Version 2.0 Update of the Puget Sound Watershed Characterization Broad-Scale Models

An Addendum to Volume 1: The Water Resource Assessments (Water Flow and Water Quality)

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Version 2.0 Update of the Puget Sound Watershed Characterization Broad-Scale Models

An Addendum to Volume 1: The Water Resource Assessments (Water Flow and Water Quality)

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Abstract

The Washington State Department of Ecology has reviewed and updated the existing broad-scale Puget Sound Watershed Characterization indices of water flow processes, which were established with the completion of Volume 1: The Water Resource Assessments (Stanley et al. 2016) originally published in 2012. This publication is an addendum to Volume 1 and documents changes to spatial data used, assessment unit boundary adjustments, testing of index stability and sensitivity to weighting opportunities, potential alternatives to the aggregation formula, and ways to categorize results into the Water Flow Management Matrix. Overall, the Water Flow Importance model was determined to be less stable than the Degradation model and warrants further investigation into ways to improve stability with alternative aggregation formulas and weighting scenarios. Additionally, preliminary conclusions of testing an alternative binning approach imply that use of a Jenks method to categorize assessment units into the Management Matrix may increase model stability, but further testing is warranted before this approach is adopted broadly. Local applications of the indices should consider specific index score distributions and determine if Jenks is a preferred method. For the purposes of providing Puget Sound-wide index results available for download, Ecology, with this addendum, applies a multiplicative aggregation step at the component level of both the Importance and Degradation models, does not assert weighting within the model (though local applications may establish these upon consultation), and retains a quartile-based method of categorizing index scores into the Management Matrix. Comparison maps of Water Resource Inventory Area 7 illustrate the changes adopted as of this addendum, Version 2.0 of the Water Flow Models.

1.0 Introduction

Purpose

This publication is an addendum to the original Puget Sound Watershed Characterization (PWSC) methods (Stanley et al. 2016, Ecology publication #11-06-016) and should be used in combination with the preceding Volume 1 and not as a standalone document. In this document, the methods and results of the original characterization are referred to as version 1.0 (v1.0) and any revised methods or results established in this addendum are referred to as version 2.0 (v2.0)

The purpose of this document is to describe:

- changes to the original assessment unit boundaries to conform with both the latest higher resolution hydrography and the floodplain mapping conducted by Konrad (2015);
- updates to some of the original geospatial layers; and
- testing of different data aggregation and calculation methods to determine which combination provides more stable results (i.e. lower uncertainty) relative to the original results and to “on the ground” conditions.

Background

The PSWC is a set of water and habitat indices that compare areas within a watershed for their relative restoration and protection value. The PSWC provides information for regional, county, and watershed-based planning. The information it provides allows local and regional governments, as well as non-governmental organizations, to base their decisions regarding land use on a systematic analytic framework that prioritizes specific geographies on the landscape as focus areas for protection, restoration, and conservation of our region’s natural resources, and that also identifies areas that are likely more suitable for development. Application of this framework should support future land use patterns that protect the health of Puget Sound’s terrestrial and aquatic resources while also helping to direct limited financial resources to the highest priority areas for restoration and protection.

The indices cover water resources (both water flow and water quality processes) and fish and wildlife habitats (in terrestrial, freshwater, and marine nearshore areas) over the entire drainage area of Puget Sound. The indices (also referred to as “assessments” in Volume 1) provide a watershed-scale perspective on the relative importance of small watersheds (from ~ 1–10 square miles) for the protection and restoration of water resources and habitats that is not generally provided by other available tools. Final results can also be analyzed to identify the basis for a small watershed’s relative importance, and to guide potential management strategies for that watershed. The intended audience is city, county and tribal government planners, watershed managers and decision-makers, the Puget Sound Partnership, other state agencies, and resource managers including non-governmental organizations.

In 2017 the Washington State Department of Ecology (Ecology) initiated a review and update (the subject of this document) of the existing coarse-scale PSWC indices of water flow processes which were established with the completion of *Volume 1: The Water Resource Assessments* (Stanley et al. 2016) originally published in 2012. Lessons learned from applying the PSWC indices, in land use and Puget Sound recovery planning processes with local governments and other organizations, highlighted several elements of the indices which warranted investigation. Additionally, the spatial data, which are the building blocks of the indices, have in many cases, improved or are more current. Hence, an update of those spatial data is warranted.

How to Use this Publication

Index results (i.e. the new v2.0 maps) and associated reference data can be downloaded on the PSWC website (https://ecology.wa.gov/Water-Shorelines/Puget-Sound/Watershed-characterization-project). The new version 2.0 maps reflect the updates documented in this publication. While some changes to the indices were implemented, and more recent data are being used, the fundamental scientific principles, literature, and guidance are consistent with what is documented in Volume 1 (Stanley et al. 2016, originally published 2012) and Volume 3 (Stanley et al. 2013).

Basic v2.0 maintenance updates to the models and indices outlined in this report include:

- **Spatial Data** - Updates to geospatial layers used in the calculation of the Water Flow assessments (Chapter 2).
- **Assessment Units** - Adjustments to Assessment Unit (AU) boundaries to reflect higher accuracy or more current data related to watershed boundaries, hydrography, and Digital Elevation Model (DEM) data. Additionally, AU boundaries were adjusted to specifically delineate lowland floodplain areas (Chapter 3).

Testing of Water Flow Index performance included:

- **V1.0 Model Stability –** A test of the v1.0 model stability in designating AUs to the Water Flow Management Matrix categories (Chapter 4).
- **Alternative Index Approaches –** A series of tests exploring alternative approaches to aggregating and categorizing index results for designating AUs into the Water Flow Management Matrix (Chapter 4).

Chapter 5 describes the final changes that were adopted for PSWC v2.0 and provides some comparison of results to the original v1.0 maps using Water Resource Inventory Area (WRIA) 7 as an example.

Technical Review Process

Ecology established a Model Update Technical Team (MUTT) to assist with the review and update process documented here. The team was comprised of experts in watershed science, ecology, statistics, hydrology, and geospatial analysis. Ecology contracted with Environmental Science Associates (ESA) to provide specific technical feedback. Members of the MUTT were:

- Stephen Stanley, Project Lead and Senior Watershed Ecologist, Ecology
- Colin Hume, Project Manager and Watershed Ecologist, Ecology
- Susan Grigsby, Geospatial Lead, Ecology
- Brad McMillan, Geospatial Specialist, Ecology
- George Wilhere, Habitat Biologist, Washington Department of Fish and Wildlife
- Aaron Booy, Environmental Specialist, ESA
- Jean Toillez, Statistician, ESA
- James Gregory, Hydrologist, ESA
- Derek Booth, Geologist and Watershed Scientist, Stillwater Associates

The MUTT convened three times over the course of 2018 to review the testing and potential updates to be incorporated into PSWC v2.0. Under guidance from Ecology lead staff, the consultant tested elements of the indices, with the results reviewed by the MUTT in a series of technical memos. The content of those technical memos are synthesized and summarized in Chapter 4.

2.0 Updates to Geospatial Layers

Table 1 lists sources for the digital data layers that are used in the Watershed Characterization modeling (Volume 1). Yellow highlighted entries indicate those layers that were updated with more current data.

Table 1. List of original v1.0 data sources for characterization analyses. Yellow highlighted and asterisk (*) entries (Precipitation, Hydrography, CCAP Land cover) are those which are updated for v2.0 Water Resources assessments.

Data	Scale	Source
Precipitation	1:2,000,000	Washington Department of Natural Resources, Forest Practices Division*
Rain-on-Snow & Snow dominated zones	1:250,000	Washington Department of Natural Resources
Surficial Geology	1:100,000	Washington Department of Natural Resources
Soils (SSURGO)	1:12,000 – 1:63,000	Natural Resources Conservation Service
Topography (Digital Model Elevation)	10 Meter	University of Washington
Hydrography (streams & lakes)	1:24,000	Washington Department of Natural Resources*
Wetlands (NWI) (also SSURGO – see above)	1:24,000	United States Fish & Wildlife Service
Channel confinement & gradient (SSHIAP)	1:24,000	Washington Department of Fish & Wildlife; North West Indian Fisheries Commission
Mass wasting (Shaw Johnson landslide risk model)	10 Meter (Western WA)	Washington Department of Natural Resources, Forest Practices Division
C-CAP Land Cover (2016)	30 Meter Grid	National Oceanic and Atmospheric Administration*

As Table 1 indicates, the data used in the characterization models is coarse-scale. This reflects that the intent of the PSWC is to use regionally available data, to provide results that compare areas relative to each other, and to support planning level decisions. Most of the data are state-wide or even region-wide, and updates to these are limited. However, for v2.0 we acquired updated layers for precipitation, hydrography, and land cover.

Precipitation

The original v1.0 precipitation layer was from the annual average precipitation isohyets developed by the Washington Department of Natural Resources Forest Practices Division.

The updated layer is from the PRISIM (Parameter-elevation Regressions on Independent Slopes Model) Climate Group at the Oregon State University, downloaded as an annual average precipitation grid for the year 2018. The yearly average annual precipitation was based on monthly modeling values.

Data	Scale	Source
Precipitation Annual Average (2018)	4 km Grid	PRISIM Climate Group, Oregon State University

Hydrography

The updated data set is an extract from the National Hydrography Dataset originally produced by USGS and EPA. The Washington state extracted data is part of the 1:24,000 high resolution data, which has additional improvements in some areas of the state.

Data	Scale	Source
Hydrography (streams & lakes)	1:24,000	Unites States Geological Survey

Land Cover

The original land cover layer for v1.0 was the 2006 Coastal Change Analysis Program (C-CAP) from the National Oceanic and Atmospheric Administration's (NOAA) Office for Coastal Management. This program documents land cover change with repeat imagery every 5 years. The updated layer is the 2016 C-CAP. It contains the same land cover codes and groupings as the 2006 data (see Table 2).

Data	Scale	Source
C-CAP Land Cover (2016)	30 Meter Grid	National Oceanic and Atmospheric Administration.

The land cover layer is used in many of the analyses of degradation to water processes. We grouped the land cover types by the intensity of development by using the code definition for the percent imperviousness. A 50% imperviousness means that half of the grid cell was covered in impervious surface, which represented a 'medium intensity' of development. It is important to remember that the land cover code and definition is not equal to a planning definition of development intensity.

We developed a 'LU_Code' to group similar land cover types from the original 22 C-CAP codes. For the purpose of our coarse scale analyses, the LU_Code was used. Thus, all wetland types were combined into one 'wetland' category. For the analysis of loss of forest, the original 22 land cover types (Table 2) were again categorized as either 'altered' or 'not altered' from what we assumed to be the historical land cover for Puget Sound. Thus, any land cover other than forest was assumed to be altered from the historic condition. A few of the land cover categories were not included in this analysis, including wetlands, water, tundra, and snow and ice. Some of the land use categories were included with conditions. For example, bare land, grassland, and scrub shrub were included as altered if they were below 2000 feet in elevation and not within selected public lands, as determined with the Major Public Lands (MPL) data. The selected public lands include National Parks and wilderness areas, which are protected from land development and conversion. We did not include categories designated as forest lands (includes national forest managed by the Forest Service) because more human alteration is permitted, including timber harvest.

Table 2. Land cover code descriptions from Coastal Change Analysis Program 2016 data, translated into LU_Code for use in PSWC v2.0

Grid Value	Description	LU_Code	Altered / Forest
2	High intensity developed, > 80% developed	High	Altered
3	Medium intensity developed, 50-79% developed	Medium	Altered
4	Low intensity developed, 21-49% developed	Low	Altered
5	Developed open space, < 21% developed	Open space	Altered
6	Cultivated	Cultivated	Altered
7	Pasture / hay	Pasture	Altered
8	Grassland	Grassland	Altered (except in MPL**)
9	Deciduous forest	Forest	Forest
10	Evergreen forest	Forest	Forest
11	Mixed forest	Forest	Forest
12	Scrub shrub	Scrub shrub	Altered (except in MPL**)
13	Palustrine forest wetland	Wetland	NA
14	Palustrine scrub shrub wetland	Wetland	NA
15	Palustrine emergent wetland	Wetland	NA
16	Estuarine forest wetland	Wetland	NA
17*	Estuarine scrub shrub wetland	Wetland	NA
18*	Estuarine emergent wetland	Wetland	NA
19	Unconsolidated shore	Shoreland	NA
20	Bare land	Bare land	Altered (except in MPL**)
21	Water	Water	NA
22	Palustrine aquatic bed	Wetland	NA
23	Estuarine aquatic bed	Wetland	NA
24	Tundra	Tundra	NA
25	Snow / ice	Snow/ice	NA

*Grid values 17 & 18 are not represented within our analysis extent **MPL – major public lands

3.0 Assessment Unit Boundary Update

Assessment units (AU or AUs) are the foundational units for summarizing and displaying results from the watershed characterization analyses. The original boundaries were developed from the Salmon and Steelhead Habitat Inventory and Assessment (SSHIAP) catchments. These catchments were often combined, and occasionally divided, to maintain the size thresholds we deemed appropriate for assessment units. The catchments were delineated primarily as salmon habitat catchments, which is not always congruent with features important in the control of watershed processes. Also, the catchments are not always consistent with current higher resolution data sets. For these reasons, a general update of the watershed characterization assessment units was necessary.

Assessment Unit Boundaries

Edits to the AU boundaries began with adjustments to make boundaries coincide with higher accuracy data. First, the outer boundaries of AUs along the WRIA borders were edited to match Ecology's updated WRIA layer. For example, Figure 1 shows the corrected (solid) line which was moved from the original dashed AU boundary for unit #7061 to the updated WRIA boundary.

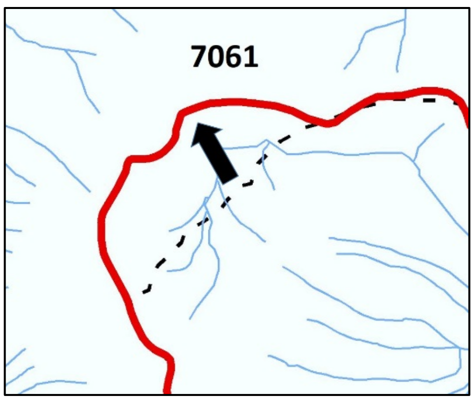


Figure 1. Corrected AU boundary (solid red line) to reflect an updated WRIA boundary layer. Dashed black line reflects previous WRIA boundary.

Additionally, all interior boundaries were edited to coincide with the current updated stream layer, namely the 24:000 National Hydrography Data (NHD). This primarily involves adjustments along all boundaries where NHD stream lines cross the original AU boundary. Forty foot contour lines produced from a 10-meter Digital Elevation Model (DEM) were also used to refine these edits. Figure 2 illustrates this type of adjustment with the corrected (solid) line which was moved in the direction of the arrow from the original dashed line so the AU boundary for unit #10025 would be coincident to the updated stream layer (NHD). Contour lines were used to help determine the best location.

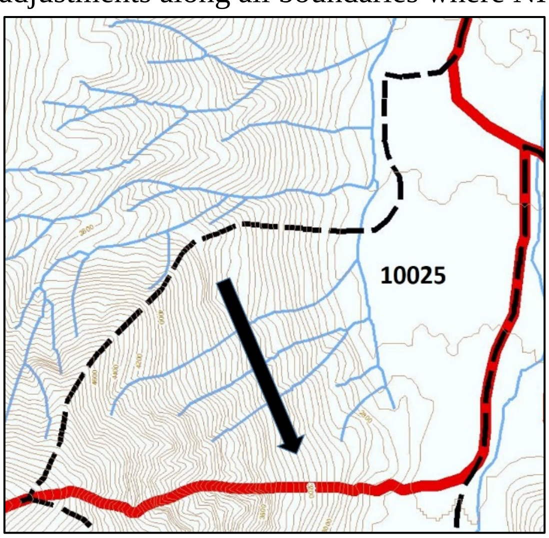


Figure 2. Example of a corrected AU boundary to the updated stream layer (solid red line).

Floodplain Boundaries

By far, the most complex and significant changes to the AU boundaries involved incorporating floodplain areas as separate assessment units. The reason for this change was the acknowledgement that floodplains are unique features on the landscape that provide important ecological functions that don't occur in other, more upland areas. Thus, combining floodplain areas with upland areas can obscure the importance of the floodplain functions as assessed by a spatial index.

Previous efforts to develop a standard sub-watershed layer were explored by several agencies who discussed the possibility of creating a joint watershed boundary layer to provide more consistency among agency work. One of the major outcomes of that effort was the desire for separate floodplain units.

A joint effort by the U.S. Geological Survey (USGS), in cooperation with The Nature Conservancy (TNC), Ecology, and the U.S. Environmental Protection Agency (EPA) culminated with the development of a coarse-scale floodplain delineation with respect to five ecological functions for the 17 major river basins flowing into Puget Sound. Please see the USGS Scientific Investigations Report 2015-5033 for documentation of the methods (Konrad 2015).

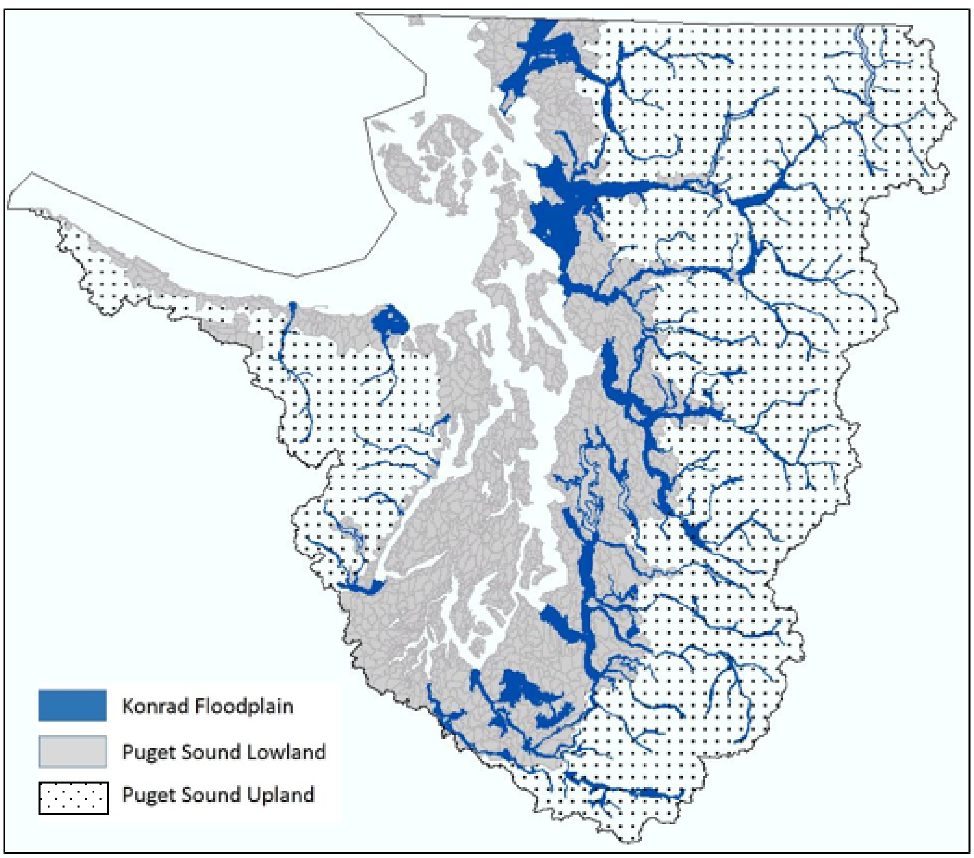


Figure 3. The major floodplain valleys of Puget Sound as mapped by the USGS (Konrad 2015).

We used the coarse-scale "ecological floodplain" (Konrad 2015) as the basis for delineating floodplain assessment units within Puget Sound. An ecological floodplain encompasses all water flow and ecological processes within the area of valley bottoms, high floodplains, low floodplains, and river areas. This contrasts with other regulatory floodplain maps, which are developed to establish flood hazard risk. Konrad (2015) modeled several versions of floodplain, which were considered, and for our purposes the "valley-wall to valley-wall" was selected, as it most appropriately represents the historic geomorphic floodplain.

Figure 3 shows the total extent of the Konrad 2015 floodplain within Puget Sound. The shaded area in Figure 3 is the Puget lowland and the general upstream limit of the Konrad floodplain that we used to define floodplain assessment units; the patterned area in Figure 3 is the Puget Sound uplands or mountainous area, which includes higher elevation valleys and large areas of major public lands. We limited the extent of alterations to floodplain AUs to the lowland area of Puget Sound in an effort to keep an average width of at least 200 feet.

Some of the large valleys and delta areas required some generalization of the floodplain layer as there are numerous small 'islands' of higher elevation within the floodplain valley that were not mapped by the Konrad 2015 modeling method. These areas were incorporated into our floodplain unit to maintain a minimum size threshold for the analysis units.

Figure 4. Generalized USGS floodplain showing small upland 'holes'.

Figure 4 illustrates the darker area as the Konrad floodplain. The lighter areas are small pockets of upland, or 'holes', that are not included in the Konrad floodplain. Any of these 'holes' that were less than one square mile in size, we included in our modified floodplain for use in developing our floodplain analysis units. To achieve this, we dissolved any 'holes' in the floodplain that were less than one square mile in size.

Figure 5 below illustrates how creating a floodplain AU can affect the analysis results for the valley included in the floodplain as well as the upland area that is removed from the AU. In this example, assessment unit #9046 had a management category of protection, labeled in panel A. The original AU includes a portion of the floodplain, the hill slope, and a lake on the upper terrace. In panel B, both the lake and hillslope are in separate AUs (9075 & 9116), resulting in their management category changing to 'restoration' and 'development' respectively. The floodplain AU #9047 becomes larger as it includes the floodplain area previously in 9046, and changes to a restoration management category. Table 3 below summarizes the rationale that supported our criteria, which guided the edits to AUs in floodplain areas.

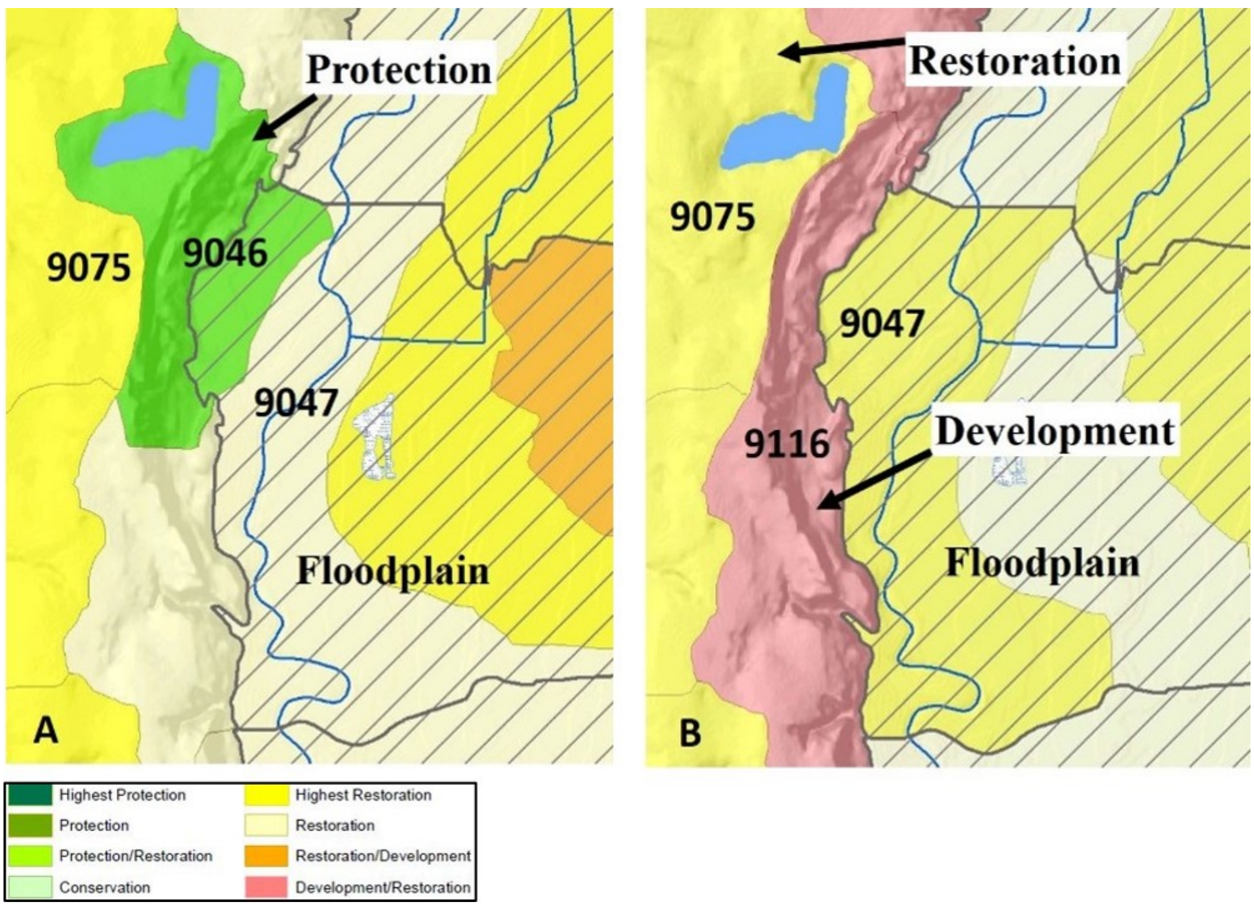


Figure 5. Changes to Water Flow management recommendations due to new v2.0 floodplain AUs (Panel A are original analysis results; Panel B are results using new floodplain AUs).

Table 3. Criteria for floodplain assessment unit editing decisions

Criteria	Rationale
Edit AU boundaries to be consistent with the NHD stream layer.	NHD layer is more current and accurate.
Konrad floodplain data defines floodplain units.	Konrad floodplain is based on best available science, and data is Sound-wide.
Konrad floodplain boundaries are generalized to eliminate small gaps.	AUs must retain general size requirements.
Floodplain units limited to lowland landscape area.	Lowland areas have more significant development pressure and degradation relative to the more intact and protected mountainous landscape units and so are important to differentiate from upslope areas.
Some exceptions for floodplain units in mountainous areas outside public lands.	A few mountainous areas have large floodplains with development pressure (e.g. North Bend) and existing land cover degradation.
Floodplain units are included if average width is 200 feet or greater.	Floodplains of at least this size provide functions that should be highlighted.
Islands in marine waters, less than 1 square mile, are deleted.	Don't meet size requirements and are a different ecological setting.

Landscape Group Assessment Unit Boundaries

The original v1.0 methods normalized model results according to landscape group. This was done in order to prevent areas, for example, with high precipitation amounts (mountain areas) from depressing the Importance score for coastal areas that are equally important ecologically.

In a given WRIA, the Importance scores are generally (unless requested otherwise for a specific application) normalized using a "group leader" approach (AU score = $X/X_{maximum}$ in that Landscape Group) so that all AUs within a given Landscape Group are scored relative to each other. The Degradation Models do not apply a Landscape Group normalization.

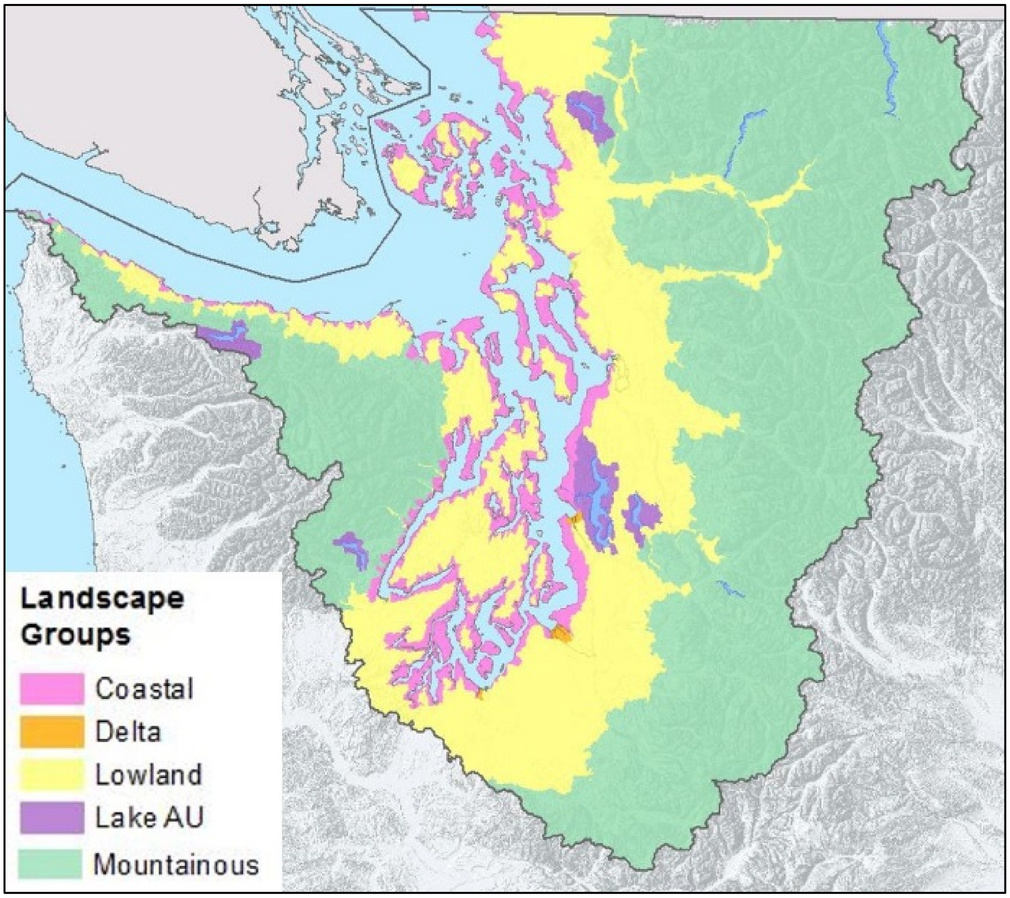


Figure 6. Landscape Groups for the Puget Sound basin.

For v2.0 the Landscape Group boundaries changed on a few of the border areas, generally between the lowland and mountainous areas, due to the edits resulting from incorporating the floodplains into the AUs. Some river valleys had large floodplains that extended up into the mountainous Landscape Group. In these cases, when the floodplain is, on average, 200-feet wide or greater, the floodplain was delineated as a separate AU and remained part of the "lowland" Landscape Group.

Figure 7, Figure 8, Figure 9, and Figure 10 below provide examples of how floodplain areas (lighter color/yellow) have altered the Landscape Group boundaries (green/darker color).

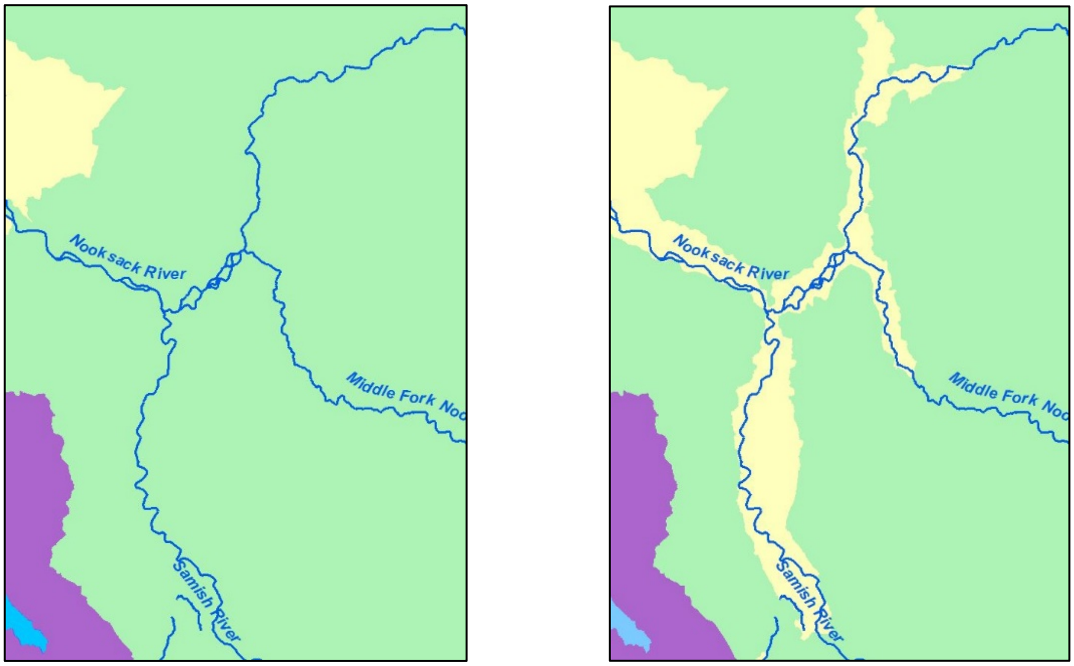


Figure 7. Landscape Group changes in the Nooksack forks area in WRIA 1. The left panel shows the original Landscape Groups. The right panel shows new floodplain AUs in both the north and south forks of the Nooksack River.

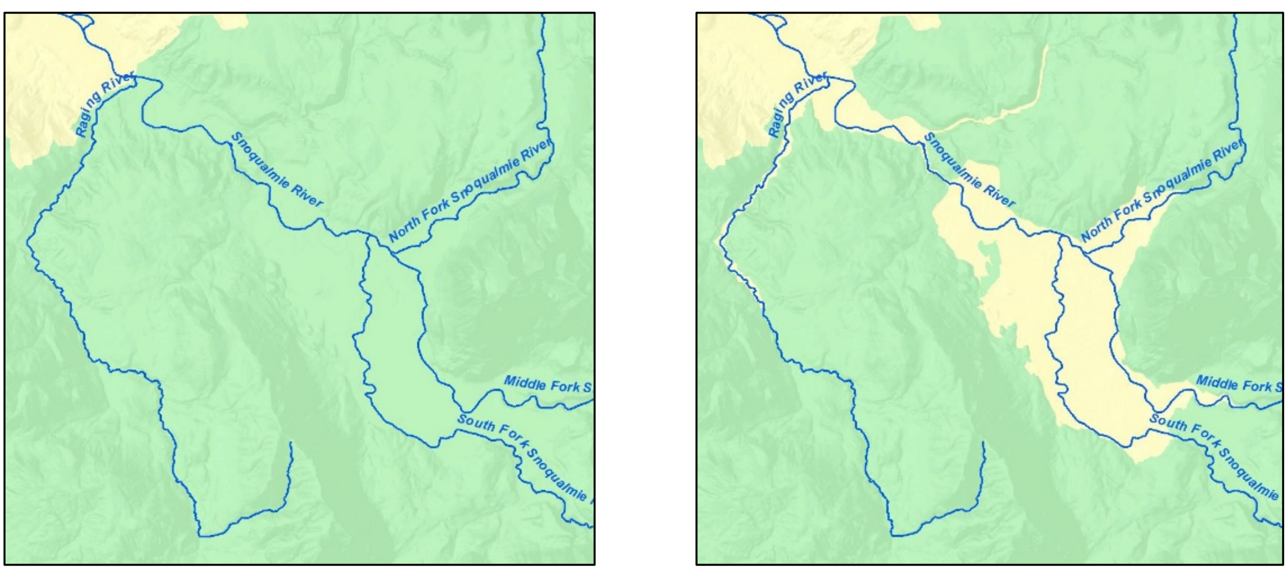


Figure 8. Landscape Group changes in the North Bend area of WRIA 7. The left panel shows the original Landscape Groups. The right panel shows new floodplain AUs in both the South Fork Snoqualmie River and the Raging River tributary.

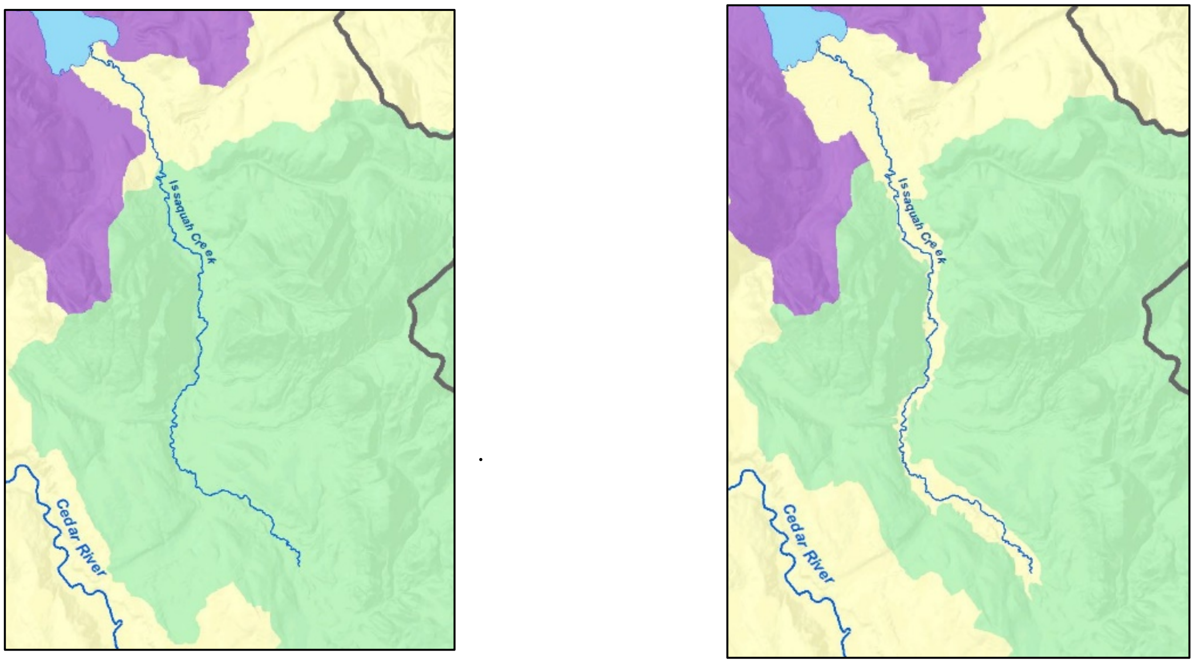


Figure 9. Landscape Group changes in WRIA 8. Left panel shows the original Landscape Groups in the Issaquah Creek area. Right panel with new lowland Landscape Group after adding floodplain AUs.

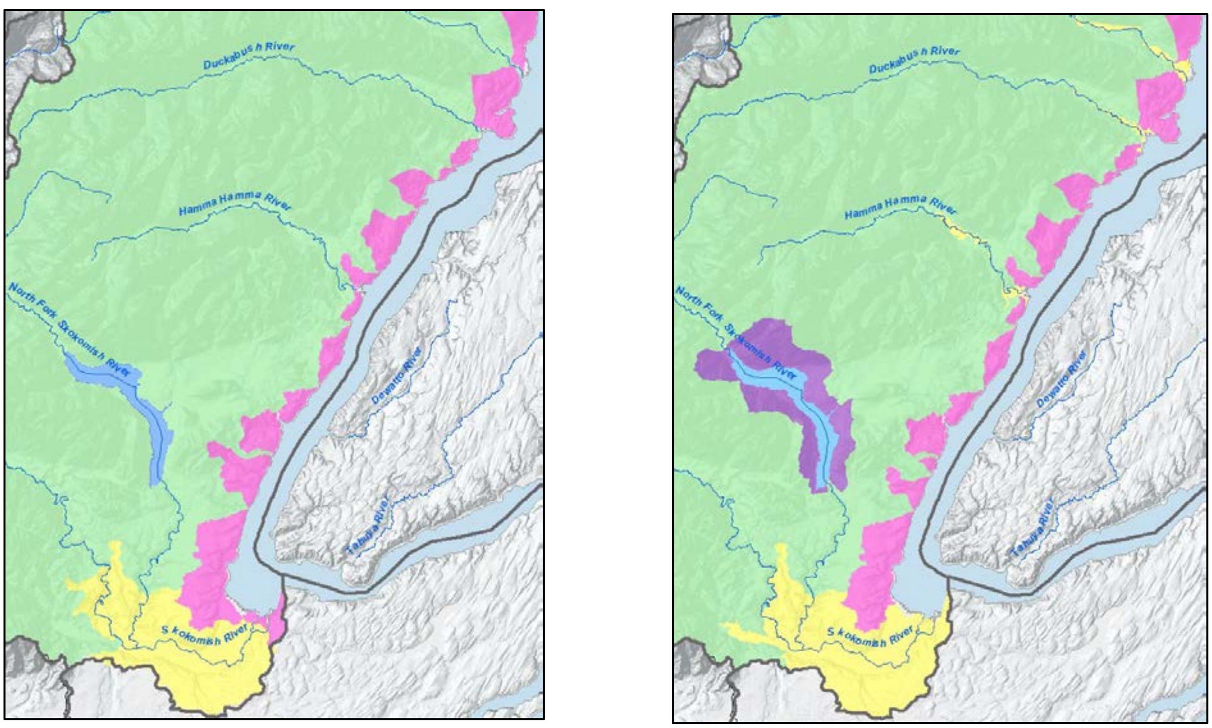


Figure 10. Landscape Group changes in WRIA 16. Left panel shows the original Landscape Groups in WRIA 16. The right panel with new Landscape Groups after adding AUs for Lake Cushman and floodplain AUs in the lower Hamma, Duckabush, & Dosewallips river valleys.

4.0 Water Flow Index Tests

Purpose

As part of the PSWC v2.0 update, Ecology investigated whether the Water Flow index as developed in Volume 1 warrants adjustments in how it uses spatial data to calculate and then "bin" or categorize the final index scores into the Water Flow Management Matrix (Figure 11).

This investigation was prompted by MUTT review of the literature on index calculation methods. The investigation focused on addressing three primary and related concepts: index aggregation, index weighting, and index categorization or "binning".

Specifically, the MUTT wanted to answer three questions through this assessment:

Investigation Question 1: Are there **alternative aggregation** approaches that better combine the underlying spatial data and improve the stability of the index?

Investigation Question 2: Would **weighting** within the aggregation approach improve index performance?

Investigation Question 3: Should **alternate categorization or "binning"** methods be applied for designating AUs into the Management Matrix?

Index stability is one measure of the "uncertainty" of the results that have used spatial data, models, and binning techniques to quantify a score which results in designating AUs into the Management Matrix. In other words, an assessment of stability quantifies the level of certainty/uncertainty a user of the index information should have regarding the resultant management designations for a given watershed or AU. Stability or uncertainty can be assessed and quantified for many different aspects of the watershed characterization models and assessment process, but we focus here on the designations of AUs into the Management Matrix categories (i.e. Protection/Restoration/Development etc.). It should be noted that the stability testing described below is only a cursory examination into what could be a more robust quantification of uncertainty in the future, but does provide some initial insights into the Overall Water Flow Model results. Using several sensitivity/stress tests we evaluated the effect of different data aggregation and weighting methods on the output of the Water Flow Importance and Degradation Models of the PSWC. The following sections provide a brief outline of the original Volume 1 approach to index calculation, a summary of the methods used to assess index stability, and associated results of those tests. We conclude with a best professional judgement validation exercise and discussion of alternative methods of index calculation and "binning". Chapter 5 describes the updates to the methods Ecology has decided to implement for v2.0 of the PSWC models.

Existing PSWC Models

> **PSWC Terminology**
>
> **Assessments:** The primary organization of the PSWC, with 1) water flow, 2) water quality, and 3) fish & wildlife habitat assessments each including models and submodels that inform understanding of respective process conditions.
>
> **Submodels:** The independent analyses within each of the assessments that provide coarse-scale understanding of process conditions; each of the submodels may also be considered a "composite indicator model" in the literature.
>
> **Indicators:** The underlying datasets that inform respective submodel analyses; within the PSWC, these are geospatial layers that inform understanding of process-specific condition. Each submodel includes specific indicators that are measured and aggregated through established PSWC formulas.

The Puget Sound Watershed Characterization (PSWC) establishes a multi-scale framework that integrates water flow and water quality assessments, along with fish and wildlife assessments, as indicators of watershed conditions (Volume 1 - Stanley et al, 2016). The following technical assessment focuses on the Water Flow assessment. The Water Flow assessment characterizes landscape-scale processes including the delivery, movement, and loss of water within a watershed. In turn these processes, form the physical structure that supports and maintains the diversity and productivity of aquatic ecosystems.

The Water Flow assessment integrates two distinct models, one for "Importance" and one for "Degradation," that are applied to every Assessment Unit (AU) across the Puget Sound region at a scale of 1 to 15 square miles in size for the AUs. The results for each AU from these two models are assessed in combination within a Management Matrix (Figure 11) that categorizes the AU relative to others and provides coarse-scale guidance designed to assist regional, county, and watershed-based planning decisions.

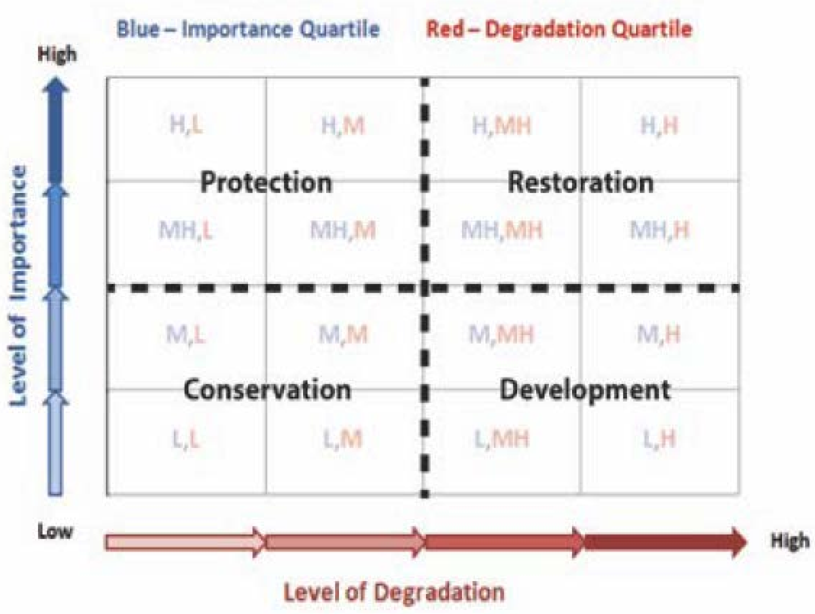


Figure 11. Management Matrix showing categories based on relative level of Importance and level of Degradation binning. Categories on each axis range from Low (L), Moderate (M), Moderate High (MH) and High (H), with the category "breaks" established through a quartile based method.

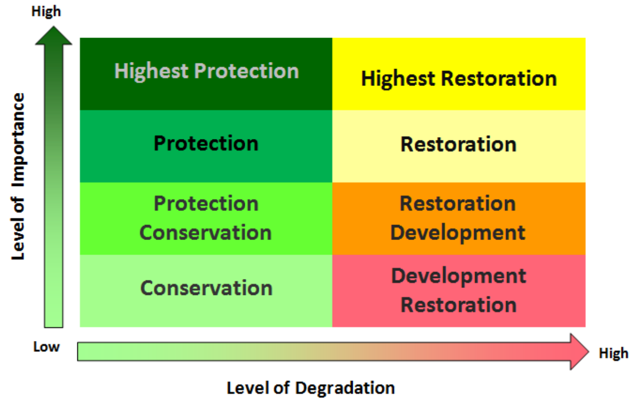


Figure 12. Color-coded Management Matrix used by the PSWC and applied in tests. This represents the simplified 4x2 version, which is used for mapping purposes.

With the Water Flow **Importance Model** (Figure 13), each process is evaluated with a different set of indicators. Delivery is evaluated by the quantity and type of precipitation. Surface storage is estimated by the amount of potential landscape storage features using data intersecting hydric soils with low gradient areas and identifying floodplains based on degree of stream confinement. The processes of recharge and discharge are evaluated using data on precipitation, coarse- and fine-grained soil deposits, slope wetlands, and alluvial floodplains.

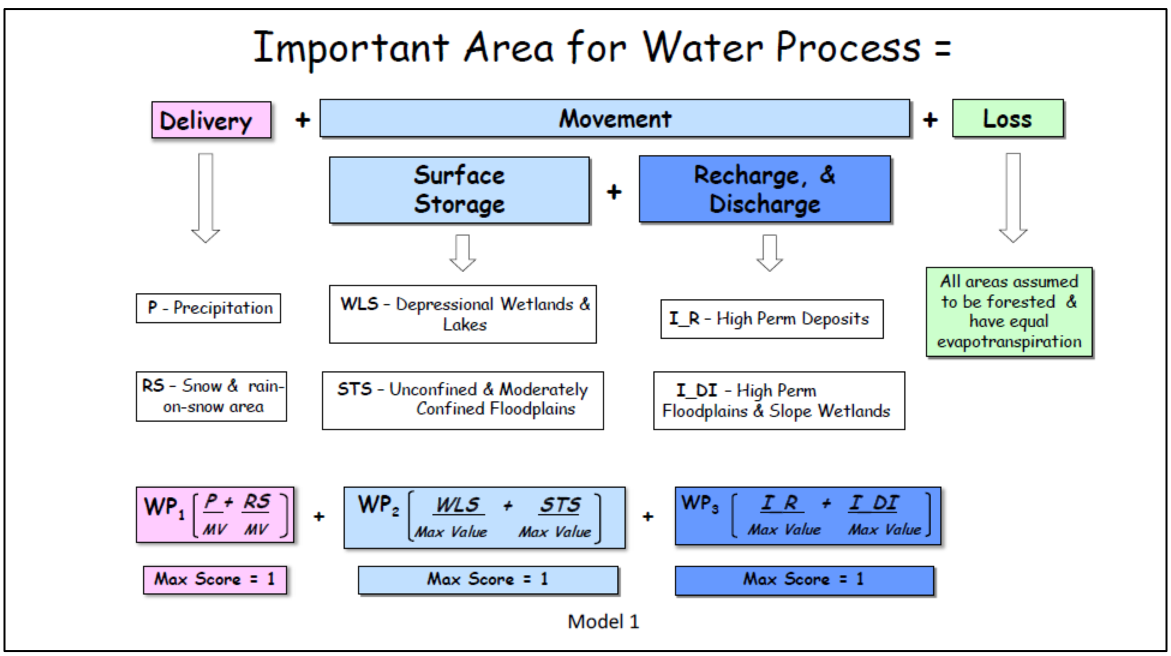
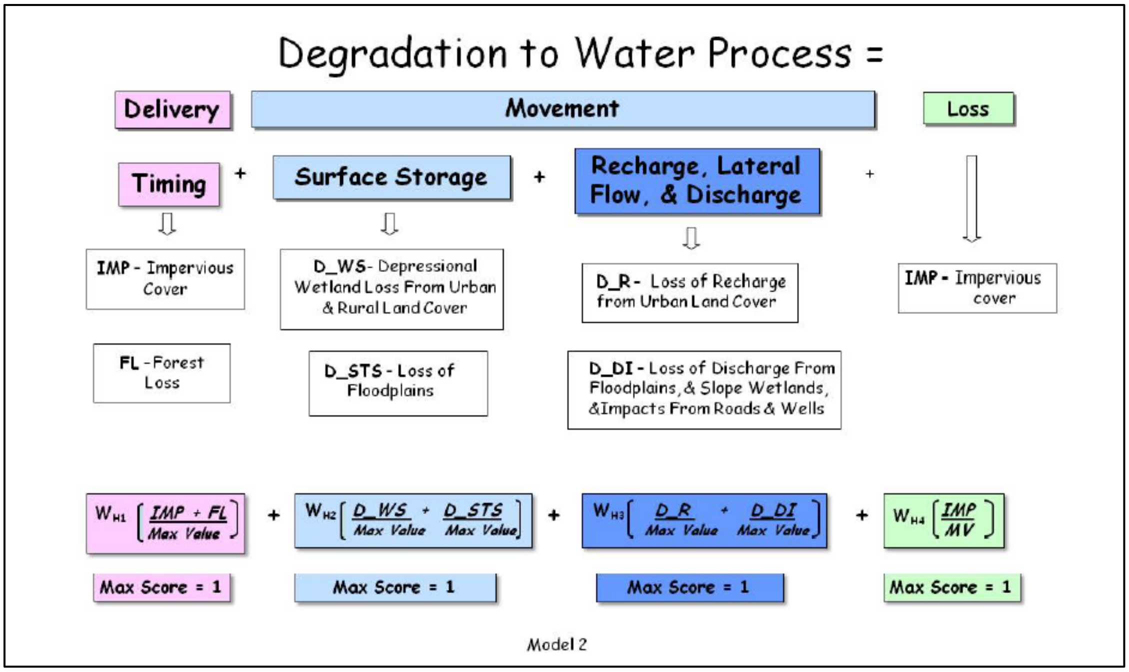


Figure 13. The Overall Water Flow Importance Model. The diagram outlines how the indicators for the subcomponents of delivery, movement, and loss are normalized and added together to provide the final score for relative importance to water flow processes.

The **Degradation Model (**Figure 14**)** evaluates the watershed in its "altered" state by considering the impact of human actions to the four water flow processes (delivery, storage, movement, and loss) across all landscape groups. As with the Importance Model, indicators of the impact upon the four water flow processes are used and principally include: the loss of forest in rain-on-snow areas (timing of delivery impact), percent of impervious surfaces, percent loss of storage areas (wetlands and floodplains), and loss of recharge and discharge areas from the increase of impervious cover, increase in roads, relative number of water wells, and the loss of evapotranspiration through conversion of forest to urban surfaces.



$$W_{H1}\left[\frac{IMP + FL}{Max\ Value}\right] + W_{H2}\left[\frac{D\_WS}{Max\ Value} + \frac{D\_STS}{Max\ Value}\right] + W_{H3}\left[\frac{D\_R}{Max\ Value} + \frac{D\_DI}{Max\ Value}\right] + W_{H4}\left[\frac{IMP}{MV}\right]$$

Figure 14. The Overall Water Flow Degradation Model. Diagram outlines how the indicators for the subcomponents of delivery, movement, and loss are normalized and added together to provide the final score for relative degradation to water flow processes.

> **Normalization**: A process used in composite indicator analysis to combine variables with different units. The PSWC uses the "group leader normalization" approach by dividing a dataset by the maximum value to produce a score ranging from 0-1 for a given assessment unit.

The PSWC v1.0 approach to aggregation employs an additive method in calculating the Water Flow index. Scores for the Importance and Degradation models are calculated based on the quantity of the indicator versus the land area of the full AU (e.g. # wells/acre). Where necessary these indicator values are then normalized to create a common unit by comparing a given AU value to the maximum possible across all AUs (group leader normalization) in the assessment being performed. These normalized indicators are then combined into a submodel score through addition of the 0-1 values for that AU. These submodel scores can be assessed independently to evaluate a given water flow process (i.e. Delivery, Surface Storage, Recharge, Discharge, and Loss) or become components in an assessment of Overall Water Flow Processes.

Aggregation under the current PSWC v1.0 Water Flow assessment methods generally **does not provide any consideration of weighting**, though Volume 1 acknowledges that weighting could be incorporated in local applications with the right technical rationale for doing so. Development of weighting for a coarse-scale regional product was deemed to be too insensitive to the array of differences in drivers of water flow processes across the Puget Sound basin. The respective indicators and algorithms established for each of the Water Flow models are detailed in Appendix D of Volume 1.

Potential Improvements to Water Flow Models Investigated

Index Aggregation and Weighting

Some literature on weighting and aggregation methods for ecological models suggests the use of equal weights is arbitrary and that aggregation methods for models using indicators with different units (e.g. temperature and precipitation) should use geometric mean instead of addition to combine variables. A brief summary of these concerns are summarized below:

- **Aggregation**: Böhringer and Jochem (2007) highlights the inherent challenges with establishing composite indices from variable indicator datasets and suggests use of the geometric mean approach for indicator aggregation.
- **Weighting**: Shultz (2001) details concerns associated with equal weighting of all submodel components (indicators), stating that, “The use of equal weights… is arbitrary in the absence of a logical weighting mechanism”. Normalization of indicators does not account for non-comparability between the underlying data (Ebert and Welsch, 2004).

The aforementioned literature and technical feedback provided by the MUTT established the basis for the Investigation Questions posed at the beginning of this chapter related to Aggregation and Weighting and are recalled below:

Investigation Question 1: Are there **alternative aggregation** approaches that better combine the underlying spatial data and improve the stability of the index?

Investigation Question 2: Would **weighting** within the aggregation approach improve index performance?

Index Categorization (“Binning”)

With the completion of Volume 1 of the PSWC (Stanley et al. 2012 and 2016) the Watershed Characterization Technical Assistance Team (WCTAT) worked to integrate the indices into many different planning processes around the Puget Sound basin. These include Comprehensive Plan updates, Sub-Area Planning, stormwater retrofit planning, and salmon recovery planning. Experience in these projects, which vary widely in scale of assessment units, extent of assessment, and decision processes they are intended to inform, highlighted the challenge of categorizing numerical index scores into “bins” of Low to High values for the purpose of establishing an AU designation within the Management Matrix.

The v1.0 Water Flow method normalizes AU scores for a watershed and bins them into quartile categories, as follows:

- Water Flow Level of Importance: Low, Moderate, Moderate-High, High

- Water Flow Level of Degradation: Low, Moderate, Moderate-High, High

Through this equal quartile binning approach, a matrix of 16 possible AU conditions is established (see previous Figure 11 or another version, Figure 24 below). These conditions are used to establish a Management Matrix.

The current binning approach is detailed by Attachment D-5 of Volume 1: Appendix D. Binning of submodel results into quartiles is completed through a standard approach developed for the Water Flow and Water Quality Assessments ('Quartile Finder' tool as Python script). Quartile binning rules are as follows (highlighted by an example in Figure 15):

A. All submodel results are ordered from lowest to highest value and divided by four (based on the total number of records) to establish four roughly equal quartiles.
B. For submodel results that have an uneven number of records, quartile groups are then adjusted such that the lowest count of records is applied to the lowest quartile bucket, and then to the second lowest quartile bucket. An uneven number of records will give the highest one or two quartile buckets an additional record.
C. Repeat AU scores (zeros and identical values) are kept in the same quartile, even if the number of records per quartile exceeds 25% of the total number of records.

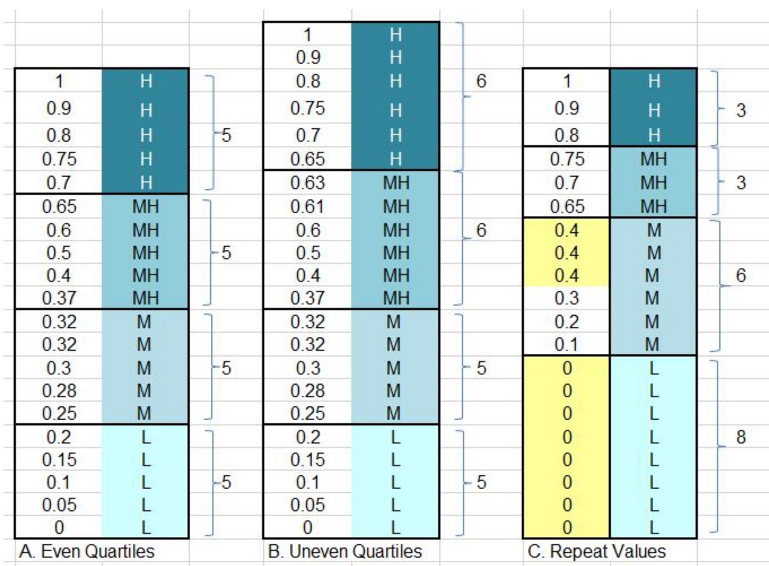


Figure 15. Examples of the v1.0 quartile binning approach (Stanley et al. 2016 - Appendix D Figure D-46).

The current quartile binning approach was established because it is consistent, repeatable, and transparent. However, the method can force groupings and associated Management Matrix designations that do not always recognize distinct breaks in the scores that may represent actual differences in watershed conditions. In addition, the current binning method includes zeros and repeat values in one bucket, which within some watershed assessment areas can result in a highly unequal distribution into the quartile bins.

The challenges of categorizing index values with different distributions of scores across different applications of the models prompted the 3rd Investigation Question posed at the beginning of this chapter:

Investigation Question 3: Should alternate categorization or "binning" methods be applied for designating AUs into the Management Matrix?

Water Flow Index Testing and Results

The following section describes the testing performed on the Water Flow Index. The section is organized around the Investigation Questions posed at the beginning of this Chapter.

Comparison of Aggregation Methods

Investigation Question 1: Are there **alternative aggregation** approaches that better combine the underlying spatial data and improve the stability of the index?

Aggregation methods are used to combine several indicators, or components, to create a single aggregate value upon which a score, and later a ranking, can be assigned to an AU. The method employed to perform this aggregation has some influence on the final score of any given AU. Therefore, understanding how these aggregation methods behave, and their impact on AU ranking, is critical. An examination of the impact of employing an additive (v1.0 Ecology method) vs. a multiplicative aggregation method was performed.

Additive Method (v1.0 Water Flow Approach)

The index aggregation method established in Volume 1 (Stanley et. al 2016) calculates an AU score and ranking for both Model 1 and 2 by linearly combining indicators and components to form a score using the summation of normalized values (Figure 13 and Figure 14 above).

$$\mathrm{AU}_{\mathrm{score}} = \sum w_i \cdot X_i;$$

Where:
X_i = the normalized score for a given component;
w_i = the weight of a given component (recall that weights are not utilized in Volume 1 but acknowledged that a local application may establish weighting)

The rationale for using an additive method is that it rewards individual high scores in a single branch of the aggregation formula. For example, if an AU displays extreme precipitation and a low storage index score, it may score higher than an AU exhibiting a more "balanced" distribution of features. In theory, if all AUs exhibit a "balanced" distribution, score and ranking should not be significantly affected by the choice of methods.

Multiplicative Method (Alternative Approach)

As a comparison to the additive method of aggregation, a multiplicative approach was applied to the exact same data set of AUs in WRIA 7. The multiplicative approach used in this comparison consisted of multiplying component results to form a score for a given AU.

$$\mathrm{AU}_{\mathrm{score}} = \prod X_i^{w_i}$$

Where:
X_i = the raw (un-normalized) score for a given component;
w_i = the weight of a given component (recall that weights are not utilized in Volume 1 but acknowledged that a local application may establish weighting). No weighting was used in this comparison.

Because the multiplicative method does not work with 0-values, linear rescaling was performed on all steps prior to calculating the multiplicative method. This rescaling was applied after normalization by landscape grouping had taken place on the model components. This prevented introduction of any bias in the calculation, allowing direct comparison of results to that of the additive method.

The multiplicative method tends to reward "balanced" AUs exhibiting more evenly distributed indicators and/or components. With this method, a more "balanced" AU will (on average) score higher than an AU, for example, having extreme precipitation and a low storage index. Aggregation of the Water Flow index using the product of the components, or geometric mean of the components, are commensurate "multiplicative" approaches and influence final index values the same way.

Method of Comparison

To compare the two aggregation approaches Water Resources Inventory Area (WRIA) 7 was used as an example watershed in which to apply both index techniques. WRIA 7 contains 268 AUs, representing one of the largest watersheds in Puget Sound. While initial conclusions can be made using the results from a single WRIA, a more robust test comparing a wider array of WRIAs, with different arrangement and number of landscape groupings is preferable.

Each method of aggregation was performed on Water Flow Models 1 & 2 (Importance and Degradation), either combining components using an additive technique or multiplicative technique as described above. Normalization of scores by Landscape Group using the "group leader" ($\mathrm{AU}_{\mathrm{score}} = X/X_{\mathrm{max}}$) was performed with both aggregation approaches consistent with the method established in Volume 1. The multiplicative aggregation results were similarly re-scaled using the "group leader" form of normalization to make the two approaches more easily comparable on a 0-1 scale for the final index score.

Final index scores resulting from each aggregation approach were categorized or "binned" into quartiles for both Model 1 and Model 2, which assigned them to a given location within the 4x4 Management Matrix (Figure 11). Results of the categorization were compared and AUs were identified, which changed designations when a multiplicative aggregation approach was used.

Results of Comparison between Additive and Multiplicative Aggregation in WRIA 7

The results of comparing the additive and multiplicative aggregation techniques are summarized below:

- Of the 268 AUs tested within WRIA 7, five of them exhibit a complete categorization mismatch (i.e. shift quartiles for both Importance and Degradation) when processed with an additive or multiplicative method; 74 exhibit a partial mismatch and only shift quartiles for one of the Models (Figure 16 and Figure 17).
- Degradation categorization is very stable regardless of the aggregation employed. Between additive and multiplicative methods, a 98% match is observed, which means that 98% of all scored AUs remain within the same Degradation quartile categories.
- The results of our analyses show that Importance scoring is less stable (i.e. more likely influenced by aggregation approach) with a 71% match in categorization when going from additive to multiplicative aggregation methods.
- Overall, there is a 71% matching rate. In other words, 71% of the AUs tested do not change in terms of categorization within the Management Matrix when aggregated with an additive or multiplicative method.

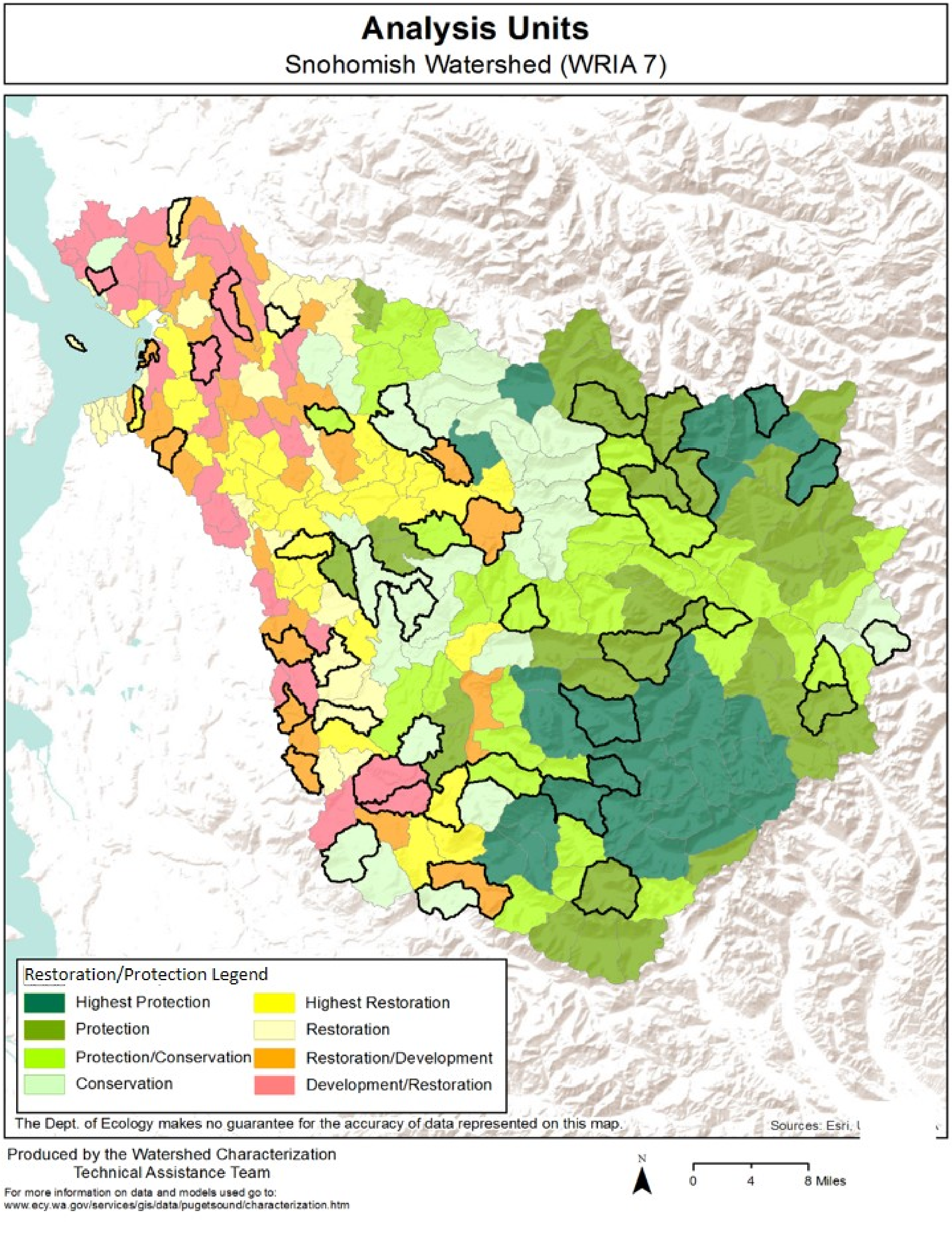


Figure 16. Assessment Unit classification into the Water Flow Management Matrix (note mapping only displays the 4x2 version) using an additive aggregation formula. AUs outlined in bold changed designations in the Management Matrix when a multiplicative approach was used to aggregate the index.

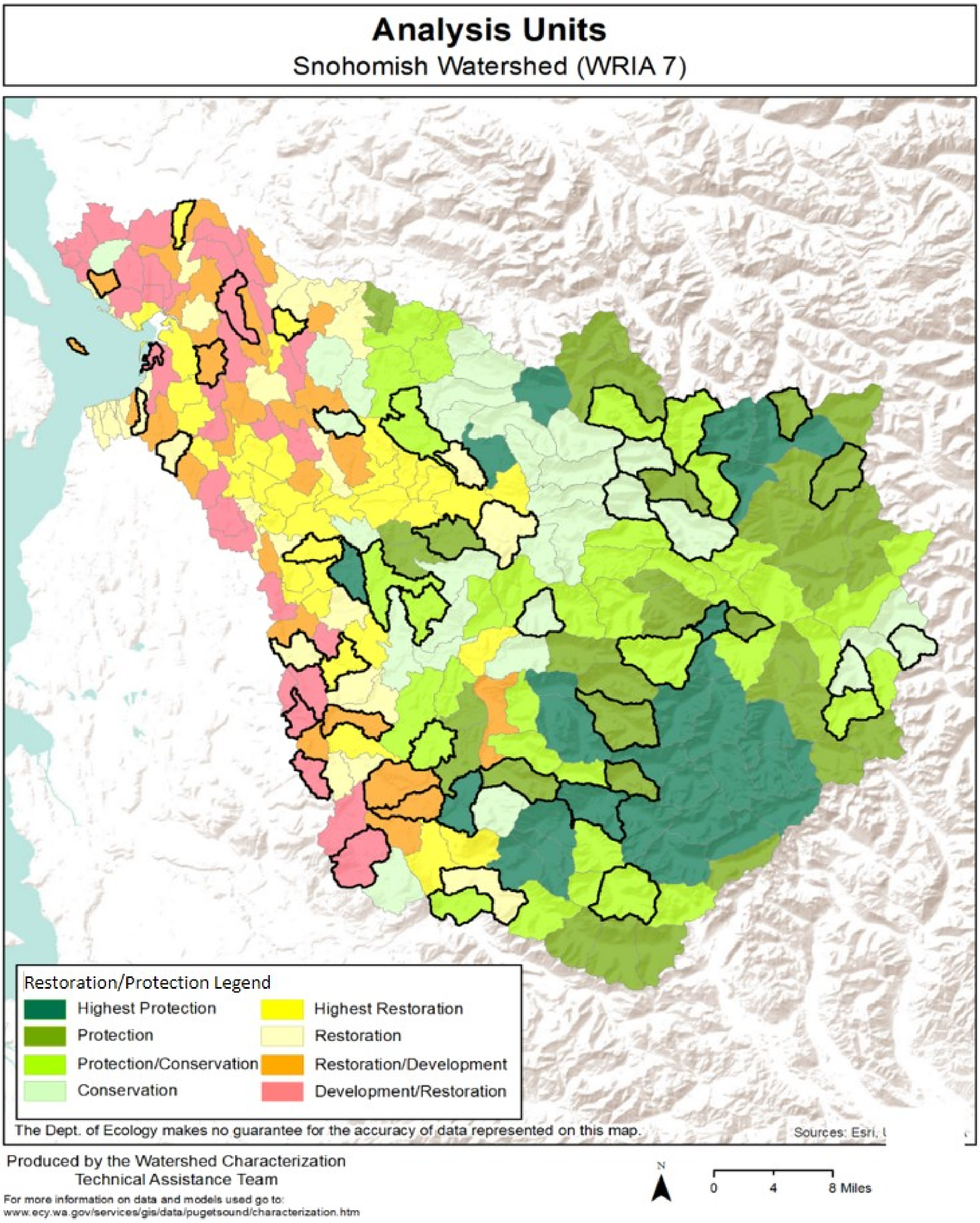


Figure 17. Assessment Unit classification into the Water Flow Management Matrix (note mapping only displays the 4x2 version) using a multiplicative aggregation formula. AUs outlined in bold changed designations in the Management Matrix compared to the additive approach to aggregate the index.

Preliminary Conclusions of Comparing Aggregation Methods

While there was a difference observed between the two aggregation methods, the results are not substantially different, with Degradation exhibiting a high degree of stability. With this in mind, the results of our analyses highlight an important corollary. Aggregation methods should not necessarily be selected solely on published literature or on what is most commonly employed in other similar composite index analyses. Instead, they should be selected based on the physical meaning of choosing one method over another.

The additive method tends to reward "extreme" values; multiplicative method tends to reward "balanced" AUs exhibiting more evenly distributed indicators and/or components. Some variations between the two methods on final scoring and ranking are inevitable, but choice of method should be based upon how the creators of an index want it to perform given the input variables and the conceptual modeling of complex ecosystem processes.

Assessing Weighting of the Water Flow Models

Investigation Question 2: Would **weighting** within the aggregation approach improve index performance?

In order to assess the potential effect of weighting it was first necessary to determine how stable Model 1 and 2 are when "noise" is introduced, and secondly what the effect of weighting has upon the models. Stability was measured by the number or percent of changes in Management Matrix designations that occurred. The effect of weighting was measured by the "distance" that an AU designation moved (i.e. changed position from one quartile to the next) through the Management Matrix. These tests, therefore, are designed to address the following questions:

Sub-Question 2a: Is the ranking of AUs within WRIA 7 stable when random noise is introduced in the existing weighing scheme (probabilistic assessment)?

Sub-Question 2b: What is the response of AU ranking when one or more weights are varied (deterministic assessment)?

Framework for Applying Tests to the Existing Model Structure

The current Water Flow Models are comprised of the Subcomponent and Components Realm (Figure 18 and Figure 19). The subcomponent realm consists of variables that indicate the effect of specific processes present within a watershed, such as the delivery of precipitation (e.g. precipitation per acre) or storage of surface water (e.g. area of wetlands). The subcomponent realm can also be considered the "Physical Realm" in that it is comprised of actual physical variables that can be measured. The Component Realm involves the aggregation of the subcomponent variables, after standardization (normalization), to produce the final Water Flow Model score.

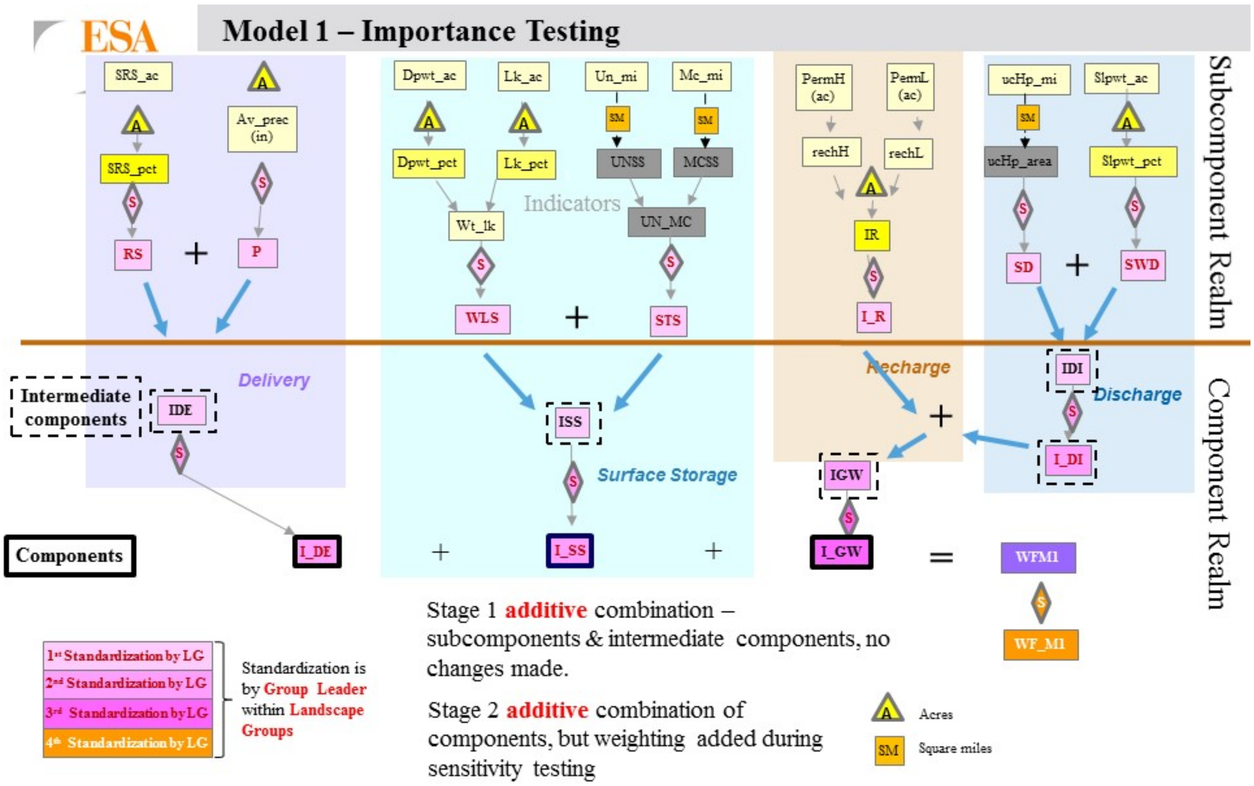


Figure 18. A detailed breakdown of the structure of Model 1, Importance, as applied in testing. Two realms, the "subcomponent" and "component", are depicted. The subcomponent realm includes the variables that capture the relative effect of physical indicators, such as the area of wetlands and floodplains for the storage subcomponent. The component realm combines the subcomponents of the model into the delivery and movement (surface storage) components. For testing the stability of Model 1, only the "component" realm variables were used.

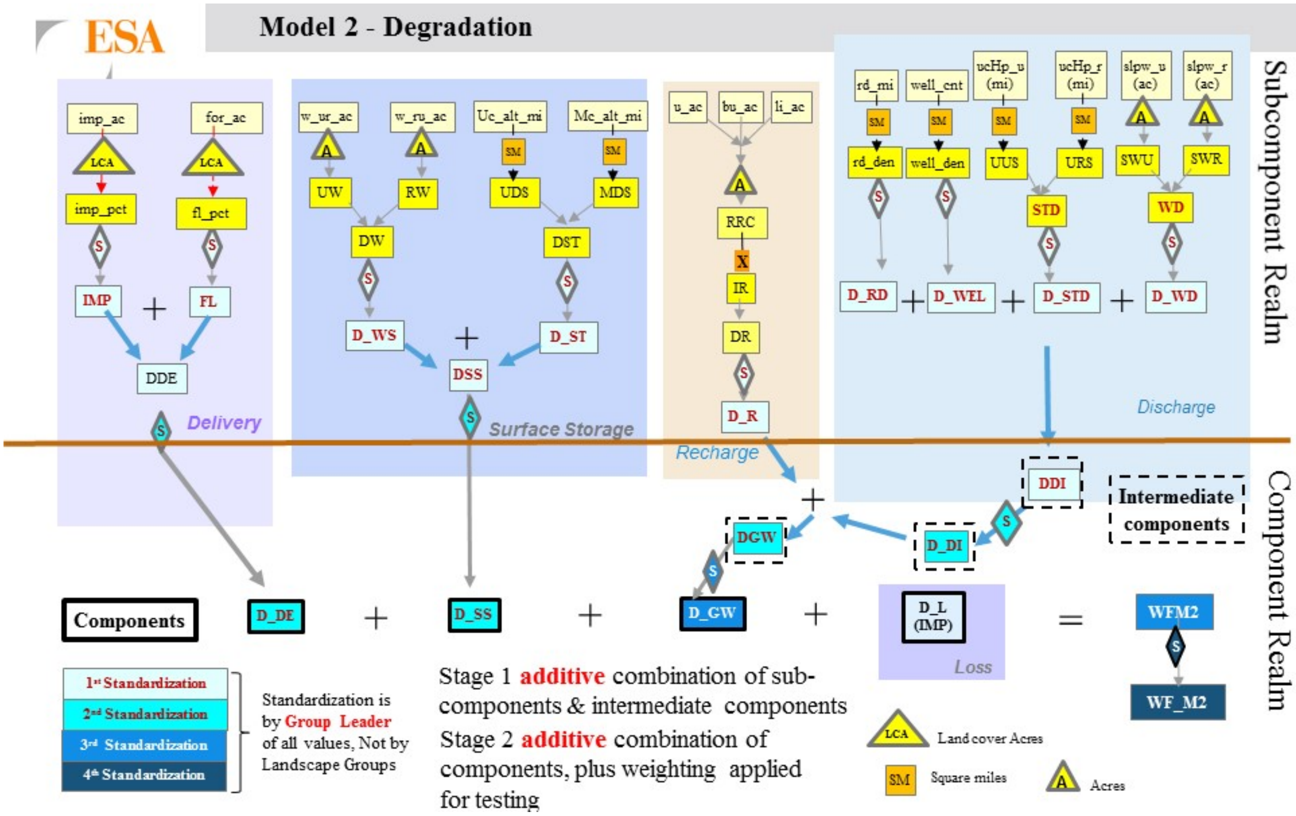


Figure 19. A detailed breakdown of the structure of Model 2, Degradation, as applied in testing. Two realms, the "subcomponent" and "component", are depicted. The subcomponent realm includes the variables that capture the relative effect of physical indicators, such as the area of impervious surface and forest loss. The component realm combines the subcomponents of the model into the delivery, movement, and loss components. For testing the stability of Model 2, only the "component" realm variables were used.

Table 4 below presents acronyms for the indicators, components, and scores for Model 1 and 2 that were used to test model stability

Table 4. Water Flow Models (1&2) nomenclature referenced in Figures 18 and 19

PARAMETER CLASS	MODEL 1	MODEL 2
Sub-indicators	P, RS, WLS, STS, I_R, SD, SWD	IMP, FL, D_WS, D_ST, D_R, D_RD, D_WEL, D_STD, D_WD
Components	IDE, ISS, IDI, IGW	DDE, DSS, DGW, IMP
Normalized Components	I_DE, I_SS, I_GW	D_DE, D_SS, D_GW, D_L
Scores	WF_M1	WF_M2
Normalized Scores	WF_M1_LG, WF_M1_CAL	WF_M2_LG, WF_M2_CAL

Staged Scheme for Assessing Index Stability

Water Flow Models 1 and 2 rely on a staged scheme to combine and generate sub-indicators, components, and scores:

- Stage 1: calculates a reduced set of sub-components by linearly combining sub-indicators
- Stage 2: combines components into one Water Flow Model Score

This is illustrated visually in Figure 20 below, and is explained in detail in the sections that follow. In this particular study, weights were only introduced as part of Stage 2.

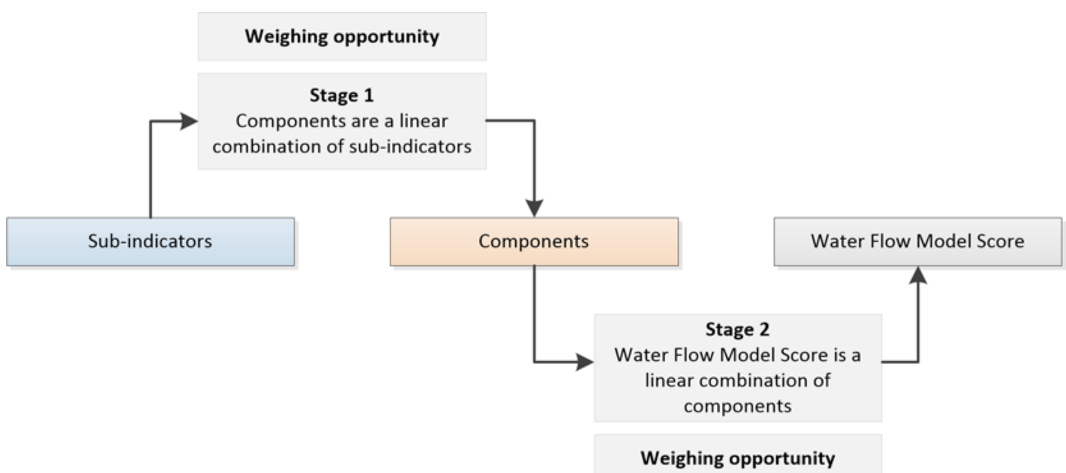


Figure 20. Schematic of the staged weighing scheme.

For the purposes of the sensitivity testing, random "noise" (sub-question 2.a, probabilistic assessment) and weighting (sub-question 2.b, deterministic assessment) were only introduced in the Stage 2 Component Realm. Future exploration of model sensitivity could include an assessment of Stage 1. To run the experiments discussed below, the bulk of the calculations were performed using Python and Excel; key outputs were generated in CSV and/or Microsoft Excel formats.

Effect of Random Noise on Model Stability

To answer **Sub-Question 2a** posed above, Gaussian white noise was randomly introduced in the weighing scheme. A Monte Carlo experiment was performed that comprised 5,000 simulations. For each simulation, the Management Matrix categorization (designation within the 4x4 matrix) of AUs was calculated. Summary statistics were extracted from the experiment as presented in the section below. Statistics were produced to summarize the overall stability of the entire AU population. In essence, this results in a stress test of the index algorithms developed in Volume 1.

Noise Generation

Noise was introduced independently in each random weight generation step in the form of Gaussian white noise[1]. A consistent increase in the value of each weight would yield zero impact on final ranking categorization, because ranking is relative to all other AUs. A simple formulation was used to generate noisy weights, based on their mean value, $\overline{a}$, and a noise amplitude, ρ, as follows:

$$a_i = \overline{a}_i + \rho \cdot \overline{a}_i \cdot \Phi(\text{seed})$$

$$b_i = \overline{b_i} + \rho \cdot \overline{b}_i \cdot \Phi(\text{seed})$$

For the purpose of assessing stability, a noise amplitude which caused 95% of the random weights (a_i or b_i) to be contained within a ±30% band from the mean unit value was retained. Note that the algorithm prevents weights from reaching negative values. Larger deviations from the mean were not considered relevant to a stability assessment, however larger variations around the mean were also considered as a part of the following experiment (below). This is illustrated below in Figure 21 for the 5,000-count Monte Carlo experiment which was also performed. By definition, weights are distributed normally.

[1] Gaussian white noise was deemed a good choice for this experiment as it denotes a wish to assess stability in the outcome of the categorization ranking process when there is uncertainty around a mean value, believed to be a reasonably accurate estimator of the weight's "true value".

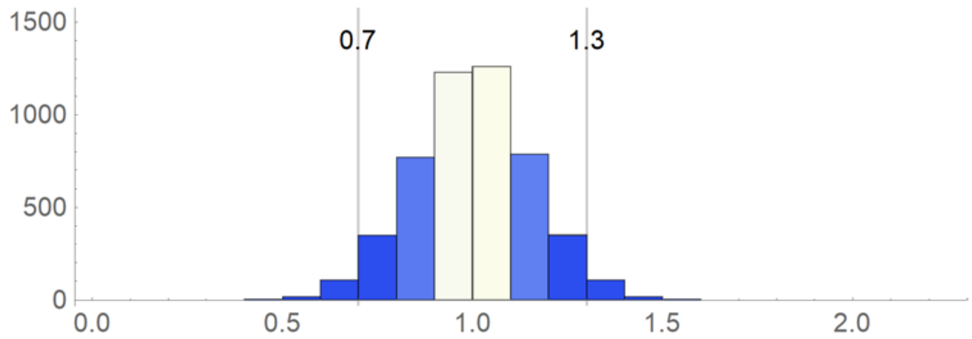


Figure 21. Illustration of the concept of noisy weight generation: in the study, noise parameters were set so that on average 95% of the weights generated randomly are contained within a ±30% band from the mean unit value. This sample series contains 5,000 individuals, with a mean value of 1. Vertical lines indicate the 2.5th and 97.5th percentiles in the sample.

Results of Testing Stability with Randomly Generated Noise

The results of the experiment show that, when random noise is applied to the Component Realm of Models 1 and 2, the Degradation Model is more stable than the Importance Model. The mean categorization ranking stability for the Degradation Model is 93.1% and for the Importance Model it is 68.8% (Table 5). The mean categorization ranking stability for both models is 64% (median of 61%).

Table 5. Statistics for Assessment Unit stability (all values in percent) when random noise is applied to the aggregation algorithm.

Field	Importance Stability	Degradation Stability	Overall Designation Stability
Mean value	68.8	93.1	64.2
Median value	31.7	41.6	22.4
Min value	100.0	100.0	100.0
Max value	63.0	99.9	60.7

These test results for WRIA 7 suggest that an AU processed according to the Volume 1 Water Flow Models (v1.0) is on average 64% likely to retain its nominal categorization ranking, and is 36% likely to undergo a change in that categorization ranking as a result of introducing noise in the weighing scheme. The 64% overall stability value is an average, and therefore must only be considered as a representative indication of the stability overall.

It is observed that some AUs exhibit good stability and are not sensitive to changes in the weights, while others are more sensitive to variations in the weights. Some AUs exhibit notable stability (95%+), while some are much less stable (less than 50%). As a caveat to this assessment, the stability distribution exhibits non-normal features, including lack of symmetry and multiple peaks. Therefore, the use of an average stability may not be the most relevant metric to assess the overall stability of the code.

The results also demonstrated the mean stability of AUs depends on their nominal location in the 4x4 Watershed Management Matrix (Figure 22). For example, AUs that have a low or high nominal importance ranking do not tend to move around when noise is introduced. On the other hand, AUs with intermediate (moderate and moderate-high) importance rankings display greater susceptibility to change when such noise is introduced.

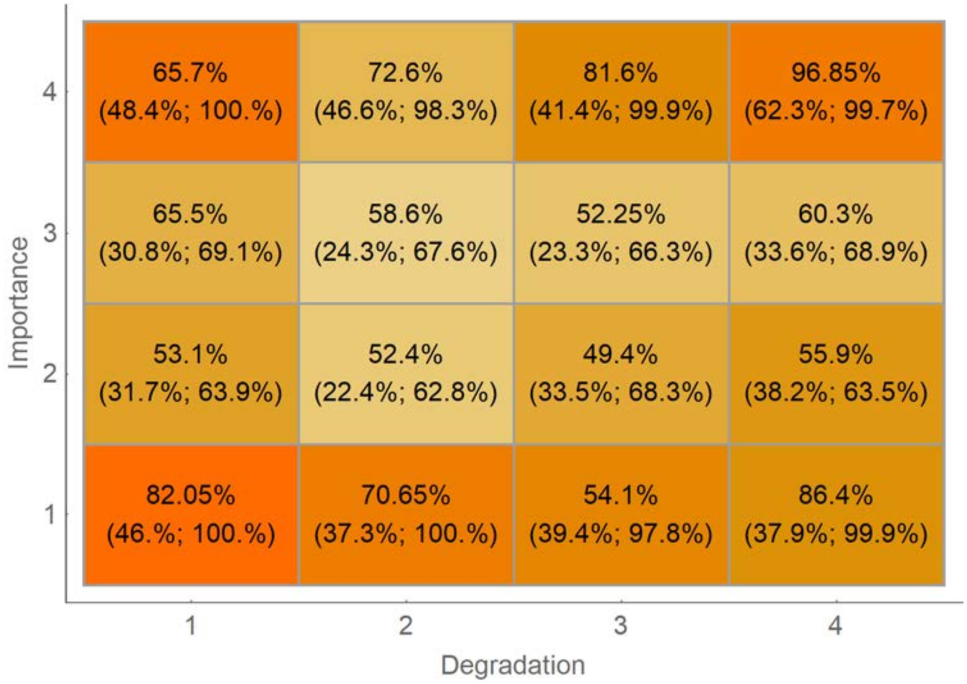


Figure 22. Mean overall stability of AU according to their nominal ranking in the 4x4 Management Matrix. Numbers in parenthesis refer to the minimum and maximum stability of AU contained within each cell. Numbers on vertical and horizontal axes correspond to the quartile designation (Low-High) location for each Importance or Degradation Model.

Effect of Weighting Applied to Model Components

To investigate **Sub-Question 2b** posed above: ***What is the response of AU ranking when one or more weights are varied?*** A deterministic assessment of how the categorization of each AU responds to variations in one component was performed using the framework previously described.

Approach to Applying Variable Weights

The approach implemented to investigate sub-question 2b is similar to that applied to answer 2a, except that in this case weights were individually varied in a deterministic manner. The goal was to identify which components contribute the most to variations in AU categorization ranking within the 4x4 Management Matrix. Each weight was varied arbitrarily from 1 to 4. The range of values retained for the weights was primarily driven by a desire to obtain "visibly meaningful" results. In no cases were any of the weights reduced to zero. As such, none of the components within the models were "muted".

To assess the strength of a particular component when weighted, a "Distance Traveled" metric was calculated for each AU in a given weighting scheme. "Distance Traveled" is defined as the number of contiguous cells in the Management Matrix an AU moves from the "base case" (no weighting applied to the aggregation formula) with a given weight applied. Strong components are those that have the ability to change an AU categorization ranking when weights are applied to them. Weak components are those that do not affect categorization ranking, even when weights are applied to them.

Results of Applying Variable Weights to Model Components

The results of the analysis show that not all components carry the same overall strength over scoring. The calculations show that among the seven components considered in this study, the following carried the most strength, in decreasing order:

- Importance to Delivery Processes (I_DE), was found to be the strongest component. When allowed to be weighed independently of all other components, the weighed component caused over 54% of the AUs tested to experience a change from their nominal designation, as measured by Management Matrix Distance Traveled.
- Importance to Surface Storage Processes (I_SS), is the 2^{nd} strongest component. When allowed to be weighed independently of all other components, the weighed component caused over 46% of the AUs tested to experience a change from their nominal designation, as measured by Management Matrix Distance Traveled.
- Importance to Groundwater Processes (I_GW) is the 3^{rd} strongest component. When allowed to be weighed independently of all other components, the weighed component caused over 39% of the AUs tested to experience a change from their nominal designation, as measured by Management Matrix Distance Traveled.
- Degradation to Delivery Processes (D_DE) is the 4^{th} strongest component and the only Degradation component greater than 10%. When allowed to be weighed independently of all other components, the weighed component caused over 11% of the AUs tested to experience a change from their nominal designation, as measured by Management Matrix Distance Traveled, significantly less than the next-strongest component.

All other components drove less than 10% of AUs tested to experience a change from their nominal designation in the Management Matrix. These results are illustrated in Figure 23. We also note that some AUs experience no change in designation, regardless of any weights being applied on the components. These results are consistent with some of the findings of the probabilistic assessment conducted above (absolute stability).

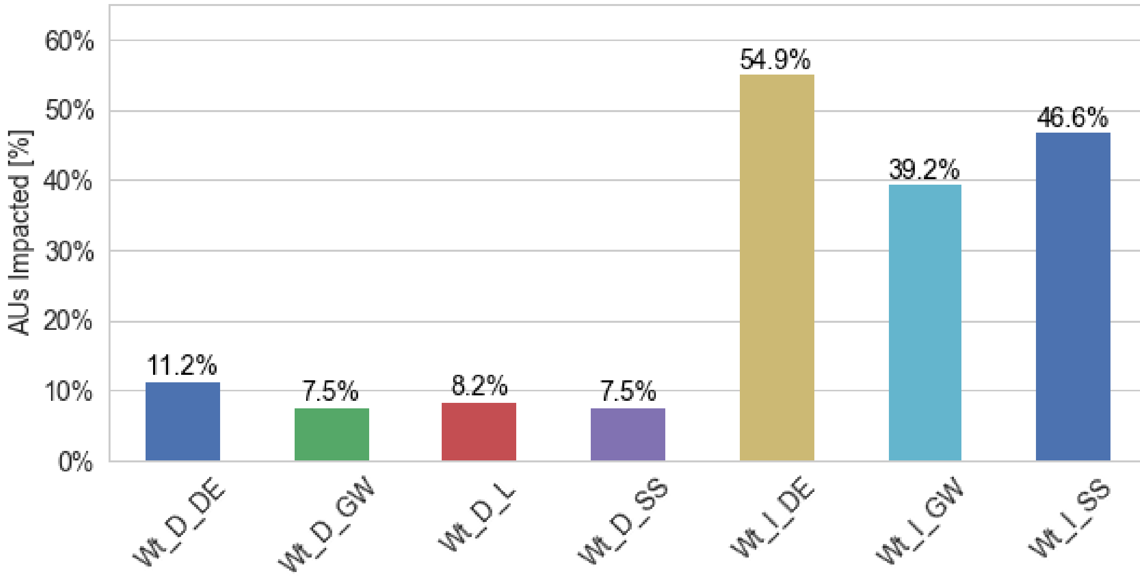


Figure 23. The relative strength of Model 1 and 2 components when using weights.

Preliminary Conclusions from the Stability Assessments

Investigation Question 2: Would **weighting** within the aggregation approach improve index performance?

These analyses provide some preliminary answers to further substantiate with regards to Investigation Question 2. It appears that, given the high degree of stability within the Degradation Model, weighting in the component realm would be unlikely to substantially change the resulting categorization of AUs into the Management Matrix. However, the Importance Model is significantly less stable, and as such our categorization of AUs into the Management Matrix vertical axis (Importance quartiles) comes with a higher degree of uncertainty surrounding that designation. Establishing weighting within the Importance Model in the future may contribute to greater stability and lessen uncertainty of those categorizations. Determining whether this should occur at the Component Realm of the model, the Physical Realm, or a combination of both would be a part of an important next step in model refinement.

There are limits to the conclusions that can be taken from the experiments described above. These were only performed on WRIA 7, and other watersheds will have different distributions of underlying physical indicators in the AUs. These will effect model performance in variable ways across watersheds. Similar investigations should occur in an array of WRIAs to confirm these initial findings. Additionally, the weighting analysis was only applied to the Component Realm of Models 1 and 2. An assessment of the effects of weighting on the Physical or Subcomponent Realm is warranted to tease out the relative influence of indicators on each other as they aggregate into submodels and ultimately into components.

Implications of Categorization ("Binning") Approaches

Investigation Question 3: Should **alternate categorization or "binning"** methods be applied for designating AUs into the Management Matrix?

The characterization results (normalized scores ranging 0-1) of each Water Flow Model (Overall Importance or Degradation) or submodel (e.g. Delivery) are categorized into equal quartiles with roughly the same number of AUs in them. Therefore, roughly 25% of the AUs in the assessment fall into each quartile, except where repeat records are found. The boundaries between quartiles depend on the distribution of scores across all AUs in the assessment. However, a quartile based method of categorizing AUs from Low to High can be influenced significantly by the number of records and is less sensitive to "clusters" within the frequency distribution of underlying scores.

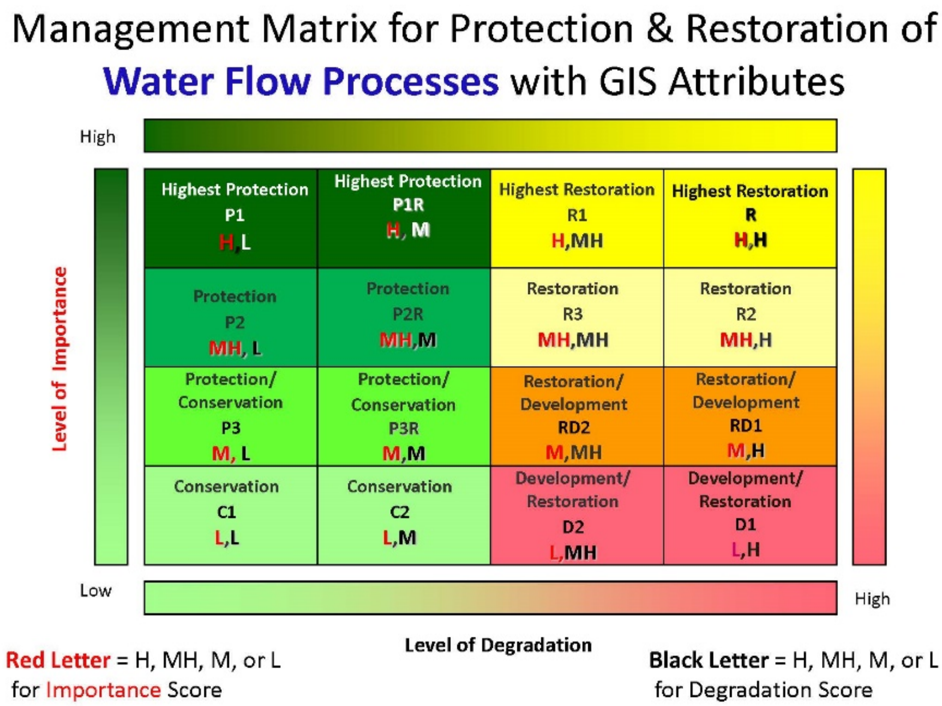


Figure 24. The 4x4 Water Flow Management Matrix with Protection & Restoration designations for assessment units is based upon the combination of its rating for Importance and Degradation. Matrix represents all possible combinations of quartile based "binning" results (i.e. High, Moderate-High, Moderate, and Low) for a given assessment unit across both models.

In order to investigate the implications of an alternative categorization (also referred to as "binning") on the designation of AUs into the Management Matrix (Figure 24), a Jenks (aka Natural Breaks) method was contrasted to the existing quartile approach. A Jenks method is more sensitive to the frequency distribution of the AUs because it sets the boundaries between the categories based on identifying "clusters" of scores which minimize variance. Figure 25 illustrates the normal distribution of Overall Water Flow Importance scores for WRIA 7. Figure 26 illustrates the right-skewed distribution of the Overall Water Flow Degradation scores for WRIA 7.

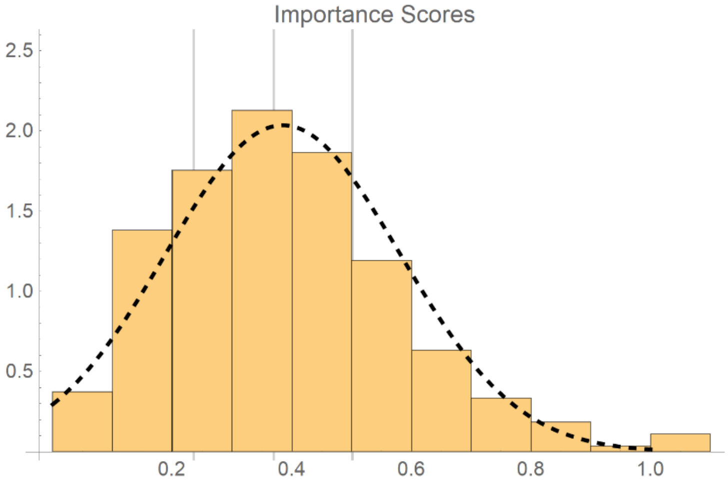


Figure 25. Frequency distribution of Overall Water Flow Importance scores for WRIA 7 using the additive method of aggregation and normalization by Landscape Group. Distribution is normally distributed.

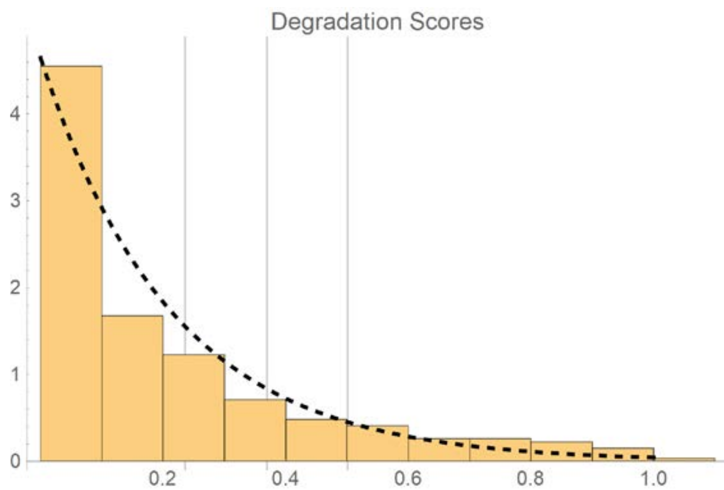


Figure 26. Frequency distribution of Overall Water Flow Degradation scores for WRIA 7 using the additive method of aggregation. Distribution is skewed.

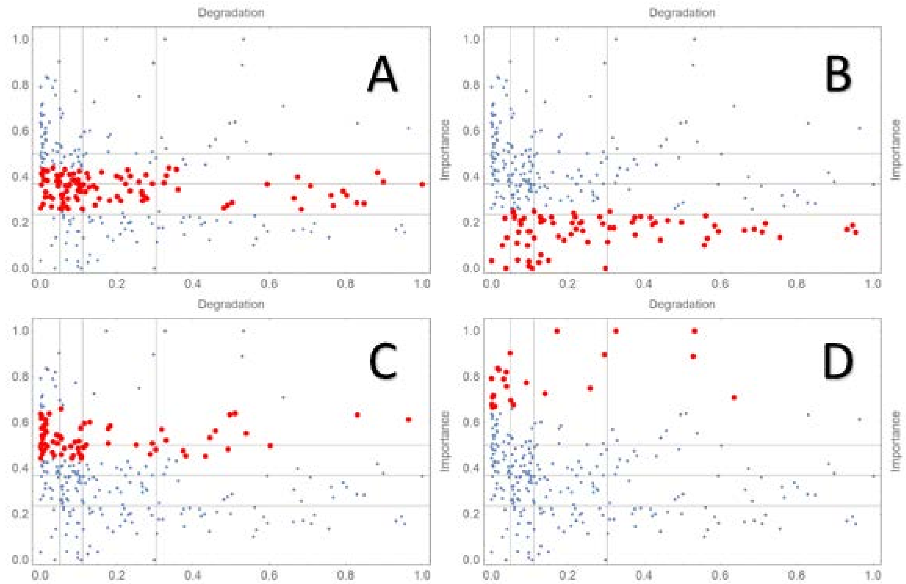


Figure 27. Comparison of Assessment Unit categorization into the Management Matrix on the Importance Axis when using a Jenks (Natural Breaks) approach. Grey lines on each panel indicate the boundaries between categories when based upon a quartile method. Red dots for each panel indicate the High (D), Moderate-High (C), Moderate (A), and Low (B) designations respectively when using the Jenks approach. The Jenks approach results in fewer assessment units being designated in the High category of Importance but other categories retain a similar number of assessment units compared to the quartile method of binning.

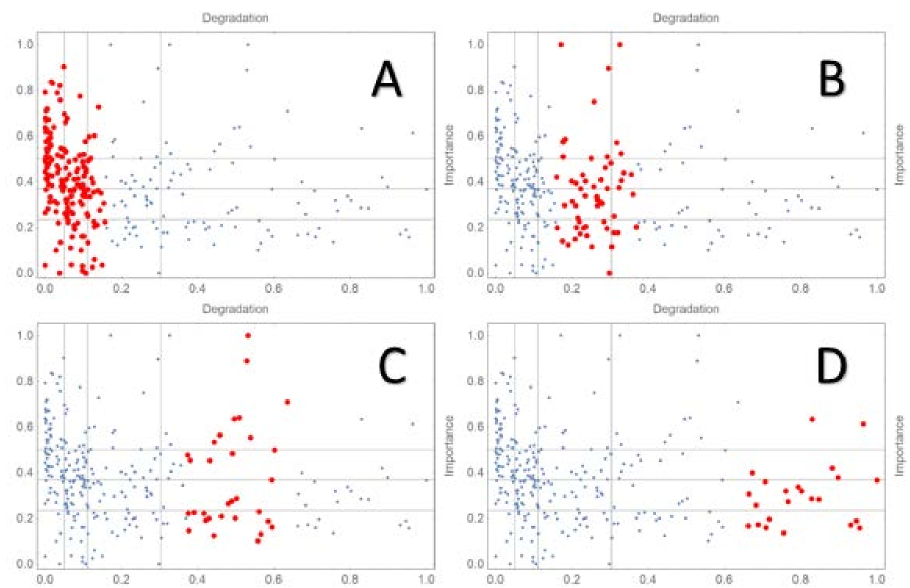


Figure 28. Comparison of Assessment Unit categorization into the Management Matrix on the Degradation Axis when using a Jenks (Natural Breaks) approach. Grey lines on each panel indicate the boundaries between categories when based upon a quartile method. Red dots for each panel indicate the High (D), Moderate-High (C), Moderate (B), and Low (A) designations respectively when using the Jenks approach. The skewed distribution of scores results in many more (greater than 50%) of the AUs being designated into the Low category, with very few falling into the High category.

Figure 27 and Figure 28 compare the designations of AUs in WRIA 7 (Overall Water Flow v1.0 approach) into the Management Matrix categories when a Jenks approach to “binning” is used versus an equal quartiles method. In each figure the red points on the plots correspond to the Jenks designations of Low, Moderate, Moderate-High, or High on each panel with the underlying grey lines showing the boundaries of the quartile-based categories for each axis.

Figure 27 compares the effect of using the equal quartile and Jenks method for designating AUs into the four categories (Low, Moderate, Moderate-High, High) on the Importance axis of the Management Matrix. The Jenks method identifies a distinct cluster of higher scoring AUs and a cluster of moderate-high scoring AUs. However, the number of AUs designated into the lower two categories (Low and Moderate bins) is largely similar for both the Jenks and equal quartile methods due to the generally normal distribution of the Importance scores.

Figure 28 compares the effect of using a Jenks or equal quartile method on the Degradation designations into the four categories of the Management Matrix. The Degradation scores are not normally distributed with the majority of them concentrated in the Moderate to Low quartiles and the remaining scores spread out amongst the Moderate-high to High quartiles. Under these circumstances, the Jenks binning clusters the majority of data into one bin (i.e. low category), which may obscure ecologically important gradients of conditions of water flow processes. In contrast, the quartile method creates two bins for this same portion of the data, which may better characterize those patterns in a watershed.

Preliminary Conclusions of the Investigation into the Effect of Categorization Methods

As described above, the choice of categorization or binning methods applied to the index scores has important consequences. Using the Jenks approach to categorize AUs into the Management Matrix identifies clusters of AUs in a way that the quartile method cannot. However, the consequence of doing so may obscure some gradients of scores that could be useful in discriminating AUs. In particular, when a skewed distribution exists, a large number of AUs will fall on one or the other end of the distribution, and in most cases the low end, when assessing a full WRIA.

One approach could be to statistically calibrate the score ranges for each category in the Management Matrix to some sort of water flow process metrics or response variable as measured with actual “on the ground” data (e.g. flow gage data). However, the coarse-scale Water Flow Models were not developed to be predictive of specific flow metrics. Rather, they are based upon simple conceptual models that are useful for assembling indicators of importance or degradation to water flow processes and assumes that greater or lesser quantity of these indicators in a watershed is a meaningful assessment for certain planning applications. As such, at this point the primary way to validate a given approach to binning AUs is to use best professional judgment when viewing different results for the same watershed. This is done in the following section.

Both approaches to categorization have their merits and should be adapted to the specific application of the indices and the distribution of scores in the assessment. Transparency of the approach to categorization is critical in documentation of an assessment. Future stability testing analogous to that which was performed (i.e. random noise generation and weighting) on the existing v1.0 aggregation approach should be done using Management Matrix designations based upon a Jenks method, or other categorization techniques. This is much more computationally intensive; however, it would assist in understanding whether uncertainty of those designations can be improved with a given binning method. Users of the indices could combine this with their own best professional judgment to select the right approaches for their specific application and watershed being investigated.

Further, it's important to emphasize that the designation of AUs into the Management Matrix using any binning approach is imperfect and is fundamentally based upon a relative assessment of the comparative levels of Importance and Degradation using imperfect data and arbitrary weighting (or non-weighting). At best, we can say that a given AU is a "higher priority" for a given management strategy (i.e. Protection). This is not an absolute determination given the uncertainty (lack of stability), which is introduced by things like the GIS data available, aggregation, and binning approaches. This again emphasizes the importance of reviewing the results of a characterization by experts with knowledge of the watershed to assess the best way to apply and interpret the data.

MUTT Proposed Updates to the Water Flow Model v2.0

Preliminary MUTT Recommendations Based Upon an Evaluation of the Three Investigation Questions

The Model Update Technical Team (MUTT) reviewed the testing results described in the sections above and made preliminary recommendations for refinements to the Overall Water Flow Models. A brief summary of the recommendations from the MUTT are described below.

Investigation Question 1: Are there **alternative aggregation** approaches that better combine the underlying spatial data and improve the stability of the index?

- **MUTT Recommendation for Water Flow Models v2.0**: Retain additive aggregation approach in the physical subcomponent realm of the Water Flow Importance and Degradation Models. Combine components with multiplicative approach (see Figures 29 and 30).

Comparatively, multiplicative and additive aggregation approaches do not substantially change the designations of AUs into the Management Matrix (quartile based), particularly for the Overall Water Flow Degradation Model. The additive method tends to favor "extreme" or outlier values; the multiplicative method tends to favor "balanced" AUs exhibiting more evenly distributed indicators and/or components. When in the subcomponent realm (i.e. Physical Realm) of indicators you are combining variables that are dealing with similar processes and functions (e.g. storage subcomponent combines % wetland with % unconfined stream), often quantifying similar units, and so extreme values may be warranted and one would not want them "masked". When in the component realm (e.g. Importance to Delivery, I_DE) you are combining dissimilar processes (storage and delivery) but don't know their relative contribution or importance to Overall Water Flow processes, so favoring a calculation approach which is balanced across all components is appropriate (multiplicative aggregation).

Further stability and comparative uncertainty testing are warranted in the future to more systematically compare the two aggregation methods and potential adjustments to how indicators and subcomponents are combined in the “physical subcomponent realm” of the Water Flow index.

Investigation Question 2: Would **weighting** within the aggregation approach improve index performance?

- **MUTT recommendation for Water Flow Models v2.0 –** <u>Do not</u> apply weighting to the Water Flow Models with this update. Consider doing so with the Importance Model in future.

Stability testing performed associated with this question indicates the Degradation Model is extremely stable and weighting would not likely alter the results significantly. The Importance Model may warrant some weighting to improve stability, however determining a scheme which could be applied regionally may not be achievable given the coarse-scale nature of these indices. Weighting of relative importance of indicators to water flow processes is very location/geologic context/watershed specific. A future effort to explore weighting of the Importance Model may be undertaken but was out of scope of the current update.

Investigation Question 3: Should **alternate categorization or “binning”** methods be applied for designating AUs into the Management Matrix?

- **MUTT recommendation for Water Flow Models v2.0 –** Perform additional stability assessments on a Jenks approach for categorizing the Water Flow model into the Management Matrix. <u>Local applications of the index results should examine underlying score distributions and determine preferred binning approach which matches best professional judgement of technical experts knowledgeable about that watershed.</u>

Investigation into Question 3 led the MUTT to recognize that alternatives (i.e. Jenks) to the categorization/binning approach to designating AUs into the Management Matrix in the Overall Water Flow v1.0 method should be explored further and may improve stability, in particular for the Importance Model. However, the analysis of this was out of the current scope of our update. Conversely, when a cluster-based approach (e.g. Jenks) is used, ecologically meaningful gradients may be obscured when the underlying score distribution is highly skewed and only one bin or category is created for potentially greater than 50% of the AUs (e.g. WRIA 7 testing described above).

As such, the MUTT recommended that future stability analysis be performed with alternative binning approaches across an array of WRIAs. Further, the right binning approach likely needs to be tailored to the specific application and watershed the models are being applied to. An assessment of the score distributions should generally be performed for a given application of the indices, and binning approach validated by technical experts knowledgeable about the hydrology of that watershed.

Recommended Validation Approach Proposed by the MUTT

For the purpose of establishing the regional v2.0 Water Flow assessment results available for viewing and download from Ecology’s website, a cursory best professional judgement exercise was performed to validate the updates that would be implemented with this effort. This was only done for WRIA 7 and may in the future be done for all the WRIAs. That exercise is described in the following section.

Finally, it is important to reemphasize, as illustrated by all of the testing performed to attempt and answer the three Investigation Questions, that there is uncertainty to varying degrees in our Management Matrix designations. Our need to illustrate the index results spatially on a map necessitates what is a simplification of complex gradients and distributions of conditions across a watershed. Management priorities (i.e. Protection, Restoration, and Development) for an AU are not "absolute", and we should improve our ability to communicate that uncertainty when presenting the results. Ecology will consider ways to do this in the future, expanding upon the type of testing which was performed with the weighting and binning exercises described above.

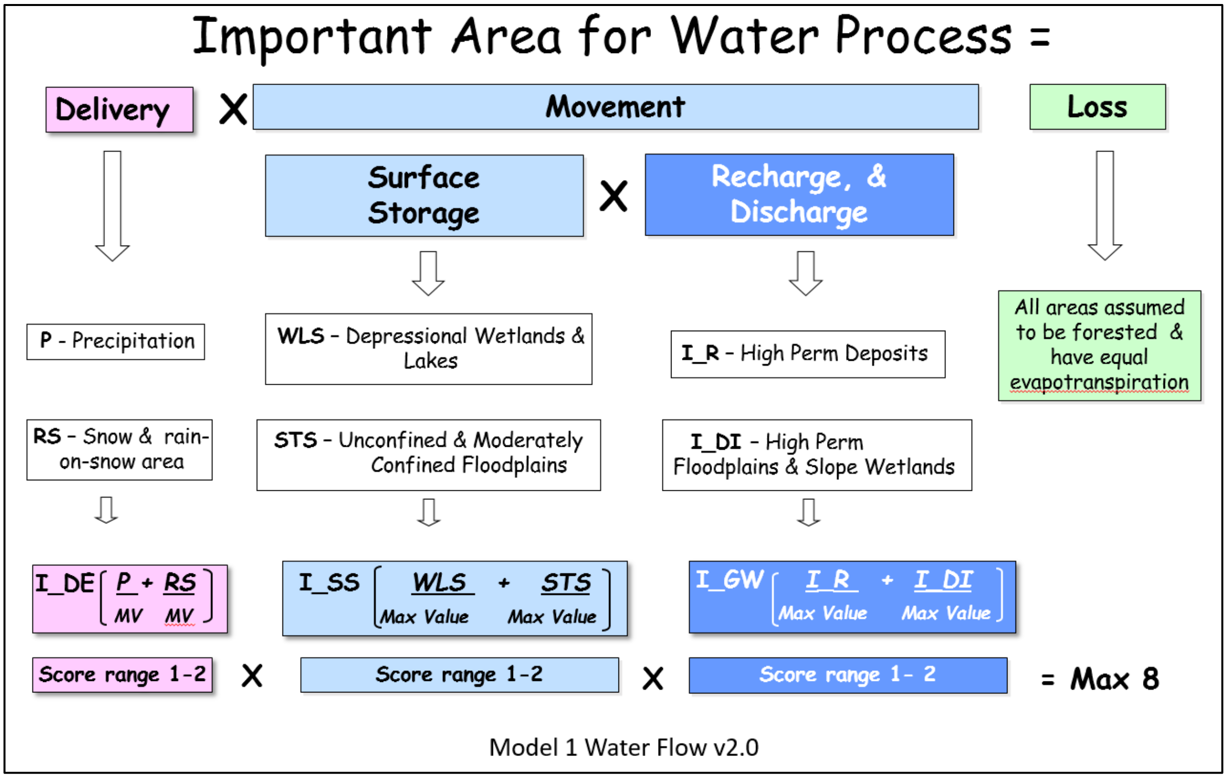


Figure 29. Overall Water Flow Importance Model aggregation formula (simplified) adopted for v2.0 update.

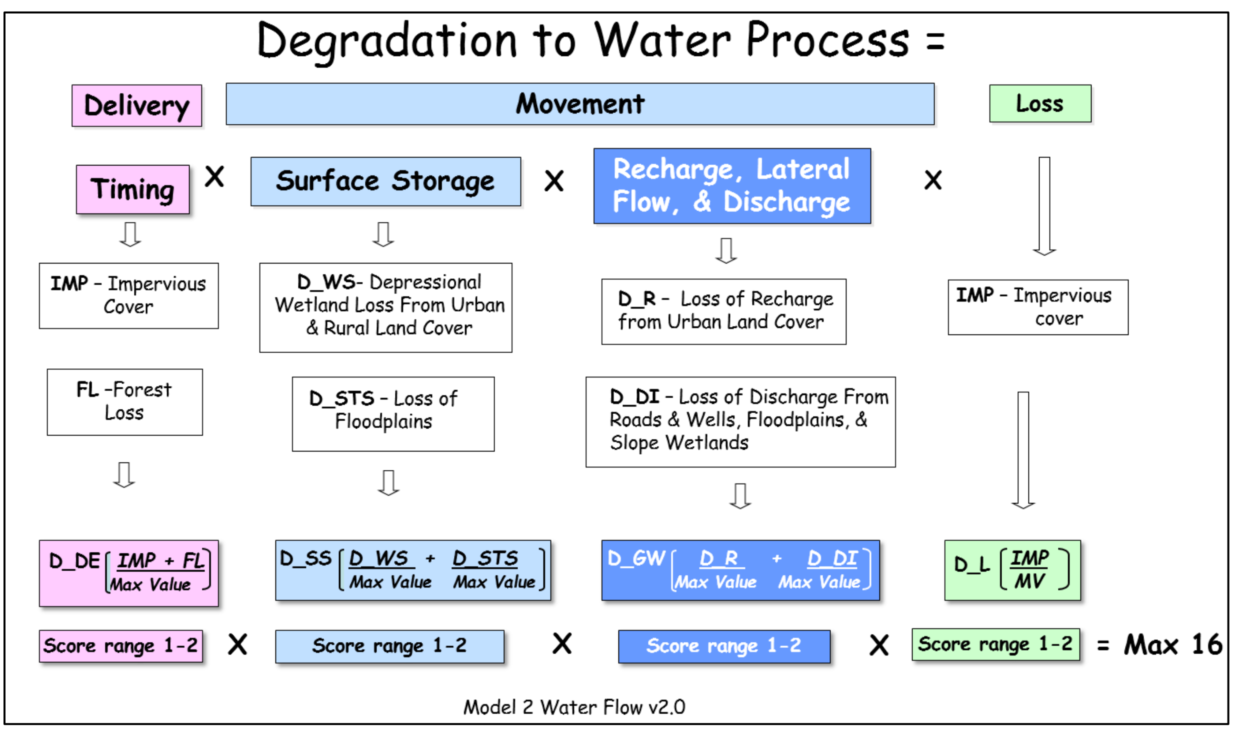


Figure 30. Overall Water Flow Degradation Model (simplified) aggregation formula adopted for v2.0 update.

Final Validation of Recommended Updates to the Water Flow Models

As noted in the previous section, the MUTT recommended that potential changes to the Overall Water Flow Model for the v2.0 update be mapped so that a best professional judgement (BPJ) exercise could inform the final decision about what should be adopted for the purposes of generating regional results viewable and downloadable on Ecology's website. This was acknowledged as being a critical final step, as our simple conceptual model attempting to represent complex ecological processes will never fully capture the nuances of conditions with an index score. The BPJ exercise involved watershed scientists with knowledge of the WRIA 7 watershed comparing maps produced by the v2.0 model with known "on the ground" conditions relative to the level of both "importance" and "degradation" for water flow indicators (e.g. area of storage, level of alteration to storage areas, area of forest, and impervious surfaces).

Three maps for overall watershed conditions (protection, restoration, development) were produced for WRIA 7 (see Figure 31):

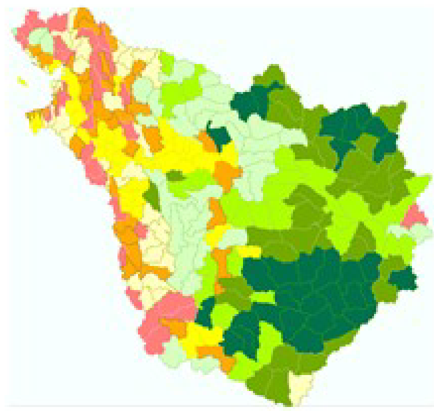
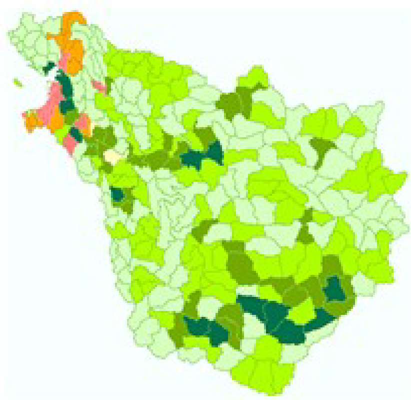
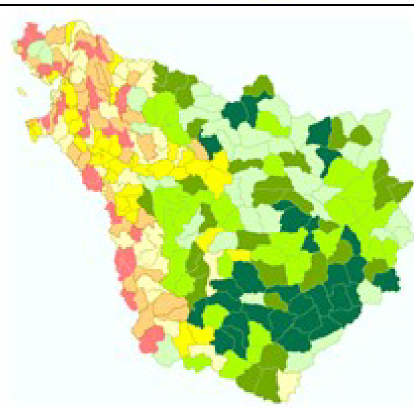
1) v1.0 characterization results for protection, restoration, and development using only the additive aggregation approach and equal quartile binning.
2) v2.0 characterization results for protection, restoration, and development using the multiplicative aggregation method and natural breaks binning;
3) v2.0 characterization results for protection, restoration, and development using the multiplicative method with quantile binning.

Ecology's Puget Sound Watershed Characterization team (Stephen Stanley, Colin Hume, and Susan Grigsby) performed this BPJ exercise.

Best Professional Judgement Comparison of Overall Water Flow v2.0 alternatives

Overall, Map 2 (Figure 31) provides the least accurate representation of the WRIA relative to known watershed conditions. Other than the I-5 development corridor around the urban growth centers in the lower watershed (Lynnwood, Everett, Marysville), the results do not completely capture the degree and gradient of degradation to water flow processes due to the smaller towns and agricultural activities along the main stem of the Snohomish, Skykomish, and Snoqualmie rivers. These areas include the towns of Monroe, Sultan, Index, Duvall, Carnation, Fall City, Snoqualmie, and North Bend. Each of these towns are within or immediately adjacent to floodplain corridors, which are highly important to water flow process due to significant areas of storage, groundwater recharge and discharge, and should score moderate to high for degradation. Typically, this combination of conditions should result in Management Matrix designations of "Restoration", as these important flow processes should be prioritized for actions which result in relatively lower levels of impervious surfaces and impairments to flow processes. Instead, Map 2 tends to emphasize a category of Protection and Conservation within these major floodplain corridors, with restoration being a secondary management category.

In addition, Map 2 illustrates a fairly uniform pattern of prioritizing mid-level categories of Protection and Conservation eastward to the headwaters of the watershed, despite the presence of areas of extensive logging within the lowlands of the mountainous landscape group, especially within the Tolt River watershed, which highly impact water flow processes. Finally Map 2 appears to identify a relatively smaller area than expected for the top Protection category, especially in the headwaters where little degradation is present and indicators for delivery should emphasize the importance of these areas.

ORIGINAL MAP 1 Additive	**Quartiles**	
MAP 2 Multiply	Natural Breaks	
MAP 3 Mulitply	Quartiles	

Highest Protection
Protection
Protection/Restoration
Conservation
Highest Restoration
Restoration
Restoration/Development
Development/Restoration

Figure 31. Three Overall Water Flow Restoration and Protection maps compared with different combinations of aggregation formula and categorization/binning approach to designating assessment units into the Management Matrix. Map 1 uses the v1.0 methods. Maps 2 and 3 use multiplicative aggregation at the component level. Map 2 uses Jenks/Natural Breaks for designating assessment units into the Management Matrix.

In summary, the aggregation methods associated with Map 2, especially with the use of Jenks/Natural Breaks, tend to capture only the most degraded or pristine areas within a watershed, leaving the majority of the watershed assessment units within a similar mid-level protection-restoration category. This homogenous result is not consistent with known conditions in WRIA 7 and as such would provide limited guidance for management of the watershed.

Contrasting with Map 2, the results depicted in Map 3 (multiplicative aggregation, use of quartiles for binning) appear to provide a more accurate depiction of known watershed conditions. The floodplain corridors for the Snohomish, Skykomish, and Snoqualmie are designated as a priority for restoration, which is consistent with known conditions of extensive areas important to water flow processes and degradation from agriculture and urban development. Areas falling into the Development category are also better represented when compared to Map 2, due to the smaller towns located along these floodplain corridors. Further, the Map 3 results capture a greater extent of priority Protection areas within the headwaters (e.g. mid-fork of the Snoqualmie River) consistent with high average annual precipitation levels and a low level of degradation present there.

Though Map 1 and Map 3 are very similar in the results they present, there are some important differences. For example, Map 3 results show a larger portion of upper watershed of the Pilchuck River as Protection and Restoration, compared to a Conservation category in Map 1; this designation is consistent with known conditions (higher levels of precipitation but with some degradation from logging). Map 3 results also categorize the lower elevation forest area of the Tolt River and adjoining watersheds at a higher level of Protection and Restoration relative to a Conservation designation depicted in Map 1; it is felt that this Map 3 designation is more representative of actual conditions. Map 3 results also indicate a higher level of Restoration in the floodplain area around the city of Duvall, whereas Map 1 results have the same assessment units designated for Restoration and Development indicating a lower level rating of Importance.

Conclusion of Best Professional Judgment Validation Exercise

The above comparisons lead Ecology to the conclusion that use of multiplicative aggregation at the component level and equal quartiles for binning AUs into the Management Matrix is the preferred approach. Additional validation by non-Ecology experts would make this exercise more robust but was not performed here. This may be done in the future for WRIA 7 and may be warranted for all WRIAs. However, it is out of the scope of this current project. As noted already, these determinations are for the purpose of providing “out of the box” results for display and download from Ecology’s website. Most users of PSWC results consult with Ecology on their specific application, and a tailored approach to the assessment is performed. This tailored approach can include alterations to the aggregation approach, weighting, and binning.

5.0 PSWC v2.0 Water Flow Process Maps

This chapter illustrates the updates adopted for the v2.0 Water Flow Process index and associated maps. Additional updates are being generated for the Water Quality indices but are not available as of the publishing of this document. When available, those results will be documented in a separate document or through an addendum to this publication.

Changes to Water Flow Models for v2.0

Chapters 2 and 3 describe updates to the spatial data inputs and AU delineations which the Water Resources (Water Flow and Water Quality indices) Models are run with. Chapter 4 describes the testing on aggregation formula alternatives (including weighting) and binning approaches for the purpose of designating AUs to a Water Flow Management Matrix category. The following series of maps use WRIA 7 to illustrate the previously generated v1.0 results for the Water Flow Models and compare them to the new v2.0 methods being adopted as of this publication, which include an adjustment to the Overall Water Flow Model (Importance and Degradation) aggregation formulas (recall Figure 29 and Figure 30) using a multiplicative approach to combining components/submodels (e.g. Importance to Delivery). Note that no adjustments were made to the submodel aggregation formulas as they retain an additive approach to the assembly of indicators into submodels and components.

The v2.0 Water Flow updates

The following series of maps illustrates the Water Flow Restoration and Protection results for WRIA 7 that will be available for viewing and download on Ecology's website (https://fortress.wa.gov/ecy/coastalatlas/wc/landingpage.html). The Restoration and Protection Management Matrix maps are based upon a combination of Importance and Degradation results. However, the single index results are available as well, though not presented below. Maps and data are available on Ecology's website for all other WRIAs in Puget Sound (WRIAs 1-19) as well. Except for the changes described above, all other scientific rationale, methods, and model inputs are based upon Volume 1 (Stanley et al. 2016, originally published 2012), which this document should be used in conjunction with for a full comprehension of what is presented.

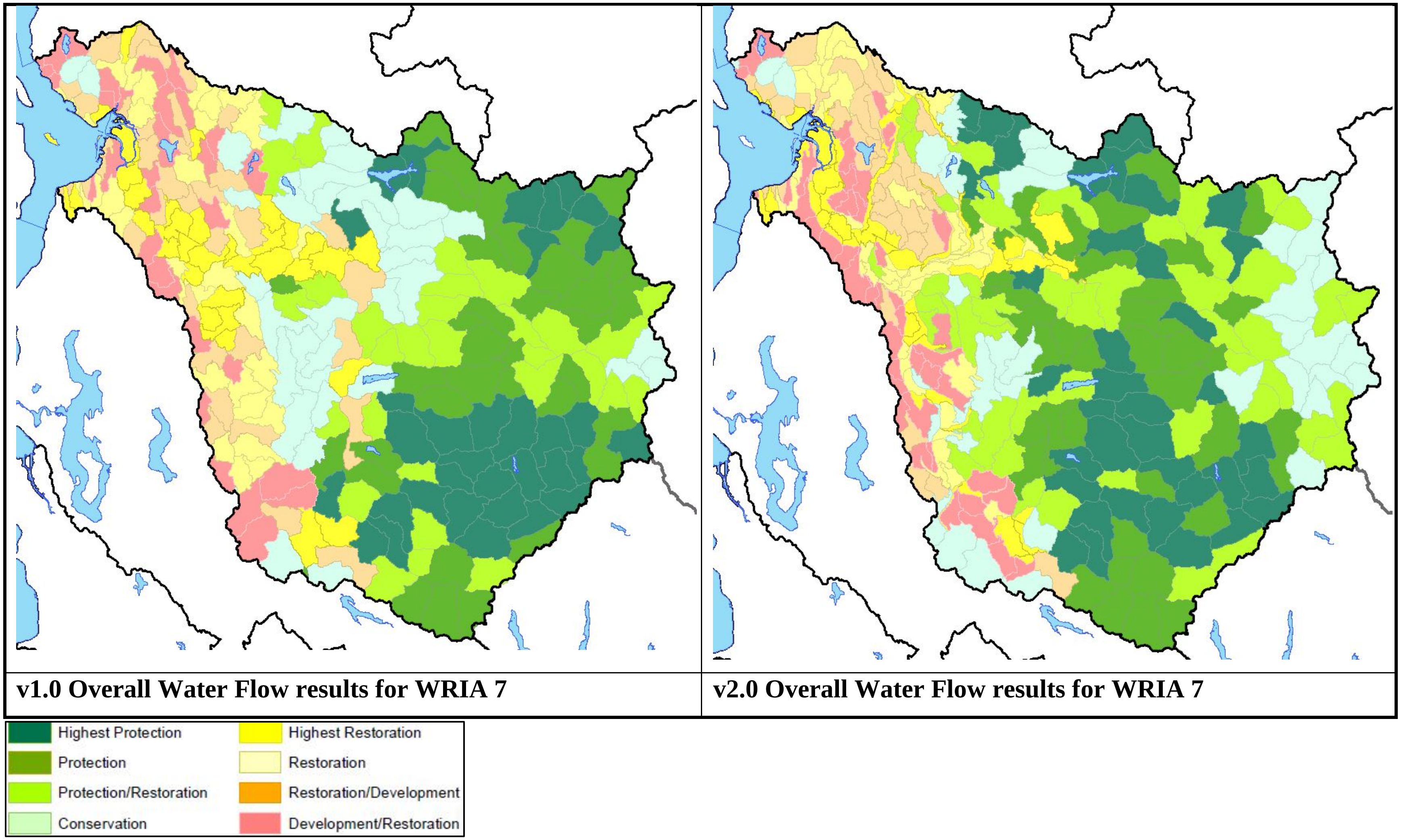


Figure 32. Overall Water Flow Results for WRIA 7. Compares Water Flow v1.0 to newly adopted Water Flow v2.0 (right panel) results. V2.0 updates include new spatial data, assessment units, and a multiplicative aggregation of components (Delivery, Surface Storage, Groundwater Processes).

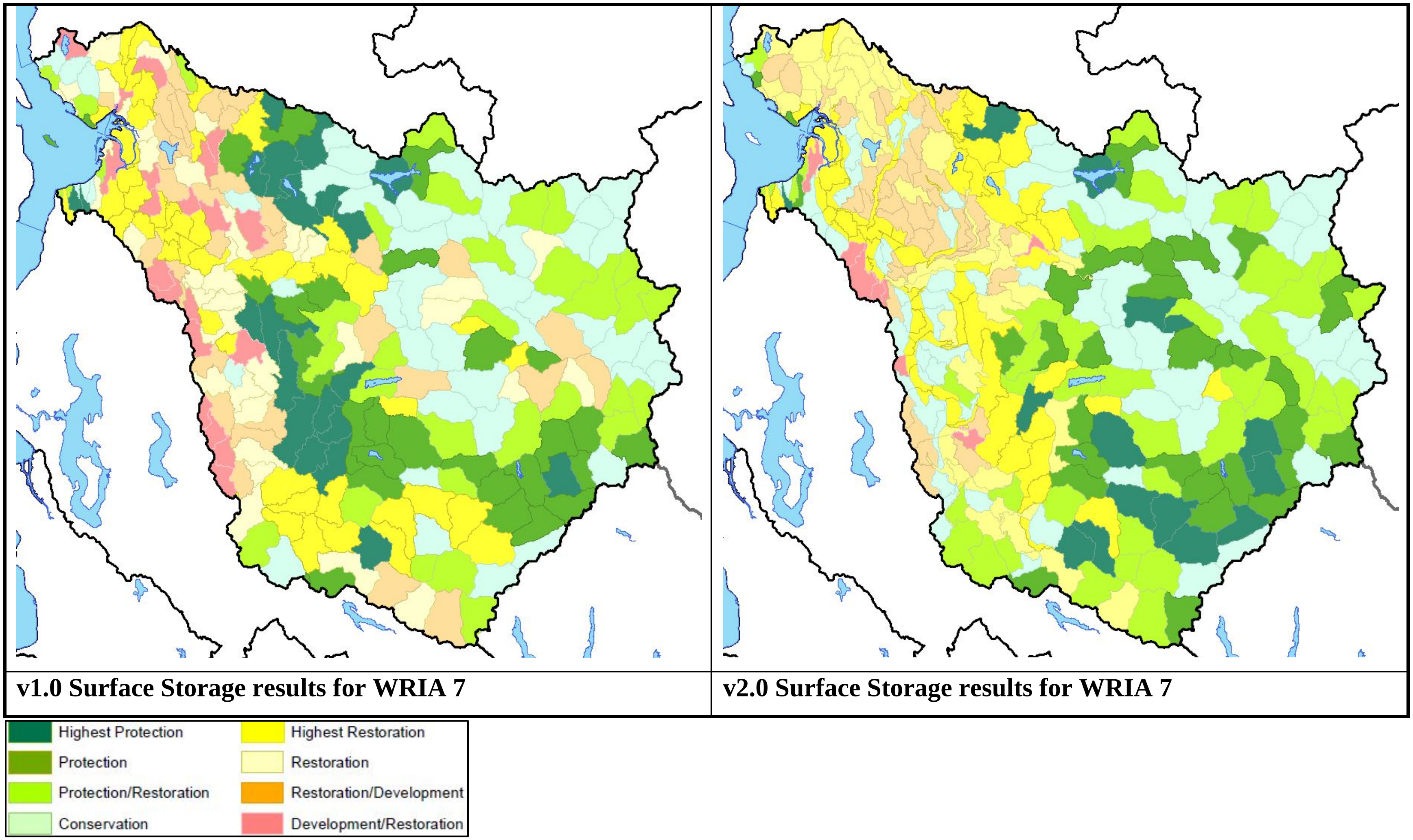


Figure 33. Surface Storage Results for WRIA 7. Compares Surface Storage v1.0 to newly adopted Surface Storage v2.0 (right panel) results. V2.0 updates include new spatial data and assessment units.

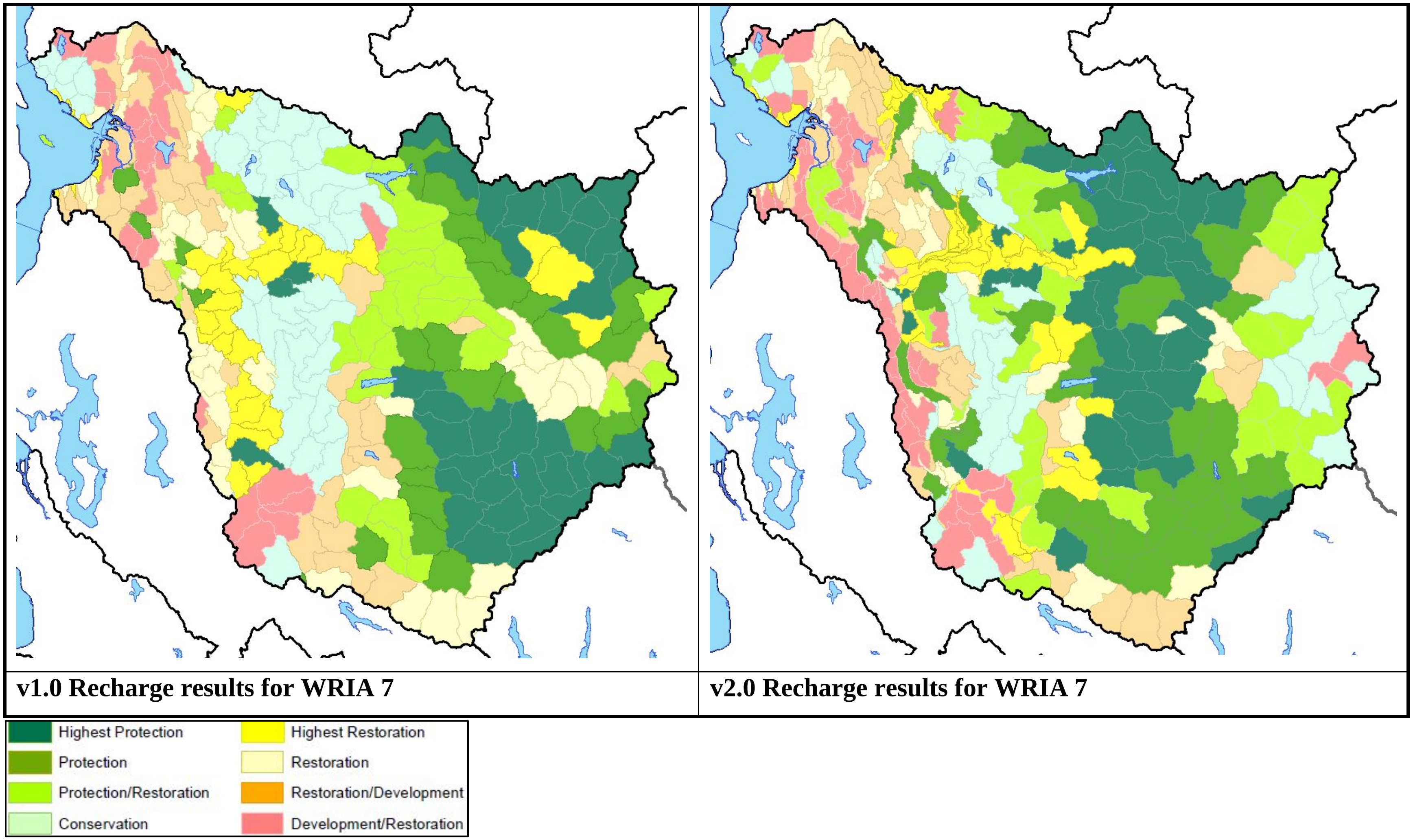


Figure 34. Recharge Results for WRIA 7. Compares Recharge 1.0 to newly adopted Recharge v2.0 (right panel) results. V2.0 updates include new spatial data and assessment units.

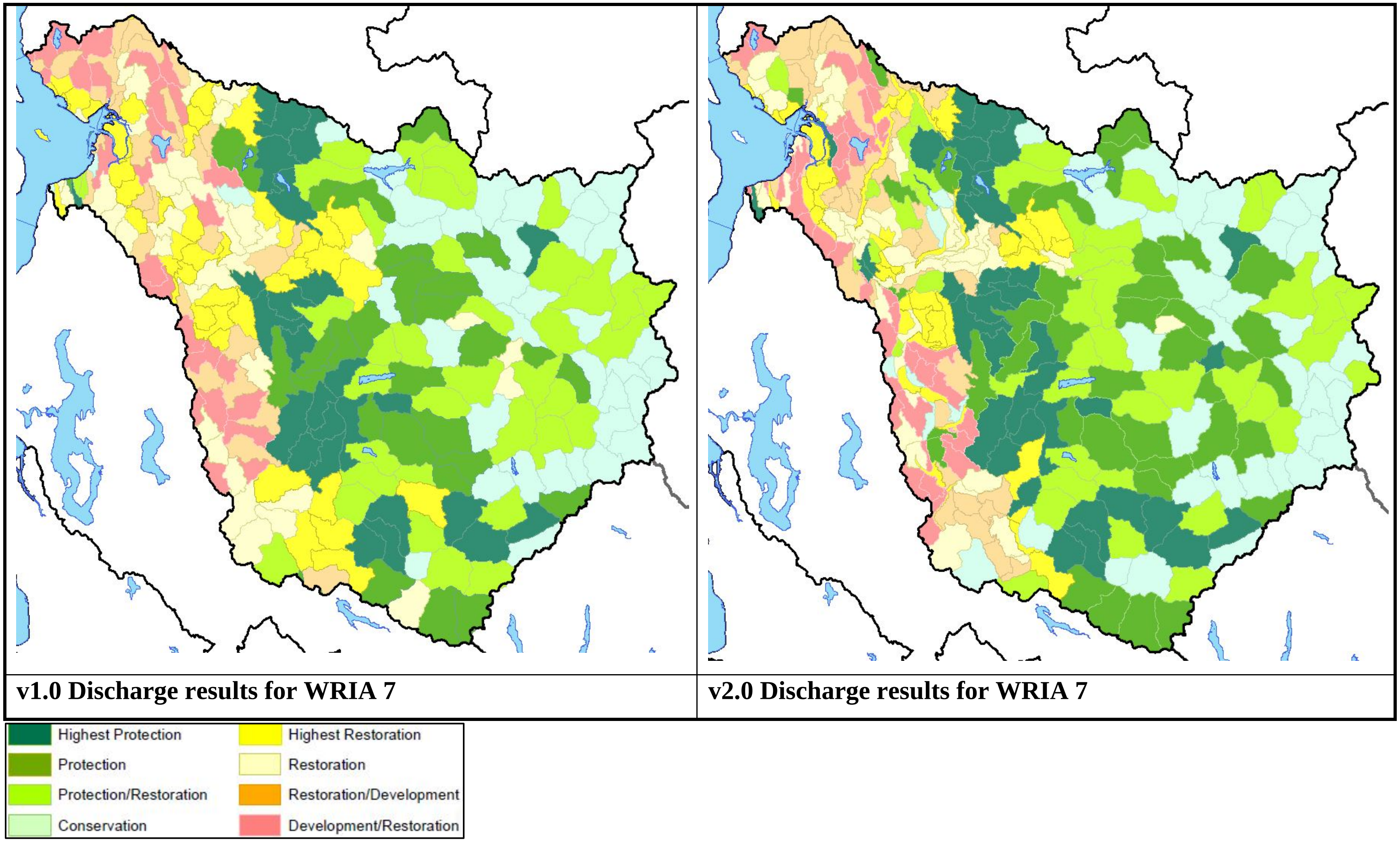


Figure 35. Discharge Results for WRIA 7. Compares Discharge 1.0 to newly adopted Discharge v2.0 (right panel) results. V2.0 updates include new spatial data and assessment units.

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