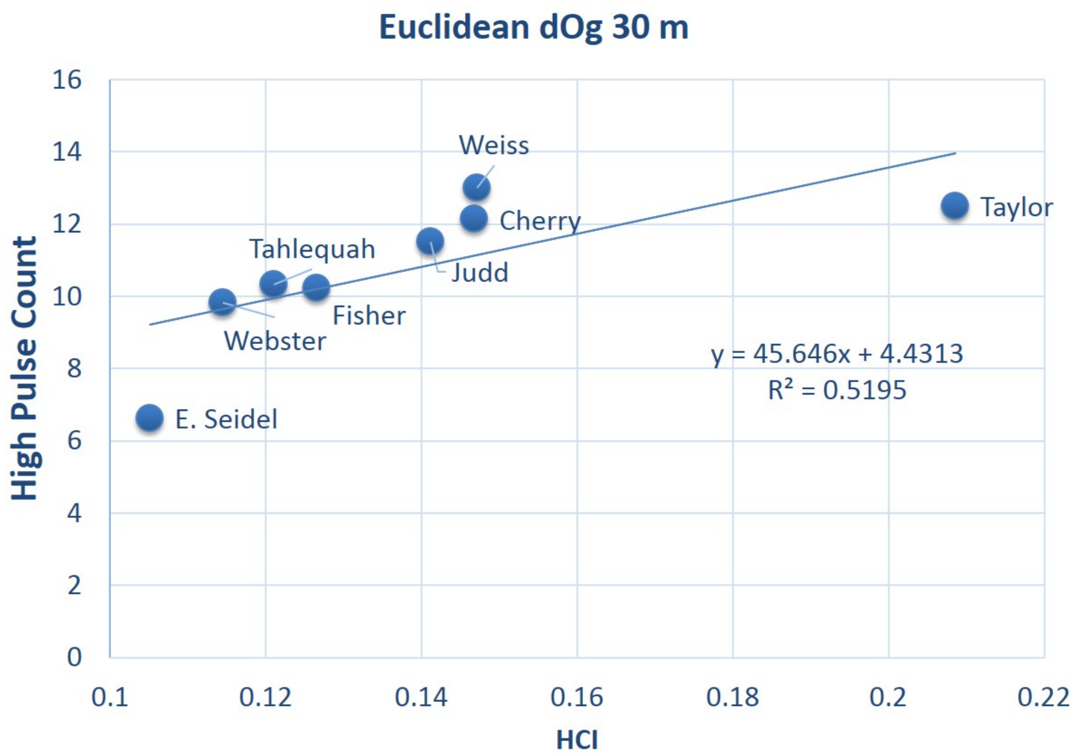

Figure 5. HCI scores from Ecology test runs in eight test watersheds, as determined during initial project HCI testing efforts. The desired High Pulse Count of 14 for maintaining good B-IBI scores corresponds to an HCI score of 0.21 (see Figure 4). Using finer scale data (1.8-m) and Natural flow distance calculation the corresponding HCI would be 0.18. Over time, watersheds with HPCs greater than 14-15 should be added to the data set and the level of correlation with their HCI scores determined.

Based on existing research, percent impervious surface and forest cover can also be used in conjunction with HPC and B-IBI data to determine if the proposed hydrologic condition categories are appropriate. Hydrologic modeling of the effects of impervious surface and forest cover in a watershed suggests that hydrologic damage occurs in streams within watersheds primarily underlain with till soils having impervious cover greater than 10% and forest cover of 65% or less (Booth et al. 2002). In watersheds underlain by permeable deposits, this hydrologic damage can occur at 10% or greater impervious surface with virtually any level of forested retention cover, and therefore these are much more sensitive to conversion of forest cover to urban or rural uses (Booth et al. 2002, 2004).

For the eight test watersheds, the impervious cover was an average of 3.4%, with the Taylor Creek watershed having the highest level of impervious cover at 7.2% and forest cover at 54% (Table 16 in Lucchetti et al. 2014). Forest cover averaged 68% for all of the test watersheds, modestly greater than the minimum 65% forest cover suggested by Booth et al. (2002) for adequately protective conditions[8]. These data, relative to the research by Booth et al., indicate an expectation that all of the test watersheds fall into a hydrologic condition that could be considered "good," albeit with some approaching the upper range of that designation. Together with the B-IBI correlation with HPC, these data also suggest that the HCI score of 0.21 is a credible boundary for predicting the upper limit of the "good" hydrologic condition category in lowland watersheds of the east-central Puget Sound.

Defining additional hydrologic condition levels (e.g., moderate and poor) for watersheds with an increasing degree of impervious cover and de-forestation is less certain because biological data, such as B-IBI, do not provide a discernable correlation with specific high pulse count levels. This could be done on the basis of impervious-area and forest-cover percentages alone, however, using available land cover data such as CCAP and established geospatial templates for the mix of development for low-, medium-, and high-intensity development[9], provides another approach. By running these CCAP land-cover scenarios, additional discrimination within the broad category of impaired hydrologic conditions can be made for a specific watershed under alternative future scenarios (Figure 6, and Table 12 in Appendix A).

The HCI scores from the scenarios illustrated in Figure 6 provide a preliminary "indexing" of what type of hydrologic score is expected with specific watershed-wide development intensities. For example, for a watershed-wide scenario using a minimum vegetated 50-foot buffer[10] on all streams, the HCI scores in Taylor increased to 0.44 for low-intensity development, to 0.67 for medium-intensity, and 0.87 for high-intensity development over the totality of the watershed (Figure 6, and Table 12 in Appendix A). Thus, even for the low-intensity development scenario at full buildout for the watershed, the HCI score doubles from the "good condition" score of 0.21, suggesting that biological condition of the stream system would also likely be measurably degraded. With this information, local land-use planners could strive to keep the HCI for future individual developments close to overall watershed HCI of 0.21 through decisions around land use type and intensity into the future.

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[8] Provided that the 10% impervious cover is not exceeded.

[9] CCAP land cover for impervious corresponds to approximately 20 to 50% impervious cover for the low intensity development, 51 to 79% for medium intensity, and 80 to 100% for high intensity.

[10] Note that actual regulatory buffers are a minimum of 165 feet along all streams in King County with fish-bearing potential. Plus, there are other measure to minimize effects of development.

Table 4. Guidance for establishing good, moderate, and poor hydrologic condition categories based on hydrologic, biological, and land cover data for east-central Puget Sound region. The same steps can be used for other regions in Puget Sound.

Steps and Data Source	**Good Condition**	**Moderate Condition**	**Poor Condition**
Step 1. Run the HCI for existing conditions in watershed	If watershed HCI is approximately 0.21 or less and generally meets the land cover characteristics (impervious & forest) in this column, then watershed is anticipated to have good hydrologic conditions.	If the HCI score is greater than 0.21 and meets the land cover characteristics in this column, then watershed is anticipated to have moderate hydrologic conditions.	If the HCI score is considerably greater than 0.21 and meets the land cover characteristics in this column, then watershed is anticipated to have poor hydrologic conditions.
Expected high pulse counts	< 14 (Taylor Creek = 12)	>14	>>14
Expected B-IBI (0-100)[11]	> 60	40 to 60	<40
Expected forest cover	> 65% (Taylor Creek = 54%)	< 65%	<20%
Expected impervious cover	<10% (Taylor Creek = 7 to 8%)	>10%	>20%
Step 2. Run the HCI for different intensity development scenarios	Use the existing conditions results if watershed meets the land cover conditions in this column.	Run low intensity development from CCAP (20 to 50% impervious) for entire watershed. If the HCI score is higher than existing conditions, consider this as the upper boundary for moderate condition within your WRIA or region.	Run moderate intensity scenario from CCAP (51 to 79% impervious); if the HCI score is less than existing conditions, then watershed is probably at the upper end of degraded hydrological conditions.
Example of HCI score for rural watershed, WRIA 8, Taylor Creek	< 0.21 - Suggested score for category based on an HCI score of 0.21 for 30-m, dOg, Euclidean.	> 0.21	>> than 0.21

[11] From the Puget Sound Stream Benthos Project: https://www.pugetsoundstreambenthos.org.

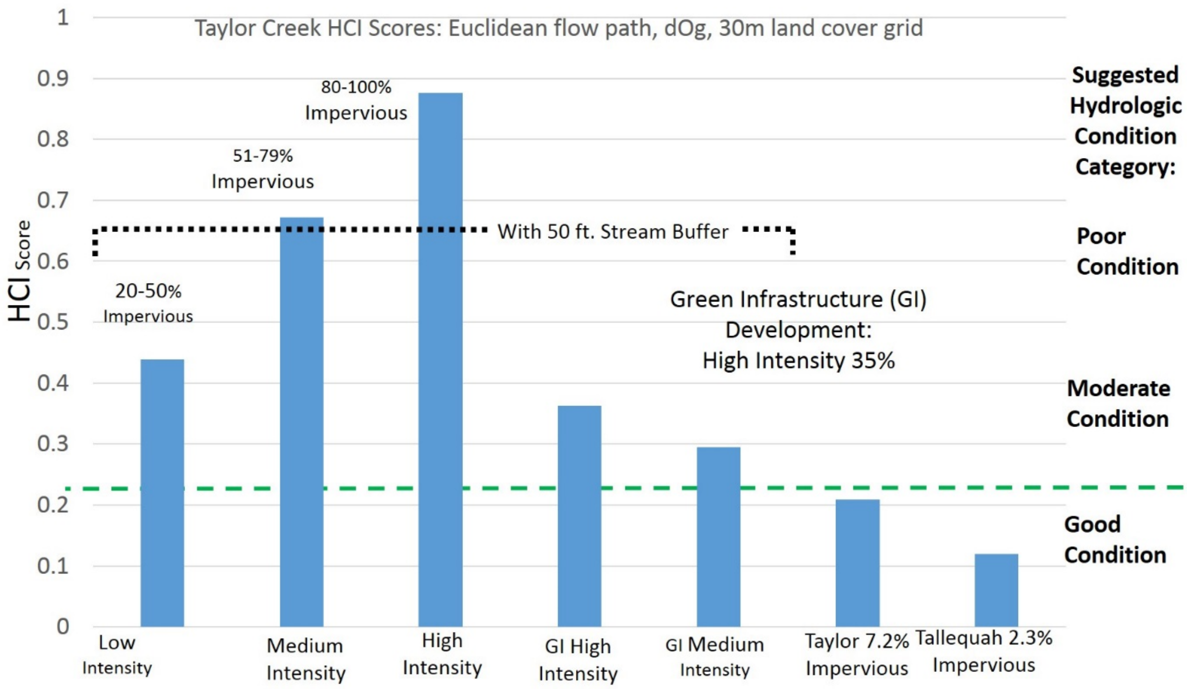


Figure 6. An example of setting up hydrologic condition categories of good, moderate, and poor in the Taylor Creek watershed, based on different watershed-wide development scenarios, B-IBI, High Pulse Count, and HCI data (see Table 12, Appendix A). The “good” condition category is based on biological data (B-IBI) showing that watersheds with lower HPC counts (i.e. an HCI score of 0.21) have greater biological integrity. The discrimination between “moderate” and “poor” conditions is less well-defined and is based on limited HCI runs in urban watersheds with increasing levels of impervious cover.

Decision-Support Framework: Integrating Mid-Scale & Broad-Scale Assessments

The addition of what we term “mid-scale tools” (i.e. the HCI) provides the PSWC with the ability to assess hydrologic conditions at a more granular level within a decision support framework. Application of this decision-support framework with the HCI tool and recommended hydrologic condition categories should help local governments minimize impacts to watershed hydrology by selecting and promoting long-range development patterns that protect and sustain not only watershed processes but also the terrestrial and aquatic ecosystems that those processes support.

This section presents a step-wise guide to assist users in applying the range of tools from the PSWC at the appropriate scale and in an integrated manner within the decision-support framework.

> Throughout this chapter, the term **Alternative Futures** is used to describe conceptualized scenarios of future land use that could be used to compare the effect of different patterns of land use upon the hydrologic health of a watershed. The scenarios may refer to build-out under existing zoning, or a change in zoning that would change the intensity of future development.
>
> Alternative Futures scenarios could address the effect of increasing riparian buffers and other protections for environmentally critical areas, as well as restoration actions.
>
> The effects of low impact development techniques could also be considered in development scenarios, including but not limited to forest canopy retention, clustering of development areas, and surface water management measures.

Decision-support Framework of Assessments

The PSWC assessment tools are best applied in a sequential, hierarchical framework. The WRIA-wide characterization identifies the best basin areas in which to focus additional development (versus protection, restoration, and/or conservation). In those basins where this overall management emphasis has been identified, HCI assessment tools can then be used to understand existing conditions and implications of additional development (or other actions) under Alternative Futures scenarios. Table 5 and Figure 7 present this recommended decision-support framework and the steps for its application.

Table 5. Decision-support framework outlining overall process for integrating the existing and new Watershed Characterization Tools (WCT). The framework helps match the type of information available with the appropriate analysis at different spatial scales. The steps for achieving this integration are illustrated in Figure 7.

Type of Information & Analysis	Watershed-wide	Sub-basin	Catchment to Reach
Spatial Scale	Broad-scale: 10 to 100s of sq. miles (1000s of acres).	Mid-scale: 0.5 sq. mile to 10 sq. miles (100's of acres).	Fine-scale: 10's of acres
Toolbox	Watershed Characterization Tools (WCT): WCT1 – Water Flow Processes WCT2 – Water Quality WCT3 – Fish & Wildlife	HCI tool and Comprehensive Integration of PSWC results with HCI scores, including high pulse counts (HPC). WCT4 – HCI Tool (New) WCT5- Decision Support Framework (New)	Finer scale hydrologic models (e.g. HSPF) and local data.
Application of Tools	Use PSWC broad-scale results (importance and degradation) to support landscape-level prioritization of watersheds and sub-basins for development, protection, & restoration actions. Example in Figure 8 for Taylor Creek.	Use sub-basin tools such as the HCI to determine overall existing and future condition of watershed. Assists buildout analysis by local governments (e.g., Buildable Lands Analysis). Use PSWC solution templates (Appendix G) and high pulse count coefficient maps to identify possible alternative development patterns. Use the HCI to further test, refine, & select best development patterns through alternative futures scenarios.	Catchment-based alternative future scenarios. Use finer scale hydrologic models to develop specific location and design of proposed development.
Availability	Can be pre-run by Ecology at WRIA scale, or custom-run at smaller extents.	Custom-run by Ecology	Project-specific. Custom run by Ecology or other collaborators.
Data Type, Scale, Flow Path	30-m CCAP	Generally 30-m CCAP Euclidean routing	May use local data, 1.8-m or finer resolution land-cover data recommended. Natural routing

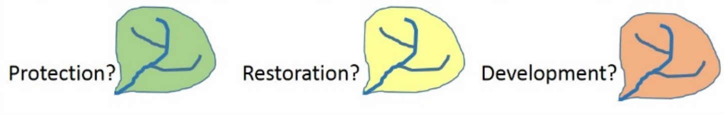
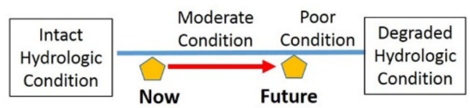
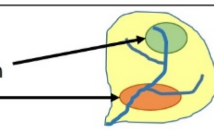
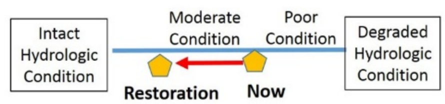
Steps	Use Tool	Examples
① What is the predominate Watershed Management Category for your watershed?	Broad scale results and local information.	
② Determine risk from future buildout. Good, moderate, or poor hydrologic condition?	HCI score for existing and full buildout.	
③ Integrate results from step 1 and 2.	Solution templates.	• For "Protection" areas and HCI < 0.21, use protection actions • For "Restoration" areas and HCI > 0.21 & < 0.44, use restoration actions. • For "Development" areas and HCI > 0.44, use LID.
④ Which areas will help maintain a healthy hydrologic condition?	HCI scores, land cover, geology, and proposed actions.	Identify areas that could improve Hydrologic condition through restoration actions or green development actions. 
⑤ Design future development alternatives and rerun HCI.	HCI score for proposed development.	

Figure 7. Decision-support framework: Steps for integrating the broad-scale assessment results of the PSWC and the mid-scale HCI tool. Use in conjunction with Table 5. Figure describes the five steps for integrating broad and mid-scale tools (WCT1&4).

Description of Integration Steps

The decision-support framework includes five general steps for applying the PSWC tools (Figure 7). Using the Taylor Creek watershed as an example, the five steps are described below:

Step 1 – What is the Predominant Watershed Management Category for your Watershed?

Volume 1 of the PSWC introduces a broad-scale assessment method that compares the relative importance and level of degradation for sub-basins (also termed Assessment Units) within a watershed. The watershed management matrix (simplified version in Figure 10) combines the categorical results of the broad-scale models for importance and degradation in a particular Assessment Unit (AU)[12] to identify the most suitable management strategy within that area of comparison.

As Table 5 indicates, it is important to run the broad-scale tools (WCT 1-3) at a scale that can answer the specific land use question being considered by a planning or resource management

[12] Assessment Unit (AU): Each analysis area is divided into many smaller "Assessment Units" for comparison of model results. All source data and model results are homogenized within each AU; their size determines the minimum spatial scale over which the Characterization results are meaningful. Using available source data, AUs are ranked from most important to least important, and most impaired to least impaired, for each process. The size and number of these units depend on the size of the analysis area, the landform types, available source data, and the planning issues a jurisdiction may be addressing.

enity. When analysis of buildout or Alternative Futures scenarios is required, then the characterization should be run at the sub-basin scale. Step 1 considers the Overall Water Flow assessment results for the Taylor Creek watershed at the sub-basin scale. The characterization results presented in Figure 8 suggest that the upper watershed of Taylor Creek should be protected (solid color green areas), whereas areas in the southwest portion of the watershed are more appropriate for development and restoration actions due to higher levels of degradation.

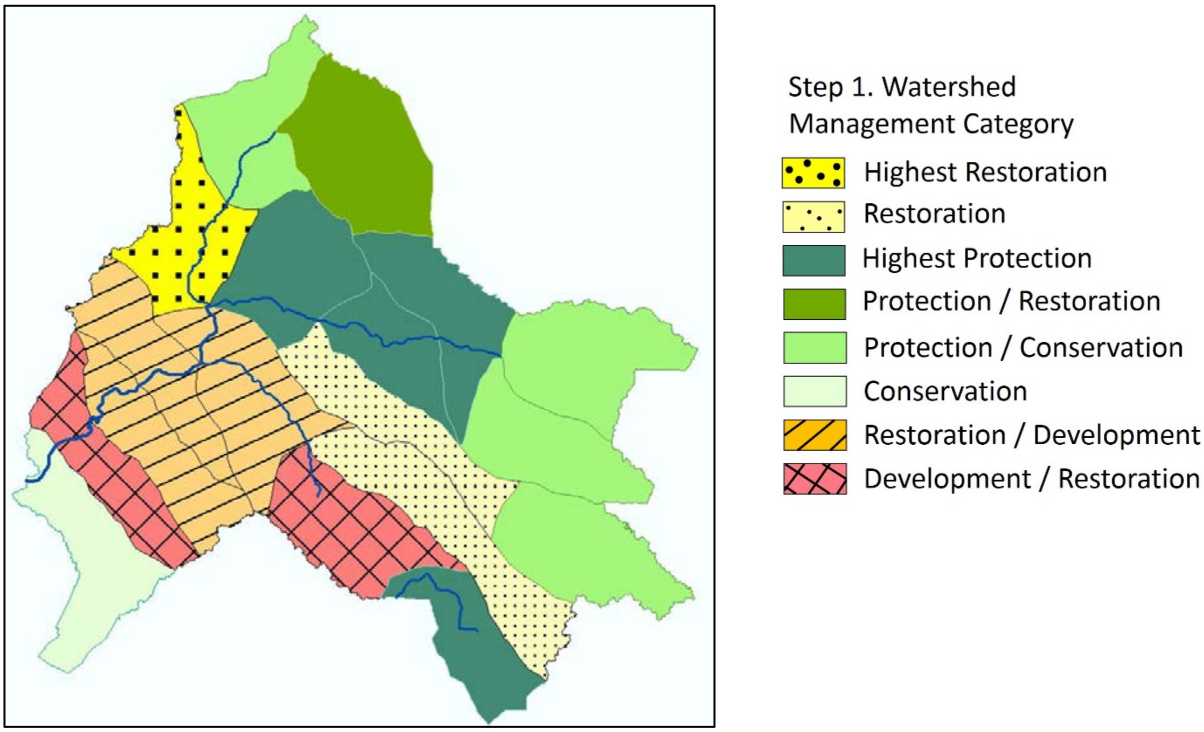


Figure 8. Watershed Characterization results using WCT1 for Assessment Units in Taylor Creek. Management categories based on Watershed Management Matrix in Fig 10. Solid color areas are in the "Protection" category indicating high relative importance to water flow processes and a relatively low level of degradation. All solid color areas should receive some level of increased protection. Areas more appropriate for development and restoration are located in the southwest portion of the watershed with pattern overlays.

Although the broad-scale characterization results for all of Puget Sound watersheds are already available on the Ecology website, characterization at the sub-basin scale (e.g., 0.5 to 10 square miles per AU) can be obtained upon request from a local government or resource management enity.

Step 2 – What is the HCI Score for Existing Conditions and Alternative Futures Scenarios?

The HCI score for existing land-cover condition can provide an initial understanding of the hydrologic condition of the watershed. Comparing this value with the HCI score for buildout under current zoning or other hypothetical land use scenarios can suggest the range over which the HCI score may increase, and potentially what the presumed hydrologic condition will be in the future (example in Figure 9). It may be difficult to detect watershed-wide changes of hydrologic condition with the HCI depending on the size of both the study watershed, and extent or intensity of development which is being proposed. However, the HCI Alternative Futures tool can be run at a sub-basin or catchment within the study watershed as illustrated in Step 5 below to improve the detection ability.

For the Taylor Creek watershed, the existing condition HCI score is 0.21 (see Figure 14), using the 30-meter land-cover data and Euclidean distance calculation. This suggests that the Taylor Creek watershed is likely still in “good” hydrologic condition but at the threshold of transitioning to a “moderate” hydrologic condition. This is consistent with the broad-scale estimate of conditions that could be made on the basis of impervious-area coverage and forest retention.

To illustrate how hydrologic processes could change in the future, a simple hypothetical watershed-wide buildout[13] assessment using conventional development patterns for low-intensity development (i.e. change all grid cells to CCAP Low-Intensity Development, 20-50% impervious cover) can be performed. It is important to recognize that this scenario does not incorporate the location or configuration of regulatory buffers such as those which would exist under Growth Management Act Critical Areas Ordinances. Under this hypothetical scenario the HCI score would predict the watershed moving into a “moderate” hydrologic condition category (Figures 9 and 12, HCI becomes 0.44). This trajectory represents about a doubling of the HCI score for the overall watershed, which indicates that the watershed would be at substantial risk of degrading to a lower hydrologic condition category[14]. This simple buildout analysis and HCI score are conducted at the watershed-scale, with a complementary analysis at sub-basin of the Taylor watershed scale presented in Step 5.

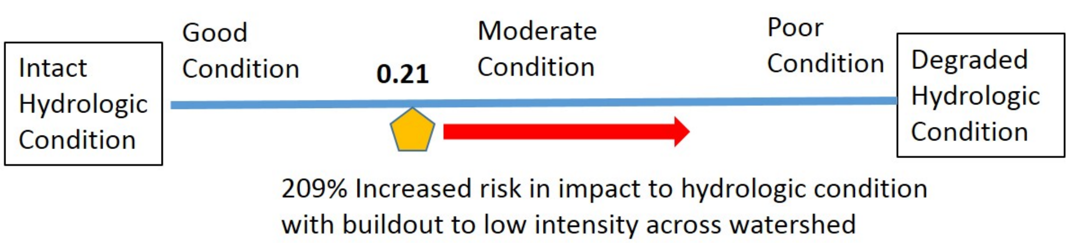


Figure 9. The HCI scores from the analysis of Alternative Futures scenarios (Figure 6) suggest that hydrologic conditions will likely significantly deteriorate (i.e. move from “good” to “moderate” condition) for the Taylor Creek watershed if the entire watershed is developed at the “low-intensity” scenario. The left side of the graph represents fully forested conditions and the right side represents a fully paved watershed. This provides an understanding of the relative levels of risk for different development scenarios at the watershed-scale.

---

[13] This HCI buildout result is based on simple development templates for low, medium, and high intensity development using 30-m CCAP data. HCI based on actual buildout at the sub-basin scale would be conducted as a “custom run” by Ecology staff using local data, preferably 1.8-meter land cover and could be used in a “buildable lands” analysis, a standard set of development templates of low, moderate, and high development categories approximating future development patterns based on zoning.

[14] Risk is not used within the context of the formal risk assessments methodology used by engineers and economists. Risk, as used here, refers to the potential for future development to harm or impact the hydrology of a watershed.

Step 3 – Integrate Results from Steps 1 and 2, Broad-Scale and HCI Results

With a general understanding of where the best locations are for protection, restoration, and development (Step 1, Figure 8) and the current and potential future Hydrologic Condition category for the Taylor Creek watershed (Step 2, Figure 9), the appropriate solution templates[15] can be assigned (Appendix G). Figure 10 outlines the protection, restoration and development categories based on both the Importance and Degradation model results, what the anticipated HCI condition category is for each and the appropriate solution templates.

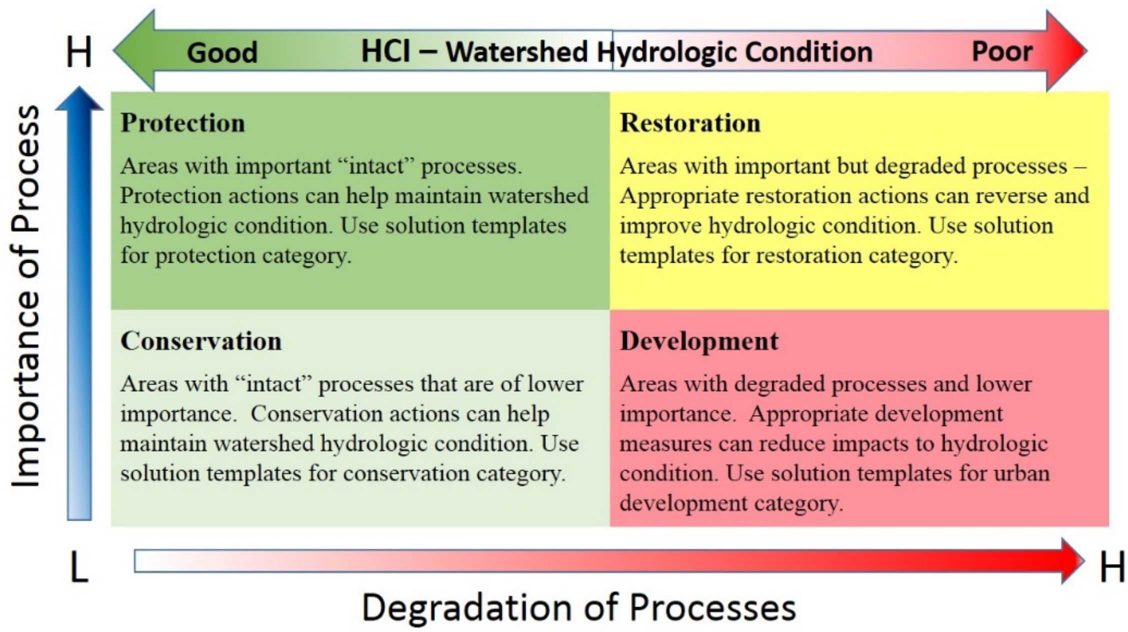


Figure 10. Integration of HCI results with the Watershed Management Matrix (WMM) categories developed for the Water Flow assessment (WCT1) of the PSWC (Volume 1). Solution templates are found in Appendix G. Figure shows the application of WCT1 and the WMM (i.e. importance and degradation scores) to the Taylor Creek watershed.

Because the future buildout analysis (assuming conversion to low-intensity development) for the entire Taylor Creek watershed (Figure 9) indicates that the HCI score will increase by more than 200% it suggests a high priority for applying protection actions in the upper watershed and restoration actions in the lower watershed using the solution templates. Additionally, green infrastruture actions can be considered over "grey" stormwater control measures at the broad-scale, such as replanting degraded areas not substantially impacted by impervious cover and restoration of historic surface and sub-surface flow patterns. In developing rural areas, this often includes agricultural lands that have impacted water flow processes through clearing of native cover and drainage of soils through ditching, diking, and channelization actions. The solution

[15] Solution templates were developed in Volume 1 of the Characterization as management strategies that would be applied to assessment units (AUs) according to the management category assigned by the Watershed Management Matrix (Figure 5c, Vol. 1).

templates outline many of these management actions according to the sub-basin characterization category (i.e., protection, restoration, development) and current land use.

Step 4 – Identify Which Areas and Actions will Help Maintain Healthy Hydrologic Conditions based on Land Use, Geology, and High Pulse Counts

The previous steps are an initial "first-cut" of identifying better development patterns for a watershed. This can be further refined by using the underlying inputs or components of the HCI, which can indicate where the areas are that contribute most to maintaining good hydrologic conditions, and where the areas of degraded hydrologic conditions are that can be restored in order to improve the existing HCI score. These areas generally include:

1) Higher permeability surficial geologic deposits such as outwash and alluvium;
2) Forested areas, including other native cover such as scrub-shrub; and
3) Areas adjacent to stream channels, such as riparian zones.

As illustrated in Figure 2 these components of the HCI are incorporated via the establishment of HPC_{coeff}, which predicts an annual count of high pulse events (i.e. HPC) based on a given combination of surficial geology and land cover.

Figure 11 presents a map of the HPC_{coeff} values for the different land use and geology types within the Taylor Creek watershed. As a general principle, all outwash areas should be protected from urban development due to their higher permeability and hence, lower HPC_{coeff} values. In other words, these outwash areas, if converted to higher-intensity land covers, represent the greatest change or potential contribution to "flashiness" downstream. Conversely, till areas that are in some type of agricultural or open space land use category provide the greatest potential for reducing high pulse counts in the watershed through restoration of those land covers to forest.

The map provides useful guidance when considering new development scenarios for buildout, by applying the following principles (listed in order of priority):

1) Avoid impervious cover in and adjacent to stream buffer.
2) Avoid impervious cover in areas with low $HPC_{coeff,}$ (the multiple green-shaded zones on the map) with first priority being forest, shrub, and pasture on outwash (darkest green zones). Areas that are naturally vegetated play a significant role in maintaining hydrologic conditions and once they are cleared and paved they cannot be recreated.
3) Apply restoration measures (e.g., replanting areas with natural cover) in areas of outwash and till that are degraded but not permanently converted to impervious cover. These include open space land uses on till and outwash (yellow and orange areas on Figure 11).
4) Focus additional development in areas with high HPC_{coeff} (red shaded zones).

For the Taylor Creek watershed, the HPC_{coeff} maps can show the areas where development decisions should attempt to reduce impacts through green infrastructure measures (i.e., areas with low HPC_{coeff} values, relative to other areas that significantly contribute to downstream flashiness that is harmful to stream ecosystems). This includes areas that are shown as "dark green" (forest on outwash). This information could help inform the current County buildout map, which presently identifies a considerable portion of the northeast area of the watershed for development. Instead, development could be concentrated in the numerous "yellow to orange" areas of Figure 11, which in conjunction with restoration measures and green infrastructure could help offset the higher HPC_{coeff} values generated by the new urban development. This same offset would not occur in areas that already have low HPC_{coeff} values.

This would suggest that new development should be located in the southwest "till" portion of the watershed and not in the northeast portion, which consists of headwaters with a large area of outwash deposits.

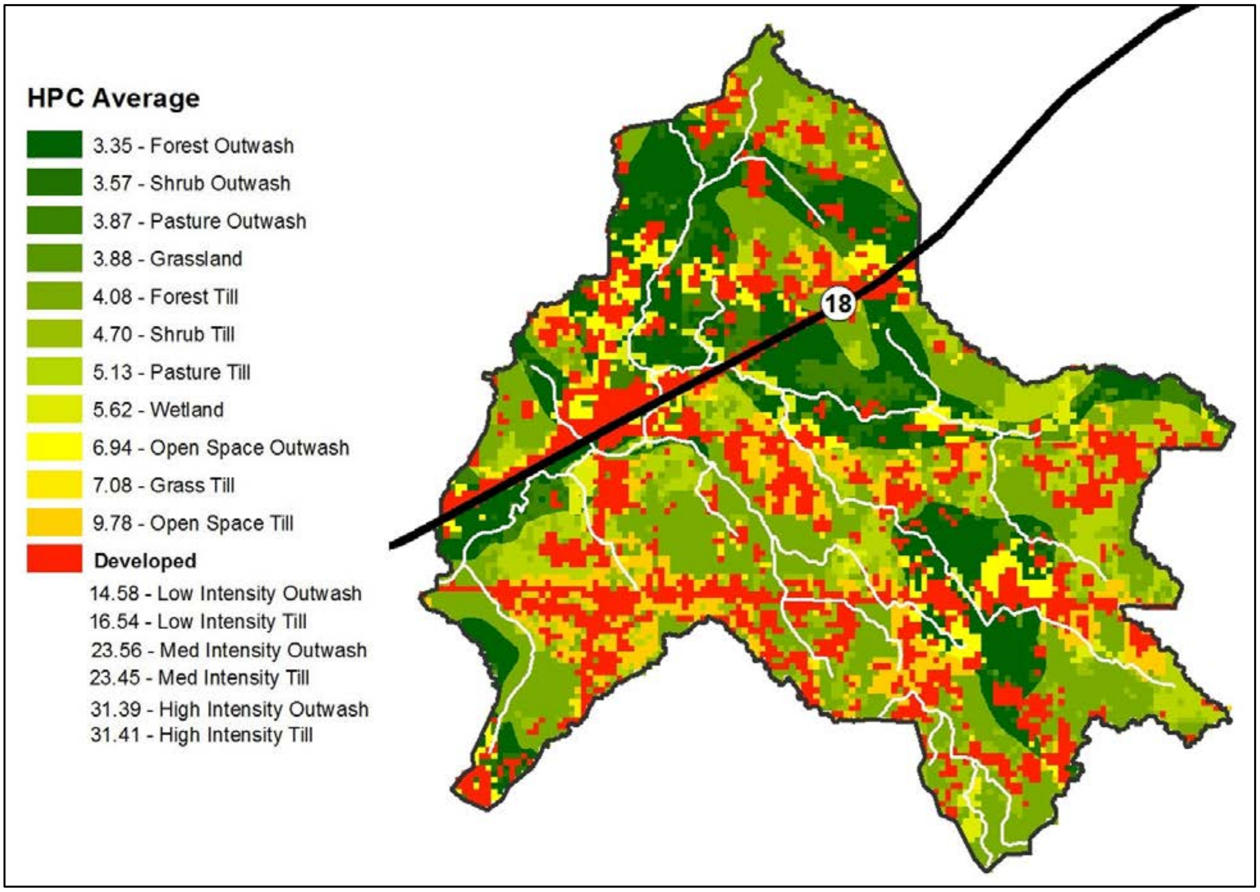


Figure 11. Map of HSPF-based HPCcoefficients (Average High Pulse Count values from the five King County watersheds) for different combinations of land cover and geology in the Taylor Creek Basin. Development occupying the higher HPCcoefficient areas (yellow to orange) should be mitigated (or restored) with green infrastructure methods; the lowest (dark green – areas of outwash) should be protected. The red areas offer less opportunity for restoration given the presence of more impervious surface (buildings and roads).

Step 5 – Develop Detailed Alternative Future Scenarios and Run the HCI at a Sub-basin Scale to Identify Best Scenarios

Once the general pattern of development for a watershed is determined (Steps 1 through 4), then the specific design and location of structures and restoration should be refined at the sub-basin level by running the HCI on several different Alternative Futures scenarios for development. These results could be used to develop and refine long- and short-term planning policies and ordinances, including buildable lands analysis. The Alternative Futures scenarios are described in the next section for the southwestern portion of the Taylor Creek watershed that was identified in Step 4 above.

Alternative Futures Scenarios

The application and comparison of HCI scores for different Alternative Futures scenarios can assist planners, citizens, and resource managers in identifying development configurations that best protect hydrologic processes. The Alternative Futures scenarios for the southwestern sub-basins of the Taylor Creek watershed presented in this section are intended as an example to guide other applications of this approach using the HCI. The analysis is based on the following principles:

1) Incorporating existing zoning. This is done to illustrate the potential application of the HCI by planners to better address the environmental impact of both individual projects and projected buildout within a watershed.
2) Comparing the specific scores for the footprint of the alternative development scenario within a sub-basin of Taylor Creek, rather than comparison of a watershed-wide score that includes the Alternative Futures scenario. The reason for this is that the increase in the HCI score for an individual development scenario is difficult to detect when calculated within the much larger extent of a watershed.
3) Applying the development principles set forth in Step 4 to the identified development area in the southwest portion of the watershed.

Assessment of Hydrologic Condition for Buildout Scenarios in the Southwest Sub-basin of Taylor Creek

Zoning Buildout Scenarios

As illustrated in the previous steps, the HCI and the associated hydrologic conditions categories can communicate shifts in HCI score, and associated increasing or decreasing risk, associated with future buildout within a sub-basin or sub-basins. These development scenarios are based on both conventional development patterns and incorporation of green infrastructure measures such as greater stream setbacks, avoidance of key areas important for water flow processes (i.e., outwash), and locating higher intensity development farther from a stream course.

Figure 12 shows the current pattern of development in the Taylor Creek watershed; Figure 13 and Table 6 describe the land-cover patterns and specific breakdown for land uses for each of the following four Alternative Futures scenarios[16]:

1) **Traditional Scenario**. Buildout incorporating existing zoning and including restoration of degraded cover within 80 feet (average) of the stream course.
2) **Riparian Scenario.** Buildout incorporating existing zoning, plus protection and restoration of riparian buffer within 150 feet (average) of the stream course.

[16] Note that the buffers used in each scenario are not representative of existing widths for regulatory buffers.

3) **Green Infrastructure Scenario**. Applies green infrastructure principles outlined in Step 4 including modifying existing zoning patterns by moving and concentrating higher intensity development farther away from the stream course (maximizing the effect of distance in reducing hydrologic impacts).

HCI scores for existing land-cover conditions and the four Alternative Futures scenarios are presented in Figure 14.

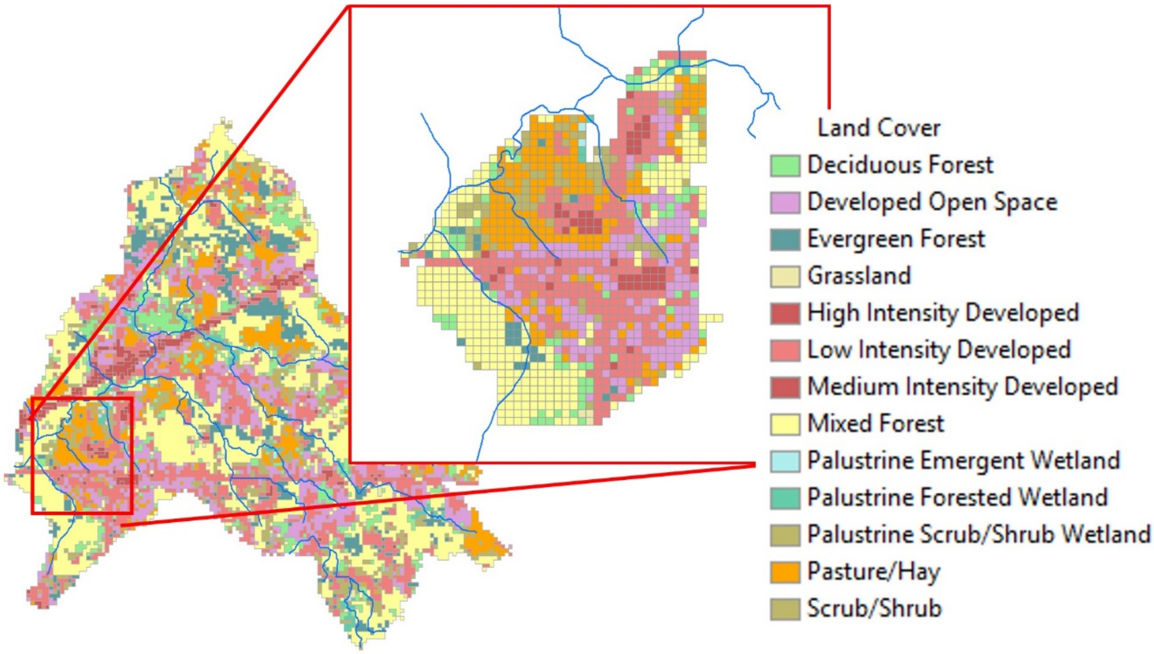
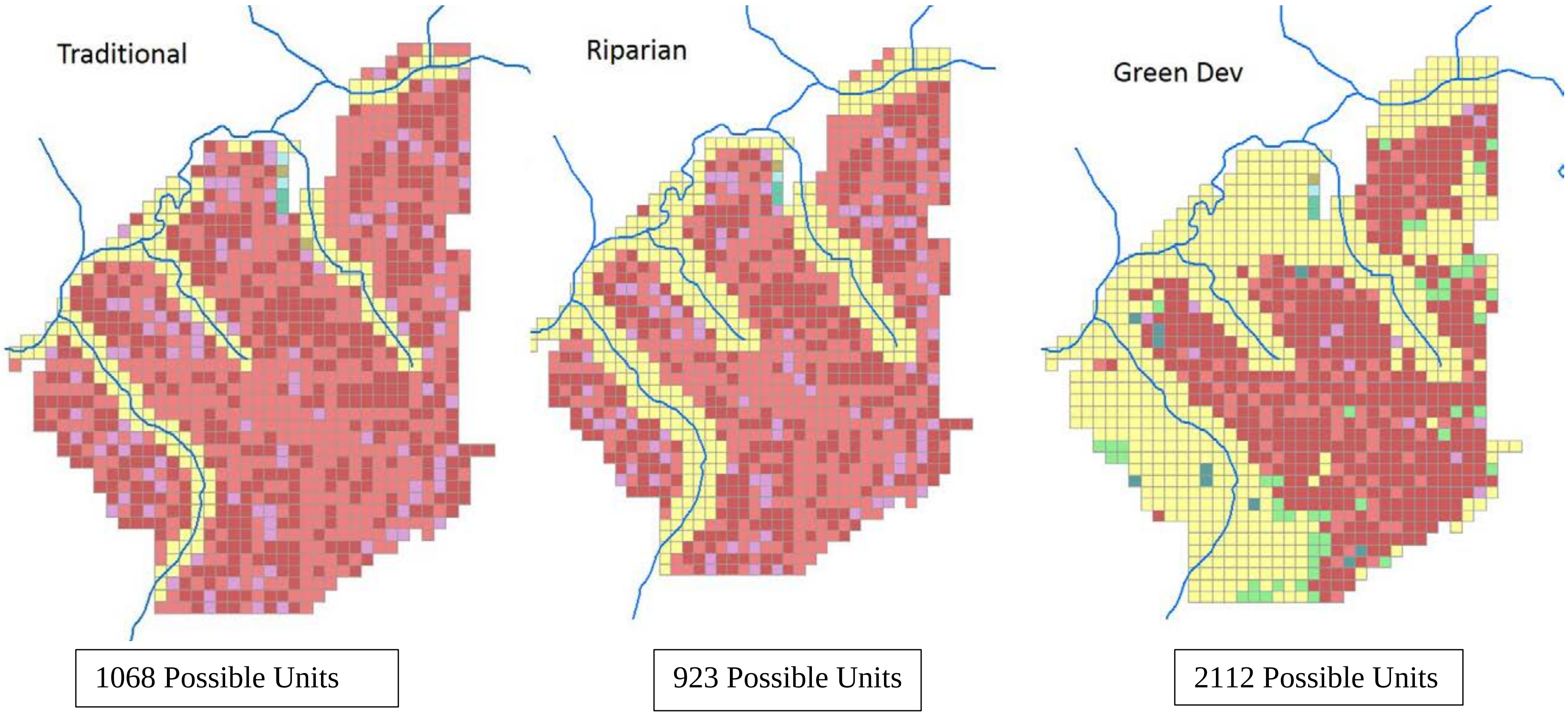


Figure 12. Existing land cover for the southwest portion of the Taylor Creek watershed. Existing patterns of development have helped protect stream ecological health, with higher intensity development farther from the stream corridors (i.e., southern portion of watershed) and either agricultural or forested land cover closer to the stream corridors. Grid blocks are 30 meter; land cover data from CCAP.



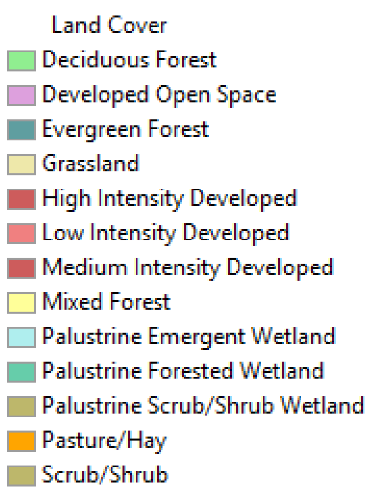


Figure 13. The three Alternative Futures scenarios compared using HCI, including Traditional, Riparian, and Green Development scenarios. Details of the land-cover types and results are presented in Table 6 and in the text. Results of the HCI runs are presented in Figure 14. See Appendix H for calculation of units for each scenario.

Table 6. Description of future land cover and protection and restoration measures for three alternative future scenarios assessed in the southwest sub-basin of Taylor Creek[17].

Application	Traditional Scenario, 80 ft. buffer (average)[18]	Riparian Scenario, 150 ft. buffer (average)[19]	Green Development Scenario (incorporation of development principles outlined in Step 4)
Stream and green infrastructure protection and restoration measures	All grid cells in riparian corridor restored to mixed forest land cover	All grid cells in riparian corridor restored to mixed forest land cover	• Protect all existing forested areas on outwash and till, primarily adjacent to stream corridors in the north and southwest areas (information from Step 4). • Restore agricultural lands within the same areas as above to mixed forest. • For all remaining stream reaches, restore riparian corridor.
Future land cover (remaining areas outside of stream treatment area)	• 50% Med Intensity • 30% Low Intensity • 15% Developed Open Space • 5% High Intensity	• 50% Med Intensity • 30% Low Intensity • 15% Open Space • 5% High Intensity	• 45% Developed Med Intensity • 15% Developed High Intensity • 35% Mixed Forest • 5% Developed Open Space
Resulting Density at Buildout (Appendix H)	1058 Units	923 Units	2112 Units

[17] For all scenarios, grid cells with the following CCAP land-cover designations are maintained as they are: Developed Low intensity; Developed Medium intensity; Developed High intensity; Wetland CCAP land cover.

[18] Riparian buffer averages 80’ based on range of 30’ to 130’ (due to irregularities introduced by 30 m pixel)

[19] Riparian buffer averages 150’ based on range of 100’ to 200’ (due to irregularities introduced by 30 m pixel)

HCI Results for Alternative Futures Scenarios in the Southwest sub-basin of Taylor Creek

The assessment results for the three Alternative Futures scenarios are presented and compared to existing conditions in Figure 14. The results suggest that buildout incorporating existing zoning and traditional development patterns will substantially impact the hydrologic condition of the scenario sub-basins (HCI score of 0.62 – poor condition category). Even with restoration of the riparian corridor (i.e., riparian scenario), the HCI score remains well within the zone of impaired hydrologic condition. The first two scenarios would, therefore, have a very high risk of impacting the hydrologic condition, and thus the biological health, of these Taylor Creek sub-basins.

Only with a green infrastructure approach (scenario 4) can the hydrologic condition be maintained at the low end of the "moderate" hydrologic condition category, which is essentially the same HCI score as found with existing land-use patterns. This development scenario would have the lowest risk in terms of maintaining water flow processes that support a healthy watershed. It should be noted that there are other considerations that would be involved in implementing a green infrastructure scenario as depicted. For example, transfer of development rights or other incentive based programs for acquiring land would be needed for implementation actions in protection and restoration zones. Additionally, potential "loss of rural character" in the development zone would have to be consistent with Growth Management Act and local ordinances.

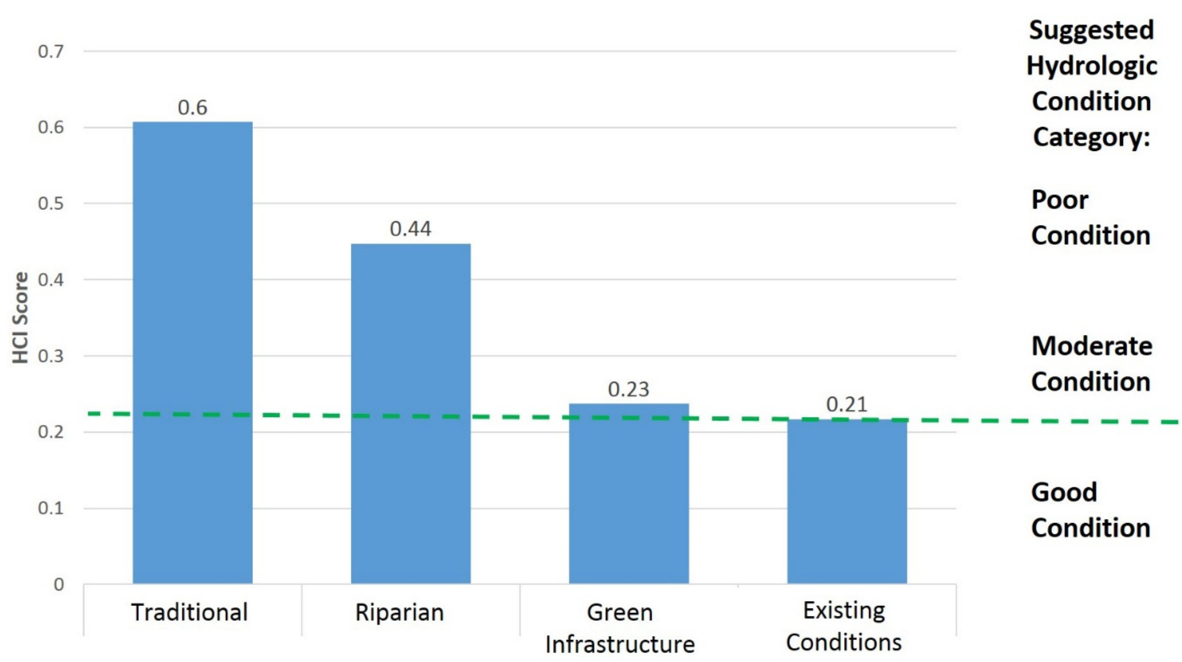


Figure 14. HCI scores (using 30 meter resolution and Euclidean distance calculation) for the three Alternative Futures scenarios and existing land cover show that only the green infrastructure scenario is successful in maintaining the existing hydrologic health of the stream systems within the southwest portion of the Taylor Creek watershed at full buildout.

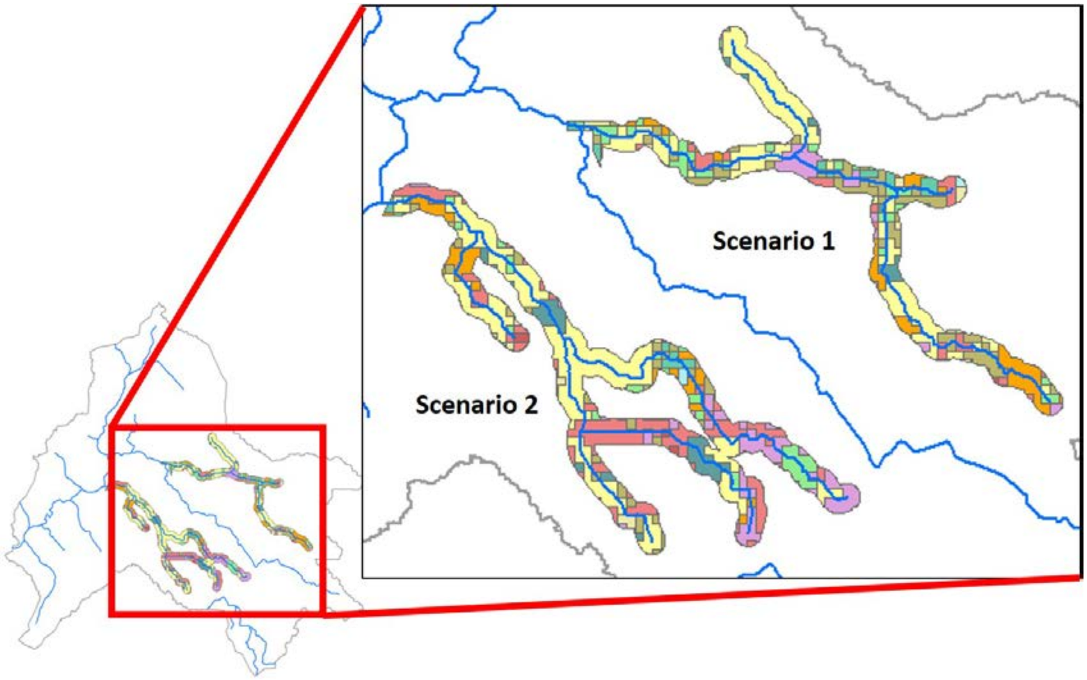
This type of analysis could be integrated into buildable lands analyses and other assessments supporting Comprehensive Plan updates, or as a tool to consider the effectiveness of development standards and the need for additional environmental protections. For example, a jurisdiction could respond to increasing development pressure within a specific area by reviewing the HCI risk implications for the sub-basin(s) in question, providing indication of need and options for additional environmental protections.

Restoration Scenarios

The HCI can also be used to evaluate the potential hydrologic improvement that would be gained from the restoration of degraded portions of a riparian corridor. This can be achieved by running the HCI for existing riparian cover within a stream system, which includes areas that are cleared for agricultural or rural land use, and comparing that HCI score to the score for the same corridor in a 100% forested condition.

Two buffer restoration scenarios were run for the Taylor Creek watershed (Figure 15). Table 7 shows the HCI scores for both restoration scenarios. Both scenarios involve a 150 foot wide buffer from stream centerline, with Scenario 1 involving land cover that has more natural riparian cover and Scenario 2 including more developed areas.

The results indicate that a greater degree of hydrologic improvement would be achieved with buffer restoration Scenario 2 (HCI score decrease from 0.21 to 0.11, relative to 0.14 to 0.10 for Scenario 1), suggesting that this scenario could be a restoration priority This type of scenario comparison could be useful in determining the best areas within a watershed to spend restoration funds.



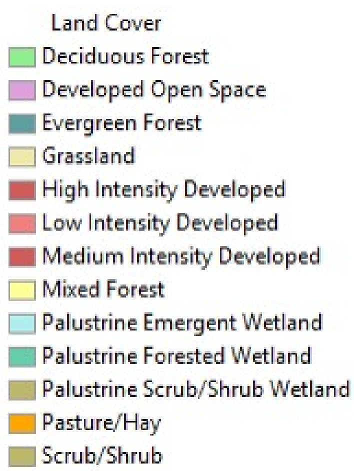


Figure 15. Location of two buffer restoration scenarios. Each buffer area is 150 ft. wide from the stream centerline. Scenario 1 is located in the upper right and has a smaller total reduction in the HCI score for restoration relative to Scenario 2, located in the lower left.

Table 7. Evaluation of restoration opportunities within a riparian zone (Figure 15).

Riparian Buffer Restoration Scenario	Grid	HCI
Scenario 1, 150-ft riparian zone of existing land cover with more natural riparian cover.	Euclidean	0.14
Scenario 1, 150-ft riparian zone restored to forest.	Euclidean	0.10
Scenario 2, 150-ft riparian zone of existing land cover with more developed cover types.	Euclidean	0.21
Scenario 2, 150-ft riparian zone restored to forest.	Euclidean	0.11

What We Have learned

The HCI tool provides a relatively easy, quick, consistent way to assess condition of hydrologic processes based on patterns of land cover and surficial geology within a watershed. It generates an “indexed” output that will allow comparison with hydrological conditions of other lowland watersheds in Puget Sound assuming future development of HPC coefficients which are calibrated adequately to areas beyond WRIAs 7, 8, 9, and 15.

Application of the HCI “mid-scale” tool within the test watersheds demonstrates its potential to help land use planners, stakeholders, and decision makers understand the effect of existing and projected future development on stream “flashiness” and the overall hydrologic condition of a watershed.

As a decision support tool it:

1) Provides a rapid, quantitative assessment of hydrologic condition within both larger watersheds (thousands of acres) as well as sub-basins (hundreds of acres);

2) Assists in identifying the best land use patterns, using alternative future scenarios, which protect the hydrologic condition of watersheds;

3) Identifies best restoration scenarios within a watershed;

4) Integrates into the existing PSWC framework and applied throughout Puget Sound watersheds in the future.

Recommendations for future use

The HCI tool is ready for application throughout Puget Sound, provided the following requirements are met:

1) Calibration of the HCI tool, other than WRIAs 7, 8, 9 and 15, is undertaken using HSPF-modeled watersheds in the region of Puget Sound that the tool application is desired. This would involve statistical comparison of the HPC values generated by gage data and by the HSPF model. Calibration would take into account the different size, shape, surficial geology, and land cover for the region. These comparisons would be used to develop new HPC_{coeff} values, as necessary.

2) Apply the HCI tool using the highest resolution data available for the region. This provides greater accuracy in the results which in turn increases the certainty of the results relative to the planning question being addressed. For example, 30 m CCAP land cover data is suitable for a general comparison of hydrologic conditions within and between watersheds, however finer resolution land cover data (e.g. 1.8 m or less) should be used for comparing the effects of alternative future scenarios at the sub-basin scale.

3) Use the HCI tool as a decision support tool in conjunction with other data and information. The results of the HCI tool should not be used solely as a decision making tool.

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Appendix A. Testing of HCI Methods

(Literature references included in Works Cited section above)

Introduction

To develop a mid-scale assessment tool that predicts hydrologic condition we tested the HCI and its associated variables under different conditions of spatial resolution and flow routing in eight test watersheds (Figure 16). The decision regarding best combination of these parameters was largely based on the degree of correlation of HCI scores with gage data in the test watersheds. A detailed description of the HCI Method and how it works is contained in the main body of this document.

Description of the Study Area

The study area for testing the HCI extends across the low-lying western portion of King County, an area of common geologic history, flora, fauna, human uses, and development pressures. The study watersheds (a.k.a. test watersheds) are located in central Puget Sound and distributed across rural King County in Water Resource Inventory Areas (WRIAs) 7, 8, and the Vashon Island portion of WRIA 15 (Figure 16).

Seven study watersheds are located in the Puget Lowland Ecoregion (PLE), which is predominantly less than 150 m (~500 feet) in elevation. The eighth study watershed (Webster) is in the Cascades Ecoregion at the east edge of the Puget Lowland Ecoregion.

These test watersheds were selected for the following reasons:

1) To facilitate comparison with existing data already collected by King County.
2) They are data-rich, including 1.8-meter resolution land-cover data and stream-gage data, as well as HCI scores for each of the test watersheds calculated from the gage record.
3) They have established high pulse count values[20] that are necessary for calculating the HCI scores.
4) Land-use patterns in these watersheds are similar to other rural areas in Puget Sound that are located on the urban fringe of urban areas, and that are likely to undergo significant future urban development.

Initial development of the HCI by King County relied on five additional lowland watersheds (Hamm, Miller, DeMoines, Newaukum, & Duwamish) within WRIA 9 (Lucchetti et al. 2014). For each of these watersheds, calibrated Hydrologic Simulation Program Fortran (HSPF) models were available and used to establish HPC_{coeff} values. The use of these five watersheds for HCI

[20] These high pulse values reflect the average number of high pulses (2X mean annual flow) generated in a year for a particular combination of land cover and surficial geology. By running a calibrated hydrologic model, historic climate data, for individual combinations of cover types and surficial geology over the entire watershed, the associated high pulse count value for that cover type is generated. These values are averaged to produce the HPC coefficients.

development is described in the 'Initial Application by King County' section (beginning on page 19) of this report and referenced elsewhere as background; however, they were not included as test watersheds by Ecology.

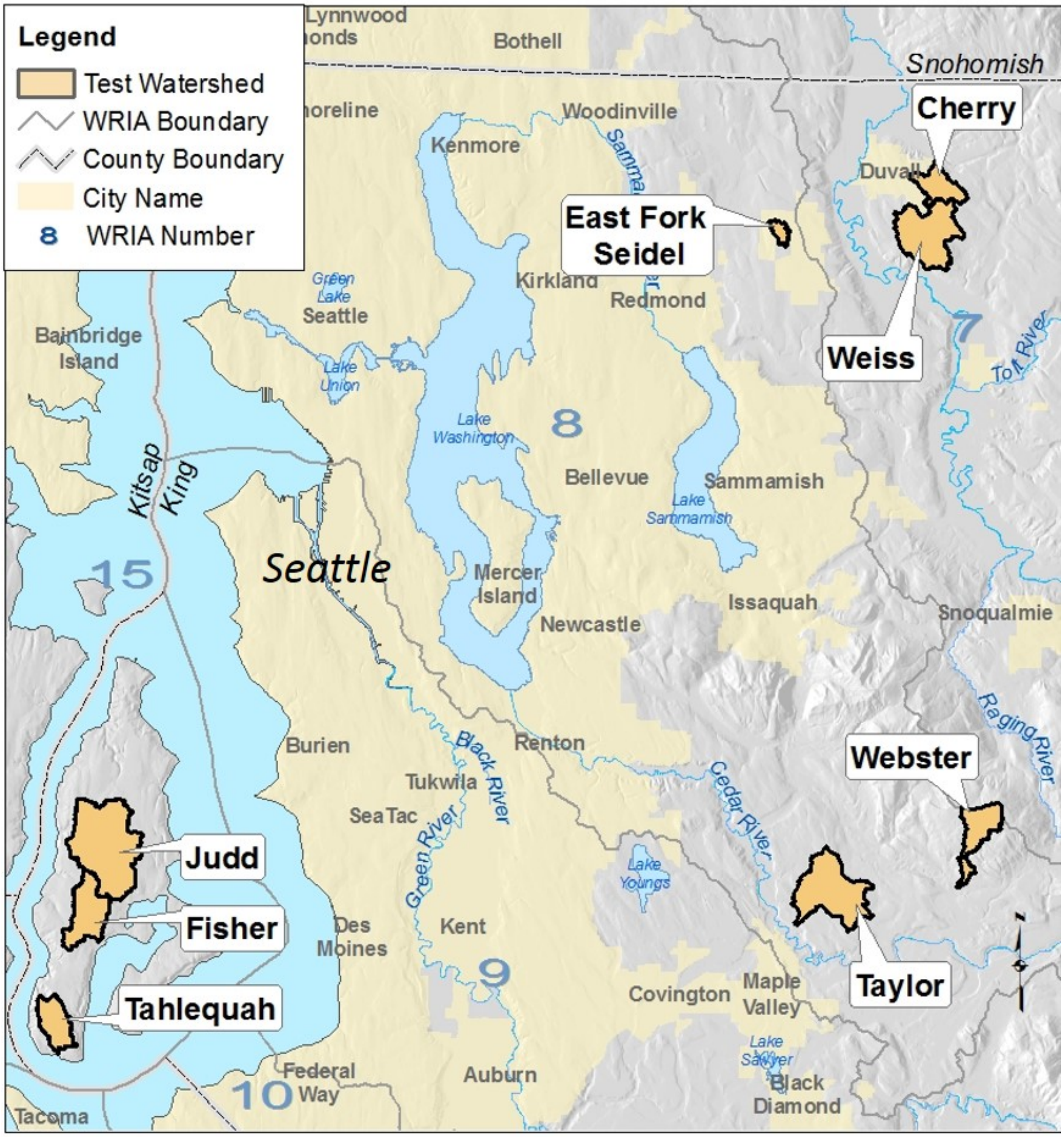

Figure 16. Eight data-rich test watersheds used by the Department of Ecology in testing the initial Hydrologic Condition method, and by King County in developing the original HCI (Lucchetti et al. 2014). Land-cover patterns in these watersheds are similar to many other developing rural and suburban watersheds in Puget Sound.

Description of Methods for Testing the HCI

Hypotheses

The design of the HCI tests was based on the following two hypotheses that allowed Ecology and the consultant team to determine whether the HCI meets “best available science” criteria (Washington Administrative Code [WAC] 365-195-905), in addition to meeting the goals and stated purpose for this Update Project:

1) The correlation between HCI scores and high pulse counts (gage data), will be similar at different resolution, distance (i.e. dOg+dSg), and flow networks (Euclidean vs Natural).

2) The HCI will be able to predict the hydrologic impacts of proposed land use in terms of location and intensity within a watershed.

The following key questions were developed to address the two above hypotheses:

1) What is the optimal scale and flow-routing method, considering both accuracy and efficiency of implementation?

2) Can the HCI predict the difference between low, medium, and high-intensity development scenarios and their impacts to hydrologic condition in the test watersheds?

3) Does the method yield meaningful results when compared to hydrologic data (e.g. gage data), where available?

Design of tests

Five sets of tests were developed to:

1) Identify the best combination of routing and grid size;

2) Identify the best distance variable in the HCI algorithm, including both overland distance to a stream (dO_g) and the combination of overland distance to stream with the distance down the stream to its outlet (dS_g) for the watershed (dO_g+dS_g).

3) Determine whether the HCI detects the impact of development relative to location, size, and land use intensity;

4) Determine whether the HCI detects the impact of Alternative Futures scenarios, including the use of green infrastructure; and

5) Help identify the methods for developing HPC_{coeff} for different regions of Puget Sound that have a distinctly different combination of geology, precipitation patterns, and topography that may change hydrologic patterns such as HPCs, relative to the test watersheds.

In addition to answering the questions set forth in the hypotheses, testing of the HCI also involved consideration of the type of data and work required to implement the method efficiently throughout the Puget Sound region. For example, a 30-meter land-cover dataset is already available for all of Puget Sound, whereas 1.8-meter land-cover data are not[21]. Flow routing can be executed as "Euclidean" (i.e., straight-line distance from a source point to a measurement point, such as a stream) or "Natural" (i.e., following the natural topographic low points from source to stream). Creating a Euclidean flow network takes significantly less time than that required for a Natural flow network.

Based on input from the WAG, Ecology and the consultant team also tested the implications of not including the distance variable within the HCI. All of these factors were incorporated into the design of the tests.

Testing for best combination of routing and grid size

Both the validation of methods and testing for the best way to implement the HCI were evaluated using regression analysis on existing gage data[22], the HCI scores for the eight test watersheds, and applying all combinations of grid cell / land-cover resolution and flow geometry. In total, Ecology and the consultant team identified ten potential test runs based on the combination of grid resolution (1.8-meter vs. 30-meter), flow path type (Euclidian vs. Natural), and distance variables (dO_g+dS_g vs. dO_g). Figure 17 provides a conceptual flow chart of the routing and grid size methods and the ten combinations of grid and flow types.

Testing the HCI algorithm for the eight test watersheds involved a multi-step process:

1) Acquiring 1.8-meter land-cover data and HCI algorithm script from King County.

2) Developing Euclidean flow networks at 1.8 meters and 30 meters.

3) Simulating Natural flow paths by establishing a natural flow network grid at 1.8 meters and 30 meters using a Digital Elevation Model (DEM).

4) Running the HCI algorithm in ten test runs (as shown in Figure 17) to compare HCI scores with different flow routing and grid scale alternatives. For all HCI test runs, average HPC values from King County's effort were used. The average of HSPF-generated values (see Appendix C) were applied as the 24 HPC_{coeff} values for each given land-cover type and geology. These were applied directly for the 1.8-meter grid resolution tests using King County high-resolution land-cover data, and adapted by Ecology and consultant team for 30-meter grid resolution tests using land-cover data from the Coastal Change Analysis Program (CCAP).

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21 NOAA C-CAP 1-m data for land cover is currently being developed for all of Puget Sound.

22 Stream-gage data for the majority of eight test watersheds covered a period from early 2000 to 2016 (the longest duration of available stream-gage data was for Taylor Creek, from 1992 to 2016). Because the HCI calculations are based on 2011 National Land-cover data, Ecology and consultant team chose to use stream-gage records that generally matched that time period, selecting 2008 to 2016. This gage data range was also chosen because King County reported that there was limited development during the study period of 2007 to 2012 due to the economic downturn that started in 2008.

5) Identifying the average (water-year) stream HPCs from King County gage data for the eight test watersheds, and using average stream flow HPCs to complete regression analysis of all HCI test alternatives.
6) Evaluating results for the ten test runs and selecting the best method for routing and resolution.

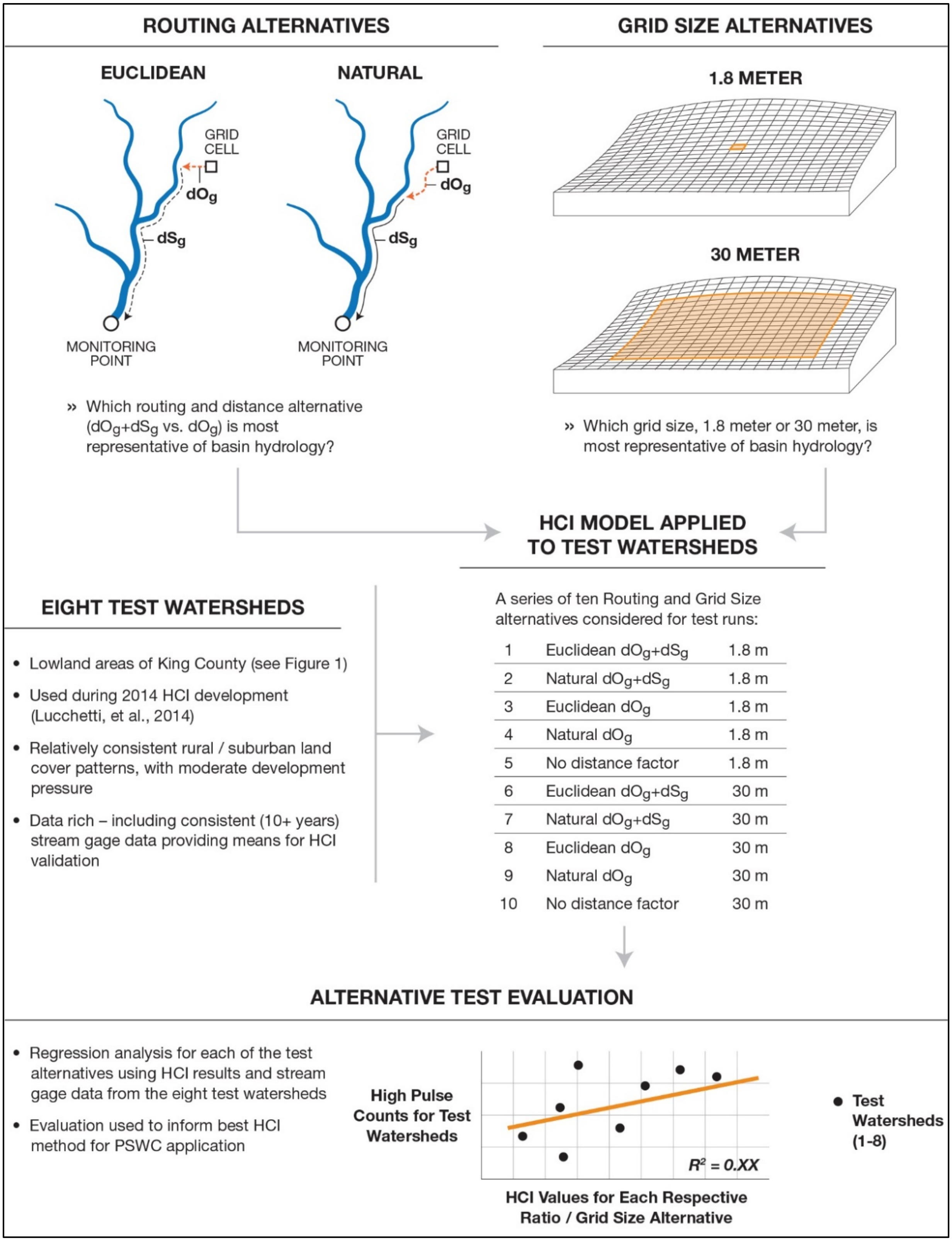

Figure 17. Conceptual flow chart of methods for evaluation of routing and grid size alternatives using eight test watersheds in King County.

Testing for the Distance Variable in the HCI Algorithm

In addition to these primary tests of flow routing and grid size alternatives, Ecology also evaluated weighting of distance within the HCI algorithm. Distance evaluation methods included:

- Conducting additional test run scenarios for different levels (i.e. % impervious surface) and locations of paving, to verify the effect of the "inverse distance" in the HCI scores (mathematically "inverse distance" will reduce the effect of an area of development as it is moved away from a stream).
- Conducting additional test runs to compare the results of the HCI algorithm when using only overland distance (dO_g) as the inverse distance variable, versus using overland distance AND stream channel distance to the outlet (dO_g+dS_g) as the distance variable.

For its HCI algorithm, King County applied distance weighting to the combination of overland distance (dO_g), to the channel and stream channel distance (dS_g). However, based on initial tests Ecology and the consultant team were concerned that the inclusion of the stream distance was incorrectly diminishing the attenuation provided by overland distance. Ecology evaluated literature on the hydrologic significance (attenuation) of overland flow paths compared to surface channels, with many studies highlighting the attenuation occurring along overland flow paths, especially in forested conditions (DeGasperi et al. 2009; King et al. 2005; Grabowski et al. 2016). Based on literature and professional judgement of the Ecology and consultant team, separate test runs were developed to independently evaluate the inclusion of overland flow only versus overland and instream flow for the HCI scores.

Testing for Sensitivity to Location, Size, and Land Use Intensity

The utility of the HCI as a mid-scale tool depends on its ability to clearly assess the degree of impact from a development, through the HCI score, in a watershed at a sub-basin size. It should, to be useful, distinguish between impacts to hydrology when land cover is changed farther from a stream, or closer to it. To test this sensitivity, methods included comparing HCI runs for polygons on the outer edge of the watershed and on the mainstem of the stream system. This involved creating polygons of 25, 50, 100, and 200 acres for the Taylor Creek watershed and comparing the HCI scores for each polygon when located closer, or farther from the streamlines.

Testing sensitivity to land use intensity involved comparing the HCI scores for a large development in one sub-watershed of Taylor Creek for low, medium, and high land use densities (CCAP land use designations) buffered from the stream course by 50, 100, and 200 feet.

Testing for Alternative Futures Scenarios and Use of Green Infrastructure Measures

A key desired feature of a HCI is the ability to provide project future hydrologic impacts under Alternative Future scenarios for a watershed. To test this, HCI runs for two Alternative Futures scenarios were completed for the Taylor Creek watershed. Based on the results of these two initial tests, an additional three alternatives were run, and are described in the Decision Support Framework chapter.

The initial tests included:

1. Watershed-wide buildout at the low-, medium-, and high-intensity development level (CCAP[23] data) using alternatively no stream buffer and a 50-foot stream buffer.
2. Buildout at the medium and high-intensity development level (CCAP data) using a hypothetical green infrastructure approach. Green infrastructure "uses vegetation, soils, and other elements and practices to restore some of the natural processes required to manage water and create healthier urban environments[24]." For this test we applied a "green infrastructure" matrix (Figure 18) that involved clustering and forested green space at a ratio of approximately 2:1 forest to development. The scenario for the entire watershed is also shown in Figure 18. This ratio is based on the work by Booth, showing that maintaining 65% forest cover helps reduce impacts to watershed hydrology (Booth et al 2002, 2004).

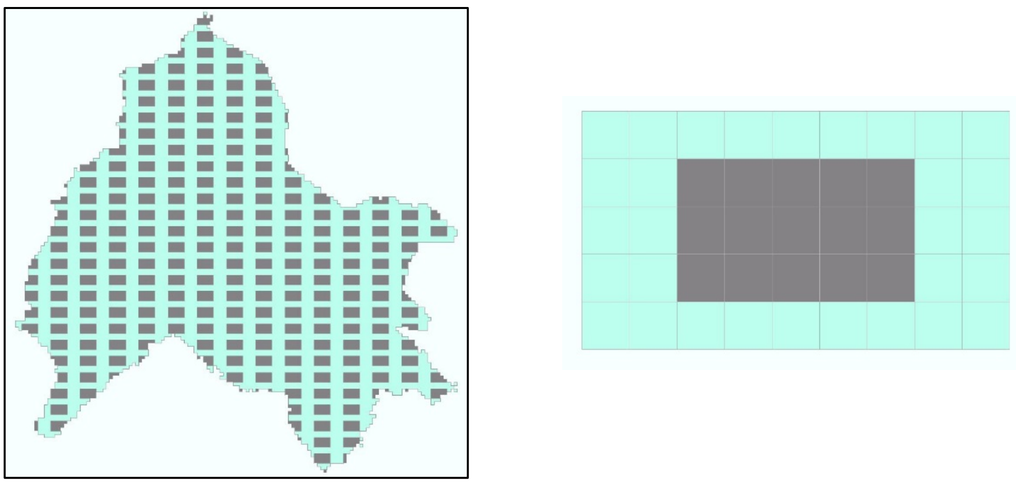

Figure 18. Green infrastructure matrix on left for Taylor Creek watershed, close-up image of each matrix cell on right. Dark gray "development" grid cells equal 3.33 acres; light green "forest" cells equal 6.67 acres for a total of 10 acres for each development polygon.

Testing for Development of HPC Coefficients in Different Regions of Puget Sound

The HPC_{coeff} values used in the HCI calculation were developed in the same region (WRIA 9) as the eight test watersheds using existing calibrated hydrologic models (HSPF) from five separate watersheds of similar size. In order to further develop the HCI for broader application, the process of developing the HPC_{coeff} values will have to be repeated for other regions of Puget Sound that have different precipitation patterns, surficial geology and topography than that of the test watersheds.

It was proposed by WAG members that another hydrologic model could be used to develop HPC_{coeff} values. Visualizing Ecosystem Land Management Alternatives (VELMA) was selected as a spatially explicit model that could also simulate the hydrology of a watershed and generate

[23] Coastal Change Analysis Program https://inport.nmfs.noaa.gov/inport/item/48336
[24] EPA Green infrastructure webpage: https://www.epa.gov/green-infrastructure/what-green-infrastructure

parallel results to compare with the gage record. By running VELMA in the same WRIA (8) as the test watersheds, the HPC_{coeff} values developed through VELMA could be compared to the HPC_{coeff} values developed in WRIA 9. This testing would help determine if the VELMA model was suitable for developing the HPC_{coeff} values for other parts of the Puget Sound basin.

EPA staff at the Office of Research and Development in Corvallis, Oregon, assisted staff at Ecology in running VELMA in the Taylor Creek watershed. The testing of VELMA involved reviewing the best fit calibration of the VELMA model to the Taylor Creek watershed hydrograph to determine if it is acceptable for evaluating high pulse counts.

Results and Discussion

Best Combination of Grid Size and Routing

As detailed in the methods section, Ecology staff identified ten alternative HCI test runs to represent all combinations of grid resolution, flow path type, and distance variable (including two tests that evaluate the HCI with no distance variable). A summary of the results is provided in Table 8 in order of decreasing correlation to stream-gage HPC data. Figures 23 through 32 in Appendix C also illustrate the results of the regression analysis.

These results suggest that the combinations using 1.8 meter land cover data with Natural and Euclidian flow path and the dOg distance have the best correlation with gage data. If 30 meter land cover data is used, then the Natural flow path in combination with the dOg+dSg distance variable have the third highest correlation.

Table 8. Regression analysis results for grid size/routing alternative tests, showing correlation to stream-gage measured High Pulse Counts for all test watersheds.

Routing	Grid Size	Regression Analysis Result (R^2 Value)	Figure # in Appendix C
Natural dO_g *	1.8 meter	0.806	23
Euclidean dO_g	1.8 meter	0.738	24
Natural $dO_g + dS_g$ **	30 meter	0.650	25
Euclidean $dO_g + dS_g$	1.8 meter	0.643	26
No Distance	1.8 meter	0.641	27
Natural dO_g	30 meter	0.614	28
Natural $dO_g + dS_g$	1.8 meter	0.582	29
Euclidian $dO_g + dS_g$	30 meter	0.540	30
Euclidean dO_g	30 meter	0.520	31
No Distance	30 meter	0.426	32

* Distance to stream; ** Distance to stream & outlet

Best Distance Variable in the HCI Algorithm

Testing demonstrated that the "overland" distance variable (dO_g) provided the best regression results (Table 8). This result was further confirmed by tests using both the dO_g and dS_g distance variables. Figure 19 shows that when both these distance variables are used they indicate that development in the upper, headwaters portion of a watershed has less effect than if located in the lower portion of a watershed. This is contrary to what hydrologists have observed relative to hydrologic impacts to streams in Puget Sound[25]. A lower HCI score represents a stream system with relatively normal flows Using both distance variables ($dS_g + dO_g$), HCI scores (Table 9) predicted that the overall condition of the watershed improved when impervious development was located in the upper watershed (HCI = 0.478) compared to impervious development located in the lower half of the watershed (HCI=0.636).

However, it should be noted that other types of watersheds relative to the test watersheds, in terms of size, shape (e.g. linear vs oval), stream density and topography may produce different results for the distance variable than encountered for the King County area. It is important, therefore, that future distance variable testing include these other factors.

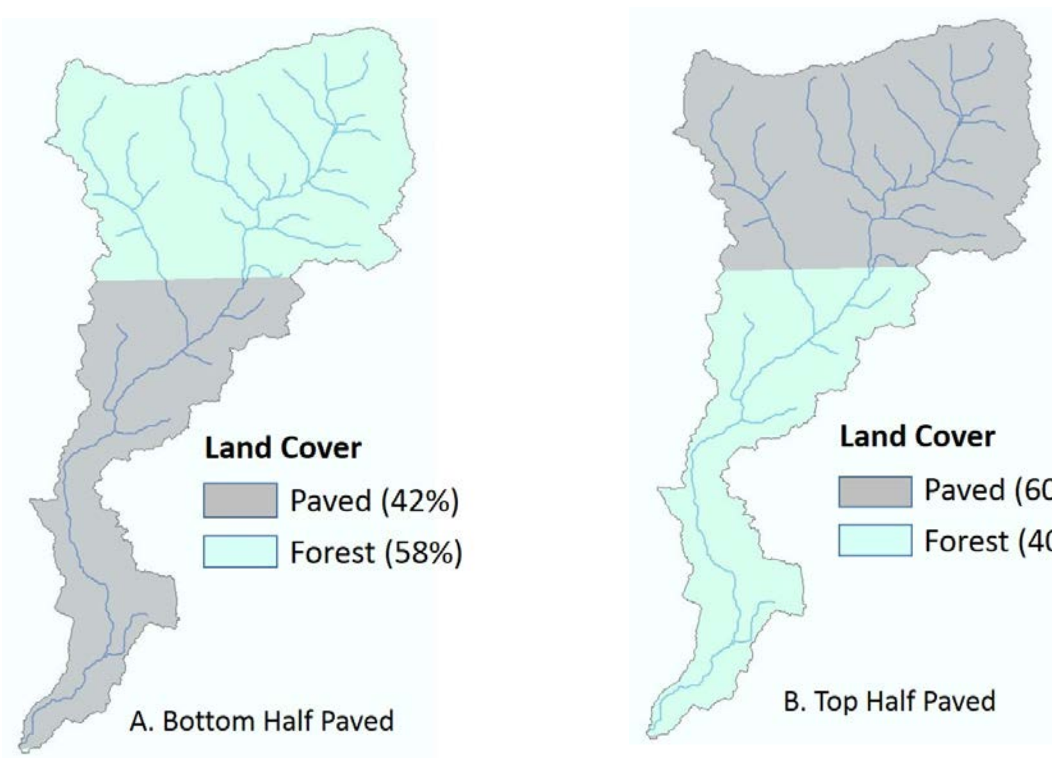

Figure 19. Depiction of bottom half / top half testing completed for the Webster Creek watershed; all paved land cover was applied first to the bottom half and then to the top half of the watershed with the resulting HCI score calculated for each scenario (Table 9).

Table 9. HCI results for lower and upper half development scenarios depicted in Figure 19.

Distance Variable	HCI for Bottom Half Paved	HCI for Top Half Paved
To stream (dOg)	0.460	0.657
To outlet (dOg + dSg)	0.636	0.478

[25] Personal communication with Derek Booth, 2/13/2018

Results for Size and Land Use Intensity Testing

Table 10 presents the HCI results for different sizes of development. Figure 20 shows the location of the development polygons involved in these tests. In all tests, HCI was able to show that the impact to hydrologic conditions would increase as the size of the polygons development increased using either Natural or Euclidean flow paths in the distance calculation of the algorithm.

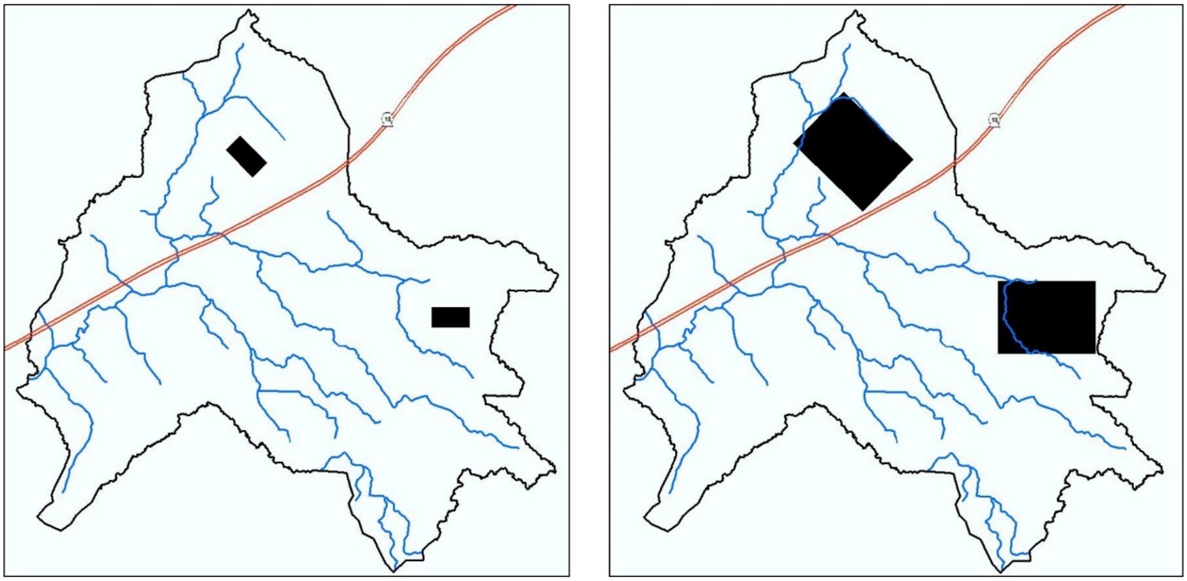

Figure 20. Location of development polygons in Taylor Creek watershed for testing HCI scores relative to size. The right hand panel shows two 100-acre polygons (200 acre test), and the left hand panel shows two 12.5-acre polygons (25 acre test). Test polygons were also created for 50-, 100-, and 150-acre tests in approximately the same two locations (see Table 10 for results).

Table 10. HCI scores for different sizes of development, no buffer, and 1.8-meter land-cover data. Polygons located on the outer perimeter of the Taylor Creek watershed (Figure 20).

Development Polygon Size	Grid Flow Path	HCI Score	% Change from Existing Cond.	Absolute Change from Existing Cond.
Existing Conditions	Natural_dOg_	0.167	NA	NA
Existing Conditions	Euclidean_dOg	0.174	NA	NA
200 acres	Natural_dOg	0.208	24.9 %	0.041
200 acres	Euclidean_dOg	0.231	32.9 %	0.057
150 acres	Natural_dOg	0.184	10.1 %	0.017
150 acres	Euclidean_dOg	0.198	14.0 %	0.024
100 acres	Natural_dOg	0.171	2.2 %	0.003
100 acres	Euclidean_dOg	0.182	4.5 %	0.008
50 acres	Natural_dOg	0.168	0.9 %	0.001
50 acres	Euclidean_dOg	0.177	1.8 %	0.003
25 acres	Natural_dOg	0.168	0.43 %	0.0007
25 acres	Euclidean_dOg	0.175	0.82 %	0.001

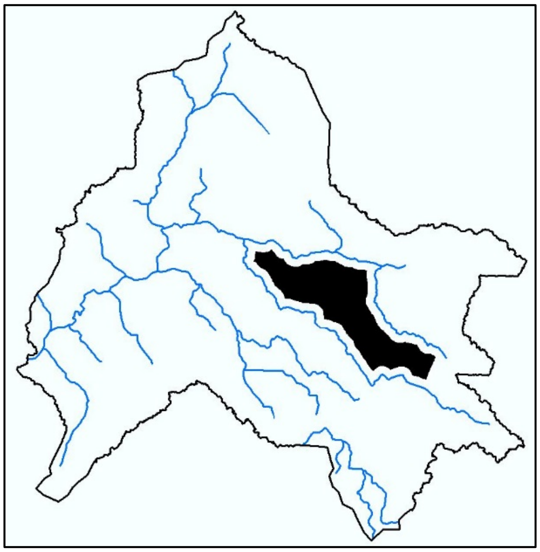

Table 11 presents the HCI results for different intensities of development and two riparian buffer widths. Figure 21 shows the location of the development polygon involving these tests. In all tests, HCI was able to show that the impact to hydrologic conditions would increase as the intensity development increases and as the buffer width decreases for both the Natural and Euclidean flow paths. For each test the Euclidean score is greater than the Natural flow path score.

Figure 21. Location of the development polygon for testing HCI results for low, medium, and high intensity scenarios at two buffer widths. Results are shown in Table 11.

Table 11. HCI results for different development intensities, 30-m land-cover data, high, medium, and low intensity, buffered from stream at 100 and 200 feet.

Development Intensity & Buffer Size	Grid Flow Path & Distance to Stream	HCI Score	% Change from Existing Cond.	Absolute Change from Existing Cond.
Existing Conditions	Natural_dO_g	0.191	NA	NA
Existing Conditions	Euclidean_dO_g	0.208	NA	NA
Low Intensity, 100-ft Buffer	Natural_dO_g	0.199	4.2%	0.008
Low-Intensity, 100-ft Buffer	Euclidean_dO_g	0.227	8.8%	0.018
Medium-Intensity, 100-ft Buffer	Natural_dO_g	0.209	9.1%	0.017
Medium-Intensity, 100-ft Buffer	Euclidean_dO_g	0.247	18.7%	0.039
High-Intensity, 100-ft Buffer	Natural_dO_g	0.217	13.4%	0.025
High-Intensity, 100-ft Buffer	Euclidean_dO_g	0.265	27.4%	0.057
Low Intensity, 200-ft Buffer	Natural_dO_g	0.196	2.3%	0.004
Low Intensity, 200-ft Buffer	Euclidean_dO_g	0.218	4.9%	0.010
Medium Intensity, 200-ft Buffer	Natural_dO_g	0.201	4.9%	0.009
Medium Intensity, 200-ft Buffer	Euclidean_dO_g	0.230	11.5%	0.021
High Intensity, 200-ft Buffer	Natural_dO_g	0.205	7.2%	0.013
High Intensity, 200-ft Buffer	Euclidean_dO_g	0.240	15.4%	0.032

Results of Alternative Futures Scenario Testing

The results from testing the HCI for different development scenarios at both the watershed and sub-basin scale are presented in Table 12 and Figure 22. A green infrastructure scenario was included. Green infrastructure "uses vegetation, soils, and other elements and practices to restore some of the natural processes required to manage water and create healthier urban environments[26]" For this test we applied a "green infrastructure" matrix (Figure 18) that would reduce the effects of development on water flow processes; this involved surrounding each high intensity development polygon with a naturally vegetated buffer zone.

This test demonstrated that the HCI can contrast and compare the impacts of different development scenarios across an entire watershed.

Table 12. HCI results for conventional and green infrastructure development across Taylor Creek watershed. Scenarios 0-3 have no buffer on the streamline, scenarios 4-10 have a 50' stream buffer.

Scenario	Development Pattern Across Entire Watershed	Natural HCI	Euclidean HCI
0	BACKGROUND HCI	0.184	0.208
1	Low Intensity, no buffer.	0.437	0.440
2	Medium Intensity, no buffer.	0.673	0.674
3	High Intensity, no buffer.	0.880	0.880
4	Low Intensity, 50' buffer.	0.329	0.439
5	Medium Intensity, 50' buffer.	0.488	0.672
6	High Intensity, 50' buffer.	0.631	0.876
7	High Intensity, Green Infrastructure, 50' buffer.	0.275	0.362
8	Medium Intensity, Green Infrastructure, 50' buffer.	0.229	0.294
9	High Intensity/Green Infrastructure Upper; High Intensity Lower Half of Watershed, 50' buffer.	0.459	0.632
10	Medium Intensity/Green Infrastructure Upper; High Intensity Lower Half of Watershed, 50' buffer.	0.438	0.598

[26] EPA Green infrastructure webpage: https://www.epa.gov/green-infrastructure/what-green-infrastructure

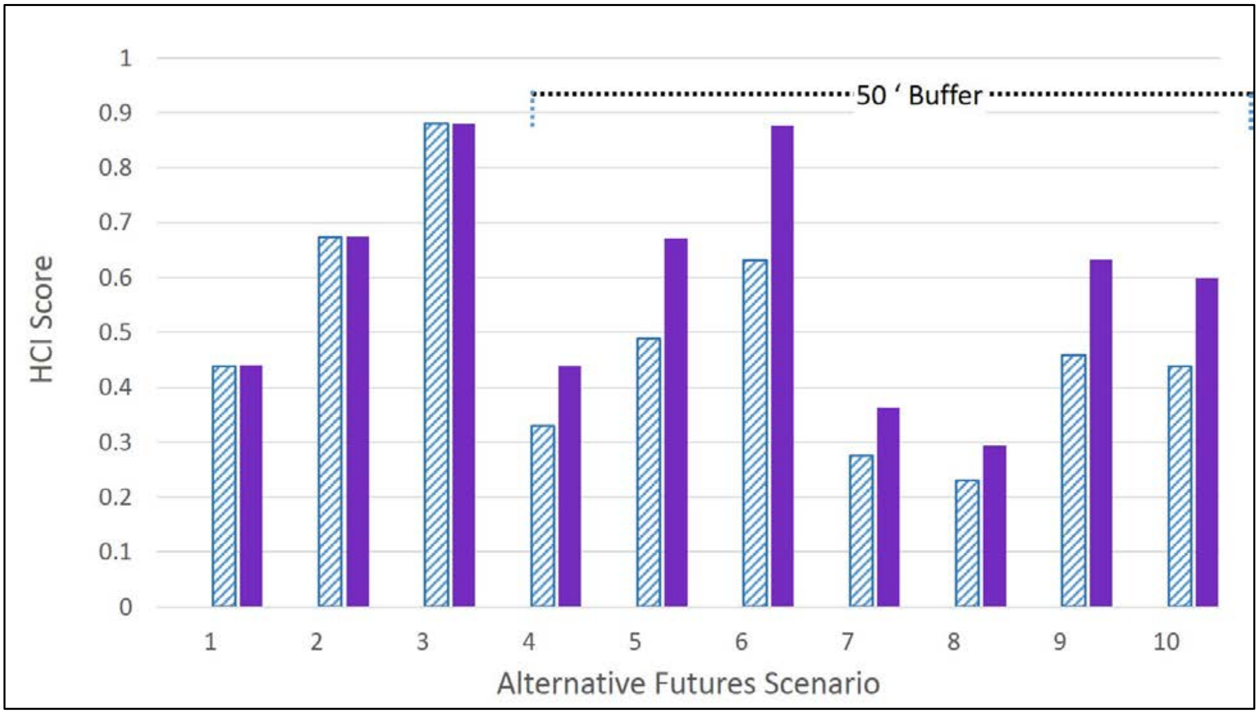

Figure 22. HCI scores for the ten Alternative Futures scenarios as described in Table 12, showing both routing schemes. The dashed bars indicate the Natural flow path, solid fill is for the Euclidian flow path. HCI scores from left to right are: (scenarios 1-3) for conventional development, no buffers, low, medium, and high intensity; (scenarios 4-6) same development with 50-ft stream buffer; (scenarios 7-8) medium and high intensity development with green infrastructure measures & 50-ft stream buffer; (scenarios 9-10) green infrastructure only in upper watershed for medium and high intensity development; and conventional in lower half, all with 50-ft buffers.

These results show the relationship between HCI and different hypothetical development scenarios that vary intensity, location, distance from streams and green infrastructure measures. The HCI score is greater (more impact to watershed hydrology) for higher intensity development that is located closer to a stream (scenarios 1, 2, 3) and significantly less when green infrastructure measures (scenarios 7 and 8) are applied.

Results for HPC Coefficient Development in Different Puget Sound Watersheds

Calibration of VELMA and HSPF

EPA staff at the Office of Research and Development in Corvallis, Oregon, assisted the Ecology and consultant team in calibrating VELMA in the Taylor Creek watershed. The results of the calibration demonstrated that the VELMA model consistently underestimated the total yearly flow for Taylor Creek and over-estimated the number of high pulse counts relative to the gage records (Table 13). The R^2 for calibration 3, which showed the best fit to the gage hydrograph, was 0.58.

Table 13. Taylor Creek watershed: high pulse counts derived from the VELMA calibration compared to actual stream gage data for years 2014-2017.

Year	Calibration 1	Calibration 2	Calibration 3	Gage
2014	18	22	26	22
2015	20	23	23	15
2016	17	18	19	11
2017	14	16	17	15
Total	**51**	**57**	**59**	**41**

In comparison, the statistical analysis completed by King County for the earlier HSPF model calibration in six WRIA 9 watersheds was variable (Table 14). For example, the Hamm, Black, and Newaukum watersheds showed similarly low R^2 values, but values were much higher on the Walker and Miller watersheds. King County relied on these calibrated HSPF models to establish HPC_{coeff} values for the HCI algorithm. Subsequently, the Ecology and consultant teams also relied on these calibrated HSPF model outputs for development and testing of the HCI. Variability of the earlier HSPF model calibration results suggests that additional validation of existing HPC values and resulting coefficients may be warranted, and would be necessary for HCI application outside of the east central Puget Sound region.

If VELMA is used to develop HPC_{coeff} values in different regions of Puget Sound, then it needs to be tested in several watersheds for each region, similar to what was done for the King County 2014 Critical Areas Ordinance (CAO) report (Lucchetti et al. 2014). However, based on the results of the HPC calibration, it was determined that VELMA could not be used for this study to validate existing HPC_{coeff} values.

Table 14. High Pulse Count statistics for the HSPF model calibrations for six watersheds in King County (King County CAO effectiveness report, Lucchetti et al. 2014).

Statistics on HPC	Black	Hamm	Big Soos	Walker	Miller	Newaukum
R-square	0.47	0.47	0.65	0.80	0.82	0.46
Number of Observations	**11**	**6**	**5**	**4**	**8**	**5**

Overall Results for Hypotheses Testing

The two following hypotheses were tested:

1) The correlation between the HCI scores and high pulse counts will be similar at different resolution and flow networks.

2) The HCI will be able to detect differences in hydrologic impacts for development of different sizes, densities and location depending only on the resolution of land cover data.

The results of testing demonstrate that hypothesis #1 was not met, since the correlation between different combinations of grid resolution, flow network, and distance variable was not "similar" This results in a recommendation that matches the different combinations with a specific application (see the recommendations in next section for flow routing, resolution, distance variable, and application throughout Puget Sound).

For hypothesis #2, the testing suggests that the HCI will be able to detect differences in hydrologic impacts for development of different sizes, densities and location.

Thus, the HCI can yield meaningful results relevant to hydrologic and biological (B-IBI) data for the test watersheds if the appropriate combination of resolution, flow routing, and distance variable is applied to answering a specific land-use question. For example, the HCI should not use the combination of 30-meter resolution land-cover data with Natural flow routing and the dO_g distance variable to assess the impact of future development at the sub-basin to catchment scale (e.g., 100's+ acres). Instead, the 1.8-meter, Natural flow and dO_g variable combination should be used on a case-by-case basis for development projects operating at the sub-basin to catchment scale. Planning questions at the broader scale should be addressed, if possible, by the combination of 30-meter resolution, Natural flow network with the dO_g distance variable.

Based on the results above, the key principals that describe how the HCI is expected to work based on the HCI algorithm, the resolution of the grids, and the flow path selected, are as follows:

1) Distance from stream. The influence of land-use types (different intensity of development) on the HCI score[27] decreases with distance from a stream.

Based on Van Sickle and Johnston (2008), Lucchetti et al. (2014), and our test results, we have determined that the inverse distance calculation (1/distance) appropriately weights the influence of land-use on stream flashiness (e.g. HPC).

2) Distance variable. The distance overland variable provides optimal HCI results.

The distance overland to the stream, dOg variable, provides HCI results that are more closely correlated with gage data relative to the dSg+dOg combination for the 1.8-meter resolution grid.

3) Grid Resolution. HCI scores tend to be higher for lower resolution land-cover data.

The testing involved use of 1.8-meter and 30-meter resolution grids for land cover. The 1.8-meter resolution grid uses land-cover data from King County, whereas the 30-meter grid uses land cover data from the CCAP. The 1.8-meter data provide for a more accurate delineation of land cover type, while the lower resolution 30-meter data tends to overestimate the amount of both forest and urban cover within a watershed. This generally increases the influence of urban land cover on the HCI score since the urban cover is assigned a significantly greater high pulse

[27] A higher HCI score indicates that hydrologic conditions are more degraded relative to a lower score.

count relative to forest cover (e.g., Hamm Creek, 2.39 HPC for forest and 34.36 HPC for paved road).

4) Natural Flow Path. The Natural flow path grid provides a higher correlation with stream-gage data, relative to a Euclidean flow path.

The HCI can use either a Euclidian or Natural flow path routing grid for the distance calculation portion of the HCI algorithm. The Euclidian path was included in the testing because it requires less time to develop a Euclidian flow path for a watershed, which will be an important consideration if the mid-scale assessment tool is employed throughout Puget Sound.

Testing of these two approaches to incorporating flow distance grids demonstrated that the Natural flow path generates HCI scores that are more highly correlated with stream-gage data (Table 8) in the eight test watersheds.

5) Euclidian Flow Path. The Euclidian flow path provides a higher HCI score than a Natural flow path.

The Euclidian flow path generates an HCI score that is generally higher than that obtained with the Natural flow path (Tables 10 and 11). This is because the Euclidian flow path is either the same or shorter distance than the Natural flow path for a given grid cell to the streamline, which increases the influence of the HPC_{coeff} in the distance calculation and subsequently raises the HCI score.

Recommendations

Recommendation for Flow Routing and Grid Resolution

The 1.8-meter resolution grid with Natural routing for only the overland distance (dO_g) is most closely correlated with HPCs calculated from the stream-gage data for the test watersheds (Table 8). The 1.8-meter resolution grid using Euclidean routing for only dO_g also provides close correlation (Table 8). The 30-meter resolution grid evaluated with no distance variable appears to have the lowest correlation (Table 8). These results, and results of the 1.8-meter resolution grid evaluated with no distance variable, show that inclusion of distance in the HCI algorithm improves correlation to stream-gage data for the test watersheds. However, the 30-meter resolution grid evaluated with Euclidean routing alternatives also shows low correlation (Table 8).

For applications relying on a 30-meter resolution grid (e.g. land cover data available Puget Sound-wide), the results show that Natural routing under both dO_g + dS_g (Table 8) and dO_g only, (Table 8) provide relatively high correlation to stream-gage data. If, however, only 30 meter resolution grid data is available and resources are not available to create a natural flow grid, then the Euclidean routing using dO_g is acceptable for generating a HCI score at a watershed-scale; this score will still provide a useful measure of the hydrologic condition that can be compared with the HCI scores for other watersheds using the same data resolutions, flow path and distance variable.

Recommendation for Distance Variable in the HCI Algorithm

For selecting which distance variable to use, the dO_g variable (Table 8) provides results that are more closely correlated with gage data relative to the dS_g+dO_g combination for the 1.8-meter resolution grid. It was also demonstrated in Table 8 that use of the dO_g variable may prevent an unintended spatial weighing with HCI scores when using both dO_g and dS_g variables; such a weighting would encourage locating impervious cover in the headwaters of watersheds, which has a greater hydrologic and ecological impact than locating such cover lower in a watershed.

However, it should be noted that other types of watersheds relative to the test watersheds, in terms of size, shape (e.g. linear vs oval), stream density and topography may produce different results for the distance variable than encountered for the King County area. It is important, therefore, that future distance variable testing include these other factors.

Recommendation for Application of HCI Puget Sound-wide

Overall, the results suggest the following four alternatives for further testing and application throughout Puget Sound:

1) 1.8-meter resolution, Natural flow, dO_g distance variable.
2) 1.8-meter resolution, Euclidean flow, dO_g distance variable.
3) 30-meter resolution, Natural flow, dO_g distance variable.
4) 30 meter resolution, Euclidean flow, dO_g distance variable.

The alternatives are listed in order of decreasing correlation. Two of the 30-meter test runs are included for consideration, despite their lower correlation values, because implementation is easier and it is the only possible approach in many areas of western Washington, given current data availability. All four of these alternatives rely on the dO_g distance only, based on results of alternative tests within the Webster Creek watershed showing the unintended effect of spatial weighing associated with inclusion of the dS_g distance (i.e., concentrating new development within the upper watershed). However, as noted in the distance variable recommendation, future testing of the HCI in other regions of Puget Sound may change the correlation results and the priority of alternatives presented in Table 8.

Each of these three alternatives could be integrated and useful within the suite of PSWC assessment tools. **HCI assessment using 1.8-meter or greater resolution with Natural flow routing for the dOg distance would provide the most accurate representation of effects of existing and future development on the hydrology of stream systems in rural and developing watersheds.** This alternative would be most useful at a sub-basin and subarea scale (0.5 to 10 sq. miles) where high-resolution land-cover data are available. Suitable applications include determining the effect of specific development proposals and Alternative Futures scenarios on sub-basin hydrology. Local government data and resources would be supported by Ecology PSWC staff, who are available to provide technical assistance in application of this method.

Additional recommendations for basin-wide application are as follows, in order of priority:

1) **Application of the HCI at the Watershed Management Unit[28] scale using 30-meter resolution land-cover data, with Natural flow (Euclidean acceptable if resources are not available to create a natural flow grid) and the dO_g distance variable.** The products would include HCI scores for: (a) existing conditions; (b) future buildout (i.e., Alternative Futures scenarios) using conventional development patterns at low, medium, and high intensity; and (c) future buildout using "green infrastructure" methods for medium- and high-intensity development.

2) **Application of the HCI at the sub-basin to catchment scale using the 1.8-meter resolution land-cover data, with Natural or Euclidian flow and the dO_g distance variable.** This application would be on a case-by-case basis and reserved primarily for addressing the effects of specific development proposals on basin hydrology. This application would be best suited for the "Alternative Futures tool" that could eventually be designed for use on the PSWC website.

Recommendation for Assessing Implications of Alternative Futures Scenarios

The results of the Alternative Futures scenario testing at the watershed scale (Figure 22) indicate that the HCI tool will allow local governments to compare the hydrologic impact of conventional development at different densities, with and without stream buffers, relative to development using green infrastructure measures. It is less useful, however, for making comparisons on an "absolute" basis on its own. The results provide an initial picture of what the HCI scores mean in terms of the severity of an impact on watershed hydrology. This is improved with knowledge and data of how intense land uses and cover impact hydrologic processes, which can be used in combination with biological indicators such as B-IBI to illustrate broader impacts. The B-IBI scores can be used with HCI to establish hydrologic condition categories to communicate things like risk to watershed hydrology from given development trajectories. Ideally, these categories can be developed and applied systematically throughout Puget Sound.

Recommendation for Developing and Testing HPC_{coeff} in Other Regions of Puget Sound and Validating the HCI Scores

The HCI was originally calibrated for lowland watersheds in the east central Puget Sound, which include WRIAs 7, 8, and 9. The calibration was completed using HSPF model runs in WRIA 9. The HSPF model runs were specifically designed to identify the high pulse values (and eventually HPC_{coeff}) for 12 different land-cover types on both till and outwash deposits (Appendix B). However, the relative response of hydrologic processes modeled in WRIA 9 cannot be assumed to be the same throughout Puget Sound. Therefore, it will be necessary to develop different sets of high pulse coefficients for different regions of Puget Sound, which are described in Appendix E along with the potential methods for calibration.

[28] A Watershed Management Unit is a sub-basin within a WRIA (100s of square miles) that typically encompasses an entire named stream system (10s of square miles).

Considering that the VELMA model requires considerably more time and skill to set up, calibrate, and run relative to HSPF, and because there are already numerous HSPF-calibrated watersheds throughout Puget Sound, it is recommended that the efforts for developing other regional coefficients for Puget Sound be followed in order of priority:

1) Identify existing HSPF-modeled watersheds in Puget Sound, compare the HPC values generated (validation between measured and modeled), and match based on size, shape, surficial geology, land cover, and region. Use this comparison to develop new HPC_{coeff} values.

2) Following additional successful calibration of VELMA, run the model in the Taylor Creek during further implementation and development of mid-scale assessment tools for the various Alternative Futures scenarios, and compare results for plausibility and utility.

Appendix B. King County HPC Values

Note that the values for each combination of geology and land cover were averaged across the five watersheds in order to obtain the HPC coefficients for use in the HCI algorithm.

Table 15. HPC values and resulting average coefficient (HPC AVG) for various land cover types on till surficial geology.

Land Cover on Till	Hamm Creek (set 1)	Miller Creek (set 2)	Des Moines Creek (set 3)	Newaukum Creek (set 4)	Duwamish Creek (set 5)	HPC AVG
forest	2.393443	2.672131	3.655738	4.606557	7.04918	4.07541
shrub	2.639344	3.311475	4.47541	6.016393	7.081967	4.704918
pasture	2.803279	4.032787	4.622951	6.590164	7.606557	5.131148
wetland	2.901639	4.868852	4.540984	7.52459	8.245902	5.616393
clear cut	3.819672	5.032787	5.360656	8.606557	8.803279	6.32459
grass	5.672131	5.213115	6.032787	9.983607	8.47541	7.07541
bare	5.114754	8.52459	7.901639	10.508197	11.459016	8.701639
building	30.508197	34.803279	33.491803	29.622951	31.836066	32.052459
pavement	26.540984	36.885246	36.508197	34.032787	35.737705	33.940984
open water	27.934426	38.163934	38.131148	36.655738	37.786885	35.734426
unpaved road	33.983607	37.180328	36.901639	34.754098	36.672131	35.898361
paved road	34.360656	37.655738	37.344262	35.180328	37.213115	36.35082

Table 16. HPC values and resulting average coefficient (HPC AVG) for various land cover types on outwash surficial geology.

Land Cover on Outwash	Hamm Creek (set 1)	Miller Creek (set 2)	Des Moines Creek (set 3)	Newaukum Creek (set 4)	Duwamish Creek (set 5)	HPC AVG
forest	2.213115	2.065574	3.360656	3.688525	5.42623	3.35082
shrub	2.229508	2.131148	3.393443	4.540984	5.57377	3.57377
pasture	2.295082	2.213115	3.262295	6.081967	5.52459	3.87541
clear cut	2.295082	2.213115	3.262295	6.081967	5.52459	3.87541
grass	2.606557	2.032787	3.409836	5.655738	5.704918	3.881967
bare	3.245902	3.311475	4.557377	7.639344	7.852459	5.321311
wetland	2.901639	4.868852	4.540984	7.52459	8.245902	5.616393
building	31.409836	35.459016	33.245902	31.737705	31.983607	32.767213
pavement	26.57377	37.114754	36.47541	35.04918	35.622951	34.167213
open water	27.639344	38.081967	37.934426	36.606557	37.819672	35.616393
unpaved road	34.016393	37.52459	37.04918	35.491803	36.819672	36.180328
paved road	34.196721	37.672131	37.229508	35.868852	37.098361	36.413115

Appendix C. Regression Results for Grid Size and Routing Testing

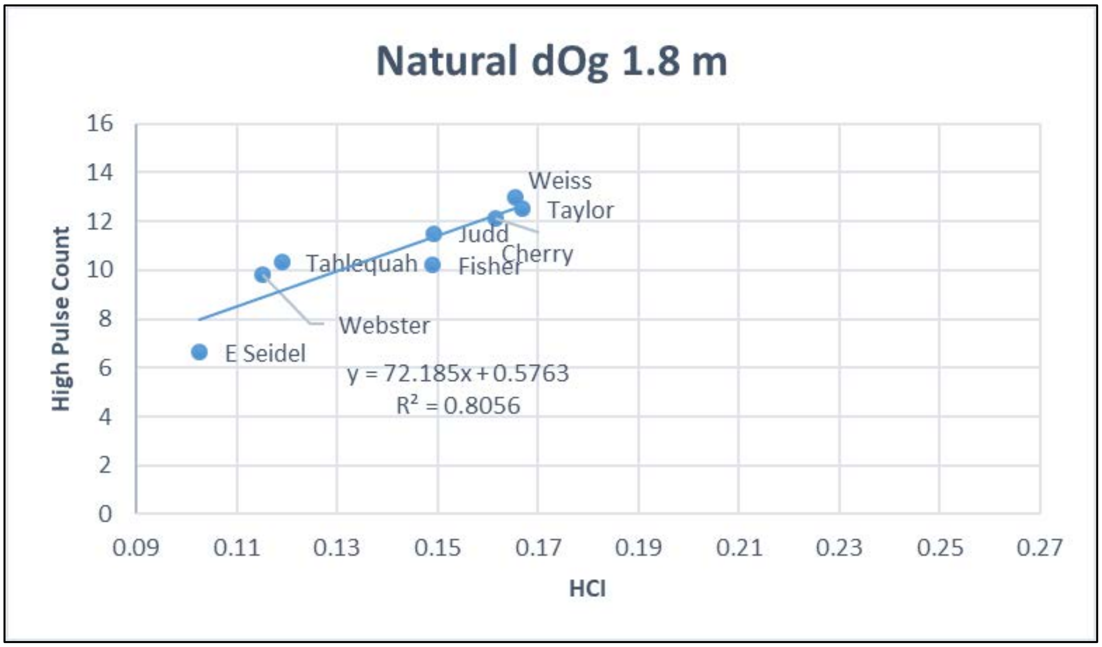

Figure 23. Regression analysis results for 1.8-meter Natural dOg.

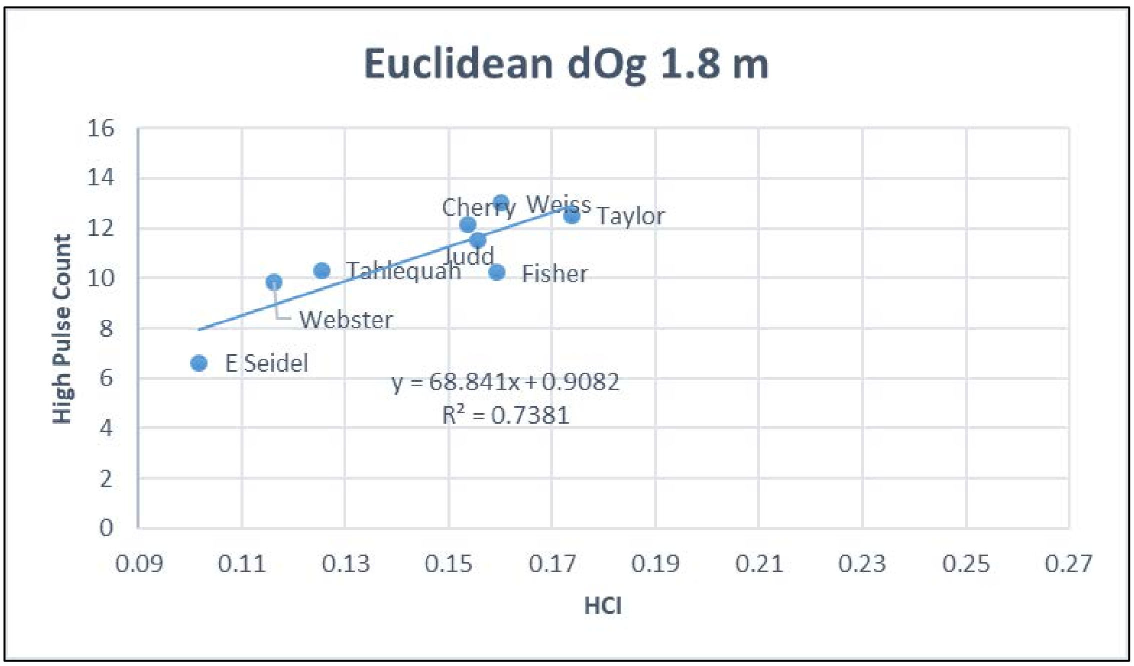

Figure 24. Regression analysis results for 1.8-meter Euclidean dOg.

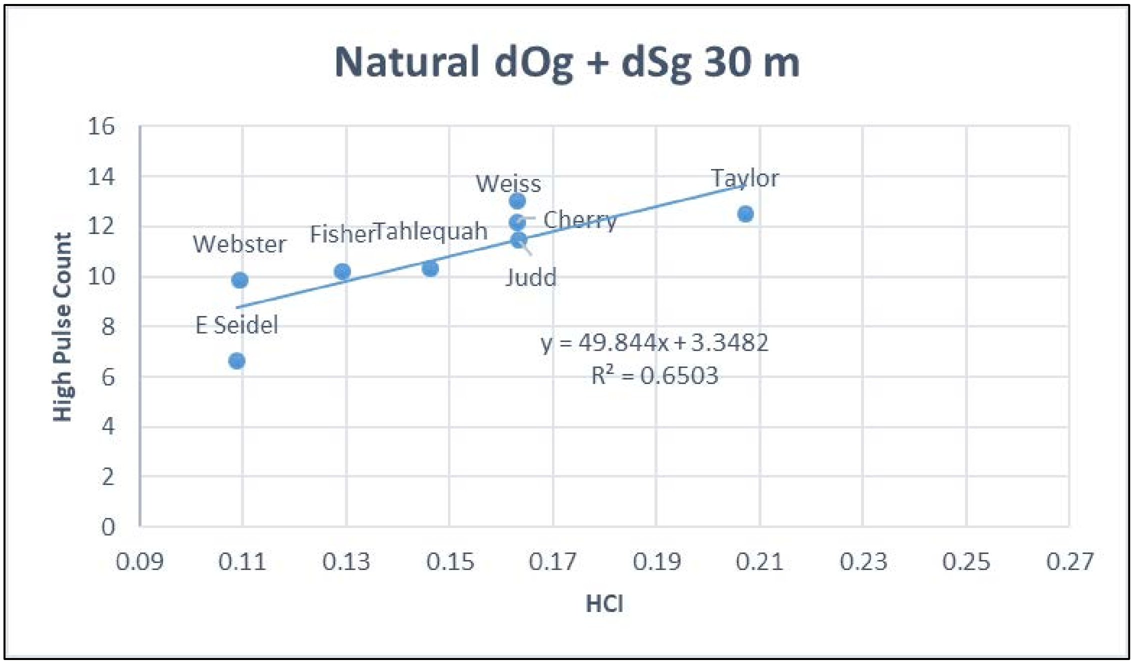

Figure 25. Regression analysis results for 30-meter Natural dOg+dSg.

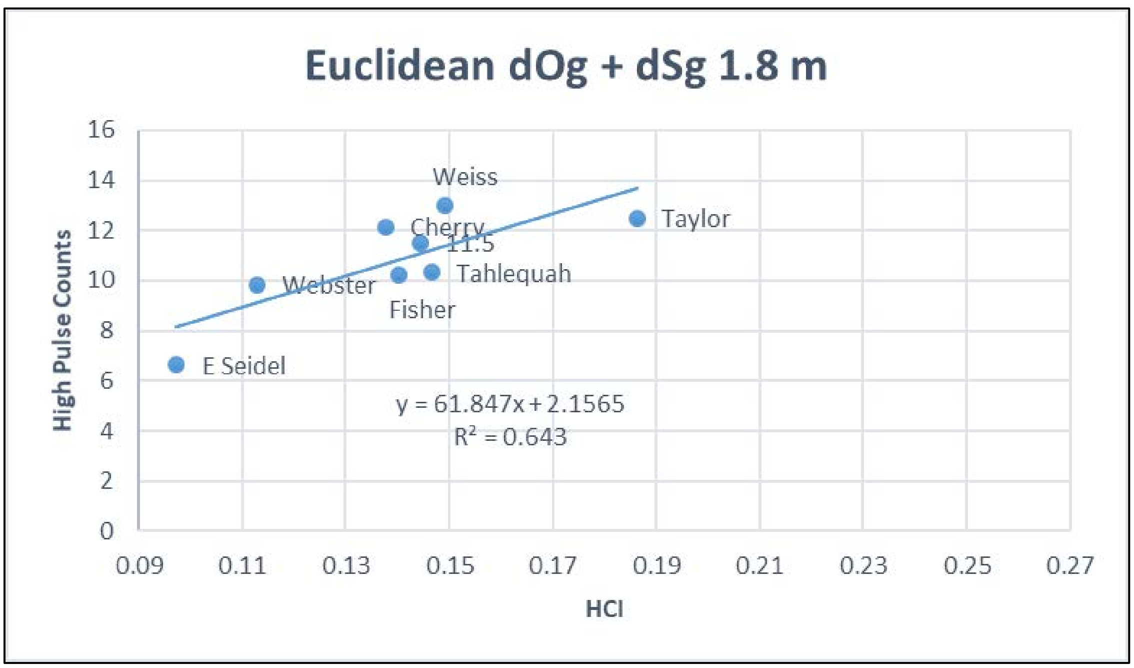

Figure 26. Regression analysis results for 1.8-meter Euclidean dOg+dSg.

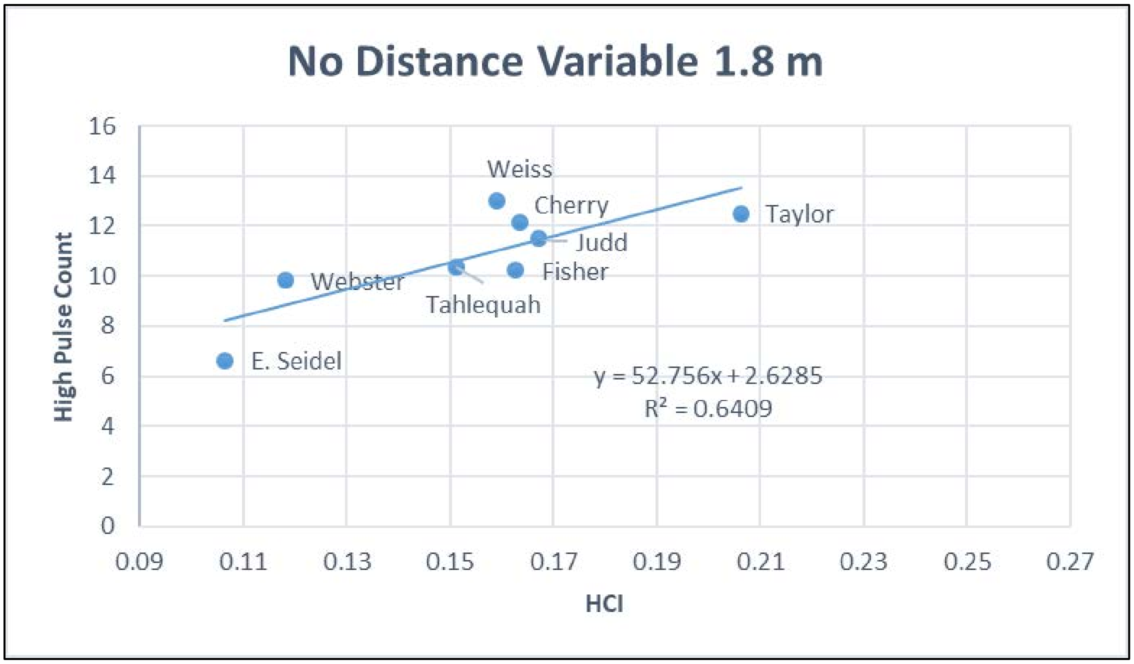

Figure 27. Regression analysis results for 1.8-meter with No Distance factor.

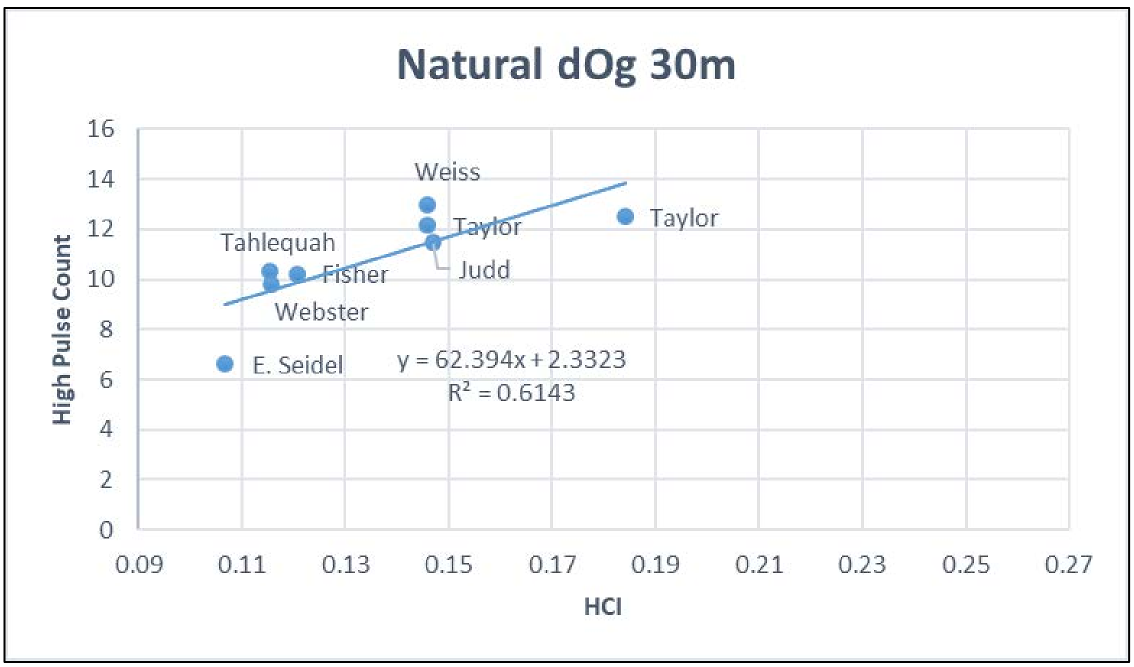

Figure 28. Regression analysis results for 30-meter with Natural dOg.

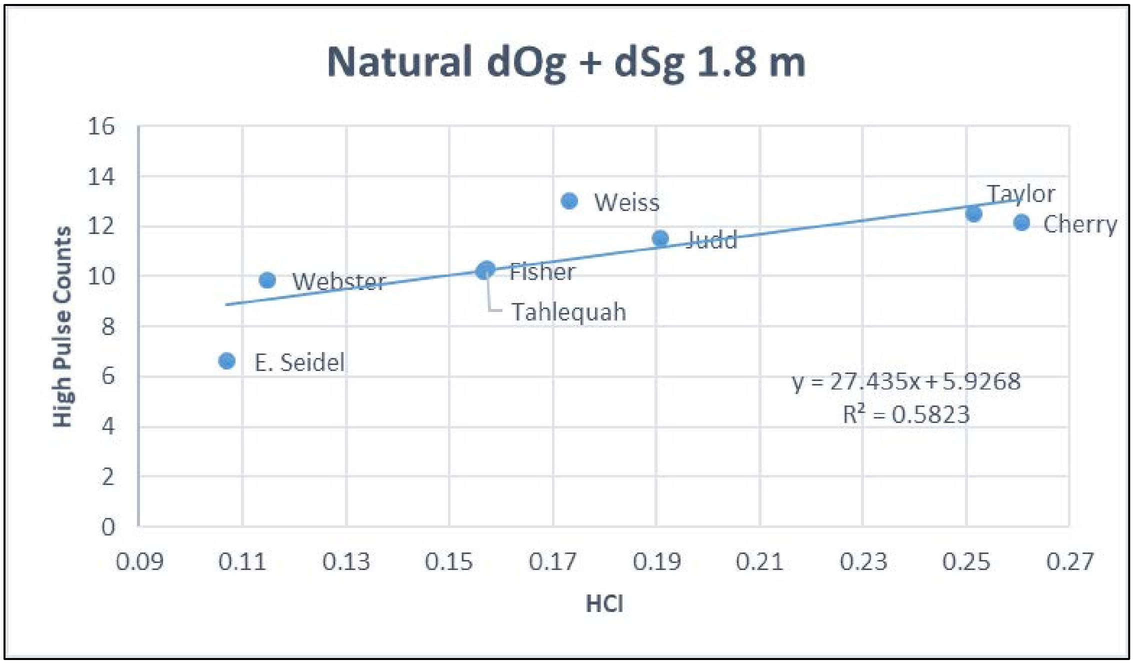

Figure 29. Regression analysis results for 1.8-meter with Natural dOg + dSg.

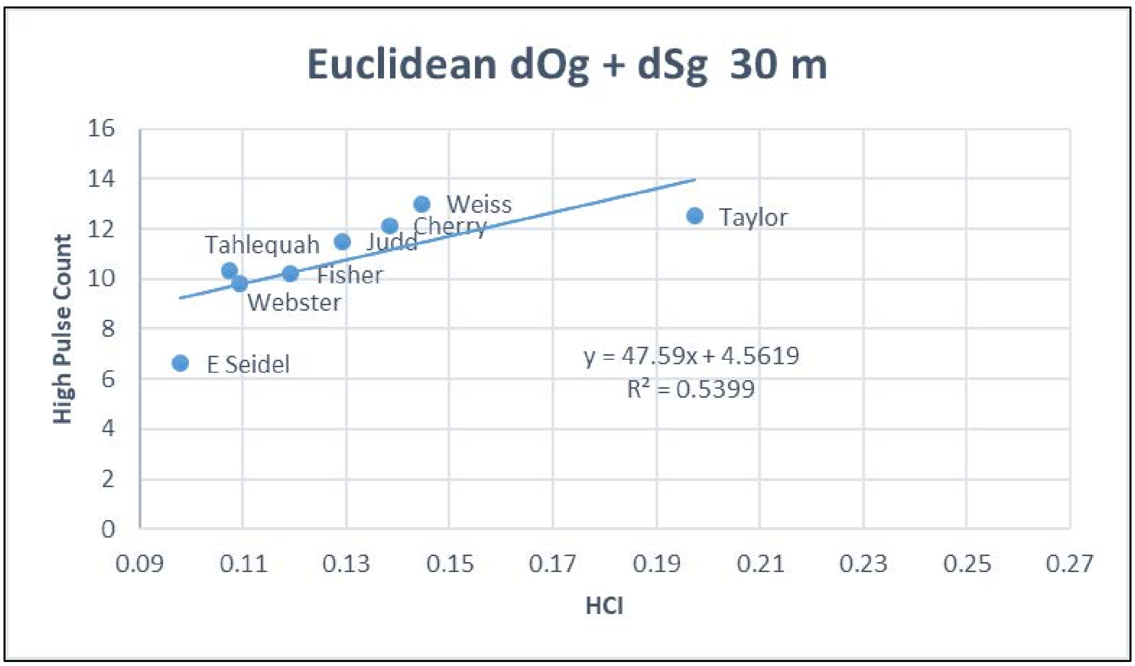

Figure 30. Regression analysis results for 30-meter with Euclidean dOg + dSg.

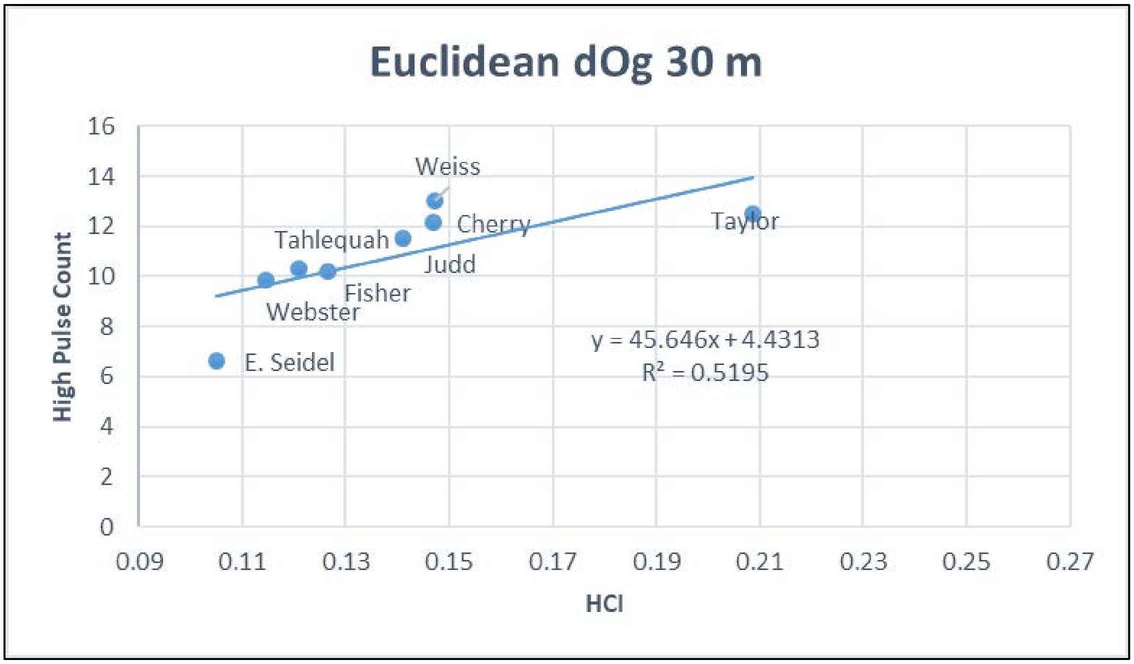

Figure 31. Regression analysis results for 30-meter Euclidean dOg.

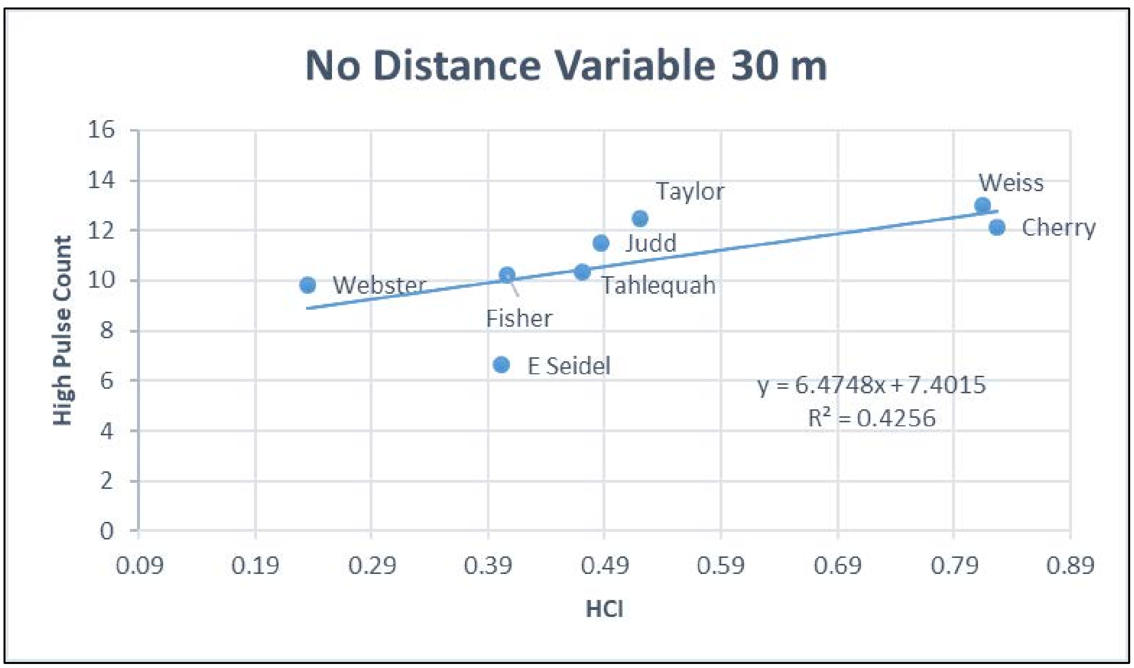

Figure 32. Regression analysis results for 30-meter with No Distance factor.

Appendix D. Uncertainty Testing

WAG members recommended performing some uncertainty testing, which was unfortunately outside of the scope of the current project. The following describes an initial approach to uncertainty testing which could be performed in the future.

The HPC_{coeff} come from one "Universal Set" (Appendix B - mean values of the five King County subsets provided for specific watersheds). The goal is to determine the uncertainty associated with using this Universal Set of HPC_{coeff}. Below we've presented a few options for what this uncertainty test could look like – all relatively simple, and all helping us to assess the uncertainty associated with our current Universal HPC_{coeff} set approach.

Based on internal discussion within the consultant team and input from a small group of WAG members, ESA proposed three different methods for a relatively simple uncertainty test focused on the mean 'universal' HPC_{coeff} set. These methods seek to enforce a key recommendation to hold HPC_{coeff} values together (as opposed to selecting individual HPC_{coeff} values between the sets that King County established using HSPF for six lowland watersheds; as a reminder, the current HCI approach being implemented is a mean value set to assign HPC_{coeff} values).

1. Discrete Values Only: If we assume that the HPC_{coeff} can only be sampled from five distinct sets, and the individual values cannot jump from one set to another, then we reduce the magnitude of the uncertainty assessment considerably. In that case, no statistical random resampling would be necessary. Under that assumption, the revised uncertainty assessment would only consist of calculating the HCI using the five sets (i.e., five separate runs, each applying the HPC coefficients from a given set) for a given study basin. Output could then report the mean value of the HCI, the lower bound, and the upper bound.

2. Interpolated Values: This approach is an extension of method 1 above. The set of HPC_{coeff} can serve as a base grid to calculate a continuously varying set of HPC_{coeff}, using parametric interpolation. This would ascertain that values are "kept together," but are allowed to continuously span the range of HPC values defined in the sets. The value of method 2 is that it allows us to visualize what happens in between sets.

3. (Unlinked/Linked) Non-parametric Approach:
    1. Estimate an empirical distribution for each HPC coefficient assigned to a land use/land-cover (LULC) type using a random resampling method with replacement; this defines a composite set of HPC_{coeff}.
    2. Proceed in two ways: (a) draw a random value for each HPC_{coeff} for each simulation; or (b) extract values for all HPC_{coeff} using a single exceedance probability for each simulation, i.e., "linked." We note that in this case, "keeping values together" is limited because our starting point is a composite set. The goal of this experiment is to assess the uncertainty around each universal value, and see how this affects the end result.
    3. For a given watershed, do the following as many times as there are simulation experiments:
        a. Lookup random value of the HPC coefficients, based on method retained in Step 2.

    b. Calculate the HCI for each simulation.
    c. Store that value along with all other completed simulation experiments.
4. Evaluate descriptive statistics on the HCI scores obtained above; report lower & upper bound, and central estimates.

Table 17 below shows the main details of how each method could be implemented. The initial recommendation is to proceed with method 3 detailed below using sub-method (a), as it will provide a more comprehensive assessment.

Table 17. Uncertainty testing methods considered by Ecology

Method	1. Discrete Values	2. Interpolated Values	3. (a Unlinked/ b Linked) Non-parametric Approach
Approach	Assess impact of using sets of HPC coefficients on the final HCI score; simply changes values of HPC coefficients based on 1 of 5 sets. Selected HPC_{coeff} values are not allowed to jump from one set to another.	Assess impact of using sets of HPC coefficients on the final HCI score; make use of the whole spectrum of values offered by the 5 sets. Again, the scanning will proceed linearly so that values are "kept together."	Apply a non-parametric bootstrapping method to assess empirical distribution of HPC coefficients for each LULC type. Random values are either (a) *independently generated for each simulation,* or (b) generated using a single exceedance probability to "keep values together."
Based on	5 specific HPC datasets	5 specific HPC datasets, interpolated parametrically.	A composite set of HPC_{coeff} derived from the 5 specific HPC datasets, with some characterization of uncertainty.
Number of experiments per study basin	5	Any number of experiments, as needed to provide smooth coverage of HCI variations (40 values would probably be sufficient).	500–1,000 per study basin.
Pros	Parsimonious method	Allows a greater combination of values for HPC coefficients, while abiding to the "keep together" condition; may detect peaks or trough not detected by the Discrete Value method.	Provides a comprehensive assessment of uncertainty.
Cons	Limited to 5 tries for HPC coefficients for a given study basin.	Burdensome; does not provide values outside the range already built into the HPC coefficient table. Not a full uncertainty assessment method.	Burdensome; simulation experiment will not provide more information than what we already have. The assumption of "keeping values together" does not apply fully because we are now using a universal set to describe HPC_{coeff}.

Method	1. Discrete Values	2. Interpolated Values	3. (a Unlinked/ b Linked) Non-parametric Approach
Computational burden	Low: could be performed on-the-fly for any study basin.	High: cannot be repeated for each study basin.	High: cannot be repeated.
HCI reporting	Mean value, lowest value ("lower bound"), highest value ("upper bound").	Same as Discrete Value method.	Same as Discrete Value method, but at the 5% level.

Appendix E. Calibration of HCI Model for Additional Regions in Puget Sound

Development of HPC coefficients for other regions of Puget Sound is a necessary next step to providing a more broadly applicable and useful tool. Other regions in Puget Sound which may need specific calibrations include the northwest, east-central, south, west-central, west, Strait of Juan de Fuca, and the islands, are described in Appendix E. For each region, average annual precipitation patterns from NOAA weather stations accessed through the "Find a Station" website (available: https://www.ncdc.noaa.gov/cdo-web/datatools/findstation) are referenced.

Northwest Puget Sound. This region includes the lowland areas of WRIA 1 (Whatcom County) and WRIAs 3 and 4 (Skagit County). Topography consists of large glacial outwash and lacustrine plains in WRIA 1, and plains formed by lahars and riverine processes (alluvial deposits) in WRIA 3. Surficial geology is dominated by marine lacustrine deposits, glacial drift deposits, and alluvium in WRIA 1, and by lahar and glacial drift deposit and alluvium in WRIAs 3 and 4. Precipitation is rainfall dominated with an average annual rainfall of 36 inches (NOAA, Bellingham station). The upper, mountainous portions of the larger lowland rivers are snow dominated (e.g. Nooksack, Skagit).

East-Central Puget Sound. This region includes the lowland areas of WRIAs 5, 7, 8, and 9. The watershed area covered by WRIAs 5, 7, 8, and 9 is characterized by a glacial drift surficial geology comprised primarily of compacted till deposits in association with recessional and advance glacial deposits that are found on terraces and terrace faces with lacustrine deposits on valley walls of major river valleys and alluvial deposits in many of the major floodplains. Precipitation in these lowland watersheds is rain dominated with an average rainfall of approximately 37 inches (NOAA, SeaTac station). The hydrology of lowland watersheds associated with medium to large river systems such as the Cedar River, Snoqualmie River, and Issaquah Creek is also influenced by snowmelt and rain-on-snow processes originating in the upper mountainous portions of these watersheds.

South Puget Sound. This region includes the lowland areas of WRIAs 10, 11, and 12. This area is characterized by the southern extent of glacial drift in Puget Sound that formed large plains at the terminus of the glaciations. This includes complex outwash plains with moraine and ice deposits, combined with pockets of glacial till and alluvium and with lahar deposits (found primarily in WRIA 10). Precipitation in these lowland watersheds is rain dominated with an average rainfall of approximately 50 inches (NOAA, Olympia Station).

West-Central Puget Sound. This region includes the lowland areas of WRIA 15 (Kitsap County). Terrace topography is dominated by glacial drift deposits, including till and outwash and areas of alluvium deposits in river valleys. Precipitation is entirely rain dominated and averages 40 inches per year. Geologically, the area is similar to the East Central lowland region.

West Puget Sound. This region includes the lowland areas of WRIA 16 (Jefferson County). These steep watersheds originate in the Olympic Mountains and plunge directly into Hood Canal, with relatively narrow coastal plains. As such they are primarily influenced by the snow-dominated hydrology of the mountainous portions of these watersheds. The lowland geology is a combination of glacial drift (till and outwash), bedrock, and alluvial deposits in the river valleys. Average annual precipitation is 60 inches.

Strait of Juan de Fuca. This region includes the lowland areas of WRIAs 17, 18, and 19. Topography consists of lowland drift plains in WRIA 17 (Port Townsend) consisting of till, outwash, and alluvium, to large river deltas formed on the Dungeness and Elwha rivers. The lowland areas are rain dominated, but the upper watersheds of most of the rivers originates in the Olympics and their hydrology is governed by snow-dominated processes. Annual rainfall in the lowland portions is approximately 15 inches.

Puget Sound Islands. This region includes the San Juan Islands complex (WRIA 2) and Whidbey and Camano Islands (WRIA 6, Island County). Geology ranges from glacial outwash terraces on Whidbey Island, to bedrock on the San Juan Islands. Both island complexes are rain dominated, with annual precipitation ranging from 27 to 33 inches.

Appendix F. Decision Support Questionnaire and Guidance

The following table shows the guidance for all of the main management categories. Based on what the user selects as the appropriate Watershed Management Category in Step 1, they would only actually see one of these:

High Protection

Full buildout within your watershed could increase risk to intact hydrologic conditions by XX% and move it into a moderate or poor hydrologic condition category.

This may not be appropriate or advisable for your watershed, which is prioritized for High Protection.

Consider the following alternatives in planning for your watershed:

- ☐ Implement “full” protection of riparian zones along streams
- ☐ Reduce land use / zoning intensity
- ☐ Provide permanent conservation of large forested tracts

Existing HCI: __________

Future HCI (traditional): _______ (XX% change)

Future HCI (green):________ (XX% change)

Restoration

Full buildout within your watershed could further increase risk to moderately degraded existing hydrologic conditions by XX%.

This may not be appropriate or advisable for your watershed, which is prioritized for Restoration.

Consider the following alternatives in planning for your watershed:

- ☒ Implement protection and restoration of riparian zones along streams
- ☐ Reduce land use / zoning intensity
- ☐ Provide permanent conservation of large forested tracts

Existing HCI: __________

Future HCI (traditional): _______ (XX% change)

Future HCI (green):________ (XX% change)

Low Protection

Full buildout within your watershed could increase risk to intact hydrologic conditions by XX%.

This may not be appropriate or advisable for your watershed, which has intact processes that should be protected.

Consider the following alternatives in planning for your watershed:

- ☐ Implement increased protection of riparian zones along streams
- ☐ Green development /Clustering to focus higher intensity uses in a smaller area
- ☐ XXXXXXX

Existing HCI: __________

Future HCI (traditional): _______ (XX% change)

Future HCI (green):________ (XX% change)

Restoration and Development

For AUs assigned to this category, a combination of restoration prioritization and development prioritization is likely most appropriate

Development

Full buildout within your watershed could degrade existing “poor” hydrologic conditions by XX% (.

While additional development is likely appropriate in this watershed, which is prioritized for Development, steps to mitigate impacts to downstream resources / remaining high priority areas should be taken.

Consider the following retrofit and mitigation strategies:

- ☐ Restore remaining riparian zones along streams
- ☐ Implement stormwater retrofits
- ☐ XXXX

Existing HCI: __________

Future HCI (traditional): _______ (XX% change)

Future HCI (green):________ (XX% change)

Appendix G. Solution Templates from Volume 1

Abbreviations common to all templates:
Management matrix results: "P" = Protection, "R" = Restoration, "C" = Conservation, "D" = Development.
Water-flow processes addressed by recommended actions: "DE" = Delivery, "SS" = Surface Storage, "RD" = Recharge/Discharge.
Light blue rows indicate solutions common to all management matrix categories; medium blue rows indicate solutions applicable to protection and restoration categories; and dark blue rows indicate restoration categories only.

ALL LAND USES	P	R	C	D
Maintain the physical integrity of stream and wetland riparian zones (DE, SS, RD)	☑	☑	☑	☑
Restore floodplains (reconnect streams, reduce channelization) (SS, RD)	☑	☑	☑	☑
Reduce surface-water diversions (RD)	☑	☑	☑	☑
Restore depressional wetlands and their adjacent riparian zones	☑	☑	☑	☑
Restore/replant riparian zones (RD)	☑	☑	☑	☑
Identify and protect aquifer recharge areas (DE, RD)	☑	☑	☑	☑
For relevant literature see: http://www.ecy.wa.gov/biblio/wetlands.html				

FOREST LANDS	P	R	C	D
Common issues: widespread loss of vegetative cover, particularly in high-elevation snow and rain-on-snow areas, high in watersheds and so affecting many reaches downstream. Creation of new impervious surfaces is rare, although a dense forest road network can greatly alter flow paths and sediment production.				
Reduce number of stream crossings by roads (SS)	☑	☑	☑	☑
Reduce interception of shallow GW in channels and road ditches (RD)	☑	☑	☑	☑
Replant deforested areas (DE)	☑	☑		
Ensure zoning is consistent with long-term protection of resources (e.g., large parcel size; stable urban growth boundary) (DE, SS, RD)	☑	☑		
Decommission and remove unneeded forest roads (SS, RD)	☑	☑		
Increase size of protected areas around streams/wetlands (DE, SS, RD)	☑	☑		

RURAL LANDS	P	R	C	D
Common issues: Rural land use can drain key headwater wetlands, with potentially great effect on downstream flooding and erosion. Septic systems can be a source of nutrients and pathogens. Forest clearing increases overland flows, affecting stream/wetland structure and function. Groundwater withdrawal in rural residential areas can affect downstream discharge areas. For relevant literature see: http://www.ecy.wa.gov/biblio/wq.html				
Require [properly functioning] septic systems (RD)	☑	☑	☑	☑
Emphasize dispersive/infiltrative stormwater management (DE)	☑	☑	☑	☑
Ensure zoning is consistent with long-term protection of resources (e.g., clustered development, stable urban growth boundary) (DE, SS, RD)	☑	☑		
Increase size of protected areas around streams/wetlands (DE, SS, RD)	☑	☑		
Reduce drainage density of artificial channels (SS, RD)	☑	☑		
Revegetate upland areas (DE, SS)	☑	☑		
Reduce GW withdrawals (RD)	☑	☑		
Reduce interception of shallow GW in channels and road ditches (RD)	☑	☑		
Replant deforested areas (DE)	☑	☑		
Set back dikes/levees in key areas to restore overbank flooding (SS)		☑		
Restore stream reaches, floodplains, or wetlands to recover lost processes and functions (SS, RD)		☑		

AGRICULTURAL LANDS	P	R	C	D
Common issues: Extensive drainage system reduces residence time of water on landscape and increases downstream delivery of water, and also compromises water-quality functions of wetlands and floodplains. Potential source of nutrients, pathogens and sediment that impact downstream aquatic area; lack of vegetated buffers increases delivery and transport. Floodplains disconnected from overbank flooding and tidal processes. Groundwater withdrawals and diversions can significantly affect low-flow regimes and wetland hydrology.				
Apply source controls for nitrogen and pathogens (SS)	☑	☑	☑	☑
Allow greater residence time of water on fields and ditches outside of growing season (SS, RD)	☑	☑	☑	☑
Encourage [properly functioning] septic systems (RD)	☑	☑	☑	☑
Ensure zoning is consistent with long-term protection of agriculture and resources (e.g., large parcel size; stable urban growth boundary) (DE, SS, RD)	☑	☑		
Reduce GW withdrawals (RD)	☑	☑		
Reduce drainage density of artificial channels (SS, RD)	☑	☑		
Establish buffers for water-quality improvement in strategic areas (DE, RD)	☑	☑		
Reduce interception of shallow GW in channels and road ditches (RD)	☑	☑		
Revegetate upland areas (DE, SS)	☑	☑		
Set back dikes/levees in key areas to restore overbank flooding (SS)		☑		
Restore degraded stream reaches, floodplains, or wetlands to recover lost processes and functions (SS, RD)		☑		
Restore highly infiltrative soils (RD)		☑		

URBAN & SUBURBAN	P	R	C	D
Common issues: Areas of impervious surface impair multiple water-flow processes, resulting in simplification of habitat structure and functions, and compromising effective restoration of structure and function of aquatic habitat. Significant transport of pollutants generated by urban uses to aquatic areas. Note that development regulations will preempt/supersede some of these recommendations.				
Emphasize dispersive/infiltrative stormwater management (DE, SS, RD)	☑	☑	☑	☑
Increase widths of protected wetland, stream, and marine riparian zones (DE)	☑	☑		
Reduce GW withdrawals (RD)	☑	☑		
Reduce interception of shallow GW in channels and road ditches (RD)	☑	☑		
Revegetate upland areas (DE, SS)	☑	☑		
Retrofit structures and roads for greater infiltration (DE, RD)		☑		
Construct stream reaches or artificial wetlands to recover lost processes and functions if/as feasible (SS, RD)		☑		

Appendix H. Unit Density Calculations for Alternative Futures Scenarios

Based on Pierce County density tables 18A
https://www.codepublishing.com/WA/PierceCounty/#%21/PierceCounty18A/PierceCounty18A15.html

Table 18. Original CCAP land cover calculations.

Land cover	SUM_calc_acres	Percentage	Unit per acre	Units
Deciduous Forest	16.023	0.06	0.0125	0.200
Developed Open Space	40.504	0.16	0.2	8.100
Evergreen Forest	5.118	0.02	0.0125	0.063
Grassland	1.335	0.01	0.2	0.267
High Intensity Developed	1.557	0.01	25	38.946
Low Intensity Developed	59.198	0.23	3	177.596
Medium Intensity Developed	9.124	0.04	6	54.747
Mixed Forest	61.869	0.24	0.0125	0.773
Palustrine Emergent Wetland	0.445	0.00	0	0
Palustrine Forested Wetland	1.780	0.01	0	0
Palustrine Scrub/Shrub Wetland	1.780	0.01	0	0
Pasture/Hay	41.839	0.16	0.2	8.367
Scrub/Shrub	18.694	0.07	0.0125	0.233
TOTAL	**259.273**	NA	NA	289.098

Table 19. Traditional scenario, 80 ft. average buffer.

Land cover	SUM_calc_acres	Percentage	Units per acre	Units
Developed Open Space	22.922	0.088	0.2	4.584
High Intensity Developed	9.347	0.036	25	233.679
Low Intensity Developed	102.151	0.394	3	306.454
Medium Intensity Developed	85.460	0.330	6	512.760
Mixed Forest	38.056	0.147	0.0125	0.475
Palustrine Emergent Wetland	0.445	0.002	0	0
Palustrine Forested Wetland	0.445	0.002	0	0
Palustrine Scrub/Shrub Wetland	0.445	0.002	0	0
TOTAL	**259.273**	NA	NA	1057.955

Table 20. Riparian scenario, 150 ft. average buffer.

Land Cover	SUM_calc_acres	Percentage	Unit per acre	Units
Developed Open Space	19.807	0.076	0.2	3.961
High Intensity Developed	8.011	0.031	25	200.297
Low Intensity Developed	90.356	0.348	3	271.068
Medium Intensity Developed	74.554	0.288	6	447.329
Mixed Forest	65.652	0.253	0.0125	0.820
Palustrine Emergent Wetland	0.222	0.001	0	0
Palustrine Forested Wetland	0.445	0.002	0	0
Palustrine Scrub/Shrub Wetland	0.222	0.001	0	0
TOTAL	**259.273**	NA	NA	923.477

Table 21. Green Infrastructure scenario

Land Cover	SUM_calc_acres	Percentage	Unit Per Acre	Units
Deciduous Forest	10.682	0.041	0.0125	0.133
Developed Open Space	3.115	0.012	0.2	0.623
Evergreen Forest	2.225	0.009	0.0125	0.027
High Intensity Developed	75.445	0.291	25	1886.13
Low Intensity Developed	20.029	0.077	3	60.089
Medium Intensity Developed	20.474	0.079	6	163.798
Mixed Forest	126.409	0.488	0.0125	1.580
Palustrine Emergent Wetland	0.222	0.001	0	0
Palustrine Forested Wetland	0.445	0.002	0	0
Palustrine Scrub/Shrub Wetland	0.222	0.001	0	0
TOTAL	**259.273**	NA	NA	2112.382