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# Assessing Land Use Effects and Regulatory Effectiveness on Streams in Rural Watersheds of King County, Washington

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April 2014



**King County**

Department of Natural Resources and Parks  
Water and Land Resources Division

**Science and Technical Support Section**

King Street Center, KSC-NR-0600  
201 South Jackson Street, Suite 600  
Seattle, WA 98104  
206-477-4800 TTY Relay: 711  
[www.kingcounty.gov/EnvironmentalScience](http://www.kingcounty.gov/EnvironmentalScience)

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# Assessing Land Use Effects and Regulatory Effectiveness on Streams in Rural Watersheds of King County, Washington

## Submitted by:

Gino Lucchetti, Senior Ecologist.  
King County Water and Land Resources Division  
Department of Natural Resources and Parks

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## **Statistical Design**

Leska Fore<sup>#</sup>

## **U.S. Environmental Protection Agency**

Jayshika Ramrakha, Tony Fournier, Krista Mendelman, Gretchen Hayslip<sup>#</sup>, Mike Rylko, John Gabrielson

## **University of Washington Urban Ecology Research Lab**

Marina Alberti<sup>\*</sup>, Julia Michalak<sup>\*#</sup>

## **U.S. Geological Survey**

Christian Torgersen<sup>\*#</sup>, Rich Sheibley<sup>#</sup>, Andrew Gendaszek, Robert Black

## **Washington Department of Ecology**

Stephen Stanley<sup>#</sup>

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Sabah Jabbouri

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\*External advisor

#Technical reviewer

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DeGasperi, Curtis – calculated the annual hydrologic metric (HPC).

Dorfmeier, Elene – statistical calculations; graphic of BIBI vs. HCI along land use gradient

Grant, Brendan – established and maintained gages; collected and QAQC'ed stream gage (flow, temperature, and conductivity) and weather station data (air temperature and precipitation).

Gregersen, Chris – data collection for stream complexity, physical habitat, water quality, and discharge; land cover digitization and calculation and assessment of land cover change, permitting, compliance, zoning, and basin characteristics; data management, QAQC, analysis; methods for final report.

Fore, Leska – data analysis and graphical summaries; statistical methods and review and comment on final report.

Fuerstenberg, Robert – study Proposal, watershed and site selection, field data collection (conductivity, tracers, physical survey).

Funke, David – established and maintained gages; collected and QAQC'ed stream gage (flow, temperature, and conductivity) and weather station data (air temperature and precipitation).

Knutson, Chris – land cover digitizing and build-out scenarios; habitat surveys, salt tracers and related data management; field equipment calibration and maintenance.

Kraus, Sandra – graphic for permit compliance decision tree

Latterell, Joshua – study proposal and QAPP; study reach layout, baseline field surveys, tracer study design, data collection, analysis, and reporting; review and comment on final report.

Lucchetti, Gino – project management, study proposal, QAPP, watershed and site selection, field data collection (conductivity, tracers, physical survey), historic and full build-out scenarios, HCI, Permit Review and Compliance, QAQC, Semi-annual and Final Reports.

McCombs, Paul – study proposal, watershed selection, GIS land cover data management, analysis and QAQC, Permit Data management, review and compliance, review and comment on final report.

Michalak, Julia – collected and analyzed historic land covers, historic land cover change report.

Pederson, Jon – permit review and compliance assessment.

Preston, Laurel – graphic for HCI methodology

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Richter, Klaus – study proposal, watershed and site selection, field data collection (conductivity, tracers, physical survey).

Smith, Dan – established and maintained gages, collected and QAQC'ed data from stream gages (flow, temperature, and conductivity) and weather stations (air temperature and precipitation).

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Vanderhoof, Jennifer – land cover digitizing and build-out scenarios and GIS land cover analysis; technical editor and document coordinator for final report.

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Zeng, Charlie – tracer database.

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### **Note about this edition**

This report was originally published and submitted to US EPA in December 2013. This April 2014 edition provides: (a) additional compliance results (tables 20 and 22), (b) an updated Figure 32, and (c) limited text edits to improve clarity and to update language related to changes as noted. No major findings or conclusions have been altered from the December 2013 version submitted to the US EPA.

\*Corresponding author at: King County Department Natural Resources and Parks,  
Water and Land Resources Division, 201 S. Jackson Street, Suite 600, Seattle, WA 98104.  
Email address: [Gino.Lucchetti@kingcounty.gov](mailto:Gino.Lucchetti@kingcounty.gov)

# Table of Contents

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<b>1.0. Introduction</b> .....	1
1.1 Background .....	1
1.2 Purpose, Key Questions, Goals, and Objectives .....	3
1.3 Project Hypothesis.....	4
1.4 The Regulatory Environment.....	4
1.4.1 Comprehensive Plan and Zoning.....	5
1.4.2 Key Ordinances - CAO, Clearing and Grading and Stormwater .....	6
1.4.3 Compliance and Enforcement.....	9
1.5 Non-regulatory Environmental Protection Measures .....	10
<b>2.0. Methods</b> .....	11
2.1 Study Design .....	11
2.2 Study Area and Watersheds.....	13
2.2.1 Watershed Selection.....	15
2.2.2 Watershed Boundaries and Attributes.....	18
2.2.3 Zoning and Parcels .....	19
2.2.4 Critical Areas .....	20
2.2.5 Study Reach Selection and Description.....	21
2.3 Measuring Environmental Response .....	26
2.3.1 Hydrology .....	28
2.3.2 Water Quality .....	30
2.3.3 Stream channel complexity: reach-averaged velocity and channel measurements.....	31
2.3.4 Biology: Benthic macroinvertebrate field collection and analysis methods .....	33
2.4 Mapping and Quantifying Land Cover Change .....	38
2.4.1 Historic Conditions .....	38
2.4.2 Current Condition.....	39
2.4.2.1 Estimating Grid Cell Distances.....	41
2.4.2.2 Estimating pre- and within-project land cover change during 2007 to 2009 .....	41
2.5 Calculating the Hydrologic Condition Index.....	42
2.5.1 Full build-out HCI.....	45

2.5.2	Juanita Creek 2007 HCI .....	47
2.6	Permitting and Compliance .....	49
2.7	Data management.....	53
2.8	Analytic Procedures .....	53
3.0	Results.....	55
3.1	Land Cover.....	55
3.1.1	Un-weighted measure of change .....	55
3.1.1.1	Watershed land cover .....	55
3.1.1.2	Regulatory Buffer land cover .....	56
3.1.1.3	2007-2009 land cover change during project window .....	58
3.1.2	Weighted Measure of Change (Hydrologic Condition Indices).....	59
3.1.2.1	Watershed HCIs.....	59
3.1.2.2	Regulatory Stream Buffer HCIs .....	61
3.1.2.3	Comparison of Watershed and Regulatory Stream Buffer HCIs.....	63
3.1.2.4	Juanita Creek, an urban comparison.....	63
3.2	Permitting and Compliance .....	64
3.2.1	Development Activity Preceding and During the Project .....	64
3.2.2	Compliance during Project Timeframe .....	65
3.2.3	Compliance by Permit Type.....	68
3.2.4	Compliance by area of change .....	69
3.2.5	Compliance in regulatory stream buffers.....	71
3.2.6	Potential Effect of Hazard Tree Removal on Compliance .....	75
3.3	Environmental Response.....	76
3.3.1	Hydrology .....	77
3.3.2	Water Quality .....	78
3.3.3	Channel Complexity .....	80
3.3.4	Biology .....	84
3.3.5	Summary of observed changes in ERVs.....	85
3.3.6	Relationship of the HCI to land cover and ERVs.....	87
3.3.7	Ordination of watersheds.....	88
4.0	Discussion.....	91
4.1	Observed and Projected Regulatory Effectiveness.....	91

4.2	Permitting and Compliance .....	93
4.3	Relevance to other studies .....	95
4.3.1	Assessment framework.....	97
4.3.2	Hydrologic Condition Index.....	98
4.3.3	Land cover mapping.....	100
4.4	Climate Change Implications.....	102
4.5	Habitat restoration implications.....	103
4.6	Sources of error, limitations, and caveats .....	103
5.0.	Conclusions .....	105
5.1	Answering the Study Questions .....	105
5.2	Answering Additional Questions .....	106
6.0.	References .....	110
7.0.	Appendices.....	119

# Figures

---

Figure 1. Generalized conceptual model for how best available science (BAS) on land use may be updated and contribute to decisions on regulations..	4
Figure 2. King County boundary and distribution of the nine regulatory effectiveness monitoring study watersheds relative to Puget Sound and ecoregions of western Washington State..	14
Figure 3. Treatment and reference watersheds used for assessing effectiveness of land use regulations in rural King County.	17
Figure 4. An example hydrograph displaying high-flow pulses (High Pulse Counts) under pre-development and developed conditions.....	29
Figure 5. Benthic macroinvertebrate sample collection steps..	36
Figure 6. Benthic macroinvertebrates were collected from 3 riffles within a stream reach starting at the downstream end and working in an upstream direction. ...	37
Figure 7. Illustration of how the Hydrologic Condition Index (HCI) is calculated.....	43
Figure 8. Excerpt of 2012 orthophoto for the Tahlequah Creek watershed with 2012 landcover polygons on left (a.) and the hypothetical full build-out (FBO) scenario on right (b.), where orange lines delineate 2012 land cover and blue lines delineate the possible location of a building, paved road, and grass. Light yellow lines are parcel boundaries.....	46
Figure 9. 2010 Juanita Creek watershed and stream network. Yellow dot indicates location of BIBI sample site “JuanitaKirk_4.” .....	49
Figure 10. The decision process for determining when a permit would likely have been required and the type of permit required for any given change in land cover. ....	52
Figure 11. Change in percent forest and impervious covers during study period (2007 to 2012) and projected under full build out.....	56
Figure 12. Hydrologic Condition Index (HCI) scores for historic (1910, 1936, 1948, and 1965), project timeframe (2007 to 2012), and full “build-out” scenarios for each treatment watershed. HCIs for best (all forest), and equal mix of forest and grass and contribution by each land cover are also shown.....	60
Figure 13. Hydrologic Condition Index (HCI) scores for project timeframe (2007 to 2012), and full “build-out” scenarios for regulatory stream buffers in each treatment watershed. HCIs for best (all forest), and equal mix of forest and grass and contribution by each land cover are also shown..	62
Figure 14. Hydrologic Condition Index (HCI) scores for Juanita Creek using 2007 land cover maps as compared to 2012 and full build-out (“BO”) scenarios for each treatment watershed.....	64
Figure 15. Entire King County Rural area building permits issued by King County preceding (2000-2007) and during (2009-2012) the study. ....	65

Figure 16. 2007-2012 land cover change in all study watersheds grouped by permit type, number of changes and area of changes that may have needed a permit.....69

Figure 17. 2007-2012 land cover change by area from any land cover type to building. ....70

Figure 18. 2007-2012 land cover change by area from forest to any other land cover type.....71

Figure 19. Compliance organized by area (ha) of land cover change and number of land cover changes for full watershed and regulatory stream buffers.....72

Figure 20. Compliance by number and area of land cover changes for treatment watersheds for full watershed and the regulatory stream buffer scales that may have required a permit .....74

Figure 21. Compliance for treatment watersheds and their regulatory stream buffers as a proportion of their respective watershed areas. ....75

Figure 22. Hydrology environmental response variable: High Pulse Counts. Change and variation in high pulse counts over time and by watershed.....77

Figure 23. Water quality environmental response variable: Conductivity. Change and variation in conductivity at baseflow over time and by watershed.....78

Figure 24. Water quality environmental response variable: 7DADMax and average annual water temperature at baseflow. Change and variation over time and by watershed. ....79

Figure 25. Channel complexity environmental response variable: RAV@MAD. Change and variation in reach-averaged velocities at mean annual discharge variables over time and by watershed.....80

Figure 26. Channel complexity environmental response variables: Thalweg depth variability and length. Change in the coefficient of variation (CV) in thalweg depth and thalweg length over time and by watershed.....81

Figure 27. Channel complexity environmental response variable: percent sand and silt. Change and variation in percent sand and silt over time and by watershed.variable. ....82

Figure 28. Channel complexity environmental response variable: Pools. Change and variation in residual pool depth and percent pool along thalweg over time and by watershed.....83

Figure 29. Channel complexity environmental response variable: Large wood. Change and variation in large wood counts over time and by watershed. ....84

Figure 30. Biological environmental response variable: BIBI. Change and variation in BIBI over time and by watershed.....85

Figure 31. Ordination of 11 response variables (red) for 9 watersheds (black) averaged over the years of the project. Additional variables related to land cover and physical features (blue) were fitted post-hoc to the ordination, where (a) is

uninterpreted scatter of all points, and (b), (c), and (d) are interpretations  
indicating potential influences. ....90

Figure 32. Comparison of HCIs and BIBI values across a gradient of land use for  
reference (undeveloped), treatment (rural), and Juanita Creek (urban)  
watersheds. HCIs are for 2007. For the nine study watersheds, BIBI values are  
median, standard deviation, and ranges for five project samples (2008-2012). .92

Figure 33. Average and variability in high pulse counts (HPCs) by twelve land cover  
types and two geologies – till (low permeability) and outwash (high  
permeability) – derived for the nine models assessed in calculating hydrologic  
condition indices..... 100

# Tables

Table 1.	Summary of King County’s Critical Areas, Clearing and Grading and Stormwater ordinances as they apply in the study watersheds. ....	7
Table 2.	King County regulatory buffer widths measured from the ordinary high water mark from each bank for streams in the study watersheds. Waters include perennial and seasonal streams. ....	8
Table 3.	Study design showing current and future development conditions for reference and treatment watersheds. ....	12
Table 4.	Environmental response variables used to environmental change in study watersheds. ....	13
Table 5.	Watershed attributes including watershed area (ha), elevation range (m), mean annual air temperature (°C), precipitation (m), discharge (MAD = Mean Annual Discharge; cfs) and percent composition of surface geology (low and high permeability and saturated conditions). ....	18
Table 6.	Zoning and Parcel information for treatment watersheds. ....	19
Table 7.	Study watershed critical areas. Area in hectares ( <i>% of overall watershed</i> ). ....	21
Table 8.	Stream and road-related statistics for study watersheds including lengths, watershed density (m/ha), stream-road crossings, and area of regulatory stream buffer. ....	23
Table 9.	Study reach characteristics including reach length, gradient (%), coefficient of variation (CV) of thalweg depths (average and), substrate composition and pools (number, length, and residual pool depths). Measurements are from starting (first) year physical survey. ....	25
Table 10.	Environmental response variables and their expected responses and mechanisms. ....	27
Table 11.	Stream characteristics measured using modified EMAP protocols. ....	32
Table 12.	Relative hydrologic conditions and description of mapped land cover. ....	40
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). ....	44
Table 14.	Percent forest cover for parcels with buildings and completely (~>99 percent) within treatment watershed boundaries and used as a basis for determining the percent cleared area for each currently undeveloped parcels under a hypothetical fully-built scenario. ....	47
Table 15.	Relationships and conversions among land cover categories and associated pervious/impervious percentages among databases used for calculating and comparing hydrologic condition indices (HCIs) between project study	

watersheds and Juanita Creek. (Source: University of Washington. 2007. Central Puget Sound 2007 Land Cover Classification. Puget Sound Regional Synthesis Model (PRISM). University of Washington.).....	48
Table 16. Percentage of 2012 (final project year) land cover for the six treatment watersheds at the watershed (WS) and regulatory buffer scales (BF). .....	57
Table 17. Total area (ha) of land cover change and area assessed for project land cover effect detection window between 2007 and 2009. ....	58
Table 18. Area (ha) of 2007 to 2009 land cover change relative to project land cover effect window.....	58
Table 19. Hydrologic Condition Indices (HCIs) for project timeframe (average of 2007-2012) and build-out conditions and ratio of watershed to regulatory stream buffer HCIs.....	63
Table 20. Total, compliant and non-compliant area of land cover change over 5-years as a proportion of treatment watersheds and their regulatory stream buffers.....	66
Table 21. Total area (hectares) and number of land cover change polygons assessed and compliance rates across six treatment watersheds and three photo time periods between 2007 and 2012.....	67
Table 22. Land cover change, compliance and noncompliance from 2007 to 2012 as a proportion of parcels in treatment watersheds, based on parcels completely within watershed boundaries (from Table 6).....	68
Table 23. Total area (ha) of forest that could have been a hazard (i.e., within 46 m of a building) and that was changed to something other than forest between 2007 to 2012.....	76
Table 24. Response variables and metrics, expected response to disturbance if regulations are ineffective, mean change for reference and treatment sites, observed difference in change for reference and test sites, p-value for T-test comparing difference in the change for reference and treatment sites, minimum detectable difference (MDD) between reference and treatment sites, possible range observed within the region, approximate number of categories that could be detected and the relative sensitivity of the metric.....	86
Table 25. Correlations of average watershed and regulatory stream buffer HCIs with averages for impervious and forest land covers and project ERVs for six treatment watersheds.....	88

## APPENDICES

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Appendix A. Key non-regulatory habitat protection programs and selected attributes (from King County 2012a).

Appendix B. Map of Study Watersheds.

Appendix C. Large study map with inset orthophotos.

Appendix D. Michalak, et al. 2013. Implications of land-cover change history for monitoring present and future ecological condition in nine basins on the urban fringe of Seattle, Washington.

Appendix E. Study watershed map panels showing:

- Steep Slopes, PBRS, CARAs,
- Wetlands, Buffers, Roads, & Crossings
- Basin Soil Permeability based on Surficial Geology
- Basin Soil Types
- Orthophotos for each photo year, locations of landcover change, and full build out

Appendix F. Lucchetti, et al. 2013. Monitoring physical changes in stream channels with salt tracers.

Appendix G. BIBI scoring thresholds and biological condition categories.

Appendix H. HPC table showing all modeled watersheds.

Appendix I. Unweighted aggregate land use / land cover tables by watershed.

## EXECUTIVE SUMMARY

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On January 1, 2005, a new set of land use regulations (*aka* The CAO<sup>1</sup>) was implemented for rural areas by the Metropolitan King County Council in accordance with the 1990 Washington State Growth Management Act (GMA). This provided an opportunity for the U.S. EPA and King County to collaborate on answering a fundamental and often asked but rarely answered question: “Are land use regulations effective at protecting aquatic habitats and associated biological resources?” To address this question for rural areas in King County, the implementation and environmental effectiveness of the County’s land use regulations was evaluated by measuring regulatory compliance and change in land covers and environmental response variables (ERVs) in streams in nine rural watersheds (11,463 acres<sup>2</sup>), including six treatment watersheds (10,144 acres) where land development was ongoing and three undeveloped, fully-forested reference watersheds (1,320 acres).

The Puget Sound’s rural lands are predominantly in low elevation (generally < 500 feet) areas situated between GMA-designated Urban Growth Areas (UGAs), where high density urban development is located, and State and Federal forest and wilderness lands in the surrounding Cascade and Olympic mountains. Many of the region’s remaining high functioning streams are in this rural environment. They support high value natural resources, including Chinook salmon, steelhead trout, and bull trout populations listed as threatened under the federal Endangered Species Act, as well as productive populations of coho, chum, pink, and sockeye salmon and cutthroat trout, and a wide range of other species contributing to the region’s biodiversity and ecological functioning.

In most rural watersheds the density of land uses is low relative to urban areas, and land development (clearing, grading, and building) is the single largest human activity that could potentially impact resources in these areas. Land use regulations are the primary method that local jurisdictions use to prevent degradation and protect existing habitat and biological productivity. However, regulations can be controversial, because they can be perceived as costly to implement. Moreover, many debate their effectiveness because they have never been rigorously assessed, even though they are ubiquitous and have formed the foundation for habitat protection and restoration efforts throughout the region for decades.

In 2008, the US Environmental Protection Agency and King County partnered in a multi-year, comprehensive scientific study to better understand the County’s new regulations and assess whether they would be effective at preventing environmental degradation from ongoing and future development. This report describes in detail the scientific approach that was developed and applied as well as results, discussion, and general conclusions. These subjects are briefly summarized below.

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<sup>1</sup> Commonly referred to as “The CAO,” the County’s critical area regulatory protections are provided by three ordinances: Critical Area, Clearing and Grading, and Stormwater.

<sup>2</sup> English units are presented in this Executive Summary; metric is the predominant usage in the body of the report.

## **Approach and Methods**

Key study questions were:

- Did the environment respond to change in land cover during the study? If so, was response related to CAO implementation?
- If response was significant, how might the CAO be modified to reduce future impact?
- How well did people follow the regulations? Do permits provide an estimate of land cover change? And did non-compliance impact the environment?
- Was the assessment framework a useful tool for measuring effectiveness? What changes are recommended for future work?
- Are there relationships among environmental variables and watersheds that provide greater understanding of the mechanisms affecting environmental response? (This key question became evident during the analysis phase of the project.)

Project goals were to: (a) develop a statistically strong experimental framework to assess implementation and environmental effectiveness of land use regulations and then (b) apply that framework over a five-year (2007-2012) period to assess regulatory compliance and change in land covers streams in rural watersheds of King County.

Study objectives were to: (1) quantify land cover and environmental change over time, (2) determine relationships between land cover change and ERVs, (3) track implementation and compliance with land use regulations, (4) provide these findings to the King County government, including the King County Metropolitan Council, and other entities as appropriate, and (5) make approach and data available to other Puget Sound jurisdictions to consider as part of best available science (BAS) when they update their land use regulations.

The study's working hypothesis was if the land use regulations are not effective or not effectively implemented, then given enough time detrimental effects of development should be detected as change in one or more aspects of the hydrology, water quality, biology, and physical condition of streams draining treatment watersheds. Furthermore, if change was detected, then the direction and magnitude of change should be commensurate with the direction and magnitude of change in land covers, presuming no major change in larger-scale background factors, such as climate or geology. Reference watersheds with relatively intact conditions (no development) are used for comparison and to discriminate between treatment effects and changes resulting from cross-category factors such as regional climate variation and other natural background variation that could mask detection of a true development impact.

A statistically-strong study design was developed to minimize the potential for concluding that the regulations are effective when in fact they aren't (i.e., Type II Error). To help achieve this, a before-after control-impact (BACI) study design was used. To address limitations of many previous land use studies, this study used multiple replicate sites and response variables and incorporated effects of both time and space.

For study sites, nine small (200 to 3500 acre) headwater watersheds were used consisting of six treatment and three reference watersheds. Watersheds were selected for similarity in geology, morphology, elevation, precipitation and types of land use and for their

relatively high capacity for future build out (i.e., “treatment”) based on undeveloped parcels at start of the project. At the outlet of each watershed, small, perennial fish-bearing streams were monitored to detect change in hydrology, biology, water quality and habitat complexity as development unfolded upstream. Small streams were used as the indicator habitats because (a) they are known to be sensitive to changes in land cover, (b) our understanding of their ecology is high relative to other aquatic habitats, and (c) there are established methods and tools to assess them.

For each watershed, land covers (forest, shrub, grass, buildings, etc.) were mapped for the project timeframe (2007, 2009, 2010 and 2012) and for historic and future full build-out (FBO) scenarios. Depending on timeframe, historic land covers were mapped using government land surveys (*ca* 1850s to 1910), aerial photos (1936, 1948 and 1965) and satellite imagery (1987 and 2007). Understanding land use history was important because current environmental conditions can sometimes reflect past rather than current land uses. The FBO was important because it defined the potential worst case, assuming full compliance and no change in zoning. Future FBO land covers were mapped using a standardized development template (building, clearing and road) applied to each undeveloped parcel. To provide comparison of the study’s rural watersheds with a representative urban watershed, 2007 land covers for Juanita Creek, an east shore tributary to Lake Washington, were used to calculate a HCI.

A novel Hydrologic Condition Index (HCI) was developed to quantify the hydrologic effect of land cover change in a way that would be comparable across space and time scales. The combined effect of geology and land cover on high pulse counts (HPCs, a measure of hydrologic flashiness) was modeled and watersheds were broken into (1.8 m) grid cells. The modeled HPC for a given grid cell’s combination of geology and land cover was weighted (multiplied) by the grid cell’s inverted distance from the watershed monitoring point (i.e., 1/distance) to make the effect of small distances large and large distances small. Resulting products were then summed to create a watershed score. To calculate the HCI, the resulting watershed scores were divided by the score for the worst possible (all paved road) condition. HCIs were estimated for project timeframe, FBO and a range of historic and reference (combinations of forest, grass and impervious) conditions.

Regulatory compliance is defined as an area of land cover change that required a permit and for which a permit was obtained. Compliance was assessed for all land cover changes for the project timeframe to determine: (a) how well regulations were followed, (b) the extent to which permits characterized actual change, and (c) the potential environmental effect of non-compliance. Compliance rates were estimated by comparing areas of land cover change with the County’s record of permits and assessing whether the change would have required a permit and, if so, what permit type (building or clearing and grading)? Only land cover change that could be seen in high resolution orthophotos was assessed; specifically, no physical survey was undertaken to ground-truth or look for non-compliant actions not observable from high resolution aerial photos.

For each of four potential types of effect, the following ERVs were measured:

- Hydrology – High Pulse Counts (HPC)

- Water Quality – conductivity, average annual temperature and the 7-day average of the daily maximum temperatures (7DADMax) (note: conductivity and annual temperature are for baseflow condition)
- Biology – Benthic Index of Biotic integrity (BIBI)
- Channel Complexity – Reach-averaged velocity at mean annual discharge (RAV@MAD), percent sand and silt, percent pool, residual pool depth, channel depth variation, thalweg length, and counts of large wood

To guide statistical analysis, a hypothesis for change if the regulations were not effective was developed for each ERV. For example, if regulations are not effective, then one or more of high pulse counts (flashiness), RAV@MAD, or conductivity should increase or BIBI should decrease, given enough time and land development. Data were collected using standard, established methods, with exception of the novel use of low amounts of salt (NaCl) as a tracer to precisely measure RAV@MAD. In contrast to other physical habitat measures, which typically have low to moderate precision, tracers were a highly precise and repeatable measure and so may have value for future habitat assessment work.

Finally, the HCI was assessed for its ability to predict ERVs, particularly HPCs on which it was based, and an ordination was conducted to assess for relationships among watersheds.

## **Results**

### *Land cover Change and Environmental Response*

Land cover change (i.e., treatment applied) in the six treatment watersheds over the five-year period was very small and an insufficient stand-alone test of regulatory effectiveness. (As expected, almost no land cover change occurred in reference watersheds.) The lack of development in treatment watersheds reflected a dramatic (75 percent) decline in building permits during the project period relative to years preceding the project. This decline is presumed due in large part to effects of a global economic recession that coincided almost perfectly with project timing.

The low amounts of change observed during the project timeframe made the historic, full build-out (FBO, where a template of development is applied to all undeveloped parcels), and urban watershed (Juanita Creek) scenarios extremely valuable for putting land cover change during project timeframe in perspective.

Estimated historic HCIs varied between ~ 0.100 and 0.150, roughly equivalent to all forest and equal parts forest and grass, respectively. This indicates that the hydrologic effect of historic land cover change over some 100 years may have been relatively small, albeit more than over the comparatively brief (2007 to 2012) project timeframe, during which the HCI was almost unvarying. Projected change between 2012 and FBO HCIs is small as well and much smaller than the amount of historic change already experienced by the watersheds. Furthermore, comparing treatment watershed HCIs at FBO (i.e., the nominal futuristic “worst case”) with urbanized Juanita Creek, the Juanita Creek HCI is 0.833, or about four times worse than projected worst case HCI at FBO for Taylor Creek (0.215).

For all study years (2007, 2009, 2010 and 2012) across all treatment watersheds, conditions were better (more forest, less developed land covers) in regulatory stream buffers than in the overall watershed.

Consistent with the small amount of land cover change observed, there was no significant change during the project timeframe in HPCs, BIBI, RAV@MAD or baseflow conductivity, which were the primary ERVs for detecting change in hydrology, biology, channel complexity, and water quality, respectively. Of the remaining ERVs, only thalweg length in reach ( $p = 0.02$ ) and percent pool along the thalweg ( $p = 0.06$ ) approached statistically significant levels of change. However, they were measured primarily to interpret change in the highly precise RAV@MAD metric, which did not change, and they are subject to high measurement error and so confidence in the significance of their change is low.

### *Compliance*

Cumulatively, over the five year (2007- 2012) study period, compliant and non-compliant land cover change accounted for 2.4 and 1 percent, respectively, of the total treatment watershed area, and 0.5 and 0.2 percent, respectively, of the regulatory stream buffer area. By far, the majority of land exhibited no change, with almost 97 percent of the watershed area and over 99 percent of the stream buffer area having no discernable change in land covers over 5 years.

When estimated as area of land cover change that likely required and obtained a permit, overall compliance rate across the six treatment watersheds was 63 percent. Compliance was much lower (35 percent) if measured as the number of times (instances) an area of land cover change was noncompliant.

Building activities had a much higher compliance rate (82 percent) than clearing and grading activities (16 percent) when estimated based on area of change. Compliance was lower for both buildings (58 percent) and clearing and grading (9 percent) when estimated as number of times an area of land cover change was noncompliant.

Compliance increased with increasing area of change for both buildings and clearing and grading activities. This relationship was statistically significant ( $r^2 = 0.64$ ,  $p = 0.01$ ) for buildings. It was weaker and more variable ( $r^2 = 0.15$ ,  $p = 0.03$ ) for clearing and grading activities.

Although compliance rate in regulatory stream buffers was low relative to overall watershed compliance, as noted above the actual area of compliant and noncompliant change was extremely small. Noncompliant land cover changes observed over five years covered a very small ( 0.2 percent) proportion of the total buffer area (1,026 acres) and largely consisted of minor shrub clearing, construction of a small amount of unpaved road, and four small (100 to 400 ft<sup>2</sup>) structures, a couple of which may not have been permanent (e.g, trailers or tarps).

Compliance rate estimation is confounded by potential hazard tree removal, which does not need a permit provided it is done outside of a regulatory buffer and when limited to only trees necessary to reduce the hazard. The estimated forest cover loss within 150 ft (~ one site potential tree height) of a building, and that therefore could have been removed due to hazard tree concerns, accounted for almost 25 percent of the conversion of forest cover to some other cover across the 6 treatment watersheds and between 70 and 80 percent of the conversion of forest cover to some other cover in the Fisher, Judd and Taylor Creek watersheds.

### *Relationship of the HCI to land covers and ERVs*

For the six treatment watersheds, the watershed HCI is highly correlated with percent impervious ( $r = 0.94$ ,  $p < 0.01$ ), percent forest ( $r = -0.91$ ;  $p < 0.01$ ), and High Pulse Counts ( $r = 0.88$ ;  $p = 0.01$ ). The high correlation of HCI with HPCs supports use of modeled HPCs from other watersheds and suggests applicability of the HCI as a metric for hydrologic condition across other watersheds. The correlation of HPCs with regulatory stream buffer HCIs is similar ( $r = 0.96$ ;  $p < 0.01$ ) to the watershed HCI.

### *Watershed Relationships*

Ordination indicates potential groupings among the nine study watersheds in regard to their response to land cover changes. These groupings appear to be based on (i) proximity to other watersheds (watersheds in close proximity to one another more similar than distant watersheds), (ii) ecoregion (Puget Lowland vs. Cascades), (iii) condition at start of project (undeveloped reference vs. low to moderately developed treatment watershed) and, (iv) stream size (large vs. small), despite their small size relative to other Puget Sound streams.

## **Conclusions and Observations related to Key Management Questions**

### (1) Were King County's regulations effective?

This question cannot be answered on the basis of this experiment. Although five years of detailed studies were conducted in six treatment watersheds very little development occurred in them due in part to a major economic recession. As a result, the ability of King County's regulations to prevent an adverse environmental response has not yet been effectively tested. However, the study has established a robust baseline of environmental conditions for comparisons in future years, after more development has occurred.

Given the lack of development, the effectiveness of the CAO was modeled in treatment watersheds under a fully "built out" condition assuming full compliance and no change in zoning. Predictions about future effects on hydrologic condition (the HCI) were generated by simulating hypothetical future land use changes under the CAO and taking into account of historic activity. These simulations are the first time the CAO has been modeled for entire watersheds in a systematic and scientific manner. The results suggest that the impact of future development on the study watersheds may be small relative to an urban basin inside the Urban Growth Area (UGA). However, these results are based on modeling and should be viewed with caution: the potential future effects of development and effectiveness of regulations have not been validated, and definitive results will require additional testing.

### (2) What recommendations emerge from the study about the CAO?

Lacking evidence of problems with regulations, changing the CAO, either strengthening or lessening its protections, is not warranted at this time. But future research appears warranted: concluding wrongly that regulations are effective when they are not is risky, as these regulations apply to a large portion of King County, rural lands that contain relatively productive salmon runs and high water quality important to the County's quality of life.

(3) What is the significance of the assessment framework?

The assessment framework – an array of nine geographically distributed, intensively monitored watersheds (six treatment, three reference) in an explicit, statistically strong study design (modified BACI) using well-established methods, metrics, and databases – provides a powerful tool for assessing change and relationships among watershed-scale land cover and ERVs. By explicitly accounting for time, rather than substituting space for time, and using replicates and controls (reference sites), the framework addresses shortcomings identified in many past land use studies. In order to increase confidence in and the utility and comparability of project approach and results, a relatively high level of effort was expended to minimize the potential for Type II error (i.e., concluding regulations were effective and there was no effect of development when, in fact, an effect occurred). High certainty was desired because regulations (a) are a primary mechanism for environmental protection, (b) can be costly to land owners, and (c) are often a highly sensitive sociopolitical issue.

(4) What is project's application to other science questions?

This method has potential to: (a) assess land cover change and regulatory effectiveness in other small watersheds, and (b) address additional needs and questions such as (i) calibration and refinement of models of land cover and watershed hydrology, water quality, hydraulics, and biology, (ii) understanding and estimating the effect of space and time in assessing land cover patterns and environmental outcomes; (iii) estimating rates of change over time, and (iv) identifying thresholds and mechanisms of environmental response to land cover change. With some modification, primarily to reduce time and costs to produce land cover maps and improve grid cell routing, the framework and associated study design, methods, and metrics could be repeated using readily available tools and datasets.

(5) How were historic and future scenarios important?

Historic and full build-out scenarios were useful for setting the context of current conditions between past and future conditions. In retrospect, such scenarios were especially helpful because of the project's combination of a relatively short study timeframe and an unexpectedly low degree of land cover change. Assessing contemporary conditions in context of historic and potential future conditions increased understanding of the range of historic variability and the future capacity for change. Without them, interpretation of project timeframe land cover change effects would have been far less informative.

(6) Did noncompliance affect outcomes?

Not over the study period. So little development occurred that the total area affected by noncompliance over five years was very small (0.9 percent of treatment watershed area), and there was no detectable effect of the combined compliant and noncompliant land cover change on ERVs. Further, the amount of noncompliant land cover change observed in regulatory stream buffers was even smaller than in the whole watershed (0.3 percent of the regulatory stream buffer area in the treatment watersheds). This very small amount of noncompliant change in regulatory buffers suggests that stream buffers are being

preferentially protected as required. As such, it may be possible that people are complying with regulations by not developing in critical areas in the first place.

It is important to note that in a future period of rapid development, noncompliance rate could become a factor at the watershed and buffer scales. If non-compliance were to continue at the observed rate for the watershed, during a period of intense development approximately twice as much unpermitted development could occur.

However, because the actual amount of change is small, the net effect of this non-compliant development would still be relatively small. While noncompliance may have relatively little hydrologic effect, loss of land could affect key areas for fish and wildlife. A future study should be undertaken to further assess potential impacts of noncompliance.

(7) What are implications for habitat restoration and protection?

Historically, the study watersheds have been subjected to a range of hydrologic conditions resulting from initial extensive deforestation followed by subsequent varying levels of reforestation and agricultural and rural residential development. Based on modeling information, relative to historic variation, hydrology of the study streams is projected to change little in the future. Furthermore, the streams are unlikely to experience conditions resembling high-impact urban hydrology. It then appears that watershed hydrology in these mostly undeveloped rural streams is relatively intact and may facilitate success in reach-scale restoration projects.

Although not directly assessed, it may be that present-day habitat conditions are constrained in part by a shared legacy of stream and riparian habitat modification (large wood removal, bank hardening, ditching, culverts) resulting from early (*ca.* ~ 1900 to mid-1900s) logging, agriculture, and rural residential development, and associated infrastructure (roads, culverts, drainage ditches).

## ACRONYMS

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7DADMax, 7-day average of the daily maximum temperatures

BACI, before-after control-impact

BAS, best available science

BIBI, benthic index of biotic integrity

BMP, best management practices

CAO, Critical Areas Ordinance

CARA, critical aquifer recharge areas

cfs, cubic feet per second

CPP, King County Countywide Planning Policies

CUT, Current Use Taxation

CVTD, coefficient of variation of thalweg depths

DDES, Department of Development and Environmental Services (now DPER)

DEM, digital elevation model

DHSVM, Distributed Hydrology-Soil-Vegetation Model

DNRP, Department of Natural Resources and Parks

DPER, Department of Permitting and Environmental Review (formerly DDES)

EMAP, Environmental Mapping and Assessment Program

EPT, Ephemeroptera, Plecoptera, Tricoptera

ERV, environmental response variable

ESA, Endangered Species Act

FBO, full build-out

FIBI, fish index of biotic integrity

FPA, Forest Practices Approval

GIS, geographic information systems

GMA, Growth Management Act

HCI, hydrologic condition index

HIC, King County Hydrologic Information Center

HPC, high pulse count

HPR, high pulse range

IMW, intensively monitored watersheds

K.C.C., King County Code  
KCCP, King County Comprehensive Plan  
LWD, large woody debris  
MAD, mean annual discharge  
MDD, minimum detectable difference  
MPP, multi-county planning policies  
NMDS, non-metric multidimensional scaling  
PBRS, Public Benefit Rating System  
PHA, programmatic habitat assessment  
PLE, Puget Lowland Ecoregion  
PSP, Puget Sound Partnership  
PSSB, Puget Sound Stream Benthos  
PSSRP, The Puget Sound Salmon Recovery Plan  
QAQC, quality assurance/quality control  
RAV @ MAD, reach-averaged velocity at mean annual discharge  
RPD, residual pool depths  
S&S, silt and sand  
SMP, Shoreline Master Plan  
TDR, Transfer of Development Rights  
U.S. EPA, United States Environmental Protection Agency  
WDNR, Washington Department of Natural Resources  
WDOE, Washington Department of Ecology  
WRIA, Water Resource Inventory Areas

## 1.0. INTRODUCTION

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In 1990, the Washington State Legislature passed the Growth Management Act (GMA) in recognition that protecting human health and safety and the environment are high priority goals for the State. In response, King County updated its land use regulations on January 1, 2005, as required by the GMA to protect environmentally critical areas and limit development in hazardous areas. The County's response resulted in some of the nation's most protective land use regulations and created the opportunity to examine whether development can co-exist with diverse, productive aquatic ecosystems.

Land use regulations attempt to avoid or minimize and mitigate the environmental effects of development, yet their effectiveness in this regard has rarely been directly assessed. To remedy this knowledge gap, this study was designed to provide greater understanding of the implementation and effectiveness of King County's land-use regulations in rural areas where valuable aquatic areas are at risk of impact from future development.

This study addresses a fundamental and often asked but rarely answered question: "Are land use regulations effective at protecting aquatic habitats and associated biological resources?" To address this question for rural areas, the environmental effects of land use and the implementation and effectiveness of King County's land use regulations in rural areas was evaluated by tracking permits and compliance, changes in land use and land covers and environmental response variables (ERVs) in reference and treatment watersheds as land development unfolded over a five-year study period.

For this study, regulations include all the things we do to manage development on a site including limitations, such as buffers and set-backs, and best management practices (BMPs) used to avoid or mitigate for development effects on hydrology and water quality. Land development (hereafter "development") refers to changes in land cover resulting from clearing, grading, and building activities that may affect watershed hydrology and associated parameters. Compliance was defined as land cover change that was permitted (i.e., required and obtained a permit). Land use effects were changes in ERVs representing hydrology, biology, water quality and physical habitat complexity as measured in stream channels draining rural study watersheds.

### 1.1 Background

Like much of low-lying Puget Sound, most watersheds in King County face land development pressures related to growth in the human population (Robinson et al. 2005). King County includes the largest cities and metropolitan areas in the Pacific Northwest (over 2 million people in 2012). In these urban areas, development is regulated by municipal regulations. Outside these heavily impacted urban areas, however, land development is mostly rural and subject to King County's land use regulations. Land uses in rural areas include agriculture, forestry, and low-density residential housing (generally zoned as one dwelling unit per 2.5 to 10 acres [1-4 ha]; KCORPP 2002). King County regulations do not apply on federal and tribal lands or to forestry regulated by Washington State Department of Natural Resources (WA DNR).

As indicated by recent assessments, “smart growth” policies that promote growth within urban areas appear to be effective, as development rates in rural areas have diminished relative to urban areas (Robinson et al. 2005; Vanderhoof et al. 2011; WRIA 9 Implementation Technical Committee 2012; Jensen 2012). Despite policies that are intended to concentrate growth in existing urban areas, capacity for development still exists in undeveloped or under-developed parcels in rural areas. Environmental conditions still appear relatively intact in these areas, and protection of high-functioning aquatic habitats and the processes that sustain them appears feasible. Puget Sound lowland streams in these relatively undeveloped rural areas contribute substantially to the region’s overall biological productivity and biodiversity but, at the same time, development represents the single most important and controllable factor that could degrade them. Therefore, because developing rural areas and the natural resources in them are at risk from land development pressures, it is important to ensure that the County’s rural land use regulations, and regulations promulgated elsewhere in rural Puget Sound, are effective at ensuring development occurs in a manner that prevents environmental degradation.

The Puget Sound Partnership’s (PSP) Action Agenda (PSP 2008) identified the need for studies that expand the scientific basis for integrated land use and water resource planning and help refine resource protection strategies. One proposed line of investigation was to explore land use patterns and biophysical correlates of aquatic habitat at various (nested) watershed scales. A second line of investigation would be aimed at assessing the effectiveness of land use regulations in protecting aquatic habitat as development occurs. Together, these studies would shed light on the effects of land use patterns on surface water runoff and aquatic habitat. They would also help measure the extent to which low impact development can help maintain surface and groundwater hydrology and aquatic habitat structure and, ultimately, help inform our understanding of aquatic habitat utilization by sensitive biota under various development scenarios. This information would help to develop and refine local and regional strategies to maintain and enhance ecological functions as development occurs.

In addition to Puget Sound plans, recovery plans for endangered salmon in fifteen Water Resource Inventory Areas (WRIAs) – four of them within the study area of King County – are in place and being implemented throughout Puget Sound. Planning includes identification of major resources at risk, causes for decline, and numerous programmatic, capital, and regulatory recommendations for protection and restoration. Determining the effectiveness of land use regulation is a common and urgent need in all these efforts. The Puget Sound Salmon Recovery Plan (PSSRP) recognized that the success and sufficiency of habitat protection through policy and regulations is largely unknown (Shared Strategy Development Committee 2007). Similarly, the Puget Sound Partnership identified the effectiveness of land use management and regulation in protecting the environment as an important but unknown factor in the recovery of Puget Sound habitats and species (PSP 2008).

Given this interest in land use effects, the importance of regulations in preventing them and the need to improve our knowledge about them, the U.S. EPA and King County initiated the five-year study described in this report. As relatively little direct observation of regulations or their effectiveness has ever been done, this study provides basic science relevant to key questions being asked about the effects of development.

This report describes the:

- purpose, goals, objectives and key questions of the study;
- regulatory environment and regulations specific to the study area;
- study methods for assessing level of land use change and environmental response
- results of 5 years of study and assessment of historic and potential future conditions; and
- discussion and conclusions related to key study questions.

## 1.2 Purpose, Key Questions, Goals, and Objectives

This study's overall purpose was to evaluate the environmental effectiveness of relatively new (adopted January 1, 2005) land use regulations codified in the King County Critical Areas Ordinance (CAO). Results of the study are intended to inform King County about the effectiveness of its land use regulations while also providing the Puget Sound Partnership, local salmon recovery planning forums, and other jurisdictions insight on land use regulations and an approach for assessing regulatory effectiveness.

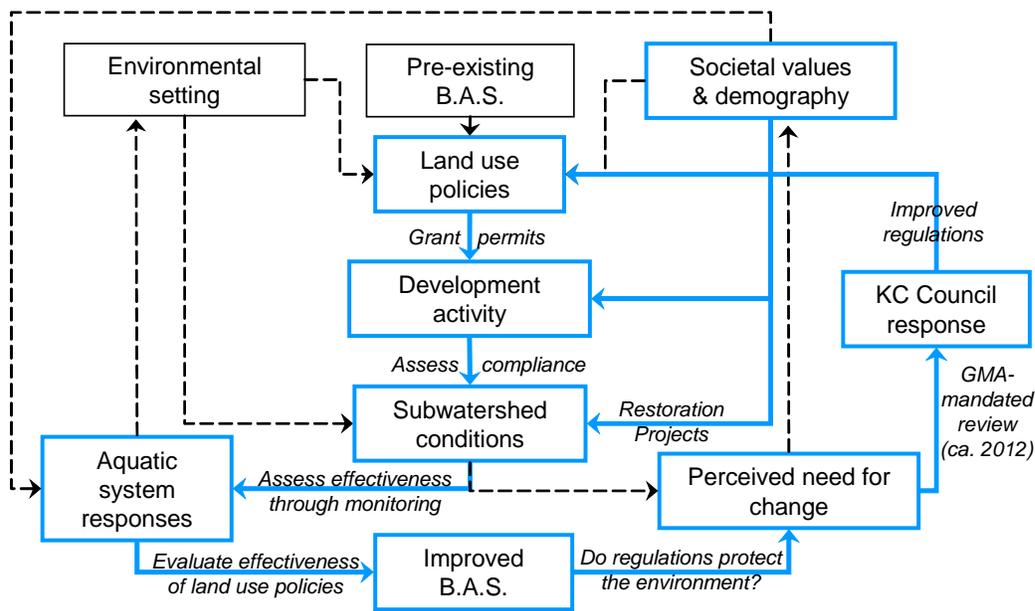
Key study questions were:

- Did the environment respond to change in land cover during the study? If so, was response related to CAO implementation?
- If response was significant, how might the CAO be modified to reduce future impact?
- How well did people follow the regulations? Do permits provide an estimate of land cover change? And did non-compliance impact the environment?
- Was the assessment framework a useful tool for measuring effectiveness? What changes are recommended for future work?
- Are there relationships among environmental variables and watersheds that provide greater understanding of the mechanisms affecting environmental response? (This key question became evident during the analysis phase of the project.)

The study goals were to (1) establish and test a framework and associated methods for quantifying land cover change and associated environmental responses to land development implemented under new (2005) land use regulations, and (2) identify where the framework and regulations may be ineffective and recommend changes as necessary based on results.

Study objectives were to: (1) quantify land cover and environmental change over time, (2) determine relationships between land cover change and ERVs, (3) track implementation and compliance with land use regulations, (4) provide these findings to the King County Council, and (5) make approach and data available to other Puget Sound jurisdictions to consider as part of best available science (BAS) when they update their land use regulations.

As modified from Grimm et al. (2005), Figure 1 shows the general process for how best available science (BAS) may be updated and used to inform updates to land use policies and regulations.



**Figure 1.** Generalized conceptual model for how best available science (BAS) on land use may be updated and contribute to decisions on regulations (modified from Grimm et al. 2005). Boxes represent factors affecting observed ecological conditions. Arrows represent influences and are annotated. Blue arrows and boxes are influences and factors addressed in this study.

### 1.3 Project Hypothesis

The study’s working hypothesis was if the land use regulations are not effective or not effectively implemented, then given enough time detrimental effects of development should be detected as change in one or more aspects of the hydrology, water quality, biology, and physical condition of streams draining treatment watersheds. Furthermore, if change was detected, then the direction and magnitude of change should be commensurate with the direction and magnitude of change in land covers, presuming no major change in larger-scale background factors, such as climate or geology. Reference watersheds with relatively intact conditions (no development) are used for comparison and to discriminate between treatment effects and changes resulting from cross-category factors such as regional climate variation and other natural background variation that could mask detection of a true development impact.

### 1.4 The Regulatory Environment

Regulations are designed to accommodate a wide range of social and economic uses while ensuring public health and safety and protection of valuable natural resources, including water quantity and quality and fish and wildlife, within a diverse but finite land base. King County is currently governed by a complex set of regulations that are nested and operate at multiple scales. The regulations determine development, including type (residential, commercial, agriculture, forestry, mining, recreation, open space), location (rural vs. urban zoning, forest and agricultural production districts), density (ranging from very low in forestry and agricultural areas to very high in urban centers), and degrees of proximity to

critical areas and their buffers. Lastly, where property rights are constrained, regulations provide conditions under which a limited set of allowed alterations to critical areas and their buffers may be permitted.

#### 1.4.1 Comprehensive Plan and Zoning

The history and requirements of King County's Comprehensive Plan (KCCP) and zoning have been variously summarized by Robinson et al. (2005) and King County (2012a).

The County developed its first comprehensive land use plan in 1964. However, its first substantial efforts to address growth occurred two decades later, when the 1985 Comprehensive Plan identified an urban growth boundary to limit urban growth to areas that could support urban levels of density and established Rural Areas and policies to conserve the natural environment and designate resource lands for long-term agriculture and forest production.

In 1990, the Washington State legislature adopted the Growth Management Act (GMA) which directed the state's most populous and fastest growing counties and their cities to prepare comprehensive land use plans anticipating growth for a 20-year horizon. In accordance with the GMA, subsequent comprehensive plans have been required to direct growth into designated urban areas and away from the Rural Area and Resource Lands. The GMA also required jurisdictions to designate and protect critical areas and commercially significant forestry, agriculture, and mining areas.

King County's first Comprehensive Plan under the GMA was adopted in 1994 and the first major review and update to that Plan was in 2000. King County continues to update the KCCP every four years for major policy changes and annually to make minor corrections or changes that do not involve a major change in policy. The KCCP provides a policy and legal framework for guiding regional growth and making decisions about land use in unincorporated King County. It is the framework for many other plans and regulations and for the King County Code that governs the location and density of land uses and provides guidance for decisions on zoning changes and developments. It also gives the County's position on proposed changes in land use, zoning, environmental protection and regulations, and broader policy issues such as use of resource lands and spending on facilities and services.

The King County Countywide Planning Policies (CPPs) set the framework for the county's and cities' comprehensive plans. The CPPs, adopted by the county and cities in 1992 and amended several times since 1992, established an Urban Growth Area within the western one-third of King County where most growth and development is targeted. Policy goals include: reducing urban sprawl, protecting the Rural Area, providing affordable housing throughout the county, and coordinating protection of environmentally critical areas.

Another planning tool in King County is the multi-county planning policies (MPPs), which the GMA requires of the most populous counties. The Puget Sound Regional Council developed the MPPs, known as Vision 2040, through extensive collaboration with four counties (Snohomish, King, Pierce and Kitsap) in the central Puget Sound. Vision 2040 is an integrated strategy to address regional issues that cannot be comprehensively dealt with within a single jurisdiction. The Vision 2040 outlines the regional growth strategy and

specifies policies to help achieve the strategy. The MPPs provide guidance and direction to regional, county, and local governments on such topics as setting priorities for transportation investment, stimulating economic development, planning for open space, making city and town centers more suitable for transit and walking, and improving transportation safety and mobility.

#### 1.4.2 Key Ordinances - CAO, Clearing and Grading and Stormwater

Although commonly referred to as the Critical Areas Ordinance (CAO), the foundation of King County's land use regulations as they pertain to the study watersheds is actually three major ordinances – Critical Areas, Clearing and Grading, and Stormwater – as found in King County Code chapters 21A.24, Title 9, 16.82, and 21A.25, respectively (Table 1).

The three ordinances work together in a nested approach, where:

- the CAO establishes critical areas and their regulatory buffers or set-backs and prohibits or limits development within them, and
- the clearing and grading and stormwater ordinances limit the location, type, and amount of clearing, grading, and impervious surfaces.

Permits and best management practices are required for clearing, grading and new or re-constructed impervious areas when minimum thresholds are exceeded (Table 1). Best management practices include silt fencing, mulching, and planting to prevent erosion and sediment mobilization as well as implementing infiltration projects to prevent or treat stormwater runoff.

For certain highly sensitive critical areas, including streams, lakes and wetlands, a “no adverse effect” standard was used to construct critical area regulations. For these areas, no impacts are allowed to critical areas or their buffers except for:

1. a limited set of pre-determined allowable alterations (see allowed alterations table in King County Code 21A.24.045), such as
  - maintenance of existing permitted structures or cleared areas where there is no expansion of the use
  - development where the surrounding land use is already highly and irreversibly developed
  - to accommodate critical infrastructure when no feasible alternative exists; or
2. to meet a landowner's constitutionally protected property right.

In any event, when impacts are allowed under the above circumstances, mitigation is required for impacts that could not be avoided or minimized.

**Table 1. Summary of King County’s Critical Areas, Clearing and Grading and Stormwater ordinances as they apply in the study watersheds.**

<b>Ordinance</b>	<b>Purpose</b>	<b>Where</b>	<b>How</b>
<b>Critical Areas</b>	Prohibit or limit development in or near hazardous and environmentally sensitive areas	Environmentally sensitive areas: streams, lakes, wetlands, wildlife habitat conservation areas, and critical aquifer recharge areas;  Hazardous Areas: 100-year floodplain, steep slope (>40%), landslide, erosion, seismic, volcanic, and coal mine high risk areas.	Establishes protected critical areas, regulatory buffers, building set-backs and other protective measures.  Prescribes regulations for avoidance and minimization and mitigation for a limited set of allowable uses in critical areas and their buffers.
<b>Clearing and Grading</b>	Regulate the amount and location of clearing and grading	At the parcel-scale or development site, depending on size of development, for all parcels and zoning	Permits issued to assess and direct protection and, where necessary, mitigation measures for erosion and sediment control.  Generally required for parcels where the cumulative clearing is in excess of 650 m <sup>2</sup> (7,000 ft <sup>2</sup> ) or soil grading in excess of 76.5 m <sup>3</sup> (100 yd <sup>3</sup> ). Exemptions include removal of hazard trees and hand-removal of invasive blackberries when outside of critical areas and their buffers. See KCC 16.82.051 for examples of other activities that do not require permits.
<b>Stormwater</b>	Regulate the amount and quality of stormwater runoff from developed surfaces	At the parcel-scale or development site, for any proposed project (except maintenance) subject to a King County development proposal, permit, or approval AND meeting any one of the following: 186 m <sup>2</sup> (2,000 ft <sup>2</sup> ) of new impervious surface; 650 m <sup>2</sup> (7,000 ft <sup>2</sup> ) of land disturbing activity; construction or modification of a 0.3 m (12”) diameter drainage pipe; contains or is adjacent to a critical area (except coal mining, seismic and volcanic hazard areas); redevelopment costing \$100,000 or more or where the new plus replaced surface is ≥ 465 m <sup>2</sup> (5,000 ft <sup>2</sup> ) and valuation is > 50% of existing site improvements	A drainage review determines type and amount of treatment sufficient to retain and treat all stormwater runoff on-site as <i>per</i> the 2009 King County Surface Water Design Manual (King County 2009). For low-density rural properties, stormwater is generally required to be infiltrated on site to the maximum extent feasible, preferably by retaining native soils and vegetation. Constructed stormwater facilities, e.g., ponds, swales or both, may be required where infiltration is not an option or is insufficient to prevent or treat runoff.

The extent of regulatory buffers for aquatic areas, including streams, is a key element of the County’s regulations. The regulations classify different types of waters and provide different buffer for each (Table 2). Regulatory buffers for aquatic areas, excluding wetlands whose buffers differ from aquatic areas, range in width from 50 m (165 feet) for Type S and F waters, 20 m (65 feet) for Type N waters and 7.5 m (25 feet) for Type O waters.

**Table 2. King County regulatory buffer widths measured from the ordinary high water mark from each bank (e.g., corridor width = buffer width x 2 plus stream channel width) for streams in the study watersheds. Waters include perennial and seasonal streams. (Note: Type S waters, which are Shorelines of the State and under the Shoreline Management Act jurisdiction, are not found in the study watersheds.)**

Water Type	Description	CAO Buffer Width, beginning 2005
Type S and F	Waters that are Shorelines of the State (Type S) and waters with fish-bearing potential that are not Shorelines of the State (Type F)	50 m
Type N	Waters with no fish-bearing potential and a surface connection to Type F water	20 m*
Type O	Waters with no fish-bearing potential and no surface connection to a Type F water	7.5 m

\*Bear Creek Type N buffers are 30.5 m (100 ft).

Rural areas are also subject to a fourth set of regulations found in the County’s Shoreline Master Plan (SMP), which was mandated by the Washington State Shoreline Management Act. Although the SMP applies to larger water bodies, such as streams with mean annual flow of 0.57 m<sup>3</sup>/s (20 ft<sup>3</sup>/s) or greater, than are found in the study watersheds, King County’s SMP applies the same regulatory standards required in the Critical Areas, Clearing and Grading, and Stormwater Ordinances. Additionally, the County’s SMP imposes limits on the type and intensity of land uses in jurisdictional shorelines based on whether they are water-dependent uses and the condition and context of shoreline reaches, ranging from high density residential, commercial, or industrial uses to low density residential, agricultural, forestry and wild, or pristine. Thus, for example, under the SMP, land uses that are not water dependent would not be allowed in a shoreline zone and high intensity uses would not be allowed in conservancy or natural shorelines, where natural resource conditions are high and protection is prioritized.

Establishment of the regulations relied heavily on a synthesis of best available science (BAS), including scientific results derived from local studies, and an assessment of the proposed ordinances (King County 2004a and b; King County 2012a; see CAO website<sup>3</sup>). The BAS describes the history, foundations, and logic train behind regulations in general. The BAS also describes how land use ordinances work in combination with the County’s restoration, protection, and stewardship efforts to facilitate development in an

<sup>3</sup> <http://www.kingcounty.gov/property/permits/codes/CAO.aspx>

environmentally sound manner while protecting the environment from the adverse effects of land use.

Key elements of the 2005 regulations were wider and more expansive regulatory buffers than required under the previous regulations (the 1990 King County Sensitive Areas Ordinance) and, in rural areas, prescribed limits on vegetation clearing to no more than 35 percent of a given parcel. In 2008, the Washington State Court of Appeals reviewed and upheld the scientific basis for the 2005 regulations but overturned the clearing limits element of the Clearing and Grading Ordinance, because they violated state law relating to how taxes, fees, and charges on development are to be imposed<sup>4</sup>. As a result, clearing limits are no longer used as a mechanism for limiting the amount of clearing outside critical areas and their regulatory buffers.

Regardless, clearing will likely be at least somewhat limited because of a combination of (a) Stormwater Ordinance best management practices (BMPs) that promote infiltration on natural soils, (b) cumulative protections provided by hazardous and environmental critical areas, regulatory buffers, and set-backs, and (c) personal choices by rural residents that tend to maintain forest cover, presumably for lower site maintenance, privacy and aesthetics that forests provide relative to other land covers. The Stormwater Ordinance promotes the protection of native soils and vegetation because it is a cost-effective way to treat and infiltrate runoff from constructed surfaces. The alternative to infiltration is relatively costly construction and maintenance of stormwater treatment facilities, such as engineered pipes, ponds, and swales. Thus, it is expected that clearing will be limited because retention of native soils and vegetation is a cost-effective way for landowners to meet their stormwater management needs.

### 1.4.3 Compliance and Enforcement

Compliance and enforcement are key elements of the County's regulatory system. The County does not use staff to actively search for non-compliant activities and instead relies on citizen complaints.

The King County Code makes it a civil violation to fail to comply with any county codes or rules that protect or regulate the environment or to fail to comply with any permit condition or code enforcement order (K.C.C. 23.02.030; see also, K.C.C. 21A.50.030.) The Code prescribes steps of escalating enforcement actions when King County determines that a code violation has occurred. These include a voluntary compliance agreement, citation, notice and order, and a stop work order. If a person is determined to be in violation, they are required to bring the property into compliance with the Code. This includes a requirement to apply for all permits that are required to make any corrective actions.

For critical area violations, the Code requires corrective work to bring the property into compliance. This includes restoring any critical area or buffer that has been illegally altered. Restoration of streams, wetlands, and their buffers must comply with the relevant restoration standards for those critical areas. A work plan is required and includes monitoring to ensure that the restoration measures have been installed and that they are

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<sup>4</sup> <http://www.kingcounty.gov/property/permits/codes/CAO/CourtRulingsQA.aspx>

being maintained. The County maintains a database of enforcement actions, including problem statement and resolution. An enforcement action remains open in the database until formally resolved.

Because critical areas such as streams and wetlands are highly susceptible to degradation caused by stormwater runoff, monitoring and remediating problems associated with ineffective or failing stormwater facilities and BMPs are critical. For these reasons, privately owned and maintained stormwater facilities and other BMPs are recorded on a property's title allowing King County to inspect them and enforce maintenance within one year of a problem being identified. For projects where a facility is not privately owned and maintained such as commercial and large-scale residential projects, King County inspects facilities at least once every two years and property owners are notified of any required maintenance. If the property owner does not conduct maintenance as directed, the County has a program to enforce compliance with required maintenance standards (King County 2012b).

## 1.5 Non-regulatory Environmental Protection Measures

In addition to regulations, King County protects aquatic areas through conservation programs, land acquisitions, and conservation easements (Lucchetti et al. 2005; Kaje 2009; King County 2012a). King County's non-regulatory protection measures can be placed into three broad categories: (1) land conservation acquisitions (fee simple and easements), (2) conservation tax incentive programs, and (3) habitat capital improvement projects (refer to Appendix A). Most of the County's habitat-based capital improvement projects have been in river channels and floodplains, which are much larger than the water bodies used in this study, although some in-stream habitat work, such as addition of large wood for habitat, has recently been done in Judd Creek, one of the project's study streams on Vashon Island.

## 2.0. METHODS

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The project consisted of nine small (62 - 1,262 ha) headwater watersheds (Appendix B) in which change in land covers and environmental response variables (ERVs) were studied over time. For each watershed, grid cells (1.8 m) were created, and change in the type, location, and extent of land covers was documented for each grid cell. The change over time was quantified using both simple aggregate measures (the percent land covers summed at the watershed or regulatory buffer scale) and an index developed for this study to quantify the hydrologic effect of land cover change. The index, called the Hydrologic Condition Index (HCI), weights each grid cell by its inverse distance from the watershed monitoring point and by the relative hydrologic effect of differing land covers and permeability of underlying geology. All land cover changes were cross-referenced with a permit database to assess amount of compliant and noncompliant land cover change (defined as whether permits were obtained when required). In addition to representing multiple effects pathways, the response variables used for this study were selected for their known sensitivity to land cover change, relatively high precision, established methodologies, reliable estimation, relatively low cost to test, and ease of sampling and replication.

The study design used multiple treatment and reference watersheds and a set of response variables considered to be most responsive to change. This approach was taken to maximize the likelihood for detection of change and reduce Type II error (a “false negative,” where an adverse impact is not detected but in fact occurs). An especially strong study design was desired because land use regulation effectiveness is critically important for many of the region’s environmental goals (PSP 2008).

The study approach was to:

- Use ERVs that could be precisely measured and known to be sensitive to land use change;
- Select treatment watersheds with relatively high development potential and naturally high sensitivity to hydrologic change in response to development (based on predominance of till-based geology and no or limited amounts of natural hydrologic buffering features such as lakes, ponds and sizable wetlands);
- Use multiple treatment and reference watersheds;
- Use time and space as variables (rather than substitute space for time) through detailed tracking of land cover and ERVs over time in multiple locations;
- Assess effects of historic conditions (which could mask or modify present-day responses) and project potential condition under a worst case full build-out;
- Use high resolution photos and a spatially explicit model to maximize precision in the measurement of the level of treatment (development) applied.

### 2.1 Study Design

As described by Roni et al. (2005), the study design is best characterized as before-after control-impact (BACI) with multiple unpaired treatment and reference sites. This design was chosen because it was anticipated that the effects of land-cover-driven change on ERVs could be difficult to detect in a limited (~5 year) timeframe because of natural variability of

the ERVs and the inability to strictly control amounts of land development as treatment. Both of these challenges are problems common to land use research (Carter et al. 2009). In an attempt to address these two challenges, replicate watersheds and ERVs representing hydrologic, water quality, biologic, and physical channel responses were used to increase the potential for detecting change in a relatively short timeframe.

Permits and compliance, as measures of regulatory implementation, and concurrent changes in land cover, hydrology, stream channel physical complexity, water quality, and benthic invertebrates were assessed over a 5-year study period across 9 small (62 to 1,262 ha) watersheds with perennial, fish-bearing headwater streams. The study watersheds were broken into six “treatment” watersheds, where land development occurred under the County’s land use regulations with no intervention or guidance by study personnel or County regulators, and three “reference” watersheds where no land development occurred (Table 3).

**Table 3. Study design showing current and future development conditions for reference and treatment watersheds.**

Category	Watersheds	Current development	Future development
Reference (n = 3)	East Seidel, South Seidel, and Webster	None	None
Treatment (n = 6)	Vashon Island: Judd, Fisher, and Tahlequah Mainland: Taylor, Weiss, and Cherry Creek Tributary	Minimal to moderate	Potentially extensive

For each watershed, values for eleven ERVs representing hydrology, water quality, physical complexity and biology were assessed (Table 4). Detailed descriptions, rationales for selection and measurement methods for the ERVs are described in Section 2.2.

**Table 4. Environmental response variables used to environmental change in study watersheds.**

Category of Environmental Response	Environmental Response Variable	Unit
Hydrology	High pulse count	Counts per year
Water quality	7-DADMAX, Average annual temperature at baseflow	degrees
	Conductivity @ baseflow	µS/cm
Stream Channel Complexity	Reach-averaged velocity @ mean annual discharge	m/min
	Thalweg length and depth, pool length and residual depth, percent sand and silt, large wood count	various (m, %, counts)
Macro-invertebrates	BIBI	score (10-50)

## 2.2 Study Area and Watersheds

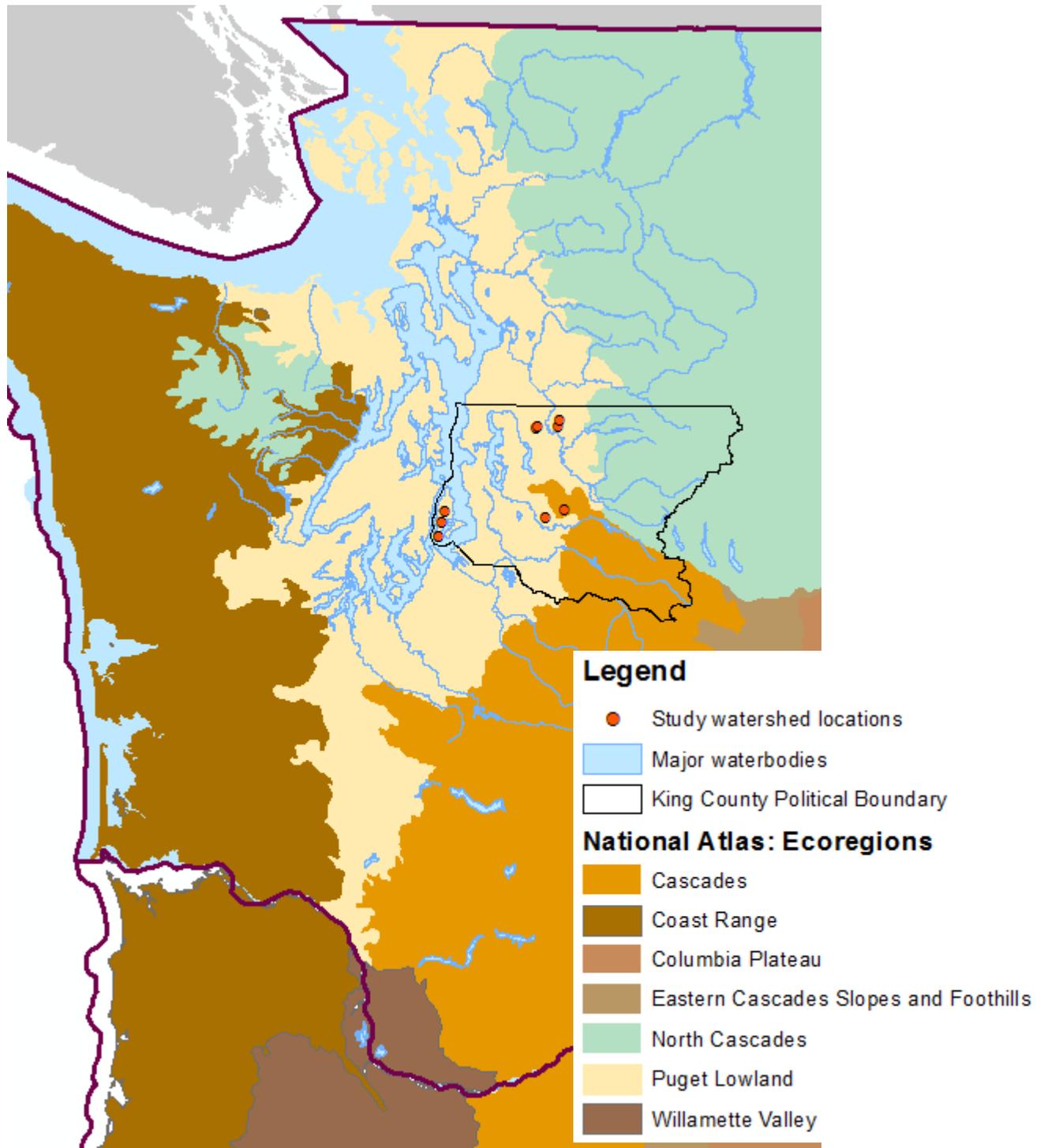
The study area covers the developing, low-lying western portion of King County, an area of common geologic history, flora, fauna, and human uses. The study watersheds are located in central Puget Sound and distributed across rural King County (Appendix B). Eight study watersheds are located in the Puget Lowland Ecoregion (PLE; Figure 2), which is predominantly less than 150 m (500 feet) in elevation. The ninth study watershed is in the Cascades Ecoregion at the eastern edge of the PLE.

Study watersheds contain headwater alluvial streams originating on low-gradient upland plateaus, dropping across steep side-slopes to low-gradient base levels set by a major river, lake, or Puget Sound. Upland and riparian forests consist of second-growth conifers (mainly Douglas-fir, western hemlock, and western redcedar) and, to a lesser extent, deciduous trees (mainly bigleaf and vine maple, red alder, and black cottonwood). Hydrology is rain-dominated, with naturally flashy flows during winter and low summer baseflows. Aquatic productivity is typically limited by low nutrient availability, low summer flows, high winter flows, and available daylight during winter.

Numerous diverse and biologically productive aquatic habitats exist in the small study watersheds and their encompassing larger watersheds. These habitats directly or indirectly support commercially and ecologically important salmonid populations, which, in addition to the aforementioned ESA-listed species, include coho, sockeye, chum, and pink salmon and resident rainbow (where not contributing to anadromous populations – i.e., steelhead) and cutthroat trout. King County’s aquatic systems also support considerable non-fish biodiversity and a wide range of recreational uses such as swimming and boating as well as important non-recreational uses, including navigation and water for drinking and commercial uses. These uses are all the more valuable because they exist in close proximity to many people, as King County is the nation’s thirteenth largest municipality and home to the Pacific Northwest’s largest metropolitan area (over 2 million people).

The study watersheds are largely rural zoned lands where the primary and typical land uses are single family residences interspersed with small-scale (~0.25 to 4 hectares) forestry and agricultural activities, public lands (parks, schools, infrastructure,) and a

panoply of protected, unbuildable areas including streams, wetlands, hazardous areas and regulatory buffers.



**Figure 2.** King County boundary and distribution of the nine regulatory effectiveness monitoring study watersheds relative to Puget Sound and ecoregions of western Washington State. Eight watersheds are located in the Puget Lowland Ecoregion and one (Webster Creek) is in the Cascades Ecoregion at its boundary with the Puget Lowland Ecoregion.

## 2.2.1 Watershed Selection

Small (62 to 1262 ha) headwater watersheds with perennial, fish-bearing streams were chosen as study watersheds for their tractability (i.e., small enough to map and track detailed land cover change but not so small as to be overwhelmed by effects of land cover changes on any single parcel). Because no undeveloped watersheds with development potential existed in unincorporated King County (i.e., all watersheds had existing development), watersheds were selected by first screening for areas with relatively high future development potential indicated by parcels for which no known land-altering permits had been issued since 1989 and parcels whose value of improvements was  $\leq 20$  percent of the total parcel value based on the King County Assessor 2007 database. A map showing all watersheds considered for this study is in Appendix C.

Subsequent selection of the study's six treatment watersheds was based on the following criteria:

- Existing monitoring site – the presence of a past or existing stream flow, water quality, or benthic invertebrate monitoring site, because existing sites indicated suitability for monitoring (accessible, land-owner permission, stable for sampling activities) as well as providing potential added value of historic data; four watersheds (Judd, Fisher, Taylor and Tahlequah) had pre-existing gages and data;
- Till-based geology – predominance of underlying glacial till-based geology, because of its greater sensitivity to hydrologic change relative to glacial outwash, the other dominant surface geology in King County lowlands; eight of the nine study watersheds had high (59 to 97 percent) proportion of till, and one (S Seidel, a reference) had relatively low (38 percent) proportion of till;
- No lakes/minimal wetlands – absence of lakes, ponds and minimization of wetland area, because these features may mask or reduce the magnitude of land-use driven hydrologic effects. Although effort was made to avoid them, it was not possible to select study watersheds with no wetlands as relatively flat topography, moist climate, and prevalence of hydric soils makes them prevalent throughout lowland western King County;
- Ecoregion – study watersheds found within the same ecoregion, to avoid potentially confounding factors related to regional differences in precipitation, geology, and vegetation. Eight of nine watersheds are in the Puget Lowland Ecoregion (PLE); Webster Creek, a reference site, is within the Cascades Ecoregion at the eastern edge of the PLE.
- Rural zoning – lack or presence of only minor areas of urban zoning or areas under the regulatory control of other local jurisdictions, to avoid confounding effects associated with the application of multiple land use regulations. Three of 9 study watersheds have small amounts of urban or urban reserve zoning. In two, (Judd and Weiss) the amounts of urban area are very small (<5 percent). Although presently developed as rural low-density, 15 percent of the Cherry Creek Tributary watershed is zoned “Urban Reserve” to provide for future expansion by the Town of Duvall.

Relative to the available treatment watersheds, suitable reference watersheds were scarce. There are no pristine areas left in lowland King County. Therefore, reference watersheds were restricted to municipal watersheds or nature reserves with no recent, ongoing or

anticipated future development. The City of Redmond's Watershed Preserve, formerly a water supply watershed<sup>5</sup> fully contained two of the project's reference watersheds. The Watershed Preserve is a 324 ha (800 acre) area of lowland western King County with small, perennial, fish-bearing headwater branches (named E and S for this study) of Seidel Creek, a tributary to Big Bear Creek in the Lake Washington Watershed. To our knowledge, the City of Redmond's Watershed Preserve has the only fully-contained undeveloped watersheds with perennial fish-bearing streams remaining in lowland western King County. As such, it is an extremely valuable area for use as reference for studies such as this. The third reference watershed, Webster Creek, is in the City of Seattle's municipal Cedar River Watershed. Because it is in a different ecoregion than the other study watersheds, it was not ideal. Finally, it should be noted that as with the treatment watersheds, all reference watersheds have a history of extensive logging some 50 to 60 years or more ago (see Michalak et al. in Appendix D).

The resulting study watersheds, shown in Figure 3, were assumed to have similar, high sensitivity to land cover change because of common geology, climate, drainage area, and gradients, and for treatment watersheds, high similarity of land uses, regulations, and development potential<sup>6</sup>.

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<sup>5</sup> <http://www.redmond.gov/cms/one.aspx?pageId=4175>

<sup>6</sup> Indicated by undeveloped and partially developed parcels.



## 2.2.2 Watershed Boundaries and Attributes

Watershed boundaries were drawn by aide of a computer program that calculated upslope contributing areas based on their topographic relationship to the pour point of each watershed (Maidment and Morehouse 2002; Poppenga et al. 2009). Resulting boundaries were manually edited to account for known topographic inconsistencies such as elevated roadways and culverts.

The 9 study watersheds range in size and elevation, with notable differences in precipitation, stream discharge, and geology (Table 5). Watershed size averages 515 hectares, with South Seidel being the smallest at 62 hectares and Judd the largest at 1262 hectares. Elevation ranges from nearly sea level for the Vashon Island treatment watersheds (Judd, Fisher, and Tahlequah), to 792 meters at the highest point in the Webster Creek watershed.

Air temperature, precipitation, and discharge data were estimated from gauges located within or in relatively close proximity of (< 16 km) each study watershed (Figure 3). Annual precipitation varies significantly among sites. During the study period, the Vashon Island and Seidel watersheds received the least amount of rainfall, whereas those closer to the Cascade foothills received more. Mean annual discharge (MAD) during the study period ranged from 0.4 cfs for East Seidel Creek to 9.4 cfs at Webster Creek.

**Table 5. Watershed attributes including watershed area (ha), elevation range (m), mean annual air temperature (°C), precipitation (m), discharge (MAD = Mean Annual Discharge; cfs) and percent composition of surface geology (low and high permeability and saturated conditions).**

	Watershed	Area (ha)	Elevation Range (m)	Mean Annual Air Temp. (°C)*	Mean Annual Precip. (m)*	MAD (cfs)*	Surface Geology, ha (% of watershed)		
							Low Permeability	High Permeability	Saturated
Reference	E. Seidel	75	110-177	10.1	1.13	0.4	51.3 (68%)	24.1 (32%)	
	S. Seidel	62	104-172	10.1	1.13	0.5	23.1 (37.5%)	38.4 (62.5%)	
	Webster	397	255-792	9.9	1.63	9.43	385.6 (97%)	11.2 (2.8%)	
Treatment	Cherry	300	30-175	9.2	1.29	1.45		10.2 (3%)	
	Fisher	512	6-134	9.6	1.14	1.58	399.2 (78%)	110.4 (22%)	2.3 (<1%)
	Judd	1262	5-143	9.6	1.14	5.82	740.5 (59%)	500.4 (40%)	21.5 (<2%)
	Tahlequah	331	2-128	9.6	1.17	0.79	215.1 (65%)	116 (35%)	0.1 (<1%)
	Taylor	936	123-224	9.9	1.63	3.2	547.7 (62%)	327.6 (37%)	5.1 (1%)
	Weiss	764	20-175	9.2	1.29	6.23	707.4 (93%)	56.1 (7%)	

\*2008-2012

Surface geology data for our study watersheds was derived from 2002 USGS surficial geology GIS data. Surface geology data was mapped for each watershed and categorized as being high or low permeability, or saturated (Table 5). Low permeability is generally characteristic of till and is the most extensive geology underlying the study watersheds.

High permeability soils are present in all study watersheds though are dominant only in the South Seidel watershed. Saturated surface geology was present in the three Vashon watersheds (Judd, Fisher, and Tahlequah) as well as Taylor and represented 2 percent or less of each watershed overall.

### 2.2.3 Zoning and Parcels

Rural zoning was the most common zoning density, accounting for an average of 92 percent of the total zoned area within each of the 6 treatment watersheds (Table 6). Rural zoning is generally designated as 1 dwelling unit per 5 or 10 acres (2 or 4 ha). Agricultural zoning designated as 1 dwelling unit per 10 or 35 acres (4 or 14 ha) is present only in Fisher Creek watershed and accounts for 5 percent of its total zoned area. Urban zoning, defined as high density ( $\geq 1$  dwelling unit per 0.4 ha) residential, industrial, business, or office zoning, is present only in Judd Creek watershed and accounts for 5 percent of its watershed area. Urban reserve zoning (1 dwelling unit per 2 ha) is present in the Cherry and Weiss creek watersheds, where they overlap with the future potential annexation area for the City of Duvall, and accounts for 15 percent and 1 percent of each watershed’s area, respectively. Urban reserve zoning is used to reserve land for potential future urban growth while allowing reasonable interim use. The three reference watersheds are in the Forest Production Zone.

Parcel-based information was used to track permits and assess compliance of land cover change and estimate conditions under full build-out (FBO). Parcel boundaries were readily available in a County GIS database. Parcels do not conform to watershed boundaries and often straddle watershed boundaries. The number of parcels containing some amount of treatment watershed area varied from 127 in the Cherry Creek Tributary watershed to 693 in the Taylor watershed, with an average of 368 parcels (Table 6). Many of these parcels fall on the watershed boundaries, with the total number of parcels that completely fall within the watershed boundaries ranging from 55 in the Cherry Trib. watershed to 502 in

**Table 6. Zoning and Parcel information for treatment watersheds.**

Watershed	Total area in Zoning Type, Ha (% of watershed)*				# of Parcels			
	Rural	Ag.	Urban	Urban Res*	<10% in watershed	>10% & <100% in watershed	100% in watershed	Total
Cherry Cr. Tributary	247 (82%)			45.4 (15%)	18	54	55	127
Weiss	734.1 (96%)			4.6 (1%)	28	98	178	304
Taylor	829.1 (94%)				34	157	502	693
Judd	1157.3 (92%)		68.6 (5%)		30	122	475	627
Fisher	469.6 (92%)	27.6 (5%)			19	85	135	239
Tahlequah	319.6 (97%)				23	53	141	217

\*Values don't equal 100% because parts of these watersheds don't have a zoning designation. Percentages don't include public rights-of-way such as roads, etc.

the Taylor watershed. Average area of study watershed per parcel for the treatment watersheds ranges from 1.38 ha in Taylor to 3.35 ha in Cherry Trib., with an average parcel size of 2.64 hectares.

#### 2.2.4 Critical Areas

In addition to streams, other areas are identified as critical areas and protected or managed under various designations throughout King County (Appendix E). In the study watersheds, additional critical areas include geologic hazard areas (steep [ $> 40$  percent] slopes, landslide-prone, and erosion-prone areas), which may require building setbacks, erosion and sediment control, and other best management practices, to avoid or minimize risk of development impacts. These geologic hazard areas are not mapped with high accuracy in the County's GIS database but were present in every watershed, and ranged from 1 percent (5.2 ha) of the overall watershed in Taylor to 80 percent (317.1 ha) of the overall watershed in Webster (Table 7).

Critical Aquifer Recharge Areas (CARAs) are another of King County's critical areas. CARAs are areas in King County that overlie significant groundwater resources and are particularly susceptible to ground water contamination. CARAs are found in all treatment watersheds (Appendix E), and range from 33.5 hectares in Cherry to 1262.4 hectares in Judd. One hundred percent of Judd, Fisher, and Tahlequah watersheds on Vashon Island are designated as CARAs because of the island geography and limited groundwater.

Another regulated critical area is the 100-year floodplain, which is mapped in small portions of Judd, Fisher, and Tahlequah watersheds. This critical area was minimally present in the study area (3 to 4 percent of the overall watersheds), and ranged from 10.7 hectares in Tahlequah to 52 hectares in Judd.

Wetlands are found throughout all of our study watersheds; however, no complete field-checked inventory exists. The King County Wetlands Inventory and the National Wetlands Inventory are two frequently used datasets, though both are known to be incomplete and in need of updating.

Through their Puget Sound Watershed Characterization, the Washington Department of Ecology (WDOE) created datasets for potential depressional and slope wetlands<sup>7</sup>. Potential wetlands were present in all 9 study watersheds, ranging from 1 percent of watershed area in Tahlequah and Webster to 14 percent in S Seidel watershed. In terms of area, wetlands ranged from 2.2 hectares in Tahlequah to 81.1 hectares in Taylor, with an average of 28.4 hectares per watershed.

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<sup>7</sup> WDOE used four GIS datasets (hydric soils from SSURGO, NWI wetlands, marsh polygons from the hydrography layer, and wetland pixels from the land cover data) to create the largest possible extent of potential wetland area. Then they intersected that extent with a slope layer from a 10 meter DEM. Any areas that were 2 percent or less were coded as "depressional wetlands," and those areas greater than 2 percent were coded as "slope wetlands."

**Table 7. Study watershed critical areas. Area in hectares (% of overall watershed).**

	Watershed	Steep Slope/ Landslide/ & Erosion Hazard Areas	CARAs	100 year Floodplain	WDOE Watershed Characterization Wetlands		
					Depressional	Slope	Total WDOE wetlands
Reference	<b>E Seidel</b>	2.2 (3%)			0.3 (<1%)	2.3 (3%)	2.5 (3%)
	<b>S Seidel</b>	1.0 (2%)			1.6 (3%)	7.0 (11%)	8.6 (14%)
	<b>Webster</b>	317.1 (80%)			0.2 (<1%)	3.0 (1%)	3.2 (1%)
Treatment	<b>Cherry</b>	47.4 (16%)	33.5 (11%)		23.2 (8%)	9.7 (3%)	32.9 (11%)
	<b>Fisher</b>	67.4 (13%)	512 (100%)	17.8 (3%)	4.8 (1%)	2.9 (1%)	7.7 (2%)
	<b>Judd</b>	169.0 (13%)	1262.4 (100%)	52 (4%)	37.0 (3%)	26.8 (2%)	64.2 (5%)
	<b>Tahlequah</b>	66.4 (20%)	331.2 (100%)	10.7 (3%)	0.3 (<1%)	1.9 (1%)	2.2 (1%)
	<b>Taylor</b>	5.2 (1%)	262.0 (28%)		45.4 (5%)	35.7 (4%)	81.1 (9%)
	<b>Weiss</b>	229.4 (30%)	50.0 (7%)		22.4 (3%)	30.6 (4%)	53.0 (7%)

### 2.2.5 Study Reach Selection and Description

To measure response, study reaches approximately 200 m in length were located at the lowermost end of each study watershed. Specific locations were based on landowner willingness to grant access and the presence of, or suitability for, a stream flow gauge<sup>8</sup>.

Once a study reach was selected, it was subdivided approximately in half to form an upper and lower reach. Reaches were split to create replicates and for detection of scale-dependency in the response of reach-averaged velocities and physical channel characteristics.

Study stream characteristics and buffers vary by size, location, and study watershed type (Table 8). Total watershed stream length ranges from 1.1 km for South Seidel to 17 km for Judd, with an average of 7.7 km<sup>9</sup>. Stream density within the watersheds ranges from 0.01 kilometers per hectare in Fisher, Judd, Tahlequah, and Taylor to 0.03 kilometers per hectare in Webster, with an average of 0.02 kilometers per hectare. Total road length and road density varied greatly between treatment and reference watersheds, with reference watersheds generally containing no or few roads. The exception is Webster, which contains 8.3 km of unpaved (gravel) logging road, much of which is in process of being decommissioned by the City of Seattle. Road length varies from 0 km (no roads) in East Seidel to 43.2 km in Taylor, with an average of 24.9 km across watersheds. Road density

<sup>8</sup> Within King County’s Science and Technical Support Section, “gauge” and “gage” are used interchangeably, but in this report they are all referred to as “gauge.”

<sup>9</sup> Based on data derived from the King County Enterprise GIS data.

varies from 0 in East Seidel to 0.08 kilometers per hectare in Taylor, with an average of 0.04 kilometers per hectare.

All study watersheds contain streams that are classified as or known to be salmonid bearing (Kerwin 2001; WDFW Salmonscape<sup>10</sup>). The salmonid-bearing portion of the overall stream lengths range from 0.2 km in Cherry Trib., to 6.7 km in Taylor, with an average of 2.9 km. Coho salmon have been observed in Judd, Taylor, Cherry, and Weiss creek study reaches. Although above a long-standing anadromous fish barrier (old water supply dam), small (< 100 mm) salmonid fry, believed to be young-of-the year cutthroat trout, were observed in the East and South Forks of Seidel Creek. Aside from coho, chum salmon have also been observed in Judd Creek, and pink salmon have been observed in the Cherry Creek mainstem at the mouth of the Cherry Creek Tributary. Taylor Creek has also been identified as habitat for steelhead and sockeye, though none were observed in the study reach during the project's field work.

Regulatory stream buffers were mapped (Appendix E) around streams based on salmonid use as prescribed by the County's Critical Area Ordinance. The Salmonscape database was used to identify distribution of salmonids. For salmonid-bearing streams, a 50-m buffer was drawn around that stream segment. For non-salmonid-bearing streams, a 20-m buffer was drawn.

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<sup>10</sup> <http://wdfw.wa.gov/mapping/salmonscape/>

**Table 8. Stream and road-related statistics for study watersheds including lengths, watershed density (m/ha), stream-road crossings, and area of regulatory stream buffer.**

	Watershed	Total Stream Length (km)	Stream Density (km/ha)	Total Road Length (km)	Road Density (km/ha)	Road Stream Crossings	Stream Portion Length (km)		Regulatory Stream Buffer Area (ha) and % of watershed (%)		
							Fish	Non-Fish	Fish	Non-Fish	Combined
Reference	East Seidel	1.4	0.02	0.0	0.0	0	0.4	1.0	4.5	5.7	10.2 (13.5)
	South Seidel	1.1	0.02	0.5	0.01	0	1.0	0.1	9.9	4.4	14.4 (23.4)
	Webster	13.8	0.03	8.3	0.03	10	4.8	9.0	47.1	57.3	104.4 (26.3)
Treatment	Cherry	5.6	0.02	5.0	0.03	3	0.2	5.3	2.5	22.6	25.1 (8.4)
	Fisher	7.0	0.01	16.6	0.05	7	2.3	4.7	24.1	28.7	52.8 (10.3)
	Judd	17.0	0.01	34.9	0.04	15	4.7	12.4	45.0	69.3	114.4 (9.1)
	Tahlequah	2.2	0.01	11.0	0.05	1	0.5	1.7	5.4	8.9	14.2 (4.3)
	Taylor	9.5	0.01	43.2	0.08	22	6.7	2.8	68.9	38.6	107.5 (12.2)
	Weiss	11.7	0.02	20.0	0.04	10	5.2	6.4	53.3	47.9	101.2 (13.3)

Study reach characteristics were measured through physical habitat surveys conducted throughout the study period. These surveys were used to track change during the study, but the initial survey also provides a baseline assessment of the streams' physical condition (Table 9). Study reach length (thalweg length) ranged from 132 meters at Tahlequah to 211 meters at Webster, with an average reach length of 185.6 meters. Reach gradient ranged from 1 percent at Taylor to 6.5 percent at East Seidel. The coefficient of variation for thalweg depth measurements ranged from 0.38 in Judd Creek to 0.53 in South Seidel and East Seidel, with an average of 0.46.

Substrate composition was measured in each study reach and grouped into 7 categories. Cherry and Weiss creek study reaches were dominated by fine and coarse gravels, which accounted for 51 percent and 78 percent of all substrate, respectively. Taylor Creek was dominated by coarse gravel and cobbles, which accounted for 73 percent of the total. Judd Creek had a broad range of sediment, with the largest proportion being sand at 28 percent of the total. Fisher Creek was dominated by sand and fine gravel (95 percent of total), and Tahlequah was dominated by fine gravel (60 percent of the total). East Seidel was dominated by sand and fine gravel (78 percent of the total), whereas South Seidel was dominated by fine gravel and coarse gravel (92 percent of the total). Webster Creek had the largest substrate on average, with 59 percent of the total being cobble and small boulders.

At the start of the project, the number of pools in the 9 study reaches ranged from 1 in East Seidel to 15 in Fisher, with an average of 6.4 pools. The percent of the total reach length contributed by pools ranged from 1 for East Seidel to 37 in both Taylor and Fisher, with an average of 18.8 percent. The average residual pool depth ranged from 17cm in East Seidel to 33.8 in Judd, with an average of 24cm.

**Table 9. Study reach characteristics including reach length, gradient (%), coefficient of variation (CV) of thalweg depths (average and), substrate composition and pools (number, length, and residual pool depths). Measurements are from starting (first) year physical survey.**

	Watershed	Thalweg Length (m)	Reach Gradient (%)	Ave. Active Channel Width (m)	CV of Thalweg depth	Substrate (expressed as % of total)							Pools		
						Silt/Clay/Muck (Up to 0.06mm)	Sand (>0.06 - 2mm)	Fine Gravel (>2 - 16mm)	Coarse Gravel (>16 - 64mm)	Cobble (>64 - 250mm)	Small Boulder (>250 - 1000mm)	Large Boulder (>1000mm)	#	Thalweg Length (% of reach)	Avg RPD
Reference	East Seidel	174	6.5	2.2	0.53	1	35	43	15	2	3		1	1	17.0
	South Seidel	210	2.0	2.2	0.53		8	68	24				5	7	17.2
	Webster	211	4.9	7.7	0.49	1	6	9	21	34	25	4	5	14	26.6
Treatment	Cherry	180	5.8	3.4	0.41	10	11	38	23	16	2	<1	9	13	22.3
	Fisher	186	2.2	3.7	0.47	5	43	52					15	37	23.7
	Judd	186	1.6	6.5	0.38	2	28	12	18	27	11	2	5	27	33.8
	Tahlequah	132	2.3	2.9	0.41		18	60	21				10	22	16.0
	Taylor	202	1.0	5.1	0.45		3	10	34	39	14		4	37	31.8
	Weiss	189	1.8	4.2	0.50	2	18	38	40	1			4	11	27.3

## 2.3 Measuring Environmental Response

A large number of hydrology-related variables have been found to respond to varying levels of land use and land cover in lowland Puget Sound streams (DeGasperi et al. 2009; Horner 2013). Of those, variables with relatively high correlation with land cover change and high precision, indicated by high signal-to-noise ratios, are important for increasing statistical power in a study design (Kaufmann et al. 1999).

For each response variable, testable hypotheses were developed based on expected responses to treatment (development) and associated mechanism for change (Table 10).

This section describes the rationale for selection and the data collection methods for ERVs used to evaluate effects of land cover change on stream flow, water quality, macroinvertebrate communities, and stream channel hydraulics. Because many of the procedures are commonly used in King County and described in detail elsewhere, some methods are summarized and references to published literature are provided.

**Table 10. Environmental response variables and their expected responses and mechanisms.**

Environmental Response		Expected response in treatment		Mechanisms
Category	Variable (ERV)	If regulations <i>are</i> effective	If regulations <i>are not</i> effective	
Hydrology	High Pulse Count (“flashiness”)	No change*	Increase	Elevated surface runoff, increased drainage density, decreased infiltration and storage
Water quality	Conductivity at Baseflow	No change*	Increase	Solute in runoff from developed land  Shade loss and altered hydrology
	Temperature (7DADMax and Average Annual Baseflow)	No change*	Increase	
Stream channel complexity	Reach-average velocity at MAD	No change* or decrease†	Increase	Reduced channel bedform complexity or roughness
	Thalweg Length in Reach	No change* or increase†	Decrease	
	CV of Thalweg Depth	No change* or increase†	Decrease	
	Large Wood	No change* or increase†	Decrease	
	Percent silt and sand	No change* or decrease†	Increase	
	Percent Pool Length of Thalweg	No change* or increase†	Decrease	
	Average Residual Pool Depth	No change* or increase†	Decrease	
Biology	Benthic Invertebrates (BIBI)	No change*	Decrease	Reduced habitat quality

\*Relative to reference sites

†If regulations are not effective, we hypothesize that stream channel complexity will either decline if stream channel is in moderate to high complexity or stay the same or decline slightly if current channel complexity is low.

### 2.3.1 Hydrology

DeGasperi et al. (2009) assessed fifteen hydrologic metrics calculated from daily average flow data for use as resource management tools in lowland Puget Sound streams. Of these, they found two, high pulse count (HPC) and high pulse range (HPR), that best met four criteria posited for a useful hydrologic indicator: (1) sensitivity to urbanization consistent with expected hydrologic response, (2) statistically significant trends in urbanizing watersheds and not in undeveloped watersheds, (3) correlation with biological response to urbanization, and (4) relative insensitivity to confounding factors like watershed area. Both HPC and HPR describe “flashiness,” which is stream flow dynamics expressed as the number or duration, respectively, of flow pulses over a unit of time. Specifically, HPC is the number of times in a water year that discrete high flow pulses occur, whereas HPR is the range in days between the start of the first high flow pulse and the end of the last high pulse during a water year. Given the relative equality of the two flashiness metrics, the HPC was selected for use in our study because it was considered a simpler metric to use and explain. Example hydrographs showing calculation of HPCs under hypothetical pre- and post-development scenarios are shown in Figure 4.

King County’s hydrologic services group installed, monitored, and maintained stream flow gauges at the downstream limit of each study watershed from September 2008 through December 2012. Stream flow was measured continuously at 15-min intervals at stream flow gauges using methods developed by King County (NPDES CM 1000 2008) and closely following guidance provided by Butkus (2005).

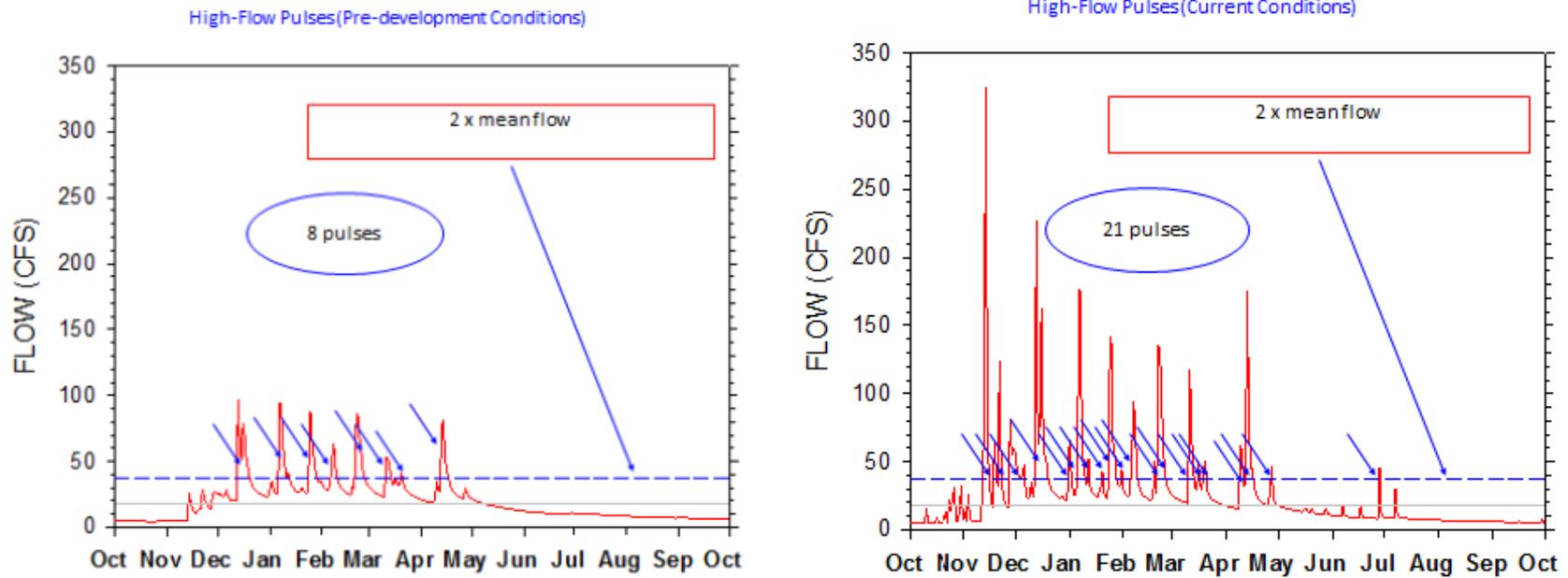


Figure 4. An example hydrograph displaying high-flow pulses (High Pulse Counts) under pre-development (left) and developed (right) conditions (from Horner 2013).

### 2.3.2 Water Quality

The term “water quality” encompasses a diverse set of physiochemical properties of water including temperature, dissolved oxygen, acidity (pH), alkalinity, conductivity, turbidity, suspended sediments, nutrients, metals and many human-derived compounds. Many natural and human-derived water quality measures were excluded from consideration because they were expensive to collect or assay, redundant, or would likely occur in low or undetectable levels in rural streams. As the goal of the study was to detect a watershed-scale response rather than document water quality *per se*, conductance and temperature were selected because they are known to respond to land cover changes, have relatively high precision (i.e., signal-to-noise ratios,) and are collected at low cost using well-established standard procedures.

Specific conductance (hereafter “conductivity”) measures water ionic activity and content by measuring water’s ability to conduct electricity normalized to 25° C (Florida DEP 2005). As such it is an indirect measure of a wide range of inorganic dissolved solids and has been found to be an indicator of the cumulative effects of urbanization in lowland Puget Sound streams (Olthoff 1994; U.S. EPA 2010). Merritt and Hartman (2009) estimated a signal-to-noise ratio for conductivity of 14.9, among the highest values of nine water quality variables assessed and exceeding Kaufmann et al.’s (1999) guidelines. Furthermore, relative to most other water quality parameters, conductivity can be measured reliably and at low cost with widely available meters.

Temperature has long been known as a fundamental property of water and a driver of many physiochemical properties and biological functions (Hynes 1970). Merritt and Hartman (2009) estimated its signal-to-noise ratio at 6.8, which is less than the ratio for conductivity but still within the moderate to high precision range defined by Kaufmann et al. (1999). As with conductivity, it is also measured reliably and at low cost with widely available meters.

At each flow gauge site, Hobo data loggers<sup>11</sup> were deployed to collect water temperature at 15-minute intervals. The data loggers were calibrated and data were downloaded at regular (1- to 3-month) intervals.

Conductivity was measured in the main flow in close proximity to the flow gauge. Conductivity measurements were taken in 3 ways: (1) bi-weekly grab samples were taken over the entire course of the project using hand-held, calibrated YSI Professional Plus (model 6050000), (2) on the days when salt tracers were deployed, a background conductivity was recorded, and (3) to provide fine-grained (15-minute) conductivity readings and for back-up should a hand-held meter fail, data loggers collected continuous (15-minute) readings starting in October 2009. Conductivity meters had a stated accuracy of 5 percent and were regularly calibrated using standard Potassium Chloride conductivity Reference Standard, 74 Microsiemens/cm at 25°C solution in an office or laboratory environment.

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<sup>11</sup> U20-001-04 HOB0 Water Level 13 Foot.

For quality control, temperature and conductivity data were visually inspected for irregularities, completeness, and other problems before being entered and stored in either the King County Hydrologic Information Center (HIC<sup>12</sup>) or a project-specific database.

### 2.3.3 Stream channel complexity: reach-averaged velocity and channel measurements

Watershed-scale development can result in physical alteration of stream channels (Booth et al. 2002; May 1996; Walsh et al. 2005; Roberts et al. 2008). Typically, channels in developed areas have low stream channel complexity (e.g., channels have fewer and shallower pools, less sinuosity, and less roughness due to low amounts of large wood and higher amounts of sand and silt in substrates) relative to channels in less developed watersheds. Mechanisms for this change include: (1) historic alteration or removal of riparian vegetation, (2) channelization and bank hardening typically involving the removal of woody material and other roughness to improve drainage or reduce erosion, and (3) increased stormwater runoff that can either erode and flush-out in-channel sediments or mobilize bank and upland sediments and inundate channels with new sediments.

To detect change in the physical complexity of the study's stream channels, a combination of solute tracers and physical channel metrics were used (Table 11). Solute tracers provide direct, highly precise estimates of reach-averaged velocity and have been used to assess change in channel condition over time following debris torrents in Oregon coastal streams (Kaufmann 1987) and, more recently, to document reduced hydraulic complexity among Puget Sound lowland stream channels in developed areas (Roberts et al. 2008; Gendaszek et al. 2009).

A solute (NaCl) was deployed in study reaches to assess changes in time-of-travel and reach-averaged flow velocity that may result from changes in channel hydraulic pathway and complexity, including thalweg length and depth profile, channel roughness (vegetation, woody debris, substrates), and pool length and residual depth. When compared against a baseline rating curve, changes in solute transport times should reflect alterations in flow pathways.

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<sup>12</sup> <http://green.kingcounty.gov/wlr/waterres/hydrology/>

**Table 11. Stream characteristics measured using modified EMAP protocols.**

Variable	Description	Precision	Location	Sites measured	2009	2010	2011	2012/2013*
Wetted channel width	Wetted channel margins	0.1 m	All transects	All	X	X	X	X
Active (unvegetated) channel width	Ordinary high water mark; to limit of perennial vegetation > 1m tall.	0.1 m	All transects	All	X	X	X	X
Substrate size class	0/25/50/75/100 % of wetted width; seven classes (silt/clay/muck; Sand; Fine gravel; Coarse gravel; Cobble ; Small boulder; Hardpan)		All transects	Dev, Ref	X	-	-	X
Thalweg length	Tape-measured distance of pathway of deepest flow	0.1 m	Reach		X	X	X	X
Thalweg depth	Five points evenly spaced between transects	1 cm	Major transects	Dev, Ref	X	X	X	X
Large wood	Length classes: 1-5; 5-15;>15 m; Diameter Classes: 10-30; 30-60; 60-80; >80 cm	Classes	Reach	All	X		X	X
Channel gradient	TruPulse laser/clinometer (Laser Technologies, Inc)	0.1%	Major transects	Dev, Ref	X	-	-	-
Pool count	Number of scoured depressions longer than one width of the active channel	1 pool	Reach	Dev, Ref	-	X	X	X
Pool length	Maximum distance between the head and tailout of pool	0.1 m	Reach	Dev, Ref	-	X	X	X
Residual pool depth	RPD is the difference between tailout and max depth	1 cm	Reach	Dev, Ref	-	X	X	X
Pool position	Longitudinal position within study reach	0.1 m	Reach	Dev, Ref	-	X	X	X

\* Due to inclement weather, some final measurements were made in January 2013.

To obtain solute transport measurements and estimate time-of-travel, the protocol developed by USGS for the National Water-Quality Assessment Nutrient Enrichment on Stream Ecosystems program (Bales, J., pers. comm., 2004) was used as a template. In summary, a mixture of solute was prepared and placed all at once into the water column at the upstream end of a study reach. The concentration of solute over time was then measured at the approximate mid-point and downstream end of the study reach. This method provided adjacent replicates for within reach comparison of travel times. Times to first detection, peak, and 95 percent reduction in concentration as indicated by change in conductivity were then calculated and converted to velocity (see Lucchetti et al. in Appendix F).

Each study reach was surveyed according to a modified EMAP protocol (Kaufmann et al. 1999), for three reasons: (1) to characterize the study streams using widely understood metrics, (2) to aid in the interpretation of any observed changes in tracer-based estimates of reach-averaged velocity,  $U$ , and (3) to compare the precision of channel survey metrics with the precision of tracer surveys.

Several modifications were made to the standard EMAP protocol, as described below. First, we used a smaller subset of measurements that we deemed most relevant to the purposes of this study. Second, we surveyed two adjacent reaches per study site instead of one. Third, the study reach length was not explicitly scaled to channel width, as recommended in EMAP protocols; however, the density of our sampling efforts was higher than EMAP guidelines. The length of many study reaches was constrained to areas where we were granted permission for access to private land, and to avoid infrastructure such as road crossings. Regardless, the combined length of two (or more) study reaches exceeds EMAP guidelines in every case. A fourth departure from EMAP was that we measured 'active width' instead of bankfull width because it could be more reliably identified. Active width often approximated bankfull but was deemed to be more sensitive to change and more repeatable among surveys. A fifth departure from EMAP was that we measured all variables along 'minor' transects as well as 'major' transects (i.e., cross-sections). For the comprehensive surveys, twenty-one transects (11 major, 10 minor) were evenly-spaced throughout each study reach (upper and lower), for a total of 42 transects per study site.

Replicate surveys were performed in 2010 by three independent field crews on Cherry Creek and Taylor Creek. The purpose was to estimate the precision of the physical stream survey protocols and to estimate errors from observer biases. Prior studies find that reach length increases up to 10 percent when measured in fine detail (many sampling points; Curran and Wohl 2003). Each team was led by one 'expert' or highly-trained leader. The same protocols were used by each team to measure the length and depth of the channel thalweg, pool counts, dimensions, and positions.

#### 2.3.4 Biology: Benthic macroinvertebrate field collection and analysis methods

Although both stream fish and benthic invertebrate communities have been shown to be sensitive to land use conditions within the study area's lowland streams (Scott et al. 1986; Lucchetti and Fuerstenberg 1993; Kleindl 1995; Ludwa et al. 1997; Serl 1999; Karr and Chu 1999; Matzen and Berge 2008; Morley and Karr 2002), freshwater benthic invertebrates

were selected to assess biological effects for this study because methodologies and metrics to assess them are relatively well-established and understood (Karr and Chu 1999; DeGasperi et al. 2009). Benthic invertebrates are animals without backbones, larger than 0.5 mm, and visible without a microscope and are primarily bottom dwellers in freshwater habitats. They are routinely and widely used in bio-monitoring programs both in King County and throughout Puget Sound because of their high abundance and diversity, limited migration patterns, predictable response to environmental disturbances and land use gradients, and a naturally-derived population structure unaltered by stocking or harvesting.

The benthic index of biotic integrity (BIBI) measures the community health of the stream benthos and compares it to what is expected at regional reference sites with little or no human impact. It is composed of ten individual metrics sensitive to changes caused by human activities<sup>13</sup>. The metric scores are totaled to produce a BIBI score to represent the overall biological condition and level of watershed impairment.

The BIBI has been calibrated to conditions in the Puget Lowlands region of Western Washington (Fore et al. 1996; Karr and Chu 1999; Kleindl 1995), and it has sufficient statistical power to detect the effects of various human actions (Karr 1996) including urbanization (Kleindl 1995; Morley 2000; Morley and Karr 2002; Rossano 1995). Merritt and Hartman (2009) rated EPT percent, a specific metric for characterizing benthic invertebrate communities, as having a signal-to-noise ratio of 2.5, within the range considered moderate to high precision by Kaufmann et al. (1999) and Crawford and Rumsey (2011).

Conversely, stream fish communities, although also extensively monitored, are not as well-suited for this study because of high diversity in behaviors, low diversity in species composition, and effects of factors outside local control, including harvest and hatchery management, migration barriers, and regional-scale changes in climate and marine conditions. For example, the ubiquitous, culturally, commercially, and ecologically important salmonids exhibit high diversity of freshwater resident and anadromous life histories while also being subject to stocking, harvesting, and disruptions to migrations by partial or total barriers, such as dams and culverts. Regardless, Lucchetti and Fuerstenberg (1993) documented differences in fish use in urban and non-urban streams, with a noticeable shift toward greater abundance of cutthroat trout relative to coho salmon in urban areas. The “cutthroat to coho ratio” was subsequently used as a measure of salmonid community health integrity (Cooper 1996; May 1996) but has not become widely used as a strong metric for evaluating land use changes. More recently, Matzen and Berge (2008) created a fish index of biotic integrity (FIBI), similar to BIBI, based on fish species differences across a gradient of land use conditions. However, their study included low-gradient, lake-oriented, and non-native species not generally found in the study’s headwater streams, where fish species diversity is low, composed predominately of juvenile and adult cutthroat trout (which may exhibit both resident and migratory behaviors), juvenile coho salmon (which are anadromous and use the study streams

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<sup>13</sup> See <http://www.pugetsoundstreambenthos.org/>

primarily for spawning and juvenile rearing), and sculpins (which are largely non-migratory). Finally, use of fish would have been problematic because the study's three reference streams have a history of being blocked to anadromous fish migrations by long-standing water supply dams and diversions and so their fish communities would not be comparable to the treatment streams.

Benthic macroinvertebrate samples were collected annually at all nine study creeks from 2008 through 2012. Sampling was conducted between early-August and mid-September following the recommended sampling protocols outlined by Karr and Chu (1999; Figure 5). At each location, a Surber sampler (500  $\mu\text{m}$  mesh, 0.3  $\text{m}^2$  [1  $\text{ft}^2$ ] frame) was used to collect three replicate samples along the midline of three distinct riffles starting at the downstream end and working upstream (Figure 6). All large material (e.g., large gravel, cobble, and woody debris) within the sampling area was scrubbed by hand within the stream flow so that any organisms or debris jarred loose flowed into the collection net. Each piece of large material was visually examined after being scrubbed to ensure no organisms were still attached and then was placed outside the Surber frame. A sturdy metal gardening hand tool was used to agitate the substrate within the perimeter of the frame to a depth of approximately 10 cm (3.9 in) for 60 seconds. Each replicate sample collected was processed and condensed separately without compositing. Processing included rinsing any remaining large material too big to fit into the sample bottle with filtered water and a 500  $\mu\text{m}$  mesh sieve and visually examining the net for any organisms or debris. The remaining materials were then transferred to a labeled sample container and preserved in the field with 90-95 percent ethanol (EtOH).

After field data collection each year, all samples were sent to a taxonomic laboratory<sup>14</sup> for identification to the lowest practical taxonomic resolution<sup>15</sup>. Non-insect invertebrates were identified to phylum (Nematoda, roundworms), class (Ostracoda, seed shrimp), subclass (Acari, mites and Oligochaeta, segmented worms), family (Pisidiidae or Sphaeriidae, fingernail or pea clams), or lowest practical taxonomic resolution (including snails, mussels, and crayfish). Each replicate was subsampled at 500 organisms, but if fewer than 500 organisms were present the entire sample was processed. Taxonomic data were uploaded to the Puget Sound Stream Benthos (PSSB) web page<sup>16</sup>.

BIBI scores were calculated within the PSSB, which serves as a data repository but also stores taxa attribute information (e.g., clingers, tolerance, long-lived status, predators). The 2012 attribute lists were used which include predator, long-lived, and clinger classifications updated from published literature and tolerant and intolerant classifications derived from empirical data (Fore et al. 2012). These attribute classifications and the macroinvertebrate taxonomic composition data were used to calculate the ten BIBI

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<sup>14</sup> ABR, Inc. identified the 2008 and 2009 samples; Rhithron Associates, Inc. identified the 2010 through 2012 samples.

<sup>15</sup> Exceptions to the lowest practical taxonomic resolution include identifying organisms to sub-family for Ceratopogonidae (biting midges) and to family level for Chironomidae (midges), Dytiscidae (predaceous diving beetles), Hydrophilidae (water scavenger beetles), Staphylinidae (rove beetles), Ephydriidae (shore flies), Muscidae (house flies and kin), Sciomyzidae (marsh flies), and Tabanidae (horse and deer flies).

<sup>16</sup> <http://www.pugetsoundstreambenthos.org/>



Figure 5. Benthic macroinvertebrate sample collection steps. Top left: scrub large materials and agitate substrate within Surber frame for 60 seconds. Top right: rinse coarse substrate. Bottom left: visually check the net, pick any remaining organisms, and add them to the sample bottle. Bottom right: condense sample into a labeled sample bottom.

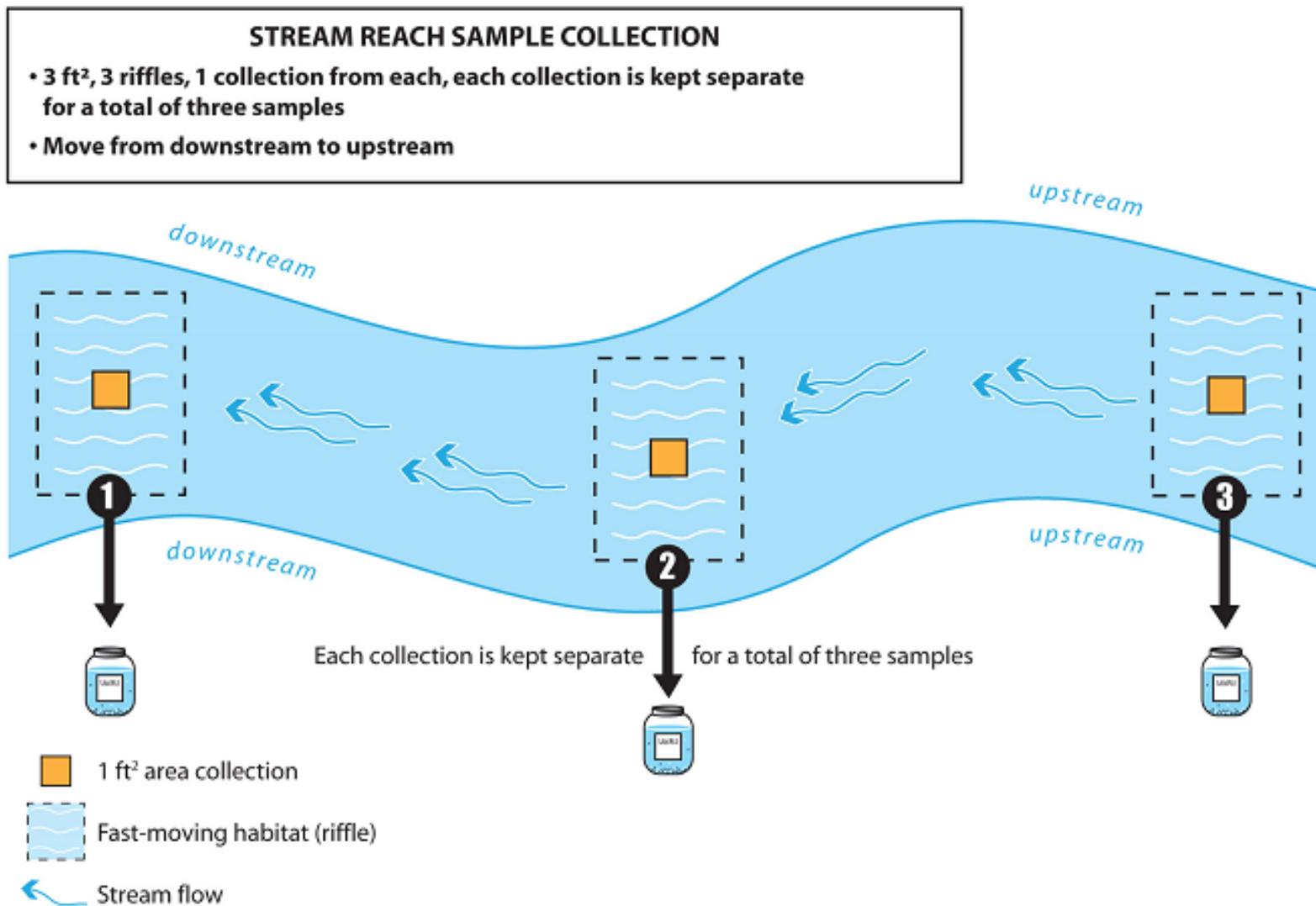


Figure 6. Benthic macroinvertebrates were collected from 3 riffles within a stream reach starting at the downstream end and working in an upstream direction.

metrics. Relative to minimally disturbed reference streams, each metric was assigned a score of 5 (minimal deviation), 3 (moderate deviation), or 1 (strong deviation) based on established BIBI scoring criteria (Appendix G). The ten metric scores were summed to provide an overall BIBI score ranging from 10 to 50 for each of the three replicates. The three replicate BIBI scores were then averaged for each site for a single overall BIBI score. The overall BIBI score corresponds to biological condition ranging from very poor to excellent (see Appendix G for BIBI categories).

## 2.4 Mapping and Quantifying Land Cover Change

Accurately and reliably measuring the type, location, and amount of land cover change was critical to assessing treatment level. This study's approach to mapping and quantifying land cover change is similar to spatially explicit hydrology models (e.g., DHSVM) in some important ways. For instance, determining contributing watershed area is important to quantify the changes in the composition and configuration of the landscape that in turn could affect response variables. In addition, determining the flow paths and distances (i.e., hydrologic connectivity) that link land covers and response measurement locations is predicated on continuous downslope movement of water, from grid cell to grid cell (Wigmosta et al. 1994). This section describes the methods used for mapping and quantifying land cover change.

### 2.4.1 Historic Conditions

In developing the study proposal, there was concern that there may be legacy effects from over 100 years of historic land uses in the study watersheds (see Harding et al. 1998; King 2005; Brown et al. 2009) and that documenting and assessing effects of historic land cover change could be important when interpreting change in contemporary conditions. Therefore, at the start of the project, King County contracted with the University of Washington's Urban Ecology Research Laboratory (UERL<sup>17</sup>) to map and assess the effect of change in historic land covers for each of the watersheds.

Historic land-cover conditions were reconstructed for six timeframes (ca. 1910, 1936, 1948, 1965, 1986, and 2007) using a combination of early (1850 to 1911) General Land Office (GLO) and timber cruise surveys, photos (1936, 1948 and 1965), and satellite-derived data (1986, 2007). These data were used to explore three questions: (1) how has forest cover changed overall within these watersheds, (2) how has forest cover changed within the riparian zone since 1936, and (3) what land-cover changes are common to all watersheds and when and how do land-cover histories diverge?

Detailed methods and results are in Michalak et al. 2013 in Appendix D of this report.

During the initial historic assessment by Michalak et al., the land covers from 1936, 1948 and 1965 photos were mapped using 90 m grids. Subsequently, those land covers were re-mapped at smaller (30 m) grids, which were then overlaid on the finer (1.8 m) grids to

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<sup>17</sup> <http://urbaneco.washington.edu/wp/>

calculate historic HCIs. Because of the relative coarseness of historic map data, this process was done for the watershed scale but not the regulatory buffer scale.

## 2.4.2 Current Condition

Land covers for the current condition (the project timeframe) were mapped using high resolution (15 cm pixels) orthorectified aerial photos for 2007, 2009, 2010, and 2012. Land cover polygons were hand-digitized using ArcGIS (ESRI 2009) with a fixed-grid mesh (460 m<sup>2</sup>) or parcel by parcel at a scale of 1:1200 to be consistent with the County's digital elevation model and because that scale was sufficient to identify and delineate small-scale land cover change for assessing compliance. Digitized land cover polygons were coded into one of twelve land covers (Table 12). At this resolution, relatively small features, such as individual mature trees, shrub patches, and cultural features as small as backyard storage sheds and landscaping were mapped as individual land cover polygons. Although visible in photos, temporary features such as cars, boats, trailers, tarps were ignored. Although 1:1200 was possibly a finer scale than necessary for assessing the effect of changing land covers on our response variables, it was an appropriate scale for assessing permit compliance, where relatively small scale features such as outbuildings as small as 18.5 m<sup>2</sup> (200 ft<sup>2</sup>) may require a permit. For quality control, initial land cover maps were reviewed and corrected at least three times, once during a thorough review and again as the initial step of the compliance review process (see Section 2.6), before being finalized and entered into the project database.

**Table 12. Relative hydrologic conditions and description of mapped land cover.**

Land cover	Hydrologic Condition	Description
Bare	Disturbed pervious	Exposed soil with no or very small amounts of vegetation
Building	Impervious	Structures, e.g., houses, garages, greenhouses, small utility or agricultural sheds, ~ 9 m <sup>2</sup> or greater
Grass	Disturbed Pervious	Low lying, ground-based vegetation, not trees or shrub, and not clearly used for farming
Forest	Undisturbed Pervious	Conifer or deciduous trees, patches or individual. If individual tree, where canopy area is ~ 20 m <sup>2</sup> or greater
Pasture	Disturbed pervious	Low-lying, ground-based vegetation, not trees or shrub, and that showed evidence of recent farming (crops or livestock grazing) or, in absence of any evidence of farming, any relatively large expanse of grass.
Paved Road	Impervious	Roads or parking areas where surface is clearly covered in asphalt, concrete or something other than dirt.
Pavement	Impervious	An area of asphalt, concrete or something other than dirt, perhaps a sidewalk, patio but clearly not a road or parking area
Shrub	Disturbed Pervious	Low-lying but not ground-based vegetation, clearly not grass or mature trees
Unpaved Road	Impervious	Roads or parking areas where surface is dirt or gravel.
Open Water	Impervious	Open water areas such as ponds, lakes, including artificial features not appearing as wetland.
Wetland	Saturated	Presence of saturated soils, wetland plants (e.g., sedges, rushes, spirea) or edges of open water that had aquatic or wetland vegetation
Clear-cut	Disturbed Pervious	Presence of tree removal and clearing associated with timber harvesting.

#### 2.4.2.1 Estimating Grid Cell Distances

The spatial arrangement of the stream (i.e., branches and their locations) was used to calculate how far changes in land cover were from watershed pour point locations where ERVs were measured. Study watershed boundaries were applied as “masks” to geographically constrain all spatial analyses. Digitized land cover polygons and the King County GIS stream layer were then clipped to each study watershed, converted to 1.8 m grid cells, and snapped to the King County DEM of the same spatial resolution. For each watershed grid cell, distance from the downstream watershed monitoring point was calculated in a multi-step process using grid datasets in a geographic information systems (GIS) computer program (ESRI 2012). Distance was calculated additively along the stream network in an upstream direction, and upslope from each stream grid cell out to the watershed boundary. This provided downslope directionality by ensuring that grid cell values always decreased as they approached the stream and that stream grid cell values always decreased as they approached watershed pour points (Maidment and Morehouse 2002). Accumulated distances upstream and upslope from watershed pour points at the downstream end of each study reach were summarized by each land cover type for each year and intervening time period at the watershed and regulatory buffer scales.

#### 2.4.2.2 Estimating pre- and within-project land cover change during 2007 to 2009

Because the orthophotos used for establishing the project’s baseline land cover were taken in spring 2007, over a year before the project started measuring ERVs in August and September 2008, some 2007-2009 land cover changes may have had their influence before project’s ability to detect them. To quantify and, if necessary, account for 2007-2009 land cover change that occurred before the project’s effect detection window, a subset of land cover changes was assessed for their timing relative to major precipitation events and start of project monitoring.

Based on SeaTac gauge precipitation records, all major precipitation events and large flows during the 2008 water year (October 2007 to September 2008) occurred before April 1, 2008<sup>18</sup>. Therefore, because they are hydrology-driven, the watershed’s environmental response to land cover change prior to that date may have occurred prior to start of the project’s monitoring in fall 2008. To identify land cover change as being in or out of the project’s effect detection window, the environmental effects of land cover changes before April 1, 2008, were considered to have occurred prior to the project’s effect detection window, and effects of land cover change after April 1, 2008, were identified as being within the project’s effect detection window. Where the timing could not be reliably determined, land cover changes were classed as indeterminate.

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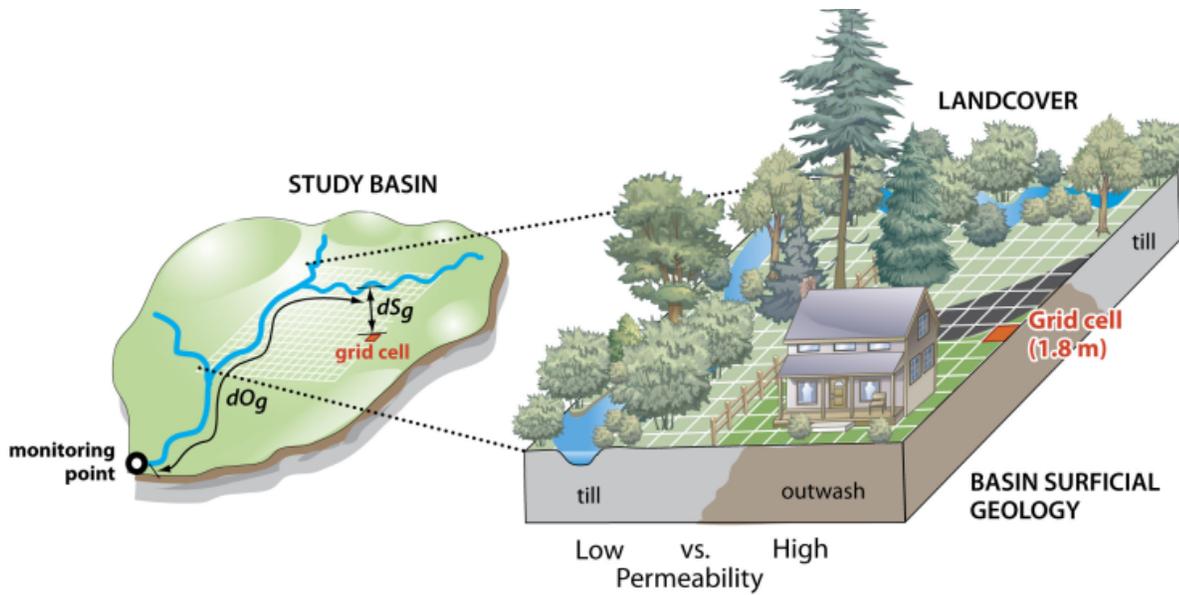
<sup>18</sup> King County Hydrologic Information Center: <http://green.kingcounty.gov/wlr/waterres/hydrology/>

## 2.5 Calculating the Hydrologic Condition Index

A Hydrologic Condition Index (HCI) was developed to quantify hydrologic condition upstream of the watershed monitoring point in a way that accounts for the effects of distance, geology, and land cover on hydrology and that would be comparable across time and space (Figure 7). In this way, the hydrologic condition for any spatial configuration of geologies and land covers could be estimated. HCI uses inverted grid cell distances for weighting HPCs derived from unique combinations of geology and land cover as follows:

- Grid cell weighting: to weight the effect of distance, grid cell distances were inverted, i.e., 1 over distance, to make the smallest distance the highest value and *vice versa* (for calculating grid cell distance, see Section 2.4.2.1).
- Estimating HPCs: for each unique combination (24 possible) of surface geology (till and outwash) and 12 land cover categories, the long-term (61-year) average HPC was estimated using a watershed Hydrologic Simulation Program Fortran (HSPF) hydrology model (Bicknell et al. 2005) for five readily available, lowland western King County watersheds (Hamm, Miller, Des Moines, and Newaukum creeks and the Duwamish subbasin) with similar glacial geology and topography, elevation, morphology, and precipitation ranges as the study watersheds (King County Science and Technical Support Section 2013). These watersheds were selected for use in this project from nine potential candidate watershed models to represent the range (low to high) of modeled HPCs for forest-on-till conditions (Table 13). A tenth watershed model was available but not considered because it generated HPC values that were considerably different from the others, and it was determined further investigation was warranted before use of that particular watershed model. HPCs for each combination of geology and land cover for all watershed models considered is in Appendix H and shown graphically in Figure 7.
- Hydrologic Condition Value (HCV): to create a hydrologic condition value for each scenario, grid cell HPCs were multiplied by their respective inverted grid cell distances and products were summed for any given scenario, e.g., project study year, historic land use, FBO or reference scenario.
- HCI: hydrologic condition index was created by dividing the HCV for a given scenario by the HCV for all paved road (worst) conditions.
- HCI average and variance: finally, HPCs from each of the five models were used to estimate average and range of HCIs for each land cover scenario.

Regarding accuracy of the models used to estimate HPCs, a study on stormwater facility retrofit planning in the Green/Duwamish River system and associated marine areas (WRIA 9) evaluated six of the ten watershed models. The models were then rated as fair ( $r^2 \geq 0.6$ ) to excellent ( $r^2 \geq 0.9$ ) for accuracy in simulating hourly flow rates and High Pulse Counts (HPC) (King County Science and Technical Support Section 2013).



$$HCI_s = \frac{HCV_s}{HCV_{s\_worst}}$$

$$HCV_s = \sum_{g=1}^n HPC_g \left( \frac{1}{dO_g + dS_g} \right)$$

$HCI_s$  = the hydrological condition index for a stream site in a watershed,  $s$ , given the LULC pattern for a particular year or simulated level of development

$HCV_s$  = the hydrological condition value for a stream site in a watershed,  $s$ , given the LULC pattern for a particular year or simulated level of development

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

$HPC_g$  = an average high pulse count value for each grid cell type,  $g$ . There are 24 values for HPC based on the combination of 12 LULC types and 2 underlying geology types

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

$dS_g$  = stream channel distance measured from the intersection of the overland distance to the grid cell,  $g$ , to the sampling point downstream.

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Figure 7. Illustration of how the Hydrologic Condition Index (HCI) is calculated.

**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).\*\***

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

HCI values were calculated for each watershed and, for treatment watersheds only, regulatory stream buffers for contemporary land cover scenarios and for a range of historic and hypothetical “reference” scenarios including full build-out (FBO). Calculating these scenarios was done to understand how the HCI varies over a wide range of land cover configurations and to provide context for changes observed during the project’s timeframe.

In all, HCI scores were calculated as detailed below.

Study watersheds:

- 2007, 2009, 2010, and 2012 orthophotos
- FBO: all currently undeveloped parcels artificially developed according to their zoning.
- Reference points, including best (all forest), worst (all paved road) and three equal combinations of forest:grass, forest:paved road, and grass:paved road, where grid cell land cover designations were alternated to create an even distribution of each combination of land covers.
- Historic scenarios: 1907-1911, 1936, 1948, and 1965 (each one five times using different HPC values). For Vashon 1907-1911, cover was set at 100% pasture to reflect large-scale loss of forest and conversion to farms and fields.
- Juanita Creek 2007 for urban comparison watershed.

Regulatory stream buffers:

- 2007, 2009, 2010, and 2012 orthophotos
- FBO: all currently undeveloped parcels artificially developed according to their zoning.
- Reference points, including best (all forest), worst (all paved road) and three equal combinations of forest:grass, forest:paved road, and grass:paved road, where grid cell designations were alternated to create an even distribution of each combination.

HCIs for historic scenarios were not calculated because the historic photos and reference materials used to map land cover are coarse-scale relative to buffer widths.

### 2.5.1 Full build-out HCI

A scenario was developed to compare the current watershed condition with an estimate of the condition under a maximally developed future scenario, *per* current zoning and assuming full compliance. For each study watershed, the full build out land cover layer was simulated by overlaying a prospective, nominally-sized residential home, associated clearing (set-backs and yards), and paved access road on each undeveloped parcel (Figure 8). Nearly all of the parcels in the study watersheds are zoned for single family residential, where one house per parcel is the Comprehensive Plan goal, except for parcels that are likely unbuildable because of extreme hazards or where sewer and potable water needs can’t be met. Therefore, the absence of a major structure likely serving as a house was considered indicative of an undeveloped parcel and such parcels were then artificially “built-out” using a standardized development footprint. Parcels with only small structures or structures likely serving as garages, sheds, etc., were considered undeveloped.

To artificially develop a parcel, an approximately 186 m<sup>2</sup> building footprint was placed on the parcel<sup>19</sup>. The structure was placed either near the geographic center of each undeveloped parcel or in a location that was considered “most likely” based on topography, access roads, and constraints caused by steep slopes, wetlands, streams, and their buffers. Once placed, an access road connecting the building polygon to the nearest existing roadway was created. In many instances, entire road systems had to be created in this simulation, because existing roads do not always yet allow access to all legal parcels. In parcels that currently have fewer houses than zoning allows (i.e., where parcel subdivision is a potential), additional homes were drawn into the lot under the assumption that the lot would be sub-divided in the future. No additional outbuildings were created in this simulation; however, it is likely that many if not most of these parcels with forecasted houses would also have one or more associated secondary buildings, as is common in rural areas.



**Figure 8.** Excerpt of 2012 orthophoto for the Tahlequah Creek watershed with 2012 landcover polygons on left (a.) and the hypothetical full build-out (FBO) scenario on right (b.), where orange lines delineate 2012 land cover and blue lines delineate the possible location of a building, paved road, and grass. Light yellow lines are parcel boundaries.<sup>20</sup> 1cm = 0.12 km.

In addition to a building and road, a cleared area designated as “grass” was placed surrounding the structure. The amount of new cleared area on a given parcel was based on the average amount of existing clearing for developed parcels in a given watershed (Table 14). Where an undeveloped parcel’s existing clearing was less than one standard deviation of the 2010 measured average for developed parcels within a given watershed, the parcel’s

<sup>19</sup> The per parcel average area of all structures on developed rural-zoned parcels is 185 m<sup>2</sup> (King County 2012a).

<sup>20</sup> Note that the FBO condition is for purposes for this study and is only an estimate of the area or configuration of actual future development. Actual future development may vary depending on site conditions including, but not limited to, topography, soils, availability of potable water or ability to site a well, and a suitable site for a septic system.

clearing was increased to approximately the average amount of clearing for developed parcels within that watershed. Where existing clearing was within or greater than one standard deviation of the 2010 measured average, the amount of clearing was left unchanged. Parcels with mapped critical areas (e.g., streams, wetlands, steep slopes, land slide hazard areas) were built out such that the building, road and clearing footprints avoided those areas and were placed at least 50m from a critical area to ensure being out of the regulatory buffer. Lastly, where parcels were constrained by critical area regulatory buffers to the extent that there was no option but to build within a buffer in order to meet a landowner’s expectation for development and allowed under a code variance (Critical Areas Alteration Exception), the standard building footprints was applied in a location as distant from critical areas as deemed reasonable and practicable depending on parcel configuration, but no additional clearing was made.

**Table 14. Percent forest cover for parcels with buildings and completely (~>99 percent) within treatment watershed boundaries and used as a basis for determining the percent cleared area for each currently undeveloped parcels under a hypothetical fully-built scenario.**

Watershed	Parcels with buildings used for FBO analysis				
	# of Parcels	Parcel Area (Ha)		% Forest Cover	
		Ave	SD	Ave	SD
Cherry Creek Trib.	41	1.7	1.5	48	25
Fisher	101	2.3	1.8	70	24
Judd	363	2	2.4	61	30
Tahlequah	87	1.3	0.9	80	15
Taylor	429	1.4	1.4	51	25
Weiss	129	2.6	2.1	69	19
Total	1150	1.8	1.9	60	27

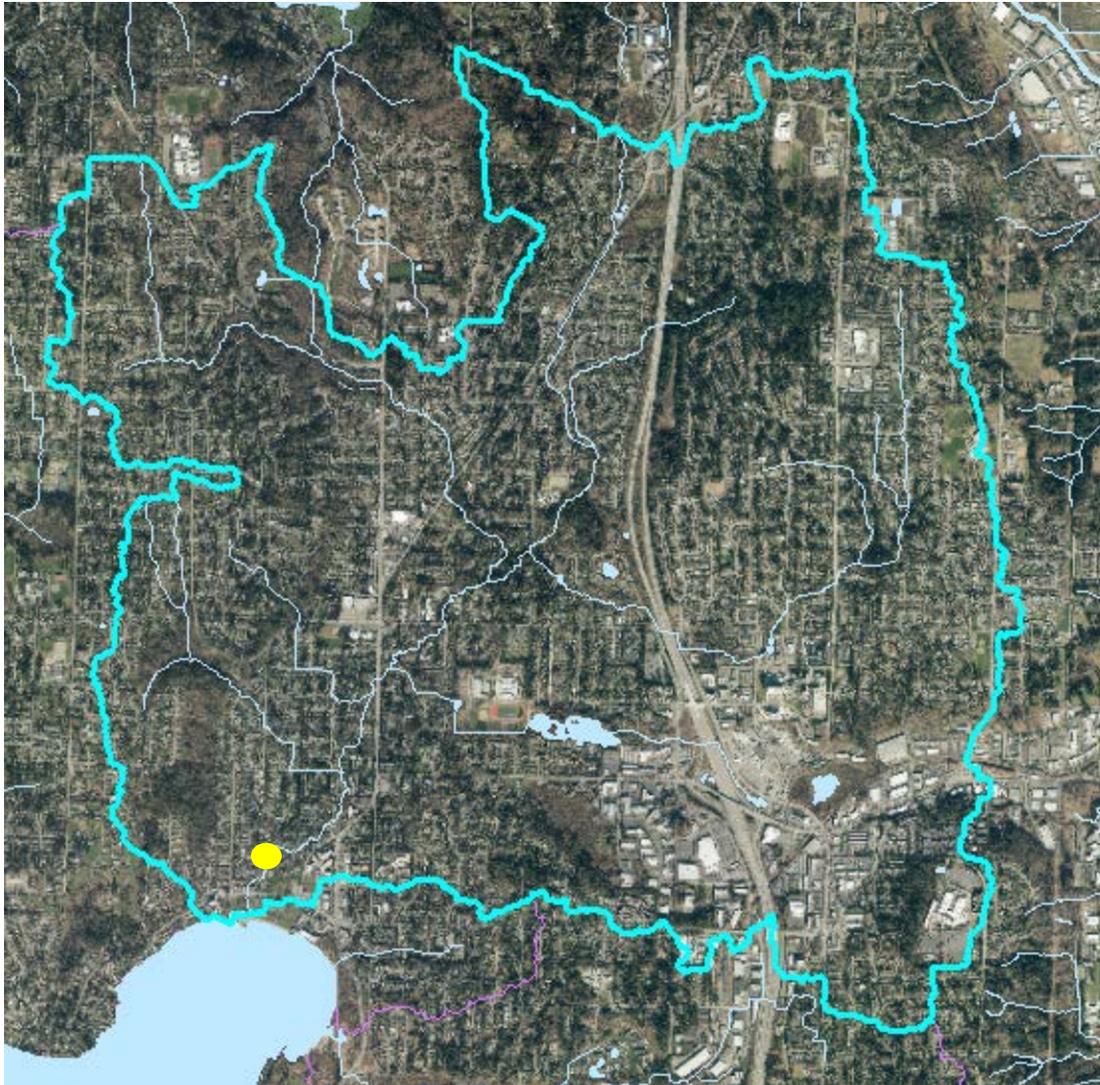
### 2.5.2 Juanita Creek 2007 HCI

To provide a representative urban comparison, Juanita Creek, an urbanized east-shore tributary to Lake Washington, was selected because it was in proximity and similar, albeit somewhat larger, in size (1,735 ha), surface geology, morphology, topography, and precipitation to the study’s watersheds and it had a readily available, calibrated watershed model (King County 2012c). Juanita Creek 2007 satellite data (University of Washington 2007) was placed into 14 land use land cover categories (University of Washington 2007; Table 15). These categories were then integrated with underlying surficial geology generalized into two categories: low permeability (till) and high permeability (outwash). Digitized land uses defined for the HCI study watersheds were also placed into 14 categories; however, these categories were different from the 2007 satellite data. Slope was not taken into account for these study watersheds, thus one slope designation (low gradient) was used for evaluating the Juanita Creek watershed as well. The level of detail and resolution associated with the heads-up method is considerably finer than remote sensing data (2007 satellite data). A translation converting the 2007 satellite data to the

heads-up categories was created to generate the composite hydrologic runoff time series used for calculating flashiness and consequently the HCI values. In the table below, the 2007 categories are portioned to either pervious or impervious fractions and associated to the HCI land cover categories. For perspective, the 2010 King County orthophoto in Figure 9 shows the Juanita Creek watershed and stream channels.

**Table 15. Relationships and conversions among land cover categories and associated pervious/impervious percentages among databases used for calculating and comparing hydrologic condition indices (HCIs) between project study watersheds and Juanita Creek. (Source: University of Washington. 2007. Central Puget Sound 2007 Land Cover Classification. Puget Sound Regional Synthesis Model (PRISM). University of Washington.)**

HCI Codes		HCI land cover	UW 2007 land cover	Juanita Creek 2007 HRUs		Fraction of HRU	
Till	Outwash			Pervious	Impervious	Pervious	Impervious
101	201	bare	Cleared	Cleared Lands	--	100%	--
102	202	building	Low Intensity	Lawns	Roof/Pavement	50%	50%
103	203	conifer	Mixed Forest	Forest	--	100%	--
104	204	deciduous	Mixed Forest	Forest	--	100%	--
105	205	grass	Grass, Grasslands	Grass	--	100%	--
106	206	mixed forest	Mixed Forest	Forest	--	100%	--
107	207	pasture	Agriculture	Agriculture	--	100%	--
108	208	paved road	Road	Lawns	Pavement	15%	85%
109	209	pavement	High Intensity	Lawns	Roof/Pavement	25%	75%
110	210	shrub	Forest Regen	Forest Regen	--	100%	--
111	211	unpaved road	Road	Lawns	Pavement	20%	80%
112	212	open water	Open water	--	Impervious	--	100%
113	213	wetland	wetlands	Wetlands	--	100%	--
114	214	clear cut	clear cut	Clear Cut	--	100%	--



**Figure 9.** 2010 Juanita Creek watershed and stream network. Yellow dot indicates location of BIBI sample site "JuanitaKirk\_4."

## 2.6 Permitting and Compliance

The King County Department of Permitting and Environmental Review (DPER, formerly Department of Development and Environmental Services, or DDES) issues land use permits for unincorporated King County. It maintains a computerized permit database which, for most areas, starts in 1989, although earlier records are in the database. Each permit is associated with a parcel identification number established by the King County Assessor for all legal parcels and is monitored from the time of application to closure, at which time an inspector has determined that all permitting requirements have been fulfilled. Where critical area mitigation is required for permit-related impacts, vegetation monitoring is done to ensure and confirm planting success.

The permit database maintains a record of hundreds of permit types (some 413 as of 2007) for a diversity of actions ranging from remodels and upgrades of existing structures to land

clearing and development actions. The latter category of actions may alter natural soil and vegetation conditions, and often there is conversion of natural pervious surfaces to a less or totally impervious condition. Forestry permits are included because timber management and harvesting typically involves soil disturbance and road construction and is a common land use in rural watersheds of Puget Sound. However, most forestry permitting is done by the Washington Department of Natural Resources (WDNR), rather than by local governments, and must comply with state forestry regulations. The exception is where forestry is undertaken with intent to convert land from forestry to a developed land use, such as housing or farming, at which point the forestry activity is subject to local land use regulations and governed by the affected local government agency (county or city), in this case King County DPER.

Regulatory stream buffers are high-priority protected areas in which vegetation growth and succession, channel migration and bank erosion, and many other natural processes are intended to unfold naturally and be relatively unaffected by development with few exceptions. As such, development-related land cover changes in regulatory buffers are intended to be avoided or, where property rights or critical infrastructure needs must be met and avoidance isn't possible, impacts must be minimized and mitigated to greatest extent feasible.

Compliance at regulatory stream buffer and watershed scales were compared to determine if regulatory buffers were affected more or less by noncompliant actions than the watersheds at large. Land cover map data are relatively fine scale (1:1200) and hand-digitized, providing sufficiently high resolution and accuracy to assess land cover change and compliance at the scale of 20 to 50 m wide regulatory stream buffers.

Compliance review was conducted by a panel of three specialists with extensive (10 to 23 years each) direct experience and knowledge of the County's land use, regulations, and permitting including: (1) a DPER Site Development Specialist or DPER Environmental Scientist, (2) a DPER GIS Specialist who was also DPER's Permit Database Manager, and (3) a KC DNRP Senior Environmental Scientist. Figure 10 shows the steps and regulatory criteria used for deciding when land cover change was real and needed permits. To estimate compliance rates, land cover change polygons ( $\geq \sim 5 \text{ m}^2$ ) in the treatment watersheds were first assessed for accuracy. This part of the quality assurance/quality control (QAQC) process resulted in removal of small (average  $4 \text{ m}^2$ ) polygons that had been created as a result of alignment errors and other polygons that were either (a) added where land cover change occurred but was not previously delineated or (b) removed or modified when change was not real or incorrectly mapped.

All land cover changes were assessed that were greater than approximately  $5$  to  $9 \text{ m}^2$  in area identified through orthophoto analysis between 2007 and 2009, 2009 and 2010, and 2010 and 2012. When the type and amount of land cover change was real and potentially warranted a permit, the change was cross-referenced with the permit database to determine if a permit record existed.

Where necessary, such as in accounting for change prior to start of 2008 monitoring in the 2007 to 2009 photoperiod, the permit closing date was used to date the timing of land cover change. The permit closing date indicates land altering activity had ceased, the site was inspected and all permit conditions were met. Where land cover changes had no

associated permit or permit closing date was uncertain, reviewers assessed photos for clear evidence of recent activity, such as ground disturbance or vegetation removal, to establish timing relative to the 2007 and 2009 photos. Land cover changes that could not be assessed with some degree of certainty were identified as “indeterminate” in their timing.

Because there are contextual decisions that are difficult to make without a site visit and the photos were not always clear at the 1:1200 scale, it was not possible to have complete certainty for all compliance determinations. Uncertainty was compounded because not all clearing or new structures require a permit, and the decision whether a given land cover change required a permit needed additional information not available through aerial photos. For example, for vegetation clearing, a permit is not required for hazard tree removal (trees within ~ 45 m of a residence) or for hand-removal of invasive weeds such as blackberries. Similarly, structures smaller than 18.6 m<sup>2</sup> do not require a permit unless they are heated or have two or more stories, which indicate potential use as a residence and, in either case, must be accessory to a primary dwelling unit. In any event, in the limited instances that structures may be allowed in a critical area or critical area buffer they must have a permit. In critical areas and their buffers such activity is allowed only when necessary to achieve a land owner’s property right, and full mitigation is required. Permit decisions were binned into one of five categories of relative certainty that a permit would have been needed for the land cover change: Yes, Probably Yes, No, Probably No, and Indeterminate. To reduce analysis complexity and because the number of “probably Yes” instances was small, all “Yes” and “Probably Yes” changes were grouped together for subsequent permit compliance analysis.

# Permit Compliance Decision Tree

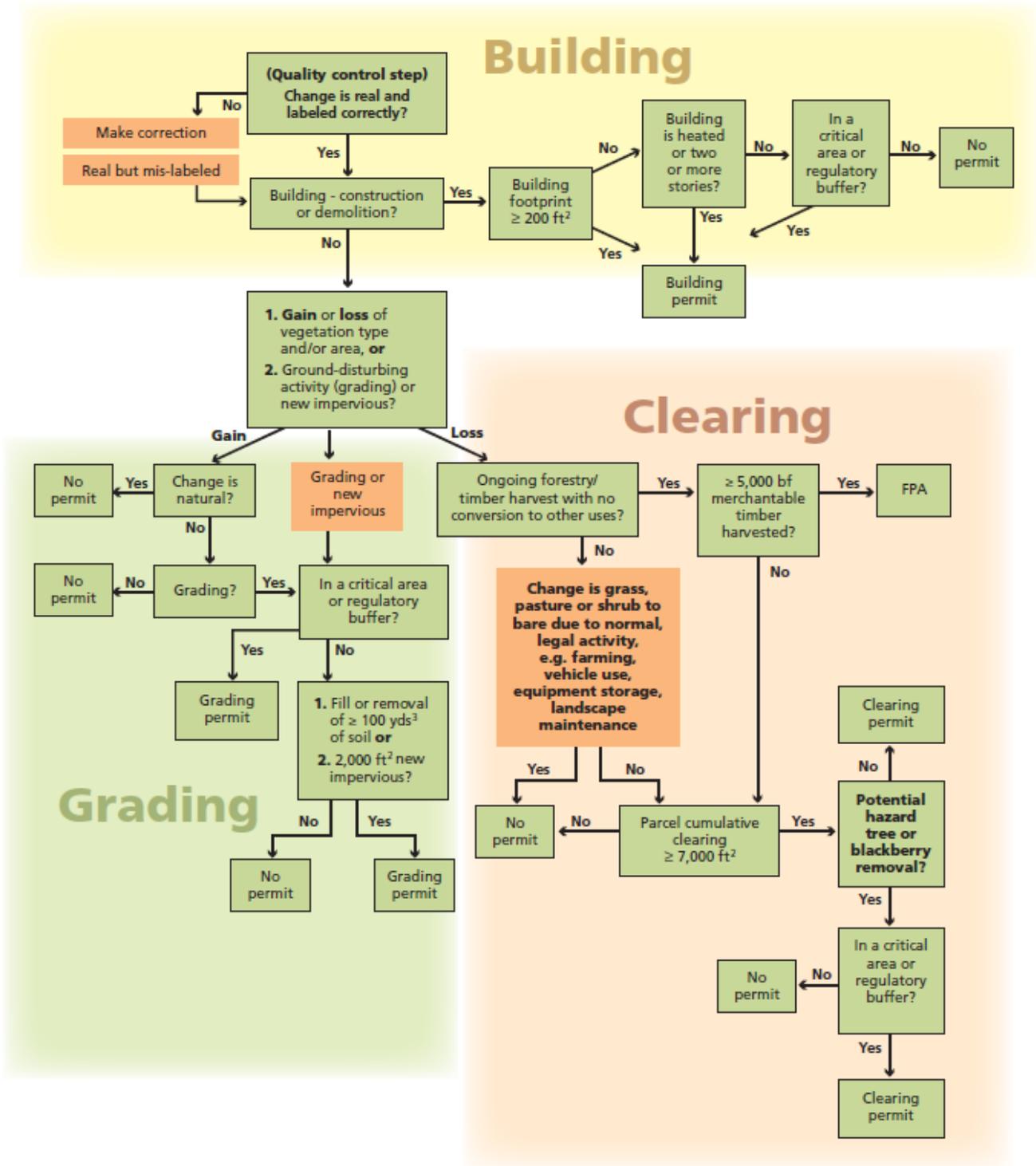


Figure 10. The decision process for determining when a permit would likely have been required and the type of permit required for any given change in land cover.

## 2.7 Data management

Project databases were developed to track, manage, and archive project data and includes information on:

- Permits including start and completion dates, location, type and area of modification,
- Surficial geology (type, location and area),
- Weather (precipitation and air temperature),
- Land cover (location, area and condition of hand-digitized, mapped land cover polygons), and
- Environmental response variables: stream flow (collected @ 15 minute intervals using flow weirs), water temperature (collected by continuously deployed temperature loggers), conductivity (bi-weekly grab samples supplemented with permanently deployed sondes collecting continuous [15-minute] readings), BIBI (three replicates per watershed annually), salt tracer results (time of travel) and periodic (mostly annual) measurements of width and depth and thalweg, pool, and substrate conditions.

## 2.8 Analytic Procedures

A statistical power analysis was conducted to evaluate the sensitivity of the project's sampling design to detect change in response variables. Statistical power is defined as the probability of detecting a difference when a difference truly exists. The sampling design for this project included three reference sites that were not expected to change and six treatment sites with a potential to change in response to land development.

Each of the response variables was evaluated separately for its statistical power to detect change. We used a before-after control-impact design (BACI) to evaluate the statistical power of each variable to detect a difference in reference and treatment sites. Data collected during the first year of sampling (2008/2009) were used as the "before" values. Data from the last year (2012/2013) were used as "after." The "control" sites were the reference sites and the "impact" sites were the treatment sites. The BACI design controls for any natural variability that might be associated with the sites by comparing each site to itself over time. The test statistic for each comparison was the difference between a site and itself. The differences were compared for the reference and treatment sites using a two-sample *t* test. The test was repeated for each response variable.

To evaluate the statistical power of each variable, we calculated the minimum detectable difference (MDD), that is, the smallest difference between the reference sites and treatment sites that would be statistically significant. We estimated the MDD for a two-sample *t* test (Zar, 1984). MDD was calculated for each response variable as follows:

$$\text{MDD} \geq \sqrt{\frac{2s_p^2}{n}} (t_{\alpha(1),v} + t_{\beta(1),v}),$$

Where  $s_p^2$  = the pooled variance for the reference sites and treatment sites,  
n = the harmonic mean of the different sample sizes,  
 $t_{\alpha(1),v}$  = the t value for alpha of 0.1 for a 1-sided test,  
 $t_{\beta(1),v}$  = the t value for beta of 0.1 for a 1-sided test, and  
v = (n<sub>1</sub> + n<sub>2</sub> - 2) = 7.

To estimate the number of categories that each response variable could potentially detect, we calculated the 90 percent confidence interval around the difference of the means for the reference sites and test sites. The 90 percent confidence interval was calculated as:

$$\bar{D}_R - \bar{D}_T \pm \sqrt{\frac{s_R^2}{n_R} + \frac{s_T^2}{n_T}} (t_{\alpha(1),v})$$

Where  $\bar{D}$  = the average of the differences for reference and treatment sites,  
 $s^2$  = the variance of the differences,  
n = the number of sites, and  
 $t_{\alpha(1),v}$  = the t value for alpha of 0.1 for a 1-sided test.

The sensitivity of each response variable was compared by dividing the possible range of the variable by the 90 percent confidence interval to obtain the number of categories within the range of the response variable that could be detected with this sampling design. More categories indicated a more sensitive response variable.

Ordination was conducted to assess similarities in response among the study watersheds and ERVs. Ordination was done using non-metric multidimensional scaling (NMDS) with Bray-Curtis dissimilarity (R package vegan 2.0; R Development Core Team 2011) derived from values of 11 response variables at 9 sites averaged over the years of the project. NMDS displays dissimilarities in site condition onto ordination space. Additional variables related to land cover and physical features were fitted post-hoc to the ordination.

## 3.0. RESULTS

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This section presents results and observations of applying the research methods described in the preceding section. The results are grouped into categories that pertain to the study questions. There are generally four groupings of questions the results section will address:

1. Level of treatment (change in land cover)
  - How did percent (un-weighted) composition of land covers vary over time in study watersheds and regulatory stream buffers?
  - How did the Hydrologic Condition Index (HCI), vary over time in study watersheds and regulatory stream buffers?
2. Permitting and Compliance
  - What was overall regulatory compliance, defined as any change in land cover that likely needed and got a permit? And how did compliance vary by time, watershed, permit type, and the type, number, and area of land cover changes?
  - What was potential effect on compliance of forest loss that could be attributed to hazard tree removal (forest removed within one site potential tree height [46 m] of a building)?
3. Environmental Response Variables (ERVs)
  - Did ERVs representing hydrology, biology, water quality and channel complexity change during project?
  - Which ERVs had the greatest statistical power?
  - Was there correlation among the ERVs and the HCI? How well does the HCI predict environmental response?
4. Watershed Groups: using ordination, do watersheds exhibit responses that indicate clustering by area or condition?

### 3.1 Land Cover

Measures of land cover change provide an indication of level of treatment applied. Both simple aggregate and hydrologically weighted measures of change are described in this section. Appendix E shows orthophotos from each year assessed for landcover change and areas of change between photo years and build-out footprints used to model FBO.

#### 3.1.1 Un-weighted measure of change

This section addresses change in percent (un-weighted) composition of land covers over time in study watersheds and regulatory stream buffers.

##### 3.1.1.1 Watershed land cover

For the most part, land cover composition changed little in treatment watersheds over the course of the project (Figure 11; also see Appendix I for complete results). Forest cover was near 100 percent in the reference watersheds and was the dominant land cover in the six treatment watersheds, ranging from an average of 54 percent in Taylor to 83 percent in Tahlequah. A noticeable decline in forest cover occurred in Cherry Creek Tributary watershed between 2010 to 2012 resulting from a clear-cut that was permitted through a

WDNR Forest Practices Approval (FPA) permit (see Section 3.2). Impervious land cover, the aggregate area of buildings, pavement, and paved and unpaved roads, varied little over the course of the study and ranged from zero or near-zero in the reference watersheds to about 10 percent in Taylor Creek.

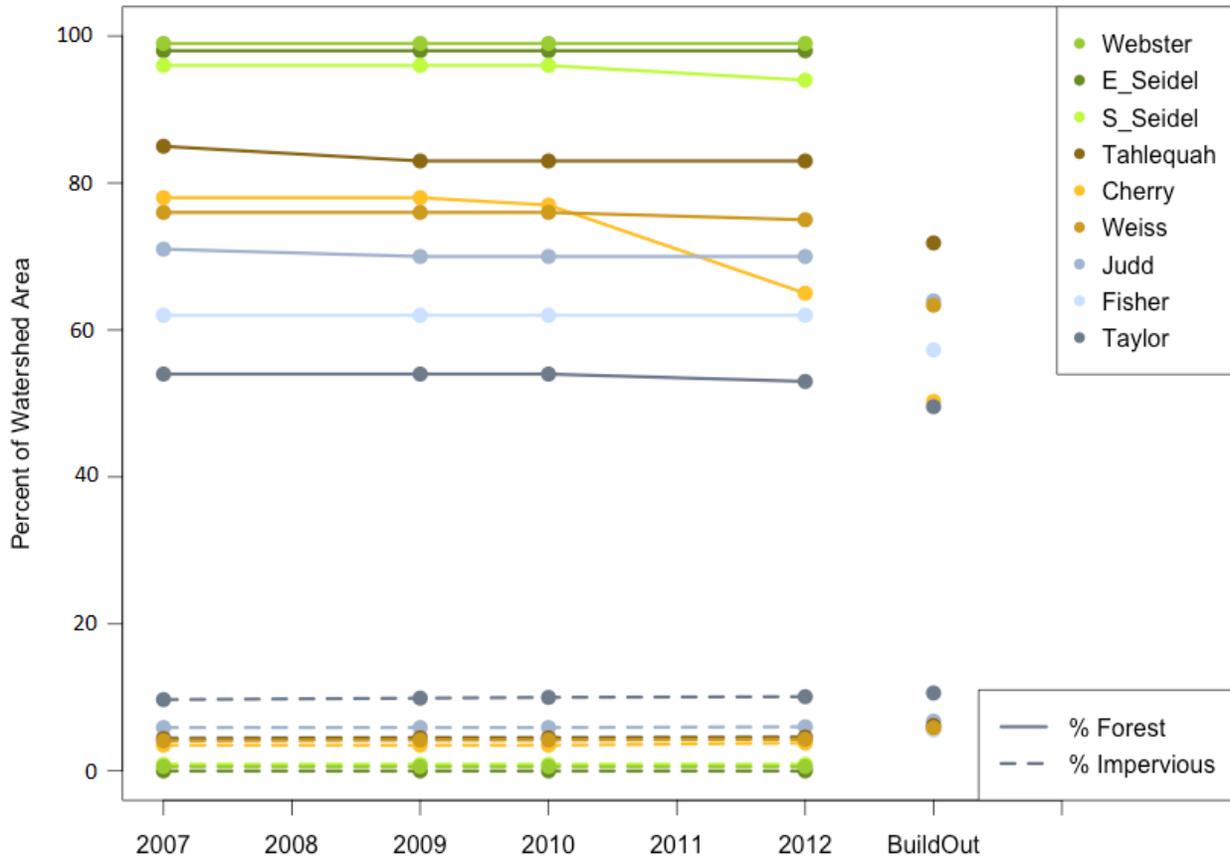


Figure 11. Change in percent forest and impervious covers during study period (2007 to 2012) and projected under full build out.

### 3.1.1.2 Regulatory Buffer land cover

For all treatment watersheds, the buffer had higher percent forest cover than the overall watershed. As at the watershed scale, composition of land cover in the regulatory stream buffers exhibited little change over the duration of the study. Therefore, only 2012 (final project year) land cover is shown in Table 16. Across all treatment watersheds, percent forest at the regulatory stream buffer and watershed scales averaged 85 percent and 68 percent, respectively, whereas percent impervious area (buildings, pavement, and paved and unpaved roads) at the regulatory stream buffer and watershed scales averaged 2.6 and 5.5 percent, respectively. Forest was a greater proportion of the land cover in regulatory buffers than the overall watershed for all six treatment watersheds; forest cover ranged from 70 percent in Taylor regulatory buffers to 96 percent in Tahlequah buffers, whereas for the total watershed forest cover ranged from 53 percent in Taylor to 83 percent in Tahlequah. Conversely, for all treatment watersheds, the proportion of impervious area was lower inside regulatory stream buffers than at the watershed scale. Taylor Creek had

**Table 16. Percentage of 2012 (final project year) land cover for the six treatment watersheds at the watershed (WS) and regulatory buffer scales (BF).**

	Cherry Cr. Tributary		Fisher		Judd		Tahlequah		Taylor		Weiss		Average	
	WS	BF	WS	BF	WS	BF	WS	BF	WS	BF	WS	BF	WS	BF
Forest	64.9	81.5	61.9	94.3	70.1	82.8	82.8	95.6	53.3	70.0	75.4	82.9	68.1	84.5
Shrub	3.7	4.6	0.8	0.3	1.8	0.7	1.4	0.3	2.5	1.1	4.1	4.2	2.4	1.9
Pasture	9.7	4.6	27.0	0.6	16.1	10.8	4.0	0.0	27.2	15.9	10.7	2.8	15.8	5.8
Wetland	1.0	1.8	0.3	0.0	0.4	0.0	0.0	0.0	1.0	3.9	0.6	3.3	0.5	1.5
Recent clear-cut	12.7	5.2	0.1	0.0	0.1	0.0	3.4	0.5	0.1	0.0	0.7	0.7	2.8	1.1
Grass	2.7	0.4	4.4	2.4	4.2	1.4	2.8	1.4	3.6	1.8	2.4	1.5	3.3	1.5
Building	0.9	0.0	1.0	0.3	1.3	0.4	0.8	0.4	2.5	0.7	1.0	0.4	1.2	0.4
Bare	1.1	0.2	0.6	0.1	0.9	0.3	0.9	0.2	1.9	0.8	1.3	0.6	1.1	0.4
Pavement	0.5	0.2	0.2	0.0	0.8	0.1	0.2	0.3	1.0	0.2	0.3	0.1	0.5	0.1
Open water	0.5	1.0	0.4	0.7	0.5	0.8	0.1	0.0	0.4	0.2	0.5	1.9	0.4	0.8
Unpaved road	1.2	0.2	1.8	0.5	2.1	1.0	2.2	0.7	2.8	1.8	2.6	1.5	2.1	0.9
Paved road	1.2	0.3	1.7	0.9	1.8	1.7	1.3	0.7	3.8	3.7	0.4	0.2	1.7	1.2

the highest percent impervious land cover both within regulatory stream buffers and at the watershed scale, at 6.4 percent and 10.1 percent, respectively. Meanwhile, the Cherry Creek Tributary had the lowest percent impervious land covers both within regulatory stream buffers and at the watershed scale, at 0.7 percent and 3.8 percent, respectively.

### 3.1.1.3 2007-2009 land cover change during project window

Between the 2007 and 2009 orthophotos, a total of 47.82 ha of land cover change occurred in the study watersheds (Table 17). Of this change, 19.19 ha (40 percent) was identified in an early round of land cover mapping quality control and subsequently used to assess timing of land cover change between 2007-2009 relative to April 1, 2008, used as the nominal start date for detecting environmental response .

**Table 17. Total area (ha) of land cover change and area assessed for project land cover effect detection window between 2007 and 2009.**

Type of Land Cover Change	Investigated	Not Investigated	Total
Forest to any land cover except Building	8.30	9.18	17.48
Any land cover to Building	0.89	0.18	1.07
All other identified changes from one land cover to another	10.00	19.27	29.27
<b>Grand Total</b>	<b>19.19</b>	<b>28.63</b>	<b>47.82</b>

Relative to April 1, 2008, 47 percent of the area of land cover change between 2007 and 2009 was identified as being after that date and therefore occurred during the project effect detection window (including 34 percent identified as occurring within the project time frame and 13 percent identified as occurring probably in). Meanwhile, 20 percent occurred before the cut-off date and prior to the project effect detection window, and 34 percent was indeterminate as to whether it occurred in or out of the effect detection window (Table 18). Because the overall amount of change in land cover over the project timeframe was small, this information was not considered integral to the study questions and is presented here for informational purposes and to provide a complete accounting of land cover change.

**Table 18. Area (ha) of 2007 to 2009 land cover change relative to project land cover effect window.**

Timing of Change	Area (ha)	Percent
Before the project timeframe	1.26	7%
Probably before project timeframe	2.54	13%
Indeterminate	6.44	34%
In the project timeframe	6.50	34%
Probably in the project timeframe	2.46	13%
<b>Total Investigated</b>	<b>19.19</b>	<b>100%</b>

### 3.1.2 Weighted Measure of Change (Hydrologic Condition Indices)

This section addresses change in the Hydrologic Condition Index (HCI) over time in study watersheds and regulatory stream buffers.

#### 3.1.2.1 Watershed HCIs

Watershed-scale Hydrologic Condition Indices (HCIs) for years within the project timeframe (2007, 2009, 2010, and 2012) as well as historic (1910, 1936, 1948, and 1965) and simulated future full build-out (FBO) scenarios were calculated for the treatment watersheds (Figure 12; see Section 2.5 for details on the HCI). HCIs for 1936 for the Cherry Creek Tributary, Taylor, and Weiss watersheds were not calculated because of an absence of photos or reference material for that time. For reference, horizontal lines in Figure 12 show HCIs for 100 percent forest (best) and an equal mixture (alternating 1.8 m grid cells) of forest and grass, where HCIs for the 100 percent forest condition are about 0.110, and HCIs for even mix of forest-grass were about 0.150. [Note: because of scale, the worst condition of 100 percent paved road (score of 1.0) is not shown in Figure 12.]

Average annual HCIs varied little during the project (2007-2012), ranging between a low (best condition) of 0.149 for Tahlequah in 2007 to a high (worst) of 0.208 in Taylor Creek in 2012. Among the treatment watersheds, Tahlequah and Cherry Creek were very similar and had the best (lowest HCI) condition while Taylor was the worst (highest HCIs). HCIs generally increased from year to year, a trend that reflects the cumulative effect of conversion of vegetation to impervious surfaces on hydrology. There were a few instances, however, where conditions improved (HCIs went down) slightly (e.g., Fisher Creek 2010 to 2012); these improvements reflect land cover changes going from bare or clear-cut to vegetation or from a relatively low quality (hydrologically speaking) vegetation, such as grass, to a higher quality vegetation, such as shrub.

In part because the time span is much longer than five years, HCIs varied more over time historically than during the project timeframe. Higher historic HCI values (worse hydrologic condition) followed periods of timber harvest and conversion to pasture and grass. It should be noted, however, that because of the poorer quality historic photos and reference materials than available for project timeframe, historic condition HCIs are less accurate than contemporary HCIs. As discussed in more detail in Michalak et al. (2013; see Appendix D), early timber harvesting and agricultural development was prevalent in all study watersheds. Conditions then generally improved as forest re-growth occurred up to 1965. After that time, conditions got worse (HCIs increased), presumably coinciding with increased regional economic growth and associated land development in rural areas. Aside from the presumed near-100-percent forest condition of a pristine landscape, the best (lowest) HCIs were in 1965 for five of the six treatment watersheds.

HCIs under full build-out (FBO), where all currently undeveloped parcels were built-out using a standardized method for applying house, road, and clearing footprints (see Methods, Section 2.0 ), are all worse than current, but the projected change is relatively small. The worst case FBO HCI of 0.215 is predicted for Taylor Creek, but it is only slightly

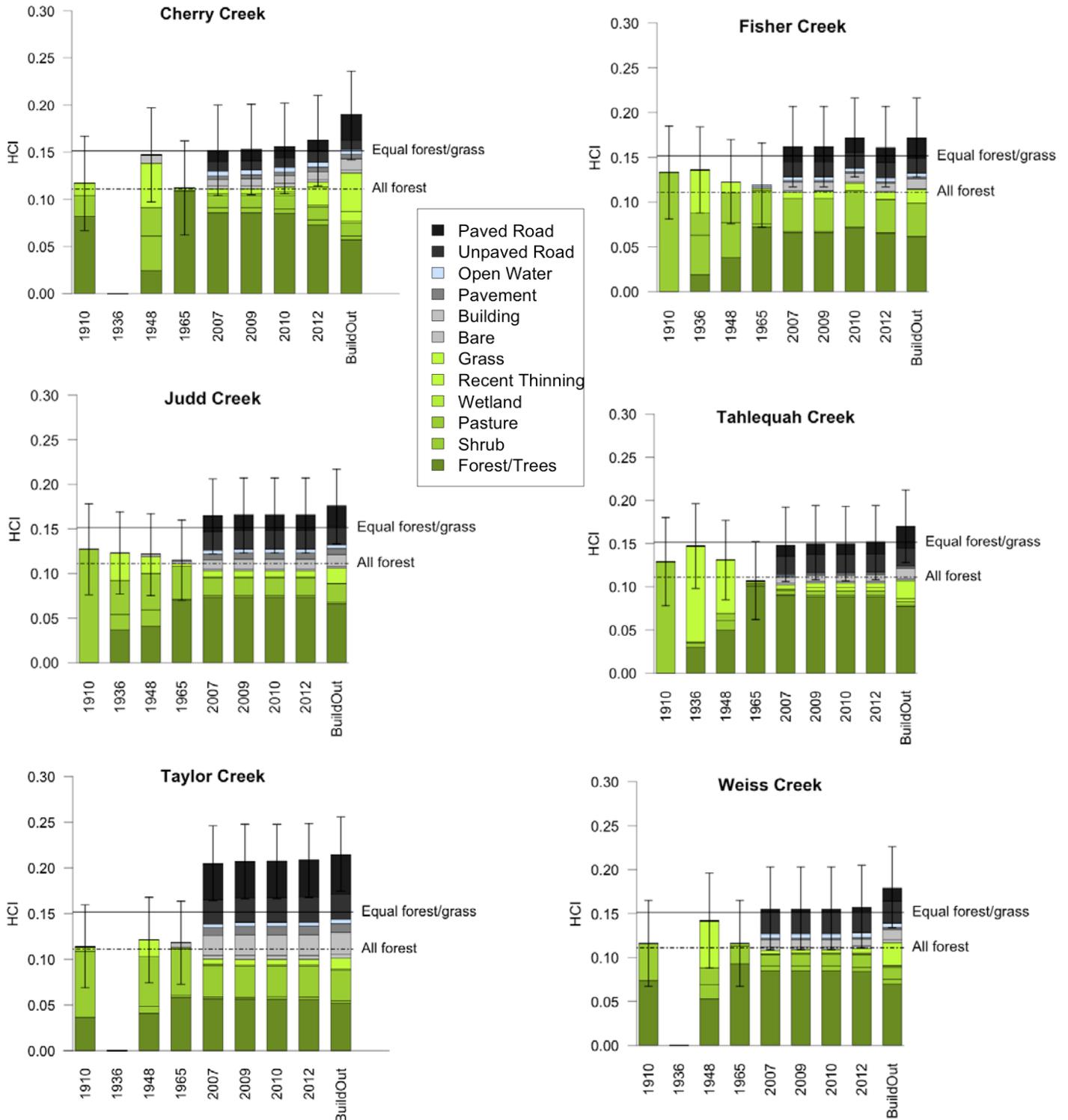


Figure 12. Hydrologic Condition Index (HCI) scores for historic (1910, 1936, 1948, and 1965), project timeframe (2007 to 2012), and full “build-out” scenarios for each treatment watershed. HCIs for best (all forest), and equal mix of forest and grass and contribution by each land cover are also shown. Scores are indexed to a worst (all paved road) condition whose value is 1 but not shown. Error (vertical) bars represent +/- 1 SD of the 5 estimates used to calculate HCI.

worse than the 2012 HCI (0.208). The largest increases in HCIs between 2012 and FBO are for Tahlequah, Weiss, and Cherry Trib., where projected HCI at FBO are 0.170, 0.180, and 0.189, respectively, all of which are below Taylor Creek's most recent (2012) HCI.

### 3.1.2.2 Regulatory Stream Buffer HCIs

HCIs for regulatory stream buffers for historic scenarios were not calculated because the photos and reference materials are coarse-scale relative to buffer widths and so confidence in historic regulatory stream buffer HCI values would have been low. Regulatory stream buffer HCIs over the project timeframe remained virtually unchanged (Figure 13). On average, during the project timeframe, regulatory stream buffer HCIs were best (lowest) in Tahlequah (0.11) and worst (highest) in Taylor (0.16). The Vashon Island streams had the best regulatory stream buffer HCIs, ranging from Tahlequah (0.11) to 0.12 to 0.13 for Fisher and Judd, respectively.

Under full build-out, HCIs do not change appreciably in two of the watersheds (Cherry Tributary and Fisher) and very little (+ 0.01 HCI units) in the other treatment watersheds. The small projected change in HCI between 2012 and FBO indicates a relatively small effect of increases in impervious land cover in the context of low-density forest-dominated rural development.

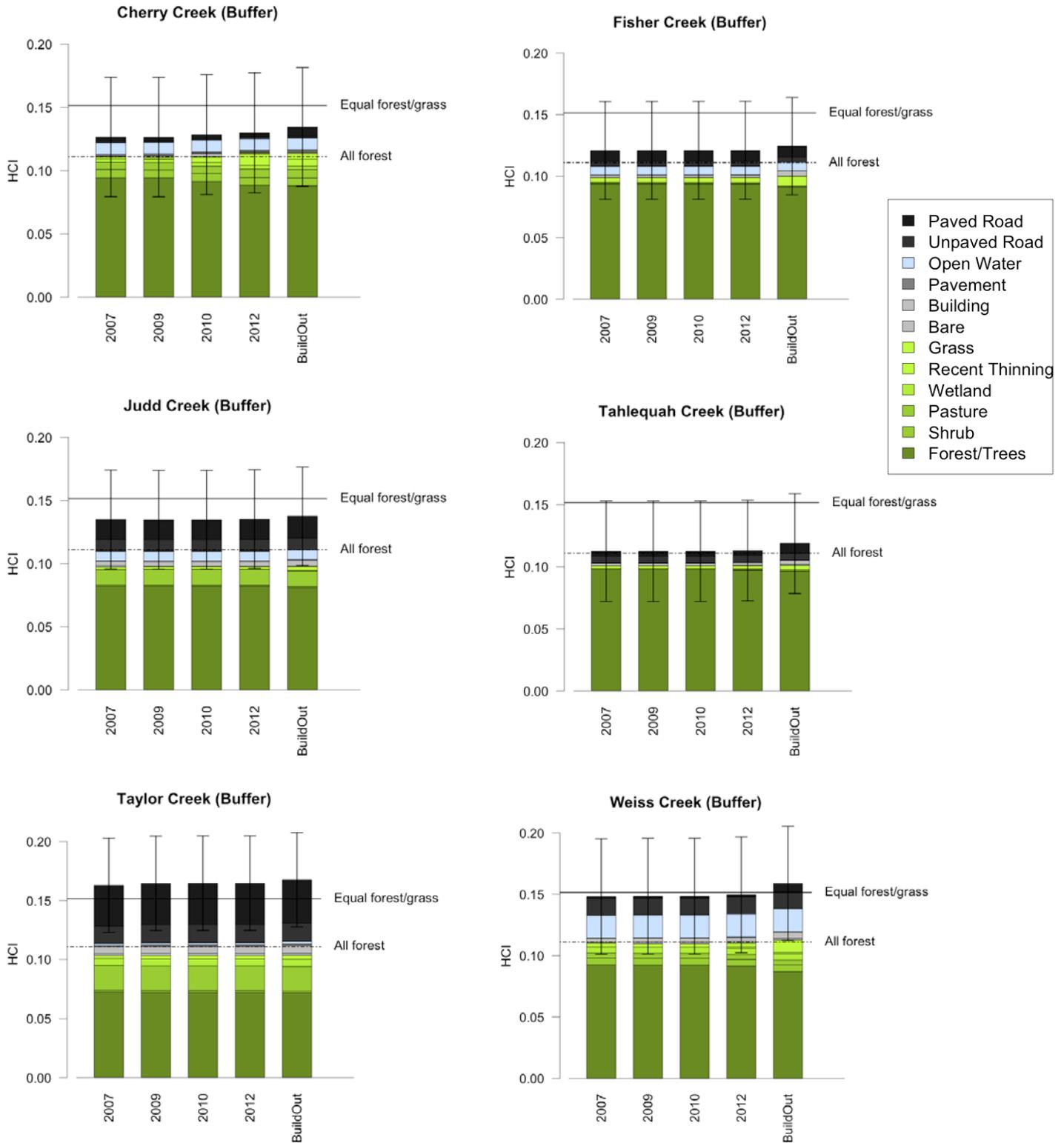


Figure 13. Hydrologic Condition Index (HCI) scores for project timeframe (2007 to 2012), and full “build-out” scenarios for regulatory stream buffers in each treatment watershed. HCIs for best (all forest), and equal mix of forest and grass and contribution by each land cover are also shown. Scores are indexed to a worst (all paved road) condition whose value is 1 but not shown. Error (vertical) bars represent +/- 1 SD of the 5 estimates used to calculate HCI.

### 3.1.2.3 Comparison of Watershed and Regulatory Stream Buffer HCIs

Comparison of HCIs for watershed and regulatory stream buffer scales provides a measure for the relative hydrologic condition of the two scales. Because of their protected status, regulatory stream buffers should be in a higher condition (lower HCI) than the overall watershed. The ratio of watershed to regulatory stream buffer HCIs provides a measure of the regulatory stream buffer condition relative to the overall watershed condition (Table 19). For the project timeframe, ratios were all greater than 1, indicating better conditions in regulatory stream buffers than in the watersheds, and ranged from 1.07 for Weiss to 1.36 for Tahlequah. Under build-out, ratios increased (buffers are relatively better) in four watersheds (Cherry, Fisher, Tahlequah and Weiss) and decreased (buffers are relatively worse) in two watersheds (Judd and Taylor). Reduction in ratios for Judd and Taylor suggests future impact to the regulatory buffer. This reduction results from projecting a development footprint on parcels that were constrained by their small area or natural features such as steep slopes or wetlands. In practice, however, where lots are constrained, King County uses avoidance and minimization and mitigation procedures. Therefore, if a parcels is in fact constrained, its future development footprint will be configured so as to avoid or minimize and mitigate impacts to critical areas and their buffers. Regardless, under FBO, regulatory stream buffer HCIs are projected to be better than for the overall watershed for all treatment watersheds.

**Table 19. Hydrologic Condition Indices (HCIs) for project timeframe (average of 2007-2012) and build-out conditions and ratio of watershed to regulatory stream buffer HCIs.**

	Watershed		Regulatory Buffer		Ratio of Watershed to Buffer	
	2007-2012 Ave.	Build Out	2007-2012 Ave.	Build Out	2007-2012 Ave.	Build Out
<b>Cherry Trib.</b>	0.156	0.190	0.127	0.134	1.228	1.418
<b>Fisher</b>	0.164	0.172	0.121	0.124	1.357	1.387
<b>Judd</b>	0.166	0.176	0.135	0.137	1.228	1.285
<b>Tahlequah</b>	0.150	0.170	0.113	0.119	1.327	1.429
<b>Taylor</b>	0.208	0.214	0.164	0.168	1.267	1.274
<b>Weiss</b>	0.156	0.179	0.149	0.159	1.044	1.126

### 3.1.2.4 Juanita Creek, an urban comparison

HCIs for Juanita Creek (see Figure 9), an urban watershed in the Lake Washington Watershed, provide an urban comparison to the study treatment watersheds. From this comparison it can be seen that Juanita Creek’s current HCI (0.833) is four times higher than the projected worst case HCI of Taylor Creek at FBO (0.208) (Figure 14). This large difference in HCI indicates a significantly more degraded hydrologic condition in Juanita Creek than is likely to ever be seen in any of the rural treatment watersheds. Furthermore, change in treatment watershed HCIs between 2012 and FBO is very small compared to Juanita Creek.

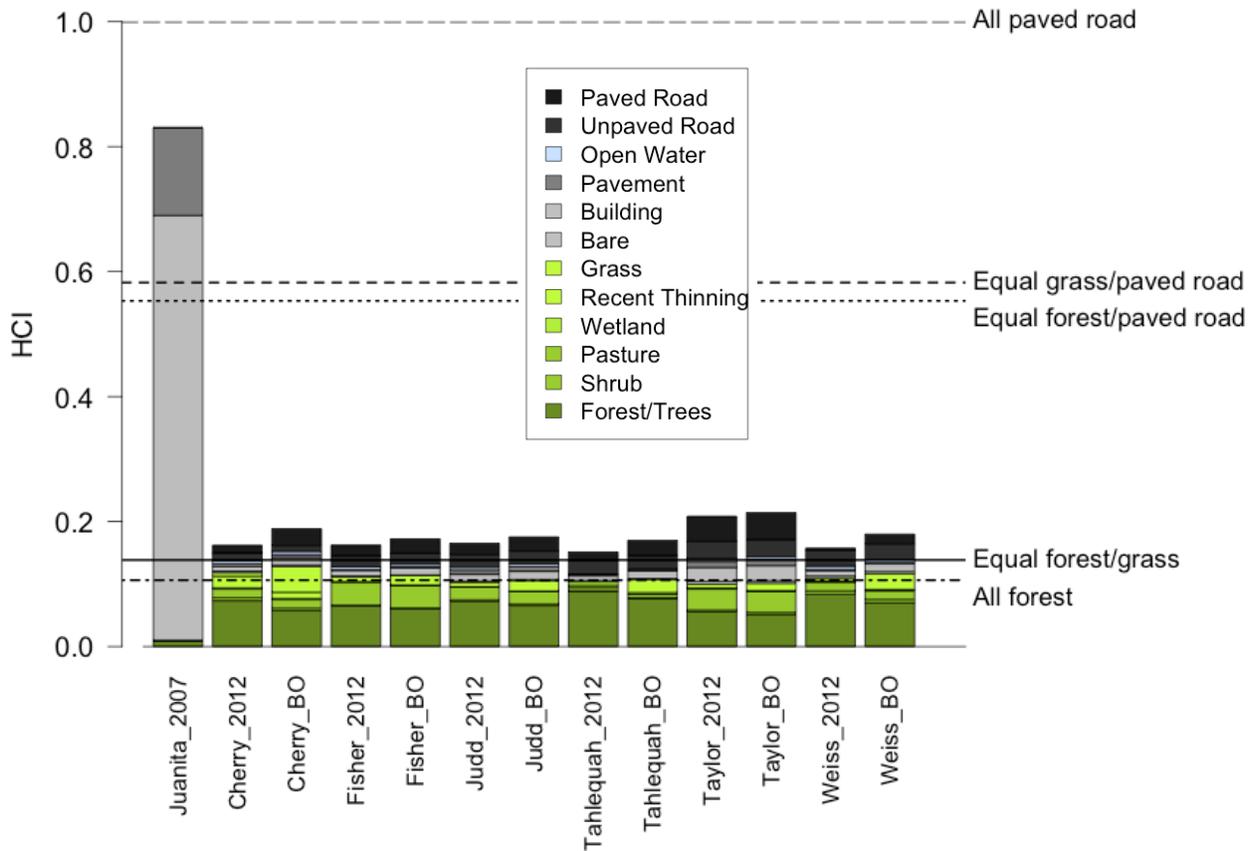


Figure 14. Hydrologic Condition Index (HCI) scores for Juanita Creek using 2007 land cover maps as compared to 2012 and full build-out (“BO”) scenarios for each treatment watershed. HCIs for best (all forest), and equal mixes of forest, grass and paved road and contribution by each land cover are also shown. Scores are indexed to a worst (all paved road) condition whose value is 1.

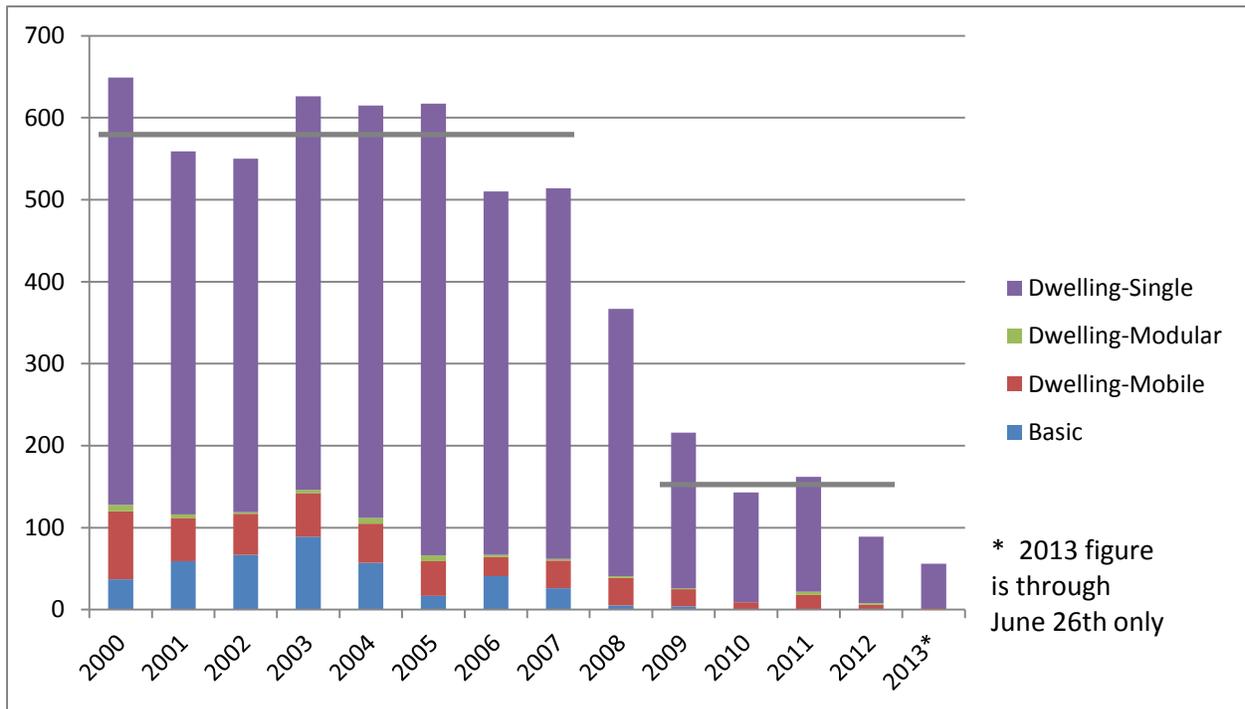
## 3.2 Permitting and Compliance

This section presents findings on permitting activity and compliance (defined as any land cover change that likely required and obtained a permit), including overall compliance rates and effects of permit type, area of change, potential hazard tree removal on compliance, and compliance in regulatory stream buffers.

### 3.2.1 Development Activity Preceding and During the Project

An important issue was whether development during the project timeframe was representative of development over the long term. As indicated by building permits issued for the County’s entire rural-zoned area, development activity was dramatically higher in the 8 year time period preceding the project (2000-2007) than during the project timeframe (Figure 15). 2008 was not included because it was a transition year between economic “boom and bust” periods. The average annual number of building permits declined almost 75 percent, from an average of 580 building permits per year for the 2000-

2007 period preceding the study to an annual average of 153 building permits per year during most of the study (2009-2012).



**Figure 15.** Entire King County Rural area building permits issued by King County preceding (2000-2007) and during (2009-2012) the study. The horizontal gray bars represent the averages of these two time periods: 580 for the period from 2000 to 2007, and 153 for the 2009 to 2012 time period. Note that 2008 is considered a transition year between “boom and bust” economic periods and so is excluded from these averages.

### 3.2.2 Compliance during Project Timeframe

Over 5 years (2007-2012), the total area of land cover change, regardless of permit need and including both positive (e.g., bare to grass, grass to shrub) and negative (e.g., forest to bare) land cover changes, across the 6 treatment watersheds and their regulatory stream buffers was 140.1 ha (3.4 percent of the treatment watershed area) and 2.8 ha (0.7 percent of the regulatory stream buffer area), respectively (Table 20). At the watershed scale, the cumulative compliant and non-compliant land cover change over five years accounted for 2.4 and 1 percent, respectively, of the watershed area. At the regulatory stream buffer scale, the percent land cover change was much lower, with compliant and non-compliant land cover change over five years accounting for 0.5 and 0.2 percent, respectively, of the regulatory stream buffer area.

**Table 20. Total, compliant and non-compliant area of land cover change over 5-years as a proportion of treatment watersheds and their regulatory stream buffers.**

Extent	Area (ha)	% area with no LC change	% area with LC change*	% area with Compliant LC change	% area with Non-compliant LC Change
Watershed	4105	96.6	3.4	2.4	1.0
Regulatory Stream Buffer	417	99.3	0.7	0.5	0.2

A total of 2,064 discrete land cover change polygons were identified and examined for whether they likely required and obtained a permit (Table 21). Across all project years, the average annual area of land cover change was 28 ha/year (0.7 percent/year of treatment watershed area), ranging from a low of 23.9 ha/year during 2007-2009 to a high of 32.8 ha/year during the 2010-2012 period. Of this total area of change, 43 ha (30 percent of total area of land cover change) was judged to not require a permit, whereas 97.1 ha (70 percent of total area of land cover change) was judged as requiring a permit. Of the 5-year cumulative area of change that needed a permit, 36.2 ha (1 percent of the total treatment watershed area) did not have one and so was judged noncompliant.

Where change was real and large enough to potentially warrant a permit, it was cross-referenced against 412 permits to estimate compliance rates over the study period. For land cover changes that likely required and obtained a permit, the overall estimated compliance rate by area and number (or instances) of land cover changes was 63 percent (60.9 ha out of 97.1 ha that needed a permit) and 35 percent (409 instances out of 1,177 instances total), respectively, across all photo years (2007-2012) for changes identified as “Yes” (i.e., high certainty that a permit would have been required) and “Probably yes” (i.e., low to moderate certainty that a permit would have probably been required) (Table 21). The average area of land cover change identified as “Yes” was almost four times larger, averaging 894 m<sup>2</sup>, than the average area of 223 m<sup>2</sup> estimated for land cover changes identified as “Probably Yes.” The difference reflects less certainty in making compliance determinations as the area of change got smaller. Notably, in a few instances (3 out of 701), permits were obtained when a change had been identified during our process as not needing a permit. Discrepancies in what was needed versus what was obtained is likely a result of incorrect determinations during the compliance review process, and such errors are inevitable when using remote spatial data to represent small-scale, real-world activities.

Compliance varied considerably depending on timeframe and was more variable when estimated by area of change than by the number of land cover changes. Using only the “Yes” changes, compliance by area of land cover change ranged from 34 percent (5.7 ha of 17 ha total needing permit) during 2009-2010 (1 year) to 80 percent (41.1 ha out of 52.8 ha total needing a permit) during 2010-2012 (2 year). When estimated by number of land cover changes, compliance ranged from 34 percent during 2010-2012 (2 year) to 48 percent during 2007-2009 (2 year).

**Table 21. Total area (hectares) and number of land cover change polygons assessed and compliance rates across six treatment watersheds and three photo time periods between 2007 and 2012.**

Permit Required?	Area with Permit / Total Area (ha)	% Compliant by Area	# changes with permit / total # changes	% Compliant by # changes
<b>2007 to 2009 (2 years)</b>				
Yes	14 / 24.1	58	195 / 407	48
Probably Yes	0.1 / 3.2	3	4 / 124	3
<b>Sub Totals</b>	<b>14.1 / 27.3</b>	<b>52</b>	<b>199 / 531</b>	<b>37</b>
Indeterminate	0 / 0.1	0	0 / 3	0
Probably No	0.01 / 1.8	NA	1 / 80	NA
No	1.8 / 18.8	NA	1 / 305	NA
<b>2007 - 2009 Totals</b>	<b>15.9 / 47.8</b>		<b>201 / 919</b>	
<b>2009 to 2010 (1 year)</b>				
Yes	5.6 / 16.6	34	69 / 151	46
Probably Yes	0.1 / 0.4	25	5 / 30	17
<b>Sub Totals</b>	<b>5.7 / 17</b>	<b>34</b>	<b>74 / 181</b>	<b>41</b>
Indeterminate	-		-	
Probably No	0.03 / 1.8	NA	2 / 39	NA
No	0.1 / 7.9	NA	2 / 183	NA
<b>2009 - 2010 Totals</b>	<b>5.8 / 26.7</b>		<b>78 / 404</b>	
<b>2010 to 2012 (2 years)</b>				
Yes	41.1 / 51.4	80	136 / 396	34
Probably Yes	0 / 1.4	0	0 / 69	0
<b>Sub Totals</b>	<b>41.1 / 52.8</b>	<b>78</b>	<b>136 / 465</b>	<b>29</b>
Indeterminate	-		-	
Probably No	0 / 1.2	NA	0 / 60	NA
No	0 / 11.5	NA	0 / 213	NA
<b>2010 - 2012 Totals</b>	<b>41.1 / 65.6</b>		<b>136 / 741</b>	
<b>2007 to 2012 (5 years) Cumulative Summary</b>				
Yes	60.7 / 92.1	66	400 / 954	42
Probably Yes	0.2 / 5	4	9 / 223	4
<b>Sub Totals</b>	<b>60.9 / 97.1</b>	<b>63</b>	<b>409 / 1177</b>	<b>35</b>
Indeterminate	0 / 0.1		0 / 3	
Probably No	0.04 / 4.8	NA	3 / 179	NA
No	1.9 / 38.2	NA	3 / 701	NA
<b>2007 - 2012 Totals</b>	<b>62.8 / 140.1</b>		<b>415 / 2,064</b>	

Expressed as a percent of parcels in the 6 treatment watersheds, the majority (61 percent) of parcels had no observed land cover change during the 2007 to 2012 project timeframe (Table 22). Of the remainder, 11 percent of parcels had only land cover change that likely would not have needed a permit because change was too small or the type of change likely didn't need a permit (e.g., bare to grass, grass to shrub, or change resulting from maintenance, such as tilling or mowing of an existing field or lawn), 5 percent of parcels had only compliant change, 20 percent had only non-compliant change and 3 percent had a combination of both compliant and non-compliant change.

**Table 22. Land cover change, compliance and noncompliance from 2007 to 2012 as a proportion of parcels in treatment watersheds, based on parcels completely within watershed boundaries (from Table 6).**

Name	% Parcels with no LC change	% Parcels with only "No Permit Required" Change	% Parcels with only Compliant Change*	% Parcels with only Non-Compliant Change*	% Parcels with Compliant and Non-Compliant Change*
Cherry Trib.	38	15	16	20	11
Fisher	70	10	5	14	1
Judd	68	11	4	15	2
Tahlequah	66	9	6	19	1
Taylor	57	11	4	25	2
Weiss	52	16	5	24	4
<b>Average</b>	<b>61</b>	<b>11</b>	<b>5</b>	<b>20</b>	<b>2</b>

\*These parcels may also have changes not requiring permits.

### 3.2.3 Compliance by Permit Type

Compliance by permit type (building, clearing and grading, or FPA) indicates how well permits represent major type of land-altering activities. Compliance varied considerably when characterized by permit type and the number or area of land cover changes needing permits (Figure 16). For example, when expressed as number of land cover changes for which permits may have been required, building permit compliance was 58 percent, but compliance was 82 percent when expressed as area. Similarly, whereas compliance with clearing and grading permits was low as a function of number of permits (9 percent), it was better but still rather low

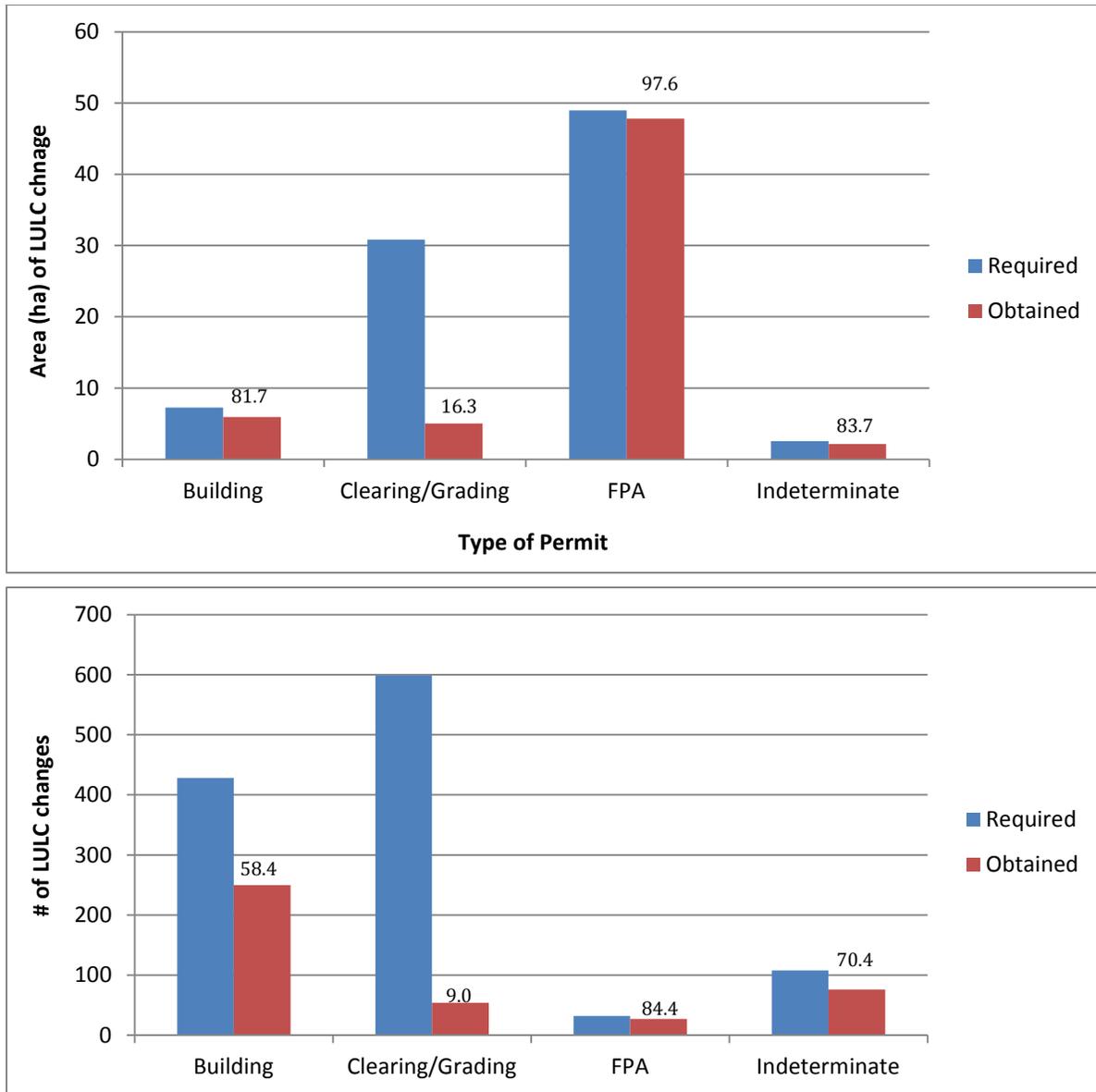


Figure 16. 2007-2012 land cover change in all study watersheds grouped by permit type, number of changes (top) and area of changes (ha; bottom) that may have needed a permit. Numbers above red bars are percent compliance.

(16 percent), when viewed as function of area. Compliance with land cover change that likely needed FPAs (clearing of relatively large stands of trees) was high for both number of changes (70 percent) and area (98 percent).

### 3.2.4 Compliance by area of change

As indicated above, compliance was positively related to area of land cover change. Whether by conversion of any non-building land cover to a building (Figure 17) or from forest to any other land cover (Figure 18), a linear trend of increasing compliance with increasing area of change was evident. For buildings, the trend is significant ( $r^2 = 0.64$ ,

$p < 0.01$ ) with compliance ranging from about 20 to 40 percent for buildings up to 100 m<sup>2</sup> and rising to 100 percent for large ( $\geq 400$  to 500 m<sup>2</sup>) buildings. The influence of area is much more variable and weaker ( $r^2 = 0.15$ ,  $p = 0.03$ ) but still positive for conversion of forest to any other land cover, varying between 20 and 60 percent for all but the very largest ( $> 1$  ha) size class of conversions.

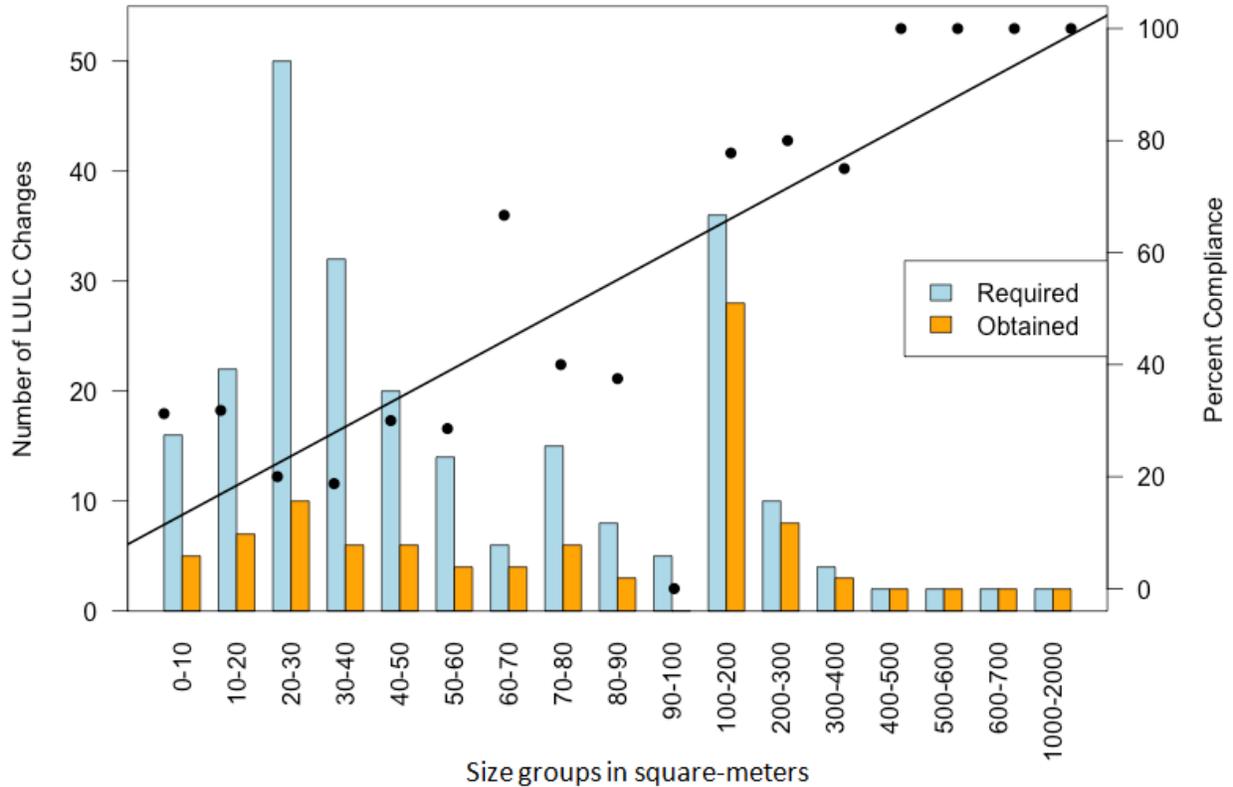


Figure 17. 2007-2012 land cover change by area from any land cover type to building.

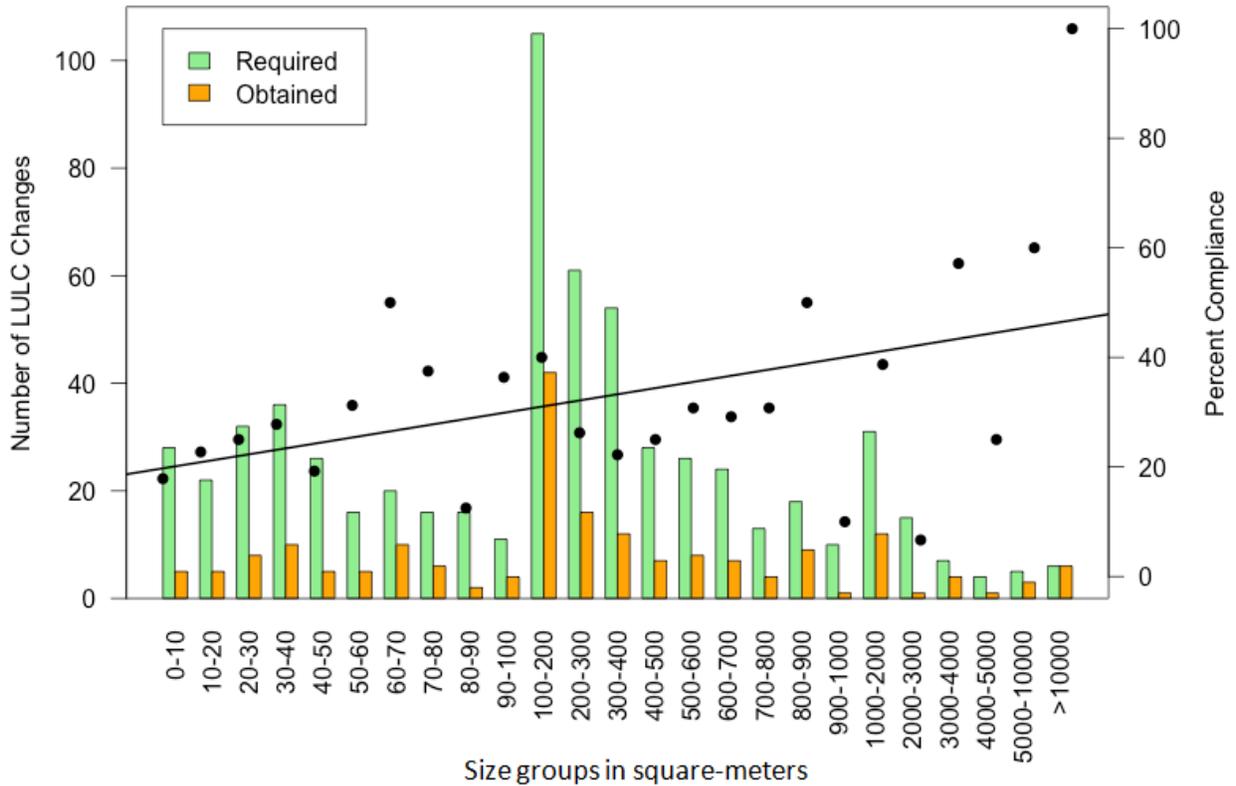


Figure 18. 2007-2012 land cover change by area from forest to any other land cover type.

### 3.2.5 Compliance in regulatory stream buffers

As at the watershed scale, compliance in regulatory stream buffers is generally higher when based on area versus number of land cover changes, although there is also considerable variability among watersheds (Figure 19). Regardless, on an actual area basis, noncompliant land cover change in regulatory stream buffers was not large (~ 1.1 ha total across six treatment watersheds), ranging from less than 0.1 ha to about 0.2 ha for all watersheds except Taylor, where noncompliant actions accounted for about 0.4 ha of land cover change. As there are about 53 km (33 miles) of stream and 415 km<sup>2</sup> (1,025 acres) of regulatory buffer in the treatment watersheds (see Table 7), the actual cumulative area of noncompliant change over 5 years was a very small (0.2 percent) proportion of the buffer area.

Of the approximately 1.7 ha of permitted land cover change that occurred in regulatory stream buffers (Figure 19), the Cherry Creek Tributary and Weiss Creek watersheds accounted for the large majority with 1 ha and 0.6 ha of land cover change, respectively. In the Cherry Creek Tributary 100 percent of the permitted land cover change in the regulatory buffer was under a WDNR-issued FPA permit, whereas in Weiss Creek 80 percent was estimated to have been done under an FPA. These large amounts of FPA-permitted change indicate the local influence of a State-wide forest harvest regulatory system that the County does not control except where land conversion is declared.

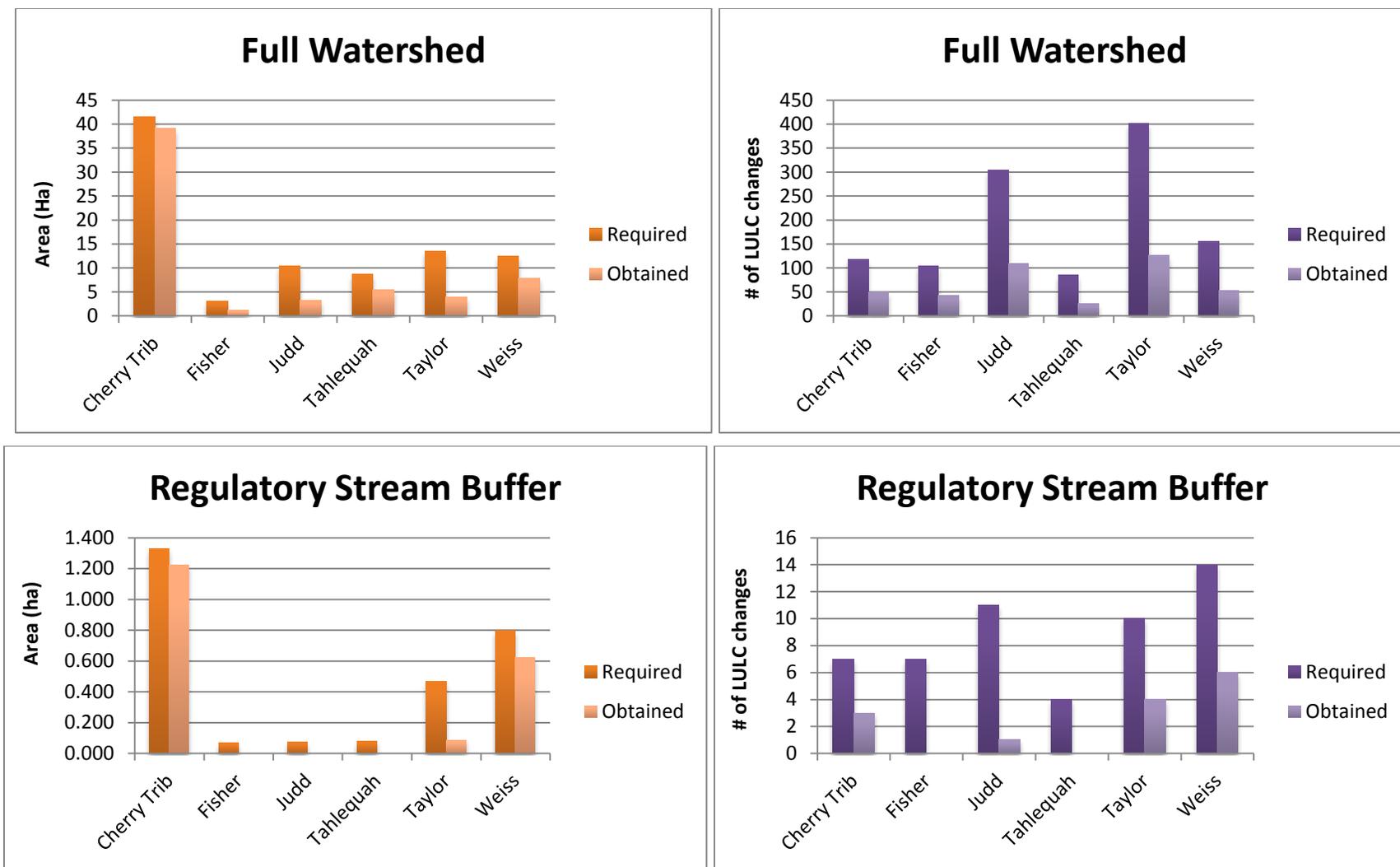


Figure 19. Compliance organized by area (ha) of land cover change (left, orange) and number of land cover changes (right, purple) for full watershed (top) and regulatory stream buffers (bottom).

Over the photo years assessed (a span of 5 years), detailed review of photos revealed that the small amount of noncompliant land cover change in regulatory stream buffers was the result of minor shrub clearing, construction of a small amount of unpaved road, and four small (~9 to 37 m<sup>2</sup>) structures, including one yurt, one small (~10 m<sup>2</sup>) farm shed, and two small features that may have been temporary structures such as trailers.

Although the area of noncompliant change in regulatory stream buffers was small, compliance rate in buffers was lower than at the watershed scale in five of six watersheds based on both number and area of noncompliant land cover changes (Figure 20). The three Vashon Island watersheds (Judd, Fisher, and Tahlequah) had very small amounts of land cover change in their regulatory stream buffers, and their compliance rates were also very low (< 5 percent).

For further perspective, noncompliant land cover change was generally less than 0.5 percent of the total watershed area, whereas at the regulatory stream buffer scale noncompliant land cover change was generally less than 0.05 percent of the total watershed area (Figure 21).

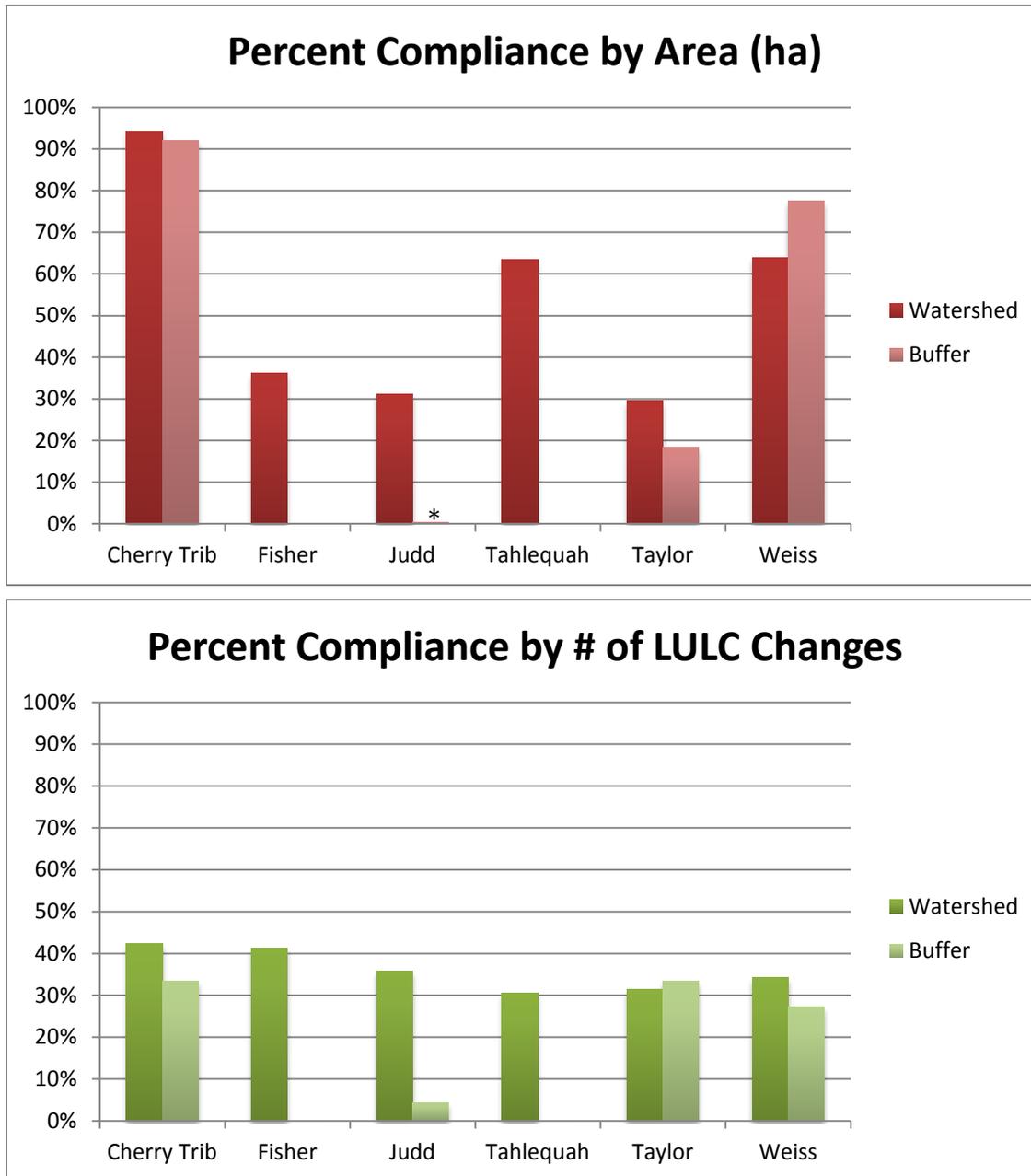


Figure 20. Compliance by number and area of land cover changes for treatment watersheds for full watershed and the regulatory stream buffer scales that may have required a permit (\* = 0.002 ha, or 0.3 percent, which is too small to be visible on the graph).

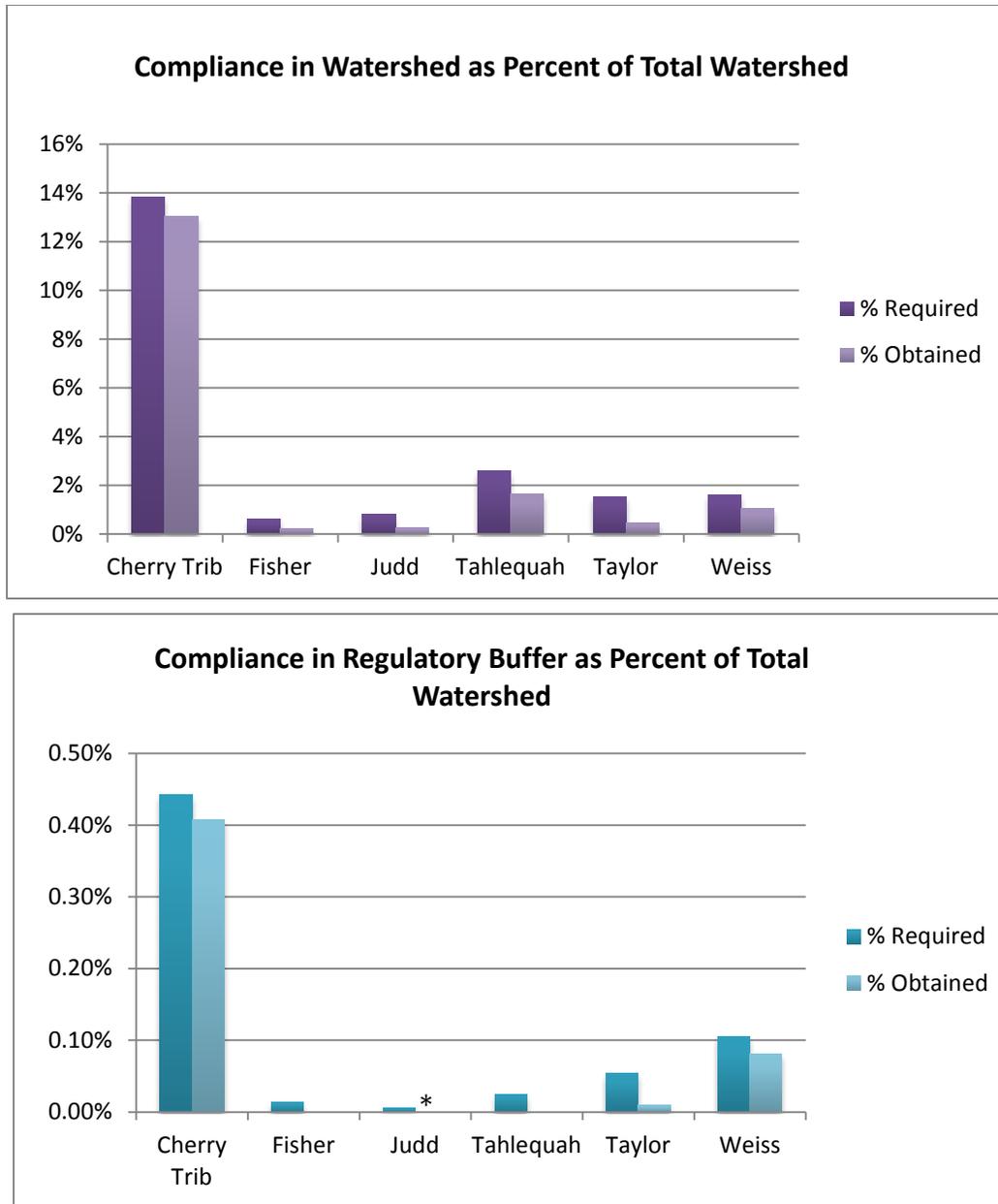


Figure 21. Compliance for treatment watersheds and their regulatory stream buffers as a proportion of their respective watershed areas (\* = 0.00002 percent).

### 3.2.6 Potential Effect of Hazard Tree Removal on Compliance

The low compliance rates for forest loss led to examination of whether hazard tree management might be a factor that skews results. Removal of hazard trees and invasive blackberries are two actions that do not require permits, provided they are not done in a critical area or regulatory buffer and, for blackberry removal, only when done by hand (i.e., no heavy machinery). Even in high-resolution (0.3 m) orthophotos, blackberries were difficult to reliably detect from other shrubs, and so the amount of invasive blackberry removal was not assessed. The maximum potential amount of hazard tree removal was

estimated by assessing the amount of forest loss near buildings that could be hit by falling trees. Depending on site conditions, a distance of 46 m (150 feet) is roughly equivalent to a site potential tree height in King County (King County 2012) and therefore was used as a maximal distance within which landowners might be expected to remove hazard trees around buildings.

All forest cover within 46 m of a building that was changed to something other than forest during the 2007-2012 timeframe was calculated. Table 23 summarizes the maximum area of forest that may have been removed as “hazard.” The results were highly variable among the 6 treatment watersheds. Forest removal within 46 m of a building ranged between 70 and 80 percent of the total forest removed for Fisher, Judd, and Taylor creek watersheds, around 20 percent for Tahlequah and Weiss creek watersheds, and about 4 percent for Cherry Creek Tributary watershed. These are almost certainly overestimates as there was no way to know with absolute certainty why trees were removed or even if they were removed by human or natural action without more information. Still, across all treatment watersheds it appears that a potentially large percentage (24.7 percent) of forest cover converted to some other land cover could have been compliant if done for hazard tree management.

**Table 23. Total area (ha) of forest that could have been a hazard (i.e., within 46 m of a building) and that was changed to something other than forest between 2007 to 2012.**

<b>Treatment Watershed</b>	<b>Total (ha)</b>	<b>Area Potential Hazard Trees (ha)</b>	<b>Percent</b>
Cherry Trib.	40.2	1.4	3.6
Fisher	2.4	1.7	72.8
Judd	6.3	4.7	74.8
Tahlequah	7.4	1.5	20.2
Taylor	8.6	6.8	79.2
Weiss	8.5	2.0	23.2
Total	73.4	18.1	24.7

### 3.3 Environmental Response

As described in the Methods (Section 2.0), twelve ERVs were assessed. The study design included six treatment and three control sites. The statistical comparisons looked at change in condition and compared the amount of change observed in the treatment sites (which were expected to change, but did not) and the reference sites (which were not expected to change). Change in condition was evaluated for each ERV between the start and end of the

project. In this way, each watershed was compared to itself over time. The treatment and reference sites were compared in terms of their change over time for each ERV.

Of the twelve ERVs, HPCs, baseflow conductivity, RAV @ MAD, and BIBI were considered the primary measures of change in hydrology, water quality, physical complexity, and biology, respectively (see Section 2.3 for rationale for choosing ERVs). Additional water-quality metrics, 7DADMAX and mean annual temperature at baseflow, were added because temperature is a fundamental property of water, relatively inexpensive to measure, and could serve as an additional ERV. The remaining five ERVs measured large wood and thalweg, pool, and substrate conditions. They were included to complement and, potentially, help interpret change in the highly precise RAV @ MAD metric while also providing additional measures of physical change in the study reaches.

Note that in this section, box plots in Figure 22 through Figure 30 are arranged in order of least to most developed. Boxes in the box plots show one standard deviation around the mean. The bar in the box is the median, and unless otherwise noted, values presented in the text are the means.

### 3.3.1 Hydrology

HPCs increase with developed land covers and higher HPCs indicate a more developed watershed condition. Across all nine watersheds and five years of study, the average annual HPC was 10.6, ranging from 7.25 for Webster, a fully forested reference watershed, to about 13.75 for Taylor Creek, the most developed treatment watershed (Figure 22). Notably, the average HPC for South Seidel, a reference watershed, was 11.25, which was higher than the annual HPCs for four of the six partially developed treatment watersheds; only Weiss (11.75 HPC) and Taylor had higher annual HPCs than South Seidel. High synchrony (responses move as a group over time) among watersheds is evident for High Pulse Counts; this synchrony indicates a cross-watershed influence of precipitation. In 2011, Taylor Creek had the highest single-year pulse count (19). In 2009, Webster Creek had the lowest annual HPC (3).

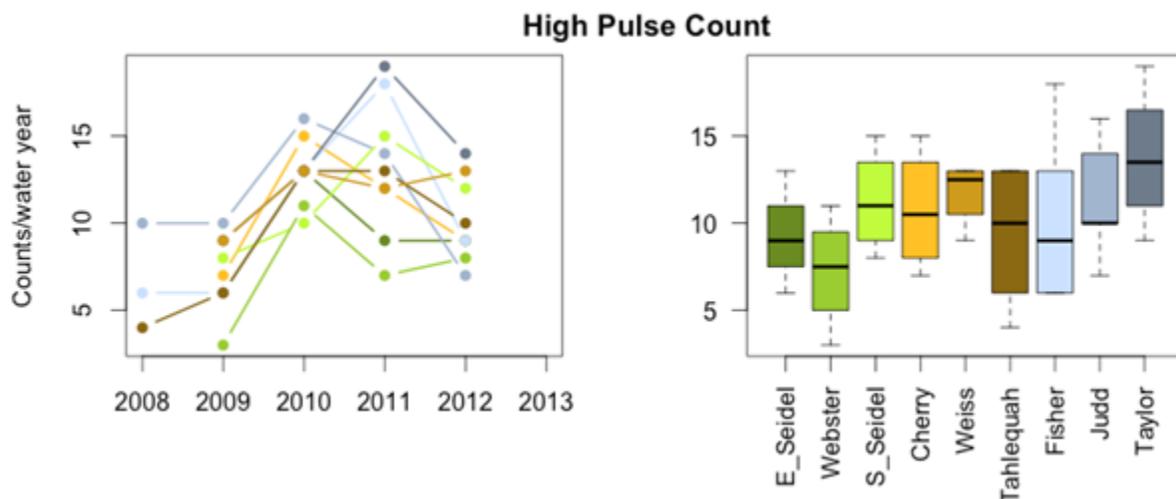
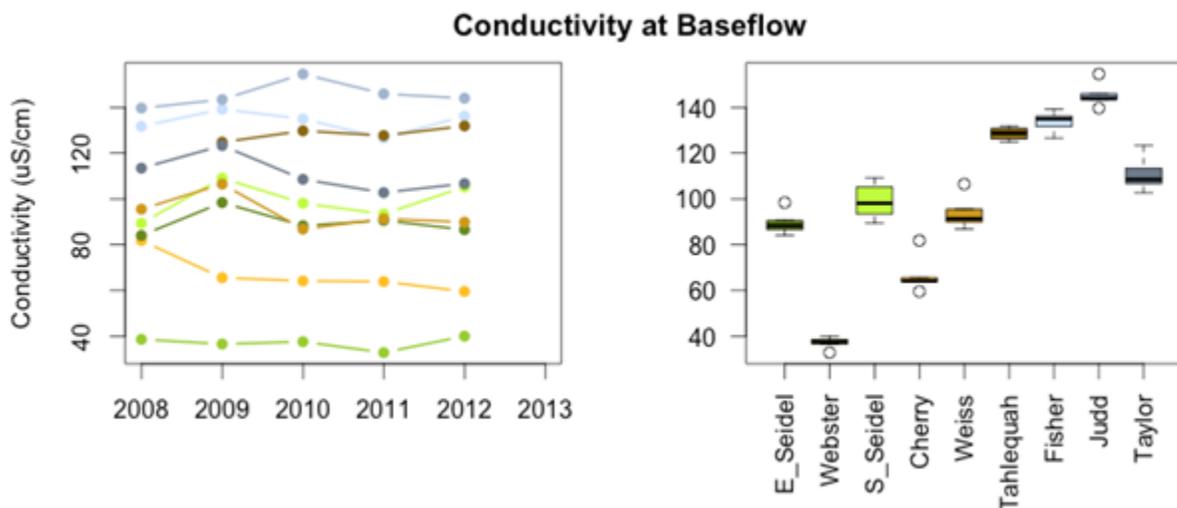


Figure 22. Hydrology environmental response variable: High Pulse Counts. Change and variation in high pulse counts over time and by watershed.

### 3.3.2 Water Quality

Conductivity at baseflow averaged 100.6  $\mu\text{S}/\text{cm}$  across all watersheds and years, ranging from 37.1  $\mu\text{S}/\text{cm}$  in Webster Creek to 145.5  $\mu\text{S}/\text{cm}$  in Judd Creek (Figure 23). As with stream temperature (see below), Vashon Island streams exhibited low variability in conductivity, varying only 17  $\mu\text{S}/\text{cm}$  between Tahlequah Creek (128.5  $\mu\text{S}/\text{cm}$ ) and Judd Creek. Low variability in conductivity among Vashon Island streams may reflect a common aquifer feeding these streams and driving ground and surface water dynamics (E. Ferguson, pers. comm., October 10, 2013). In contrast to its high spatial variability, conductivity varied little over time. It was highest (154.6  $\mu\text{S}/\text{cm}$ ) in 2010 in Judd Creek and lowest (32.8  $\mu\text{S}/\text{cm}$ ) in 2011 in Webster Creek.



**Figure 23. Water quality environmental response variable: Conductivity. Change and variation in conductivity at baseflow over time and by watershed.**

Stream temperature was characterized for 7DADMax and the average annual temperature at baseflow. The 7DADMax averaged 16.4  $^{\circ}\text{C}$  across all watersheds and years. It was coldest in East Seidel (14.2  $^{\circ}\text{C}$ ) and highest (18.1  $^{\circ}\text{C}$ ) in Cherry Creek Tributary. It varied considerably among reference streams, ranging from the aforementioned East Seidel to 17.1  $^{\circ}\text{C}$  and 18.0  $^{\circ}\text{C}$  for Webster and South Seidel, respectively. Webster and South Seidel had higher average 7DADMax values than all of the treatment watersheds except Cherry Creek Tributary.

The average annual baseflow temperature was 9.5  $^{\circ}\text{C}$  across all watersheds and years. The reference streams had both the coldest and warmest average annual baseflow temperatures, with values ranging from 8.1  $^{\circ}\text{C}$  in Webster Creek to 10.2  $^{\circ}\text{C}$  in South Seidel. Among treatment watersheds, Tahlequah had the lowest average annual baseflow temperature at 9.2  $^{\circ}\text{C}$ , and Weiss had the highest at 10.0  $^{\circ}\text{C}$ . The three Vashon Island streams exhibited high similarity in that they had the lowest temperatures among treatment watersheds and were generally colder than the reference watersheds. These

similarities provide further evidence, along with conductivity, that the Vashon Island watersheds are heavily influenced by groundwater.

Synchrony across years and among watersheds is evident for both 7DADMax (Figure 24) and average annual temperature at baseflow (Figure 24). In contrast to conductivity, temperature metrics varied considerably among years; this variability indicates a cross-watershed influence of air temperature. The 7DADMax was highest (20.1 °C) in 2009 in Webster Creek and lowest (13.2 °C) in 2012 in East Seidel, both of which are undeveloped reference streams. Notably, although East Seidel 7DADMax was in synchrony with other watersheds for most (3 out of 4) years, it was colder in 2012 whereas the other eight watersheds were warmer.

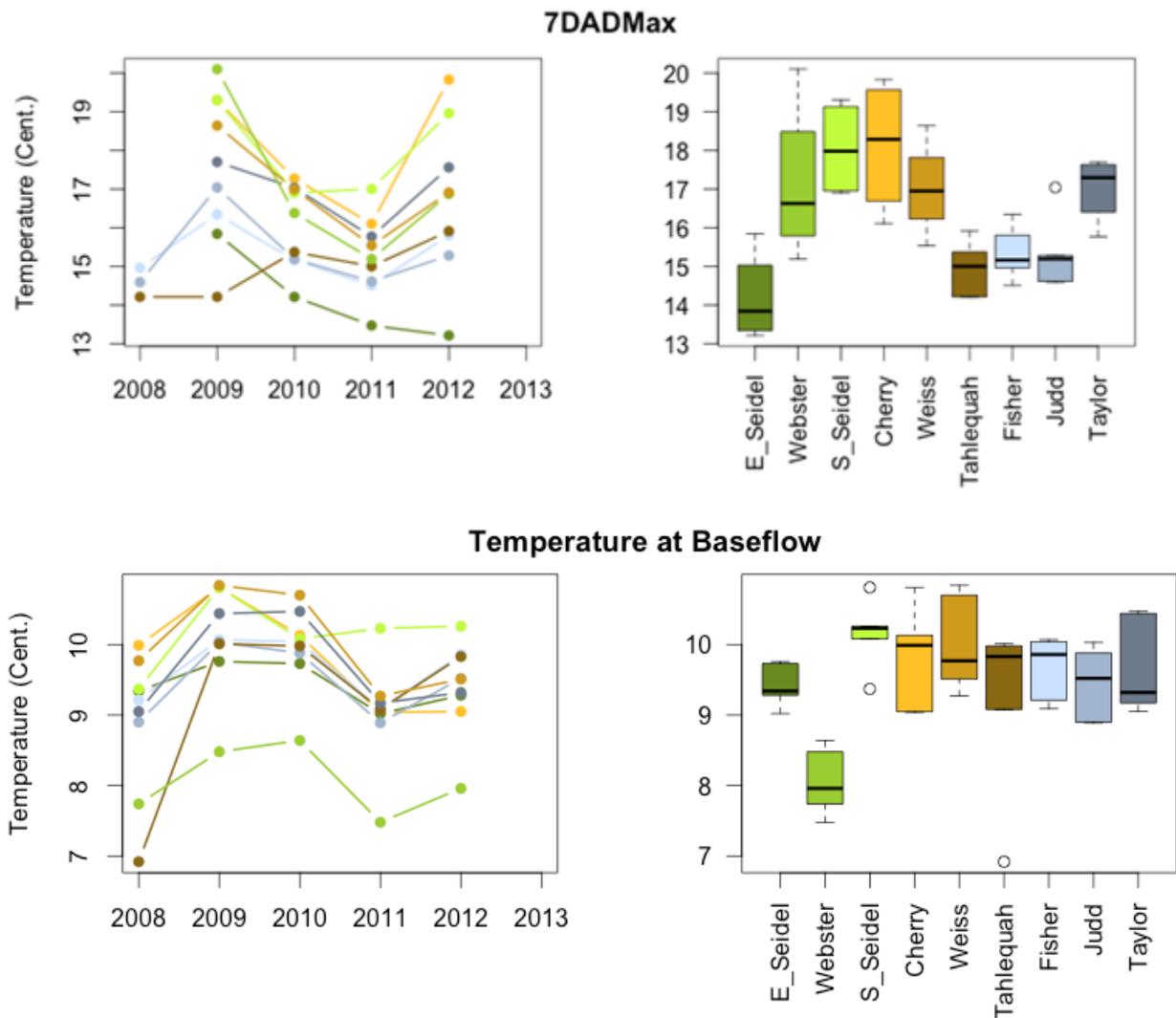


Figure 24. Water quality environmental response variable: 7DADMax and average annual water temperature at baseflow. Change and variation over time and by watershed.

### 3.3.3 Channel Complexity

Of the channel complexity metrics, the project’s key metric for measuring change was the highly precise RAV @ MAD, which showed no strong trend over time or among watersheds. An effect of stream size on RAV @ MAD may be present, however. Averaged over the study period by watershed, velocities were most similar among the smallest (E and S Seidel, Tahlequah and Cherry Tributary) streams, where they ranged from 8.9 m/min for Tahlequah to 12.8 m/min for Cherry Creek Tributary, and the largest (Webster, Weiss, Taylor, and Judd) streams, where they ranged from 17.9 m/min for Taylor to 24.1 m/min for Webster (Figure 25). Fisher, an intermediate-sized stream, was also intermediate (13.3 m/min) in its RAV @ MAD. Among the remaining physical complexity variables, few reference-treatment, stream size, or location trends or influences are obvious with possible exception of synchrony in large wood and thalweg length measurements.

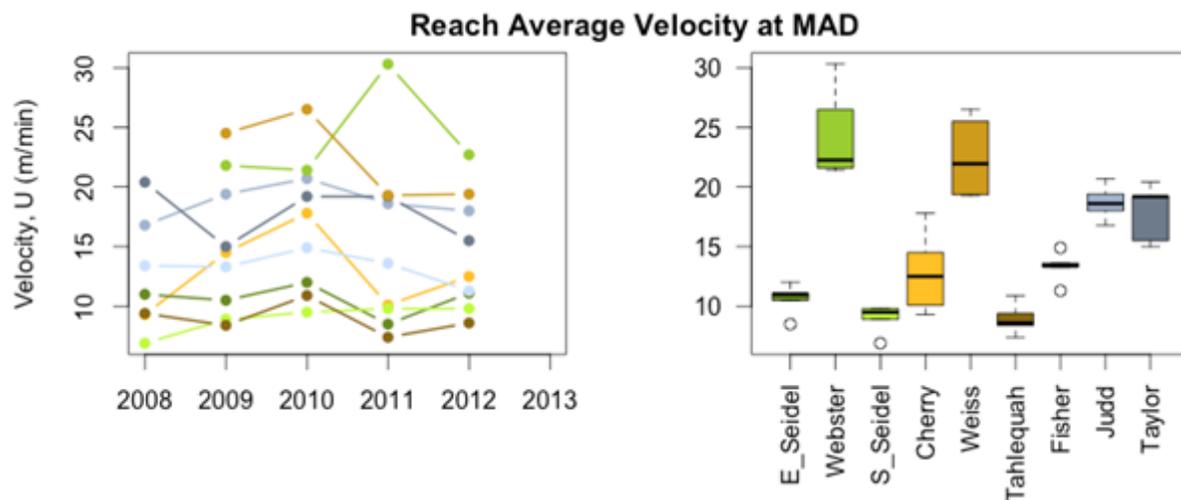


Figure 25. Channel complexity environmental response variable: RAV@MAD. Change and variation in reach-averaged velocities at mean annual discharge variables over time and by watershed.

Of the two thalweg-based measures of change (Figure 26), the coefficient of variation of thalweg depth (CVTD) appears to have declined but variability also increased, thus reducing confidence that the changes between first (2009) and last (2013) measurements was a trend. Strong synchrony in change observed among thalweg lengths between the first (2009) and second (2010) measurements may reflect a systematic change in how measurements were made. In 2009, a measuring tape was strung for a relatively long but variable distance following the thalweg as measurements were made. In 2010 and thereafter, thalweg lengths were measured in 10 m increments in an effort to be more precise; this change in method may have created a systematic bias toward increasing thalweg lengths.

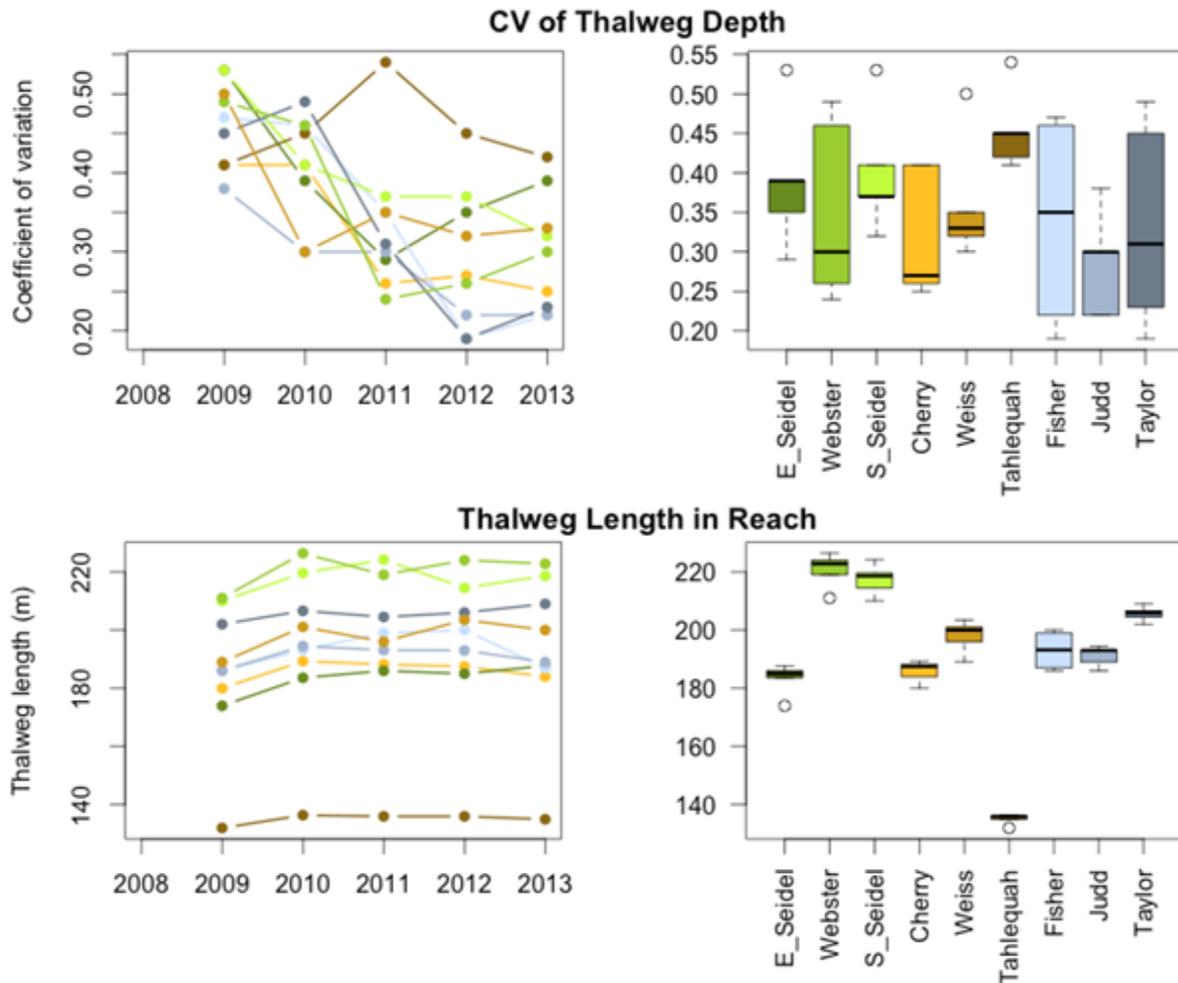


Figure 26. Channel complexity environmental response variables: Thalweg depth variability and length. Change in the coefficient of variation (CV) in thalweg depth and thalweg length over time and by watershed.

Coefficient of variation of thalweg depths, CVTD, and percent silt and sand, S&S (Figure 27), and average residual pool depths (RPDs) all appear to have changed between first (2009) and last (2013) measurements: CVTD and percent S&S declined while RPDs increased. However, the variability over time of these measurements also changed (CVTD and RPD increased, whereas variability in percent S&S decreased). This change in variability over time reduces confidence that the changes between first (2009) and last (2013) measurements were a statistically significant trend. No strong synchrony over time or effect of location is apparent in CVTD, percent S&S, or RPD measurements.

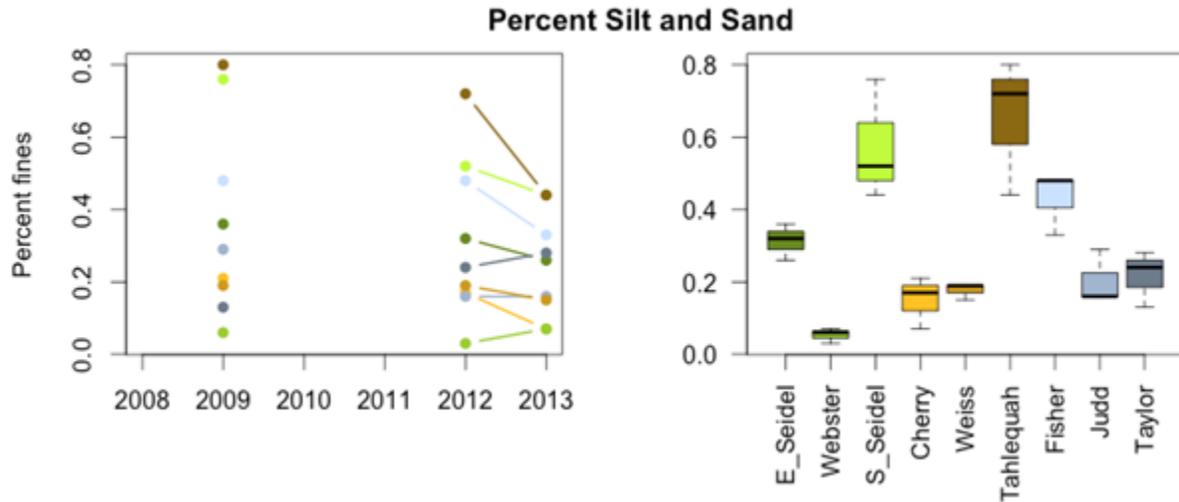


Figure 27. Channel complexity environmental response variable: percent sand and silt. Change and variation in percent sand and silt over time and by watershed.variable.

Percent pool length of thalweg showed little synchrony or net change over time (Figure 28). Among watersheds there appears to be similarity among (a) reference sites (E and S Seidel and Webster), where median values ranged between about 5 and 15 percent, (b) Vashon Island sites where median value ranged between 20 and 25 percent, and (c) Weiss and Cherry Creek tributary with median values ranging between about 8 and 12 percent pool length of thalweg.

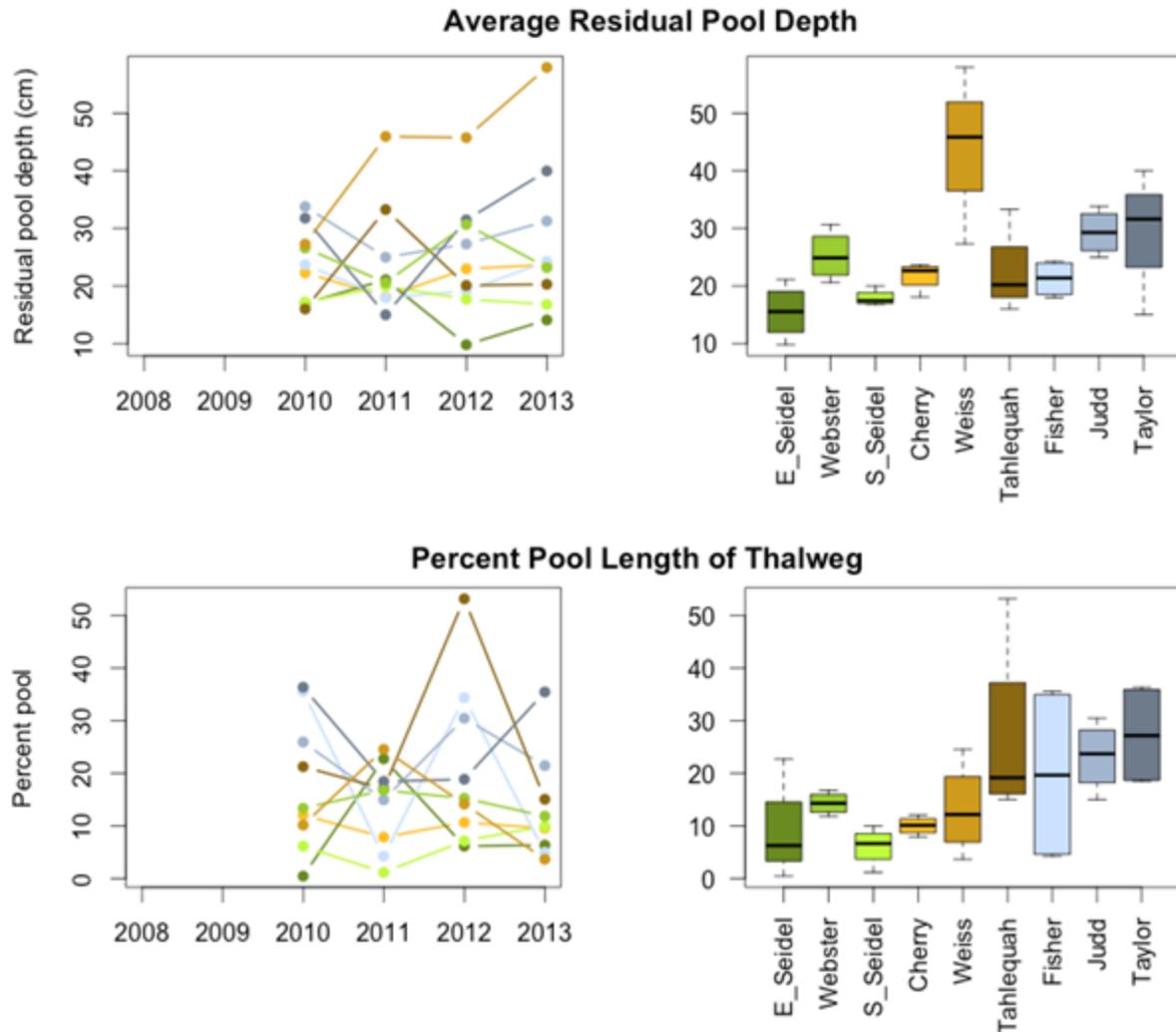


Figure 28. Channel complexity environmental response variable: Pools. Change and variation in residual pool depth and percent pool along thalweg over time and by watershed.

Large wood counts averaged 21.1 pcs/100 m and varied from 9.3 pcs/100 m in Tahlequah to about 32.2 pcs/100 m in E Seidel (Figure 29). Although overlap was high among all watersheds, the reference streams had consistently higher median counts, ranging from 25.1 to 32.2 pcs/100m for Webster and E Seidel, respectively. In treatment watersheds, large wood counts ranged from 9.3 to 27.1 pcs/100m for Tahlequah and Taylor, respectively. Although historic data are not available, the low levels of wood in Vashon Island streams may reflect a common history of initial logging and subsequent development for agriculture *ca* late 1800s/early 1900s.

High synchrony of large wood counts is apparent among 2009, 2011, and 2012, where counts systematically increased between 2009 and 2011 and then systematically declined between 2011 and 2012. In December 2010, a large storm event occurred over the study watersheds and may be the primary cause of synchronous decline (loss) of large wood

among study sites. In Judd Creek, for example, the December 2010 storm generated the highest hourly flow (10 m<sup>3</sup>/s) on record for that site<sup>21</sup>. This occurrence indicates the importance of understanding the effect of singular events for variables like large wood that may be subject to rapid loss (flushing) or gain (tree fall) resulting from periodic events such as large rain and wind storms.

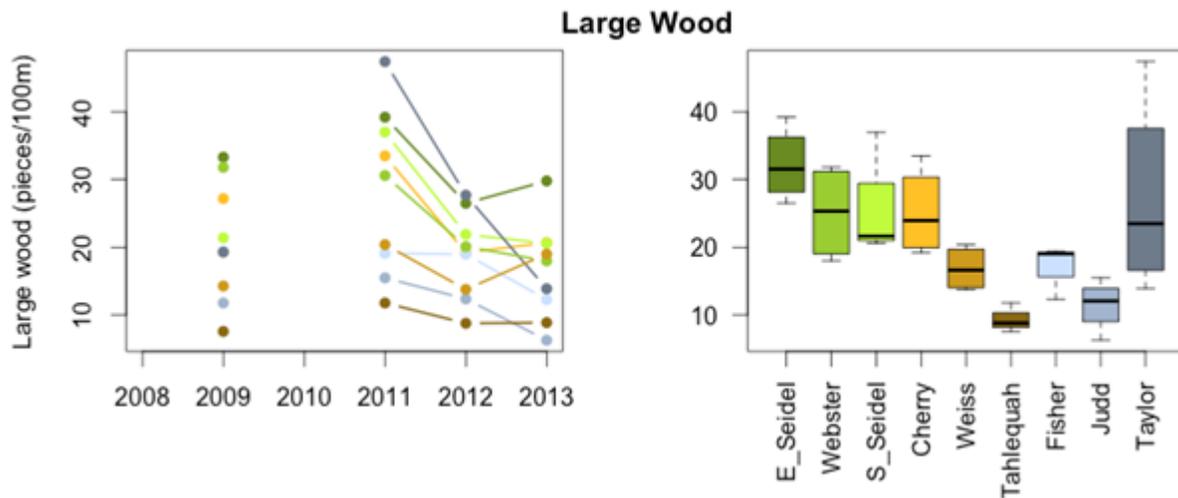


Figure 29. Channel complexity environmental response variable: Large wood. Change and variation in large wood counts over time and by watershed.

### 3.3.4 Biology

BIBI scores averaged 33.4 across all watersheds and years but were highly variable and showed no trends over time (Figure 30). The lack of cross-watershed spatial trend suggests localized (site or reach) factors may be driving BIBI more than watershed factors. For example, reference sites had the best (Webster, average BIBI = 41.7) and worst (S Seidel, average BIBI = 22.3) scores. Weiss and Cherry Tributary Creeks, which are adjacent to each other, had very high and similar average BIBI scores (37.2 and 39.6, respectively), and the Vashon Island streams (Judd, Fisher, and Tahlequah) had moderate agreement amongst their scores. Notably, Taylor Creek, the most developed of the 9 watersheds, had the second highest (best) average BIBI score (42).

At the start of the study there was a concern that the salt used for tracers would affect the benthic invertebrate community in subsequent years. The lack of change in BIBI over time suggests that the small amounts of salt used as a tracer probably did not influence benthic invertebrate communities.

<sup>21</sup> King County Hydrologic Information Center: <http://green.kingcounty.gov/wlr/waterres/hydrology/>

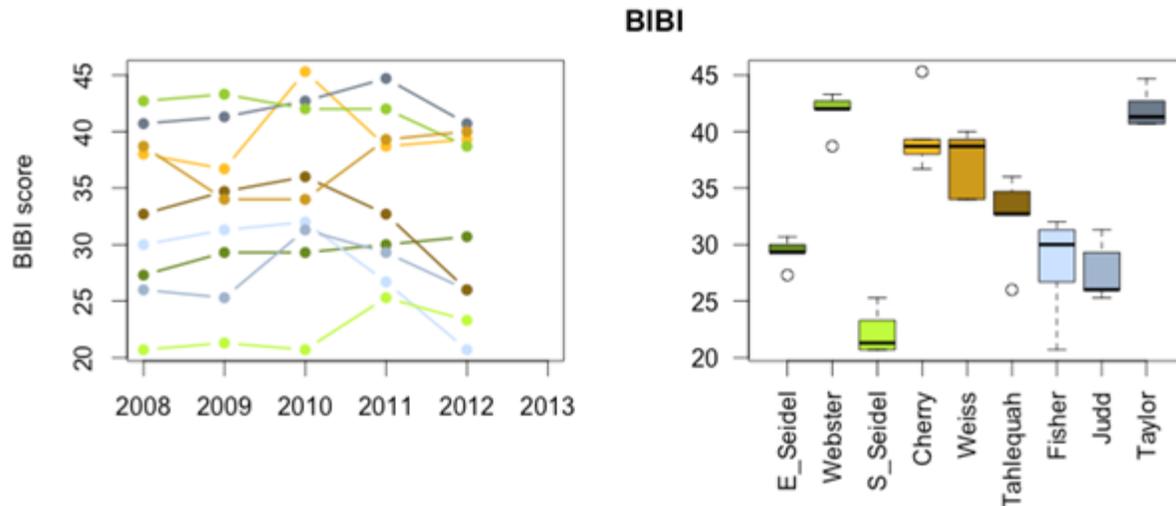


Figure 30. Biological environmental response variable: BIBI. Change and variation in BIBI over time and by watershed. Note that BIBI scores can range from 10 to 50.

### 3.3.5 Summary of observed changes in ERVs

In summary, none of the four primary ERVs (HPC, Conductivity, RAV @ MAD, or BIBI) used to assess change in hydrology, water quality, channel physical complexity, and biology, respectively, changed significantly. Of the eight other ERVs, only change in thalweg length ( $p = 0.02$ ) and percent pool length of thalweg ( $p = 0.06$ ) showed significant or near-significant change (Table 24). Both metrics increased, the opposite of what would have been expected if regulations had not been effective (see Table 10). Confidence in these two variables being able to detect change is low because of variability and lack of precision among observers in the field and, for thalweg length, a limited range of potential response. As noted earlier, thalweg length may have been affected by a change in measurement technique. Percent pool along thalweg is subject to high observer bias as it can be difficult for observers to accurately and precisely identify the start and stop of a pool. As a result, although their change was significant, confidence is low in the statistically significant difference detected between their start and end conditions.

The number of categories that can potentially be detected summarizes the relationship between the size of the significant difference and range of possible values for each variable (Table 24). The Minimum Detectable Difference (MDD) divided in to the range of possible values provides an estimate of the number of categories the response variable can potentially discern. Stated another way, a response variable that can potentially detect more categories is likely more sensitive to change over time. Therefore, considering only data collected for this project, baseflow conductivity and large wood are the most sensitive measures for comparing treatment and reference sites. Four metrics (high pulse count, RAV@ MAD, percent pool length of thalweg, and BIBI) were rated as having moderate sensitivity to detect difference in the response of treatment and reference sites.

**Table 24. Response variables and metrics, expected response to disturbance if regulations are ineffective, mean change for reference and treatment sites, observed difference in change for reference and test sites, p-value for T-test comparing difference in the change for reference and treatment sites, minimum detectable difference (MDD) between reference and treatment sites, possible range observed within the region, approximate number of categories that could be detected and the relative sensitivity of the metric. Change is measured as the difference between the value observed during the most recent year and the earliest year of sampling.**

Response variable	Metric	Expected Response in Treatment sites	Mean change for Reference sites	Mean change for Treatment sites	Difference in change between Reference and Treatment sites	p-value (T-test)	MDD	Possible range	Number of categories	Sensitivity	Min.	Max.
Hydrology	High Pulse Count	Increase	4.0	2.5	1.5	0.29	4.99	18	3.6	Moderate	2 <sup>¥</sup>	20
Water Quality	Conductivity at Baseflow	Increase	6.6	-3.1	9.7	0.19	20.47	572	27.9	High	28 <sup>€</sup>	600
	7DADMax	Increase	-2.1	-0.3	-1.7	0.18	2.79	9	3.2	Low	13 <sup>*</sup>	22
	Average annual temperature at baseflow	Increase	-0.12	0.78	-0.90	0.21	2.1	4	2	Low	7	11
Complexity	Reach Average Velocity at MAD	Increase	1.3	-1.4	2.7	0.13	5.80	25	4.3	Moderate	5 <sup>¥</sup>	30
	Thalweg length in reach	Decrease	11.4	4.8	6.5	0.02	6.69	NA	NA	NA	NA	NA
	CV of Thalweg depth	Decrease	-0.2	-0.2	0.0	0.61	0.16	0.35	2.2	Low	0.2 <sup>¥</sup>	0.55
	Large wood	Decrease	-6.0	-3.1	-3.0	0.55	11.04	90	8.2	High	10 <sup>€</sup>	100
	% Silt + sand	Increase	-0.1	-0.1	0.0	0.84	0.33	0.9	2.7	Low	0.05 <sup>€</sup>	0.95
	% Pool length of thalweg	Decrease	2.7	-8.5	11.3	0.06	19.02	100	5.3	Moderate	0 <sup>€</sup>	100
	Average residual pool depth	Decrease	-2.2	7.1	-9.3	0.12	20.53	50	2.4	Low	10 <sup>¥</sup>	60
Biology	BIBI	Decrease	0.7	-2.2	2.9	0.38	8.88	40	4.5	Moderate	10	50

<sup>€</sup> Source for min. and max. = Merritt and Hartman (2012)

<sup>\*</sup> Source for min and max. = Mantua et al. (2009)

<sup>¥</sup> Source for min and max. = This dataset

### 3.3.6 Relationship of the HCI to land cover and ERVs

The project average HCIs for the six treatment watersheds and their regulatory stream buffers were correlated with project averages of impervious and forest land covers and ERVs to assess how well the HCI predicts other conditions (Table 25). The sample size used here (six treatment watersheds) does not include the three reference watersheds because comparable regulatory stream buffer HCIs for reference watersheds were not available at time of writing.

Of the two land cover classes with divergent hydrologic effect, percent impervious ( $r = 0.94$ ,  $p < 0.01$ ) and percent forest ( $r = -0.91$ ;  $p < 0.01$ ) were both significantly ( $p < 0.05$ ) correlated with watershed HCI. Conversely, neither was significantly correlated with regulatory stream buffer HCI. HCIs for watershed and regulatory stream buffers were close but not significantly correlated with each other ( $r = 0.71$ ,  $p = 0.06$ ).

HPCs were significantly correlated with HCIs for treatment watersheds ( $r = 0.88$ ;  $p = 0.01$ ) and their regulatory stream buffers ( $r = 0.96$ ;  $p < 0.01$ ). Of the remaining ERVs, the 7DADMax was significantly correlated with watershed HCI ( $r = 0.94$ ;  $p < 0.01$ ) while RAV@MAD ( $r = 0.85$ ;  $p = 0.02$ ) and percent sand and silt ( $r = -0.78$ ;  $p = 0.03$ ) were significantly correlated with regulatory stream buffer HCIs.

**Table 25. Correlations of average watershed and regulatory stream buffer HCIs with averages for impervious and forest land covers and project ERVs for six treatment watersheds. (Correlation of HCI with reach thalweg length is not show as the length was artificially imposed.)**

	Average Watershed HCI		Average Regulatory Stream Buffer HCI	
	r	p-value	r	p-value
Watershed Percent Impervious	0.94	<0.01	0.68	0.07
Watershed Percent Forest	-0.91	<0.01	-0.58	0.12
Average Watershed HCI	-	-	0.71	0.06
Average Regulatory Stream Buffer HCI	0.71	0.06	-	-
Ratio of watershed and buffer HCIs	0.05	0.46	-0.66	0.08
High Pulse Count	0.88	0.01	0.96	<0.01
Average Annual Temp at Baseflow	0.20	0.36	0.6	0.10
Conductivity at Baseflow	0.08	0.44	-0.24	0.33
Percent Pool Length of Thalweg	0.44	0.19	-0.03	0.96
CV of Thalweg Depth	-0.44	0.19	-0.55	0.13
Average Velocity at MAD	0.36	0.24	0.85	0.02
Average Residual Pool Depth	0.08	0.44	0.68	0.07
Large Wood per 100m	0.64	0.09	0.55	0.13
Percent Silt and Sand	-0.36	0.24	-0.78	0.03
BIBI	0.42	0.21	0.56	0.12
X7DADMax	0.94	<0.01	0.68	0.07

### 3.3.7 Ordination of watersheds

Ordination is an exploratory technique that allows for detection of similarities among watersheds and, potentially, grouping of them according to their response to land cover change. The results of applying ordination to the study watersheds indicate systematic influences of location, watershed condition, and stream size in their response to land cover change (Figure 31). It suggests that change in land cover and regulatory effectiveness are not the only determinant in how watersheds respond.

Groupings among watersheds appear attributable to a longitudinal (east-west) gradient that coincides with effects of location (i.e., Vashon Island vs. mainland) and the Puget Lowland vs. Cascades Ecoregions (Figure 31b), as well as effects of reference vs. treatment (Figure 31c), and large vs. small stream size (Figure 31d). There is a high degree of coherence in the arrangement of the watersheds in ordination space and their real-world configuration. For example, the Vashon Island streams group together and are arrayed in much the same configuration as they exist on the island. Similarly, the East and South Seidel watersheds are in close proximity to each other, both in the real-world and

ordination space. Also, Weiss, Cherry Tributary, and Taylor watersheds are close to each other and physically situated close to Webster in real-world and ordination space. Yet the Webster Creek watershed is distinct and apart from the others in the ordination possibly because of its location in the Cascades Ecoregion. The Cascades Ecoregion is different in many respects from the PLE, including being steeper, wetter, and less influenced by glacial till and outwash geology.

A difference in condition between reference and treatment sites appears to exist (Figure 31c) and therefore indicate reference and treatment sites were not the same condition at the start of monitoring. The difference between the groups may provide a potential basis for adjusting expectations for response between reference and treatment watersheds in future studies. Notably, the group containing the reference sites also includes one treatment watershed, the Cherry Creek Tributary; this arrangement makes sense because while the Cherry Creek Tributary is one of the two least developed along with Tahlequah, it has a shorter and less extensive history of land development as Tahlequah.

At the scale of the relatively small headwater streams used for this study, there appears to be a strong association with stream size in watershed response (Figure 31d).

Ordination reveals relationships among ERVs that, for the most part, are highly consistent with what would be expected (e.g., velocity and fines as well as percent pools and large wood are in strong opposition to each other in ordination space). Notably, High Pulse Count is centrally located in the ordination. This central location suggests an underlying but weak association of HPCs with other ERVs. It may further indicate that HPCs are integrators but not strong determinants of the ERVs.

Finally, although the dataset is relatively small, confidence in ordination results is increased because of their coherence with the real-world (it did what was expected) and because it is supported by multiple (3 to 5) years of underlying environmental response data.

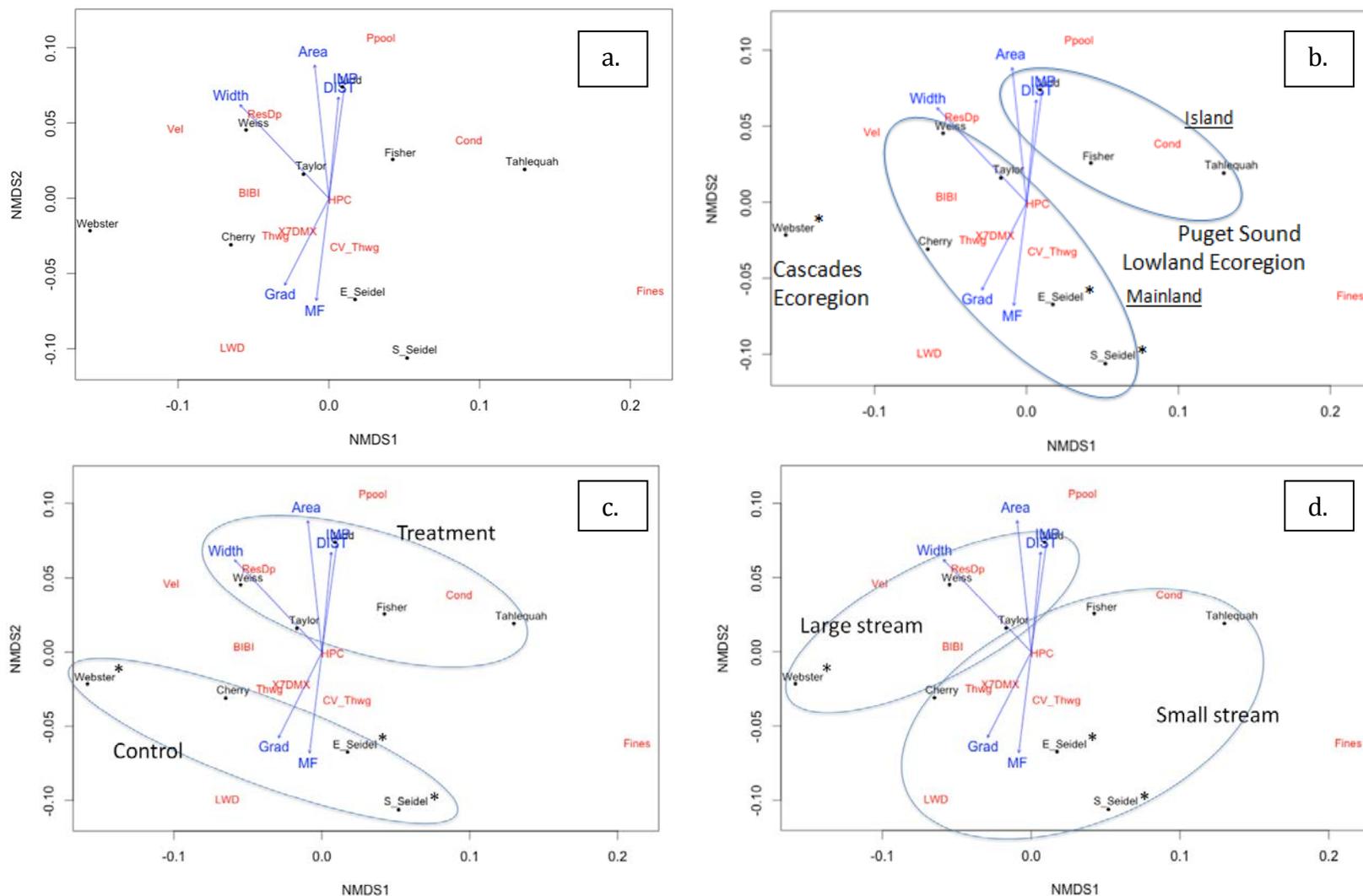


Figure 31. Ordination of 11 response variables (red) for 9 watersheds (black) averaged over the years of the project. Additional variables related to land cover and physical features (blue) were fitted post-hoc to the ordination, where (a) is uninterpreted scatter of all points, and (b), (c), and (d) are interpretations indicating potential influences. MF = undisturbed pervious, i.e., forest; Dist = disturbed pervious, i.e., combination of shrub, pasture and grass, and IMP = impervious, i.e., combination of buildings, pavement and paved and unpaved roads; Width = study reach active channel width; grad = study reach gradient; area = watershed area upstream of study reach.

## 4.0. DISCUSSION

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Environmental effectiveness of land use regulations and regulatory compliance are issues of high importance for recovery of endangered salmon and ecosystem health in the Puget Sound region (Washington State 2010). Despite this importance, basic scientific information to inform management and policy on these issues was lacking. This study addresses that information gap while providing additional detailed information on relationships between the ecology and land use in rural watersheds.

Although a significant amount of information was gathered during the course of this study, this discussion is limited to:

- Observed and projected regulatory effectiveness
- Permitting and Compliance
- Relevance to other studies
- Assessment framework utility, applicability, and potential improvements
- Habitat restoration implications

### 4.1 Observed and Projected Regulatory Effectiveness

No significant environmental changes were observed over the course of the project. However, an extreme and unforeseen global economic recession that started about the same time as this study (*ca.* 2007/2008) resulted in a steep drop-off in development activity (see Figure 15). As a result, the amount of land cover change, *i.e.*, “treatment,” during the project timeframe was small and land cover change during the project timeframe was insufficient as a “stand alone” test from which to draw a strong inference about regulatory effectiveness. In other words, the level of treatment was not enough for a severe test of the CAO.

Because of the lack of land cover change, the study used scenarios to provide historic context and assess the potential for future change under a hypothetical FBO. Future scenarios were used to estimate the effect of FBO on land cover assuming full compliance with existing regulations. Such scenarios can be valuable (Alberti 2008 and Sohl et al. 2010) by providing a far-sighted and comprehensive tool for predicting land use effects.

From the perspective of historic and futuristic scenarios, it can be seen that (a) HCIs varied considerably in the past (early to mid-1900s) under previous land covers/use, (b) project timeframe HCIs are within the range of variability of what may have occurred historically, and (c) HCIs aren’t likely to change much in the future under FBO.

To provide additional perspective on the potential for a response to future rural development in study watersheds, Figure 32 provides a comparison of BIBI scores and HCIs for project watersheds with Juanita Creek, a well-studied east-shore Lake Washington tributary representative of an urbanized Puget Sound lowland watershed (see King County 2012). In short, from this comparison it appears that (a) BIBI may be significantly affected

by watershed land cover conditions that are more developed than those of this study but less than that of Juanita Creek, (b) the rates of change in HCI and BIBI may be disproportionate, (c) a biological response threshold likely exists in the transitional area between rural conditions assessed in this study and the level of urban development represented by Juanita Creek, and (d) relative to rural streams, BIBI variability over time is low in urban streams, an observation consistent with the premise that the potential for good scores in an urban setting may be limited (Horner 2013). It may also be that the project data are insufficient or the analytical framework is inadequately structured to isolate and account for effects of other limiting factors, such as poor local conditions in an otherwise undeveloped watershed. For example, although not directly assessed, the suspected driver of low BIBI scores in South Seidel, a fully forested reference watershed where the five-year average BIBI score was 22, is dominance of fine sands in the substrates where benthic invertebrate samples were taken. Whether the presence of fine sands is a naturally occurring condition or the result of past extensive logging or other channel-altering activities by people is unknown.

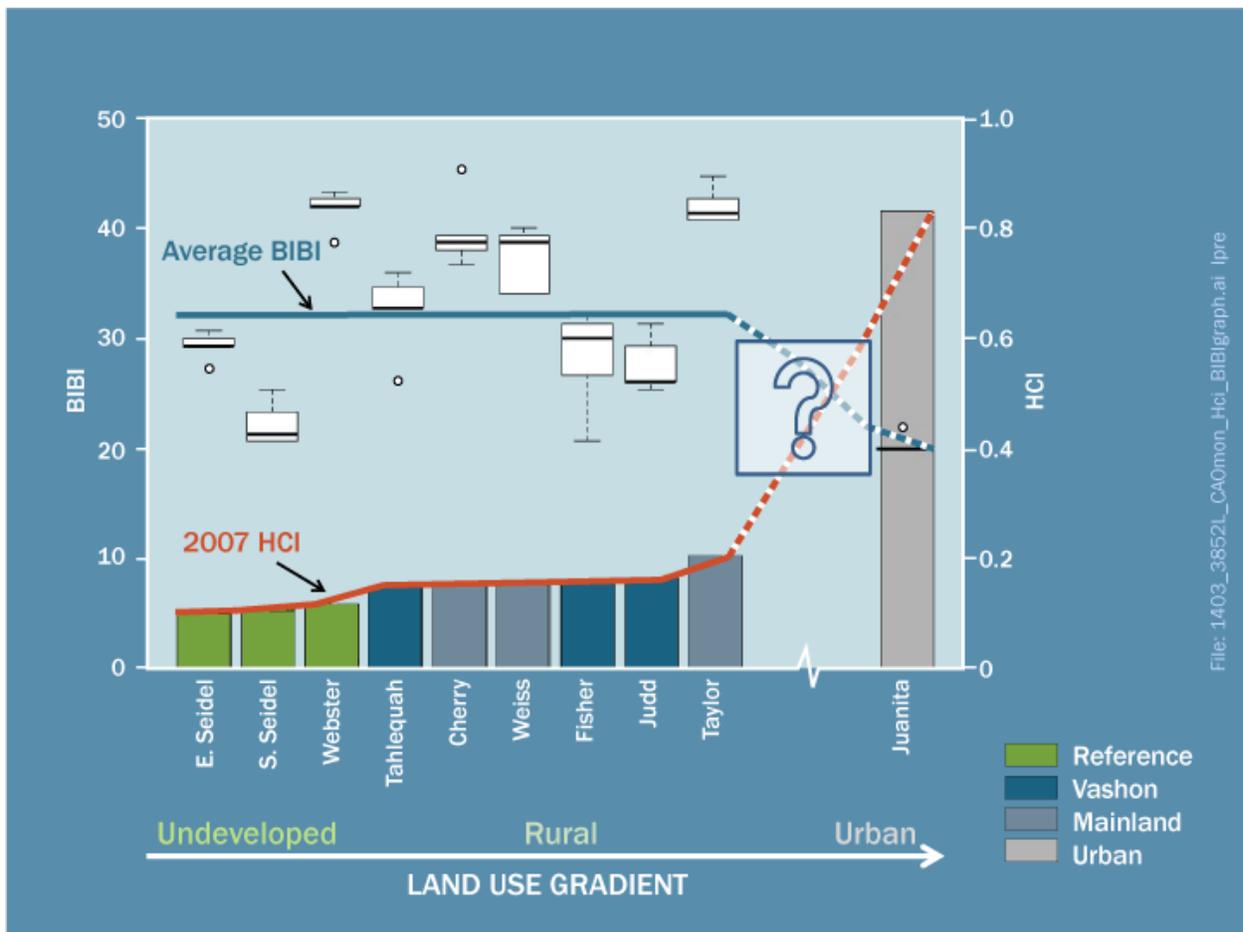


Figure 32. Comparison of HCIs and BIBI values across a gradient of land use for reference (undeveloped), treatment (rural), and Juanita Creek (urban) watersheds. HCIs are for 2007. BIBI values are median, standard deviation, and ranges for 2008-2012. For Juanita Creek, BIBI values are for the lower-most monitoring site (Juanita4) in the Puget Sound Stream Benthos database website (<http://www.pugetsoundstreambenthos.org/> downloaded April 4, 2014).

In summary, the amount of development during the project timeframe was small and therefore the CAO was not effectively tested. Simulation of FBO in rural treatment watersheds predicts that hydrologic conditions will not change appreciably under a FBO scenario and should remain far less impaired than an urban watershed.

## 4.2 Permitting and Compliance

Compliance in our study is defined as a land cover change that required a permit and for which a permit was obtained. Measuring compliance allows us to assess how well regulations were followed, and thus to what degree land use activity allowed in permits reflects actual land cover change.

In the Puget Sound, both adequacy of and compliance with land use regulations are major uncertainties (Washington State 2010). Regulations are prioritized as a ubiquitous, stabilizing, and protective foundation for actions to restore salmon habitat (Washington State 2012). However, as there are no known similar studies of the effectiveness of local-government regulations, there are no data on which to judge regulatory performance and guide management.

Local governments issue permits as the primary mechanism to review proposed land-altering activities such as building, clearing, and grading and, when necessary, modify them to avoid or minimize and mitigate impacts. In most cases these permits are obtained before an action, but sometimes actions requiring permits are discovered after-the-fact, either as an enforcement action or when a landowner becomes aware a permit was needed for a past action and applies retroactively. In any event, if permits are not obtained, jurisdictions are unable to assess and regulate development to ensure goals are being met.

This study provides information on the regulatory system's actual implementation and compliance. Although land use regulations are widely promulgated for land management (Sohl et al. 2009) they apparently have never been directly assessed for this application. Thus, this study provides valuable insight on actual behaviors of landowners to help judge the real-world strength and effectiveness of regulations and, where deemed necessary, improve compliance and environmental outcomes.

To measure compliance, the location, type, and extent of permitted and unpermitted (noncompliant) land cover changes were assessed between photo dates (2007, 2009, 2010, and 2012). This method was an efficient way to make compliance estimates using use readily available information. In retrospect, the approach has limitations including uncertainty of causes of small-scale change ( $\sim <18$  to  $50 \text{ m}^2$ ) among non-"building" land covers, where it was sometimes difficult to discern if change was the result of human activity, natural causes (inter-annual vegetation growth and loss), or variation in photographic angle and clarity. Similarly, the County allows limited clearing for hazard tree removal (20 trees or less) and hand removal of invasive blackberries outside of critical areas and their regulatory buffers without permits. Actions for hazard or invasive species management are difficult to distinguish from those requiring permits using only photo analysis.

The assessment of permitting and compliance accounted for changes among vegetated land covers (forest, shrub, pasture, and grass) and from vegetation to bare and built (roads,

buildings, parking lots) covers. It did not, however, assess the compliance of changes among already-built surfaces (e.g., transitions between buildings, paved roads, and pavement). This omission was because the change from one already built impervious surface to another was considered not as critical to understanding hydrologic and ecological impacts as the transitions among vegetated and bare land covers and transitions from those covers to built covers. As a result, a compliance rate for altering already-built surfaces was not estimated. It appears, however, that permits for roads and buildings were more likely to be obtained than for clearing and grading.

As a follow-up to this work, it may be valuable to inspect a sub-set of land cover changes identified in this study in more detail further to determine rates of natural versus human caused changes. It may be valuable to interview landowners to better understand their awareness and motivations and determine if (and why) they vary spatially (e.g., between Vashon Island and the mainland watersheds). This would help determine if compliance is driven by awareness of the regulations, desire to follow them or, perhaps, other issues. Knowing this information may help craft better regulations or develop effective programs to improve compliance.

Major questions that arose from this analysis include: (a) are the cumulative effects of noncompliance environmentally significant, and (b) if so, should the County modify clearing, grading, and stormwater thresholds for permitting? Although noncompliance occurs frequently, its actual cumulative area over 5 years was small (1 percent of area at watershed scale and 0.2 percent of area at regulatory stream buffer scale over five years) and its cumulative watershed-scale effect was not detected during the study period. Therefore, there is no basis for modification to the County's current approach.

The effect of noncompliance was not estimated for full build out. If future compliance is similar to the study period, noncompliance could account for 50 percent more land cover change than permits would indicate. It is important to note that adding an additional fifty-percent more change due to non-compliance to the already small amount of change projected in the HCI between 2012 and the FBO is still a very small amount of overall change. Furthermore, forest would still be the dominant land cover with other vegetated land covers (grass, pasture and shrub) being secondary. Because the large majority of noncompliant actions involved small clearing and small structures, it is possible that their effect on hydrology would be small at the watershed scale. Conversely, new amounts of impervious covers (roads, buildings, parking lots), which have a large effect on and are the primary driver of watershed hydrologic condition, would still be very small and, for the most part, would be required to meet more stringent stormwater standards than existed in the past.

Regardless, depending on where land cover change occurs, it could have impacts on fish and wildlife not related to hydrology. For example, regulatory buffers are often critical, high-use areas for fish and wildlife reproduction, rearing, migration, and refugia. Therefore, even small amounts of unmitigated, noncompliant clearing, grading, or building in those areas could impact fish and wildlife. This study suggests, however, that change in buffers is very small and that they are being preferentially protected as required. Outside of regulatory buffers, removal of forest cover could have major impacts on birds and other wildlife when upland nesting trees or forested migration corridors are lost or fragmented.

In this regard, however, much of the observed forest loss is around buildings where it may have been allowed without permits as hazard tree removal.

It is possible that compliance rates have varied significantly over time, and noncompliance may have been much worse in the past and could worsen in the future. For example, although not assessed for this project, land development rates during the 1990s, a decade of “booming” economy and land development in the Puget Sound region, may have been high relative to the economically depressed timeframe assessed by this project. If deemed important, and where historic environmental data and aerial photos of sufficient quality to detect relatively small scale change are available, project methods could be applied retrospectively to assess historic change and compliance. For example, during the 1990s several of the study treatment watersheds (Judd, Fisher, and Taylor creeks) had aerial photos taken and were monitored for flow. In combination with permit data, this historic information could be used to estimate compliance rates and assess effects of land cover changes retrospectively. However, the poorer quality of historic photos may reduce or limit the detection of small changes in vegetation and structures that were possible in this study because of high resolution orthophotos.

As to adequacy of the County’s regulations and permitting process, the current process works at the watershed scale to protect against environmental impacts of development while resulting in mostly small individual areas of noncompliant change, much of it potentially hazard tree removal that may not have needed permits.

The study did not assess all aspects of natural resources found in the study watersheds, including terrestrial wildlife and wetlands. To corroborate and boost confidence in this study’s findings, additional research, including in the same study watersheds and elsewhere in Puget Sound, should be done. Furthermore, land use effects on other factors that are not as influenced by hydrology, such as terrestrial wildlife, or chemicals that may be toxic at low levels, should be assessed.

### 4.3 Relevance to other studies

Many cross-sectional studies have examined land cover impacts on streams but none that have attempted to isolate and evaluate the effects of a single suite of local land use regulations in a longitudinal study. Although, as noted below, in 2007 Carter et al. (2009) initiated an as-yet unfinished study that is similar. More studies like this one are needed because land use is an important issue and environmental regulations are a nearly ubiquitous and an often contentious element of land use management. Studies of land use effects across the urban-rural have been reviewed extensively (Alberti 2008; Carter et al. 2009; U.S. EPA 2010). This study contributes to the body of knowledge at the rural end of the gradient. By being a “longitudinal” study, where the effect of time is explicitly assessed, it also addresses some of the shortcomings of “cross-sectional” studies, where space was substituted for time. The use of a BACI design with multiple treatment and reference watersheds as replicates strengthens the study’s statistical design (Roni 2005).

Carter et al. (2009) summarized shortcomings of a wide range of watershed studies and then described a new study that addressed those shortcomings in order to assess stormwater BMP effectiveness under high and low density development in the Etowah

Watershed, Georgia. Their project is highly similar to this project in that it uses time as variable rather than substituting space for time. It also uses multiple reference-treatment watersheds, a statistically-strong BACI design, and concurrent measurement of change in multiple environmental response variables and land cover over time. Their project differs from this study in that they are attempting to control amounts of treatment through an orderly build out of their treatment watersheds. Interestingly, land use as treatment in their study was delayed because of the same economic downturn that affected this project.

Prior to this study, the County's assessment of its land use regulations was limited to three studies. The most recent was conducted as part of a comprehensive programmatic habitat assessment (PHA) to assess sufficiency of land use regulations for compliance with the federal ESA in mapped 100-year (FEMA) floodplains in unincorporated King County (King County 2012a). Two earlier studies were intended to detect and rectify parcel-scale problems caused by noncompliance. In those, Baker and Haemmerle (1990) assessed encroachment into native growth protection easements and, more recently, MacWhinney and Schlemmer (2009) assessed compliance with stormwater drainage best management practices (BMPs). None of the three previous studies measured or controlled for environmental response to actual development, however.

Two major watershed studies are being conducted in western Washington and the Puget Sound region to better assess and improve effectiveness of land management and habitat restoration. In the first, State, Federal and Tribal agencies and a private timber company have jointly established ten intensively monitored watersheds (IMWs) in western Washington, including three in the Strait of Juan de Fuca, four in Hood Canal, and three in the Lower Columbia (IMW Scientific Oversight Committee 2004). The IMWs were established to improve understanding of productivity and habitat relationships primarily to assess effectiveness of restoration actions on salmon. Although not an expressed goal, the IMW studies also ostensibly assess land development and the so could be used as additional watersheds to assess regulatory effectiveness and corroborate this project's findings. As of the time of this report, project findings are limited to baseline (pre-restoration) estimates of salmonid productivity (Zimmerman et al. 2012).

In addition to IMWs, ecological processes affecting water, sediment, plants, and animals at the scale of small (~ 1300 ha) watersheds has been characterized for the Puget Sound Basin<sup>22</sup> (Stanley et al. 2009). The characterization was developed to help land managers identify areas and appropriate actions for habitat protection and restoration at a scale relevant to local government to assess and make decisions on identifying and prioritizing protection and actions. The characterization potentially complements this study by providing a comprehensive, Puget Sound-scale contextual framework within which the watersheds assessed for regulatory effectiveness can be nested to understand effects and ramifications of land use in other areas and at larger scales. Where conditions are similar, the characterization could calculate HCIs for their analysis units as a way to integrate conditions and express hydrologic condition in a manner comparable across Puget Sound watersheds.

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<sup>22</sup> [http://www.ecy.wa.gov/puget\\_sound/characterization/index.html](http://www.ecy.wa.gov/puget_sound/characterization/index.html)

### 4.3.1 Assessment framework

The assessment framework – an array of nine (six treatment, three reference) broadly distributed, intensively monitored watersheds (IMWs) in an *a priori* study design (modified BACI) using precise and simple methods, metrics, and databases – provides a potentially powerful tool for assessing change and relationships among watershed-scale land cover and ERVs. Within time and cost constraints, the assessment framework was intended to be as comprehensive in scope (time, space, and range of variables), rigorous in experimental design, and comparable in methods and metrics with other regional land use studies as feasible. A relatively high level of effort was expended to minimize the potential for Type II error (wrongly concluding that regulations are effective) in order to increase confidence in and the utility and comparability of project approach and results. High certainty was desired because (a) regulations are an important and primary mechanism for environmental protection, (b) they can be costly to land owners, and (c) they are often a highly sensitive sociopolitical issue.

As noted earlier, by explicitly accounting for time, rather than substituting space for time, and using replicates and controls in a BACI design (for this study, control and reference are used interchangeably), the framework helps to address shortcomings of past land use studies (Carter et al. 2009) with the exception of controlling the amount of treatment (land cover change). Controlling development to achieve prescribed treatment levels would have been extremely difficult, if not logistically and politically infeasible (see Carter et al. 2009). It would also have precluded assessing real-world actions and natural behaviors thus losing valuable insight on landowners as they follow a set of regulations *in situ*. This study's approach carried the risk of insufficient treatment resulting from unforeseen external factors. This concern was realized because of the economic recession, which severely reduced development and lowered change in land cover relative to expectations. As discussed later, modeling historic and future scenarios helped fill the gap in lieu of greater levels of observed land cover change during the project timeframe.

A key consideration in project planning was allocation of sampling effort across sites and years. Liermann and Roni (2008) assessed optimal sampling design strategies for assessing effects of watershed restoration and concluded more information was gained by adding more sites and distributing them broadly than having more years, unless each additional site had high incremental costs. The project timeframe of this study was limited by funding and management need for timely information (specifically, by 2012, when King County Council was to reevaluate regulations under the GMA). Furthermore, the incremental cost to establish a stream flow gauge and conduct monitoring efforts on an additional watershed was relatively small, although certainly not trivial. Therefore, more study watersheds distributed across a wider area were added to the study rather than more intensive or longer-term sampling in an even smaller, geographically limited set of watersheds.

This study uses parcel, permit, and GIS systems and databases common to King County and many, if not all, land-regulating jurisdictions in Puget Sound. It employs commonly used and statistically powerful methods for assessing hydrology, water quality, and benthic invertebrates. It also uses relatively simple, precise, repeatable methods and comparable metrics for assessing change in stream channel hydraulics. Finally, it indexes the effect of

distance, geology, and land covers on watershed hydrologic condition. As such, the methods should be applicable for areas containing similar geology, topography, vegetation, and precipitation. Furthermore, the methods may be applicable in dissimilar areas where hydrologic relationships among land covers and geology can be modeled. As with IMW studies, the methods may also be useful for setting watershed-scale context to better assess the effects of restoration (culvert removal, large wood additions, riparian restoration, enhanced stormwater treatment) and protection (land acquisitions and conservation easements) actions commonly used for recovery of salmon and Puget Sound aquatic habitats (Roni 2005; Lucchetti et al. 2005).

The assessment framework used a spatially explicit approach to assess the effect of differing compositions of land cover on watershed-scale hydrology and hydrology-driven ERVs. Although the models and metrics used should be applicable throughout the PLE, results will vary depending on each watershed's history and each watershed's unique array of zoning, regulations, geology, aquatic habitats, land uses, and land covers. Therefore, comparable studies should be conducted in other areas and jurisdictions in the PLE.

Based on five years of implementation, the project methods and metrics could be modified several ways to reduce costs and increase reliability and applicability. In general, suggested modifications largely involve improving understanding of the drivers of hydrologic response to varying land covers and geology and reducing time and cost to assess permitting and compliance and mapping land cover change.

#### 4.3.2 Hydrologic Condition Index

Although it was based on models of watersheds that were not the same as those assessed in this study, the HCI was a good predictor of the 4-year average annual HPCs for the study watersheds. This finding suggests utility of the HCI as a metric for quantifying hydrologic condition across watersheds, provided they have similar hydrologic response to changing land covers.

The HCI uses hydrologic modeling to scale the relative hydrologic value of differing land covers and index them to the worst possible condition (paved road) for a watershed or unit area of land. It integrates and weights the effect of distance, geology, and land cover on hydrology and provides an alternative or complement to current land cover metrics where land cover is often quantified as unweighted proportions of watershed area. The HCI model could probably be improved in several ways, including: (a) accounting for the hydrologic value of increasing forest biomass over time, (b) using overland flow path distances derived from digital elevation models rather than Euclidean distances, (c) weighting overland distances to reflect the much longer time required for water to flow through soils than in an open channel, and (d) improved hydrologic modeling, primarily to better account for factors driving variability in flashiness among watersheds.

In calculating change in HCI between years, no accounting was made for the hydrologic value type or maturity level of forest or the effect of growth in forests that weren't removed, yet these variables could affect hydrologic performance. Barring actions to increase stormwater treatment in existing built areas, it is likely that the value of building, pavement, roads, grass, and pasture and most other land covers will not change much over

time. The same is likely not true for forests and individual trees, however, which grow and increase in biomass and structural complexity until they are removed by people or natural causes. When compared to the relatively small amounts of forest removed during this study, the annual accumulation of new biomass in forests not removed may be partly compensatory. For example, Grier (1979) estimated the average net primary productivity (P) under full canopy closure of major forest zones of the Pacific Northwest as 17.4 Mg/ha/yr. Hutyra et al. (2010) found the average above-ground biomass (B) for mixed forests in lowland (< 500 m elevation) Central Puget Sound was 102 Mg/ha. Thus a rough estimate of the turnover ratio ( $TR = P/B$ ) for lowland PSLE forests is 0.17 or 17 percent of new forest biomass accumulating annually in existing forests. Total forest cover loss for the 6 treatment watersheds across 5 years was 29.7 ha and the average annual loss of forest biomass was about 600 Mg/yr (29.7 ha/4 yr\*102 Mg/ha). Meanwhile, the 6 treatment watersheds contained roughly 2,739 ha of forest cover (66 percent of 4,150 ha; Table 5) and therefore could have produced about 466 Mg/ha, equal to about 75 percent of the forest biomass that was removed. The type and distribution of forest biomass are critical, as hydrologic value would be expected to differ based on maturity level, dominant tree type (e.g., conifer vs. deciduous), and spatial configuration (e.g., distributed or clumped, far or near) relative to stream channels. Regardless, relative to the small amount of clearing and forest loss observed, change in the existing forest biomass was not accounted for, yet it may be substantial and could plausibly help to mask or off-set the hydrologic effect of small-scale, patchy forest loss common in King County's rural-zoned lands.

Van Sickle and Johnson (2008) note the importance of parametric distance weighting and differentiating between overland and stream channel effects when assessing influence of landscapes on streams. The HCI uses distance weighting but used Euclidean distances rather than digital elevation model (DEM)-derived flow path distances because the DEM model for at least one study watershed (Taylor Creek) was heavily affected by culverts and road fills. These features created an upstream "skating" effect in the DEM-based routing that caused obvious and major errors in flow pathways and watershed boundaries. An alternative to the use of Euclidean distances would have been to measure culvert bottom (invert) elevations and embed those points in the DEM model. This modification was not done because it was considered too costly to measure culvert elevations at the time the distance grids were established. Greater realism could also have been achieved by differentiating between in-channel and overland pathways by applying an attenuation factor to overland distances. Van Sickle and Johnson (2008) suggest an exponential decay relationship for modeling the effect of overland distances. Relative to effects transmitted via a stream channel, such an attenuation factor would greatly dampen the hydrologic effect of land cover change the farther it occurs from a stream channel.

The HCI's accuracy and reliability is affected by the accuracy of modeled relationships of flow and land covers. The nine watershed models effectively discriminate hydrologic differences between groupings of built (pavement, roads, buildings) and un-built (forest, shrub, pasture, grass, and bare) land cover. Among land covers within those two basic groupings, there is variation in hydrologic response even among watersheds with similar geology and morphology and within close proximity to each other (Figure 33). Although variability in hydrologic modeling can result from imprecise stream flow measurements and inaccurate characterization of land cover, the within-group variance is likely driven by

presumed homogeneity of mapped geologies and inaccuracies associated with precipitation measurements. Variations in the extent and permeability of till and outwash geologies are difficult to map and account for accurately, yet they can be major drivers of hydrology at the scale of relatively small watersheds (Jensco et al. 2009; Weekes et al. 2012).

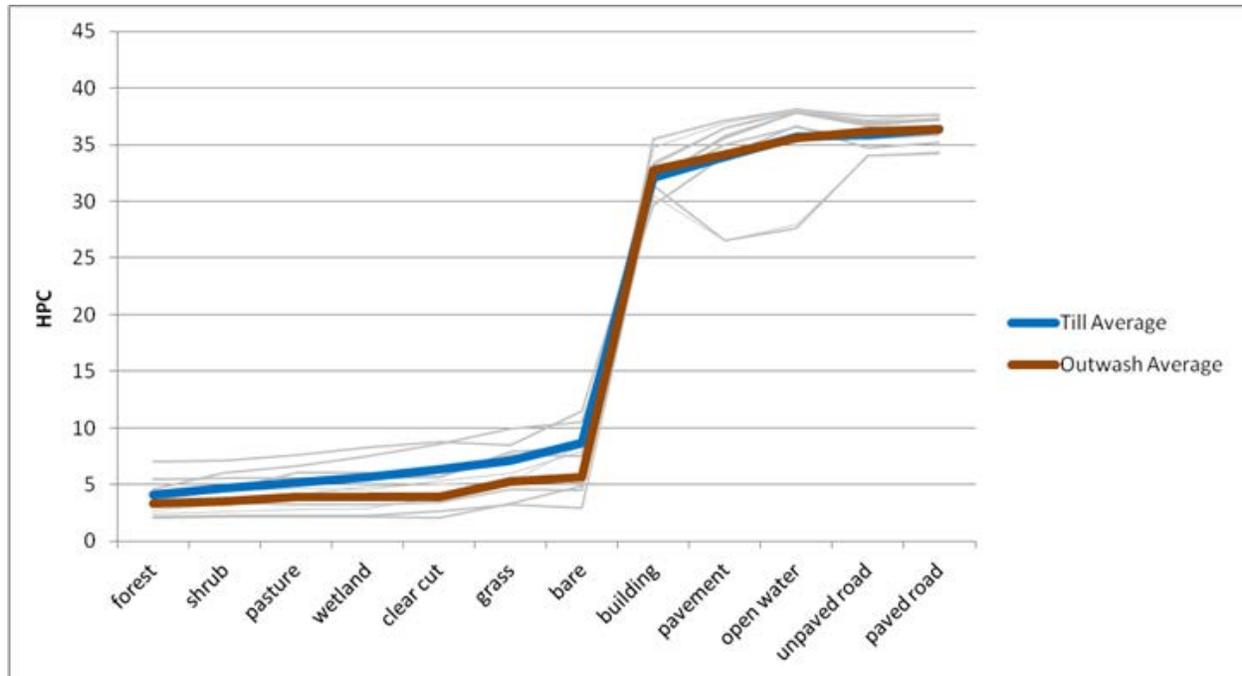


Figure 33. Average and variability in high pulse counts (HPCs) by twelve land cover types and two geologies – till (low permeability) and outwash (high permeability) – derived for the nine models assessed in calculating hydrologic condition indices (HCIs; see Table 13). Gray lines indicate nine study watersheds.

The location of storm events can be highly variable at the scale of the study’s relatively small watersheds, but precipitation is measured at a relatively limited number of sites across the county. Precipitation among the study’s nine watersheds was characterized using three precipitation gauges, and the ten modeled watersheds used to generate the five sets of HPCs used for HCIs used only the SeaTac rain gauge data.

#### 4.3.3 Land cover mapping

Having a high-quality land cover database was of high importance for assessing relationships between land covers and ERVs and to estimate compliance. As a result, considerable effort was made to construct and conduct QAQC on hand-digitized land cover maps. The process entailed constructing a hand-digitized base map (2007, 1:1200 scale) against which ortho-rectified photos from other years or of artificial scenarios, such as the fully-built condition, could be compared and updated to identify and track land cover change over time. The fine scale resulted in a much more labor intensive, costly, and complicated effort than originally anticipated. In retrospect, more detail was likely captured in this approach and at this scale than was necessary for assessing watershed-scale hydrologic change. The level of detail was valuable, however, for assessing permitting

and compliance, as relatively small scale changes in vegetation and built surfaces can require permits under the County's regulations. Furthermore, these efforts provide the Puget Sound region a series of nine IMWs with highly detailed, spatially-explicit land cover datasets that can be re-arranged (aggregated or dis-aggregated) as needed. Such a database may be valuable for other purposes as well, including conducting retrospective and future condition analyses for improving hydrologic or other environmental models and assessing land use interactions with other natural elements such as wildlife and various invasive species known to respond to development-related habitat loss and fragmentation (Robinson et al. 2005).

Although hand-digitized land cover maps are presumably more accurate than automated computerized approaches, which can introduce commission and omission errors, their creation presented their own set of problems. Key among these problems was developing and applying a consistent set of interpretations for each land cover. For example, the distinction between grass and pasture or between unpaved and paved roads was often difficult even with high resolution photographs. Similarly, delineating forest boundaries required judgment to determine the point at which forest stopped and another land cover (e.g., pasture with low density or isolated trees) began. A third vexing problem was that the software did not consistently save changes to the database. Once discovered, this problem slowed digitization because extra care and time were needed to ensure changes were successfully saved. To address these issues and improve their quality for this project and future research, land cover maps were reviewed and edited in at least three quality control steps after their initial production.

Given the high level of land cover detail provided by hand digitization, the project's land cover database may be valuable for assessing and rectifying the accuracy of land cover databases developed from less precise satellite imagery or relatively low resolution historic photos. Relative to the project's fine-scale (1.8-m grids) land cover database, the National Land Cover Database (NLCD) is coarse-grained (30-meter resolution); despite its coarse grain, the NLCD has been identified as "the definitive Landsat-based, land cover database for the Nation" (Homer et al. 2012). As such, it has been used to characterize and track trends in King County watersheds, including the Green River and Lake Washington/ Cedar/ Sammamish watersheds in which seven of the nine study watersheds are found (e.g., Vanderhoof et al. 2011; WRIA 9 Implementation Technical Committee 2012). To assess accuracy of the NLCD dataset and provide a simple "crosswalk" comparison, estimates of percent forest canopy cover and impervious area from the 2006 NLCD (Fry et al. 2001) could be made and compared against estimates using the project's hand-drawn land using high-resolution orthophotos.

A fast and accurate computerized approach to mapping land cover change has recently been developed by WDFW to reduce time and cost to map land cover change (Pierce, K. in progress). The WDFW-Pierce approach uses high resolution ( $\leq 1\text{m}$ ) aerial imagery captured by the National Agriculture Imagery Program to generate maps with sufficiently high locational precision to map land cover change at parcel and small watershed scales which are highly relevant and useful to local governments, as opposed to larger, whole watersheds. This method has the potential to greatly reduce time and effort needed to apply the framework and methods used in this study. When combined with a common

approach for delineating upstream areas and establishing and routing grid cells within those areas, the WDFW-Pierce methodology would allow for repeat of this project's methods and a quick estimation of HCIs elsewhere in the PSLE. Use of the HCI or similar integrating metric would allow for a standardized estimation of hydrologic condition currently lacking for lowland Puget Sound. For example, in Whatcom County Wahl et al. (2013) assessed effectiveness of riparian buffers across a range of land uses (forested, cultivated, developed), but without stream gauging and constructing hydrologic models for each of their twelve watersheds and monitoring points they lacked a common metric to express and compare hydrologic condition.

## 4.4 Climate Change Implications

The projected potential effects of climate change on project results were not assessed. Projected climate change effects for the Puget Sound include increased winter flooding, decreased summer and fall stream flows, and elevated warm season stream and estuary temperatures (Snover et al. 2005). Because of their low elevation, the project's streams are rain-fed systems. Snover et al. (2005) and Raymond et al. (2013) suggest that rain-fed streams have probably already experienced much if not most of the range of variability in flow that is expected over the next century. Temperature effects, however, are likely to continue and create new (warmer) conditions for low-elevation rain-fed streams. Even the most conservative scenarios show air temperatures of the Pacific Northwest warming significantly more than was experienced during the 20<sup>th</sup> century (Snover et al. 2005): models project a warming rate in the Pacific Northwest of roughly 0.2 - 1.0 °F (0.1 - 0.6 °C) per decade at least to 2050, with average warming of 1.8 °F (1.0 °C) by the 2020s and 3.0 °F (1.7 °C) by the 2040s.

Based on the above information, it appears that increased temperature may be the primary effect of climate change in lowland streams rather than increased flashiness. This conclusion is tempered by uncertainty, as no climate model can predict with perfect accuracy. In any event, significant correlations of the HCI with high pulse counts and temperature indicate that both may be affected at the local (small watershed) scale by changes in land cover (see Table 25). Because forests have the strongest moderating effect on flow (Figure 31) and provide a host of benefits including shade and microclimate control (King County 2004), forests provide the greatest hedge against the risk of adverse effects of climate change. It appears then, that to the extent practicable, protection and restoration of forest cover in rural watersheds and stream buffers is the primary way to minimize the effects of climate change.

The establishment of these nine study watersheds may provide an opportunity to assess the effects of climate change on flow and temperature at the small-stream scale. Their historic and contemporary land cover and ERVs are well known and their future condition has been modeled using the HCI. Therefore, these watersheds may be good sentinel sites for monitoring the long-term effects of future climate change on flow and temperature. Such monitoring may provide an opportunity to create accurate local-scale climate change models to help better understand the effects of climate change at the local level while providing information that could improve larger-scale models.

## 4.5 Habitat restoration implications

Almost 40 years ago, Hynes (1975) noted that the physical, chemical, and biological properties of streams largely reflect the condition of their watersheds. Since that time, a considerable amount of stream habitat restoration has been conducted and assessed for effectiveness, and results have mostly borne out Hynes' conclusion. Indeed, most assessments of restoration have concluded that where restoration failed or achieved only limited success, a large and sometimes overwhelming contributing factor was inadequate consideration of the watershed-scale ecological processes within which restoration actions occur (Roni et al. 2009; Barnhardt and Palmer 2011). In general, it appears that reach-scale restoration actions are more likely to be effective if they are conducted in the context of a stable or improving reach or watershed condition.

Results of this study indicate that in rural lowland King County, watershed-scale hydrology and associated ERVs are relatively stable. Furthermore, with respect to hydrologic flashiness, they are not much changed from their historic (*ca.* early to mid-1900s) condition and all rural scenarios are dramatically better than urban. Therefore, to the extent they are limiting, restoration of degraded in-channel and riparian habitats probably has good potential to be effective or, at least, not be undone by a degrading watershed context.

## 4.6 Sources of error, limitations, and caveats

"All models are wrong but some are useful" – George Box

At the start of the project, a Quality Assurance Project Plan (QAPP) was developed (Lucchetti and Latterell 2008), and throughout all steps of the project great attention has been given to ensure the quality of the data. Regardless, a study of this scope and complexity will inevitably have sources of error, the effects of which can be managed for but not entirely eliminated.

This study relies on models and land-cover data derived from a variety of historic and contemporary sources. Land cover change during the project was tracked with high resolution photos but was not field checked. Similarly, historic land cover change relied on a combination of maps, photos, and satellite imagery that could not be field checked.

Models themselves are approximations based on assumptions and as such have limitations. As a result, when model-generated data are used to generate more data it must be understood that it is only one possible view of reality but almost certainly it is not a perfect representation of the condition. Uncertainties are larger for historic and future scenarios than for contemporary conditions.

Not all possible effects of development or aspects of regulatory effectiveness relative to goals of the CAO were assessed. In particular, the presence or effects of regulations on toxics and wildlife species were not assessed, and yet clean water and wildlife protection are goals of our land use regulations.

Although impacts of climate change are predicted, we did not directly assess or model the effects of climate change (see Section 4.4).

As to the future condition, several assumptions were made when constructing the FBO scenario. For example, it was assumed that every undeveloped parcel that could be developed would be developed (including subdividing large lots to create the number of parcels allowed under current zoning). It is likely, however, that at least a few will not be developed for a variety of reasons including landowner desires or limitations that are not obvious from photos but that may include presence of hazardous conditions or inability to provide septic and potable water (see also King County 2012). To create parcel-scale clearing consistent with surrounding conditions, the watershed-average amount of clearing for parcels with existing buildings was used as a guide. However, landowners may create smaller yards on forested lots or larger clearings for agriculture and other uses.

Some additional assumptions of the FBO analysis:

- Outbuildings, such as detached garages or barns, were not mapped but are inevitable in some if not many parcels.
- All new clearing for yards was assumed to be grass, but it is likely vegetation will be much more variable and include shrub, pastures, and even trees.
- No sub-platting of large parcels to densities higher than allowed by current zoning, but comprehensive plan polices are subject to change and so localized or widespread sub-platting and re-zoning to higher densities could occur given sufficient population or economic pressures.
- Small residential structures, such as mobile homes, were not replaced with new houses that would likely have larger footprints, but it is likely that at least some small structures will be replaced with larger ones.
- Driveways were drawn as straight lines and assumed to be paved, but many driveways have curves and some may be unpaved.
- Whether small (< 10 m<sup>2</sup>) structures were habitable or used solely for storage or agricultural activities could not always be reliably determined.

Multiple sets of data checking (QAQC) were performed on the land cover data while it was being created and refined in GIS. However, mistakes (human error) are inevitable when hand digitizing at a fine scale of resolution across nine entire watersheds. Regardless, after much checking it is suspected that errors are probably small and would not affect the outcome of the HCIs.

In assessing the FBO, full compliance was assumed and the effect of an additional amount of non-complaint land cover was not estimated, although observed compliance rates suggest about 50 percent more land cover change may occur than would be predicted by permits. Therefore, the FBO may be an underestimate.

In assessing compliance, not all possible noncompliant changes were assessed. Only land cover changes observed through high resolution photos were documented. Changes that may have occurred under forest canopy or in shadows that sometimes occurs in orthophotos could not be assessed for compliance. Also, apart from the project's study reaches, no systematic physical survey was conducted to ground-truth or identify additional changes that may have been made in the stream channel or its banks.

## 5.0. CONCLUSIONS

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This section addresses the initial study questions as well as some additional anticipated questions.

### 5.1 Answering the Study Questions

#### **(1) Did the environment respond to change in land cover during the study? If so, was response related to CAO implementation?**

No conclusive evidence of flashier flows, reduced stream channel complexity, reduction in biotic integrity, or increases in conductivity or temperature was observed in streams in the six treatment watersheds by the end of a five-year field experiment. However, because of a lack of significant development activity – due to the economic recession that corresponded with the study period, a factor beyond our control – the CAO could not be effectively tested. Therefore, there is insufficient evidence to tell whether the regulations are working or not. However, the study has established a robust baseline for comparisons in future years, after more development has occurred.

Given the lack of development, the effectiveness of the CAO was modeled in treatment watersheds under a fully “built out” condition assuming full compliance and no change in zoning. Predictions about future effects on hydrologic condition (the HCI) were generated by simulating hypothetical future land use changes under the CAO and taking into account of historic activity. These simulations are the first time the CAO has been modeled for entire watersheds in a systematic and scientific manner. The results suggest that the impact of future development on the study watersheds may be small, particularly relative to an urban basin inside the Urban Growth Area (UGA). However, these results are based on modeling and should be viewed with caution: the potential future effects of development and effectiveness of regulations have not been validated, and definitive results will require additional testing.

#### **(2) If response was significant, how might the CAO be modified to reduce future impact?**

As indicated above, insufficient development occurred to effectively test the effectiveness of the CAO at protecting aquatic resources. Furthermore, from five years of orthophoto examination, no obvious problem (e.g., egregious or rampant unpermitted clearing and building in or out of regulatory stream buffers) was evident. Consequently, no modifications can be recommended on the basis of this study.

#### **(3) How well did people follow the regulations? Do permits provide an estimate of land cover change? And did non-compliance impact the environment?**

Compliance, defined here as a function of any land cover change that likely required and obtained a permit, over 5 years across 6 treatment watersheds was 63 percent. Based on this finding, if the rate of noncompliance remains the same in the future, then ~50 percent more land cover change by area could occur than predicted under full build out. In any event, actual amounts of change were small. For example, over 5 years, about 96 percent of

the treatment watershed area exhibited no land cover change. Regulatory stream buffers exhibited even less change, with over 99 percent of the buffer area exhibiting no discernable land cover change.

**(4) How was the assessment framework a useful tool for measuring effectiveness? What changes are recommended for future work?**

The study framework for assessing CAO effectiveness proved implementable and robust, designed to capture spatial variability and inter-annual variability in environmental response variables. However, it was subject to the downturn in the economy. Suggested improvements include (a) improved mapping and modeling of geology and local precipitation events to more precisely understand hydrologic conditions at the scale of study watersheds ( $\leq \sim 2,000$  ha), (b) improvements to reduce time and cost in mapping land cover change, and (c) using sites with a longer gauge record to better ascertain cause and effect. One aspect of the study is that its timeframe was limited to a five year period, and it is possible that the impacts of development activity could take longer to occur. Therefore, continued monitoring of the study watersheds is recommended to measure response variables over longer time. Future monitoring and studies would be relatively cost-effective to conduct, given that the study design, methods and gauging stations are now in place.

**(5) Are there relationships among environmental variables and watersheds that provide greater understanding of the mechanisms affecting environmental response? (This key question became evident during the analysis phase of the project.)**

Ordination of ERVs, land cover, and physical features (i.e., the grouping of watersheds by similar characteristics) suggests environmental responses in watersheds are likely to differ by location (within and between ecoregions), starting condition (undeveloped vs. partially-developed), and streams size. This analysis technique is largely exploratory, however, and does not support strong inferences about differences between streams or their sensitivity to land use changes. Those answers may be resolved in future studies after more development has occurred.

## 5.2 Answering Additional Questions

**(1) Were/are King County's regulations effective at preventing an adverse environmental response?**

This question cannot be answered on the basis of this experiment. Although five years of detailed studies were conducted in six treatment watersheds very little development occurred in them due in part to a major economic recession, As a result, the ability of King County's regulations to prevent an adverse environmental response has not yet been effectively tested. However, the study has established a robust baseline of environmental conditions for comparisons in future years, after more development has occurred.

A simulated comparison of historic and hypothetical full build-out scenarios of development *predicts* that the hydrologic impact of future development on the study watersheds will be small, relative to variability in past conditions and when compared to

an urban basin inside the UGA. On the basis of these simulations, current regulations are expected to avoid adverse changes in hydrologic flashiness and associated metrics, assuming full compliance and no change in zoning. However, these predictions are speculation; the actual effects of future development on aquatic resources, whether small or large, cannot yet be known. A future study is needed to validate (1) whether development was accurately predicted and (2) whether the effects of that development were small as predicted.

### **(2) What recommendations emerge from the study about the CAO?**

Lacking evidence of problems with regulations, changing the CAO, either strengthening or lessening its protections, is not warranted at this time. But future research appears warranted: concluding wrongly that regulations are effective when they are not is risky, as these regulations apply to rural lands that contain relatively productive salmon runs and high water quality important to recovery of salmon and the Puget Sound as well as quality of life in rural King County.

This study positions King County to effectively test the CAO in the future by establishing a network of study watersheds with robust baseline measurement of environmental conditions and land covers. Additional research over longer timeframes in the same study watersheds and over a range of development spanning the rural-to-urban gradient elsewhere in Puget Sound is recommended. Additional environmental response variables should be considered to determine whether regulations protect wildlife and provide clean, nontoxic water, as these are also goals of King County's environmental regulations but were not assessed in this study.

### **(3) What is the significance of the assessment framework to our understanding of the effectiveness of environmental regulations?**

The assessment framework – an array of nine geographically distributed, intensively monitored watersheds (six treatment, three reference) in an explicit, statistically strong study design (modified BACI) using well-established methods, metrics, and databases – provides a powerful tool for assessing change and relationships among watershed-scale land cover and ERVs. By explicitly accounting for time, rather than substituting space for time, and using replicates and controls (reference sites), the framework addresses shortcomings identified in many past land use studies. In order to increase confidence in and the utility and comparability of project approach and results, a relatively high level of effort was expended to minimize the potential for Type II error (i.e., concluding regulations were effective and there was no effect of development when, in fact, an effect occurred). High certainty was desired because regulations (a) are a primary mechanism for environmental protection, (b) can be costly to land owners, and (c) are often a highly sensitive sociopolitical issue.

### **(4) What is the framework's potential application for other important science questions?**

This method has potential to: (a) assess land cover change and regulatory effectiveness in other small watersheds, and (b) address additional needs and questions such as (i) calibration and refinement of models of land cover and watershed hydrology, water quality, hydraulics, and biology, (ii) understanding and estimating the effect of space and

time in assessing land cover patterns and environmental outcomes; (iii) estimating rates of change over time, and (iv) identifying thresholds and mechanisms of environmental response to land cover change. With some modification, primarily to reduce time and costs to produce land cover maps and improve grid cell routing, the framework and associated study design, methods, and metrics could be repeated using readily available tools and datasets.

**(5) Why was it important to develop and analyze historic and future scenarios important?**

Historic and full build-out scenarios were useful for setting the context of current conditions between past and future conditions. In retrospect, such scenarios were especially helpful because of the project's combination of a relatively short study timeframe and an unexpectedly low degree of land cover change. Assessing contemporary conditions in context of historic and potential future conditions increased understanding of the range of historic variability and the future capacity for change. Without them, interpretation of project timeframe land cover change effects would have been far less informative.

However, models are only simulations of the real world. While helpful, historic and futuristic models are hampered by uncertainty over actual conditions and responses.

**(6) Did noncompliance affect outcomes?**

Not over the study period. So little development occurred that the total area affected by noncompliance over five years was very small (1 percent of treatment watershed area), and there was no detectable effect of the combined compliant and noncompliant land cover change on ERVs. Further, the amount of noncompliant land cover change observed in regulatory stream buffers was even smaller than in the whole watershed (0.2 percent of the regulatory stream buffer area in the treatment watersheds). This very small amount of noncompliant change in regulatory buffers suggests that stream buffers may be being preferentially protected as required. As such, it may be possible that people are complying with regulations by not developing in critical areas in the first place. It is important to note, that in a future period of development, noncompliance rate could become a factor at the watershed and buffer scales. If it continues at the observed rate for the watershed, approximately twice as much development may occur as what has been permitted. Because the actual amount of change is small, the net effect of 50 percent more change that is noncompliant would still be small. However, even small amounts of forest cover loss could be significant for fish and wildlife in both regulatory buffers as well as upland areas where nesting trees and forested migration corridors are important. Unanticipated loss of habitat may be especially important for species that have a low tolerance for proximity to people and development.

**(7) What are implications for habitat restoration and protection?**

Historically, the study watersheds have been subjected to a range of hydrologic conditions resulting from initial extensive deforestation followed by subsequent varying levels of reforestation and agricultural and rural residential development. Based on modeling information, relative to historic variation, hydrology of the study streams is projected to change little in the future. Furthermore, the streams are unlikely to experience conditions

resembling high-impact urban hydrology. It then appears that watershed hydrology in these mostly undeveloped rural streams is relatively intact and may facilitate success in reach-scale restoration projects.

Although not directly assessed, it may be that present-day habitat conditions are constrained in part by a shared legacy of stream and riparian habitat modification (loss of old growth forests and woody debris, bank hardening, ditching, culverts) resulting from early (*ca.* ~ 1900 to mid-1900s) logging, agriculture, and rural residential development, and associated infrastructure (roads, culverts, drainage ditches).

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## 7.0. APPENDICES

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See separate PDF doc of Appendices.