Fall 2018

Evaluation of the Stream Function Assessment Methodology (SFAM) in watersheds of the Puget Sound lowlands

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Recommended Citation

Bahnick, Michelle, "Evaluation of the Stream Function Assessment Methodology (SFAM) in watersheds of the Puget Sound lowlands" (2018). *WWU Graduate School Collection*. 798.
https://cedar.wwu.edu/wwuet/798

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By

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Accepted in Partial Completion
of the Requirements for the Degree
Master of Science

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Master's Thesis

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November 2, 2018

Evaluation of the Stream Function Assessment Methodology (SFAM) in watersheds of the Puget Sound lowlands

A Thesis
Presented to
The Faculty of
Western Washington University

In Partial Fulfillment
Of the Requirements for the Degree
Master of Science

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November 2018

ABSTRACT

Effective protection, restoration, and mitigation efforts require identification of anthropogenic degradation effects on stream functioning and ecosystem services. However, few stream assessment protocols aim to evaluate the processes that generate and maintain stream ecosystems, integrate multiple disciplines, or combine stream reach assessment with landscape-level context. To address these shortcomings, the Willamette Partnership collaborated with the Oregon Department of State Lands, the US Environmental Protection Agency, and the US Army Corps of Engineers to develop the Stream Function Assessment Methodology (SFAM). SFAM aims to provide a more comprehensive rapid stream assessment through multimetric ratings for hydrological, geomorphological, biological, and water quality stream functions than is currently available. During development, Willamette Partnership vetted this protocol against scores generated from best professional judgement at 39 streams throughout Oregon, but has not tested SFAM against other established protocols. Addionally, some SFAM metrics have no equivalent data sources outside of Oregon. To evaluate the feasibility and accuracy of SFAM to determine stream degradation, I conducted SFAM (November 2015 draft version) on 36 stream reaches in Water Resource Inventory Area 8 in King and Snohomish Counties, WA. I used correlations to assess the final SFAM scores, individually and combined through Principal Components Analysis, compared to commensurate data from the King County WRIA 8 Status & Trends Monitoring Program and the WA State Department of Ecology Puget Sound Watershed Characterization Project. I also evaluated the potential effects of unavailable data inputs using simplified sensitivity analyses.

Overall, SFAM function scores did not correlate with measures of anthropogenic degradation or stream condition, while SFAM value scores were generally higher in reaches with more watershed-level anthropogenic degradation. SFAM function scores rarely correlated with the Benthic Macroinvertebrate Index of Biotic Integrity, percent watershed imperviousness, and Status & Trends metrics. The high proportion of SFAM function metrics measuring physical structures in the riparian area may have caused the general lack of correlation. SFAM value scores generally indicated higher hydrology, geomorphology, and biology value in reaches with more developed watersheds, reflecting sensitivity to watershed-level anthropogenic degradation but not necessarily functioning of stream processes. In contrast, SFAM generally indicated higher water quality value in less disturbed reaches, but only outside of Urban Growth Areas. The sensitivity analyses revealed small, predictable changes in SFAM outputs when unknown metric inputs were varied, suggesting that SFAM is fairly robust to unknown data when comparing across streams. However, the changes were not consistent across metrics.

A rapid assessment of stream functions like SFAM could help quantify mitigation efforts. A final version of SFAM was released in June 2018; however, many of the potential concerns identified through these analyses remain relevant. Future studies of SFAM should focus on verification of scores through comparison with direct measures of stream function and across a broader spectrum of stream condition and location. Additionally, further evaluation should assess SFAM's ability to differentiate between pre- and post-management actions on the same reach, as would occur with mitigation credit and debit calculations.

ACKNOWLEDGMENTS

There are many people and organizations without whom this project would not have happened. First, I would like to thank my thesis advisor, Dr. David Hooper, and my thesis committee members, Dr. Merrill Peterson and Dr. John Rybczyk. Thank you to Nicole Manness and Willamette Partnership for letting me assess SFAM in addition to providing feedback and answering questions. I would also like to thank Chris Gower for his help collecting field data. A special thank you to the Biology Department stockroom and office staff, especially Peter Thut and Mary Ann Merrill, for troubleshooting, loaning me gear, and getting forms figured out. Thanks as well to the R community at large for providing open-access code and trouble-shooting for statistics. Many thanks also to my fellow biology graduate students, friends, and family for providing advice and encouragement, acting as a sounding board, and being an excellent support network. This project could not have happened without access to stream sites and data. Thank you to Scott Stolnack and Dan Lantz at King County for guidance on selecting and accessing stream reaches throughout WRIA 8. Additional thanks for permission and advice for accessing stream reaches to Wayne Miller, Kit Paulsen, Dwayne Paige, Barbara DeCaro, Joe Starstead, Frank Leonetti, Emily Drushcba, Tom Hardy, Brian Ballard, Paul Footen, Dana Zalteff, and Peter Kiffney. Additional thanks to Glenn Griffith, Ali Tabaei, Ryan Thompson, and Paul Adamus for providing information on context data in Washington. Thank you. This research was funded by the WA State Lake Protection Association Dave Lamb Memorial Scholarship, the WWU Biology Department Hodgson Graduate Fellowship, the Biology Alumni Fellowship for Student Research, the Biology Faculty Fellowship Fund, the Fraser Scholarship, and the WWU Graduate School Fund for the Enhancement of Graduate Research.

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INTRODUCTION

Overview

The effects of increased development on stream ecosystems have led to policies and management strategies aimed to protect, restore, and mitigate anthropogenic damage to stream ecosystem services. Section 404 of the Clean Water Act, the primary policy regulating surface waters in the United States, mandates that development must limit impacts on the processes that create and maintain aquatic ecosystems (functions) and mitigate unavoidable impacts (Kimbrell 2016). As a consequence of unavoidable impacts, compensatory mitigation costs nearly $3 billion annually in the United States (Environmental Law Institute 2007, Bronner et al. 2013). Additionally, river and stream restoration has been conservatively estimated to cost over $1 billion annually (in 2005 dollars) in the United States (Bernhardt et al. 2005). However, mitigation and restoration projects frequently remain unevaluated for effectiveness at improving impaired stream functions (Bender and Ahn 2011, Jähnig et al. 2011, Doyle and Shields 2012, Palmer et al. 2014, Barnas et al. 2015). The deficit of adequate evaluation has contributed to projects failing to restore lost aquatic functions, insufficient information to determine effective strategies, and inefficient site selection for projects (Bronner et al. 2013, Mathon et al. 2013, Railsback et al. 2013, Habberfield et al. 2014).

The Puget Sound region is no exception to the above issues. Approximately four million people live in the region with one million more expected by 2040 (Puget Sound Regional Council 2016). Growing human populations and subsequent development drive multiple mechanisms that cause stream degradation including increased impervious land cover, increased water conveyance through piping, removal of native vegetation, and increased agricultural intensity (e.g., Allan and Castillo 2009, Bierman and Montgomery 2014). Additionally, the listing of Puget Sound Chinook salmon as a federally threatened species spurred the collaborative creation of the Puget Sound Chinook Recovery Plan, which established adaptive management plans for Chinook conservation in Puget Sound watersheds (King County 2005, NOAA Fisheries West Coast Region 2017). Within the Puget Sound region, agencies have spent hundreds of millions of dollars on salmon conservation and restoration projects (Barnas et al. 2015). Most of these restoration efforts focus on stream habitat structure (e.g., adding boulders or woody debris, planting native riparian vegetation, removal of bank armoring) and are rarely evaluated for biological effectiveness (Morley and Karr 2002, O'Neal et al. 2016). Having an assessment protocol to rapidly quantify the effects of mitigation and restoration on stream functions could inform management strategies and greatly improve compliance with regulations.

Considerations for an assessment of stream functions

While existing stream assessment methodologies aim to measure stream processes, none of them includes all of the attributes required for mitigation (e.g., rapid, easily quantifiable and interpretable, and reflecting multiple spatial and temporal scales of stream processes). This may be, in part, due to the difficulty of obtaining direct measurements of functions coupled with the complex interactions of stream attributes. Measurable components of stream functions can span long time frames, may have a delayed response to management actions, and can require specialized and potentially costly equipment (Doyle and Shields 2012, Yeung et al. 2017). For example, detecting changes in streamflow can require decades of continuous flow data using a stream gauge to generate representative measurements (Gordon et al. 2004). Without previously existing data, a rapid assessment would need to use surrogate metrics to capture important components of the less accessible processes. Surrogate metrics can provide rapid, effective, and repeatable snapshots of stream condition when validated (Ward et al. 2003, Kilroy et al. 2013, Habberfield et al. 2014, Lisle et al. 2015). However, insufficient knowledge of potential surrogates can lead to ineffective proxies due to confounding variables (Kemp 2014), lack of defined connections between the proxy and the function of interest (Wilhere et al. 2013, Nicholson et al. 2013, Palmer et al. 2014, Bodinof Jachowski et al. 2016), or a lower level of precision (Nichols et al. 2006).

Methodologies can incorporate several approaches to account for the various contributing metrics and the multiple spatial scales that affect stream reaches. Stream functions can affect and be affected by multiple stream- and landscape-scale attributes (Máčka et al. 2010, Dahm et al. 2013, Lisle et al. 2015, Fellman et al. 2015). For example, sediment continuity[1] in a stream reach is driven by the ability of stream flow to transport the material to and out of the reach, the availability of material from upstream and upland sources, and biotic influences like plant roots that can trap sediment (Bierman and Montgomery 2014). In turn, sediment continuity affects bank erosion, channel forms, hydraulic diversity, and habitat availability (Allan and Castillo 2009). One method to capture the information from multiple attributes is through integrating multiple metrics into a single multimetric score representing the overall condition of a stream (Morley and Karr 2002, Blocksom 2003, Schoolmaster et al. 2013). However, interpretation of

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[1] “The balance between transport and deposition of sediment such that there is no net erosion or deposition (aggradation or degradation) within the channel” (Willamette Partnership 2013).

multimetric scores requires understanding the ecological roles of the input metrics and how the metrics are combined to create the score (Morley and Karr 2002, Blocksom 2003). Another approach is pairing reach-level assessments with watershed-level data (e.g., coarse-scale evaluation of the basin) to gain insight into overall stream or basin condition, such as potential causes of degradation (Bender and Ahn 2011, Lisle et al. 2015, Kuehne et al. 2017).

Stream Function Assessment Methodology (SFAM)

To improve compliance with Section 404 of the Clean Water Act[2] and the Oregon Removal-Fill Law[3] in Oregon, the Willamette Partnership developed the Stream Function Assessment Methodology (SFAM; Willamette Partnership 2013). This effort was in collaboration with Oregon Department of State Lands, Region 10 of the U.S. Environmental Protection Agency, and the Portland District of the U.S. Army Corps of Engineers (Willamette Partnership 2013). SFAM aims to combine a variety of stream attributes from different spatial scales to provide a more comprehensive and rapid stream assessment than is currently available (Willamette Partnership 2013). SFAM combines metrics observed in the field or gleaned through office work (e.g., communicating with land managers, GIS analyses) and then integrates the metrics in an Excel spreadsheet that calculates two types of subscores, one for “functions” and one for “values.” SFAM defines functions as “the processes that create and support a stream ecosystem” and values as “the ecological and societal benefits that riverine systems provide”

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[2] Department of Defense, Department of the Army, Corps of Engineers and Environmental Protection Agency 2008

[3] Oregon Department of State Lands 1967

(Willamette Partnership 2013, pg. 6). SFAM calculates the function and value scores in four different stream function categories, hydrology, geomorphology, biology, and water quality, meant to capture different dimensions of stream processes. As an example, hydrology functions entail the movement of water from the watershed to the stream channel, the movement of water through the stream channel, storage of surface water, and the transfer of water between surface water and groundwater. Hydrology values, in contrast, consider the ability of the reach to provide the hydrology functions in the context of how rare those abilities are in the watershed and if they benefit existing infrastructure. As such, a reach that can store water during a flood, for example, has higher societal value than either a reach that cannot store floodwater or a reach that can store floodwater but has no downstream infrastructure that would be protected.

A final version of SFAM was released in June 2018 and has undergone limited testing in Oregon. The developers used expert opinion for initial development of metrics and for feedback regarding draft usability. Subsequently, two evaluators conducted SFAM at 39 reaches throughout Oregon. The SFAM scores from the field testing were compared to ratings of the 11 SFAM functions as determined by best professional judgement conducted by the same two evaluators. SFAM has yet to be evaluated against existing quantitative stream and watershed metrics in Oregon or Washington State. This study used a previous draft (completed in November 2015) and aimed to evaluate the response and potential usability of SFAM in Puget Sound streams. The stream condition data collected by agencies in the Puget Sound region in support of watershed management provided an opportunity to test SFAM against existing data sets that encompassed a broad range of sites, used standard techniques, and assessed both reach and watershed-scale characteristics.

Current stream assessments in the Puget Sound Region

In the Puget Sound region, several government agencies are working to provide data and tools to improve watershed management and policy decisions. These include King County's WRIA 8 Status & Trends Monitoring Program and the Washington Department of Ecology's Puget Sound Watershed Characterization Tool, the two primary data sets used for comparison with SFAM in this study.

1. *King County Status & Trends Monitoring Program (S&T)*

From 2010 to 2013, King County conducted the Water Resource Inventory Area (WRIA) 8 Status & Trends Monitoring Program to inform adaptive management about the effects of anthropogenic development in WRIA 8, as part of the Chinook Conservation Plan (King County 2005). Using a modified U.S. Environmental Protection Agency Environmental Monitoring and Assessment Program (EMAP) protocol (Peck et al. 2006, King County 2015), the Status & Trends Monitoring Program assessed and characterized stream and riparian habitat condition of wadeable salmon streams. The assessments consisted of repeated annual collection of hydrology, geomorphology, habitat, and biotic data at each reach in the study (King County 2005, 2015, Berge 2010). EMAP is a previously validated, but relatively time intensive, national Status & Trends ecological monitoring program (Hughes and Peck 2008, Paul and Munns 2011). The stream assessment data from the Status & Trends Monitoring provided a reach-scale approach against which to test the stream reach attributes assessed by SFAM function scores. King County also measured a variety of other common metrics used to assess potential stream degradation, including percent watershed imperviousness and the Puget Lowland Benthic Macroinvertebrate Index of Biotic Integrity (B-IBI).

Percent impervious. Watershed imperviousness is a widely used proxy for watershed degradation, making it a useful metric against which to test new methodologies. Percent watershed impervious cover is easily and reliably quantified and is generally a good indicator of anthropogenically degraded or at-risk streams (Schueler et al. 2009), making it a good variable against which to test methodologies. Impervious surfaces alter stream hydrology by decreasing local infiltration rates and increasing runoff (Booth and Jackson 1997, Alberti et al. 2007, Chen et al. 2017, Han et al. 2017), increasing winter peak flows while decreasing winter base flows (DeGasperi et al. 2009), and increasing stream flashiness (DeGasperi et al. 2009, Rosburg et al. 2017, Booth and Konrad 2017). Alterations to both watershed and stream hydrology generally increase the transport of fine sediment to streams (Booth and Jackson 1997, Russell et al. 2017) and increase the potential for erosion and degradation of channels (Booth and Jackson 1997, Bledsoe et al. 2012), which simplifies, widens, and deepens channel morphology (Booth and Jackson 1997). The higher runoff and increased fine sediment, in turn, can increase turbidity (Russell et al. 2017) and increase the input of nutrients and other chemical contaminants (DeGasperi et al. 2009, Feist et al. 2011). Additionally, the loss of riparian woody vegetation generally associated with increased imperviousness can also decrease bank stability, increase stream temperatures, reduce leaf litter inputs, and decrease woody debris (Booth and Jackson 1997, Swanson et al. 2017). All of these hydrologic, geomorphic, and water quality alterations, in turn, impair biotic processes and stream biota, including benthic macroinvertebrates (Morley and Karr 2002, DeGasperi et al. 2009) and salmonids (Feist et al. 2011).

Even so, a number of studies have also shown that watershed imperviousness is not a perfect proxy for stream degradation. Watershed imperviousness does not directly measure any aspect of the stream, instead relying on well-established correlations between watershed imperviousness and indicators of stream condition (Wissmar et al. 2004, Allan and Castillo 2009, Harman et al. 2012, Rhea et al. 2015, Beck et al. 2016). Percent impervious does not account for impervious surface connectivity, distance from the stream, or nearly-impervious land cover (Morley and Karr 2002, Alberti et al. 2007, DeGasperi et al. 2009, Schueler et al. 2009, Beck et al. 2016, Kuehne et al. 2017). Other studies have identified percent urban land cover or percent effective imperviousness in the contributing basin as better predictors of stream degradation (Morley and Karr 2002, DeGasperi et al. 2009, Vietz et al. 2014). This study used percent impervious land cover as the proxy for watershed development because it has a longer history in the literature, is more easily understood, is highly correlated with percent urban area in WRIA 8 (tau = 0.883, $p << 0.001$), and was readily available from the Status & Trends Monitoring data. I did not have data for effective imperviousness in the contributing basins.

<u>Benthic Macroinvertebrate Index of Biotic Integrity (B-IBI)</u>. The B-IBI is a well-established and reliable multimetric index that provides an extended snapshot of stream condition (Carter et al. 2017), making it a good variable against which to test new assessment methodologies. Benthic macroinvertebrate populations reflect stream conditions because insect nymphs and larvae, the most common life stages collected in streams, are fairly stationary and constantly immersed in the stream (Harman et al. 2012, Parr et al. 2016). Every SFAM stream function category can

affect B-IBI scores. B-IBI responds to several measures of streamflow in the Puget Sound region, including higher B-IBI scores in reaches with higher average annual flow and less flashy flows (Booth et al. 2001, Morley and Karr 2002, DeGasperi et al. 2009). Increased prevalence of small-sized sediment and embeddedness contribute to lower B-IBI scores in the Puget Sound region (Morley and Karr 2002, King County 2014a). Available food sources can drive the composition of invertebrate species and functional feeding groups within a stream (Allan and Castillo 2009). B-IBI scores in Puget Sound streams also respond to some water quality variables, with lower B-IBI scores in reaches with higher total phosphorus, lower dissolved oxygen, higher turbidity, and, to a lesser degree, highly acidic or alkaline pH (King County 2014a). While B-IBI is widely used and accepted, the use of B-IBI for rapid stream assessment is limited because B-IBI is relatively costly, requires specialized knowledge, and is methodologically intensive (Parr et al. 2016, Carter et al. 2017). While B-IBI has drawbacks as a rapid assessment, this study considered B-IBI to be the best metric against which to test SFAM function scores, for the above reasons, and it was readily available from the Status & Trends Monitoring data.

2. Puget Sound Watershed Characterization Project (PSC)

The Washington State Department of Ecology released the Puget Sound Watershed Characterization Project, currently in the beta-stage, as a landscape-scale decision-support tool for regional and local government planning (Stanley et al. 2015c). The Puget Sound Watershed Characterization Project uses GIS layers to assess the suitability and value of watershed sub-basins for protection, restoration, conservation, or development relative to the other sub-basins within the greater Puget Sound basin (Stanley et al. 2015c). The Puget Sound Watershed Characterization separates the importance and potential of the assessment area to perform ecological functions from human degradation of that potential (Stanley et al. 2015c). The Puget Sound Watershed Characterization Project assesses the relative importance and degradation of water flow processes[4], relative export potential and export degradation of water quality processes[5], and relative conservation value of fish and wildlife habitats (Washington Department of Ecology 2013a). The sub-basins, called assessment units, are determined by the total size of the analysis area, landform types, available sources of data, and planning issues within associated jurisdictions (Stanley et al. 2015c). Within WRIA 8, the average assessment unit size was 1,036 ha but ranged from 26 ha to 3,885 ha. The watershed modeling used by the Puget Sound Watershed Characterization Project provided a larger-scale, process-oriented approach against which to test the watershed attributes assessed by SFAM value scores.

Water Resource Inventory Area (WRIA) 8 stream condition

I used the existing assessments of stream condition in WRIA 8 to test SFAM. WRIA 8 is the most populous WRIA in Washington State, with distinct gradients in urbanization and

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[4] Water flow importance evaluates the potential for each assessment unit to contribute to water-flow processes. Water flow degradation considers human impacts from current land use on the water flow processes (Stanley et al. 2015a).

[5] Water quality export potential refers to the assessment unit's ability to generate and transport contaminants downstream if the system is disturbed. Water quality degradation refers to the levels of pollutants generated by existing land uses in the assessment unit (Stanley et al. 2015b).

elevation (Figures 1-3). The western end of WRIA 8 is low elevation with high levels of development, and includes the cities of Seattle and Bellevue (Berge 2010). The eastern end is higher elevation with limited development and includes the protected Cedar River Municipal Watershed in the western foothills of the Cascade Mountains. WRIA 8 stream condition tends to reflect the overarching urban lowland to rural upland watershed gradient, with degraded streams in the west and healthier streams generally in the east, as indicated by B-IBI scores (King County 2014b, Figure 3). Additionally, the designation of urban growth areas[6] further drives the WRIA 8 development gradient. In this study, reaches with more than 14.2% watershed imperviousness in the contributing basin were all within urban growth areas, while reaches with less than 3.6% watershed imperviousness were exclusively outside of urban growth areas; reaches with 3.6-14.1% watershed imperviousness could be either within or outside of urban growth areas (Figures 2 & 3). WRIA 8 reaches in urban growth areas generally had very poor to fair biological condition, as indicated by B-IBI, while non-urban growth area reaches had good to excellent biological condition[7] (Figure 3).

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[6] Urban growth areas are areas designated for current and future urban growth and development as part of Washington State's population growth management act (Washington State 2010).

[7] The Puget Lowland B-IBI uses five categories of biological condition: very poor (0 to < 20), poor (20 to < 40), fair (40 to < 60), good (60 to < 80), and excellent (80 to 100) (King County 2014).

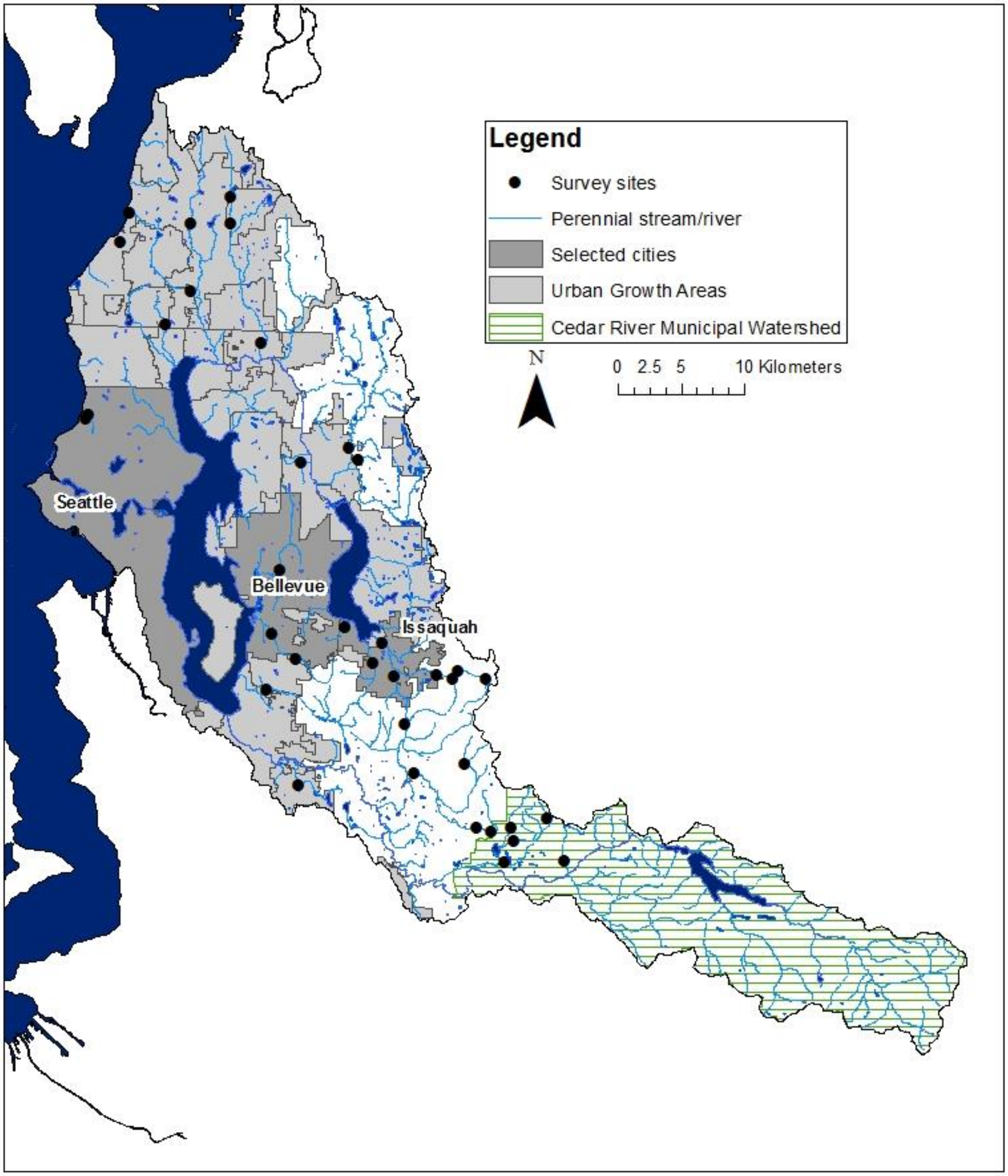

Figure 1. Map of Water Resource Inventory Area (WRIA) 8, including the urban areas in the western lowlands and the protected Cedar River Municipal Watershed in the eastern highlands.

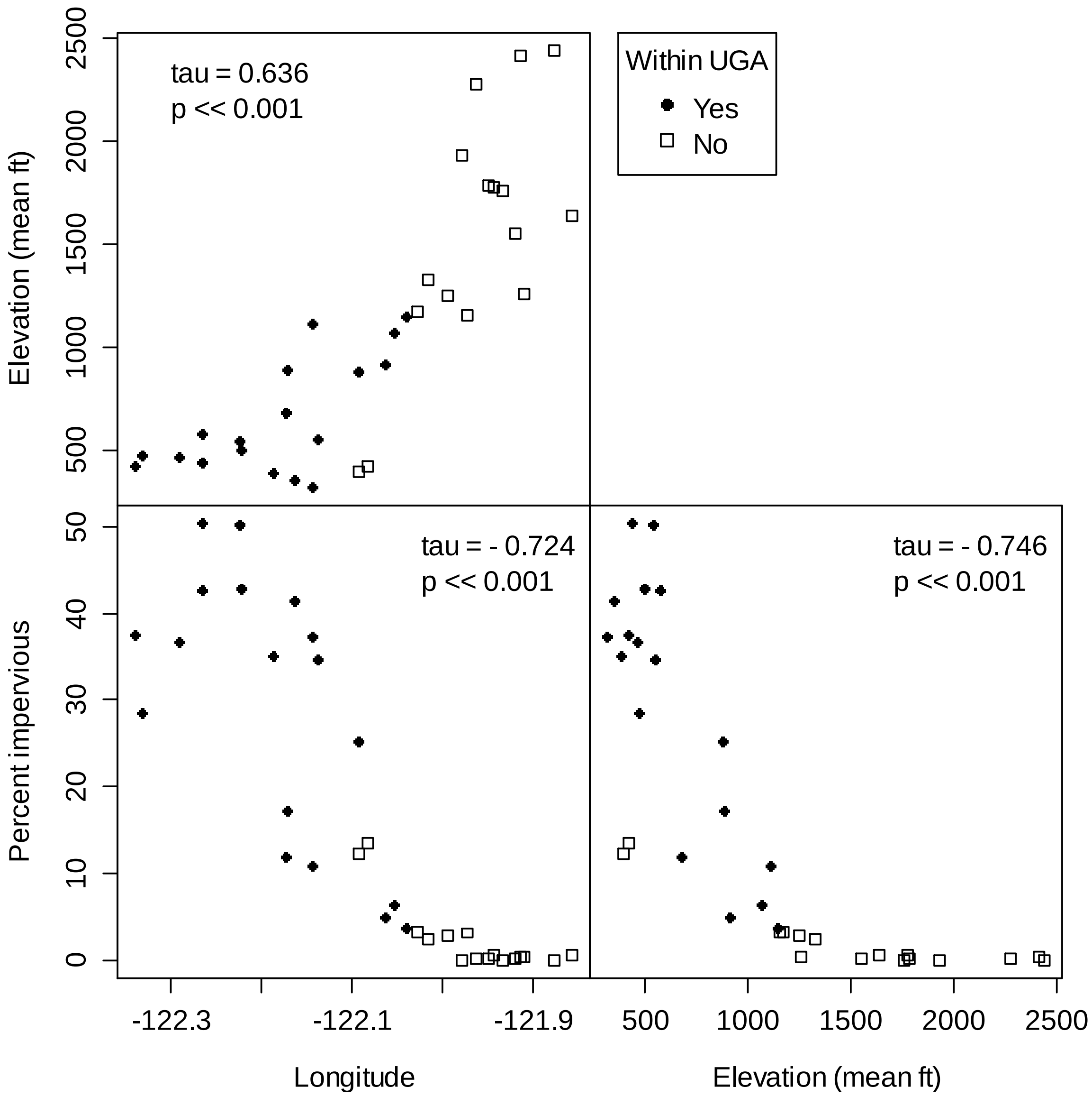

Figure 2. Landscape gradients in Water Resource Inventory Area (WRIA) 8 from King County's WRIA 8 Status & Trends Monitoring Program as reflected by 34 stream reaches throughout the watershed. Metric definitions are in Table S1. UGA refers to designated urban growth areas.

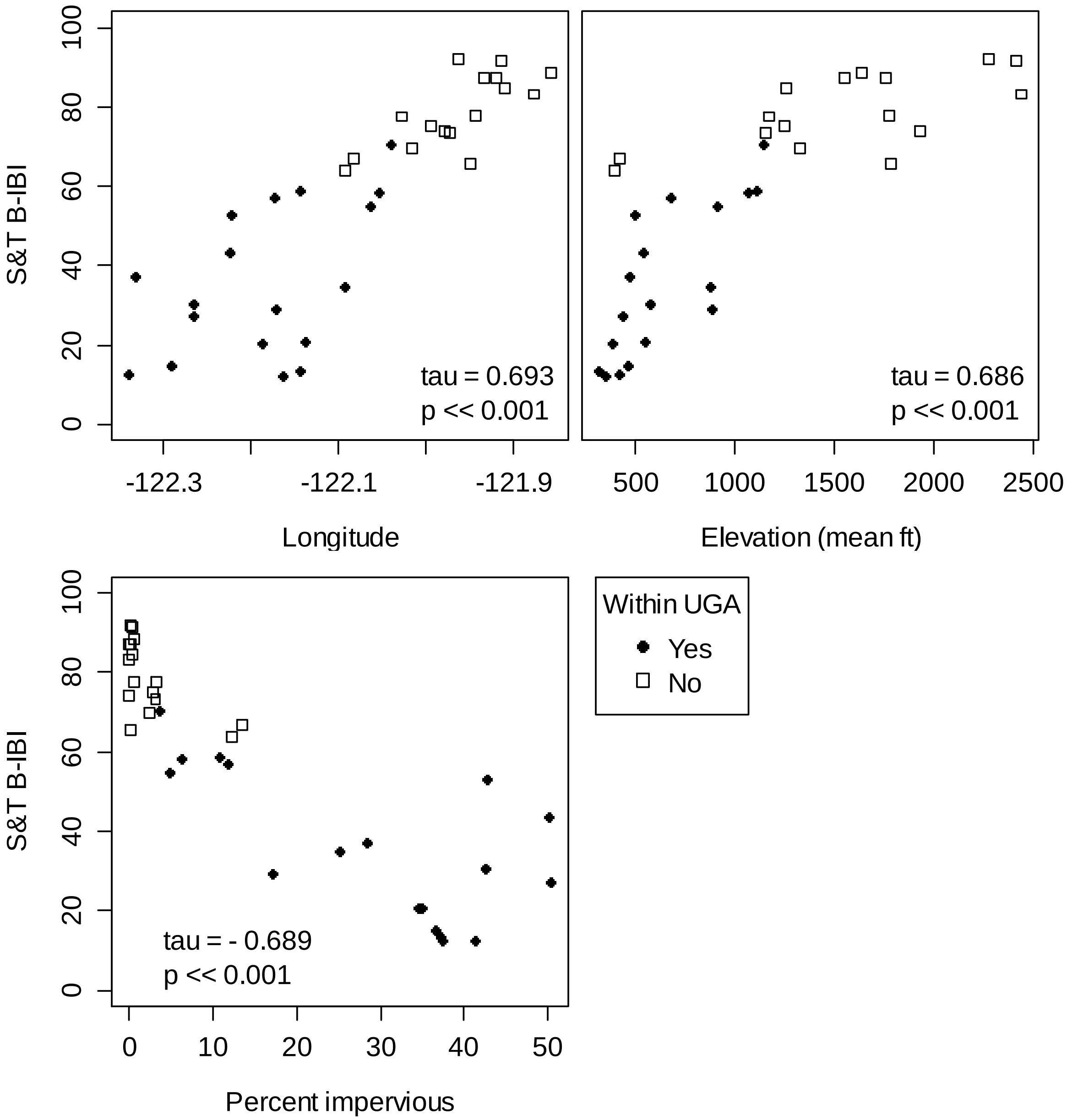

Figure 3. Average Puget Lowland Benthic Macroinvertebrate Index of Biotic Integrity (B-IBI) scores compared to landscape gradients for 34 stream reaches in Water Resource Inventory Area (WRIA) 8. B-IBI scores were collected annually at each reach by King County for the WRIA 8 Status & Trends Monitoring Program (S&T) from 2009-2013 (King County 2015) and were then averaged together by reach. UGA refers to designated urban growth areas.

Unavailable SFAM data

Not all data used in SFAM are available in other states, which could limit the model's broader applicability. For example, SFAM uses the US Geological Survey StreamStats program (U.S. Geological Survey and U.S. Department of the Interior 2016) and the Oregon Rapid Wetland Assessment Protocol (ORWAP; Rempel et al. 2009, Adamus et al. 2010) to derive mean daily streamflow and rare species occurrence data, respectively. However, only some Washington streams have daily flow calculations in StreamStats (personal communication, Ryan Thompson, U.S. Geological Survey) and there are no equivalent, readily available resources for ORWAP in Washington (personal communication, Paul Adamus, Adamus Resource Assessment, Inc.). There are also insufficient data in Washington to assess the occurrence of annual and sub-annual flooding downstream of the reach (personal communication, Robert Mitchell, Western Washington University). In addition, the pre-set answers for "ecoregion type" are all EPA level IV ecoregions found in Oregon, which do not include ecoregions unique to other areas such as the Central Puget Lowland ecoregion, and are not readily transferable to other regions (personal communication, Glenn Griffith, U.S. Geological Survey). To accommodate unknown measures, SFAM allows the user to not enter scores (i.e., leave the data entry blank in the calculator), but it was unclear how blank entries would affect SFAM outputs.

Experimental overview

The goal of this project was to test SFAM for potential use in water resource management of wadeable streams in western Washington. I used the draft version of SFAM released in November 2015 for this study; a final version 1.0 of SFAM was released in June 2018. I completed SFAM field surveys for 36 stream sites in WRIA 8 during summer 2015 and finished gathering background data in spring 2016. I revisited 11 sites during summer 2016 after the November 2015 SFAM update. I compared the outputs of the SFAM assessments to two existing WRIA 8 data sets: Status & Trends Monitoring Program and the Puget Sound Watershed Characterization Project. I expected higher SFAM function scores in reaches the Status & Trends Monitoring Program indicated to be in better condition and higher SFAM value scores in reaches the Puget Sound Watershed Characterization Project indicated to be in better condition (higher importance and lower degradation). I also assessed the potential influence of several unavailable metrics on SFAM scores through simplified sensitivity analyses of both simulated and field data because not all of the data used by SFAM are available in Washington State. I expected the absence of data for the Richards-Baker Flashiness Index (which is no longer included in the 2018 version of SFAM), rare species occurrence (as modelled by ORWAP), downstream flooding, and ecoregion types to decrease their associated SFAM final scores (hydrology function, hydrology value, biology value, and water quality value, respectively).

METHODS

Study system

For this study, I selected 36 stream reaches in WRIA 8 that were previously used for the King County Status & Trends Monitoring Program. All 36 reaches were wadeable, perennial, accessible to anadromous salmon, contained at least one riffle in the 150 m reach, and were publicly accessible. King County sampled 57 reaches for the Status & Trends Monitoring Program, which were selected from the statewide Ecology Master Sample using a generalized random tessellation stratified sample design (King County 2015). This created a spatially balanced, probabilistic study design, which increased the ability to extrapolate from the subset of streams to the larger population (King County 2015). Of the original 57 reaches, I excluded the EPA Sentinel[8] sites that are not in WRIA 8 (n=5) and the erroneously surveyed WRIA 8 ERR Sites (n=2) (King County 2015). Any sites missing data from 2013, other than hydrology data, were also excluded (n=5). Of the remaining 45 sites, nine were not publicly accessible (empty symbols in Figure 4). The removal of the 21 reaches was not randomized, which will limit extrapolation of any findings from this study to the broader watershed condition in WRIA 8.

I used Principal Components Analysis (PCA) to determine if the 36 accessible reaches were representative of the variation across the 45 potential study sites. Specifically, I used a singular value decomposition of the data matrix (prcomp in R; R Core Team 2014) with a scaled/centered correlation matrix and no rotations to analyze site landscape metrics collected by

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[8] EPA and state-designated Puget Sound Sentinel sites are stream reaches selected as relatively undisturbed reference condition for current and future monitoring efforts (King County 2015).

King County (Table S1). I excluded the metric for total road crossings as it was redundant with and more sensitive to watershed size than the metric for road crossings per km. I used Kaiser's criterion (eigenvalue ≥ 1, Kaiser 1960) to identify significant principal components (PCs) and the guidelines established by Mardia (weighting value ≥ 0.7*max weighting; 1979) to identify driving metrics for each PC. Consistent with the previously mentioned WRIA 8 gradients, positive values of PC1 reflected rural, forested, upland stream reaches while negative values reflected urban lowland reaches (Table S1). Negative values of PC2 reflected reaches in watersheds with more agricultural, undeveloped open area[9], and fragmented forest cover. PCA has had mixed results when determining environmental condition (e.g., Fore et al. 1996, Primpas et al. 2010). However, PCA was the best option for this project as it provided a quick and interpretable way to combine individual stream attributes.

Overall, the stream reaches selected for this study covered the range of available site conditions in WRIA 8, although coverage was not balanced (Figure 4). Most of the lowland reaches were in urban watersheds (top left), and included several reaches in forested urban parks (e.g., Pipers and Venema Creeks in Carkeek Park in Seattle, Lunds Gulch Creek in Meadowdale Beach Park in Edmonds). There were very few lowland creeks in open/agricultural watersheds (bottom left), with only Bear Creek (WAM06600-057527) and Bear Creek tributary (WAM06600-111639) included in this study. Most of the upland, rural reaches were in forested watersheds (top right), including all five of the stream reaches in the Cedar River Municipal Watershed and other nearby stream reaches (e.g., East Fork Issaquah Creek, Carey Creek) (Figure 4). There were no upland sites with high percentages of agriculture, open area, or forest

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[9] Areas dominated by bare land, non-cultivated grasses/forbs, or shrubs (King County 2015).

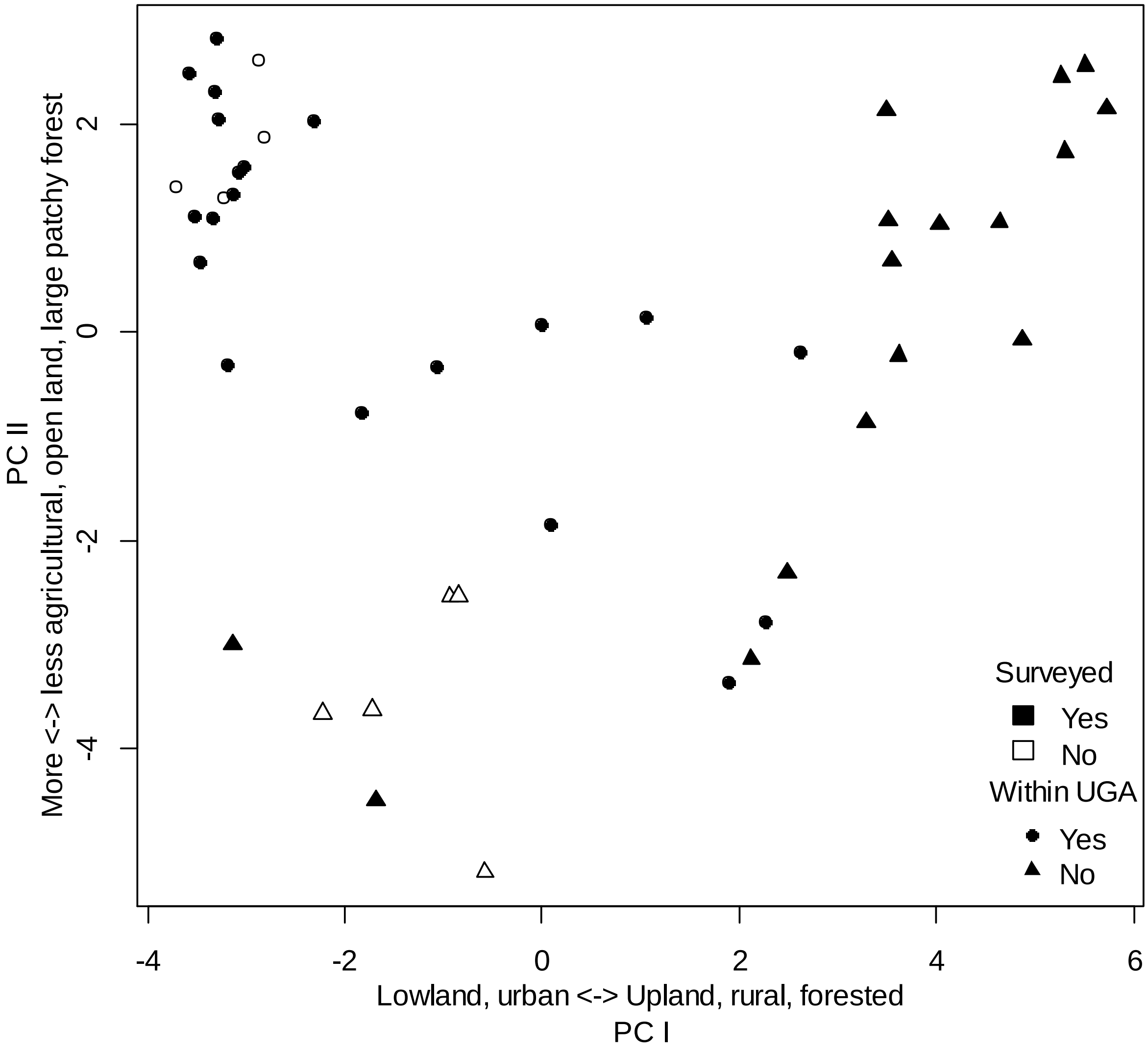

Figure 4. Ordination of 45 stream reaches in WRIA 8 using principal components (PCs) of landscape metrics from King County's Status & Trends Monitoring Program. Black coloration indicates the 36 publicly accessible stream reaches surveyed for this project. Open symbol reaches were eliminated for reasons described in the text. Circles indicate reaches in urban growth areas (UGAs). PC descriptions are in Table S1.

patches in this study or the potential WRIA 8 reaches (bottom right); the group of four reaches closest to the bottom right corner includes all four of the reaches along Issaquah Creek.

Stream Function Assessment Methodology

I evaluated the draft version of SFAM released in November 2015 for this study. A final version of SFAM was released in June 2018. The two versions share many metrics and formulas used to calculate scores. However, there are several notable differences. Eight metrics were removed in the final version: Richards-Baker Flashiness Index, non-native aquatic species, B-IBI, temperature exceedance, native coniferous tree presence, geomorphic successional stage, vegetation on bars, and beaver presence/absence. Additionally, several of the calculations, in particular for metrics of vegetation, now include modifications based on ecoregions and stream size. For example, in the 2015 draft version of SFAM, all streams needed more than 75% canopy cover to receive the highest possible measure score (1.0). In the 2018 version of SFAM, on the other hand, a small stream (≤ 50 feet wide) needs over 95% cover to receive the highest possible measure score (1.0) while a large stream (>50 feet wide) needs over 70% cover to receive the same score. Because of these differences, scores produced by the 2018 version of SFAM likely differ somewhat from the 2015 draft version I assessed in this study. Further evaluation of the newest version is warranted but quantitative assessment of the differences in scores between the two versions was beyond the scope of this study due to the very recent release of the final SFAM version. However, wherever possible, I discuss specific differences between the two versions throughout the manuscript.

I conducted SFAM field assessments initially using the April 2014 draft SFAM protocol at the selected Status & Trends stream reaches during summer 2015. David Hooper, Ph.D., conducted training for a research assistant and me in spring 2015 with permission from the Willamette Partnership (personal communication, Nicole Manness, Ecosystem Services Project Manager, Willamette Partnership). Each assessment comprised a 150 m longitudinal stream reach, matching the Status & Trends Monitoring reach length[10], with a 15.2 m lateral boundary on each bank[11]. In November 2015, the Willamette Partnership updated the SFAM calculator, which included a significant change in recording the presence of wetland indicator plant species[12]. I was able to update scores for all revised metrics at 25 sites through a combination of spatial analyses, field notes, and site photos. I revisited the remaining 11 sites in summer 2016 to collect additional data for the modified metrics. I substituted Washington-specific data sources where necessary (e.g., streamflow data from King County's Hydrologic Information Center). An overview of the November 2015 draft SFAM protocol is in Appendix C.

I did not include B-IBI scores in the SFAM calculations because the B-IBI scoring systems were different between SFAM and the Puget Lowland B-IBI. Additionally, B-IBI was removed from the 2018 version of SFAM due to the general dearth of B-IBI data in Oregon, and the substantial time and resources required to obtain B-IBI scores (Nadeau et al. 2018b).

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[10] King County standardized all sample reach lengths to 150 m (King County 2015) to match the minimum reach length required by the Washington Department of Ecology Quality Assurance Monitoring Plan (Cusimano et al. 2006) which matched the Environmental Monitoring and Assessment Program protocol developed by the Environmental Protection Agency (Peck et al. 2003).

[11] Lateral boundaries of the Proximal Assessment Area are two times the active channel width or 50 feet (15.2 m), whichever is greater (Czarnomski et al. 2015). Most reaches used for the Status & Trends Monitoring Program were less than 8 m bankfull width (~26 ft) (King County 2015), which is wider than the active channel width. Therefore, I standardized all streams to the minimum lateral boundary.

[12] The Dominant Vegetation metric changed from "is the dominant vegetation in the riparian area an obligate, facultative wet, or facultative wetland indicator species" to "are plants with wetland indicator status absent from or present along the stream banks and floodplain of the Proximal Assessment Area?"

I created three SFAM data sets, as not all data sources were available for every stream reach. The first and second data sets used all available data sources ("All Available Data") and included all 36 stream reaches surveyed. Within All Available Data, I used two methods to determine floodplains: field assessments and GIS. For the field-determined floodplains, I looked for evidence of past flood events (e.g., debris pushed up against the upstream side of vegetation) and deposition of streambed materials outside of the stream during field surveys, as per the SFAM instructions. For the GIS-determined floodplains, I accessed the FEMA regulatory 100-year floodplain layer from King County, the lowest flooding level available, and determined if the reach was within the floodplain. Unlike the 2015 draft version of SFAM, the 2018 version of SFAM specifies the use of the same 100-year regulatory floodplain GIS layer for stream assessments. The third data set used only data sources available to all included stream reaches and GIS-determined floodplains ("Matched Data"), excluding context data that did not contribute to score calculations, and included 34 of the surveyed stream reaches[13]. Additionally, within each data set, I also created a subset of reaches that had streamflow data for assessment of the hydrology function scores (n=14) for comparison with the Status & Trends hydrology data. The 2018 version of SFAM does not require daily streamflow data. For the results, I only describe the Matched Data with GIS-determined floodplains because the data sets had qualitatively similar results (Figures S5 & S6).

I chose to use the SFAM function scores for the analyses and not the SFAM function scores with context, an SFAM calculator addition in the 2015 update, for several reasons. First, the geomorphology (Figure S7b) and water quality scores (Figure S7d) were unaffected by

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[13] Data set excluded Pipers (WAM06600-063831) and Venema (WAM06600-057739) creeks as both were missing soil survey data.

landscape context in this study, either because the SFAM calculator did not include landscape context qualifiers to weight the function score[14] or because the qualifier was derived from the unavailable ecoregion data[15]. Second, using the original biology function scores as opposed to the biology function scores with landscape context was more consistent with WRIA 8 context (Figure S7c). The default ecoregion type in the SFAM calculator was non-forested when ecoregion was left blank. This artificially inflated some biology measure scores in WRIA 8, which was historically forested[16] (Pater et al. 1998). For example, the raw measure subscore for large woody debris increased from either 0% (n=31) or 25% (n=3) to 50% in the biology function context score calculation when ecoregion was left blank. As such, using the original biology function scores, which would have resulted in the same scores as the biology function with landscape context scores in forest-dominated ecoregions, was appropriate for WRIA 8. Third, stream order affected the hydrology function context scores by halving the flow variation subscore if the stream order was 1 (Figure S7a). However, some of the reaches did not have stream order data (n=7) but were included in the Matched Data set because stream order did not affect score calculations before the 2015 update. While I could have derived stream order from maps, I decided to have all of the stream order classifications from the same publicly-accessible source. In hindsight, completing the stream order assignment for all reaches would have been the ideal approach for this study. However, due to resource and time constraints this did not occur.

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[14] Neither of the geomorphology subscores nor the chemical regulation subscore in the water quality function score had landscape qualifiers for weighting the score (Willamette Partnership 2015).

[15] The cover scores in the water quality function landscape context subscores were modified by ecoregion. Heavily forested (type 1) or heavily and moderately forested ecoregions (type 2) resulted in no change to the subscore. Non-woody dominated ecoregions (type 7) removed the cover score from the function with context score. Any other ecoregion input resulted in canopy cover scores less than or equal to 50% being reassigned a score of 50%, and any canopy cover score above 50% being reassigned a score of 100% (Willamette Partnership 2015).

[16] WRIA 8 includes the 2e (Eastern Puget Lowlands), 2f (Central Puget Lowlands), and 4a (Western Cascades Lowlands and Valleys) level IV ecoregions.

In the end, this was a moot point because the context scores were removed from the 2018 version of SFAM.

Question 1: How does SFAM compare to other stream assessment protocols for rating stream functions and values?

I used Kendall tau ranked correlations (R Core Team 2014b) to compare SFAM scores to commensurate data in WRIA 8 (Figure 5, Table 1). I compared all SFAM scores to the WRIA 8 geographic and development gradients. Furthermore, I compared SFAM function scores to principal components derived from relevant Status & Trends reach-scale data and SFAM value scores to relevant Puget Sound Watershed Characterization Project variables. These comparisons are described in more detail below.

SFAM variables

I ran correlations separately for individual SFAM hydrology, geomorphology, biology and water quality function and value final scores (Figure 5, Table 1). I also combined all four SFAM final function scores using Principal Components Analysis (PCA) to evaluate SFAM's overall functional rating of stream reaches. I did a similar, but separate, analysis for the SFAM value scores. I used the same PCA methodology as described previously in the Study system section. For all correlations, I tested both the whole SFAM data set and subsets of reaches

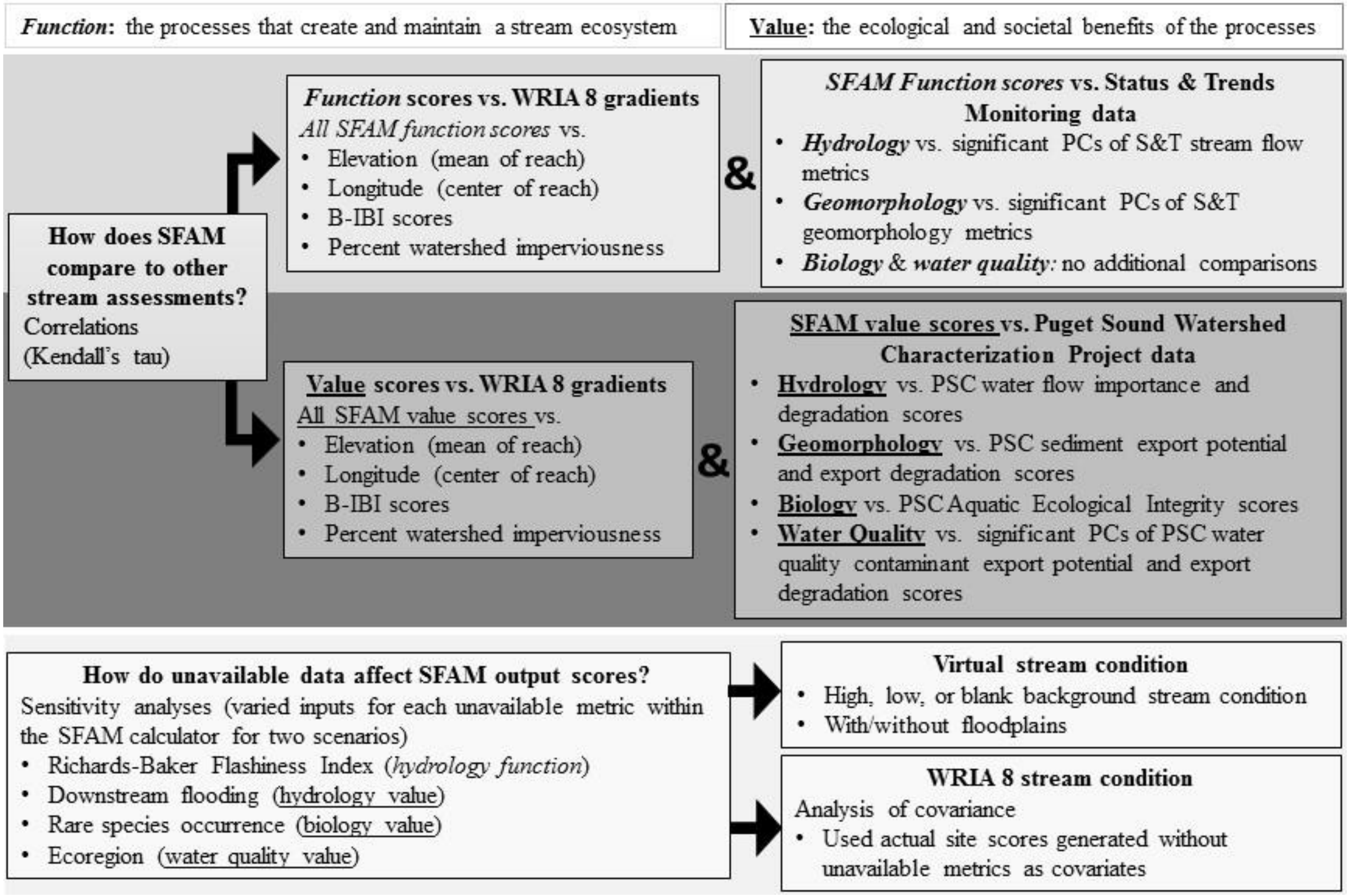

Figure 5. Overview flow chart of the statistical approaches used to evaluate the Stream Function Assessment Methodology (SFAM). Function comparisons in bold italic font; value comparisons in bold underlined font. PCs are principal components.

Table 1. Variables for correlations to assess the ability of SFAM to determine stream function compared to outputs from the WRIA 8 Status & Trends Monitoring Program (S&T) and from the Puget Sound Watershed Characterization Project (PSC). Principal Components Analysis (PCA) was used to combine multiple metrics into more concise principal components. Variable definitions are in Tables S2, S3, and S4, respectively. The Richards-Baker Flashiness Index (RB.Index) was only included in PCAs for the assessment of SFAM function scores when streamflow data were included.

SFAM function	S&T variable(s) to compare with SFAM function scores	PSC variable(s) to compare with SFAM value cores
Hydrology	**PCA** (Flow.Reversals, High.Pulse.Count, High.Pulse.Duration, High.Pulse.Range, Low.Pulse.Count, Low.Pulse.Duration, RB.Index, X30.day.summer.low.flow, X7.day.summer.minimum.flow)	Water flow importance scores, water flow degradation scores
Geomorphology	**PCA$_1$** (BFWidth_BFDepth, D50, PCT.Cobble, PCT.Fines, PWP.All, RBS, ResPoolArea100, X.BFDepth, X.BFWidth, X.Embed, X.TWDepth)	Sediment export potential scores, sediment degradation scores
	PCA$_2$ (LWDSiteVolume100m, PWP.All, X.DensioBank, X.Embed	
Biology	B-IBI scores	Aquatic ecological integrity score
Water quality	B-IBI scores	**PCA** (export potential and degradation of metals, nitrogen, phosphorus, and sediment)
PCA (Hydrology, geomorphology, biology, and water quality scores)	**PCA** (X.7DMax, X.DensioBank, LWDSiteVolume100m, PWP.All, X.Embed, RB.Index**)**	**PCA** (Water flow importance and degradation; aquatic ecological integrity; export potential and degradation of sediment, phosphorus, nitrogen, and metals)

separated into urban growth area or non-urban growth area designated groups. Due to multiple correlation analyses, I used Holm's sequential Bonferroni procedure to determine the critical alpha for each correlation (Abdi 2010). I used this correction for all of my correlation tests using the SFAM data because several raw measure subscores contributed to multiple SFAM scores. All corrected critical alphas ranged from 0.0002 to 0.0003. To balance the conservative correction, I described "potential correlations" as those with a p-value equal to or less than 0.01 but larger than the Holm's corrected p-value.

Comparison with WRIA 8 Gradients

I compared individual SFAM function and value scores to several overarching gradients in WRIA 8 to assess SFAM's ability to differentiate sites based on reach location within the watershed and common measures for anthropogenic degradation (Figure 5, Table 1). I used both elevation and longitude to test whether SFAM was sensitive to the reach location in the watershed; these metrics also reflect the population density gradients from low density in the eastern uplands to high density in the western lowlands (Figures 2 & 3). I used percent watershed imperviousness to represent watershed-scale anthropogenic degradation in WRIA 8. I used the average Puget Lowland Benthic Macroinvertebrate Index of Biotic Integrity (B-IBI) score from the Status & Trends Monitoring Program to represent stream biological condition. Each average score comprised of 4-7 B-IBI scores per reach as King County collected B-IBI annually at each reach from 2009 to 2013 during the Status & Trends Monitoring. The variation in the number of B-IBI scores per reach resulted from data collection beginning in 2010 for half of the 36 reaches and 11 reaches having replicate samples collected throughout 2010-2013. All four of the WRIA 8 gradients strongly correlated with each other across the study sites (Figures 2 & 3). I also compared SFAM function PCA scores and value PCA scores to the averaged B-IBI scores.

Additional SFAM function comparisons

The King County WRIA 8 Status & Trends Monitoring Program data were spatially comparable to SFAM reach-level data for stream functions (Figure 5, Table 1). King County collected data on aquatic communities and stream habitat characteristics during annual site visits from 2009-2013 at each stream reach to determine changes in WRIA 8 Status & Trends with a focus on Chinook salmon habitat (Table S3). I averaged all five years of data together, by site, to reduce the effect of inter-annual variation. In addition to the field-collected data, King County developed landscape metrics for each site using geospatial data (King County 2015). With the exception of the indexes of biotic integrity, the Status & Trends Monitoring Program did not create multimetric indices for rating overall stream condition from these data. No multimetric index using variables from the EPA's Environmental Monitoring & Assessment Program currently exists and creating and validating such an index was outside the scope of this project. All of the Washington State Status & Trends data, including the King County data, are available online at the Washington Department of Ecology Environmental Information Management System website (Washington Department of Ecology 2015).

I compared SFAM hydrology function scores to significant principal components derived from the Status & Trends hydrology metrics (Table 1). Only 14 stream reaches had flow gauges that were reasonably near the reach and did not have substantial gaps in flow data collection during the Status & Trends Monitoring. I used PCA to combine all nine relevant Status & Trends hydrology metrics for the 14 reaches (Table S5).

I compared SFAM geomorphology function scores to significant principal components derived from Status & Trends habitat data (Table 1). I used PCA to combine 11 Status & Trends geomorphological habitat metrics that King County identified as important to stream Status & Trends[17] while also reducing the correlation among variables (Table S6). However, most of these principal components reflected stream structure and shape associated with stream reach location in the watershed (e.g., wider streams with higher amounts of fine sediment and embeddedness are found lower in watersheds) rather than stream function and are not discussed further in this paper. For an improved geomorphology function PCA, I combined four Status & Trends habitat variables (Tables 1 & S7) that most closely matched the metrics that contribute to the SFAM geomorphology function scores (Table S2).

Due to a lack of appropriate comparable data, the SFAM biology and water quality function scores were only compared to the previously mentioned WRIA 8 gradient data (Table 1). I initially compared SFAM biology and water quality function scores to averaged Fish Index of Biotic Integrity (F-IBI, Matzen and Berge 2008) scores. However, despite the F-IBI being designed for use in Puget lowland streams, King County found that F-IBI scores were confounded by contributing basin area and suggested further work to improve F-IBI (King County 2015), so I do not report those results here. The Status & Trends Monitoring Program

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[17] The metrics identified as stressors for benthic macroinvertebrate and/or fish communities through boosted regression tree models (King County 2015).

had no direct measures of water quality against which to test SFAM function scores other than seasonal water temperature, which I did not use in these analyses.

For comparison with the significant principal components of the four final SFAM function scores (Tables S8 and S9), I used the significant principal components of five Status & Trends metrics (six metrics when Richards-Baker Flashiness Index was included for the hydrology subset of reaches) (Table 1). I chose a subset of Status & Trends metrics that were ecologically relevant, did not correlate with each other, King County identified as important, and were associated with at least one of the SFAM function groups. The reduction in metrics was necessary because using all of the non-redundant Status & Trends variables (n=110 metrics) or all of the metrics used in the individual correlations (n=14 metrics[18]) would have been unwieldy, risked unfocused comparisons, and could obscure underlying mechanisms. The PCA results were qualitatively similar with or without including the Richards-Baker Flashiness Index (Tables S10 & S11).

Additional SFAM value comparisons

The Puget Sound Watershed Characterization Project data were spatially comparable to the basin-level assessment of SFAM value scores for each reach (Figure 5, Table 1). In the analysis of a larger watershed (i.e., WRIA 8), the Puget Sound Watershed Characterization Project created multimetric scores for water flow importance and degradation, water quality

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[18] Not including the first Status & Trends geomorphology PCA (n=9 additional metrics).

export potential and export degradation, and relative conservation value of habitats for sub-watersheds referred to as assessment units (Table S4). As mentioned in the Introduction, the Puget Sound Watershed Characterization Project removed anthropogenic degradation from the importance and export potential scores of an assessment unit by evaluating the underlying processes available in each assessment unit. This approach differed substantially from the combination of importance and opportunity subscores in SFAM value scores. The Puget Sound Watershed Characterization Project data are publicly available online as an interactive map and as downloadable data layers at the Washington Department of Ecology Puget Sound Watershed Characterization Project website (Washington Department of Ecology 2013b).

I compared SFAM hydrology value scores to the Puget Sound Watershed Characterization Project water flow importance and degradation scores (Table 1). Water flow importance evaluated the potential for each assessment unit to contribute to surface water storage (depressional wetlands and lakes as well as unconfined or moderately confined floodplains) and water recharge/discharge (permeability of deposits and floodplains, as well as the presence of slope wetlands) (Stanley et al. 2015a). Water flow degradation considered human impacts from current land use on water delivery (e.g., percent impervious area, percent of non-forest vegetation area), surface storage (e.g., loss of wetlands and floodplains), recharge/discharge (e.g., percent urban land cover, loss of floodplains and wetlands), and loss (e.g., loss of transpiration due to increased impervious cover) (Stanley et al. 2015a).

I compared SFAM geomorphology value scores to the Puget Sound Watershed Characterization Project sediment export potential and degradation scores (Stanley et al. 2015b) (Table 1). The Puget Sound Watershed Characterization Project sediment export potential assessed the relative ability of the assessment unit to generate and transport sediment to downstream aquatic areas if disturbed. Specifically, the sediment export potential score determined the assessment unit’s ability to deliver sediment at higher levels than natural quantities (surface erosion, mass wasting, and channel erosion) against the assessment unit’s ability to retain sediment in sinks (depressional wetlands, lakes, and unconfined or moderately confined floodplains). The degradation score used the Non-Point Source Pollution and Erosion Control Tool (N-SPECT, National Oceanic and Atmospheric Administration 2004) erosion model to estimate the sediment yield from the assessment unit during a single storm-event, as functions of storm runoff volume, peak runoff rate, soil erodibility, land cover classes, slope length, and gradient.

I compared SFAM biology value scores to the Puget Sound Watershed Characterization Project aquatic ecological integrity scores, which measured of the relative conservation value of freshwater habitats (Wilhere et al. 2013) (Table 1). The aquatic ecological integrity score was based on in-stream structural measures and the status of the assessment unit. The aquatic ecological integrity score focused on the presence, stock status, and habitat requirements of salmonids, chosen as umbrella taxa because salmonid habitat encompasses the needs of many other species as well. The aquatic ecological integrity scores also included hydrogeomorphic features (wetland and undeveloped floodplain density), habitats in the assessment unit (salmonid habitat amount and quality), and availability of downstream habitats affected by, but outside of, the assessment unit (Wilhere et al. 2013).

I compared SFAM water quality value scores to significant principal components derived from eight Puget Sound Watershed Characterization Project water quality export potential and export degradation scores (Tables 1 & S12). I did not include the Puget Sound Watershed Characterization Project scores for pathogens in the PCA because SFAM did not assess pathogens and had no equivalent input or output. The Puget Sound Watershed Characterization Project determined the export potential of an assessment unit through its ability to deliver a given contaminant (sediment, phosphorus, nitrogen, or metals) at higher levels than background quantities (i.e., surface erosion, mass wasting, and channel erosion) minus the assessment unit's ability to retain contaminants in sinks. The Puget Sound Watershed Characterization Project used the sediment export potential model as a base for the export potential models of the other contaminants. The phosphorus export potential model added local phosphorous enrichment to sediment export potential sources and added soil clay content as a phosphorus contaminant sink. The Puget Sound Watershed Characterization Project did not include sources of nitrogen and metals for the export potential model as these were not considered significant across assessment units, but the model combined sediment sinks with denitrification for nitrogen (wetland/lake water storage and riparian area denitrification potential) and soil retention of metals (cation exchange capacity). The Puget Sound Watershed Characterization Project generated assessment unit degradation scores using N-SPECT to estimate pollutant loading from the assessment unit during a single storm-event. For all pollutants other than sediment, described previously in this subsection, N-SPECT estimated the pollutant load for each land use pixel in the assessment unit using pixel area, runoff, and concentration of the pollutant of interest (Stanley et al. 2015b).

I compared the significant principal components of the combined SFAM value scores to the significant principal components of the combined Puget Sound Watershed Characterization Project scores (Tables 1, S13, & S14). I included all of the Puget Sound Watershed Characterization Project scores used in the individual metric assessments, described above, in the Puget Sound Watershed Characterization Project PCA (Table 1).

Question 2: How do unavailable data affect SFAM output scores?

I performed targeted sensitivity analyses of missing SFAM metrics: Richards-Baker Flashiness Index, downstream flooding, rare species, and ecoregion type. To do so, I used two different data sets, virtual stream reach data and field-collected stream reach data, to investigate the influence of background stream condition on effects of the different missing metrics (Figure 5). In both analyses, I used all pre-determined bins of unavailable metric inputs and compared the resulting SFAM final scores (Table 2). Because each of the unavailable metrics contributed to different SFAM output calculations, they acted independently of each other in the calculator and I assessed them without testing for interactions among unavailable metrics.

Virtual stream conditions

For each run of the unavailable data, I tested for interactions of the unavailable metric data with stream condition by creating three levels of virtual background stream condition: high, low, and blank. High stream condition had all available SFAM metrics set to the highest possible score (generally 100%) to create a hypothetical best condition stream. I set the context data for high stream condition as moderately erodible (100% measure subscore) with high aquifer and soil permeability (100% for both), perennial flow (100%), and left all other context data blank. Low stream condition had all metrics set to the lowest possible score (generally 0%) to create a hypothetical worst condition stream. I set the context data for low stream condition as easily erodible (25% measure subscore) with low aquifer and soil permeability (0% for both), perennial

Table 2. Pre-determined input bins for SFAM metrics that are generally unavailable in Washington and, in parentheses, the final score to which the unavailable metric contributed. The SFAM calculator combines ecoregion with canopy cover to create the subscore for cover context, used in the water quality value final score. The SFAM calculator uses the same response bins for ecoregions dominated by wet dense forest, wet dense and moderate forest, or dryland vegetation (ecoregions 1, 2, and 7, respectively). Ecoregions 3-6 include areas dominated by moderately dry or patchy vegetation (e.g., dense riparian area surrounded by woodlands and open meadows). "NA" is a measure subscore assigned by the SFAM calculator and is functionally the same as no measure subscore. Both "NA" and "No measure subscore" remove the metric from SFAM score calculations.

Unavailable metric (Associated output)	**Potential input**	**Measure subscore**
Richards-Baker Flashiness Index (Hydrology function)	Blank (no input)	No measure subscore
	Stable/Flashy	50%
	Mean	100%
Downstream flooding (Hydrology value)	Blank (no input)	No measure subscore
	None (no downstream flooding)	0%
	Low (only large, infrequent flooding events)	30%
	Moderate (infrequent flooding)	60%
	Regular (flooding several times a year)	100%
Rare species occurrence (Biology value)	Blank (no input)	0%
	Not Known	No measure subscore
	None	0%
	Low	25%
	Intermediate	50%
	High	100%
Ecoregion type (Water quality value)	Blank (no input); 0 - 50% canopy cover	50%
	Blank (no input); > 50% canopy cover	100%
	Ecoregions 3 - 6; 0 - 50% canopy cover	50%
	Ecoregions 3 - 6; > 50% canopy cover	100%
	Ecoregions 1, 2, or 7; 0 - 50% canopy cover	NA
	Ecoregions 1, 2, or 7; > 50% canopy cover	NA

flow (100%, but consistent with my stream reaches), and left all other context data blank. Blank stream condition had all available metrics set to unanswered (blank or “no input”), including the context data, to determine how the unavailable or non-applicable data affected the scores independent of other SFAM metrics. I only evaluated high and low virtual stream conditions for downstream flooding, rare species, and ecoregion because blank stream condition did not produce final scores for their associated outputs. I ran each assessment in factorial combinations of background stream condition (high, low, blank) and floodplain presence or absence to assess if floodplain determination, which could easily be misidentified, influenced how unavailable metrics affected SFAM outputs. Only downstream flooding was excluded from the factorial procedure because it did not contribute to the calculation of hydrology value scores when floodplains were absent. Additionally, ecoregion was combined with canopy cover to create the cover context measure in the water quality value scores, so ecoregion inputs were also evaluated in a factorial combination with high (100%) and low (50%) canopy cover.

WRIA 8 stream condition

I assessed how the SFAM scores of the 34 surveyed stream reaches (Matched Data) responded to variations in the unavailable data inputs. I varied the inputs of each unavailable metric within the SFAM calculator for each surveyed stream. I only conducted the downstream flooding variation on the subset of stream reaches with floodplains (n=20). I used analysis of covariance (ANCOVA) to determine statistically significant ($\alpha = 0.05$) differences among levels of scores generated from the different unavailable data inputs. I used baseline scores (unavailable data input as blank) as the covariate. Specifically, I used ANOVA with type III sum of squares (aov in R) and evaluated the covariate-adjusted means (effects from the “effects” package in R) for normally distributed, homoscedastic data (R Core Team 2014b) and a nonparametric analysis of covariance (comparison of nonparametric regression curves using sm.ancova from the “sm” package in R) for non-normally distributed, homoscedastic data (Bowman and Azzalini 2014). Normality of data was determined by the Shapiro-Wilk normality test (R Core Team 2014c). All of the data used in the WRIA 8 stream condition sensitivity analyses were homoscedastic, as determined by either the Bartlett test of homogeneity of variance for data that were normally distributed (R Core Team 2014d) or the Fligner-Killeen test of homogeneity of variance for data that were not normally distributed (R Core Team 2014e).

RESULTS

Unless otherwise specified, all results used the SFAM draft completed in November 2015.

SFAM scores

SFAM produced relatively restricted ranges of function and value scores for the WRIA 8 stream reaches used in this study, despite sites from a broad spectrum of geographic and land-use settings as indicated by percent impervious and B-IBI (Figures 2 & 3). Overall, the stream reaches received moderate to high function and value scores, though ranges typically covered less than half of the total possible SFAM score range (Figure 6). As an example, hydrology function scores ranged from 5.2 to 7.9, a span of 2.7 points. Overall, function ranges spanned 2.4 – 4.2 points and most value ranges spanned 1.6 – 3.6 points, except for the 6.0 hydrology value point spread. Additionally, all reaches fell into the middle part of the condition spectrum: none had function scores below 3.8 and only one value score (in hydrology) was below 2.5. Neither hydrology nor biology functions had scores above 7.9, and no value score was above 8.3.

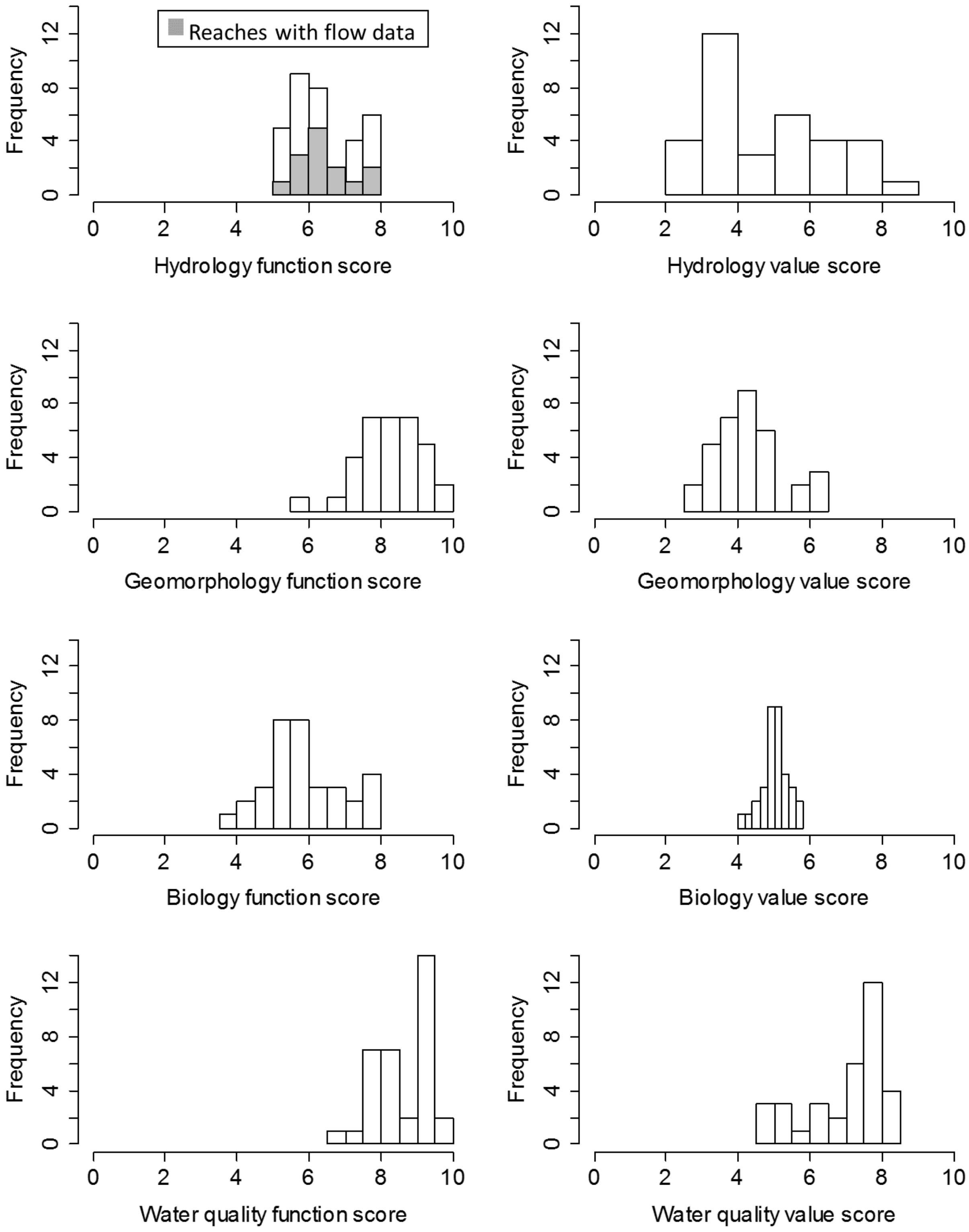

Figure 6. Histograms of the Stream Function Assessment Methodology function and value scores in 34 stream reaches in Water Resource Inventory Area 8. The gray distribution shows the subset of 14 reaches that had stream gauge-generated flow data.

Question 1: Comparing SFAM stream ratings to other stream assessments

SFAM function scores

Surprisingly, SFAM function scores rarely correlated with major WRIA 8 geographical or land use gradients or with commensurate Status & Trends data. SFAM hydrology function scores did not correlate with metrics reflecting WRIA 8 development gradients, metrics of watershed condition, or principal components reflecting anthropogenic alterations in streamflow (Figure 7, Table S5). SFAM geomorphology function scores did not correlate with longitude, percent impervious, or B-IBI (Figure 8). However, higher geomorphology function scores generally occurred in higher elevation reaches and in reaches with less anthropogenic degradation of the stream bank and nearby uplands (Figure 8a & f; Table S7). SFAM biology function scores did not respond to the physical gradients in WRIA 8 (Figure 9) but did suggest, outside of urban growth areas only, higher biology function in reaches with better biotic condition (higher B-IBI scores; Figure 9d). SFAM water quality function scores did not correlate with any comparable data (Figure 10). Furthermore, none of the SFAM function scores visibly differentiated among reaches within or outside of urban growth areas, unlike the WRIA 8 gradients.

The SFAM function scores combined using principal components were not substantially different from the assessment of the individual SFAM function scores except for hydrology function. SFAM function PC1, which largely reflected geomorphology, biology, and water quality function scores, did not correlate with B-IBI scores or the Status & Trends data that reflected anthropogenic degradation of the reach (Figure 11, Tables S8 & S10). On the other hand, SFAM function PC2, which largely reflected hydrology, suggested higher hydrology function in reaches with lower B-IBI (Figure 11d) and more adjacent anthropogenic degradation, in contrast to my original hypotheses (Figure 11e). SFAM function PC2 did not correlate with changes in bank canopy cover as reflected in the Status & Trends PC2 (Figure 11f). There were no relationships among SFAM function PCs and the Status & Trends PCs when only reaches with hydrology data were assessed (results not shown; Tables S9 & S11).

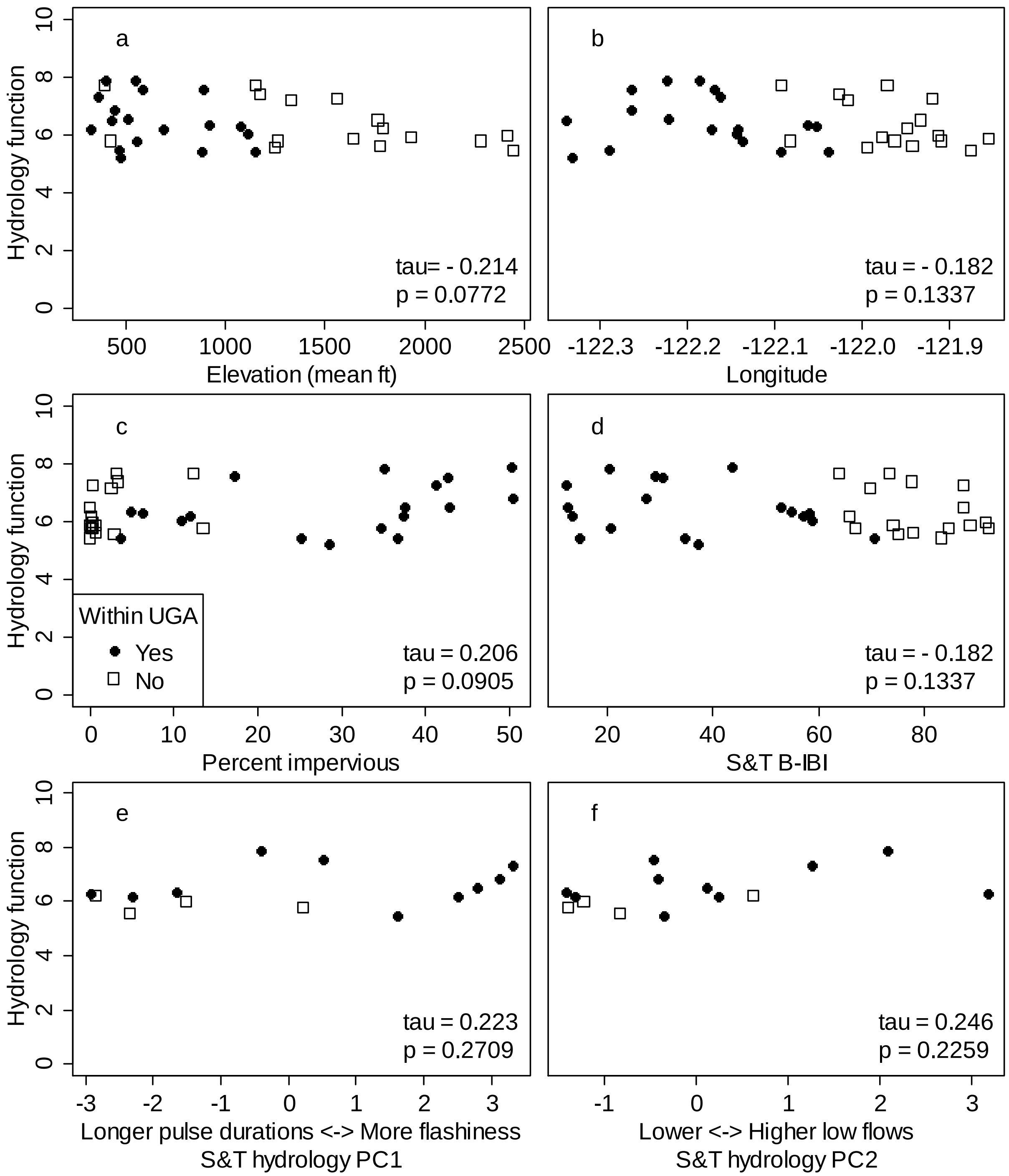

Figure 7. SFAM hydrology function scores against WRIA 8 gradients and commensurate data from the WRIA 8 Status & Trends Monitoring Program (S&T; n=34). The correlations against the S&T hydrology principal components (PCs) had 14 reaches. S&T hydrology PC descriptions are in Table S5. Correlation results refer to all reaches. Separating stream reaches by urban growth area (UGA) designation did not result in significant correlations.

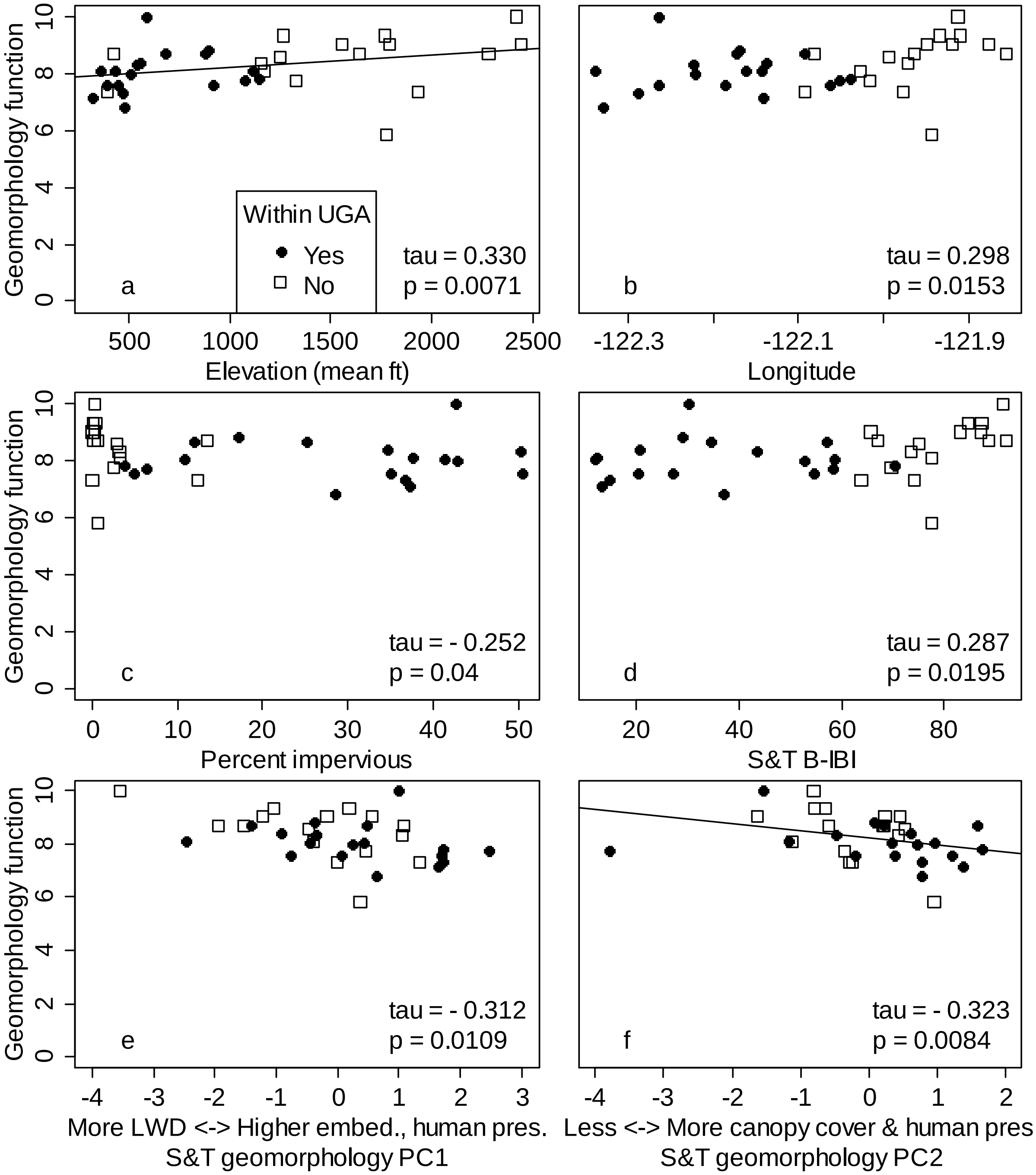

Figure 8. SFAM geomorphology function scores against WRIA 8 gradients and commensurate data from the WRIA 8 Status & Trends Monitoring Program (S&T; n=34). S&T geomorphology principal component (PC) descriptions are in Table S7. The correlation results shown refer to all reaches. The trend lines indicate a potential correlation using all stream reaches based on a non-corrected critical α of 0.01. Separating stream reaches by urban growth area (UGA) designation did not result in significant correlations. LWD refers to the metric quantifying large woody debris in the stream, embed refers to streambed embeddedness, and human pres. refers to human alterations in and around the reach (PWP.All).

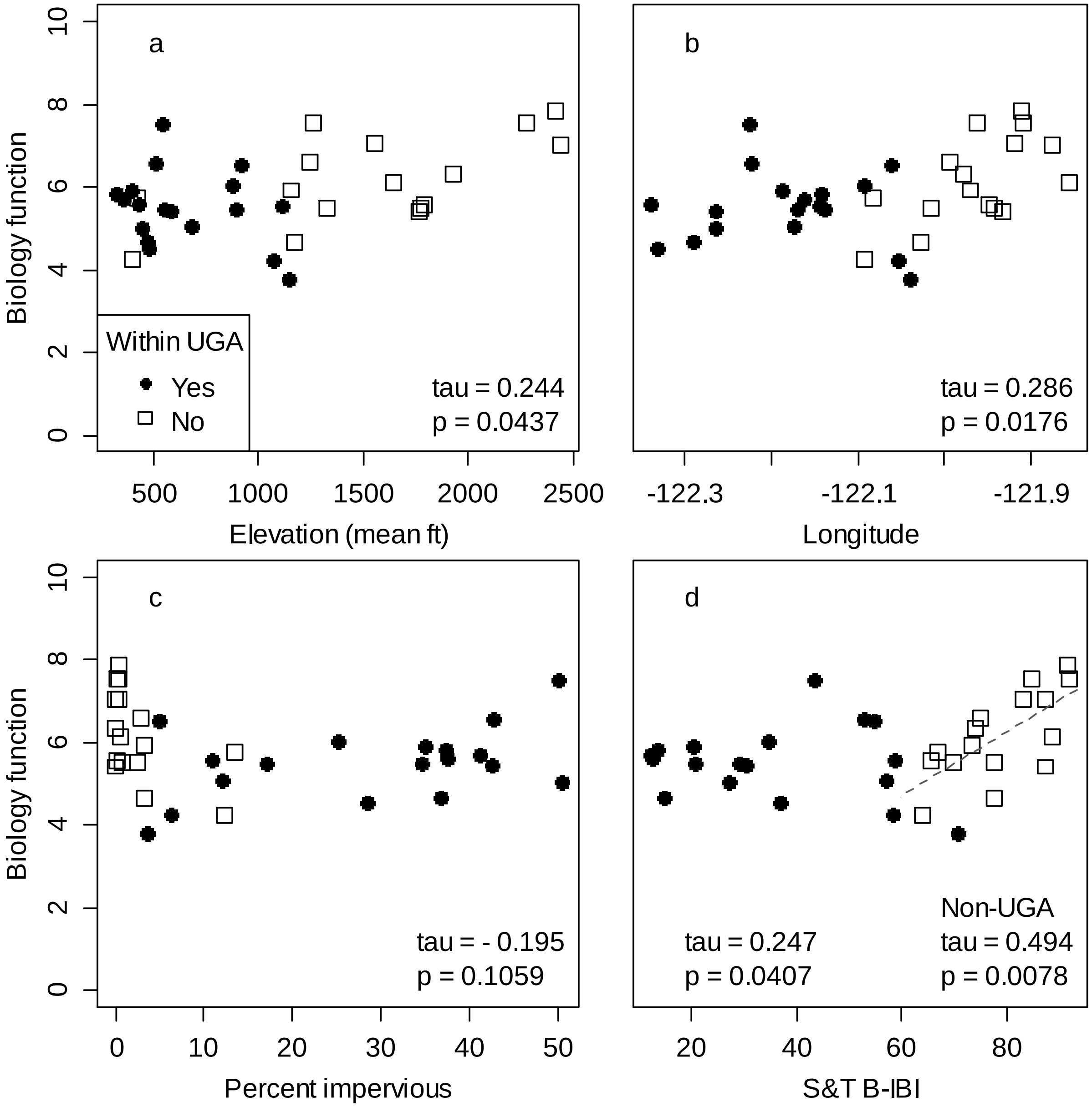

Figure 9. SFAM biology function scores against WRIA 8 gradients and the averaged Benthic Macroinvertebrate Index of Biotic Integrity (B-IBI) scores from WRIA 8 Status & Trends Monitoring Program (S&T; n=34). Unless otherwise specified, correlation results refer to all reaches. The dashed trend line in panel d indicates a potential correlation using stream reaches that are outside of urban growth areas (UGAs), based on an uncorrected critical α of 0.01.

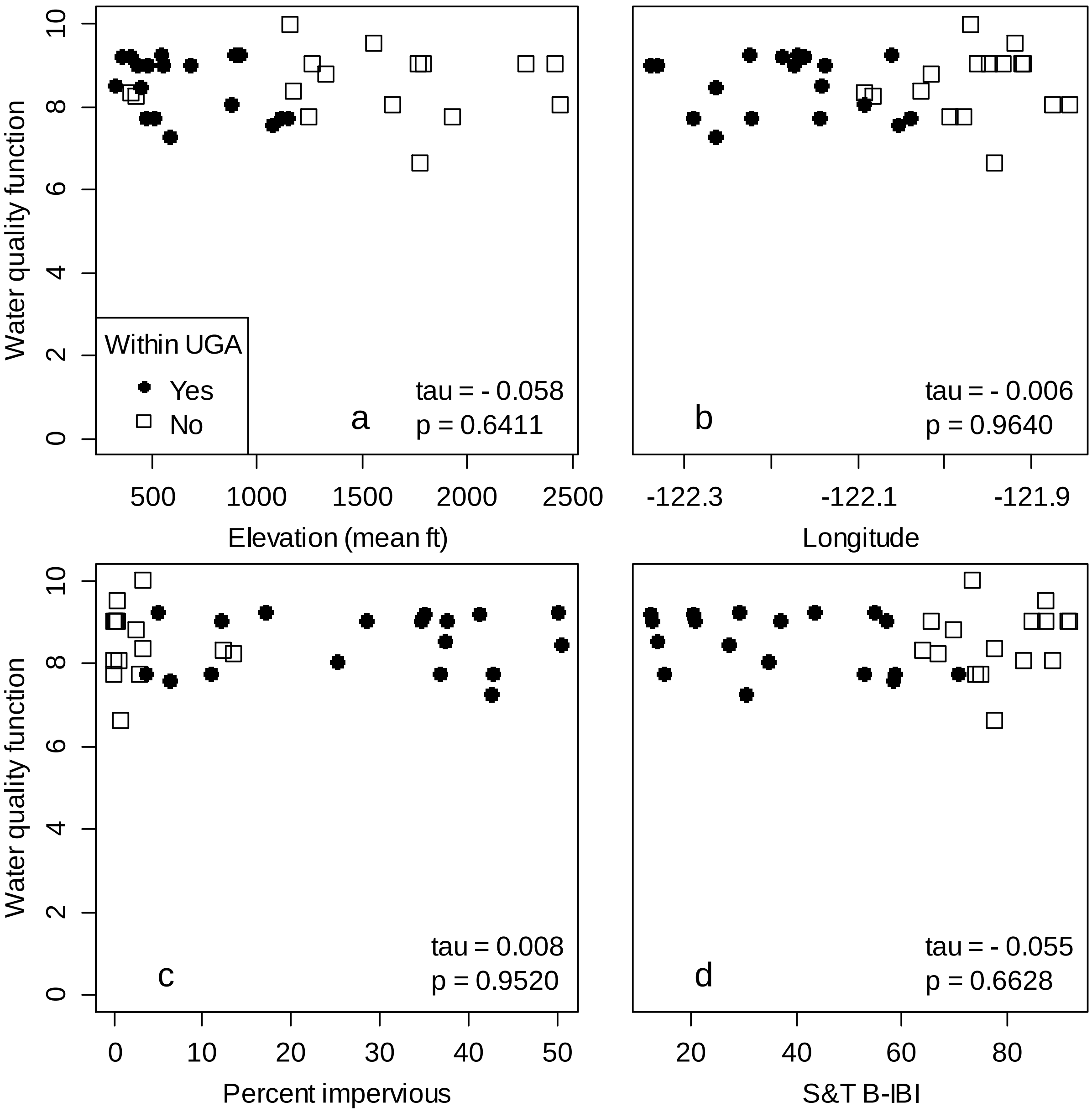

Figure 10. SFAM water quality function scores against WRIA 8 gradients and the averaged Benthic Macroinvertebrate Index of Biotic Integrity (B-IBI) scores from the WRIA 8 Status & Trends Monitoring Program (S&T; n=34). Correlation results refer to all reaches. Separating stream reaches by urban growth area (UGA) designation did not result in significant correlations.

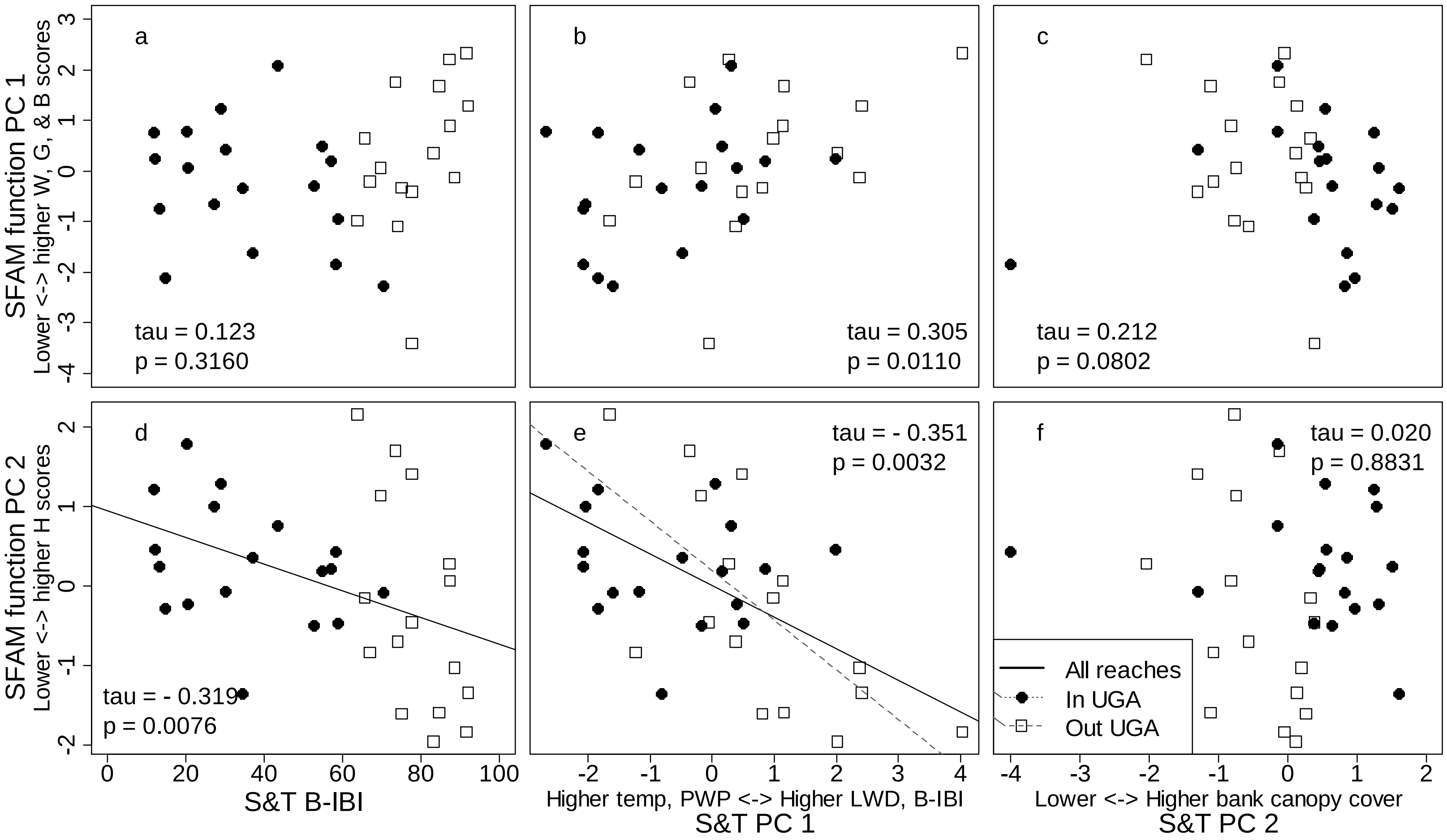

Figure 11. Comparisons of principal components (PCs) from SFAM function scores against the averaged Benthic Macroinvertebrate Index of Biotic Integrity (B-IBI) scores from the WRIA 8 Status & Trends Monitoring Program (S&T) and S&T PCs. Trend lines indicate potential trends based on a non-corrected critical α of 0.01. All correlation results refer to all reaches. Panel e includes a potential correlation in reaches outside of urban growth areas (UGAs; tau= - 0.533, p = 0.0033). SFAM assessed hydrology (H), geomorphology (G), biology (B), and water quality (W) functions. PWP is the S&T metric for proximity-weighted anthropogenic alterations (e.g., bank armoring) in the assessment area. LWD refers to large woody debris in the stream PC descriptions are in Table S8-Table S11.

SFAM value scores

SFAM value scores generally suggested higher hydrology, geomorphology, and biology value in more urban, low elevation, western stream reaches. SFAM hydrology value was higher in reaches with more anthropogenic degradation, as indicated by all of the WRIA 8 gradients and B-IBI (Figure 12). Likewise, SFAM indicated higher hydrology value in reaches with higher water flow importance (Figure 12e) and with more water flow degradation (Figure 12f). The separate hydrology value opportunity and significance subscores were also higher in reaches with more anthropogenic degradation (Figure S10). Inside of urban growth areas, SFAM geomorphology value was generally higher in higher elevation, western reaches with more developed watersheds (Figure 13). The geomorphology value scores did not correlate with changes in B-IBI scores or sediment export potential (Figure 13d & e). Interestingly, the geomorphology opportunity subscores were higher in reaches with higher percent impervious and lower B-IBI scores while the geomorphology significance subscore did not correlate with either (Figure S11). In contrast to the other patterns, SFAM geomorphology value was higher in reaches with less sediment export degradation (Figure 13f), but the direction of this relationship likely resulted from the N-SPECT model not including metrics for erosion-control practices especially in areas with industrial logging[19]. The reaches also generally had higher SFAM geomorphology significance subscores in reaches with lower Puget Sounds Watershed Characterization sediment export degradation scores (Figure S11). Despite a small overall range,

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[19] The N-SPECT model did not account for erosion control measures, especially in industrial forestry zones, which lead to higher modeled erosion in higher elevation areas with steeper slopes and commercial logging (Stanley et al. 2015b). This likely over-estimated the degradation from higher elevation assessment units and resulted in lower relative sediment export degradation ratings for more urbanized assessment units.

SFAM biology value scores were generally higher in western reaches with more watershed imperviousness (Figure 14). Biology value did not correlate with reach elevation (Figure 14a) nor, surprisingly, with either B-IBI scores (Figure 14d) or the aquatic ecological integrity scores (Figure 14e). However, the SFAM biology opportunity subscores were generally higher and the SFAM biology significance subscores were generally lower in less degraded reaches, as indicated by lower watershed imperviousness and higher biotic condition (Figure S12). The directions of the biology opportunity and significance scores were opposite my expectations. Overall, the biology opportunity and significance subscores were negatively correlated to each other, which likely contributed to the narrow range of overall values. In contrast to the other value scores, SFAM water quality value was generally higher in rural, high elevation, eastern stream reaches, but only in reaches outside of urban growth areas (Figure 15). Two groups of sites appeared to have a large influence on the potential trends between water quality value scores and elevation, longitude, and percent impervious (Figure 15a, b, and c, respectively). The first group comprised two relatively high elevation agricultural sites, Bear Creek (WAM06600-057527) and Bear Creek tributary (WAM06600-111639)[20], while the second and less consistent group comprised of relatively high elevation forested sites including reaches in the Cedar River Municipal Watershed. Water quality value scores did not correlate with B-IBI scores nor with commensurate Puget Sound Watershed Characterization Project water quality data (Figure 15d, e, & f, Table S12). Separating the water quality value scores into water quality opportunity and significance subscores also did not result in correlations with commensurate data (Figure S13).

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[20] Neither Bear Creek nor Bear Creek tributary were statistical outliers for SFAM water quality value, longitude, elevation, or B-IBI. However, they were statistical outliers for percent impervious (when only considering reaches outside of urban growth areas).

The SFAM value PCs were somewhat consistent with the negative correlations seen when the value scores were assessed independently. SFAM value PC1, which largely reflected hydrology, geomorphology, and biology value scores (Table S13), were higher in reaches with lower B-IBI scores (Figure 16a) and in reaches with higher sediment export degradation as reflected in the Puget Sound Characterization PC3 (Figure 16d, Table S14). However, the potential negative correlation between SFAM value PC1 and PC1 of the Puget Sound Characterization, which primarily reflected sediment export degradation, was primarily driven by Issaquah Creek (mouth; WAM06600-123207). This site had the highest sediment export score of all the reaches[21]. The SFAM value PC1 did not correlate with the Puget Sound Characterization PC1, which largely reflected a gradient between aquatic ecological integrity and water flow degradation, water quality contaminant export degradation, and export potential (Figure 16b). SFAM value PC1 also did not correlate with the Puget Sound Characterization PC2, which largely reflected sediment and metals export potential (Figure 16c, Table S14). The SFAM value PC2, which largely reflected water quality value scores, did not correlate with any commensurate data (Figure 16e-h).

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[21] Issaquah Creek (mouth) was not a statistical outlier in terms of sediment export.

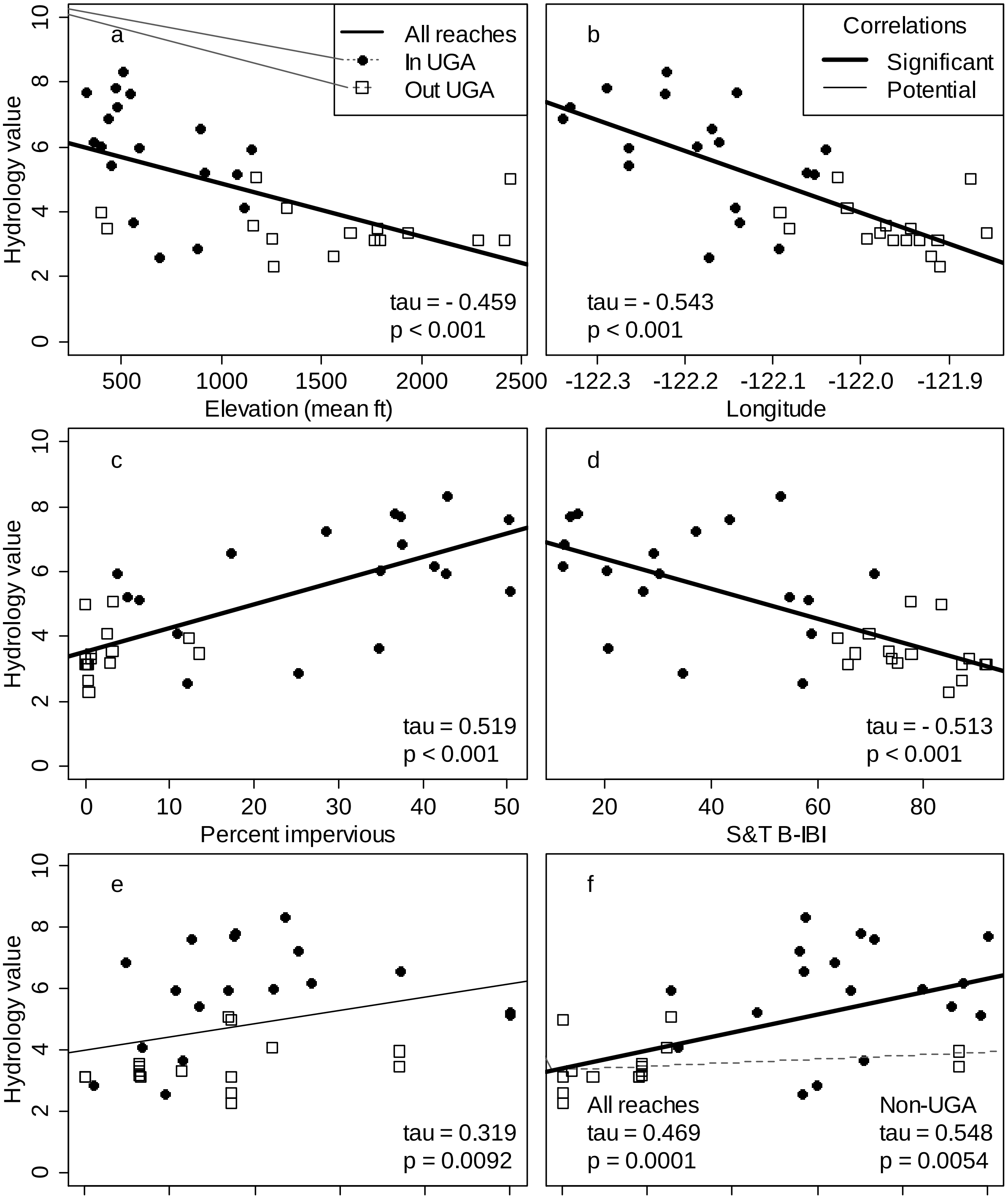

Figure 12. SFAM hydrology value scores against WRIA 8 gradients and commensurate data from the Puget Sound Watershed Characterization Project (PSC; n=34). Potential correlations were based on a non-corrected critical α of 0.01. Unless otherwise specified, correlation results refer to all reaches. UGA refers to designated urban growth areas.

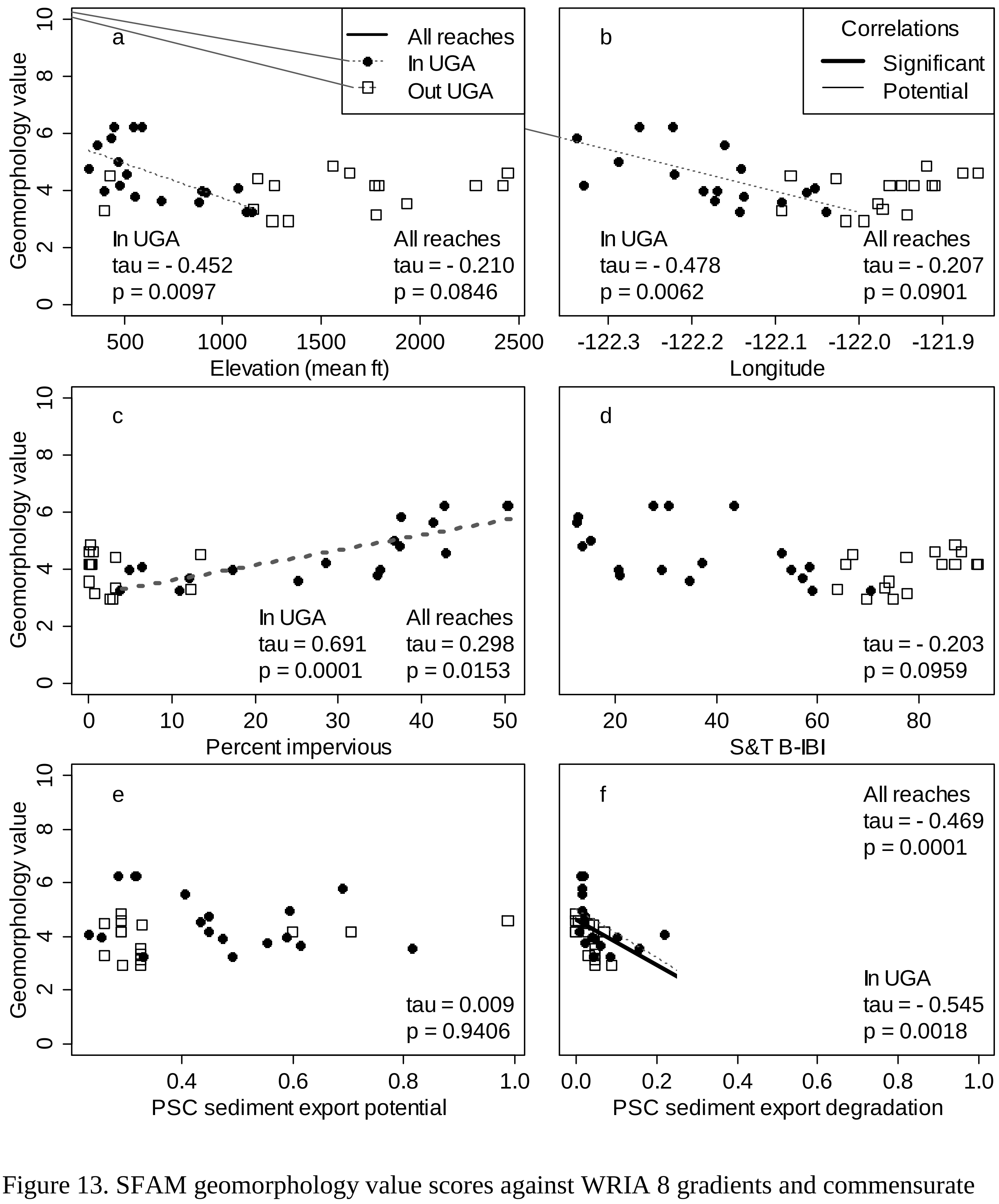

Figure 13. SFAM geomorphology value scores against WRIA 8 gradients and commensurate data from the Puget Sound Watershed Characterization Project (PSC; n=34). Potential correlations were based on a non-corrected critical α of 0.01. Unless otherwise specified, correlation results refer to all reaches. UGA refers to designated urban growth areas.

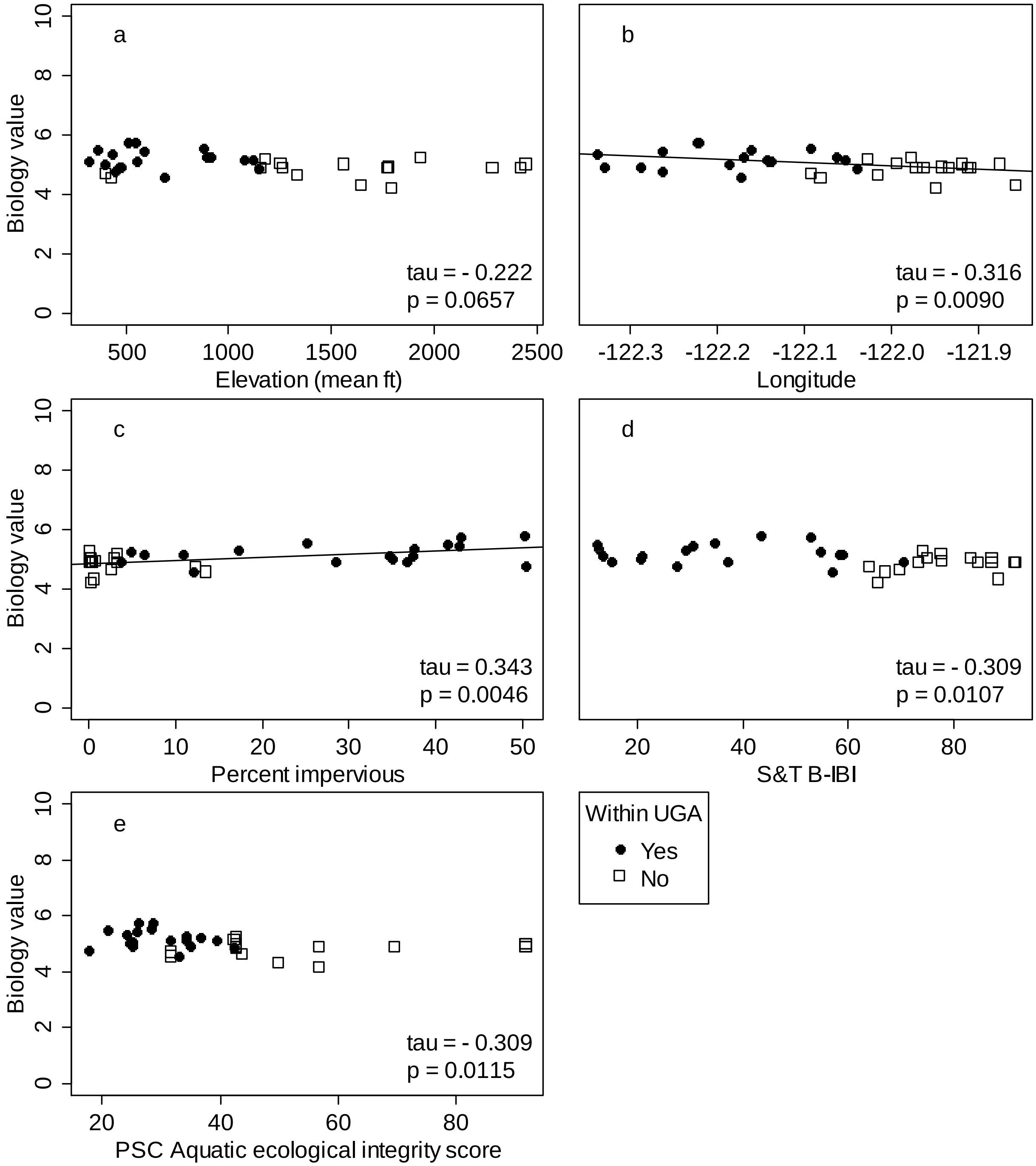

Figure 14. SFAM biology value scores against WRIA 8 gradients and commensurate data from the Puget Sound Watershed Characterization Project (PSC; n=34). The trend lines indicate a potential correlation using all stream reaches based on a non-corrected critical α of 0.01. Separating stream reaches by urban growth area (UGA) designation did not result in significant correlations.

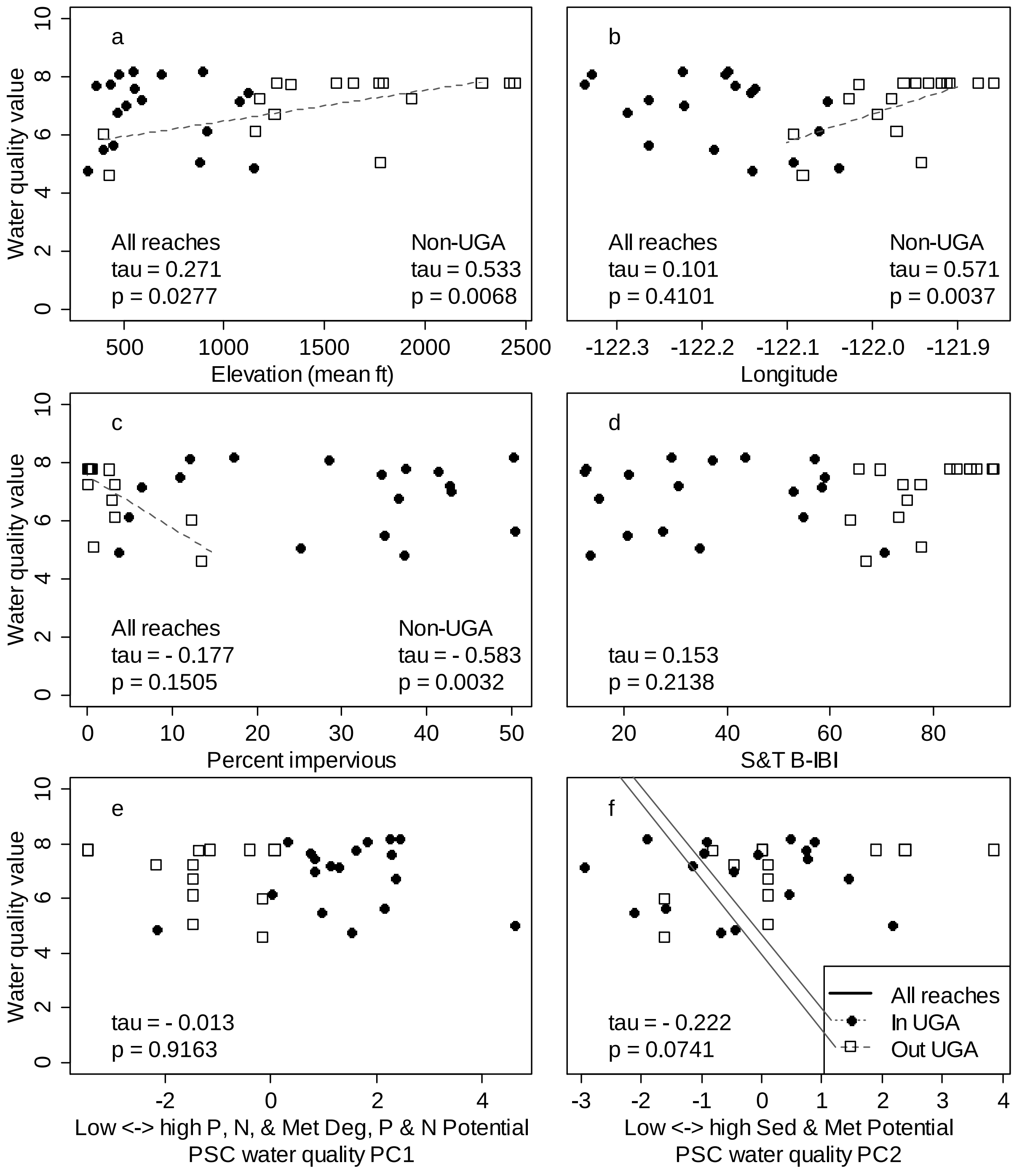

Figure 15. SFAM water quality value scores against WRIA 8 gradients and commensurate data from the Puget Sound Watershed Characterization Project (PSC; n=34). Positive values of PSC PC1 reflected higher levels of metals export degradation, nitrogen export potential and degradation, and phosphorus export potential and degradation. Positive values of PSC PC2 reflected higher levels of sediment and metals export potential (Table S12). Potential correlations were based on a non-corrected critical α of 0.01. Unless otherwise specified, correlation results refer to all reaches. UGA refers to designated urban growth areas.

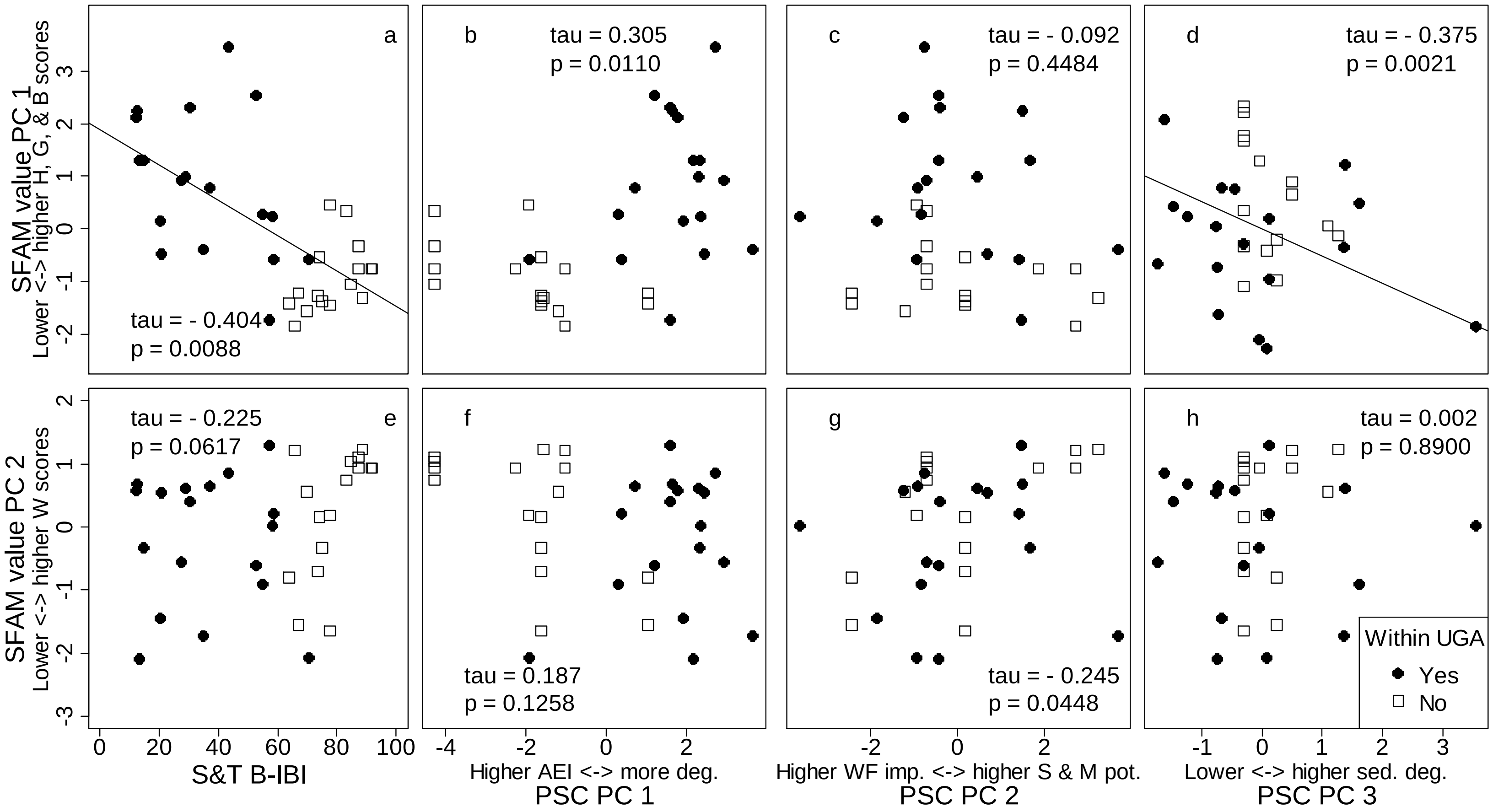

Figure 16. Comparisons of principal components (PCs) from the SFAM value scores against averaged Benthic Macroinvertebrate Index of Biotic Integrity scores from the WRIA 8 Status & Trends Monitoring Program (S&T B-IBI) and the Puget Sound Watershed Characterization Project (PSC; n=34). SFAM assessed hydrology (H), geomorphology (G), biology (B), and water quality (W) values. Negative values of PSC PC1 reflected higher aquatic ecological integrity (AEI) while positive values reflected more human degradation (higher water flow degradation, phosphorus export degradation, nitrogen export potential and degradation, and metals export degradation). Negative values of PSC PC2 reflected higher water flow importance while positive values reflected higher sediment and metals export potential. Positive values of PSC PC3 reflected higher levels of sediment export degradation. Trend lines indicate potential trends based on a non-corrected critical α of 0.01. UGA refers to designated urban growth areas. PC descriptions are in Tables S13 & S14.

Question 2: Effects of unavailable data on SFAM outputs

Virtual stream conditions

As expected, unavailable metrics generated small, generally predictable changes in their associated SFAM outputs, although the changes were not consistent among the metrics. Within each virtual stream condition in the November 2015 draft version of SFAM, the change in associated SFAM outputs from modifying the unknown metric input ranged from 0 - 1.7 points (Figure 17). Changes in associated SFAM outputs generally corresponded to the raw measure subscores of the inputs when background condition and floodplain designation were held constant. For example, changing the rare species occurrence inputs from none (raw measure subscore of 0%) to low (25%) to intermediate (50%) increased the biology value score by +0.1 points for each change, while changing the input from intermediate to high (100%) increased the biology value score by +0.2 points, a commensurate 2x increase (Figure 17c).

The inclusion or exclusion of floodplain-dependent metrics in the SFAM calculator created interactions between floodplain designation and both Richards-Baker Flashiness Index and rare species inputs (Figure 17a & c, respectively). In the blank background stream condition, the unanswered metric for stream entrenchment received a raw measure subscore of 100% when floodplains were present and no raw measure subscore when floodplains were absent[22]. This

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[22] The measure subscore calculation for entrenchment specifies that, for a perennial stream with a floodplain, “IF(H30="A",0,IF(H30="B",0.25, IF(H30="C",0.5,IF(H30="D",0.75,1))))” with H30 being the cell in which the user selects the appropriate category classification for their entrenchment data. The intent behind the code is that

change in the entrenchment measure score resulted in the Richards-Baker Flashiness Index score being averaged either with another scored metric when floodplains were present or or with no other scored metrics when floodpains were absent to create the hydrology function score. Outside of blank background condition, floodplain presence/absence did not affect how Richards-Baker Flashiness Index scores influenced the hydrology function score. In the biology value score, the metric for floodplain exclusion is removed from the calculation when floodplains were absent. The removal of the exclusion metric from both the "create and maintain biodiversity" and "sustain trophic structure" subscores resulted in the rare species occurrence scores and other metrics having more influence on the biology value score because fewer metrics contributed to the calculation of the final biology value score.

The effects of blank inputs on SFAM outputs were not consistent across unknown metrics (Figure 17). Leaving the input blank for both the Richards-Baker Flashiness Index and downstream flooding resulted in that metric not contributing to the calculation of the associated SFAM output, which resulted in an interaction between metric inputs and background condition. In blank background condition, changing the Richards-Baker Flashiness Index input from blank (no raw measure subscore) to stable/flashy (50%) to mean (100%) resulted in a consistent, small increase in hydrology function score (+0.83 points for each change, Figure 17a). In low background condition, a blank Richards-Baker Flashiness Index input resulted in the same hydrology function score as a stable/flashy input; however, changing the Richards-Baker Flashiness Index from blank or stable/flashy to mean increased the hydrology function score

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"E," the only data entry option left, should receive a score of 1. However, because this code indicates that any value in H30 other than A, B, C, or D receives a score of 1, leaving H30 blank also results in a measure subscore of 1.

(+0.56 points). In high background condition, changing the Richards-Baker Flashiness Index from blank to stable/flashy slightly decreased the hydrology function score (-0.14 points) while blank to mean increased the hydrology function score (+0.42 points). For downstream flooding, the absence of the downstream flooding raw measure score resulted in the hydrology value score reflecting the background condition (Figure 17b). In other words, a blank downstream flooding input resulted in the same hydrology value score as a no flooding input (0%) in low background condition or as a regular flooding input (100%) in high background condition. However, leaving rare species occurrence and ecoregion inputs blank resulted in these measures contributing to their associated outputs, but in an equivalent manner to a known data input. For rare species occurrence, blank inputs (no entry in the SFAM calculator) generated the same biology value score as entering the rare species occurrence inputs of none and not known in the calculator (Figure 17c). For ecoregion, blank input generated the same water quality value score as moderately dry or vegetatively patchy ecoregions (types 3-6; Figure 17d).

Ecoregion inputs interacted with both background condition and canopy cover to affect water quality value scores (Figure 17d). Canopy cover was excluded from the water quality value score calculation for ecoregions with wet densely forested (type 1), wet densely and moderately forested (type 2), and dryland vegetation (type 7). The exclusion of these ecoregion types led to no difference in water quality value score from changes in canopy cover. However, when ecoregion was unknown or entered as moderately dry or patchy vegetation (types 3-6), higher canopy cover resulted in a slight increase in water quality value score (+0.28 points) compared to lower canopy cover, regardless of background condition.

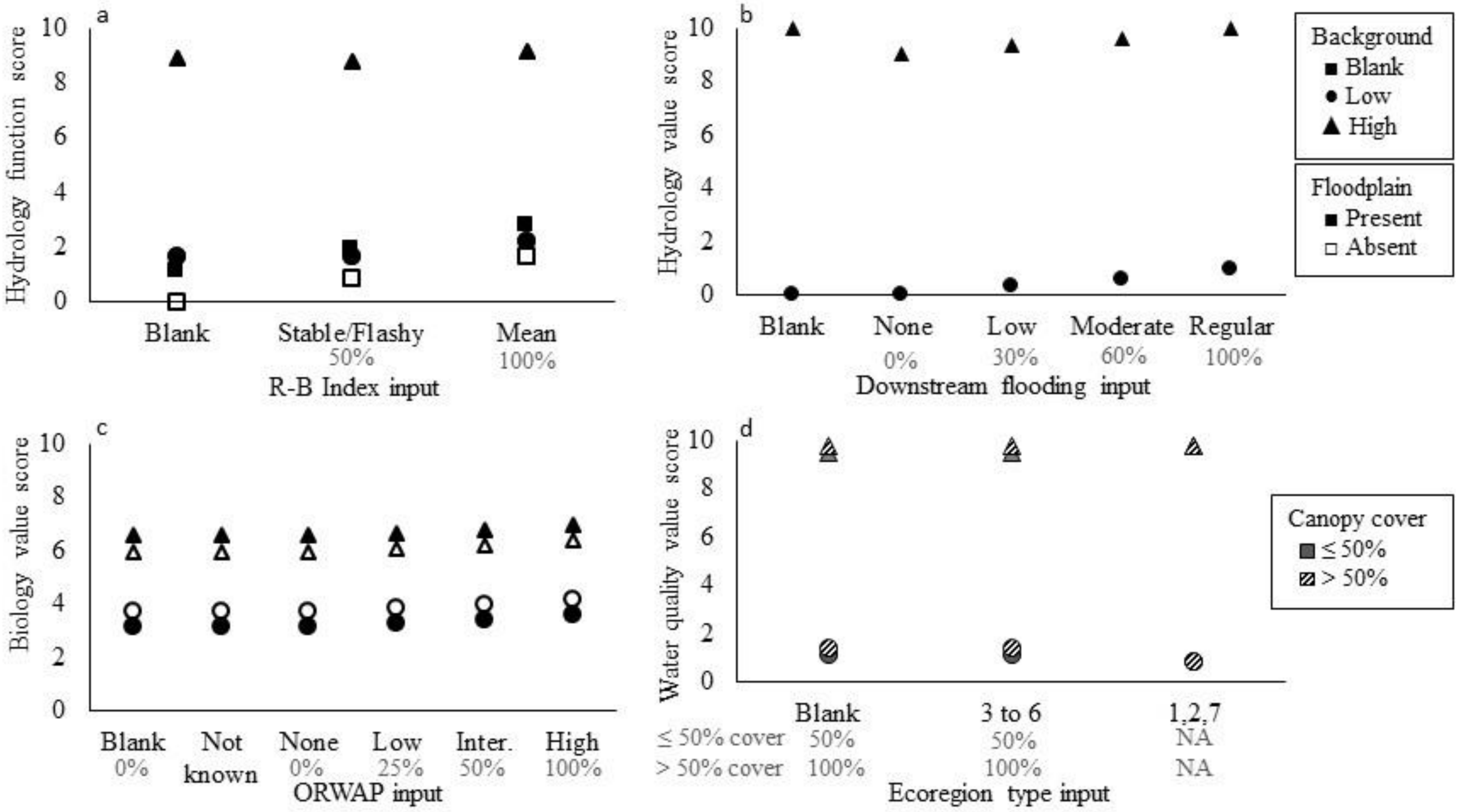

Figure 17. SFAM scores with variation in four metrics that are unavailable in Washington State: a) Richards-Baker Flashiness Index (R-B Index), b) downstream flooding, c) rare species occurrence as modelled by the Oregon Rapid Wetland Assessment Protocol (ORWAP), and d) ecoregion type. Each metric was assessed using high and low virtual stream background conditions, with the R-B Index also using blank background (no data inputs entered). Grey percentages under each input are the assigned raw measure subscore for the input; no percentage indicates that no subscore was assigned. For panel d, floodplain presence/absence did not affect ecoregion influence on water quality value.

WRIA 8 Stream Condition

The results of the sensitivity analyses using WRIA 8 stream condition were consistent with the sensitivity analyses using virtual stream condition. Changing unknown metric inputs in WRIA 8 stream reaches produced the same changes in their associated SFAM outputs as in the virtual stream condition. All modified SFAM scores were significantly positively correlated with their equivalent baseline SFAM scores (p-value <<0.001), had regression line slopes near one, and all R^2 values were ≥ 0.988. The small variation seen when changing Richards-Baker Flashiness Index, downstream flooding, and rare species occurrence inputs from blank to a scored input were caused by the variation in the raw measure subscores with which the unknown metrics were averaged (e.g., not all other metrics had raw measure subscores of 100%) (Figure 18a, b & c). Unlike the other unknown metrics, changing the ecoregion input from blank to scored inputs revealed a significant interaction (p << 0.001) between ecoregion inputs (Figure 18d). Consistent with the virtual stream condition analysis, moderately dry or vegetatively patchy ecoregions (types 3-6) and blank inputs produced the same water quality value scores. However, changing the ecoregion input from blank to wet densely forested, wet densely and moderately forested, and dryland vegetation ecoregions (types 1, 2, and 7, respectively) generally resulted in lower water quality value scores when the baseline water quality value scores were less than 7. The same input change generated equal or higher water quality value scores when the baseline water quality value scores were 7 or higher. Also consistent with the sensitivity analysis under virtual stream conditions, floodplain absence or presence did not influence how the changes in SFAM inputs for Richards-Baker Flashiness Index and rare species occurrence affected the modified SFAM scores (Figure 17a & c).

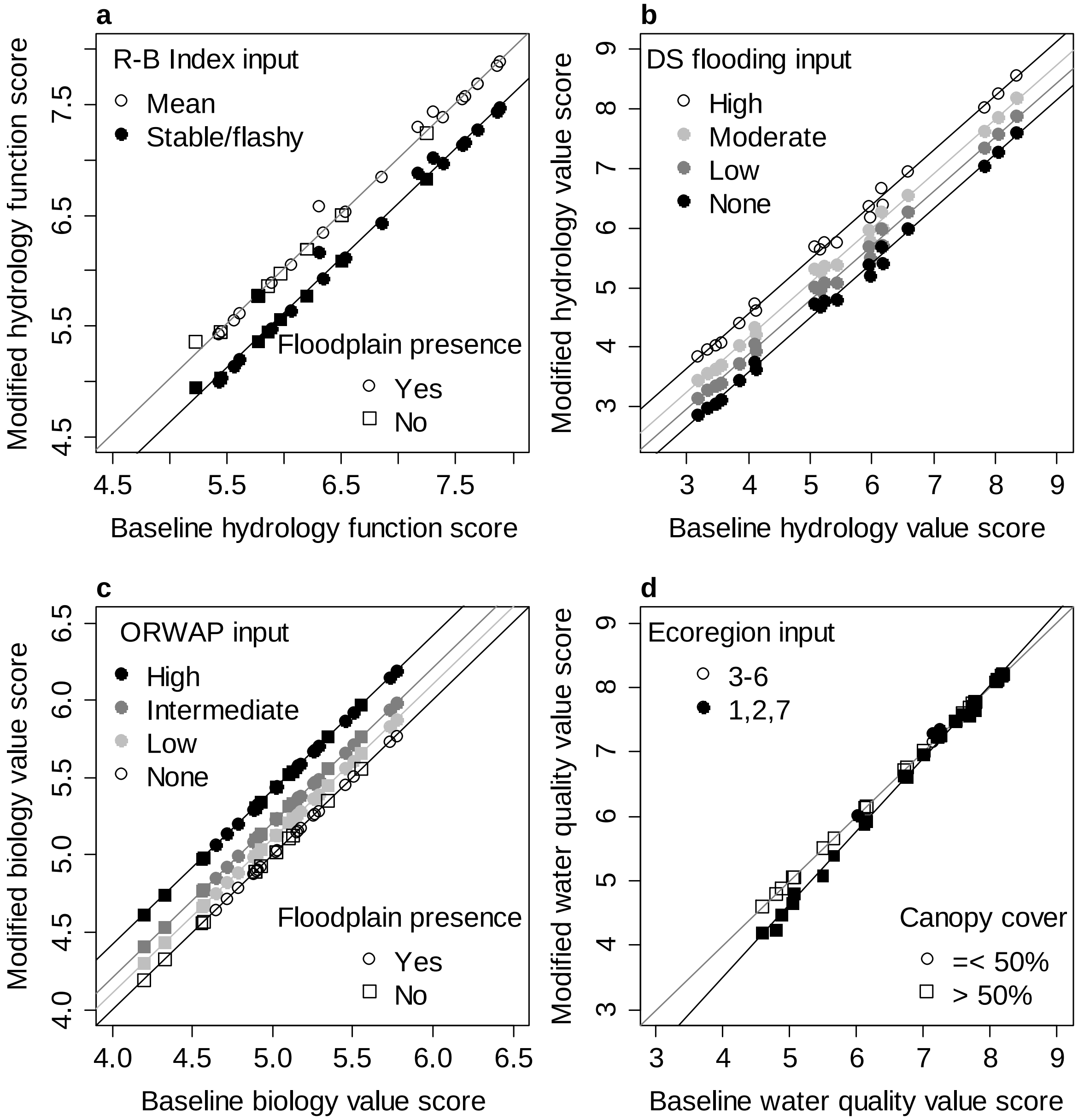

Figure 18. Baseline SFAM scores (scores created with all unavailable data left as “blank”) compared to SFAM scores for all potential inputs of four metrics that are unavailable in Washington State: a) Richards-Baker Flashiness Index (R-B Index), b) downstream (DS) flooding, c) rare species occurrence as modelled by the Oregon Rapid Wetland Assessment Protocol (ORWAP), and d) ecoregion type. N=34 except for panel b with n=20 (only included streams with floodplains). In panel d, the shapes representing canopy cover are used regardless of ecoregion type. Only 3 reaches had canopy cover ≤ 50%.

DISCUSSION

Overview

This study found a general lack of agreement between SFAM (November 2015 draft version) and the other measures of stream condition in Puget Sound lowland watersheds. None of the SFAM function scores consistently captured the established gradients in watershed development or stream biotic condition, as represented by percent watershed imperviousness and B-IBI scores, respectively. Previous studies have associated higher percent watershed imperviousness and lower B-IBI with the degradation of stream processes (e.g., Alberti 2008, Rosburg et al. 2017, Russell et al. 2017), suggesting either that the comparison metrics and SFAM are capturing different aspects of stream function or that SFAM is not effectively quantifying stream functions. If the latter, the SFAM function results were likely influenced by the high proportion of contributing metrics measuring structural components in the adjacent riparian area. Riparian conditions, especially forested buffers, can protect or improve stream processes (e.g., Tabacchi et al. 2000, Sweeney and Newbold 2014, Cristan et al. 2016, Warren et al. 2016, Keeton et al. 2017, Mondal and Patel 2018). However, the effectiveness of riparian areas to provide or support functions can vary greatly based on buffer width (Sweeney and Newbold 2014), watershed land use (Wahl et al. 2013, Covarrubia et al. 2016), and other influences. Not capturing that watershed context could result in the relatively narrow range of SFAM function scores and the lack of correlation with more established metrics of watershed condition. This over-reliance on riparian condition to represent stream function appears to also apply to the 2018 version of SFAM.

In contrast to my expectations, SFAM generally indicated higher hydrology, geomorphology, and biology value in reaches with higher levels of anthropogenic degradation in the basin. These results indicate that the SFAM hydrology, geomorphology, and biology value scores assign higher value to reaches with rarer stream functions. While assigning higher value to reaches that provide rare functions can reflect the relative importance of those processes, such a scoring method could skew project prioritization. Land managers may focus their resources on reaches in degraded watersheds because SFAM value scores designate the reaches as more valuable. However, attempts to restore or re-create stream functions in degraded areas are generally less successful than protecting existing watershed functions (Roni et al. 2002, Bates 2012). Additionally, SFAM value scores were likely influenced by combining the opportunity and significance subscores. Combining these different components of “value” can potentially hide trends when the two subscores do not correlate with commensurate data in the same way, such as occurred with the geomorphology and biology value scores (Figures S11 & S12). Previous studies have also noted the potential loss of data from combining metrics to produce multimetric scores (e.g., Reynoldson et al. 1997, McCune and Grace 2002, Herman and Nejadhashemi 2015). The potential masking of trends from combining opportunity and significance subscores in the final value scores may also apply to the 2018 version of SFAM.

The sensitivity analyses revealed relatively small and predictable changes in SFAM outputs when unavailable metric inputs were varied, suggesting that the November 2015 draft version of SFAM is fairly robust to unknown data when comparing across streams. However, the sensitivity analyses found small potential issues at a highly detailed level of evaluation. These concerns include the high repetition of metrics within final scores, several metrics not being readily available both before and after a management action, and several context metrics in the SFAM calculator not contributing to scores. Differences in how the SFAM calculator accounted for unknown metrics suggest that further evaluation and clarification regarding how metrics influence the SFAM scores is needed. Additionally, more information on how to interpret SFAM scores, especially in the context of generating mitigation credits and debits, could benefit future SFAM users.

A future study comparing the 2018 version of SFAM to quantitative data, as I did here for the draft version, could help validate SFAM in a more transparent and defensible way. The 2018 version of SFAM was validated in 39 reaches throughout Oregon using best professional judgement to represent stream processes. While best professional judgement methodologies can be an effective tool (e.g., Proper Functioning Condition; Prichard et al. 1998, Stoddard et al. 2006, Swanson et al. 2017), they also require substantial documentation of the methods and results (Stevens et al. 2002, Stoddard et al. 2006). The 2018 release of SFAM included little information about the methodology used to create the best professional judgement function scores and no data from the correlations used to validate SFAM (Nadeau et al. 2018a, 2018b). Future evaluation should determine the extent of these potential issues, especially considering that many of these concerns also appear relevant in the 2018 version of SFAM.

Correlations of SFAM against other metrics

Correlations of SFAM function scores against WRIA 8 gradients and Status & Trends data

The correlation results suggested that the SFAM function scores did not reflect known levels of anthropogenic degradation. The general lack of correlation between SFAM function scores and any of the known WRIA 8 gradients – elevation, longitude, percent impervious, and B-IBI – or Status & Trends Monitoring data was unexpected. Together, longitude and elevation captured an expected gradient of human impacts on stream function in WRIA 8 from rural, upland, eastern watersheds to urban, lowland, western watersheds. Longitude and elevation also correlated very strongly with percent impervious and B-IBI (Figures 2 & 3). Previous studies have found strong correlations among percent imperviousness, B-IBI, and the degradation of stream hydrology, geomorphology, biology, and water quality at the reach-level in Puget Sound lowland streams (e.g., Booth and Jackson 1997, Morley and Karr 2002, DeGasperi et al. 2009). As described in the Introduction, watershed imperviousness can directly and indirectly alter stream processes. In particular, increased impervious cover creates more extreme flow regimes and increases sediment movement to and within the reach (Booth and Jackson 1997, Alberti 2008, DeGasperi et al. 2009, Rosburg et al. 2017, Booth and Konrad 2017). These alterations in turn affect stream biota and their habitats, as well as stream water quality (Booth and Jackson 1997, DeGasperi et al. 2009, Feist et al. 2011). The Puget Sound Lowland B-IBI responds to anthropogenic degradation and is a primary methodology used to evaluate biological condition of streams in the region (King County 2014a, 2014c). While less widely used, the WRIA 8 Status & Trends Monitoring Program was developed to assess stream and riparian habitat condition at the reach–level to inform natural resource management of the broader watershed (King County 2015). Many of the Status & Trends metrics were qualitatively similar to SFAM metrics, making the overall lack of correlation surprising.

Given the individual SFAM score results, it was not surprising that the SFAM function PC1 (driven by geomorphology, biology, and water quality function scores) did not correlate with commensurate data. On the other hand, the SFAM function PC2 suggested higher hydrology function scores in reaches with more anthropogenic degradation, including lower B-IBI scores (Figure 11), which was not indicated by the individual comparison between hydrology function and B-IBI (Figure 7). It is unclear why hydrology function scores only showed potential correlations when part of a principal component.

The prevalence of metrics measuring the adjacent riparian area likely influenced the general lack of correlation between SFAM scores and both watershed-level and in-stream influences on stream processes. Many of the SFAM function metrics serve as indicators of function presence at the reach-level for rapid assessment, including in Washington State (Hruby 2009). However, previous studies have found proxies using stream structure to be insufficient to predict stream processes or biological condition (e.g., Karr 1991, Riipinen et al. 2009, Bernhardt and Palmer 2011, Palmer et al. 2014). The SFAM function score calculations heavily utilized measures of the assessment area directly adjacent to the stream channel. About two-thirds of the 20 SFAM function measures and at least half of the contributing metrics for each SFAM score quantified a physical component of the stream banks or riparian area/floodplain (Table S2). This included nine of 11 hydrology metrics, six of eight geomorphology metrics, eight of 14 biology metrics, and four of eight water quality metrics. Where potential correlations occurred, they supported the apparent influence of the riparian area on SFAM function scores. Most of the geomorphology metrics accounted for physical structures outside of the stream channel (e.g., the ratio of bank incision, vegetation on stream bars), including direct anthropogenic alterations to the stream bank (i.e., bank armoring/erosion, barriers to lateral stream migration). These metrics likely drove the potential positive correlations between SFAM geomorphology function scores and the Status & Trends principal components that reflect gradients of human disturbance around the reach (PWP All[23]) and streambank canopy cover (Figure 8). The potential correlation indicating higher SFAM biological function scores in reaches with higher B-IBI scores outside of urban growth areas suggests that the pervasiveness of riparian metrics effectively differentiated stream biological condition when basins had less development. The high proportion of structural metrics remains in the 2018 version of SFAM, in which all 17 function metrics are measured in the field at the reach-scale and 14 quantify a physical component of the stream banks or riparian area/floodplain. Additionally, only the flow variation function subscore includes a metric outside of the immediate assessment area (upstream impoundments).

The prevalence of measures quantifying near-stream riparian physical components may have led to the SFAM function scores capturing the effects of riparian restoration efforts (Bates 2012, Conlon Jensen 2012, King County 2017), but not the degradation occurring outside the

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[23] PWP All measured anthropogenic disturbance and weighted the disturbance by proximity to the stream in four distance classes (Peck et al. 2006, Berge 2010). The distance classes were 1) at least partially within the bankfull channel, 2) present within the 10 x 10 m riparian plot area but not on the bank, 3) present outside of the 10 x 10 m riparian plot area but within 30 m of bankfull, or 4) absent from the assessment area (Berge 2010).

immediate reach-level assessment area. Because of riparian habitat protection and restoration efforts in WRIA 8 for salmon habitat, almost all of the reaches in this study were located in green spaces or had substantial vegetated riparian buffers. Riparian conditions, especially forested buffers, can protect or improve stream condition and functions. These benefits extend to stream hydrology (e.g., Tabacchi et al. 2000, Mondal and Patel 2018), geomorphology (e.g., Cristan et al. 2016, Keeton et al. 2017, Mondal and Patel 2018), biology, and water quality (e.g., Sweeney and Newbold 2014, Warren et al. 2016). Specifically in terms of the potential correlations, previous studies have found that vegetated riparian forest buffers can influence stream channel geomorphology and biology. Vegetated buffers can reduce bank erosion, increase stream channel width, and trap sediment from upland areas (e.g., Sweeney and Newbold 2014, Keeton et al. 2017). Natural, vegetated riparian buffers can also maintain or improve stream biological condition in basins with low to moderate development, including in Puget Sound streams (Morley and Karr 2002, Wahl et al. 2013).

However, previous studies have also found that riparian buffers alone may be insufficient to mitigate widespread disturbance in more developed watersheds. For example, the positive effects of buffers can be reduced if the buffers are too narrow, are breached by street or agricultural field drainage systems, have highly degraded uplands (e.g., clear-cut forestry practices), or the catchment is particularly erosion-prone (e.g., steep slopes) (Morley and Karr 2002, Wahl et al. 2013, Nigel et al. 2013, Sweeney and Newbold 2014, Cristan et al. 2016, Covarrubia et al. 2016). Additionally, the effectiveness of riparian areas to provide or support stream functions can vary greatly based on vegetative structure (Tabacchi et al. 2000, Lecerf et al. 2016) and ecoregion (Binckley et al. 2010). In WRIA 8, the level of development in contributing basins varied from almost no development (less than 1% urban land cover in and immediately around the Cedar River Municipal Watershed) to dense urban land cover (some creeks in Seattle and Bellevue had over 80% urban land cover in their contributing watersheds). The overwhelming influence of intense watershed development on the effects of riparian buffers on biological stream condition may explain why SFAM, with its abundant use of riparian metrics, generally did not correlate with B-IBI when reaches within urban growth areas were considered. The 2018 version of SFAM added explicit justification for each metric and built more context for metrics of riparian structure into the calculator. However, based on the continued high prevalence of function metrics that measure riparian and near-stream structure, the recently released final version of SFAM needs further evaluation to determine if the scores it produces effectively predict stream processes across entire urban to rural gradients.

Correlations of SFAM value scores against WRIA 8 gradients and Puget Sound Watershed Characterization Project data

SFAM value scores generally reflected anthropogenic degradation of the reach, but in the opposite direction of what I expected. SFAM had higher hydrology, geomorphology, and biology scores in reaches with higher anthropogenic degradation in the contributing basin (Figures 12-14). The higher hydrology, geomorphology, and biology value scores in more degraded reaches, while in an unexpected direction, suggests that these SFAM scores prioritize, at least in part, the rarity of the functions the reach provides within its watershed. This approach implies that the loss of a few, rare ecosystem processes would be more detrimental to the overall watershed than the degradation of a more pristine reach, which is similar to the Endangered Species Act (Kimbrell 2016). However, there are several potential problems with this negative correlation that need explanation in SFAM. First, highly disturbed reaches like those found in urbanized areas may have limited potential for ecological lift of stream functions if their watersheds are highly degraded or if there are built barriers to restoration, such as a road limiting lateral channel migration (Harman et al. 2012). Second, WRIA 8 reaches that are relatively untouched and higher in the watershed received the lowest SFAM hydrology, geomorphology, and biology value scores. Protecting intact habitat is much easier and more successful than trying to recreate or restore degraded habitat (Roni et al. 2002, Bates 2012), which is why many management plans prioritize the protection of high-quality habitat over the restoration of degraded habitat (Vanderhoof et al. 2011, Bates 2012, Conlon Jensen 2012).

While likely not a primary driving factor for the value scores, the combination of opportunity and significance subscores likely influenced the strength and, potentially, the direction of the correlations (Appendix G; Willamette Partnership 2013). In terms of opportunity (the ability of a reach to provide a given function), reaches lower in the watershed generally provide multiple functions that do not occur in higher elevation reaches (Wilhere et al. 2013), including increased surface water storage, water transfer, geomorphic buffering and resilience, and species diversity (Allan and Castillo 2009, Bierman and Montgomery 2014). In terms of significance (the local importance of that function), streams with more human development generally have reduced stream functioning (Walsh et al. 2005, Allan and Castillo 2009, Kaushal and Belt 2012, Bierman and Montgomery 2014), which would increase the relative scarcity and the importance of reaches performing processes in degraded watersheds. Additionally, developed watersheds can greatly benefit from intact functions for protection of both infrastructure and the environment, including surface water storage for flood mitigation and increased habitat availability for at-risk species. The resulting increased opportunity and significance in downstream, degraded reaches would reasonably increase the value of those reaches. However, combining opportunity and significance of a reach into a single score can obscure the contributing components. It is not possible to determine from a single score which components have high values or low values unless the reach is extremely poor or extremely high quality (i.e., both values are low or both are high, respectively). This problem was most notable in the biology value subscores. The inverse correlation between biology opportunity and significance scores (Figure S8c) likely drove the very narrow biology value score range (Figure 14). The obscuring of score components in multimetric indexes is a previously identified problem for interpretation and usefulness of multimetric indexes as a diagnostic tool (Reynoldson et al. 1997, Green and Chapman 2011). More guidance on how to interpret SFAM value scores could benefit users and land managers, as it is currently unclear how the value scores connect to their associated stream processes and potential watershed management goals. Even in the 2018 version of SFAM, there is insufficient information on how to interpret value scores that are not extremely high or low (Nadeau et al. 2018a).

In contrast to the other value correlations, SFAM determined higher water quality value in reaches with lower anthropogenic degradation in the contributing basin, outside of urban growth areas only (Figure 15). The weak correlations between water quality value scores and commensurate data, which were in the direction I expected, were highly leveraged by two groups of sites. As noted in the Results, the first group consists of the two most developed sites outside of urban growth areas: Bear Creek (WAM06600-057527) and Bear Creek tributary (WAM06600-111639). Without these two reaches with high percent watershed imperviousness and low SFAM water quality value there was no correlation (tau = - 0.17, p = 0.19). The relatively high amount of watershed imperviousness of Bear Creek and Bear Creek tributary compared to other non-urban growth area sites may result from their close proximity, less than 0.2 km, to the Redmond urban growth area boundary (King County 2018). The second group consisted of six reaches that included all five of the reaches in the Cedar River Municipal Watershed and a segment of Carey Creek (WAM0660-006355) less than 1 km from the boundary of the Cedar River Municipal Watershed and within King County's Taylor Mountain Forest. All of these reaches had the highest water quality value score (7.8 points) of the non-urban growth area reaches. The remaining nine non-urban growth area stream reaches created a relatively scattered clump of scores with no apparent pattern (Figure 15).

Furthermore, the general dearth of state-listed water quality impairment ratings for individual stream reaches likely contributed to the lack of correlation between SFAM water quality value scores and commensurate Puget Sound Watershed Characterization Project data. The SFAM water quality value opportunity subscores quantified the likelihood that the reach is impaired by assessing land use, riparian buffers, and 303(d) or other Total Maximum Daily Load listings in all three subscores (nutrient cycling, chemical regulation, and thermal regulation). SFAM heavily weights water quality impairment designations in the opportunity subscores when the reach is listed as impaired[24], which I expected to increase the likelihood of correlation between the SFAM water quality value scores and the water quality export degradation scores from the Puget Sound Watershed Characterization Project. Water quality export degradation scores result from the amount of contaminants that are likely to enter a waterbody due to human alterations of the contributing basin. Both the water quality export degradation and 303(d) listings in SFAM assessed phosphorus, nitrogen, and metals. However, the use of 303(d) listings as the primary indicator of nutrient, chemical, or temperature impairment potentially limits the usability of SFAM water quality value scores because many reaches do not have available data. The Washington State Department of Ecology estimates that they have data for one or more parameters for only 10% of the National Hydrography Data set reaches in the state (personal communication, Patrick Lizon, Water Quality Assessment Coordinator at Washington State Department of Ecology). As of 2012, five[25] of the 36 reaches in this study had 303(d) listings for nutrient impairment and two of those reaches also had temperature impairment. The remaining reaches either did not have any assessment data (n=25) or had data for water quality metrics not used in SFAM (e.g., pH; n=6). This appears to be a problem for the final version of SFAM as well. The 2018 SFAM still relies exclusively on 303(d) and other Total Maximum Daily Load listings to indicate water quality impairment. However, it is currently unclear what percentage of Oregon reaches have applicable data. The Oregon Department of Environmental Quality is

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[24] When a reach has a 303(d) or other Total Maximum Daily Load listing that affects the specific function (nutrients, toxins, or temperature), the impairment is multiplied by 4 and is added to the average of all the other contributing raw measures subscores (thus providing up to four-fifths of the opportunity subscore).

[25] Swamp (WAM06600-083131), Kelsey (WAM06600-080407), Issaquah (WAM06600-035623), Lewis (WAM06600-020391), and Tibbetts (WAM06600-062567) all had 303(d) listings for nutrient impairment; Lewis and Tibbetts were also listed as having temperature impairment.

aiming to calculate the percentage of reaches with data for the 2018 Integrated Report (personal communication, Becky Anthony, WQ Assessment Program Lead at the OR Dept. of Environmental Quality).

Sensitivity analyses

Interpreting outputs with missing data

The sensitivity analyses revealed relatively small and predictable effects of data typically missing in Washington, although the effects were not consistent across metrics. The change in final SFAM outputs between leaving the input blank and entering a known input varied both across and, at times, within the four unavailable metrics. Additionally, there was variation in how the unavailable metrics did or did not interact with the background stream condition and floodplain presence/absence. As the most extreme example, changing the score between the highest known metric (regular flooding) and the unanswered entry (blank) in the assessment of downstream flooding in low background condition changed the final hydrology value score up to ± 0.97 points, covering nearly 10% of the total possible SFAM score range. However, the same change in metric scoring for downstream flooding in high background condition resulted in no change in the final hydrology value score.

The various small interactions in the sensitivity analyses resulted from four causes, all of which could be important for interpreting SFAM results. First, removal of a metric from an average simultaneously increases the weight of the other metrics and increases the uncertainty of the overall score. Most unanswered SFAM metrics are removed from the calculation of their associated SFAM final score through the use of the AVERAGE function in Excel (Microsoft Corporation 2017a), which is how the Draft SFAM User Manual states it will treat unanswered metrics (Willamette Partnership 2013, pgs. 15 & 16). However, the metric for floodplain exclusion is removed from the biology value score calculation when floodplains are absent. This metric removal caused the interaction between background condition and floodplain designation when assessing effects of unknown rare species occurrence scores. Not using the floodplain exclusion metric to calculate biology value is appropriate if floodplains are not present to exclude. However, the biology value score decreased when floodplain designation changed from present to absent in high background condition, but the biology value score increased with the same change in floodplain designation in low background condition (Figure 17c). The interaction suggests that floodplains are beneficial in high background condition but detrimental in low background condition. However, the interaction is more likely the by-product of averaging together the remaining high and low scores in the significance subscores for the “create and maintain habitats” and the “sustain trophic structure” value subscores. The interaction could complicate the interpretation of SFAM scores when the floodplain designation differs between sites. The 2018 version of SFAM does not specify how users should answer the floodplain exclusion metric if there is no floodplain (Nadeau et al. 2018a).

Second, the use of the MAX function in Excel has the potential to artificially lower and remove data from the biology value score. The MAX function reports the group’s largest value as zero if all of the cells in the group are blank (Microsoft Corporation 2017b). As a result, not knowing the rare species occurrence resulted in the same SFAM biology value score as entering the lowest possible known entry (none, 0%) in the SFAM calculator (Figure 17c and Figure 18c), artificially decreasing the biology value score by up to 0.42 points. In addition, the use of the MAX function could mask biodiversity conditions at the site because the MAX function excludes five of the six rare species occurrence scores from the SFAM biology value calculation. In other words, improving any of the lower rare species occurrence scores will not affect the biology value score if any other rare species occurrence scores were already higher than or equal to the improved rare species occurrence score. On one hand, this has the effect of giving a site a high-value rating if it has at least one important species. However, it could also have unintended implications for mitigation or restoration efforts by encouraging efforts to focus only on improving the best biodiversity score. Having all of the rare species occurrence inputs contribute to the biology value score, perhaps with a weighting in the calculation, and changing the score calculation to exclude unknown metrics, could eliminate these concerns. In the 2018 version of SFAM, the MAX function is used in ten separate value subscore calculations. With the additional resources provided to SFAM users (including an online mapping tool that produces data reports), all of the data should be available (McCune et al. 2017). However, the concern that data are being removed from the calculation and that potential management plans may focus on only improving the best component are still relevant concerns.

Third, ecoregion entries also inadvertently included blank inputs into calculations and lacked a clear rationale for their use in the SFAM drafts. For both the sensitivity analyses (virtual and WRIA 8 stream condition), not entering an ecoregion led to the same raw measure subscores for cover context as for moderately dry or vegetatively patchy ecoregions (types 3-6). This score assignment implies that the base ecoregion type in SFAM is a moderately dry or patchy ecoregion, which does not reflect many regions. For example, as noted in the Methods, the ecoregions in WRIA 8 were historically forested (Pater et al. 1998), so the expected vegetation type would not be represented adequately without entering an ecoregion, an issue that was not clearly documented in the SFAM drafts. In contrast, wet densely forested (type 1), wet densely and moderately forested (type 2), and dryland vegetation (prairie, sagebrush steppe) (type 7) were assigned no raw measure subscore for cover context, implying that cover is not an important metric for differentiating thermal regulation value among reaches in those ecoregions. However, neither the draft SFAM User Guide (2013) nor the draft SFAM Desk Guide (2015) provided a rationale or other explanation for the ecoregion types or cover context. This potential concern is not relevant for the recently released final SFAM version, which provided much clearer and ecologically relevant rationales. The rationales allow users to select the appropriate general type of ecoregion even if the assessment is outside of Oregon. For example, the metrics quantifying canopy cover and large woody debris in the stream are modified to account for even pristine reaches in xeric climates having less expected cover and in-stream wood than western reaches (Nadeau et al. 2018b). It is unclear how not answering the ecoregion type would affect the 2018 SFAM scores.

Fourth, variation in known SFAM metrics can influence the effects of unknown metrics. For example, in the sensitivity analyses using the WRIA 8 stream condition, some deviations in SFAM final scores from the baseline score resulted from variation in known SFAM metrics (Figure 18). In the Richards-Baker Flashiness Index sensitivity analysis, four reaches had modified hydrology function scores that were above the trend line. The small increases in modified hydrology function scores occurred because each of the four reaches had at least one known metric with a raw measure subscore of 50% that also contributed to the flow variation function subscore (Figure 18a). For the other 30 reaches in the sensitivity analysis, all of the metrics that contributed to the flow variation function subscore other than Richards-Baker Flashiness Index had raw measure subscores of 100%. This difference resulted in an increase of 0.14 points (when one other subscore was 50%, n=3) or 0.28 points (when two other subscores were 50%, n=1) in the hydrology function score relative to the other reaches when changing the Richards-Baker Flashiness Index score from blank to a known Richards-Baker Flashiness Index score. While the Richards-Baker Flashiness Index was removed from the final version of SFAM, this potential concern could still occur with other metrics. SFAM users need to be aware that variations in other contributing metrics can alter the effects of an intended modification in stream management.

One solution for missing metrics would be to calculate an average SFAM score across the potential range of unknown metric values. The user could calculate SFAM outputs for each raw measure subscore for the unknown metric, or all combinations of several missing metrics, and then use the mean and standard error of the resulting SFAM outputs for the calculation of final SFAM scores. This range of potential scores could account for the uncertainty that enters the SFAM final score when data are missing.

Potential concerns for SFAM use/interpretation

The correlations and sensitivity analyses identified several SFAM components that could use more explanation or justification in future versions of SFAM. First, SFAM has a high prevalence of metrics that contribute to multiple subscores, even within a single final score. Reuse of metrics for different subscores is a nontransparent way of weighting metrics. Every SFAM final score except for geomorphology function includes metrics that contribute to more than one subscore in the calculation of the final score (Figure S4, Appendix F). The draft SFAM User Guide briefly addresses that a single measure may contribute to multiple functions (Willamette Partnership 2013, pg. 9); however, it did not expand the description to the amount of repetition within the calculator or potential limitations from the repetition of metrics. The metric quantifying channel bed variability (BedVar) was the most repeated metric in the SFAM calculator. BedVar was used eight times in the function calculations, including in each of the three hydrology function subscores, one of two geomorphology function subscores, two of three biology function subscores, and two of three water quality function subscores (Table S16). When assessing the final scores, water quality function has the most repetition of metrics with only eight unique metrics contributing to the 15 raw measure subscores that comprise the final score (Table S16). While no metrics were repeated within an individual water quality subscore[26], using different combinations of eight original metrics to create 15 subscores creates an unwarranted perception that more information is contributing to the assessment than actually is. While this

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[26] Impervious area appears twice in the list of metrics for the chemical regulation subscore in the water quality value score, but only contributes once to each subscore (opportunity and significance) calculation (Table S17).

study did not specifically evaluate the effects of repeated metrics, highly correlated subscores, which can occur when metrics contribute to multiple subscores, can lead to overall lower precision, responsiveness, and sensitivity of assessments (Sickle 2010). The 2018 version of SFAM also repeats metrics throughout the calculator. The effects of repeating metrics requires further evaluation relative to simpler, more transparent approaches, such as just taking the average of all the metrics.

Second, several metrics are not available both before and after a management action (any metric that requires extensive time to respond to changes in the system), which could complicate SFAM's ability to estimate mitigation credits or debits. This study did not evaluate how widespread this problem could be within the SFAM calculator or the magnitude of this potential issue in terms of SFAM scores. However, metrics that have potentially delayed responses to management actions include, but are not limited to, any metric based on streamflow measurements (e.g., Richards-Baker Flashiness Index, the occurrence of downstream flooding, overbank flow) and those based on biological responses (rare species occurrence, canopy cover, and B-IBI). These measurements may be limited by the time required to collect representative data or may require time for stream processes to adjust to management changes in the stream or basin. Delays in metric response could compromise mitigation credits calculated by assessing pre-and post-impact condition (e.g., U.S. Army Corps of Engineers et al. 2013, 2017, U.S. Army Corps of Engineers, Omaha District 2013) unless follow-up assessments confirm that the expected improvements occur. The Draft SFAM Desk Guide briefly addresses that the period of record for the Richards-Baker Flashiness Index, which has been removed from the 2018 version of SFAM, may be insufficient for assessing differences between pre- and post-restoration condition (Czarnomski et al. 2015, pg. 14), but does not discuss how to account for this uncertainty when interpreting SFAM scores. Additionally, the 2018 version of SFAM briefly discusses that SFAM assessments of the predicted state of an impacted reach may be necessary for regulatory purposes, but does not include detailed information on how to perform the predicted state assessment[27] (Nadeau et al. 2018a). While delayed responses in metrics to actions are not unique to SFAM, having consistent strategies to estimate or calculate changes in delayed-response metrics could be a potential solution.

Third, some metrics, in particular the Richards-Baker Flashiness Index (which was removed from the final version of SFAM) were used in ways not generally seen in the literature and need additional validation or justification for users. SFAM used a single Richards-Baker Flashiness Index score to represent stream flashiness (Czarnomski et al. 2015). However, the Richards-Baker Flashiness Index was designed to characterize changes in flashiness over time by calculating Index scores for different timeframes (e.g., water years) within a longer period of time (e.g., decades) (Baker et al. 2004, Rosburg et al. 2017). The typical Richards-Baker Flashiness Index approach may be less feasible than the SFAM approach within the context of annual monitoring for mitigation (U.S. Army Corps of Engineers 2008). However, without the context of previous flow data, a single Richards-Baker Flashiness Index score does not necessarily indicate more or less flashy flows than occurred historically. The SFAM calculator modified Richards-Baker Flashiness Index scores based on whether the watershed area is greater

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[27] The User Manual for the 2018 version of SFAM suggests "using a reference site, if available, or by assuming the site has had time to adjust to a variety of flow conditions and planted vegetation has time to mature" (Nadeau et al. 2018a, page 79)

or less than 78 km^2, likely because flashiness tends to decrease with increasing basin size (Baker et al. 2004). However, SFAM does not provide justification for the specific basin area cut off. Additionally, controlling for the watershed area does not provide adequate context regarding deviations from historic flashiness within a single stream reach, such as the reach becoming flashier with increased basin imperviousness. To provide the missing context, the SFAM calculator could incorporate ecoregion, stream order, and geographical topography such as the slope of the stream and surrounding landscape to model a range of expected Richards-Baker Flashiness Index scores or use a range of measured scores for undisturbed streams of that particular stream order and in that ecoregion. The modeled score could then be compared to the user-calculated Richards-Baker Flashiness Index. Although the Richards-Baker Flashiness Index was removed from the 2018 version of SFAM because daily flow data are lacking for many streams, these concerns should be addressed for future versions of SFAM if the Richards-Baker Flashiness Index or similar inputs are used.

Fourth, SFAM should further address context metrics included in the calculator cover page and were identified as important for reviewers but which never contribute to any SFAM scores. These included Q_2 discharge, grain-size distribution (obtained using a zig-zag pebble count protocol), and site history (Czarnomski et al. 2015). For example, grain-size distribution is controlled by stream hydrology and geomorphology (e.g., areas with faster flows generally have larger sediment, activity of bed and bank erosion) (Gordon et al. 2004, Bierman and Montgomery 2014), and describes the availability of important habitat for algae, macroinvertebrate, and fish communities (Gordon et al. 2004, Allan and Castillo 2009). For example, a stream reach with a bed composed primarily of fine sediment could be a lowland, naturally depositional, healthy stream or it could be a highly disturbed reach with high levels of sediment loading from upland alterations like agriculture or clearcutting (Bierman and Montgomery 2014, Russell et al. 2017). The inclusion of grain-size distribution could be combined with context from slope and ecoregion or stream type to determine how dissimilar the reach is from expected natural conditions. While grain-size distribution was removed from the 2018 version of SFAM, the stream discharge and project area history are still both included in the SFAM calculator cover page without directly contributing to any SFAM scores.

Conclusions and future research

SFAM is a potentially groundbreaking model for rapid stream function assessment, created from extensive background research and effort. The evaluation of stream functions in stream assessments is becoming more common in monitoring and management goals (Kollmann et al. 2016), but has a much scarcer literature and history than assessment of stream structure (Palmer et al. 2014). The metrics and general structure of SFAM (e.g., multimetric, separating stream function types within the methodology) overlap with those used in other rapid stream function assessment protocols (Harman et al. 2012, Starr et al. 2015). However, the results of this study suggested that SFAM function scores do not reflect known gradients in anthropogenic degradation of stream condition. The SFAM value scores also did not reliably reflect levels of anthropogenic degradation of stream condition, with the exception of hydrology value scores. SFAM value scores, when they did correlate with commensurate data, were generally higher in reaches with more watershed and in-stream degradation - the opposite direction from expected. While this study used the November 2015 draft version of SFAM, many of the potential concerns identified in this study appear to apply to the SFAM version released in June 2018. The recently released SFAM still has a high prevalence of function metrics that quantify in- and near-stream physical structure without additional context regarding overarching watershed condition. Additionally, the SFAM value scores still combine the opportunity and significance subscores, which can conceal trends and, thus, complicate interpretation of the value scores. Future versions of SFAM should also address the removal metrics through the use of the MAX function and the repetition of metrics across subscores and within final scores. The results of this study suggest that more validation through empirical, quantitative evidence could help determine if the SFAM scores can predict levels of stream functions with the precision required for the legal mandates set forth for compensatory mitigation by the Clean Water Act.

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APPENDIX A: WRIA 8 DESCRIPTIONS

Table S1. Variable weighting of significant principal components (PCs) for landscape metrics of 45 stream reaches in King County, WA. PC significance was determined using Kaiser's Criterion (eigenvalue ≥ 1; Kaiser 1960). Bolded weightings indicate the driving metrics for the PC (weighting value ≥ 0.7*max weighting; Mardia 1979).

Metric	Weighting **PC1**	 **PC2**	Metric definitions (copied from data for King County 2015)
Elev_mean_ft	**0.290**	0.085	Mean elevation (ft)
Pct_agriculture	-0.191	**-0.274**	Percent agriculture - cultivated, and pasture/hay (%)
Pct_barren	-0.057	**-0.287**	Percent barren - bare land (bare earthen material with little to no vegetation) (%)
PCT_EDGE	**-0.234**	-0.149	Percent of land cover in watershed classified as forested 'edge' (100 m perimeter of core areas)
Pct_forest	**0.301**	-0.076	Percent forest - deciduous, evergreen and mixed (%)
Pct_grassland	-0.184	**-0.321**	Percent grasslands - grassland (naturally occurring grasses and non-grasses (forbs) that are not regularly cultivated) (%)
Pct_imp	**-0.273**	0.186	Percent developed impervious surface (%)
PCT_LG_CORE	-0.024	**-0.386**	Percent of land cover in watershed classified as forested 'large core' (100 m from the nearest non-forest pixel). Large core patches have an area greater than 500 acres
PCT_MED_CORE	**0.249**	-0.099	Percent of land cover in watershed classified as forested 'medium core' (100m from the nearest non-forest pixel). Medium core patches have an area between 250-500 acres
PCT_PATCH	0.021	**-0.304**	Percent of land cover in watershed classified as forested 'patch.' Patch pixels are small forested areas that do not contain any core pixels
PCT_PERF	0.015	-0.234	Percent of land cover in watershed classified as forested 'perforated.' Perforated pixels define the boundary between core forest and relatively small clearings inside forested land cover, or pixels along the inside edges of small non-forested gaps in forested land cover
Pct_shrub	0.056	**-0.385**	Percent shrub - scrub/shrub (areas dominated by woody vegetation less than 5 m in height) (%)
Pct_slope_mean	**0.264**	0.031	Mean percent watershed slope (%)
PCT_SM_CORE	**0.290**	0.107	Percent of land cover in watershed classified as forested 'small core' (100m from the nearest non-

Metric	Weighting **PC1**	 **PC2**	Metric definitions (copied from data for King County 2015)
			forest pixel). Small core patches have an area less than 250 acres
Pct_urban	**-0.284**	0.160	Percent urban - high intensity, medium intensity, low intensity, and open space developed (%)
Pct_wetland	-0.132	-0.211	Percent wetland - palustrine forested, scrub/shrub, emergent wetlands (%)
Pop_dens_persqkm	**-0.253**	0.217	Population density derived from 2010 census (#/km2)
Precip_mean_mm	**0.298**	0.033	Mean precipitation (mm), 1981-2010
Rd_dens_persqkm	**-0.282**	0.139	Road density derived from USGS National Map transportation data layer (km/km2)
Rd_xings_perkm	0.042	-0.069	Number of road/stream crossings per kilometer of stream in the reporting unit (count)
Stream_dens_persqkm	**0.265**	0.013	Stream density derived from 1:24,000-scale National Hydrography Data set (km/km2)
WA_ha	0.019	-0.247	Watershed area (ha)
Proportion of variance	0.477	0.222	

APPENDIX B: METRIC DEFINITIONS

Table S2. Metrics used to calculate function and value scores for stream functions in the Stream Function Assessment Methodology (SFAM) (Willamette Partnership 2013). Metrics obtained through office work are italicized, metrics obtained in the field have normal font.

Specific functions	**Function metrics**	**Value metrics**
Hydrology functions		
Surface Water Storage	Overbank flow, channel entrenchment, *floodplain exclusion*, beaver activity, *side channels*	*Impervious area, downstream flooding and floodplain presence*
Sub/Surface Water Transfer	Overbank flow, channel entrenchment, *floodplain exclusion*, beaver activity, *side channels,* channel flow pattern, floodplain dominant vegetation	*Aquifer and soil permeability*
Flow Variation	Overbank flow, channel entrenchment, *RB Flashiness Index*, channel flow pattern, channel bank stability, channel bed variability	*Impervious area, downstream flooding and floodplain presence, withdrawals and impoundments, proximity to natural areas*
Geomorphology functions		
Sediment Continuity	Overbank flow, channel entrenchment, vegetation on bars, bank armoring, channel bank stability	*Impervious area, up- and downstream impoundments, land use, erodibility, 303(d) sediment listing*
Sediment Mobility	Channel entrenchment, bank armoring, channel bank stability, channel bed variability, channel constraints	*Impervious area, upstream impoundments,* bank armoring, *land use, erodibility, withdrawals*
Biology functions		
Maintain Biodiversity	Overbank flow, channel entrenchment, *floodplain exclusion*, channel bed variability, large woody debris, vegetation on bars, beaver activity, noxious weeds, native woody vegetation, mature tree, conifers, in-stream habitat complexity, *non-native aquatic species*, *side channels*, *BIBI*	*Priority watershed status, impervious area*, unique habitat features, *rare species, waterbird habitat, fish passage barriers, proximity to natural areas*

Specific functions	**Function metrics**	**Value metrics**
Create and Maintain Habitat	Channel entrenchment, *floodplain exclusion*, channel bed variability, large woody debris, vegetation on bars, beaver activity, noxious weeds, native woody vegetation, mature tree, conifers, in-stream habitat complexity, fish passage barriers, *side channels*	*Impervious area, impoundments*, *proximity to natural areas*, unique habitat features, *upstream and downstream fish passage barriers, upstream intact riparian area, upstream riparian connectivity,* floodplain exclusion
Sustain Trophic Structure	Overbank flow, channel entrenchment, *floodplain exclusion*, riparian buffer, beaver activity, *non-native aquatic species*, *BIBI*, canopy cover	*Proximity to natural areas*, *upstream intact riparian area, upstream riparian connectivity, 303(d) nutrient and temperature listings, temperature exceedance*, floodplain exclusion
Water quality functions		
Nutrient Cycling	Overbank flow, channel entrenchment, *floodplain exclusion*, beaver activity, riparian buffer, *BIBI*, floodplain dominant vegetation	*Land use, 303(d) nutrient and sediment listings, upstream intact riparian area, upstream riparian connectivity*, floodplain exclusion, overbank flow, riparian buffer, *proximity to natural areas*
Chemical Regulation	Channel entrenchment, *floodplain exclusion*, beaver activity, riparian buffer, *side channels*, channel bed variability, soil permeability	*Impervious area, 303(d) toxic listing, upstream intact riparian area, upstream riparian connectivity, floodplain exclusion*, overbank flow, riparian buffer, *proximity to natural areas*
Thermal Regulation	Canopy cover, *temperature exceedance*, channel flow pattern, *BIBI*	*303(d) temperature listing, temperature exceedance, proximity to natural areas, upstream intact riparian area, upstream riparian connectivity,* canopy cover

Table S3. Definitions of metrics used in this study from King County's Water Resource Inventory Area 8 Status & Trends Monitoring Program (S&T) (copied from data for King County 2015).

Metric name	Definition
Habitat metrics	
BFWidth_BFDepth	Bankfull width:depth ratio
D50	Median particle diameter (mm), from size class estimates
LWDSiteVolume100m	Volume of LWD standardized per 100m of site reach (m3/100 m)
PCT.Cobble	Percentage of substrate classified as 'cobble' (>64-250 mm)
PCT.Fines	Percentage of substrate classified as 'fine' (silt, clay, non-gritty)
PWP All	Proximity weighted presence metric, all disturbance classes combined
RBS	Relative bed stability (Kaufmann, P.R., J. Faustini, D.P. Larsen, and M. Shirazi. 2008. A roughness-corrected index of relative bed stability for regional stream surveys. Geomorphology 99:150-170.)
ResPoolArea100	Vertical residual pool area, standardized m2 per 100 m of site reach
X DensioBank	Reach average, densiometer readings at channel center
X Embed	Reach average, substrate embeddedness
X.BFDepth	Reach average, bankfull depth (cm)
X.BFWidth	Reach average, bankfull width (m)
X.TWDepth	Reach average, thalweg depth (cm)
Temperature metrics	
7DMax	Maximum (July-August) 7-Day moving average of the daily maximum temperature
Hydrology metrics	
30-day summer low flow	Centered 30-day moving average of the summer (Jul-Oct) minimum flow
7-day summer minimum flow	Centered 7-day moving average of summer (Jul-Oct) minimum flow
Flow Reversals	The number of times that the flow rate changed from an increase to a decrease or vice versa during a water year. Flow changes of less than 2 percent are not considered
High Pulse Count	Number of times each water year that discrete high flow pulses occur
High Pulse Duration	Annual average duration of high flow pulses during a water 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

Metric name	Definition
Low Pulse Count	Number of times each calendar year that discrete low flow pulses occurred
Low Pulse Duration	Annual average duration of low flow pulses during a calendar year
R-B Index	Richards-Baker Flashiness Index - A dimensionless index of flow oscillations relative to total flow based on daily average discharge measured during a water year

Table S4. Model variables used in calculating Washington State Department of Ecology Puget Sound Watershed Characterization Tool (PSC) scores (copied from data for Wilhere et al. 2013, Stanley et al. 2015a, 2015b).

Model variable	**Metric**	**Metric notes**
Water flow importance		
P- Precipitation	Average yearly amount of precipitation per unit area that falls within an analysis unit	
RS- Snow rain-on-snow area	Percent area of rain-on-Snow + Snow Dominated area, per area of the analysis unit	
WLS- Depressional wetlands and lakes	Percent of depressional wetland area per area of the analysis unit + Percent of lake area per area of the analysis unit	
STS- Unconfined & moderately confined floodplains	Miles of stream in unconfined floodplain in analysis unit/mi^2 per area of analysis unit *(3) + Miles of stream in modified confined floodplain in analysis unit/mi^2 per area of analysis unit *(2)	The 3 and 2 are importance factors used to weight the relative degree of surface storage capacity in the assessment unit
I_R- High permeability deposits	Recharge for coarse grained deposits and recharge for fine grained deposits per area in analysis unit	Recharge is calculated by regression equations of water budget components from the Hydrogeologic Framework for Puget Sound (Vacarro, 1998): equation 6 for coarse-grained deposits and equation 3 for fine-grained deposits.
I_DI- High permeability floodplains & slope wetlands	Miles of streams & rivers in permeable deposits of unconfined floodplains per area of the analysis unit + Percent area of potential slope wetlands per area of analysis unit	
Water flow degradation		
IMP- Impervious Cover	Percent of impervious area per area of analysis unit	
FL- Forest Loss	Percent of non-forest vegetation area per area of analysis unit	

Model variable	Metric	Metric notes
D_WS- Depressional wetland loss from urban & rural cover	Area of wetlands lost in urban area per area of analysis unit *(3) + Area of wetlands lost in agricultural and rural area per area of analysis unit * (2)	The 3 and 2 are importance factors used to weight the relative degree of surface storage capacity in the assessment
D_STS- Loss of floodplains	Miles of channelized stream in unconfined floodplain per area of analysis unit * (3) + Miles of channelized stream in moderately confined floodplain per area of analysis unit * (2)	The 3 and 2 are importance factors used to weight the relative degree of surface storage capacity in the assessment
D_R- Loss of recharge from urban land cover	Total recharge * recharge coefficient ([area of land use cover type*recharge coefficient] per area of analysis unit)	The land cover types are from the Coastal Change Analysis Program (C-CAP) with reduction coefficients based on percent impervious (high intensity (80-100% impervious)=0.9; medium intensity (51-79% impervious)=0.7; low intensity (20-50% impervious)=0.35)
D_DI- loss of discharge from floodplains, slope wetlands, & impactions from roads & wells	- Road density (miles of roads per area of analysis unit) - Well density (density of class A and class B wells per area of analysis unit) - Floodplain discharge loss (miles of urban unconfined streams in higher permeability deposits per area of analysis unit * (3) + miles of rural unconfined streams in higher permeability deposits per area of analysis unit * (2)) - slope wetland discharge degradation (area of slope wetlands within urban land use per area of analysis unit * (3) + area of slope wetlands within rural land use per area of analysis unit * (2))	The 3 and 2 are importance factors used to weight the relative degree of surface storage capacity in the assessment
IMP- Impervious Cover	Percent acres of impervious cover per area of analysis unit	
Water quality export potential		

Model variable	Metric	Metric notes
S_SO- Source	Surface erosion (rainfall erosivity, soil erodibility, average slope) + Mass wasting (landslide hazard, aquatic system density) + Channel erosion (erodible streams, average slope)	Sediment
S-SI- Sink	Surface storage (from Water Flow)	Sediment
P_SO- Source	S_SO + Phosphorous enrichment (if local data; rock and soil phosphorous content)	Phosphorus
P_SI- Sink	Surface storage (from Water Flow) + Soil clay content	Phosphorus
M_SO- Source	*Not significant	Metals
M_SI- Sink	Surface storage (from Water Flow) + Soil cation exchange capacity	Metals
N_SO- Source	*Not significant	Nitrogen
N_SI- Sink	Surface storage (from Water Flow) + Riparian denitrification (unconfined floodplains in hydric soils)	Nitrogen
Aquatic ecological integrity		
Aquatic ecological integrity	Hydrogeomorphic features (wetland density, undeveloped floodplain density) Assessment unit habitats (salmonid habitats [habitat amount, habitat quality {ecological integrity from upstream and local conditions} and IP models], combined with species presence and stock status) Accumulative downstream habitats	

APPENDIX C: SFAM DESCRIPTION

Every version of SFAM generates scores from data collected in the field and gleaned through office work. Fieldwork primarily involves observing, measuring, and estimating stream physical and biological characteristics within a pre-defined assessment area (Table S2, Figures S1 & S2). The office component entails compiling watershed-scale contextual data (Table S2) and entering data into the SFAM calculator Excel spreadsheet. The SFAM office metrics include data from a variety of buffer sizes ranging from 61 m to 3.2 km radius (area = 1.3 to 3,265 ha) around the assessment site, plus data from the entire watershed. The SFAM calculator creates multimetric function[28] (Figure S3) and value[29] scores (Figure S4) by integrating field and office metrics (Table S2) (Willamette Partnership 2013). In general, the calculator bins metric data into pre-determined categories, assigning each data category a percentage score between zero and 100; more desirable characteristics generally receive higher scores. The calculator groups the raw measure scores into subscores for the different stream functions, usually by averaging a pre-determined set of 2-14 metric scores and then scaling the resulting score to be between zero and ten (Willamette Partnership 2013). Several metrics contribute to more than one subscore (e.g., percent impervious in Figure S4). The calculator also determines the relevancy of sub-scores at the site by adjusting the original sub-score based on the presence or absence of specific stream characteristics that have a large impact on functioning (e.g., ecoregion).

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[28] Function scores aim to represent reach-scale processes (Willamette Partnership 2013).

[29] Value scores aim to capture the importance of that reach to broader watershed-scale benefits (Willamette Partnership 2013).

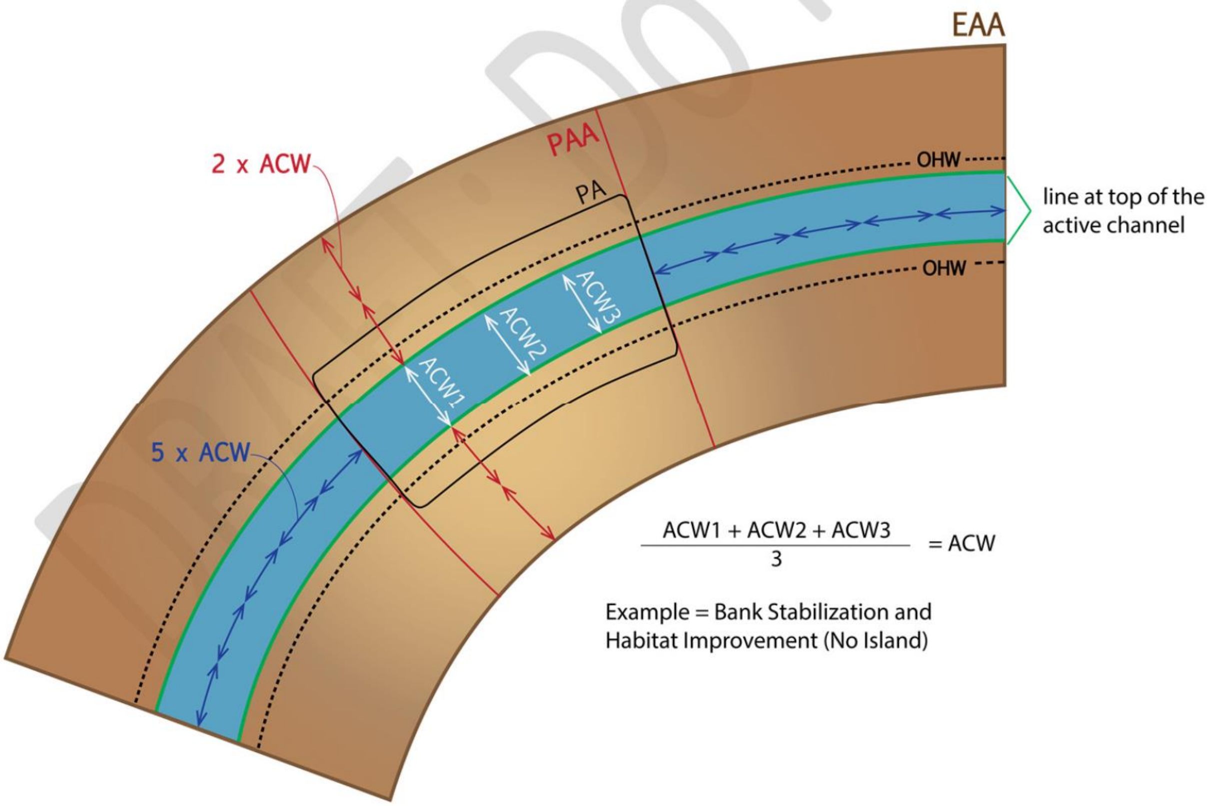

Figure S1. Schematic of the pre-defined assessment areas for SFAM fieldwork from the Draft SFAM Desk Guide (Czarnomski et al. 2015). ACW is the active channel width[30]. PA is the project area, which extends the length of the direct impact of a project. PAA is the proximal assessment area. EAA is the extended project area. OHW is the ordinary high water mark.

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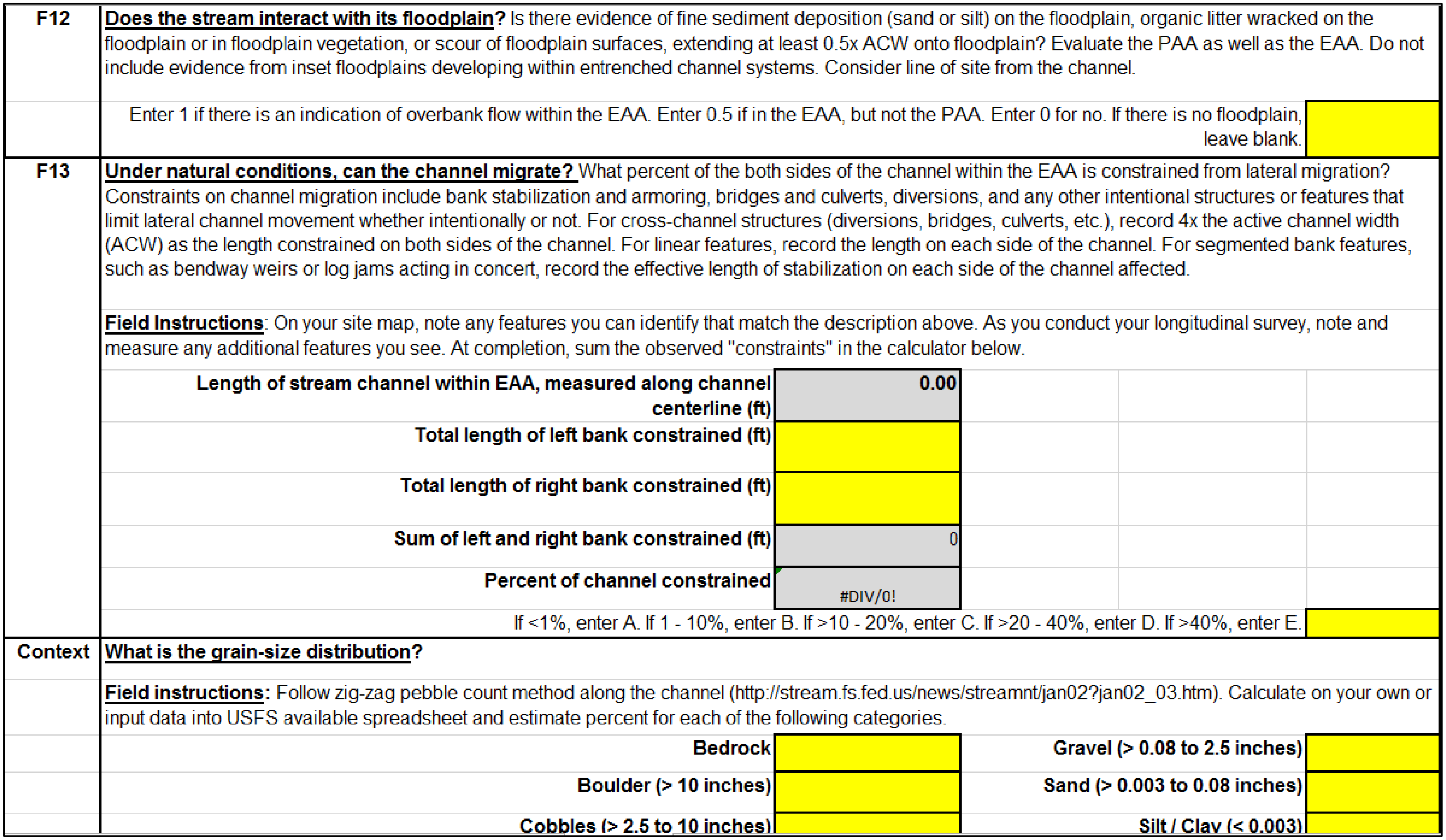
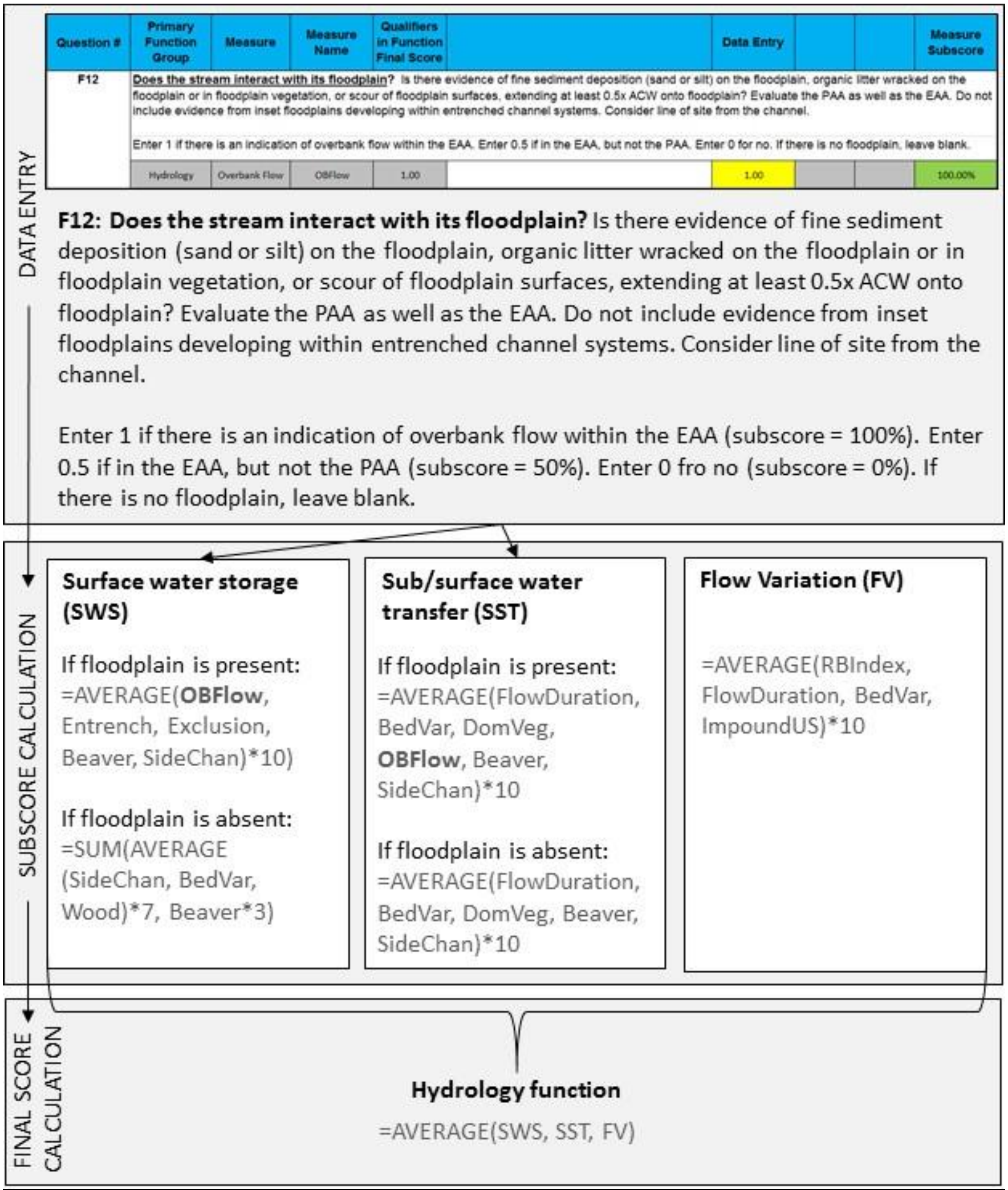
[30] "The active channel is the portion of the channel that is lower than bankfull and commonly wetted during and above winter and spring base flows… the ACW can be identified by a break in bank slope or the 'line' on each stream bank below which perennial vegetation does not grow and above which it persists" (Czarnomski et al. 2015).



F12	**<u>Does the stream interact with its floodplain</u>?** Is there evidence of fine sediment deposition (sand or silt) on the floodplain, organic litter wracked on the floodplain or in floodplain vegetation, or scour of floodplain surfaces, extending at least 0.5x ACW onto floodplain? Evaluate the PAA as well as the EAA. Do not include evidence from inset floodplains developing within entrenched channel systems. Consider line of site from the channel.			
	Enter 1 if there is an indication of overbank flow within the EAA. Enter 0.5 if in the EAA, but not the PAA. Enter 0 for no. If there is no floodplain, leave blank.			
F13	**<u>Under natural conditions, can the channel migrate?</u>** What percent of the both sides of the channel within the EAA is constrained from lateral migration? Constraints on channel migration include bank stabilization and armoring, bridges and culverts, diversions, and any other intentional structures or features that limit lateral channel movement whether intentionally or not. For cross-channel structures (diversions, bridges, culverts, etc.), record 4x the active channel width (ACW) as the length constrained on both sides of the channel. For linear features, record the length on each side of the channel. For segmented bank features, such as bendway weirs or log jams acting in concert, record the effective length of stabilization on each side of the channel affected.			
	<u>Field Instructions</u>: On your site map, note any features you can identify that match the description above. As you conduct your longitudinal survey, note and measure any additional features you see. At completion, sum the observed "constraints" in the calculator below.			
	Length of stream channel within EAA, measured along channel centerline (ft)	**0.00**		
	Total length of left bank constrained (ft)			
	Total length of right bank constrained (ft)			
	Sum of left and right bank constrained (ft)	0		
	Percent of channel constrained	#DIV/0!		
	If <1%, enter A. If 1 - 10%, enter B. If >10 - 20%, enter C. If >20 - 40%, enter D. If >40%, enter E.			
Context	**<u>What is the grain-size distribution</u>?**			
	<u>Field instructions</u>: Follow zig-zag pebble count method along the channel (http://stream.fs.fed.us/news/streamnt/jan02?jan02_03.htm). Calculate on your own or input data into USFS available spreadsheet and estimate percent for each of the following categories.			
	Bedrock		**Gravel (> 0.08 to 2.5 inches)**	
	Boulder (> 10 inches)		**Sand (> 0.003 to 0.08 inches)**	
	Cobbles (> 2.5 to 10 inches)		**Silt / Clay (< 0.003)**	

Figure S2. A portion of the SFAM field data entry form including field instructions for data collection.



Question #	Primary Function Group	Measure	Measure Name	Qualifiers in Function Final Score		Data Entry			Measure Subscore
F12	**Does the stream interact with its floodplain?** Is there evidence of fine sediment deposition (sand or silt) on the floodplain, organic litter wracked on the floodplain or in floodplain vegetation, or scour of floodplain surfaces, extending at least 0.5x ACW onto floodplain? Evaluate the PAA as well as the EAA. Do not include evidence from inset floodplains developing within entrenched channel systems. Consider line of site from the channel. Enter 1 if there is an indication of overbank flow within the EAA. Enter 0.5 if in the EAA, but not the PAA. Enter 0 for no. If there is no floodplain, leave blank.								
	Hydrology	Overbank Flow	OBFlow	1.00		1.00			100.00%

F12: Does the stream interact with its floodplain? Is there evidence of fine sediment deposition (sand or silt) on the floodplain, organic litter wracked on the floodplain or in floodplain vegetation, or scour of floodplain surfaces, extending at least 0.5x ACW onto floodplain? Evaluate the PAA as well as the EAA. Do not include evidence from inset floodplains developing within entrenched channel systems. Consider line of site from the channel.

Enter 1 if there is an indication of overbank flow within the EAA (subscore = 100%). Enter 0.5 if in the EAA, but not the PAA (subscore = 50%). Enter 0 fro no (subscore = 0%). If there is no floodplain, leave blank.

Surface water storage (SWS)

If floodplain is present:
=AVERAGE(**OBFlow**, Entrench, Exclusion, Beaver, SideChan)*10)

If floodplain is absent:
=SUM(AVERAGE (SideChan, BedVar, Wood)*7, Beaver*3)

Sub/surface water transfer (SST)

If floodplain is present:
=AVERAGE(FlowDuration, BedVar, DomVeg, **OBFlow**, Beaver, SideChan)*10

If floodplain is absent:
=AVERAGE(FlowDuration, BedVar, DomVeg, Beaver, SideChan)*10

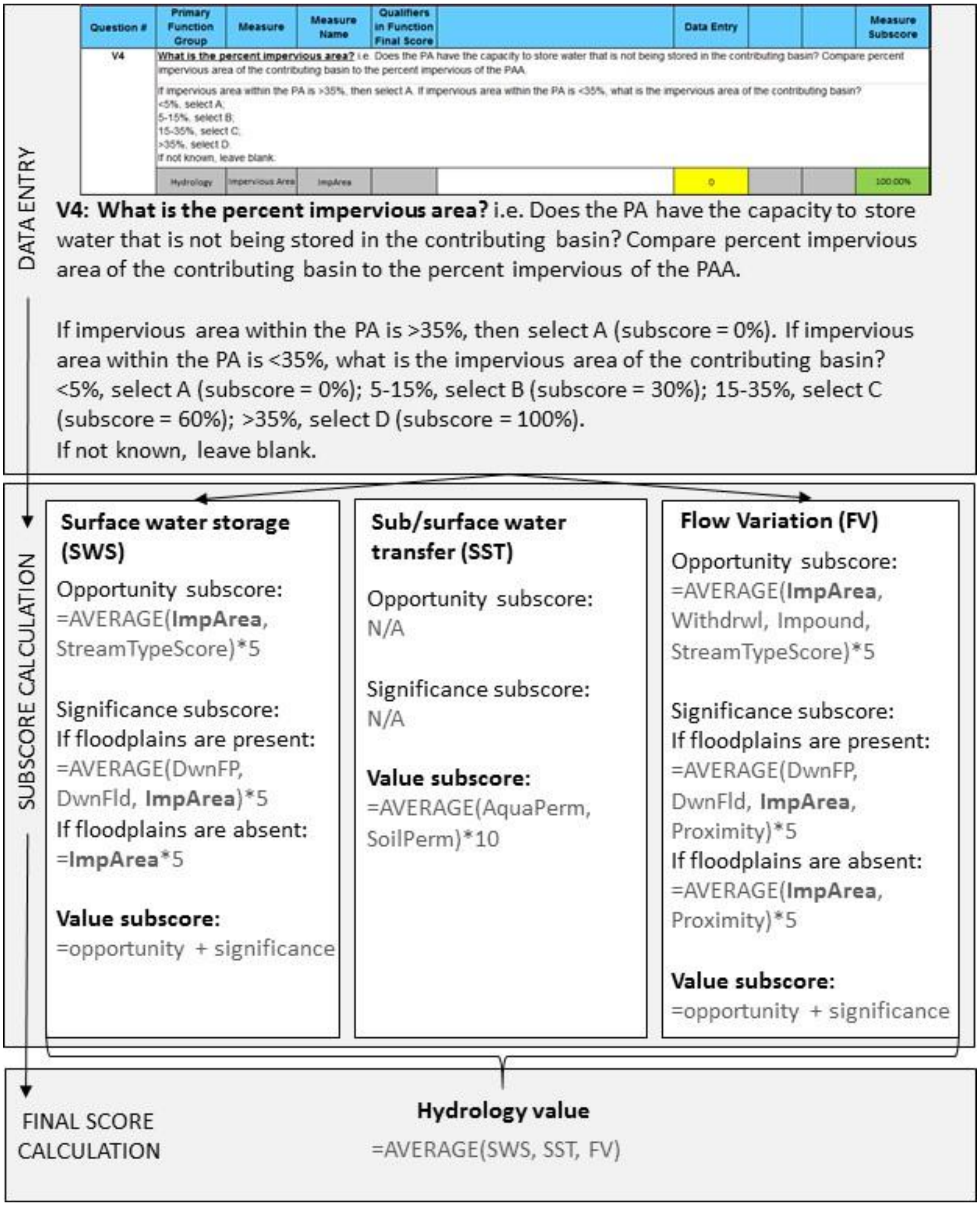
Flow Variation (FV)

=AVERAGE(RBIndex, FlowDuration, BedVar, ImpoundUS)*10

Hydrology function

=AVERAGE(SWS, SST, FV)

Figure S3. The progression of function calculations in the SFAM spreadsheet following the measure for overbank flow (OBFlow) from data entry, to function subscore calculation, to final function score calculation. Metric definitions are in Table S2. The PAA, or Proximal Assessment Area, covers the length of the project area with a lateral boundary extending 2x the active channel width or 50 ft, whichever is greater, parallel to the channel edge. The EAA, or Extended Assessment Area, includes the PAA and further extends a distance equal to 5x the active channel width both up- and downstream of the PAA (Czarnomski et al. 2015).



Question #	Primary Function Group	Measure	Measure Name	Qualifiers in Function Final Score		Data Entry			Measure Subscore
V4	**What is the percent impervious area?** i.e. Does the PA have the capacity to store water that is not being stored in the contributing basin? Compare percent impervious area of the contributing basin to the percent impervious of the PAA. If impervious area within the PA is >35%, then select A. If impervious area within the PA is <35%, what is the impervious area of the contributing basin? <5%, select A; 5-15%, select B; 15-35%, select C; >35%, select D. If not known, leave blank.								
	Hydrology	Impervious Area	ImpArea			0			100.00%

V4: What is the percent impervious area? i.e. Does the PA have the capacity to store water that is not being stored in the contributing basin? Compare percent impervious area of the contributing basin to the percent impervious of the PAA.

If impervious area within the PA is >35%, then select A (subscore = 0%). If impervious area within the PA is <35%, what is the impervious area of the contributing basin? <5%, select A (subscore = 0%); 5-15%, select B (subscore = 30%); 15-35%, select C (subscore = 60%); >35%, select D (subscore = 100%).
If not known, leave blank.

Surface water storage (SWS)

Opportunity subscore:
=AVERAGE(**ImpArea**, StreamTypeScore)*5

Significance subscore:
If floodplains are present:
=AVERAGE(DwnFP, DwnFld, **ImpArea**)*5
If floodplains are absent:
=**ImpArea***5

Value subscore:
=opportunity + significance

Sub/surface water transfer (SST)

Opportunity subscore:
N/A

Significance subscore:
N/A

Value subscore:
=AVERAGE(AquaPerm, SoilPerm)*10

Flow Variation (FV)

Opportunity subscore:
=AVERAGE(**ImpArea**, Withdrwl, Impound, StreamTypeScore)*5

Significance subscore:
If floodplains are present:
=AVERAGE(DwnFP, DwnFld, **ImpArea**, Proximity)*5
If floodplains are absent:
=AVERAGE(**ImpArea**, Proximity)*5

Value subscore:
=opportunity + significance

Hydrology value
=AVERAGE(SWS, SST, FV)

Figure S4. The progression of value calculations in the SFAM spreadsheet following the measure for impervious area (ImpArea) from data entry, to function subscore calculation, to final value score calculation. Metric definitions are in Table S2. The PA, or Project Area, is the area in or along the stream that will be directly impacted by the project. The PAA, or Proximal Assessment Area, covers the length of the project area with a lateral boundary extending 2x the active channel width or 50 ft, whichever is greater, parallel to the channel edge (Czarnomski et al. 2015).

APPENDIX D: COMPARISON OF SFAM DATA SETS

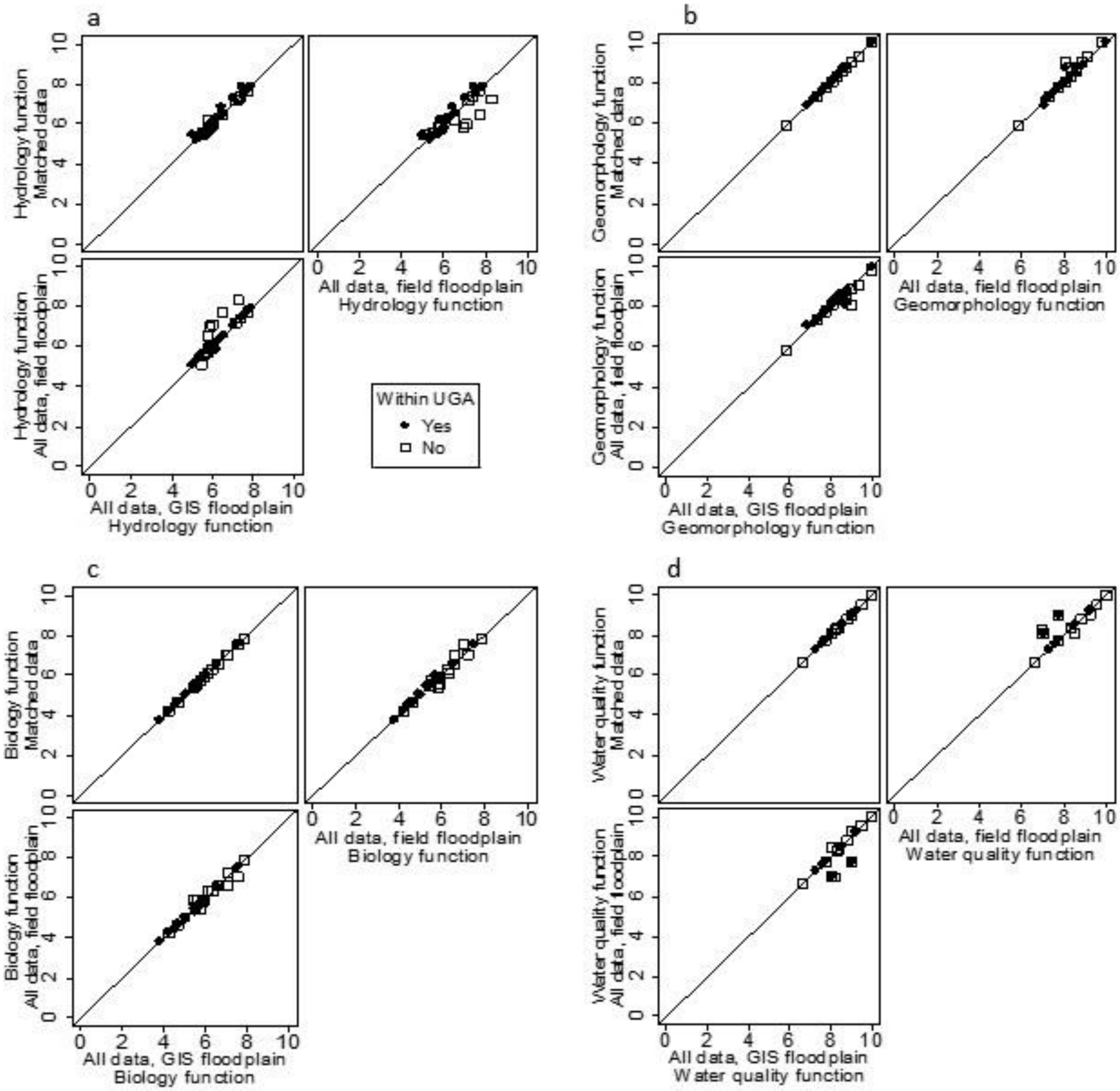


Figure S5. Comparison of SFAM function scores across three variations of data input. Matched data only included data from sources available to all reaches with GIS-determined presence of floodplains. All data included all available data for each stream reach, with either GIS-determined or field-determined presence of floodplains. The diagonal line in each panel is a 1:1 line, which indicates that the scores were mostly identical among data input variations.

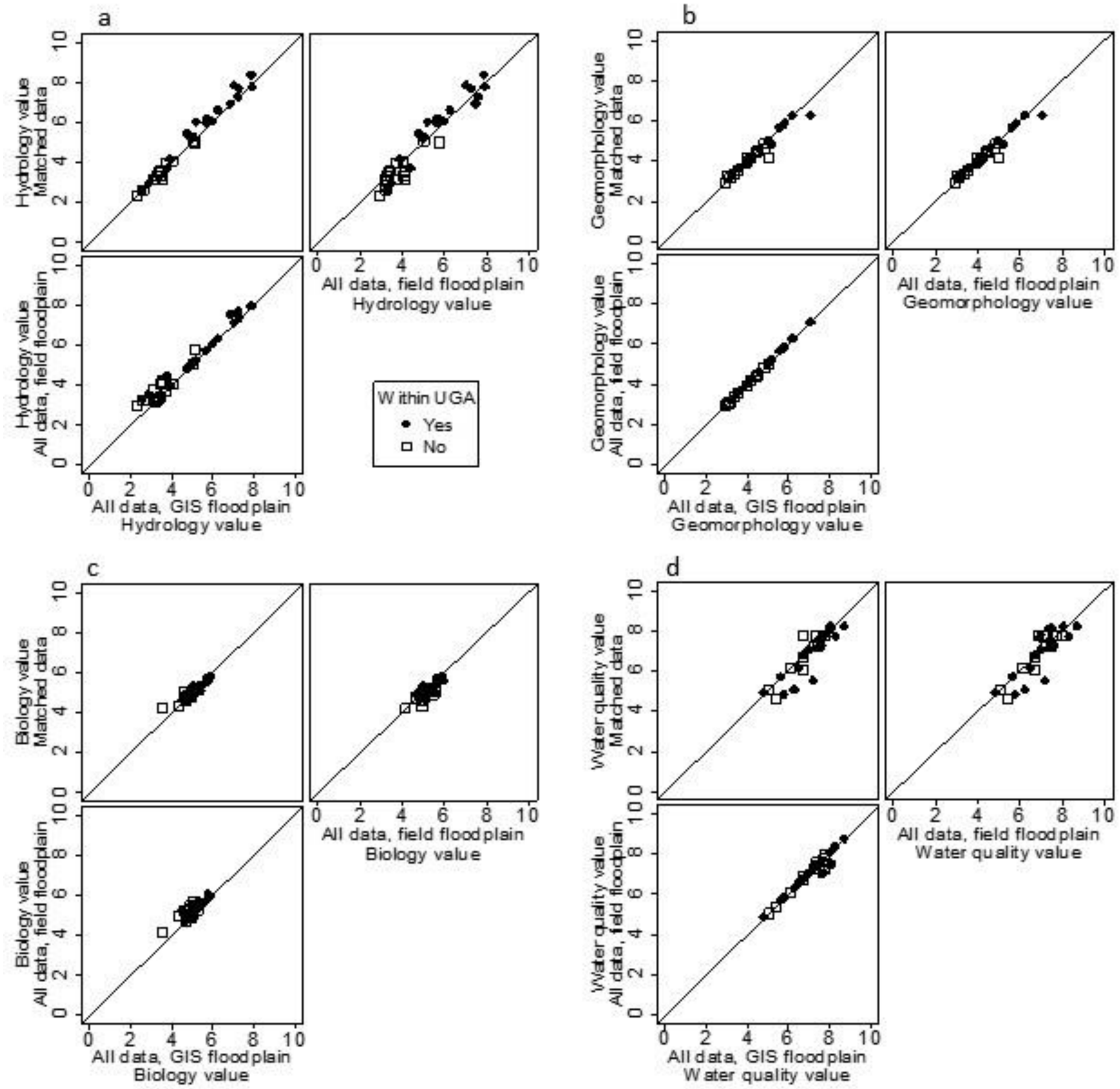


Figure S6. Comparison of SFAM value scores across three variations of data input. Matched data only included data from sources available to all reaches with GIS-determined presence of floodplains. All data included all available data for each stream reach, with either GIS-determined or field-determined presence of floodplains. The diagonal line in each panel is a 1:1 line, which indicates that the scores were mostly identical among data input variations.

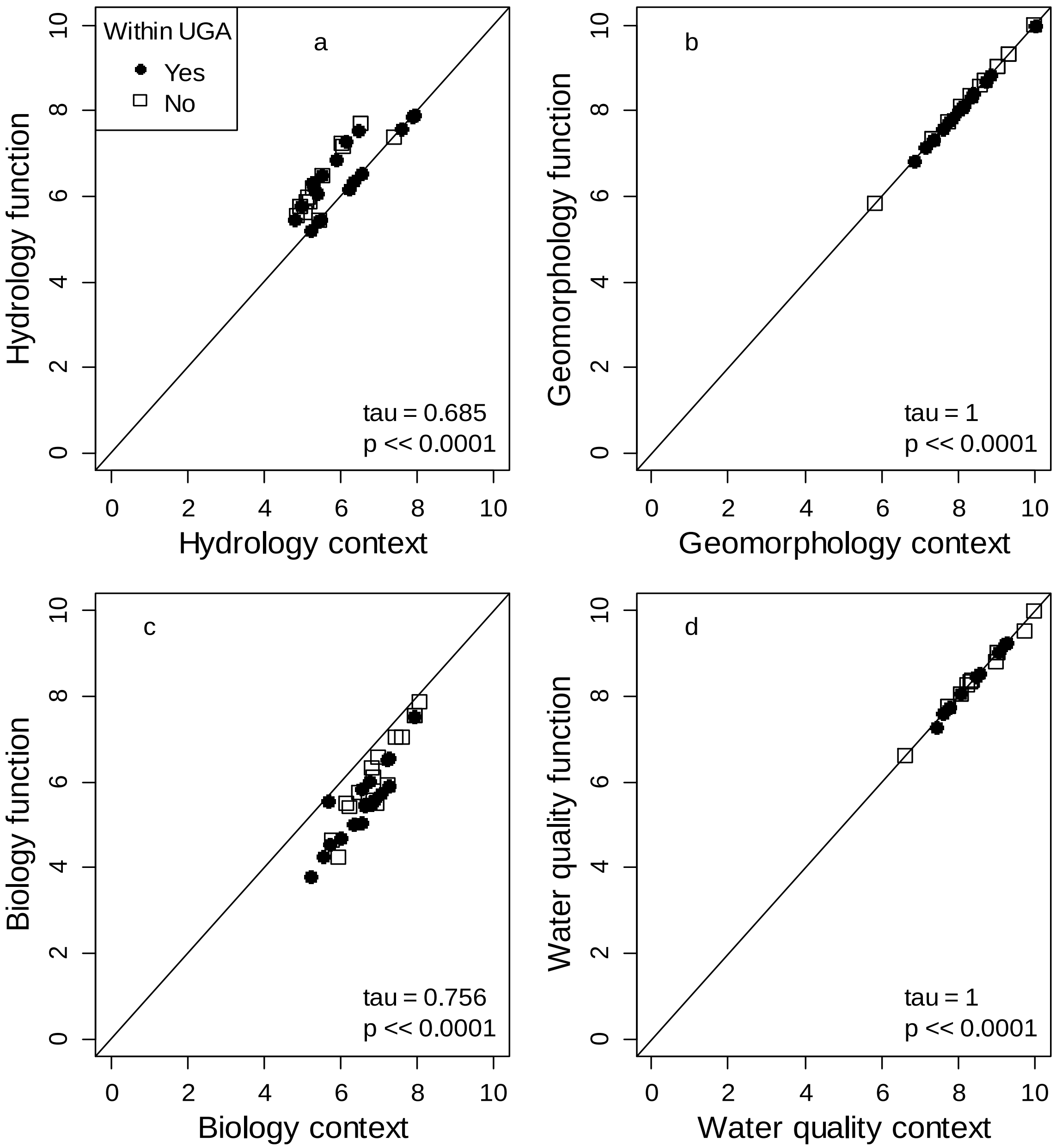


Figure S7. Comparison of SFAM function scores against SFAM function scores with context data across 34 stream reaches in Water Resource Inventory Area 8. The context scores were a new addition in the fall 2015 update of the SFAM calculator. The diagonal line in each panel is 1:1 line, which indicates that the scores were similar (panels a & c) to mostly identical (panels b & d) between the original function scores and the function scores with context.

APPENDIX E: PRINCIPAL COMPONENT WEIGHTINGS FOR CORRELATIONS

PCAs for assessment of SFAM function scores

Table S5. Hydrology metrics from King County Status & Trends Monitoring Program for comparison with SFAM hydrology function scores. Variable weighting of significant principal components (PCs) for 14 stream reaches in King County, WA. PC significance was determined using Kaiser's Criterion (Kaiser 1960). Bolded weightings indicate the driving metrics for the PC using the guidelines established by Mardia (1979) (weighting value ≥ 0.7*max weighting). Metric definitions are in Table S3.

	Weightings	
Metric	**PC1**	**PC2**
X30.day.summer.low.flow	-0.188	**0.638**
X7.day.summer.minimum.flow	-0.185	**0.642**
Flow.Reversals	**0.346**	0.010
High.Pulse.Count	**0.376**	0.198
High.Pulse.Duration	**-0.364**	-0.282
High.Pulse.Range	0.277	0.233
Low.Pulse.Count	**0.408**	-0.076
Low.Pulse.Duration	**-0.373**	-0.026
RB.Index	**0.393**	0.039
Cumulative variance	0.600	0.814

Table S6. Geomorphology metrics from King County Status & Trends Monitoring Program for comparison with SFAM geomorphology function scores. Variable weighting of significant principal components (PCs) for 34 stream reaches in King County, WA. Notation as in Table S5. Metric definitions are in Table S3.

	Weightings			
Metric	**PC1**	**PC2**	**PC3**	**PC4**
BFWidth_BFDepth	0.052	**0.310**	-0.448	**-0.526**
D50	-0.288	**0.341**	-0.113	0.316
PCT.Cobble	**-0.325**	**0.335**	-0.028	0.148
PCT.Fines	0.217	**-0.420**	-0.282	-0.094
PWP.All	0.150	0.026	**0.725**	0.001
RBS	-0.055	0.207	0.360	**-0.709**
ResPoolArea100	**0.439**	0.158	0.076	0.092
X.BFDepth	**0.396**	0.279	0.008	0.202
X.BFWidth	**0.339**	**0.383**	-0.197	-0.071
X.Embed	0.303	**-0.390**	-0.081	-0.075
X.TWDepth	**0.424**	0.231	0.020	0.175
Cumulative variance	0.403	0.662	0.786	0.885

Table S7. Revised selection of geomorphology metrics from King County Status & Trends Monitoring Program for comparison with SFAM geomorphology function scores. Variable weighting of significant principal components (PCs) for 34 stream reaches in King County, WA. Notation as in Table S5. Metric definitions are in Table S3.

	Weightings	
Metric	**PC1**	**PC2**
LWDSiteVolume100m	**-0.591**	-0.362
PWP.All	**0.503**	**0.483**
X.DensioBank	-0.344	**0.675**
X.Embed	**0.528**	-0.425
Cumulative Proportion	0.423	0.713

Table S8. Combined SFAM function outputs. Variable weighting of significant principal components (PCs) for 34 stream reaches in King County, WA. Notation as in Table S5. Metric definitions are in Table S2.

	Weightings	
Metric	**PC1**	**PC2**
Hydrology function	0.340	**0.728**
Geomorphology function	**0.545**	-0.348
Biology function	**0.514**	-0.485
Water quality function	**0.569**	0.337
Cumulative variance	0.446	0.738

Table S9. Combined SFAM outputs for comparison to the subset of stream reaches with flow gauges. Variable weighting of significant principal components (PCs) for 14 stream reaches with stream gauges in King County, WA. Notation as in Table S5. Metric definitions are in Table S2.

	Weightings	
Metrics	**PC1**	**PC2**
Hydrology function	0.082	**0.632**
Geomorphology function	**0.527**	-0.446
Biology function	**0.724**	-0.122
Water quality function	0.437	**0.622**
Cumulative variance	0.366	0.665

Table S10. Combined metrics from King County Status & Trends Monitoring Program for comparison with the SFAM. Variable weighting of significant principal components (PCs) for 34 stream reaches in King County, WA. Notation as in Table S5. Metric definitions are in Table S3.

	Weightings	
Metric	**PC1**	**PC2**
X7DMax_Avg	**-0.510**	-0.072
X.DensioBank_Avg	0.243	**0.688**
LWDSiteVolume100m_Avg	**0.467**	-0.094
PWP.All_Avg	**-0.464**	0.347
X.Embed_Avg	-0.324	-0.477
ST.BIBI_Avg	**0.377**	-0.406
Cumulative variance	0.392	0.605

Table S11. Combined metrics from King County Status & Trends Monitoring Program from the subset of stream reaches with flow gauges for comparison with the SFAM. Variable weighting of significant principal components (PCs) for 14 stream reaches with stream gauges in King County, WA. Notation as in Table S5. Metric definitions are in Table S3.

	Weightings	
Metric	**PC1**	**PC2**
X7DMax_Avg	**0.375**	0.037
RB.Index_Avg	**0.405**	-0.401
X.DensioBank_Avg	-0.047	**-0.714**
LWDSiteVolume100m_Avg	**-0.430**	-0.039
PWP.All_Avg	**0.426**	-0.014
X.Embed_Avg	0.263	**0.565**
ST.BIBI_Avg	**-0.507**	0.087
Cumulative variance	0.471	0.700

PCAs for assessment of SFAM value scores

Table S12. Water quality metrics from WA. Dept. of Ecology Puget Sound Watershed Characterization Tool for comparison with SFAM water quality value scores. Variable weighting of significant principal components (PCs) for 34 stream reaches in King County, WA. PC significance was determined using Kaiser's Criterion (Kaiser 1960). Bolded weightings indicate the driving metrics for the PC using the guidelines established by Mardia (1979) (weighting value ≥ 0.7*max weighting). Metric definitions are in Table S4.

	Weightings	
Metric	**PC1**	**PC2**
MetalsExport.Av_zncuco	**0.404**	-0.380
MetalsExport.Potential	0.230	**0.496**
NitrogenExport.ntNco	**0.459**	-0.265
NitrogenExport.Potential	**0.396**	0.152
PhospohrousExport.ntPco	**0.453**	-0.288
PhospohrousExport.Potential	**0.362**	0.286
SedimentExport.nmusl	0.178	-0.021
SedimentExport.Potential	0.221	**0.593**
Cumulative variance	0.495	0.754

Table S13. Combined SFAM value outputs. Variable weighting of significant principal components (PCs) for 34 stream reaches in King County, WA. Notation as in Table S12. Metric definitions are Table S2.

	Weightings	
Metric	**PC1**	**PC2**
Hydrology value	**0.612**	-0.230
Geomorphology value	**0.556**	0.232
Biology value	**0.554**	-0.142
Water quality value	0.097	**0.934**
Cumulative variance	0.481	0.745

Table S14. Combined metrics from Washington Department of Ecology Puget Sound Watershed Characterization Project for comparison with the SFAM. Variable weighting of significant principal components (PCs) for 34 stream reaches in King County, WA. Notation as in Table S12. Metric definitions are in Table S4.

	Weightings		
Metric	**PC1**	**PC2**	**PC3**
WaterFlow.Importance	0.090	**-0.435**	0.457
WaterFlow.Degradation	**0.380**	-0.233	-0.063
AquaticEcologicalIntegrity.Score	**-0.383**	0.022	0.100
SedimentExport.Potential	0.089	**0.529**	0.220
SedimentExport.nmusl	0.136	0.015	**0.751**
PhospohrousExport.Potential	0.271	0.281	0.311
PhospohrousExport.ntPco	**0.415**	-0.077	-0.090
NitrogenExport.Potential	**0.306**	0.284	-0.110
NitrogenExport.ntNco	**0.415**	-0.054	-0.088
MetalsExport.Potential	0.086	**0.527**	-0.084
MetalsExport.Av_zncuco	**0.393**	-0.171	-0.180
Cumulative variance	0.488	0.739	0.834

APPENDIX F: REPEATED METRICS IN SFAM

Table S15. Measures from the Cover Page of the SFAM calculator as well as the final SFAM functions and the specific functions to which the metrics contribute. Metric and subscore definitions are in Table S2.

	SFAM functions and specific SFAM functions																							
	Hydro F			Geo F		Bio F			WQ F			Hydro V			Geo V		Bio V			WQ V		
Measure name	SWS	SST	FV	SC	SM	MB	CMH	STS	NC	CR	TR	SWS	SST	FV	SC	SM	MB	CMH	STS	NC	CR	TR
Elevation																						
Latitude																						
Longitude																						
StreamType												1		1								
AqPerm													1									
SoilPerm													1									
Gradient																						
Stream Order																						
Floodplain																						
Erode															1	1						
Flow		1	1		1						1											
Ecoregion type																						1
Q2 discharge																						
Basin area																						
Grain-size distribution																						
External data																						
History																						

Table S16. Measures from the Functions page of the SFAM calculator as well as the final SFAM functions and the specific functions to which the metrics contribute. Metric and subscore definitions are in Table S2.

		SFAM functions and specific SFAM functions																							
		Hydro F			Geo F		Bio F			WQ F			Hydro V			Geo V		Bio V			WQ V		
#	Measure name	SWS	SST	FV	SC	SM	MB	CMH	STS	NC	CR	TR	SWS	SST	FV	SC	SM	MB	CMH	STS	NC	CR	TR
F1	Exclusion	1						1											1	1	1	1	
F2	RB Index			1																			
F3	NNAquSpp						1																
F4	SideChan	1	1				1	1															
F5	BIBI									1	1	1											
F6	TempEx											1											1
F7	Entrench	1			1																		
F8	Cover								1	1		1											1
F9	InvWeed						1	1	1														
F9	WoodyVeg						1	1	1														
F9	MatTree						1	1															
F9	Conifer						1	1	1														
F10	DomVeg		1				1		1	1	1												
F11	GeoSuc				1																		
F12	OBFlow	1	1						1	1	1										1	1	
F13	LatMigr				1																		
F14	RipBuff									1	1										1	1	
F15	Wood	1					1	1															
F16	BarVeg					1		1															
F17	Armor				1												1						
F18	BankStab				1																		
F19	BedVar	1	1	1		1	1	1		1	1												
F20	Beaver	1	1					1															

Table S17. Measures from the Values page of the SFAM calculator as well as the final SFAM functions and the specific functions to which the metrics contribute. Percent impervious (ImpArea) was listed twice for the chemical regulation (CR) subscore in the water quality value score. Metric and subscore definitions are in Table S2.

		SFAM functions and specific SFAM functions																					
		Hydro F			Geo F		Bio F			WQ F			Hydro V			Gro V		Bio V			WQ V		
#	Measure name	SWS	SST	FV	SC	SM	MB	CMH	STS	NC	CR	TR	SWS	SST	FV	SC	SM	MB	CMH	STS	NC	CR	TR
V1	Proximity														1			1	1	1	1	1	1
V2	DwnFP												1		1								
V3	DwnFld												1		1								
V4	ImpArea												1		1	1	1	1	1			2	
V5	Withdrwl														1		1						
V5	Impound			1											1	1	1		1				
V6	LandUse															1	1				1		
V7	PriorSt																	1					
V8	NonAFish																	1					
V8	RarInvert																	1					
V8	RarAmRep																	1					
V8	Waterbird																	1					
V8	RarBdMm																	1					
V8	RarPlant																	1					
V9	WBHab																	1					
V10	Passage																	1	1				
V11	RipArea																		1	1	1	1	1
V12	RipCon																		1	1	1	1	1
V13	SedList															1					1		
V13	NutrImp																			1	1		
V13	ToxImp																					1	
V13	TempImp																			1			1
V14	HabFeat																	1	1				

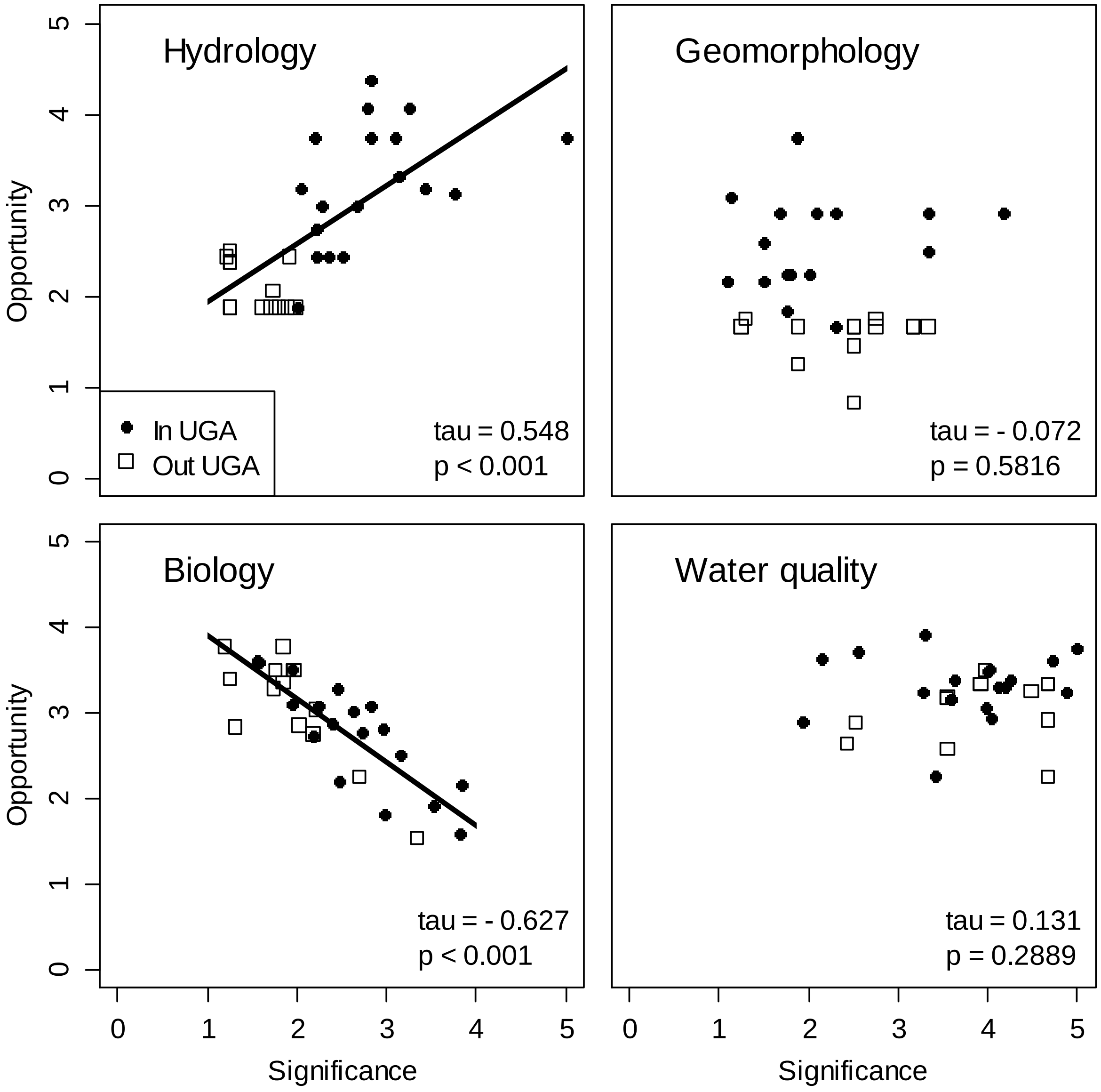


Figure S8. Correlations between SFAM opportunity and significance subscores within the four SFAM processes. Subscores could be between zero and five, and are then added together to create the final SFAM value score for each process. Opportunity aims to reflect the ability of the reach to provide a particular function, whereas significance aims to reflect the local importance of that function.

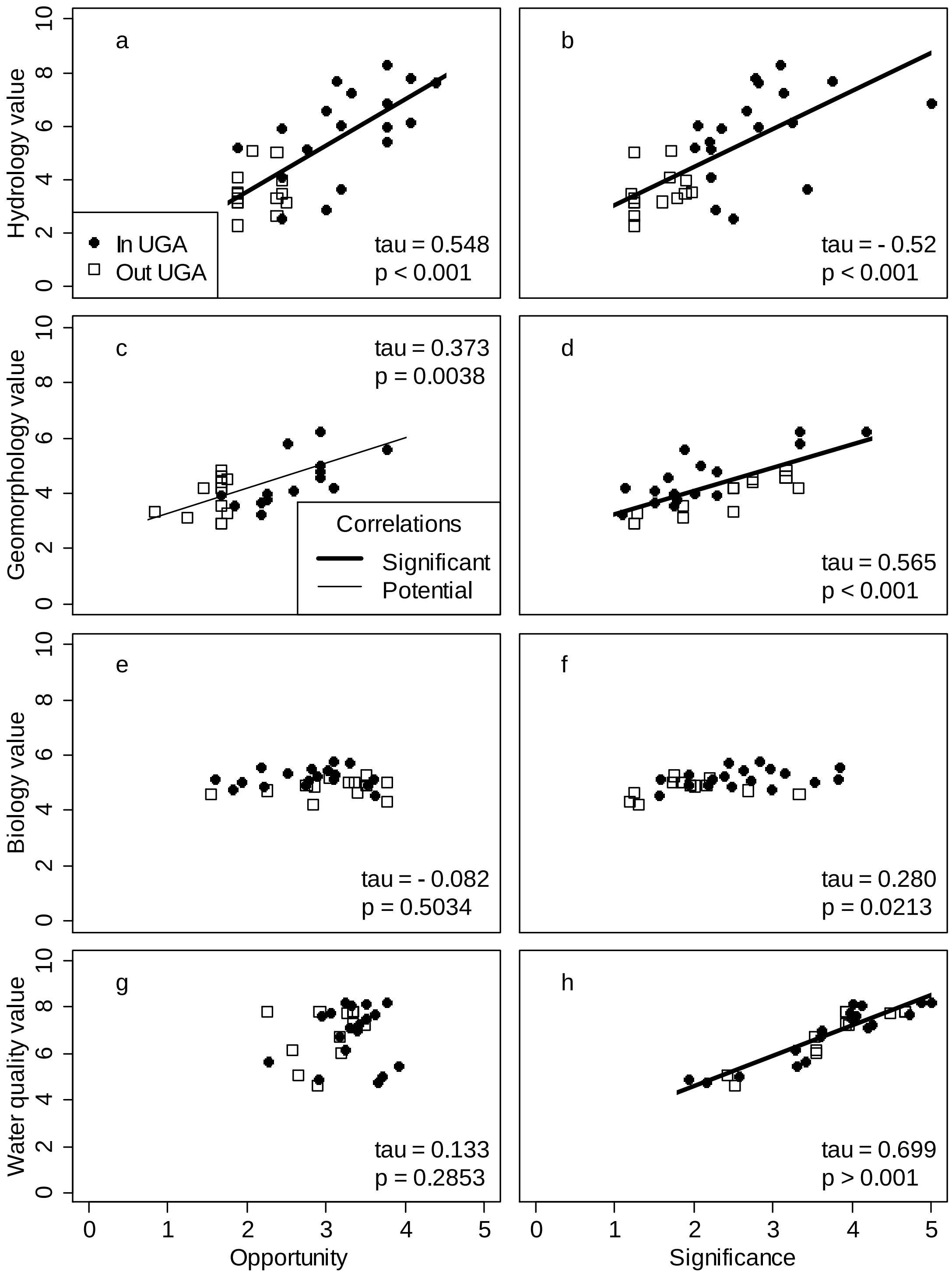


Figure S9. SFAM value scores against their contributing opportunity and significance subscores. Notation as in Figure S8.

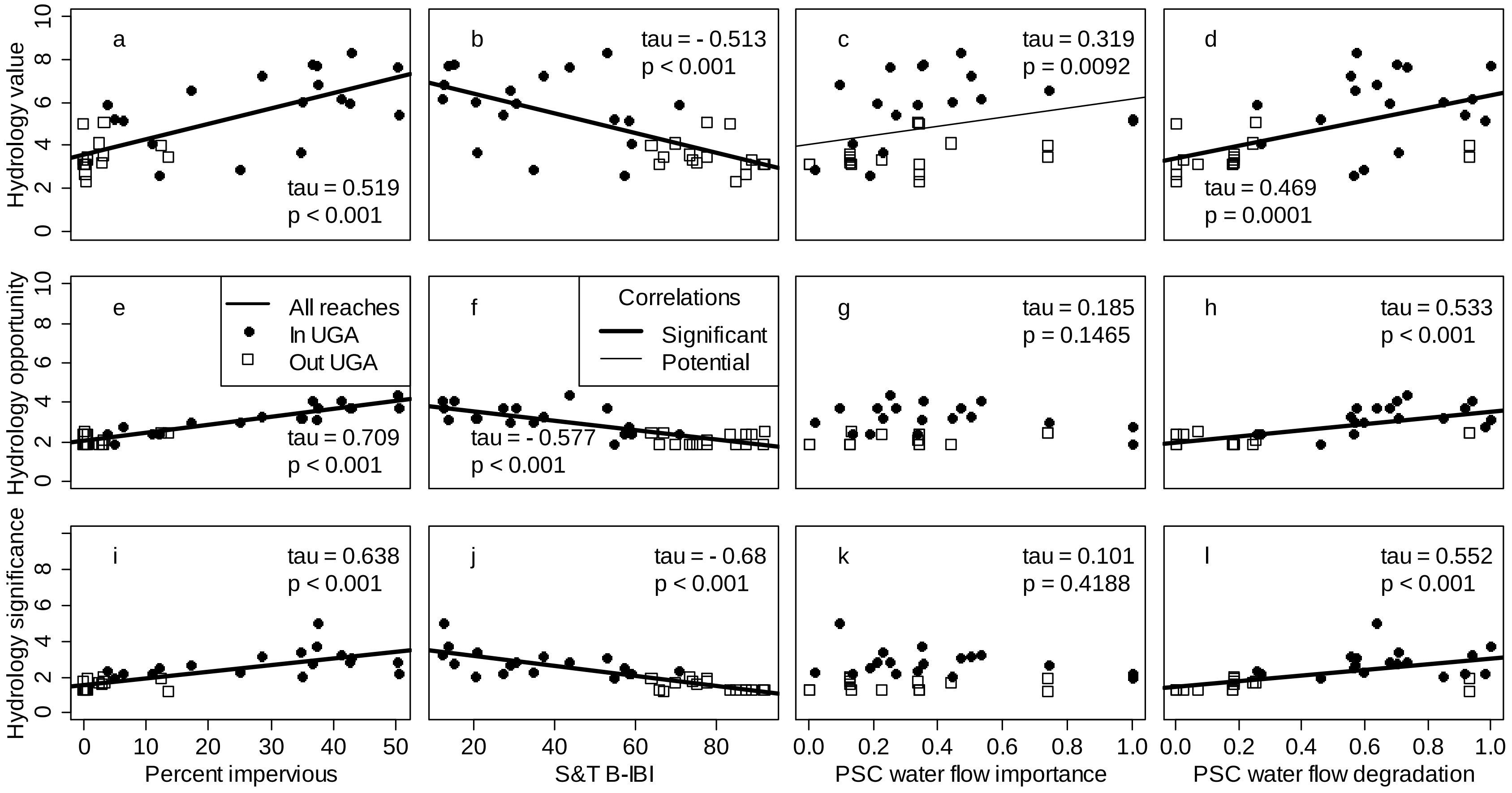


Figure S10. SFAM hydrology value scores and hydrology opportunity significance subscores against percent watershed impervious cover, Status & Trends Benthic Macroinvertebrate Index of Biotic Integrity (S&T B-IBI), and the Puget Sound Characterization water flow importance and degradation scores. Notation as in Figure S8.

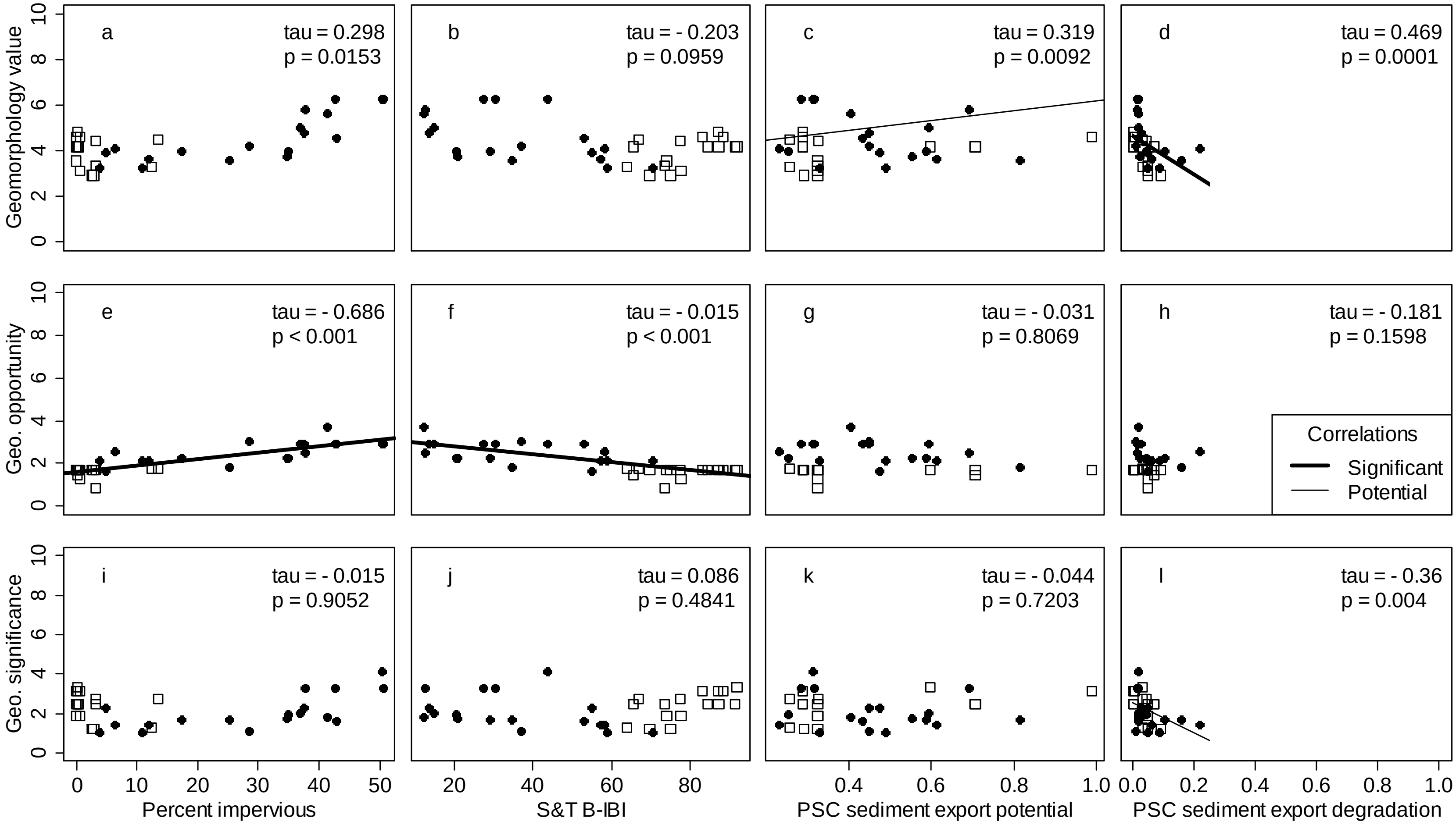


Figure S11. SFAM geomorphology value scores and geomorphology opportunity significance subscores against percent watershed impervious cover, Status & Trends Benthic Macroinvertebrate Index of Biotic Integrity (S&T B-IBI), and the Puget Sound Characterization sediment export potential and degradation scores. Notation as in Figure S8.

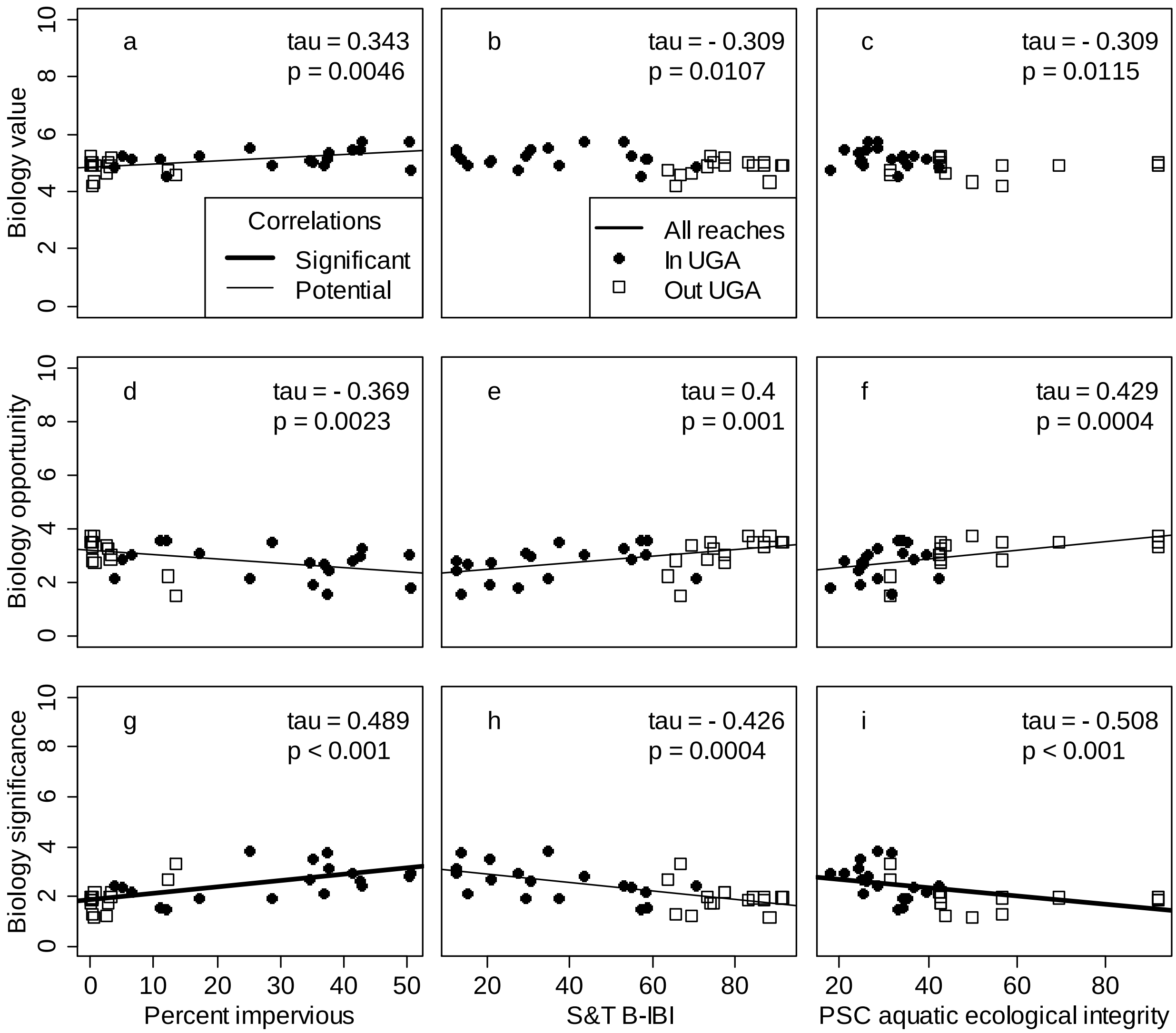


Figure S12. SFAM biology value scores and biology opportunity significance subscores against percent watershed impervious cover, Status & Trends Benthic Macroinvertebrate Index of Biotic Integrity (S&T B-IBI), and the Puget Sound Characterization aquatic ecological integrity scores. Notation as in Figure S8.

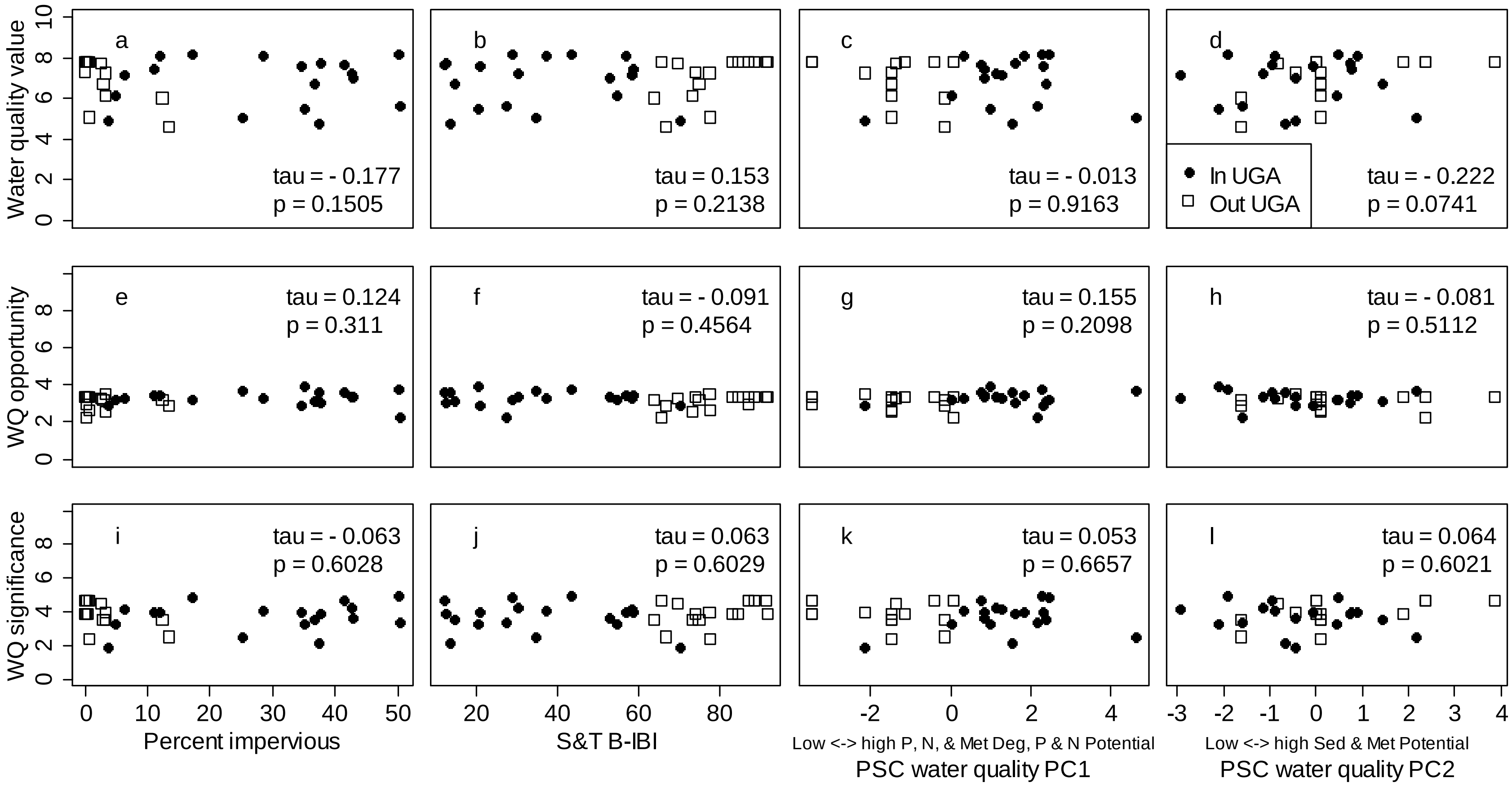


Figure S13. SFAM water quality value scores and water quality opportunity significance subscores against percent watershed impervious cover, Status & Trends Benthic Macroinvertebrate Index of Biotic Integrity (S&T B-IBI), and significant principal components created from the Puget Sound Characterization water quality export potential and degradation scores. Notation as in Figure S8.