

Memorandum

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to Watershed Advisory Group

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Consultant Support by ESA and Stillwater Sciences

subject Updates to the Puget Sound Watershed Characterization
Task 2: Development and Initial Results of Hydrologic Condition Index

Introduction

The overall goal of the Puget Sound Watershed Characterization (PSWC) Update Project (PSWC 2.0 Project) is to develop a multi-scale decision support framework that integrates information from abiotic and biotic assessments, allowing users to:

- Infer root causes of environmental problems in a watershed at multiple scales; and
- Identify solutions at a scale that matches local government management tools (zoning, permitting, development standards).

The original PSWC framework was designed to help users make “watershed-based” land-use decisions at a broad scale (1,000s of acres), supporting the protection and restoration of ecologically important lands, and identifying where development will be least likely to impact watershed processes and functions.

To attain the overall goal of the PSWC of an integrated, multi-scale decision support network, we have initiated the development of mid-scale tools (i.e. 10’s to 100’s of acres), which involve the testing of an index that measures the condition of stream hydrology during peak flow events based on land cover, surficial geology, and distance of respective contributing areas to basin stream network. This index is known as the Hydrologic Condition Index (HCI) method as originally developed by King County (Lucchetti, 2014), and will be tested in nine pilot watersheds (Figure 1) for eventual application as the mid-scale assessment model framework for Puget Sound.

This memo presents the results of Task 2 of the work plan for the PWSC 2.0 Project. Task 2 involved applying the HCI method in eight test watersheds at different resolutions and routing methods (see Task 2 of the PWSC 2.0 Project Work Plan in Appendix A).

Study Area

The study area for testing the HCI method 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 are located in central Puget Sound and distributed across rural King County (Figure 1). 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 eastern edge of the Puget Lowland Ecoregion.

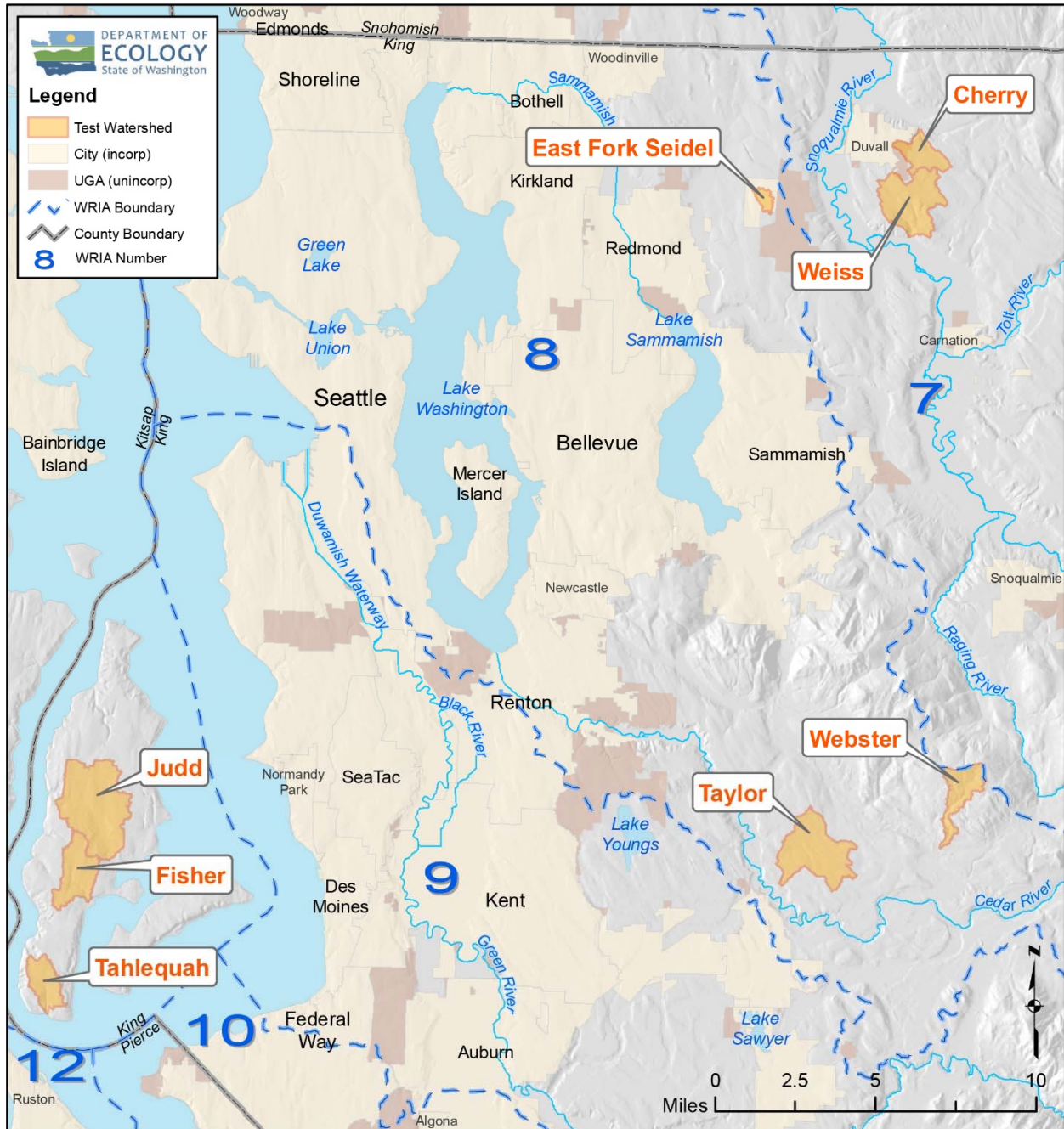
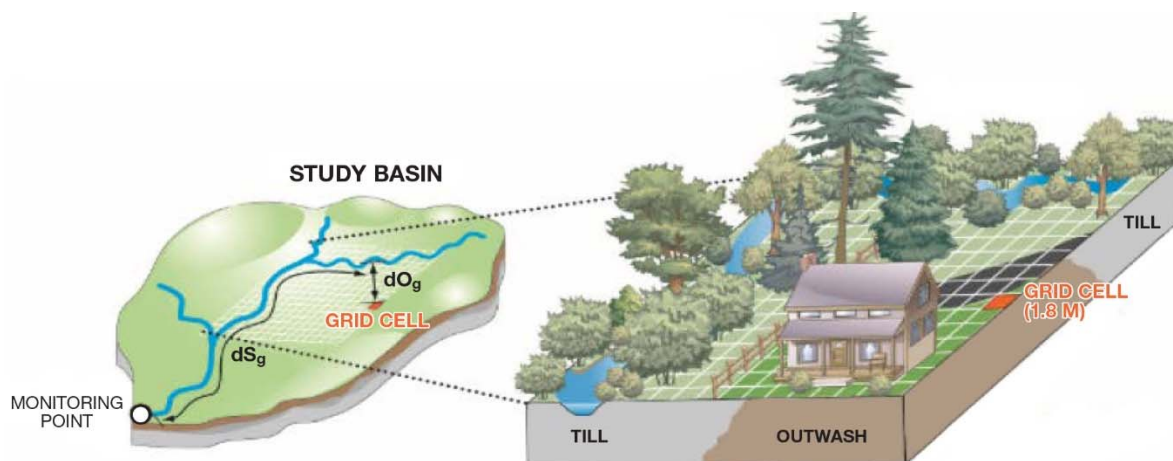


Figure 1. Eight data-rich test watersheds used by King County in developing HCI (Lucchetti, et al., 2014). These watersheds have land cover pattern similar to many other developing rural and suburban watersheds in Puget Sound.

Each of these eight test watersheds were assessed by King County during initial development of the HCI. The watersheds are consistently “data rich”, with consistent records of stream gage data, as well as high-resolution land cover and surficial geology. King County’s approach to establishing calibrated HCI values for each of these watersheds is detailed below.

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 new critical areas and land use regulations, and assessing effectiveness at preventing environmental degradation from ongoing and future development (Lucchetti, 2014). King County used a quantitative index, the HCI, to measure the effect of land cover change resulting from development on flows in lowland streams and rivers (Figure 2).



CALCULATION OF THE HYDROLOGIC CONDITION INDEX

STEP 1:
Determination of distance-weighted high pulse contribution for each grid cell:

$$HPC_g = HPC_{coeff} * \left(\frac{1}{dO_g + dS_g} \right)$$

STEP 2:
Summation of high pulse count contributions across a watershed:

$$HCV_s = \sum_{g=1}^n HPC_g$$

STEP 3:
Determining the Hydrologic Condition Index:

$$HCI = \left(\frac{HCV_s}{HCV_{s_worst}} \right)$$

HYDROLOGIC CONDITION INDEX COMPONENTS

g = An index from 1 to n for all the grid cells within a watershed

HPC_{coeff} = An average high pulse count coefficient for each grid cell type. There are 24 total HPC_{coeff} values based on the combination of 12 LULC types and 2 underlying geology types. One HPC_{coeff} value is applied to each grid cell type within a watershed

dO_g = Overland distance (Euclidean) from the grid cell, g , to the stream channel

dS_g = stream channel distance measured from the intersection of the overland with the stream channel, to the monitoring point downstream

HPC_g = the distance-weighted high pulse count contribution for each grid cell within a watershed.

HCV_s = the hydrologic condition value for a stream site in a watershed, s (the monitoring point), given the LULC pattern for a particular year or simulated level of development. HCV_s is the summation of all HPC_g values for a watershed.

HCI_s = the hydrologic condition index for a stream site in a watershed, s (the monitoring point), given the LULC pattern for a particular year or simulated level of development. HCI_s calculated by dividing the HCV_s by the worst case HCV scenario, where a watershed is 100% paved.

Figure 2. Algorithm and method for applying and testing the Hydrologic Condition Index (adapted from Lucchetti, 2014).

Based on land cover type and surficial geology, the HCI method uses a calibrated hydrologic model to define a set of High Pulse Count¹ (HPC) coefficients that are calculated for each grid cell in a watershed.

To determine HPC coefficients for use in the HCI algorithm, King County used previously calibrated hydrologic models developed in five lowland King County watersheds (Appendix B). These watersheds are different than the eight currently being used for HCI development and testing, and were selected by King County because calibrated Hydrologic Simulation Program Fortran (HSPF; Bicknell et al. 2005) models were already established. King County used these “virtual” watersheds to generate HPC coefficients for 12 established land cover types (ranging from forested to urban cover) on both till and outwash (for a total of 24 total HPC coefficient values) using 61 years of past climate data. The HPC coefficients represent an average high-pulse count across all 61 years of HSPF model runs for each combination of land cover type and geology.

For every individual grid cell, the calculated HPC coefficient represents the “raw value” for a high pulse based on the HSPF modeling for the cell’s land use and surficial geology, but without consideration of the effect of distance between the grid cell and the stream channel (“dOg” on Figure 2) or the distance down the channel to the basin outlet (“dSg”). HPC coefficient values are displayed in Appendix B for each of the land cover types for both till and outwash geology. To include consideration of distance, King County’s algorithm takes the HPC coefficient score for each grid cell and multiplies by an inverse distance weighting factor ($1/dOg+dSg$). This results in unique distance-weighted HPC values (HPC_g in Figure 2) for every grid cell within a watershed.

Summing all distance-weighted HPC_g values provides a total hydrologic condition value (HCV) score for all grid cells across a watershed. Normalized HCI values are achieved by dividing the HCV (representing conditions in a particular year or simulated development scenario) by the HCV for the same watershed assuming the worst case where every grid cell is “fully paved.”

Consideration of distance in HCI development: When King County 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, with grid cells farther from the point of monitoring discounted to reduce the relative contribution of associated HPC coefficient values to the overall watershed HCI. To factor in distance, grid cell distances were inverted (i.e., 1 over distance), to give the shortest distances the highest weightings.

Methods

Current Task 2 efforts for the PSWC 2.0 Project are intended to establish an HCI method which can be applied to watersheds across the Puget Sound, providing effective tools for evaluating existing and potential future watershed hydrologic conditions (and correlated stream condition and biological integrity).

¹ A **high pulse** is defined as 2X the mean annual flow for that water year. The number of high pulses over any given 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 have been found to show a strong negative correlation with biological indicators such as a Benthic Index of Biotic Integrity (B-IBI).

Testing of the HCI method focuses on answering two questions:

1. Does the method yield meaningful results when compared to actual hydrologic data, where available?
2. What is the optimal scale and flow-routing method, considering both accuracy and efficiency of implementation?

The implementation considerations for testing the HCI method involve the fact that a 30-meter land cover dataset is already available for all of Puget Sound whereas 1.8-meter land cover data are not. 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.

Both the validation of methods and testing for the best way to implement the HCI were evaluated by applying regressions analysis to existing gage data, and the HCI results for the eight test watersheds, using all combinations of grid cell / land-cover resolution and flow geometry. Figure 3 on the following page provides a conceptual flow chart of the Task 2 methods.

Testing the HCI equation for the eight pilot 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 and 30 meters.
3. Simulating Natural Flow Paths by establishing a natural flow network grid at 1.8 and 30 meters using a DEM tool.
4. Running the HCI algorithm in eight test runs (as shown in Figure 3) to compare HCI results with different flow routing and grid scale alternatives. For all HCI test runs, average HPC coefficients from King County’s effort were used. The mean of HSPF-generated values (see Appendix B) were applied as the 24 HPC coefficient values for each given land cover type and geology.
5. Identifying the average stream flow 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 eight test runs and selecting the best method for routing and resolution.

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

- Conducting additional test run scenarios for different levels and locations of paving, to verify the effect of “inverse distance” in the HCI results (“inverse distance” should reduce the effect of development as it is moved away from a stream).
- Conducting additional test runs to compare the results of the HCI equation using only overland distance “dOg” as the inverse distance variable, relative to overland distance AND stream channel distance “dOg+dSg” as the distance variable.

The HCI formula established by King County uses both overland distance (“Euclidean” dOg, measuring the straight-line distance to the channel without considering the potential effects of intervening topography) and stream channel distance (dSg) to determine the IDW applied to each grid cell. In evaluating the HCI and considering application for the updated PSWC, the Ecology team identified factoring in the full distance along the stream channel as a component of the HCI formula for additional evaluation. There is concern that including the stream channel distance may be overly (or unnecessarily) weighting the hydrologic attenuation provided once runoff reaches a stream channel. 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., 2007; King et al., 2005; Grabowski et al., 2016). Based on literature and professional judgement of the Ecology and consultant technical team, separate test runs were developed to independently evaluate the inclusion of overland flow only versus overland and in-stream flow in HCI results.

In total, the Ecology team identified eight potential test runs based on the combination of grid resolution (1.8-meter vs 30 meter), flow path type (Euclidian vs. Natural), and distance variable (dOg+dSg vs dOg). See Figure 3. Two of the test runs have not yet been completed because the GIS method for calculating distance for the Natural flow path does not allow the dOg component (grid cell to stream distance) to be easily extracted. These tests will be completed later when a suitable method is developed.

Updates to the Puget Sound Watershed Characterization
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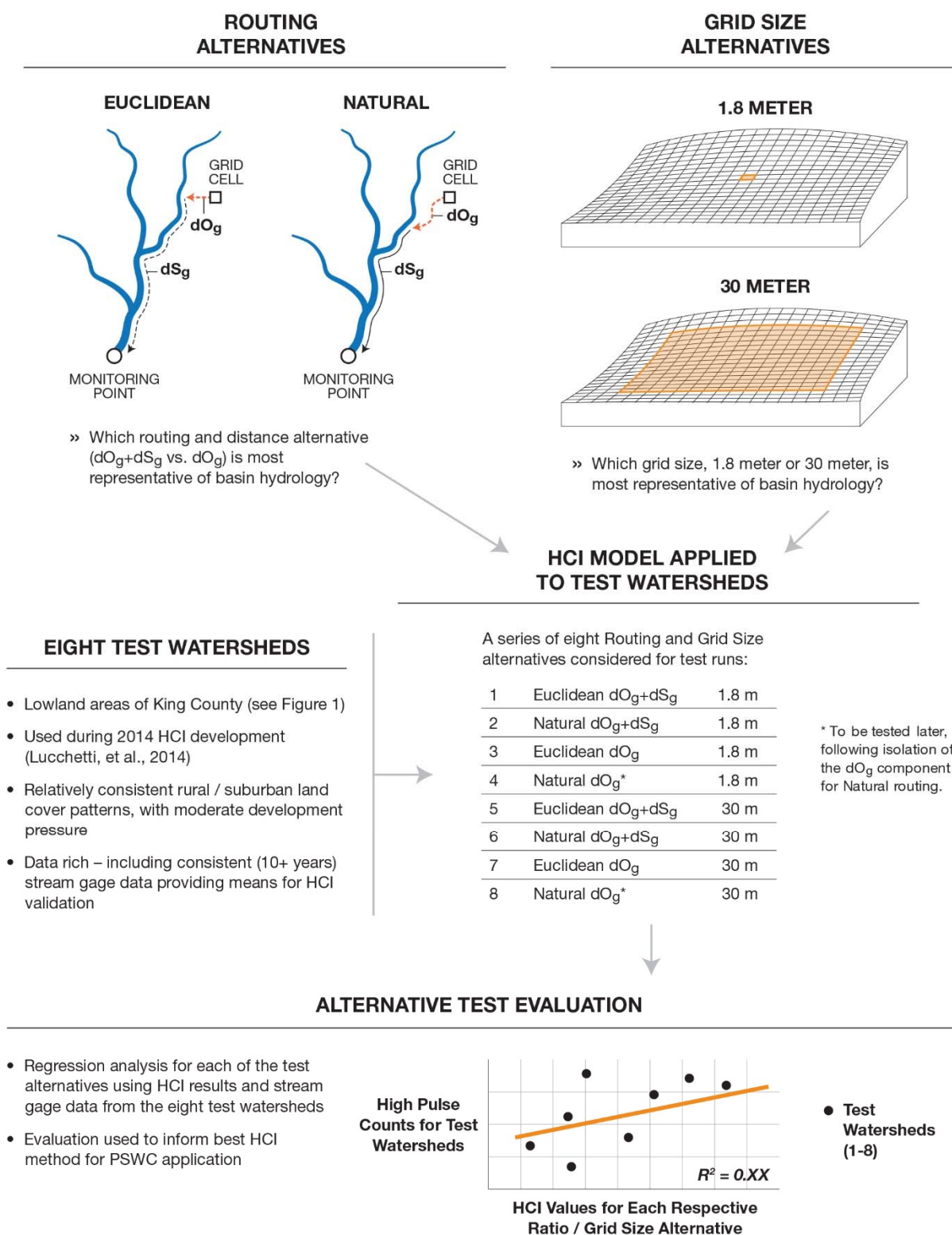


Figure 3. Conceptual flow chart of Task 2 methods for evaluation of routing and grid size alternatives.

Results

HCI Alternative Tests

Ecology staff applied the HCI equation (as shown in Figure 2) initially to the Webster Creek watershed and then to all eight test watersheds. During the initial runs of the HCI for the Webster Creek watershed, it was noted that urban land cover (e.g., pavement) in the upper watershed appeared to have a “less than expected” effect upon the total HCI value for the watershed. This result was contrary to what hydrologists have generally observed with the effect of headwater development upon stream hydrology. To investigate further, two scenarios were created: one in which the upper half of the watershed was developed and the lower half remained forested; and another where the location of developed and forested portions were reversed (Figure 4).

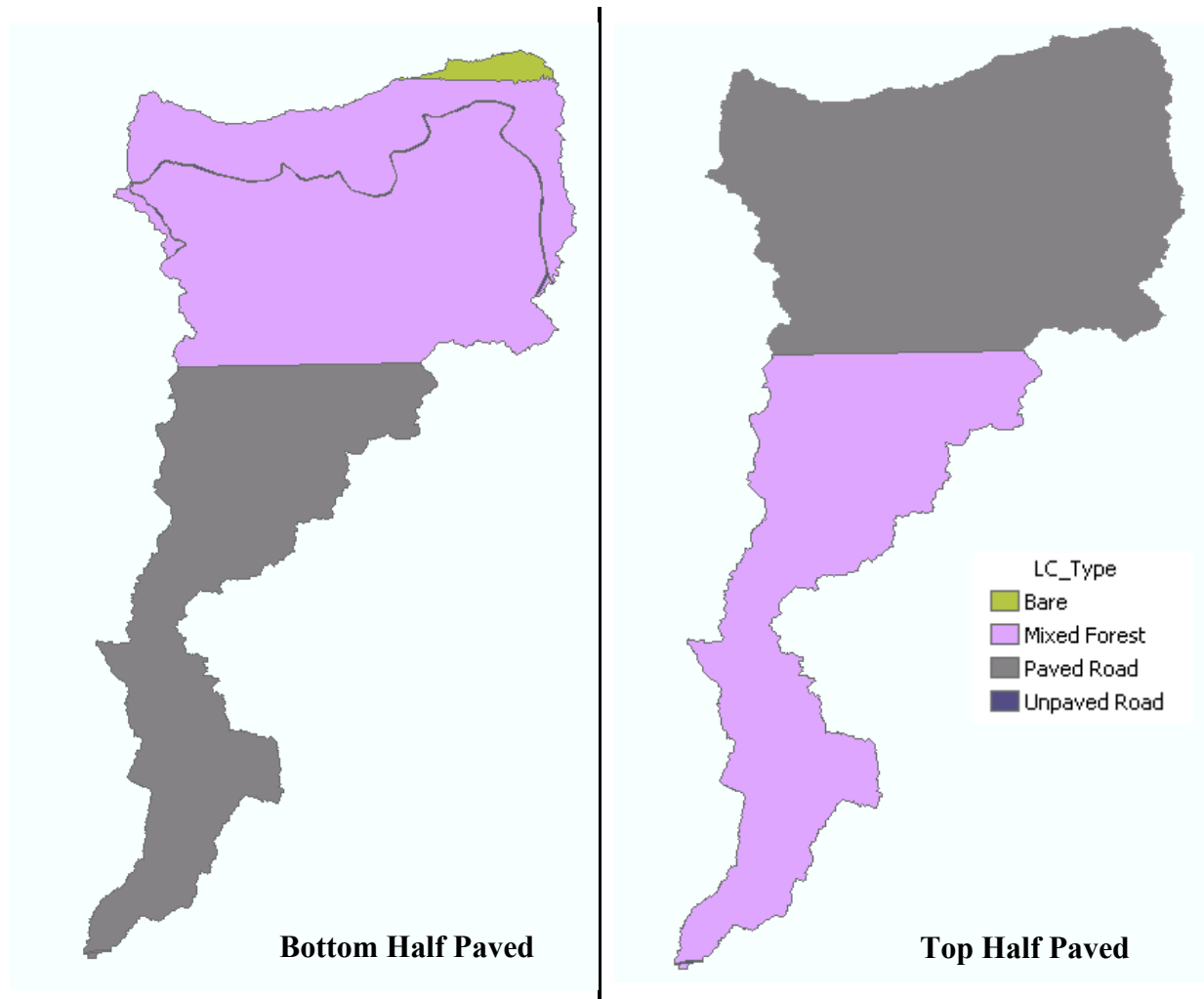


Figure 4. Depiction of top half / bottom half testing completed for the Webster Creek watershed; all paved land cover was applied first to the bottom half and then to the top half of the watershed.

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Using both distance variables (dSg + dOg), HCI results (Table 1) 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 being located in the lower half of the watershed (HCI=0.636).

Table 1. Results from tests of HCI Inverse Distance Variables (dSg + dOg & dOg), as applied through the developed upper watershed and forested lower watershed scenario. A lower HCI value represents a stream system that has relatively normal flows. Flow network is Euclidian.

Bottom Half Paved, Top Half Forested							
Land cover type	Percent area	SUM (HCVs)		SUM (HCVs_worst)		Total HCI dSg+dOg	Total HCI dOg
		dSg+dOg	dOg	dSg+dOg	dOg		
bare	1.44%	2.467	636.18	↓	↓	↓	↓
mixed forest	57.58%	85.097	34255.37				
paved road	40.44%	1092.303	194673.05				
unpaved road	0.54%	6.370	2189.44				
Totals	-	1186.237	231754.04	1864.824	503058.90	0.63611205	0.46068968
Top Half Paved, Bottom Half Forested							
Land cover type*	Percent area	SUM (HCVs)		SUM (HCVs_worst)		Total HCI dSg+dOg	Total HCI dOg
		dSg+dOg	dOg	dSg+dOg	dOg		
mixed forest	40.42%	115.330	21447.29334	↓	↓	↓	↓
paved road	59.56%	775.030	309115.8748				
unpaved road	0.02%	1.441	72.099851				
Totals	-	891.801	330635.27	1864.824	503058.90	0.47822247	0.65724961

*In Top Half Paved, Bottom Half Forested scenario, small areas of “bare” land cover type became “paved road” as it occurred in the top half of the watershed.

In consultation with hydrologists from Environmental Science Associates (ESA) and Derek Booth from Stillwater Sciences, it was determined that a modified HCI equation without using the dSg variable should be tested in the bottom half / top half scenario. The results of this test, with only the overland distance (dOg) factored into the HCI formula, showed a reversal of HCI results (Table 1). This predicted that development in the upper watershed had a greater effect on stream hydrology relative to development being located in the lower watershed. Because this result better represents the observed effect of development upon stream hydrology (where land cover alterations in upper, contributing areas of watersheds have greater impacts than

development near the mouth of a watershed), the Ecology and consultant team recommended that the HCI results using only the dOg variable be tested separately using regression analysis.

Further testing of the HCI equation in the Webster Creek watershed was conducted using smaller paved polygons located at varying distances from a stream system (Figure 4). Results from the testing confirmed the assumption that developed polygons located further from a stream system (outer blue polygons) resulted in a watershed HCI that was greater than the HCI where developed polygons were located closer to a stream system (inner orange polygons), except for the natural flow grid run that included both the distance overland from a grid cell plus the distance along the stream to its pour point (Table 2).

Test results indicate that the “inverse distance” variable, when only applied for the overland distance (dOg), does decrease the HPC coefficient for “paved” grid cells (and all other land cover types) the farther those cells are located from a stream course.

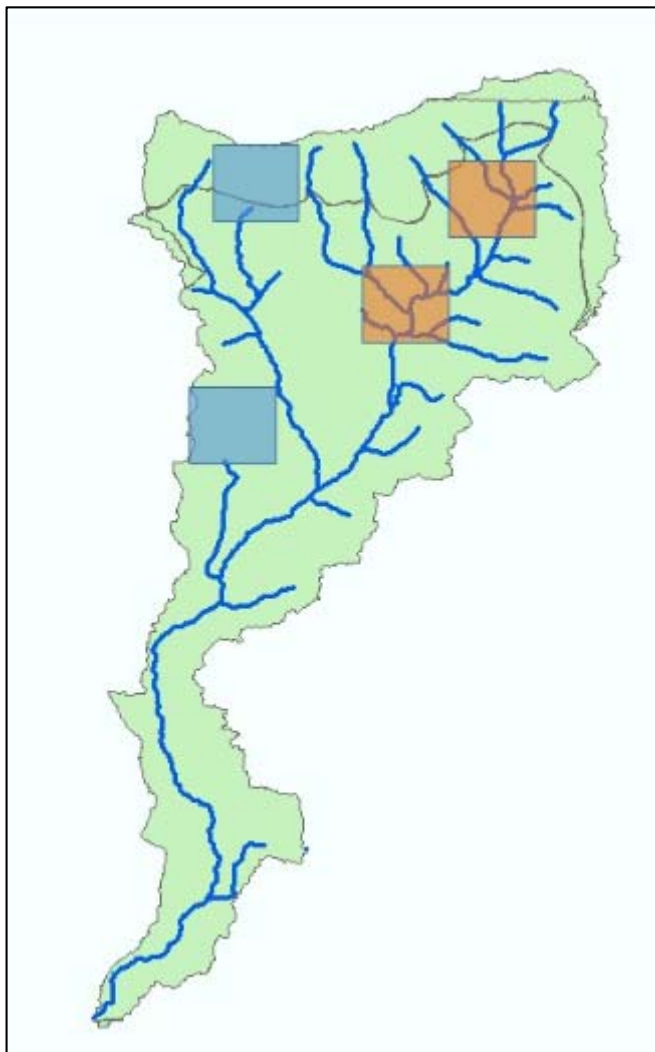


Figure 5. HCI distance factor sensitivity testing within the Webster Creek Watershed. Test completed to detect the effect of development polygons located closer to a stream system (orange polygons) and further away (blue polygons) in the Webster Creek watershed.

Table 2. HCI Distance Inverse testing in the Webster Creek Watershed. See also Figure 4.

	HCL Euclidean dOg	HCI Natural dOg+dSg	HCI Euclidean dOg+dSg
Blue polygons	0.130	0.126	0.128
Orange polygons	0.207	0.125	0.162

Regression Results

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, we chose to use stream gage records that generally match that time period and selected 2008 to 2016. We also chose this gage data range because King County reported that there was limited development during their study period of 2007 to 2012 due to the economic downturn that started in 2008. A summary of the results is provided in Table 3 in order of decreasing correlation to stream gage HPC data. Figures 5 through 10 additionally represent the results of the regression analysis.

Table 3. Regression analysis results for grid size / routing alternative tests, showing correlation to stream gage HPCs for all test watersheds.

Grid Size / Routing Test Alternative	Regression Analysis Result (R² Value)	Figure #
1.8 Meter Euclidean dOg	0.7831	Figure 5
1.8 Meter Euclidean dOg+dSg	0.6421	Figure 6
30 Meter Euclidean dOg+dSg	0.6402	Figure 7
30 Meter Euclidean dOg	0.6083	Figure 8
1.8 Meter Natural dOg+dSg	0.5825	Figure 9
30 Meter Natural dOg+dSg	0.4555	Figure 10

The 30-meter Natural regression uses a flow grid that calculates the total distance from the grid cell to pour point of the watershed as one distance value; as such it is equivalent to a dOg+dSg combination of distance variables used in the Figure 5 and 6. As detailed in the methods section, Ecology staff identified eight potential test runs to represent all combinations of grid resolution, flow path type, and distance variable. Two of the test runs are still pending (tests #4 and #8 as shown in Figure 3), and will be completed once GIS methods for isolating the overland (dOg) distance for the Natural flow path are developed.

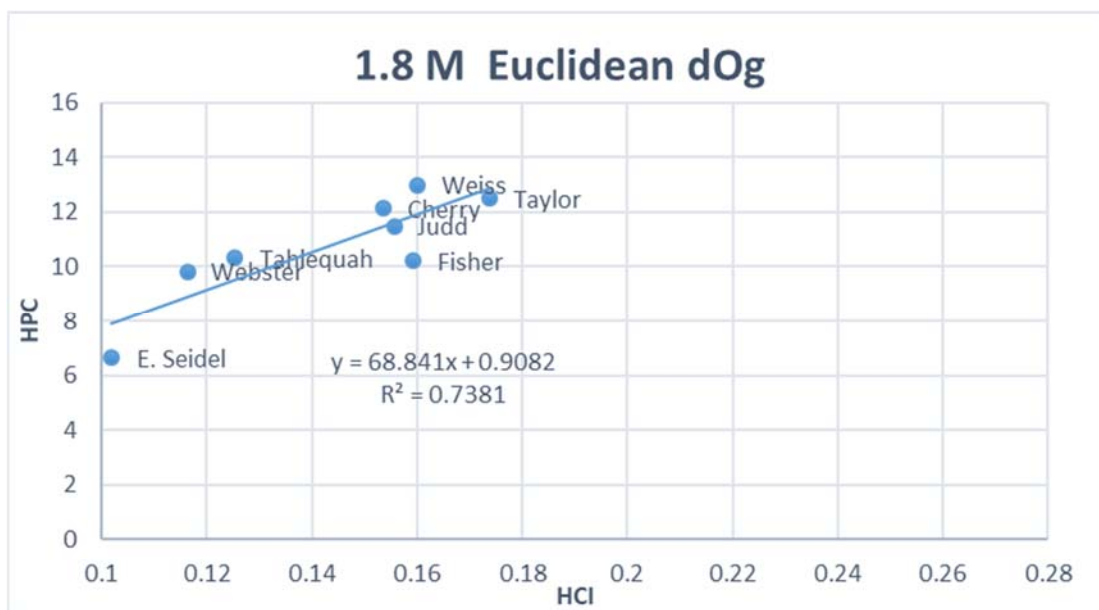


Figure 5. Regression analysis results for 1.8 meter Euclidean dOg.

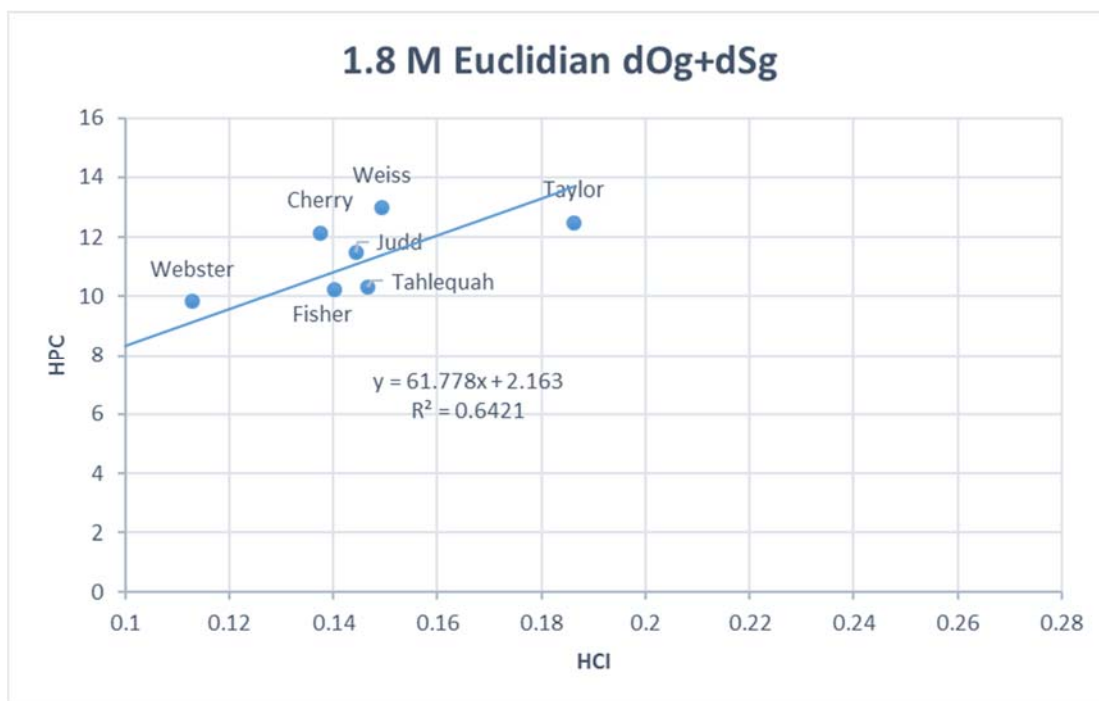


Figure 6. Results of regression analysis for 1.8m Euclidean dOg+dSg.

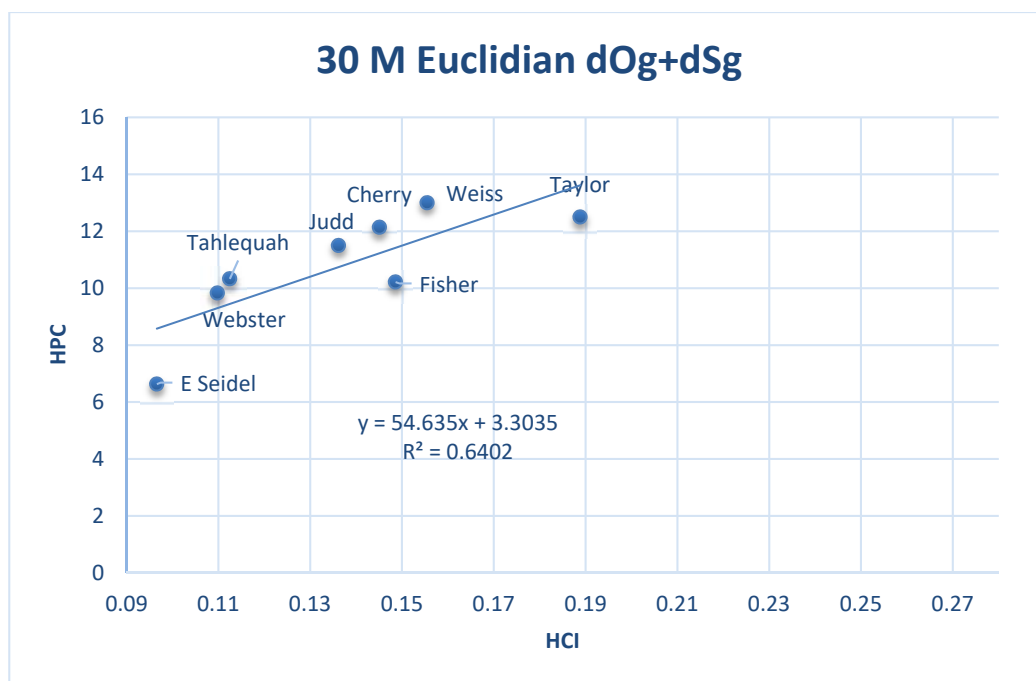


Figure 7. Regression analysis results for 30 Meter Euclidean dOg+dSg.

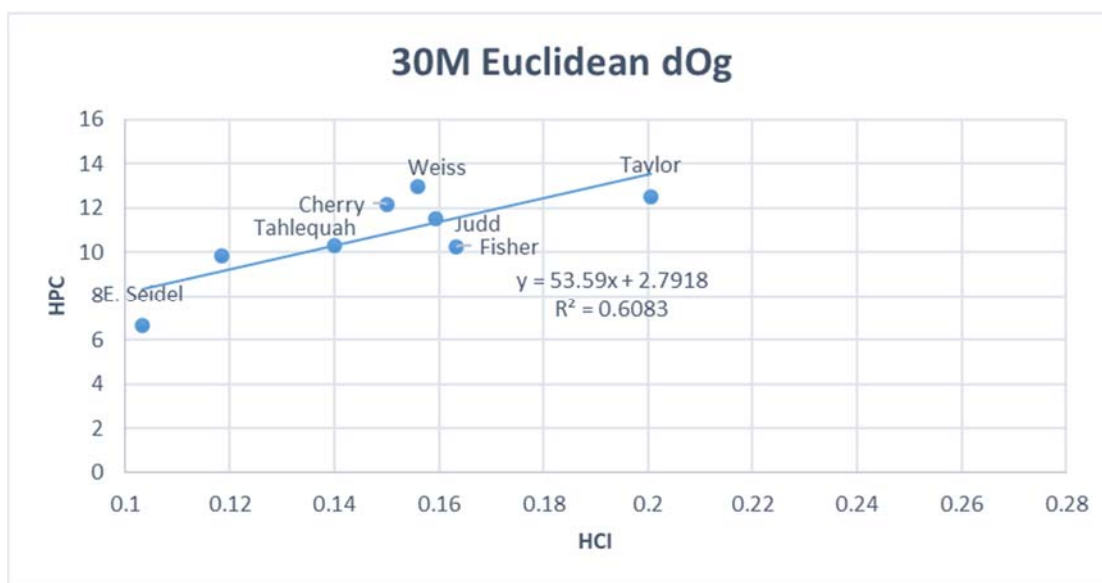


Figure 8. Regression analysis results for 30 meter Euclidean dOg.

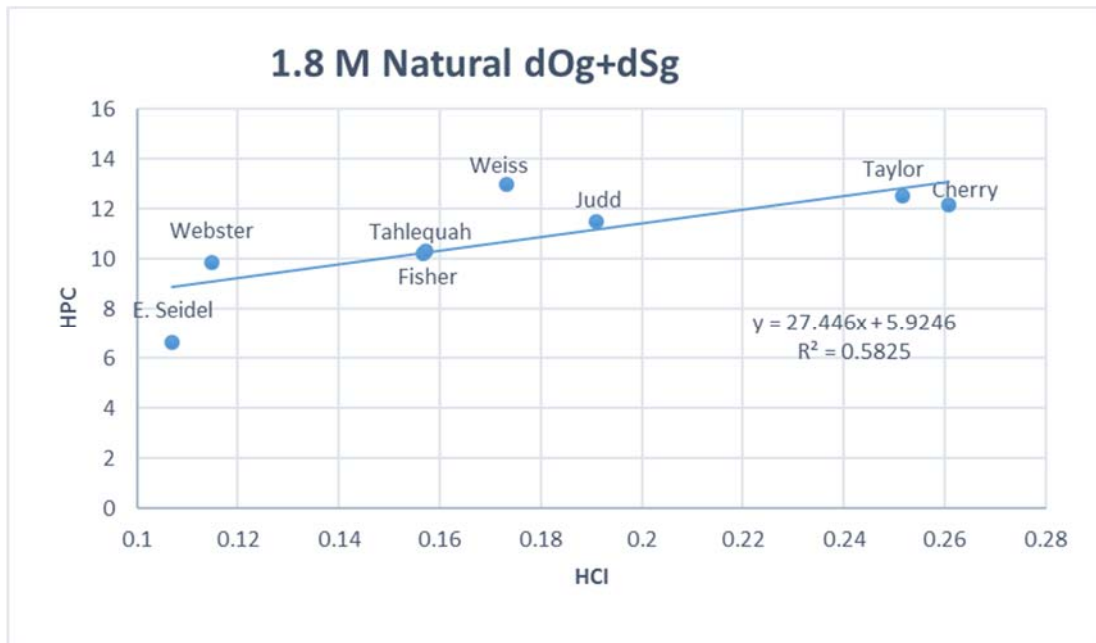


Figure 9. Results of regression analysis for 1.8m Natural dOg+dSg.

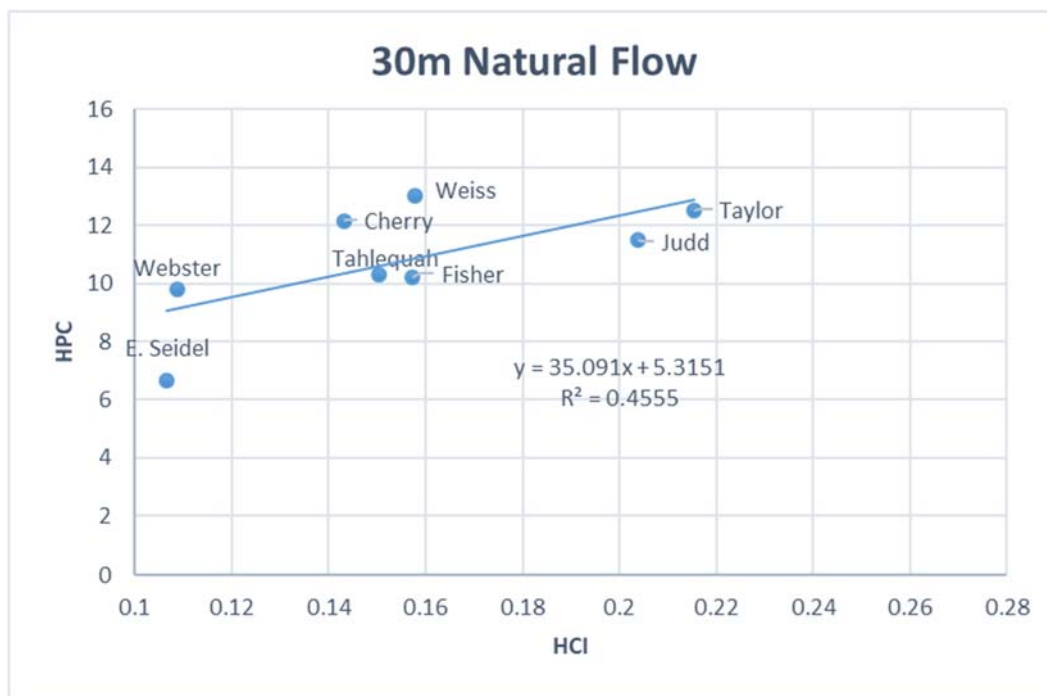


Figure 10. Regression analysis results for 30 meter Natural Flow.

Discussion

The regression results show that the 1.8-meter resolution grid using the Euclidean and the overland distance variable dOg is most closely correlated with HCPs calculated from the stream gage data for the test watersheds (Table 3; Figure 5). The 30-meter resolution grid using a Natural flow path appears to have the lowest correlation (Figure 10). However, the results also show that both the 30-meter and 1.8 meter resolution grid using Euclidean flow path and the overland plus stream distance variable (dOg+dSg) have the second highest correlation with stream gage data (Figures 6 and 7).

In regards to which distance variable method to use, the dOg variable (Figure 5) provides results that are more closely correlated with gage data relative to the dSg+dOg combination for the 1.8-meter resolution grid. It was also demonstrated in Table 1 that use of the dOg variable prevents an unintended spatial weighing with HCI results, using both dOg and dSg, that would encourage locating impervious cover in the headwaters of watersheds.

Overall, the results suggest consideration of the following four alternatives for further testing and potential application throughout Puget Sound. The alternatives are listed in order of decreasing correlation and include one of the 30-meter test runs for consideration, despite their lower correlation value, because implementation is significantly easier (and the only possible approach in many areas of western Washington, given data availability):

- 1) 1.8 m resolution, Euclidean flow, dOg distance variable
- 2) 1.8 m resolution, Euclidean flow, dOg+dSg variable
- 3) 30 m resolution, Euclidean flow, dOg+dSg variable
- 4) 30 m resolution, Euclidean flow, dOg distance variable

Because a small sample size, as with this series of regression tests, can produce results that may not be representative of the full range of conditions exhibited by lowland watersheds in King County, it is recommended that testing be expanded, as time permits, to include other King County watersheds. This could include urbanized watersheds such as the Mercer watershed, which has a long available stream gage record and existing HPC analysis.

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Appendices

Appendix A. (Work Plan)

3.4.1 Detailed tasks required to complete this project:

- 1.0 Acquire Data, Select Test Watersheds in Snohomish or King County and form the Watershed Assistance Group (WAG). For Task 2.0, the nine existing test watersheds in King County (Figure 2) will be used. The HCI model and gage data for these watersheds has been developed and collected by King County. For task 5.0, the “alternative futures” test watershed would have to be identified in either Snohomish or King County.
- 1.1 Meet with King and Snohomish County staff to acquire data and initially identify “alternative futures” test watershed in Snohomish or King County. County staff will work with Ecology GIS staff to transfer test watershed data and setting up the HCI model.
- 1.2 Form Watershed Assistance Group (WAG). The purpose of this team is to bring together both watershed scientists familiar with the development of watershed assessment methods and local planners who have experience with the interpretation and application of watershed assessment results to local planning and permitting issues. Solicit participation from local government planners and watershed scientists (WDOE, WDFW, EPA and consultants) familiar with use and application of the PSWC and watershed assessment methods to local and regional planning issues.
- 2.0 Select the Best Method of Routing and Resolution (Grid Size). Compare HCI results and existing stream gauge High Pulse Count (HPC) data using nine test watersheds in King County.
- 2.1 Develop Euclidian flow network at 1.8, and 30 meters
- 2.2 Simulate Natural Flow Path. Create a natural flow network grid at 1.8 and 30 meters using a DEM tool.
- 2.3 From existing King County gage data for the nine test watersheds (Figure 2) identify the average High Pulse Counts..
- 2.4 Ecology GIS staff acquires and runs HCI Model in four suggested test runs (Figure 5) in order to compare flow path results at existing 1.8 meter resolution flow network with HCI results at 30 meters resolution. Using the decision matrix, or similar, presented in Table 4 evaluate results statistically (Ott 1995) for the test runs (Figure 3) and select the best method for routing and resolution. Present results to WAG for their review and comment.
- 2.5 WDOE GIS staff makes any needed changes to incorporate selected routing and resolution method into PSWC methods.

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Appendix B. (King County HPC Coefficients)

Table 13. Five sets of modeled (61-yr averages) yearly high pulse counts (HPCs) arranged from lowest to highest for mixed forest on till geology used to scale hydrologic influence of land cover and geology in a hydrologic condition index (HCI).**

Geology	Land Cover	Hamm Creek (set 1)	Miller Creek (set 2)	Des Moines Creek (Set 3)	Newaukum Creek (set 4)	Duwamish LCL1 (set 5)
Till	forest	2.393443	2.672131	3.655738	4.606557	7.049180
	shrub	2.639344	3.311475	4.475410	6.016393	7.081967
	pasture	2.803279	4.032787	4.622951	6.590164	7.606557
	wetland	2.901639	4.868852	4.540984	7.524590	8.245902
	clear cut	3.819672	5.032787	5.360656	8.606557	8.803279
	grass	5.672131	5.213115	6.032787	9.983607	8.475410
	bare	5.114754	8.524590	7.901639	10.508197	11.459016
	building	30.508197	34.803279	33.491803	29.622951	31.836066
	pavement	26.540984	36.885246	36.508197	34.032787	35.737705
	open water	27.934426	38.163934	38.131148	36.655738	37.786885
	unpaved road	33.983607	37.180328	36.901639	34.754098	36.672131
	paved road	34.360656	37.655738	37.344262	35.180328	37.213115
Outwash	forest	2.213115	2.065574	3.360656	3.688525	5.426230
	shrub	2.229508	2.131148	3.393443	4.540984	5.573770
	pasture	2.295082	2.213115	3.262295	6.081967	5.524590
	clear cut	2.295082	2.213115	3.262295	6.081967	5.524590
	grass	2.606557	2.032787	3.409836	5.655738	5.704918
	bare	3.245902	3.311475	4.557377	7.639344	7.852459
	wetland	2.901639	4.868852	4.540984	7.524590	8.245902
	building	31.409836	35.459016	33.245902	31.737705	31.983607
	pavement	26.573770	37.114754	36.475410	35.049180	35.622951
	open water	27.639344	38.081967	37.934426	36.606557	37.819672
	unpaved road	34.016393	37.524590	37.049180	35.491803	36.819672
	paved road	34.196721	37.672131	37.229508	35.868852	37.098361

*For reference only - not used for scoring.

** Because HPC are whole numbers, decimal places were carried to millions when computing averages to reflect fine-scale (1:1200) resolution of land cover mapping and high density (millions) of 1.8 m grid cells per watershed.

Appendix C. (Excel Spreadsheet Data)

Excel spreadsheet data providing HCI test runs and regression analysis available upon request.