Development of a Stormwater Retrofit Plan for Water Resources Inventory Area (WRIA) 9 and Estimation of Costs for Retrofitting all Developed Lands of Puget Sound

DEVELOPMENT OF FLOW AND WATER QUALITY INDICATORS

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INTRODUCTION

Conceptual Framework

Figure 1 presents a basic concept of the major components of concern in WRIA 9 stormwater retrofit planning project ("the project") and the relationships between them. Watershed land use/land cover (LU/LC) characteristics affect stream habitat conditions, upon which aquatic life forms depend.

The term "land use" refers to functions served by terrain for human purposes, such as agriculture, residential, and commercial. "Land cover" means the surface description of a parcel; for example, forested, pasture grass, lawn, impervious material. "Habitat" represents numerous conditions, such as water flow and water quality, each measured in many different ways; soil and geological materials making up the bed and banks; and riparian vegetation. Among the aquatic biota are fish, invertebrate animals, attached and planktonic algae, and rooted plants.

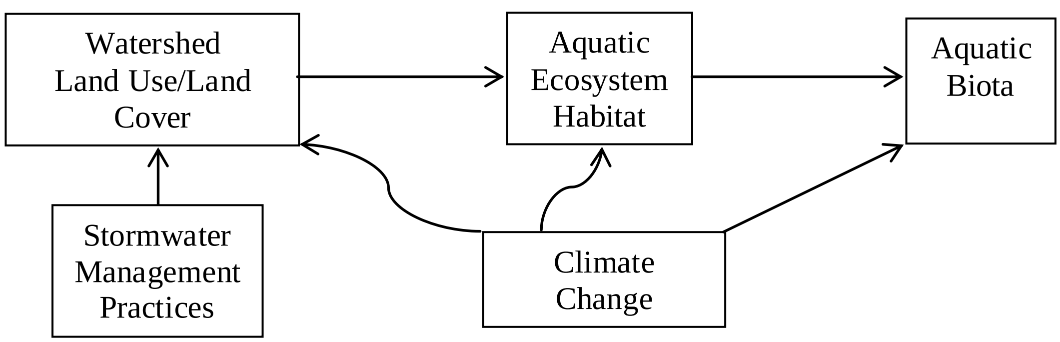

Figure 1. Components and Relationships of a Watershed Ecosystem

Aquatic organism physiology and behavior evolved in relation to the complex of habitat attributes existing over the thousands of years of their presence. A water body's habitats, in turn, developed as a direct result of its physiographic setting (latitude, elevation, topography, geology, etc.) and delivery of water and materials from the landscape making up the area contributing drainage to it (i.e., the watershed). Changes in land use, land cover, or both imposed by humans modify water and materials delivery, and possibly even physiographic elements; and, consequentially, alter habitats. These changes occur over very short time frames in relation to the original development period of habitats and evolution of aquatic biota, which are challenged to adjust abruptly. Often, they cannot adapt and decline in numbers or go locally or broadly extinct as a result of loss in efficiency of their life-supporting processes (e.g., growth, reproduction, mobility) or direct mortality.

Management practices are intended to allow humans to occupy a watershed and use its land for their purposes while sustaining other life. The principal concern of this project is to determine the most cost-effective combination of practices for managing stormwater on this basis in the defined study area.[1] Stormwater runoff from the landscape is the largest and most pervasive influence on this watershed's aquatic habitats, and hence its aquatic life. The project will accomplish its goal with the use of computerized, mathematical, predictive models representing the system components and calibrated with measured data taken on their key elements.

The project's scope recognizes that climate change likely will affect the three fundamental system components, over and above human-induced LU/LC alterations, through the approximately 30-year time interval over which it will perform analyses. Accordingly, the analyses will incorporate plausible climate-change scenarios to examine their possible effects on conclusions regarding strategies. Work by the Climate Impacts Group (2009) at the University of Washington is available to support this assessment.

Summary of Methods

Watersheds and aquatic ecosystems embrace immense numbers of variables, all of which have some role in their definition and operation. Hydrologic cycle inputs (precipitation, surface runoff and groundwater discharges) and outputs (evapotranspiration, groundwater recharge) govern fluvial processes such as stream flow hydrography (flow rate over time). Thousands of materials, in the categories of sediments, nutrients, metals, organic chemicals, and microorganisms, entering with the hydrologic inputs, constitute the physical and chemical quality of water and underlying sediments. As already pointed out, many characteristics, and associated variables, go into making up a habitat. Each aquatic life form consists of distinct species populations, each of which represents an individual biological variable; and combinations of species assemblages comprise community variables. All of these variables represent **metrics**, that is quantities that can potentially be measured and contribute to understanding relationships existing within the system.

Obviously, no study can measure all, or even a substantial fraction, of these variables. An assessment of this sort relying on data supporting computer models is likewise limited in the number of variables it can consider. Even those variables that can be measured generally differ in their contributions to understanding. The solution is to identify those variables that can best represent a component and its linkages to other components. In this project such variables are termed "**indicators.**" The term "metric" applies to a measurable variable, a number of which are evaluated as "candidate indicators;" designation as an "indictor" signifies such a variable with demonstrated ability to link events in one system component to responses in another. Specifically selected for use are a small set of stream hydrology and water quality indicators with documented linkages to watershed conditions on the one hand and aquatic biological community integrity on the other, as established through research performed in the Puget Sound region (see summary below).

[1] Most of Water Resources Inventory Area (WRIA) 9, the Green-Duwamish watershed plus adjacent direct drainages to Puget Sound, excluding headwaters above Howard Hanson Dam, the main step of the Green River, and its lower reach (Duwamish River) and tributaries thereto within the City of Seattle

The research further provides the basis to set numerical "**targets**" for these habitat indicators to achieve specific biological goals, attained through appropriate stormwater management strategies. These goals will aim, in general, at protection to sustain no further losses of biological integrity in the watershed's streams and at selected enhancements to restore some lost resources. This report covers the selection of indicators, while a companion report to be presented at the next workshop will document target assignments.

Figure 2 illustrates how the project will function. The project team will use LU/LC data already assembled for near-present-day and future (based on population forecasts) conditions as starting-point scenarios. With the addition of climate-change projections, these scenarios will provide input data sets for running the calibrated Hydrologic Simulation Program—FORTRAN (HSPF) model. Its time-series flow predictions, in turn, will serve as input to the System for Urban Stormwater Treatment and Analysis INtegration (SUSTAIN) model. SUSTAIN allows convenient testing of extensive stormwater best management practice (BMP) scenarios for their predicted ability to regulate discharges to meet targets set for the selected hydrologic and water quality indicators and achieve protection or restoration goals. These goals will be set and modeling will be performed for multiple, key locations in the watershed stream network.

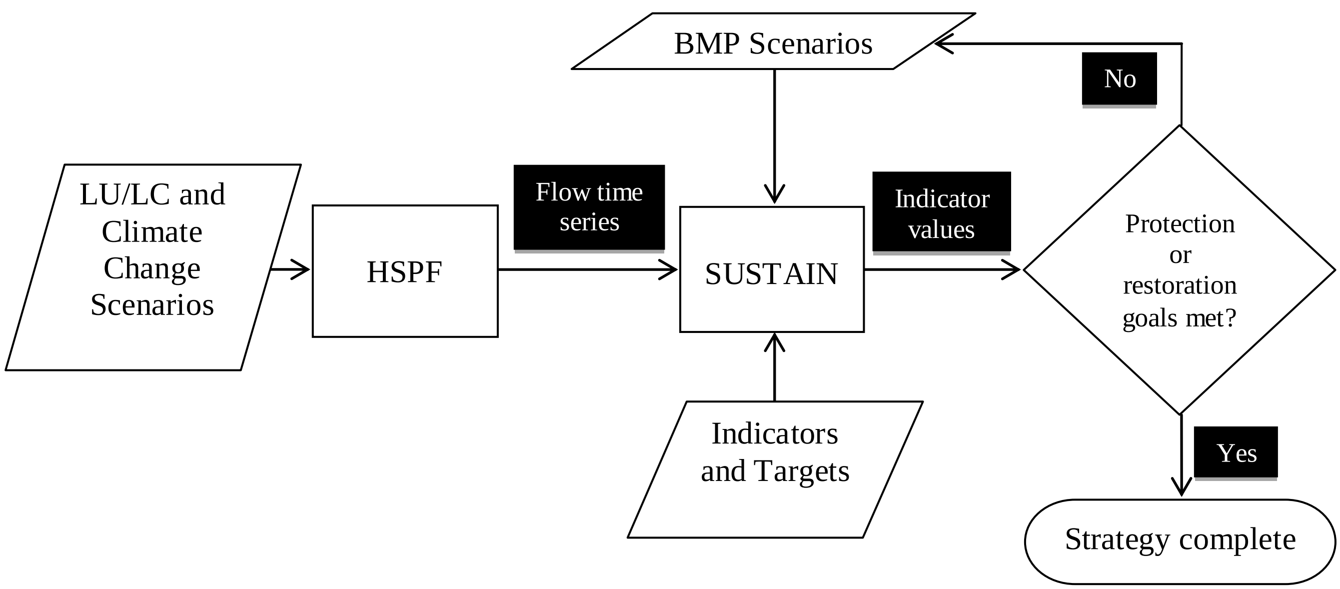

Figure 2. Project Modeling Framework

Scenarios will cover three stages of watershed land use change: (1) new developments on "greenfields", (2) redevelopment of already developed property, and (3) retrofitting static existing development. Most management heretofore has concentrated on the first of those stages. However, redevelopment presents significant opportunities for bringing in protective measures where none previously existed. All urban areas are redeveloped at some rate, generally slowly (e.g., roughly one or at most a few percent *per annum*) but still providing an opportunity to ameliorate aquatic resource problems over time. Extending stormwater requirements to redeveloping property also gradually "levels the playing field" with new developments subject to the requirements. It is important to mention that not only residential and commercial properties redevelop, but also streets and highways are periodically rebuilt.

Opportunities to apply stormwater management practices are obviously greatest at the new development stage, somewhat less but still present in redevelopment, but most limited when land use is not changing. Still, it is extremely important to utilize all readily available opportunities and develop others in static urban areas, because compromised aquatic ecosystem health is a function of the development in place, not what has yet to occur. To meet the project study area's goals, the expectation is that it often will be necessary to retrofit a substantial amount of the existing development with stormwater management measures. A major question for this project is, To what extent can goals be met through management of new development and redevelopment, and how much retrofitting will be necessary to achieve them?

Stormwater management approaches will emphasize natural drainage system designs, frequently termed "low impact development" (LID), but will also include longer-used conventional practices. LID aims at reducing the quantity of surface runoff produced, above that generated by a natural landscape, and improving the quality of any remnant by exploiting vegetation and soils to infiltrate and evapotranspire water. Soils can be amended, generally with organic compost, to increase water storage and advance these processes. Additional, and equally important, LID strategies are preventing pollutant contact with rainfall or runoff (source controls) and harvesting rainwater for some use, such as gray and irrigation water supply.

Conventional stormwater practices include detention devices, which reduce runoff peak flows but often not total volumes and durations of elevated flows, and treatment facilities, whose main purpose is to capture pollutants and lower their concentrations in the effluent discharged. They differ from LID practices in not emphasizing runoff reduction, taking incidental advantage of whatever water loss occurs, but not explicitly designing to boost water extraction through infiltration, evapotranspiration, and harvesting. Some such practices, for example media filters constructed in a concrete chamber, capture pollutants but do not reduce runoff quantity. Compared to conventional methods, the LID-based practices have been found to be clearly superior in runoff quantity control and cumulative pollutant mass loading reduction and usually better in decreasing the concentrations[1] of pollutants in the remnant effluent (Horner 2010).

SYNOPSIS OF THE SCIENCE

Aquatic Biological Patterns in Relation to Land Use/Land Cover

Research was initiated at the University of Washington in 1994 to test the broad hypothesis that watershed and riparian characteristics determine habitat conditions, which, in relation to evolved organism preferences and tolerances, set the composition of the biological communities (i.e., the premise represented by Figure 1 above). This hypothesis was tested across a gradient of urbanization, as represented by the total impervious area (TIA) as a proportion of the entire watershed area draining to a stream sampling point. Biological health was assessed according to: (1) the benthic index of biotic integrity (B-IBI) and (2) the ratio of young-of-the-year coho salmon (*Oncorhynchus kisutch*, a relatively stress-intolerant fish) to cutthroat trout (*Oncorhynchus clarkii*, a more stress-tolerant species). B-IBI is a benthic (streambed-dwelling) macroinvertebrate community measure composed of multiple variables expressing the presence of certain species or organism types (Fore, Karr, and Wisseman 1996).

[1] Pollutant concentration is the mass per unit volume of a water sample. Loading is the mass delivered per unit time and equals the multiplication product of concentration times flow volume over time.

Both biological measures declined with TIA increase without exhibiting a threshold of effect; i.e., declines accompanied even small levels of urbanization (May 1996; Horner et al. 1997; May et al. 1997). However, stream reaches flanked by relatively intact, wide riparian zones in wetland or forest cover exhibited higher B-IBI values than reaches equivalent in TIA but with less riparian buffering. TIA increase also appeared to have less of a negative effect on the biota with a relatively greater degree of upland forest retention. Accompanying LU/LC alteration was a loss of habitat features, like large woody debris and pool cover, and deposition of fine sediments that reduce dissolved oxygen in the bed substrata where salmonid fish deposit their eggs.

With these results in hand, the research turned to investigating in more detail how watershed and riparian zone land cover affects stream biology and devising formal mathematical constructs to increase the utility of the biological and watershed indices as assessment and management tools (Horner, May, and Livingston 2003). Geographic information system (GIS) analysis delineated watershed pervious and impervious cover. GIS data were used to develop a multi-variable Watershed Condition Index (WCI). Variables composing the WCI are either relatively highly correlated to biological indices or were identified in preliminary stepwise multiple and logistic regression exercises as instrumental in linking watershed and aquatic biological states. The WCI is composed of three variables applied in one or more zones (all as percentages of the total area represented by each zone):

VARIABLE ZONE	TIA	Forest Cover[a]	Paved + Urban Grass-Shrub Cover
Overall watershed	X	X	
300-meter wide band on both sides of stream	X	X	X
50-meter wide band on both sides of stream	X	X	

[a] ≥ 86% of pixels in forest cover

Achieving B-IBI ≥ 85 percent of maximum integrity only occurred when WCI was at least 75 percent of the best value, with most of the highest B-IBI scores lying above a WCI of 90. While these watershed conditions are generally necessary for good biological health, they are not sufficient alone, as demonstrated by the numerous points representing lower biological integrity at relatively high WCI values. B-IBI was inevitably below 50 percent of the best if WCI fell beneath 35 percent, and always dropped again to under 30 percent with WCI less than 20 percent.

Booth et al. (2001) added to the Puget Sound database in research also employing the B-IBI and land cover measures. The work demonstrated that urban land cover correlated approximately equally well with B-IBI at each of three spatial scales (Booth et al. 2001, Morley and Karr 2002): (1) subbasin (i.e., the entire watershed area contributing to the sample point), (2) riparian (a 200-meter-wide buffer on each side of the stream extending the full length of the upstream drainage network), and (3) local (a 200-meter-wide buffer on each side of the stream extending 1 km upstream). Even with the general equivalence of correlations, though, seven of the ten variables that comprise B-IBI were better predicted by subbasin rather than local land cover.

Observations on two streams with multiple sampling locations were revealing in regard to the smaller scales. All Swamp Creek sites had watershed urban land cover of about 60-65 percent, local-scale urban land cover generally around 50 percent, and B-IBI scores in the range 22-32. Little Bear Creek was overall less urbanized, at approximately 50 percent for the watershed; but urban land cover varied from 32 to 71 percent at the local scale. In that stream B-IBI ranged with the local urban land cover from 40 to 16, demonstrating the strong effect of nearby urbanization (Booth et al. 2001). These results and those of Horner, May, and Livingston (2003), through somewhat different analyses, thus consistently demonstrated the principal role of watershed-scale land use and cover and the secondary, but still important, function of cover near streams, in general, and in the riparian corridor in particular.

McBride and Booth (2005) examined physical habitat conditions at 70 sites on three urban streams and a non-urban reference stream. They found that the independent variables "intense and grassy urban land" in the watershed overall and in a zone within 500 meters of the site, as well as "proximity of a road crossing" best explained variance in habitat in the three urban streams. Analyses of longitudinal trends within the three urban watersheds showed that conditions improved when a stream flowed through an intact riparian buffer with forest or wetland vegetation and without road crossings.

McBride and Booth (2005) concluded that a strategy that imposes only a watershed-wide limit on development to protect streams is inadequate. Local land cover is also important to physical stream conditions, and therefore this zone of the watershed should have high priority in planning and regulations. If urban development can proceed while maintaining intact, undeveloped riparian buffers, the impact of urbanization should be less than from traditional development patterns. The results also suggest restoration potential for degraded urban streams. If riparian buffers can be reforested and road crossings eliminated or avoided in certain reaches of streams in watersheds with moderate urbanization, partial recovery of a stream's physical and biological integrity is possible.

Hydrology Linkages with Land Use/Land Cover and Aquatic Biology

The regional research described above also examined the occurrence and consequences of what is often termed hydrologic "flashiness;" i.e., the frequency and rapidity of short-term changes in stream flow, especially during runoff events (Baker et al. 2004). Flashiness can be expressed in a number of ways. One productive measure was the ratio of the 2-year frequency peak flow rate to the winter (October 1-April 30) base flow rate characteristic of each stream, obtained generally through modeling verified with stream flow records when available (Cooper 1996, Horner et al. 1997, May et al. 1997). The highest biological integrity (> 90 percent of maximum possible B-IBI) was possible only if the ratio remained below 10, as it did only with TIA < 5 percent. Ratios above 30, always the case with TIA > 45 percent, were associated with invertebrate communities exhibiting indices half or less of the maximum B-IBI. These results demonstrate the use of an **indicator** (2-year Peak:Winter Base Flow Ratio), conclusively linked to both watershed conditions and aquatic biological health, and identification of **targets** (e.g., indicator value < 10) necessary to meet a protection **goal** (e.g., B-IBI > 90 percent of maximum).

Booth et al. (2001) and Konrad and Booth (2002) gave substantial attention to the contrast of storm and base flow patterns (i.e., hydrologic flashiness) that are likely to have a persistent influence on the biological conditions of streams. They defined three hydrologic statistics and related them to B-IBI. The two with the most strengths and least limitations are: (1) T_{Qmean}—fraction of a year that mean daily discharge rate exceeds annual mean discharge for a forested condition; and (2) $T_{0.5y}$—cumulative duration that stream flow exceeds the discharge of a flood occurring, on average, twice a year. T_{Qmean} is a reliable meaasure of hydrologic change over time in a stream basin, but it varies with drainage area and other physiographic conditions. $T_{0.5\ yr}$ shows little sensitivity to drainage area but must be estimated using discharge data of high temporal resolution (e.g., 15-minute or hourly) from a period of multiple years.

The highest levels of biological integrity (B-IBI > 80 percent of the maximum) occurred only with T_{Qmean} > 0.35 and $T_{0.5yr}$ > 0.03. These statistics, along with the the 2-year Peak:Winter Base Flow Ratio described earlier, are candidate hydrologic indicators for assessing watershed-hydrology-aquatic biology linkages.

Researchers elsewhere have also taken an interest in possible indicators linked to watershed conditions and aquatic biology (e.g., Richter et al., 1996, 1997, 1998; Clausen and Biggs 2000; Baker et al. 2004). Altogether, the various workers have introduced more than 50 hydrologic metrics. King County investigated the utility of many of them as a first step in developing a valid and defensible set of hydrologic and biological indicators as a basis for flow assessment and formulating flow management actions (Cassin et al. 2005). DeGasperi et al. (2009) performed additional evaluation of a subset of 15 metrics for the strength of their associations with urbanization and biological response and relative insensitivity to potentially confounding variables. Indicator selection for this project made heavy use of this work.

Water and Sediment Quality Linkages with Land Use/Land Cover and Aquatic Biology

Setting water quality criteria, generally in terms of concentrations in receiving waters, is well institutionalized in Washington and other states. Ironically, though, water quality variables have not been directly examined in the same detail as hydrologic metrics in relation to watershed conditions and actual aquatic biological responses. Perhaps the relative dearth of equivalent research stems from the large number of pollutants with numerical criteria and the even much larger number of water contaminants emanating from point and dispersed sources of pollution. Also, the strong role of hydrology in determining the health of the Pacific Northwest's salmonid spawning and rearing streams has been recognized for at least 30 years (e.g., Pederson, 1981; Richey et al., 1981; Perkins, 1982; Richey, 1982; Scott et al., 1986).

The research beginning in 1994 at the University of Washington described above did give substantial attention to the subject (Bryant 1995, May et al. 1997, Horner et al. 1997). Water quality was examined in wet and dry season base flow and during runoff from a range of storm sizes. Storm event mean concentrations of several water quality variables were found to be related to both storm size and TIA. B-IBI was significantly, negatively correlated with total suspended solids (TSS) and total zinc. However, zinc concentrations were well below regulatory water quality criteria with TIA < 40 percent, beyond which those concentrations approached and in some cases exceeded the criteria.

Sediment metals concentrations were also measured and compared to effect thresholds set by Washington Department of Ecology (1991). Lead and zinc concentrations were significantly correlated with TIA (positively) and B-IBI (negatively). However, sediment metals concentrations never approached the thresholds and did not exhibit a consistent increase until TIA was above 40 percent (Bryant 1995, May et al. 1997, Horner et al. 1997). It thus did not appear that water column or sediment contamination could explain the biotic decline seen at relatively low and moderate levels of urbanization, which appeared to be associated more strongly with hydrologic alteration. However, reduced water quality would be an additional burden to aquatic life, along with hydrologic stress, at greater levels of urbanization.

INDICATOR SELECTION

Procedure

As addressed above, the central focus of this project is to identify the most cost-effective combination of stormwater management practices to meet stream habitat targets necessary to achieve defined goals offering protection or enhancement of aquatic biological integrity for most of WRIA 9. The intention is to set numeric stream habitat targets on the basis of a small set of hydrologic and water quality indicators with documented linkages to watershed conditions on the one hand and aquatic biological community integrity on the other. An initial task, therefore, was selecting effective indicators, to be followed by establishing the targets. The search was broadest for hydrologic indicators, because the project scope *a priori* had been delineated to concentrate on TSS as the water quality indicator (Simmonds et al. 2010). However, in the next phase of work relationships will be explored between TSS and other water quality variables having known aquatic biological effects, often the subject of water quality criteria, and supported by data collected mainly within WRIA 9.

As the first step, all potential hydrologic indicators were gathered. This collection went beyond the measures of "flashiness" discussed earlier to include the full range of hydrologic metrics introduced in the literature. The full compilation was pared to some degree based on the King County work described earlier to produce a candidate list. It should be noted that the hydrologic metrics considered are those most related to the patterns represented by stormwater discharges. Washington has issued flow guidelines pertaining only to low flows, mainly applying to water withdrawals from relatively large rivers. The elevated flows associated with stormwater discharges are of considerable interest not only in those cases but also in relatively small streams (i.e, third order and smaller) hosting salmonid spawning and rearing.

Next, selection criteria were drafted, reviewed by the full project team, and refined. Candidates were evaluated relative to criteria based on objective evidence (e.g., documented statistically significant correlation between candidate indicator and criterion variable). The evaluations were then tallied for each candidate and each criterion and compiled for all criteria to reach final selections.

Candidate Hydrologic Indicators and Evaluation Criteria

Attachment A lists and defines all candidate hydrologic indicators. The assessment considered 20 candidates classified in five groups based on similarity in the hydrologic phenomena represented.

The criteria for final selection among candidates were:

1. Extent and quality (relative certainty) of the research database linking the metric to watershed land use/land cover, and demonstrated ability to track trends in these system components and support adaptive management;

2. Extent and quality (relative certainty) of the research database linking the metric to aquatic biological integrity, and demonstrated ability to track trends in these measures;

3. Demonstrated ability of the metric to be established reliably by the available stream gauge data and calculated by HSPF in relatively good agreement with gauge data;

4. Relatively independence from potentially confounding variables (basin area, channel slope, soil type, elevation, precipitation);

5. Ability to add information independent of other metrics;

6. Strength of the basis for setting numerical targets for the metric; and

7. Ability to obtain SUSTAIN model output for the metric.

The principal reference for applying criteria 1 and 2 was the work by DeGasperi et al. (2009), which investigated correlations between hydrologic metrics and measures of urbanization and biological integrity on 16 streams with continuous flow gauge records. The results were generally consistent with those of Cassin et al. (2005), which used gauged and HSPF-generated flow data on a somewhat larger number of sites but drawn from fewer different watersheds. Also, that work covered some metrics of potential interest not assessed by DeGasperi et al. (2009), notably Time above 2-year Mean Flow and Onset of Fall Flows. The latter metric is problematic in that the 7-day minimum flow often does not actually occur in the fall season. Subsequent work under this project constraining the period to September 1-November 30 found a lack of significant correlation between the metric and TIA and B-IBI, and it was dropped from further consideration. The King County work did not consider the 2-Year Peak:Winter Base Flow Ratio candidate indicator, and the data of Cooper (1996) were used to evaluate it.

The analysis of Cassin et al. (2005) of the significance of correlations between metric values computed from gauged and modeled data was the primary basis for judging candidate adherence to criterion 3. Cooper (1996) did not independently calculate values of 2-Year Peak:Winter Base Flow Ratio with both data types, and thus a correlation analysis could not be done in this case.

DeGasperi et al. (2009) was the main source for assessing criteria 4 and 5. Cooper's (1996) data were employed under this project to do an equivalent analysis of potentially confounding variables for the 2-Year Peak:Winter Base Flow Ratio candidate. Judgments by Cassin et al. (2005) and participants in this project added to evaluating candidates for ability to add independent information.

Criterion 6 was ultimately judged to be equivalent to criterion 2, because the ability to set a target for an indicator is directly related to the extent and quality of the database linking it to biological integrity. Criterion 7 did not come into the selection, because the hydrologic output available from SUSTAIN applies no better to calculating one metric than another.

<u>Application of Criteria to Select Hydrologic Indicators</u>

Table 1 ranks the candidates according to criteria 1 and 2 based on the correlation coefficients in cases where there is a significant correlation ($p < 0.01$) between the candidate indicator and TIA or B-IBI, respectively. The table designates those metrics that meet criterion 3 by having a significant correlation between values computed from gauged and HSPF data. As attested by table notes, there is little distinction among the candidates for criteria 4 and 5, because most are independent of potentially confounding variables; and only two have a clear ability to add information independent of others, at least those ranking highly in terms of the first three criteria.

The exercise revealed two clear choices for indicators, High Pulse Count and High Pulse Range. Most other candidates significantly correlated to both TIA and B-IBI are subject to potentially confounding variables. Time above 2-Year Mean Flow is not subject to this drawback, and 2-Year Peak:Winter Base Flow Ratio is considered by the project team to be in the same category. Both can add information independent of the two pulse indicators. Although neither have demonstrated close correspondence in computation results from both gauged and modeled data, their close associations with LU/LC and biological measures and ability to add information were taken as overriding considerations. Accordingly, they were also selected as indicators.

Table 1. Ranking of Candidate Indicators for Criteria 1-3

Candidate Indicator	Criterion 1	Criterion 2	Criterion 3	Notes
Low Pulse Count	ns[a]	7	sig[a]	
High Pulse Count	4	2	sig	Strong match with criteria 1-3
Low Pulse Duration	8	4	ns	
High Pulse Duration[b]	7	3	ns	
Low Pulse Range	ns	ns	ns	
High Pulse Range	2	1	sig	Very strong match with criteria 1-3
7-day Annual Minimum Flow	ns	ns	ns	
Date of the 1-day Minimum Flow	ns	ns	ns	
Onset of fall Flows[c]	ns	ns	sig	
Fall count	ns	ns	ns	
Rise Count	ns	ns	ns	
Fall Rate	ns	ns	sig	
Rise Rate	ns	ns	ns	
Flow Reversals[b]	5	8	ns	
T_{Qmean}[b]	ns	6	sig	
R-B Index[b]	3	5	ns	
Time above 2-Year Mean Flow[c]	1	10	ns	Strong match with criteria 1-2; potential ability to provide independent information
2-Year Peak:Winter Base Flow Ratio [c]	6	9	na[a]	Strong match with criteria 1-2; potential ability to provide independent information
Normalized Effective Stream Power	ns	ns	ns	
$Q_{2\ current}$:$Q_{10\ forested}$	ns	ns	ns	

[a] ns—not statistically significant correlation between candidate indicator and TIA (criterion 1) or B-IBI (criterion 2); sig— significant correlation at $p < 0.01$; na—not available
[b] Significantly correlated with a potentially confounding variable and thus does not meet criterion 4
[c] Not highly correlated with other candidates and therefore can provide independent information according to criterion 5

In addition to ranking highly in extent of correlation with TIA, the two pulse indicators are highly correlated with two other LU/LC measures. DeGasperi et al. (2009) found High Pulse Range to rank first and High Pulse Count second in correlation with percent urban land cover and percent forest cover.

Along with being significantly correlated with B-IBI, the selected indicators all have relatively strong associations with other biological system components as well. As shown by Cassin et al. (2005), High Pulse Count is significantly correlated with two B-IBI components, clinger invertebrates and total number of taxa that have one or fewer generations per year (univoltine plus semivoltine taxa). Time above 2-Year Mean Flow is significantly correlated with those two variables plus Baetids, a mayfly family. High Pulse Count has a significant correlation with univoltine plus semivoltine taxa. Work under this project with Cooper's (1996) data showed that the 2-Year Peak:Winter Base Flow Ratio is significantly correlated with the ratio of young-of-the-year coho salmon to cutthroat trout at $p < 0.05$ (but not $p < 0.01$).

Further Discussion of Selected Hydrologic Indicators

Figures 3 to 6 graphically portray the four chosen hydrologic indicators. Figures 3 and 4 compare high-flow pulses with urban development versus pre-developed LU/LC. A greater high pulse count and range tend to accompany development. Figure 3 shows a high pulse range from a date in November to late June, while pre-development the range extended from December to April. A protection goal in this case would be to apply stormwater management to hold the high pulse count and range within the current parameters, while a partial restoration goal could be controlling runoff discharges to reduce the count and range toward the former state.

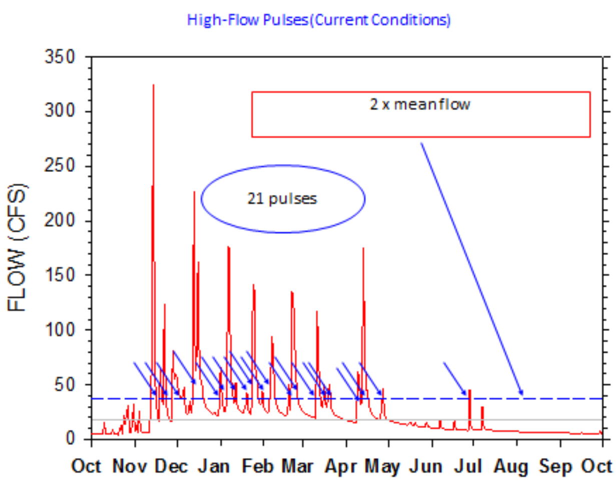

Figure 3. Hydrograph Displaying High-Flow Pulses with Developed Land Use/Land Cover

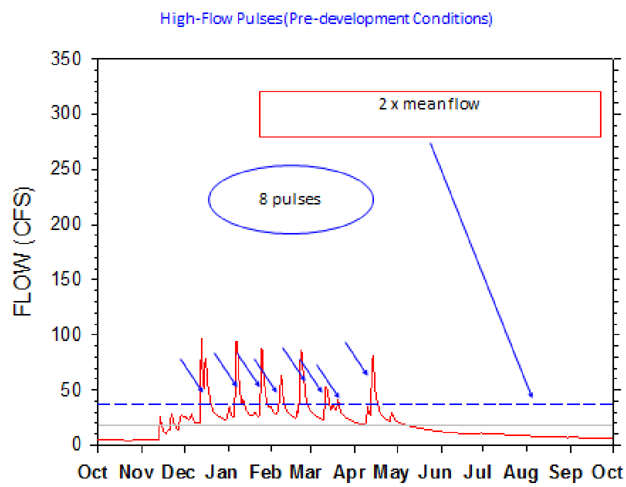

Figure 4. Hydrograph Displaying High-Flow Pulses Pulses with Pre-development Land Use/Land Cover

Figures 5 and 6 depict the remaining two selected hydrologic indicators. Time above the 2-Year Mean Flow Rate is found as a count of days on which the flow rate exceeds the long-term mean 2-year frequency return rate. The latter quantity is also the basis for determining the 2-Year Peak:Winter Base Flow Ratio. Values of both indicators tend to increase with landscape conversion from natural to developed LU/LC.

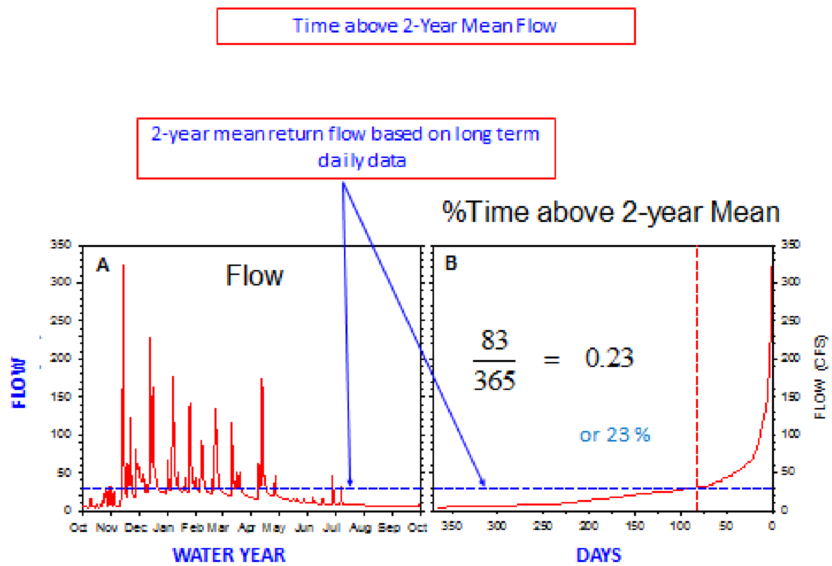

Figure 5. Hydrograph Illustrating Determination of Time above 2-Year Mean Flow Rate

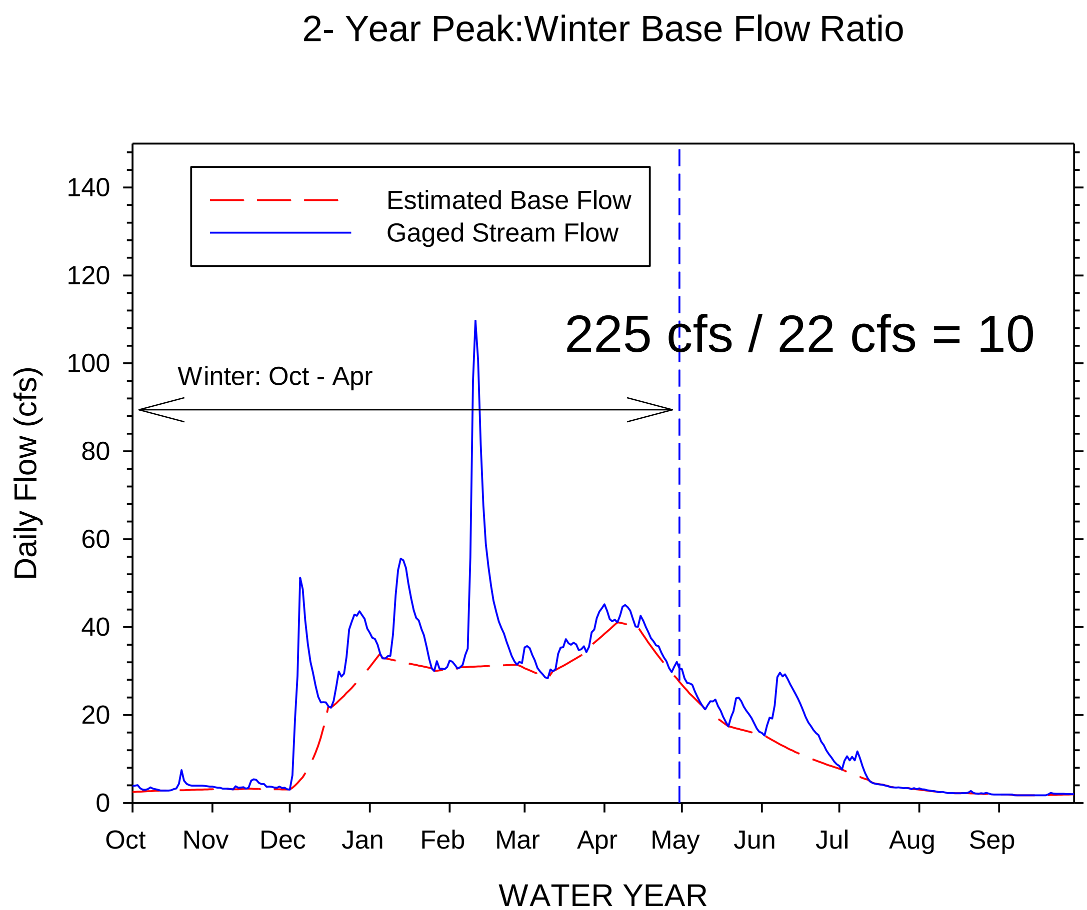

Figure 6. Hydrograph Illustrating Determination of 2-Year Peak:Winter Base Flow Ratio (note: 2-year frequency peak flow rate did not occur in the year portrayed)

Water Quality Indicators

As pointed out above, the project scope designated TSS as the principal water quality indicator. The primacy of sediments is appropriate, in that they are an instrumental feature of water quality because of their numerous ecological consequences, including:

- Covering and seeping into coarse bed materials where fish spawn and eggs develop; in filling the pore spaces, sediments restrict the flow of water carrying dissolved oxygen, resulting in asphyxiation of the young;
- Covering the surfaces serving as habitat for fish food sources (e.g., insects, algae);
- Filling deeper areas, tending to produce a more homogeneous bed and less habitat diversity and specifically reducing pools where fish rest and seek refuge from predators;
- Reducing visibility, making it harder for fish to find food and avoid predators;
- Reducing light penetration to underwater plants and algae;
- Abrading the soft tissues of fish, especially gills; and
- Transporting other pollutants present in the soil or picked up in transport.

Regarding the latter impact, sediments are a transport medium for many contaminants in other categories of water pollutants: metals, organic chemicals, nutrients, and pathogens.

Despite this high level of importance, the association between TSS, or any other measure of sediments, and biological integrity has not been established or even much investigated for regional streams. Unlike with the selected hydrologic indicators, therefore, a basis does not exist to set TSS targets to meet specific goals for the protection or restoration of aquatic life.

Furthermore, water quality criteria are not formulated in terms of TSS. Turbidity, a measure of the light scattering ability of particles suspended in a water sample, is a basis for existing criteria. However, SUSTAIN provides only TSS as sediment output and not turbidity. Other criteria are stated as concentrations of specific metals (as dissolved quantities), organic chemicals, and pathogen indicator organisms. SUSTAIN does model metals discharge. There is a strong interest in this project in evaluating in some way the ability of stormwater management strategies to aid in meeting at least some of these water quality criteria and advancing protection and restoration goals.

Fortunately, a previous King County project in the Green River watershed produced a large database containing TSS, turbidity, three metals (copper, lead and zinc, all in both total recoverable and dissolved forms), and phosphorus (total and orthophosphate), as well as flow rate. The database has over 1000 measurements for TSS and turbidity and almost 900 for the other contaminants. These large numbers offer at least potential ability to develop statistical relationships between TSS and other measures with strong confidence levels. Work to proceed as a next step in this project will investigate relationships between TSS and each of the other water quality variables and between dissolved metals and both total recoverable metals and flow rate.

Depending on the results of this investigation, the project could proceed in one or more directions, such as

- TSS targets could be set at values ranging from not surpassing a high concentration associated with a developed condition to selected reduction levels down to as low as the concentration associated with forested land cover. While these selections would not have an immediate tie to biological outcomes, they could be related to the results of applying hydrologic controls. Broad stormwater management actions, such as LID methods, reduce both high-flow and water quality impacts. As discussed above, the research has shown that hydrologic alteration has a greater negative effect on Puget Sound stream biological integrity than water quality degradation until development reaches a moderately high level of urbanization. Therefore, if management were pointed first at controlling hydrology, the SUSTAIN TSS output for that strategy could be compared to TSS targets to see if, indeed, a protection goal of no further water quality degradation would be met or, alternatively, how much TSS reduction would occur toward meeting a restoration goal.

- If a statistically justified relationship (or a set of relationships for different portions of the watershed) between TSS and turbidity is found, turbidity targets could be set on the basis of water quality criteria, translated to TSS based on the relationship(s), and used to gauge the effectiveness of stormwater management scenarios.

- If reasonably strong relationships are found linking TSS, total recoverable metals, and dissolved metals, a judgment could be made about the probability of meeting metals water quality criteria as a function of success in controlling TSS.

- If very strong relationships are found linking TSS, total recoverable metals, and dissolved metals, metals targets could be set on the basis of water quality criteria and investigated in the same way as described for turbidity.

Before the team proceeds, these possibilities will be discussed with participants in the project's first workshop. The advice received will be taken into account in performing the investigation and utilizing its results.

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ATTACHMENT A: CANDIDATE HYDROLOGIC INDICATORS AND THEIR DEFINITIONS

GROUP 1: PULSE METRICS

Note: A low-flow pulse is defined as the occurrence of daily average flows that are equal to or less than a low-flow threshold set at half (50 percent) of the long-term mean daily flow rate. A high-flow pulse is defined as the occurrence of daily average flows that are equal to or greater than a high-flow threshold set at twice (two times) the long-term mean daily flow rate.

Low Pulse Count— Number of days each calendar year that discrete low flow pulses occur

High Pulse Count— Number of days each water year that discrete high flow pulses occur

Low Pulse Duration—Mean number of days per occurrence that the daily time-step hydrograph is below the low-flow threshold for each calendar year

High Pulse Duration—Mean number of days per occurrence that the daily time-step hydrograph is above the high-flow threshold for each water year

Low Pulse Range— Range in days between the start of the first low-flow pulse and the end of the last high flow pulse during a calendar year

High Pulse Range— Range in days between the start of the first high-flow pulse and the end of the last high flow pulse during a water year

GROUP 2: MINIMUM FLOW METRICS

7-Day Annual Minimum Flow—Minimum mean flow rate over a 7-day period for each calendar year

Date of the 1-Day Minimum Flow—Julian date of each annual daily minimum flow

Onset of Fall Flows—Julian date of the day after the annual 7-day minimum flow period for the dry season

GROUP 3: HYDROGRAPH PATTERN METRICS

Fall Count—Number of days for each water year in which the change in daily flow from the previous day is more than 10 percent of the current day’s flow rate and declining

Rise count—Number of days for each water year in which the change in daily flow from the previous day is more than 10 percent of the current day’s flow rate and rising

Fall Rate—Mean rate of fall for all falling portions of the daily time-step hydrograph for each calendar year

Rise Rate—Mean rate of rise for all rising portions of the daily time-step hydrograph for each calendar year

Flow Reversals—Number of times per water year that a trend change occurred in the daily time-step hydrograph (rising to falling limb or falling to rising limb, except for minor variations [< 2 percent])

GROUP 4: FLASHINESS METRICS

T_{Qmean}—Fraction of the time in each water year that the daily time-step hydrograph exceeds the annual mean discharge for that year

Richards-Baker (R-B) Index—Mean daily rate of change (absolute value) of daily time-step hydrograph for each water year

Time above 2-Year Mean flow—Fraction of the time in each water year that the daily time-step hydrograph exceeds the 2-year mean flow rate for a forested condition

GROUP 5: RELATIVE STREAM POWER METRICS

2-Year Peak:Winter Base Flow Ratio—Ratio of peak flow rate with a 2-year return frequency to the mean base flow rate during the period October 1-April 30

Normalized effective Stream Power—Percentage increase in stream power (rate of energy dissipation against the bed and banks of a stream) between forested condition and point in time of analysis

$Q_{2\ current}$:$Q_{10\ forested}$—Ratio of hourly flow rate with a 2-year return frequency at point in time of analysis to the hourly flow rate with a 10-year return frequency in a forested condition