Puget Sound Characterization

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

Ecology Publication #11-06-016
October 2016 Update

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Editor's Note: The March 2015 revision of the original document, published in April 2012, corrected an equation calculating recharge described in Appendix B. Appendix C (dated August 2012) remained the same, but the associated water quality maps reflected a correction to the model script regarding the N_SPECT sediment degradation analysis to not apply landscape groups. This October 2016 update includes minor edits to Appendices B and C, and the addition of Appendix D.

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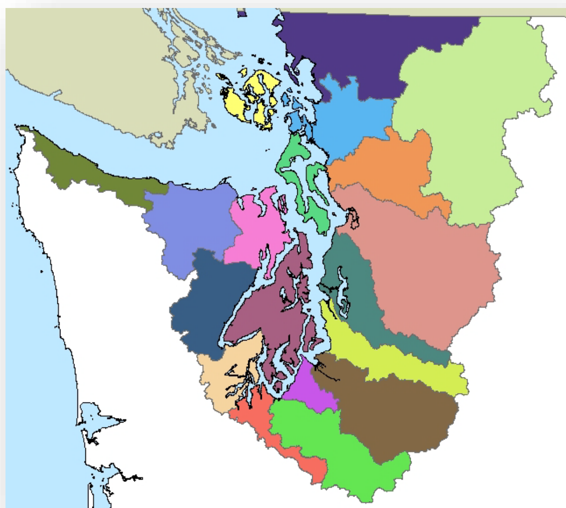
THE PUGET SOUND CHARACTERIZATION
Volume 1—The Water-Resource Assessments

Executive Summary

The Puget Sound Characterization is a set of water and habitat assessments that compare areas within a watershed for restoration and protection value. It is a coarse-scale decision-support tool that provides information for regional, county, and watershed-based planning. The information it provides will allow local and regional governments, as well as NGOs, to base their decisions regarding land use on a systematic analytic framework that prioritizes specific geographic areas 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 method should result in 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.

> *Throughout this document we will speak of the Puget Sound basin, landscape, region, or watershed and be referring to the same geographic area (the 19 uniquely colored "water resource inventory areas" [WRIA's] on the map).*
>
> *When we refer to the Puget Sound "ecosystem," we include the biological community along with the physical environment.*



The assessments cover water resources (both water flow and water quality) and fish and wildlife habitats (in terrestrial, freshwater, and marine nearshore areas) over the entire drainage area of Puget Sound. The assessments provide a watershed-scale perspective on the *relative* importance of small watersheds (~ 1–10 square miles; i.e., up to a few tens of square kilometers) 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.

The present version of the Characterization comprises two volumes. Volume 1 (this report) briefly describes the overall conceptual framework for the Puget Sound Characterization and describes details for the assessment of water resources using analyses of watershed processes. Volume 2, with an anticipated completion in 2012, covers habitats across multiple environments (freshwater, terrestrial, and marine) for which a watershed framework is not everywhere as applicable. Both are intended for application by regional and local governments for landscape-level planning. When completed, a single guidance document (Volume 3, planned for 2013) will explain how to synthesize the results of each volume into an integrated framework to support protection and restoration actions.

Characterization results should be used to address two fundamental questions:

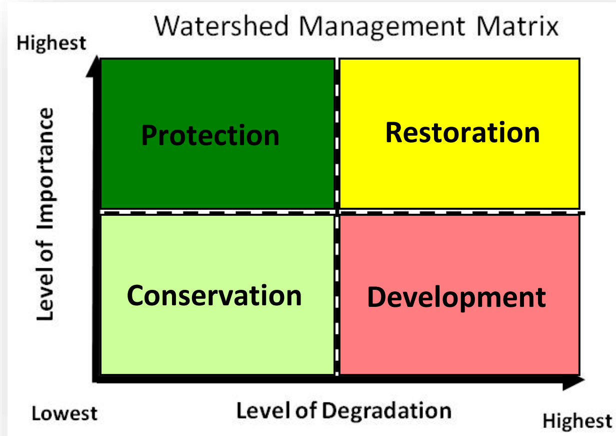
(1) ***where* on the landscape** should management efforts be focused first, be they actions for planning (e.g., protection) or mitigation (e.g., restoration); and

(2) ***what types* of activities and actions** are most appropriate to that place, be they restoration, protection, conservation, or development?

The Characterization therefore addresses both the "where" and the "what" to focus on, in terms of four discrete categories of actions (restoration, protection, conservation or development). However, because assessments are done in 1- 10 mi^2 areas, the specific "how" to act (i.e., how to restore a specific site within a small watershed tagged for restoration) will always require additional site-specific information that is not included in the Characterization datasets. The framework provided here, however, offers a systematic approach to supporting land-use decisions that have a higher likelihood of improving the health of aquatic and terrestrial resources of the Puget Sound region than prior approaches.

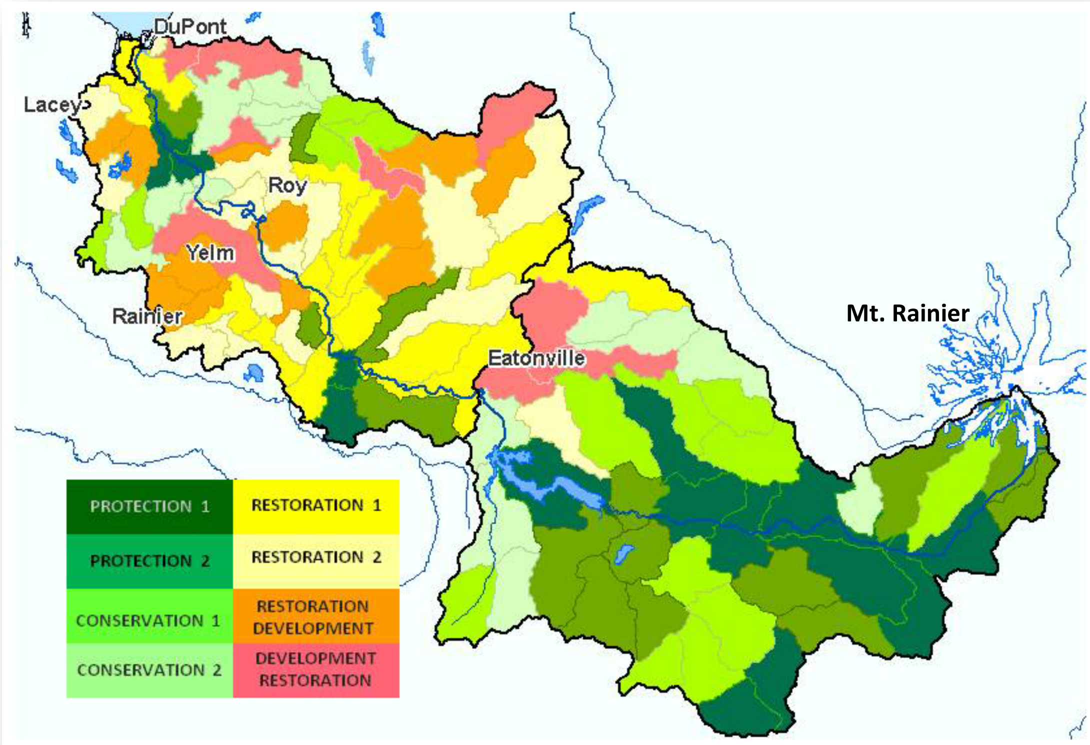
The primary products of the water-resource assessments included in this volume are maps that show the relative value of small watersheds, henceforth referred to as "Assessment Units" (**AU's**), throughout the Puget Sound basin. Their relative conditions are expressed as quantitative indices that can be used to compare AU's across the entire Puget Sound basin or within a single water resource inventory area, or WRIA.

These indices can be used to recommend broad management strategies for specific AU's. The most intensive strategies (broadly denoted "**Restoration**") apply to those AU's judged most important to restoring water-resource functions but that also have experienced the greatest degradation. Conversely, areas of low importance but also low degradation should require a much lower level of management attention (here termed "**Conservation**").



Those with high importance and low existing degradation may need little or no active intervention (other than appropriate zoning or protective easements) to maintain their high functional conditions ("**Protection**"). Those with low importance and significant existing human impact are broadly the most appropriate areas for "**Development**," given continued population pressures on the Puget Sound region.

The indices, rankings, and all data used to calculate the indices are stored in a geographic database available for use by any member of the public, providing a common foundation for participating in watershed planning and restoration. The numerical scores permit either a coarse "lumping" of results into as few as four primary categories (as in the matrix above) or a more finely divided "splitting" of those results into additional sub-categories. The map-based display for the Nisqually River watershed in the southeast Puget Sound region (below), for example, shows the results of subdividing the "Level of Importance" for each AU into 4 categories (instead of just 2).



Solution Templates can be associated with every AU, depending on their recommended management strategies (protection, restoration, conservation, or development). They offer potential strategies and actions to address the typical causes of resource degradation associated with particular land uses. The templates are specific to broad land-use categories (forest lands, rural lands, agricultural lands, and urban/suburban), with the recommended management strategies drawn from an understanding of the conditions of water-flow processes most common in each particular land use. Certain management strategies or actions described in the solution templates are so fundamental that they should be applied in *every* part of a watershed regardless of land use, importance ranking, or level of degradation; others are recommended only for AU's with a particular combination of importance and degradation.

ALL LAND USES	P	R	C	D
Maintain the physical integrity of stream and wetland riparian zones	☑	☑	☑	☑
Restore floodplains (reconnect streams, reduce channelization)	☑	☑	☑	☑
Restore depressional wetlands and their adjacent riparian zones	☑	☑	☑	☑
Restore/replant riparian zones	☑	☑	☑	☑
Identify and protect aquifer recharge areas	☑	☑	☑	☑

Example of a solution template for all land uses. (Management Types : P= protection, R=restoration, C=conservation, D=development)

Unique to the Characterization is the ability to scale the results to the Puget Sound, a WRIA, or even a single sub-basin within a WRIA. This flexibility of analysis scale, limited only by the resolution of the underlying data, creates a powerful tool for supporting regional and local land-use planning decisions and designations. However, the Characterization is a *decision-support* tool, not a *decision-making* tool. It is designed to provide an overview of likely conditions, problems, and opportunities based on available digital data, organized and analyzed in accord with well-established scientific principles. This is a critical first step, too often overlooked—but carrying these analyses forward, as either final decisions on priority efforts, designations of expanded Urban Growth Areas, or specific on-the-ground actions, requires further levels of information and expertise that generally are not provided by this report or its associated map products.

List of terms and acronyms used in this document

Analysis Area: The geographic extent of an assessment. It can range in scale depending on the size of a jurisdiction (city vs. county) and the type of landforms being considered (e.g., coastal terrace vs. large river basin). The methods and assessment models of the Characterization are not limited to a single scale but they do require source data that are both suitably detailed and sufficiently comprehensive across the analysis area.

Assessment Models: Methods that provide a quantitative analysis of abiotic and biotic components outlined in the conceptual model. This includes processes for water flow and water quality (sediment, metals, pathogens, nutrients), and terrestrial, freshwater, and marine/nearshore habitats. The models generate quantitative *indices of relative condition* for each **Assessment Unit** relative to all others, but they do not provide a measurement of the actual rate or quantity of the presence or movement of water, sediment, pathogens or organisms.

Assessment Unit (AU): Each analysis area is divided into many smaller “Assessment Units” for comparison of model results. All source data and model results are homogenized within each AU; their size determines the minimum spatial scale over which the Characterization results are meaningful. Using available source data, AU's are ranked from most important to least important, and most impaired to least impaired, for each process. The size and number of these units depends on the size of the analysis area, the landform types, available source data, and the planning issues a jurisdiction may be addressing.

Assessing Watershed Processes: The application of abiotic and biotic methods for analyzing watershed processes and environments presented in the conceptual model. In this document, 'assessment', 'watershed assessment', or 'assessment of processes' have the same meaning.

Characterization: The integration of multiple assessments, following an explicit conceptual model, that describes landscape conditions from the basin to sub-basin scale.

Conceptual Model: A simplified representation of a complex system that emphasizes the interrelationship of the major elements rather than the details of each element. For the Characterization, its conceptual model qualitatively describes the biotic/abiotic elements that are judged to drive and control physical and chemical **processes**, and the **structure** and **functions** of three biological environments (freshwater, terrestrial and marine) across multiple scales. Conceptual models are useful complements to (but not substitutes for) more detailed quantitative models.

Function: Role(s) provided by the local **structures** of the landscape at the site or reach scale, such as wildlife habitat, salmon spawning habitat, flow attenuation, flood storage, groundwater recharge, etc.

Impervious Surfaces: Constructed surfaces, such as pavement for transportation, buildings, roofs, and sidewalks, that effectively prevent or retard the movement of water vertically through the underlying soil and geologic deposits. The percentage of impervious surfaces in an assessment unit is the largest single determinant of that AU's degree of degradation.

Landscape Group: A group of AU's within the analysis area that each have similar environmental characteristics, such as precipitation, landform, and/or geology. In the current version of the Characterization models, landscape groups are identified strictly on geographical position (coastal, lowland, and mountain, plus a subset of lowland analysis units that drain to one of four large lakes). In the models that assess AU "importance," the assessment units are compared only to others within the same landscape group and not to assessment units in a different landscape group.

Method(s): The quantitative analysis of an individual watershed process. The method applied for analyzing each process are presented in the appendices.

Multi-Scale Framework: An analytical hierarchy of abiotic and biotic assessments, information, and data across multiple scales within a watershed. The framework acts as decision-support tool to help interpret and apply Characterization results to planning and permitting decisions. The Characterization's "analysis framework" is an example of a multi-scale framework; it is based on a conceptual model that generally describes the freshwater, terrestrial and marine environments in Puget Sound.

N-SPECT: The "Nonpoint-Source Pollution and Erosion Comparison Tool," developed and supported by the National Oceanographic and Atmospheric Administration (NOAA). N-SPECT is GIS-based model that uses pollutant export coefficients to quantify the relationship between land use/land cover and pollutant amounts. It is most useful in planning-level assessments such as the Characterization, providing estimates of the change in pollutant amount in response to a change in land use/land cover (see also http://www.csc.noaa.gov/digitalcoast/tools/nspect).

Process: Physical and chemical fluxes of water, sediment, nutrients, and organic material across large land areas (e.g., watersheds or drift cells) that form and maintain the landscape and the **structure** and **function** of their ecosystems over multiple scales. The movement of water, sediment, metals, pathogens, and nutrients constitute the processes addressed in this document (Volume 1 of the Characterization).

Scale: The typical geographical extent of interest. The range of scales (and the terminology we adopt) in this document includes "basins" (>100 mi^2); "sub-basins," "valley segments," and "drift cells" (commonly, 1 to 100 mi^2); "reaches" and "waterbodies" (100 acres to 1 mi^2); and individual "stream segments" and "sites" (normally, <100 acres).

Structure: Features of the landscape at the site scale created and maintained by the controlling **processes**, for example stream channel shape, floodplain, slope wetlands, estuaries, etc.

Watershed Management Matrix: A matrix that combines the categorical results of the models for importance and degradation for any single process in a particular AU to identify the most suitable management strategy (described by the terms protection, restoration, conservation, or development) for that process within that area.

Water Resource Inventory Area (WRIA): Administrative watershed boundaries designated by the State of Washington's natural resource agencies.

Acronyms:

AU – Assessment Unit (see above)

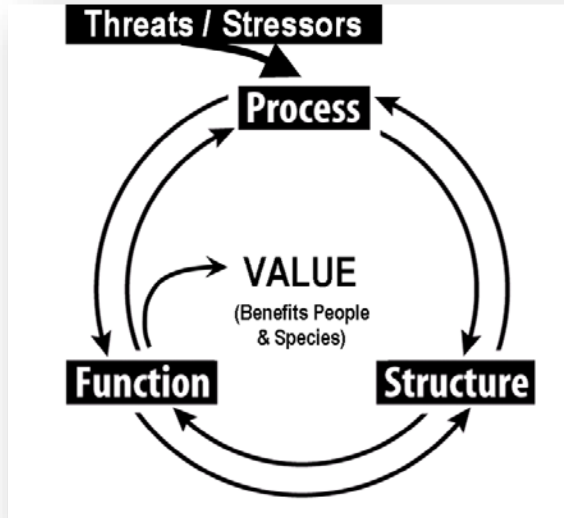
GIS – Geographic Information Systems

SSHIAP – Salmon and Steelhead Habitat Inventory and Assessment Program

WRIA – Water Resource Inventory Area: the major watershed areas of Washington State, of which 19 drain into Puget Sound and the Strait of Juan de Fuca

Introduction

The Puget Sound Characterization is built on the basic relationships between ecosystem processes, structure and function. Environments are influenced by the broad physical and chemical fluxes (the driving **processes**) of water, nutrients, sediment, and organic material. In turn, these processes lead to **structures** which provides **function**. In a river, for example, the processes of water and sediment movement produce sediment bars and channel features, which in turn provide off-channel rearing habitat. To maintain or restore the structure and function of the Puget Sound ecosystem, important watershed processes that are still intact must be identified and protected, and those that have been severely degraded must be restored.



<u>Watershed Processes</u>

These processes are defined as the dynamic physical and chemical interactions that form and maintain the landscape and ecosystems on a geographic scale of watershed to basins (i.e., hundreds to thousands of square miles).

This includes the movement of water, sediment, nutrients, pathogens, chemicals, and wood.

This guidance document has been developed in response to the need for coordinated action that considers ecosystem processes, and the resulting structures and functions, at multiple spatial scales (basin, watershed, sub-watershed, reach, and segments). It builds on watershed characterization work pioneered at the Washington State Department of Ecology (see Stanley et al. 2005, Stanley and Grigsby 2008) and work by other scientists demonstrating the need to consider watershed scale processes in planning and restoration actions (NRC 1996 and 2001, Spence et al. 1996, Dale et al. 2000, Roni et al. 2002, Simenstad et al. 2006, Beechie et al. 2010).

In its current form, this guidance document (1) describes a multi-scale framework for land-use planning, (2) provides results from assessments that can guide protection and restoration efforts for aquatic ecosystems, and (3) outlines how to integrate these assessments into a cohesive framework.

Specifically, it describes a process that can:

- Develop, prioritize, and implement solutions to environmental problems based on an understanding of processes at watershed (water assessment) or landscape (habitat assessment) scales;
- Replace planning based on jurisdictional or statutory boundaries (e.g., shorelines of the State) with coordinated regional planning;
- Provide a watershed-scale context to help guide site-scale reviews that not only meet regulatory requirements but also more fully achieve their intended outcomes;
- Move toward integrated resource planning and management grounded in a landscape-scale understanding of how ecosystems work.

What This Document (Volume 1) Includes

The Characterization allows planning and land-use decisions to be made with the understanding of how they affect, and are affected by, broad-scale landscape conditions. The intent is to inform policy and planning decisions, and in turn protect people and other species and the landscapes upon which all rely for their well-being. To accomplish this, the Characterization includes the following assessments:

- Water-flow processes – these are defined as the delivery, movement, and loss of water within the watersheds of the Puget Sound basin. These form the most important set of process for aquatic resources (NRC 1992); they also play critical roles in assessing many other landscape processes
- Water-quality processes – include sediment, metals, pathogens, and nutrients

Pending additions to the Characterization will comprise two additional volumes:

- Volume 2 (anticipated late 2012), which will cover freshwater, terrestrial, and marine nearshore habitats; and
- Volume 3 (anticipated 2013), a decision-support tool that shows planners and citizens how to integrate, interpret and apply the results of volumes 1 and 2 to planning actions.

In summary, the assessments and the guidance herein can provide watershed-based information within a science-based framework for application by local governments. The anticipated audience is city, county, and tribal planners; watershed managers and decision-makers; and the Puget Sound Partnership and other state agencies, tribes, and other resource managers including non-governmental organizations. Citizens throughout the Sound should also be able to make use of the Characterization, providing them with a common foundation for participating in watershed planning and restoration.

These assessments provide information to help guide the protection, conservation or restoration of water resources, and fish and wildlife habitats throughout Puget Sound. They also identify areas that should be most appropriate for additional development. The primary products of the water-flow and water-quality assessments are maps that show the relative value of AU's throughout the Puget Sound basin. Their relative conditions are expressed with quantitative indices that can be used to compare AU's across the entire Puget Sound basin or within a single WRIA. The indices, rankings, and all data used to calculate the indices are stored in a geographic database available for use by any member of the public. The analytical framework can also be applied in other regions and at other scales, limited only by the suitability of available data.

A Conceptual Model of the Puget Sound Ecosystem

Integrating information from several assessments results in a more robust characterization of a watershed, and ultimately more effective management recommendations, than any single perspective. Developing this kind of integrated approach requires at its foundation a conceptual model that reflects the basic workings of the ecosystem. Figure 1 offers such a model for the three primary environments of the Puget Sound basin (freshwater, terrestrial, and marine), reflecting the importance of integrating information from assessments for these environments across multiple spatial scales. Implementing the core attributes of this model within a framework to regional planning and decision-making should result in more effective, more successful restoration and protection actions and ultimately increase the overall health of Puget Sound. Thus, this model provides the guidance for the Characterization approach, described in the next section.

The patterns we observe in ecosystems are the result of events occurring at multiple spatial scales of organization (Figure 1). Large-scale drivers (outermost ring in Figure 1), such as climate and ocean dynamics together with such human activities as urbanization and deforestation, operate at a regional scale and directly interact with the controls of watershed processes. Those watershed controls include such physical attributes as geomorphology, geology and soils (turquoise ring in Figure 1); they also include the wide variety of human actions that individually and collectively affect watershed processes. Those processes (inner gray ring) include the movement, delivery, and loss of water, sediment, nutrients and wood. Together, the interaction of these natural and human-induced drivers and controls govern the processes, structure, function and, finally, ecological "health" (Beechie and Bolton 1999, Dale et al. 2000, Gove et al. 2001, Hidding and Teunissen 2002, Beechie et al. 2010). This expresses the scientific consensus that proper functioning of our most highly valued ecosystems depends on what happens in the larger landscape, not just at the site or reach scale. This is particularly true of aquatic ecosystems, which express most directly the connectivity between different parts of a landscape.

Human drivers alter the watershed controls, such as land cover, topography and soils, that control processes and, in turn, alter the structure and function of a given habitat. For example, ecosystem processes can be disrupted or degraded[1] by activities such as forest clearing, draining/diking and filling of wetlands and floodplains, removal of riparian vegetation, and excessive loading of nutrients, sediment, pathogens and toxic materials; and built structures such as impervious surfaces, roads and associated storm drainage systems, shoreline armoring, and overwater buildings and docks.

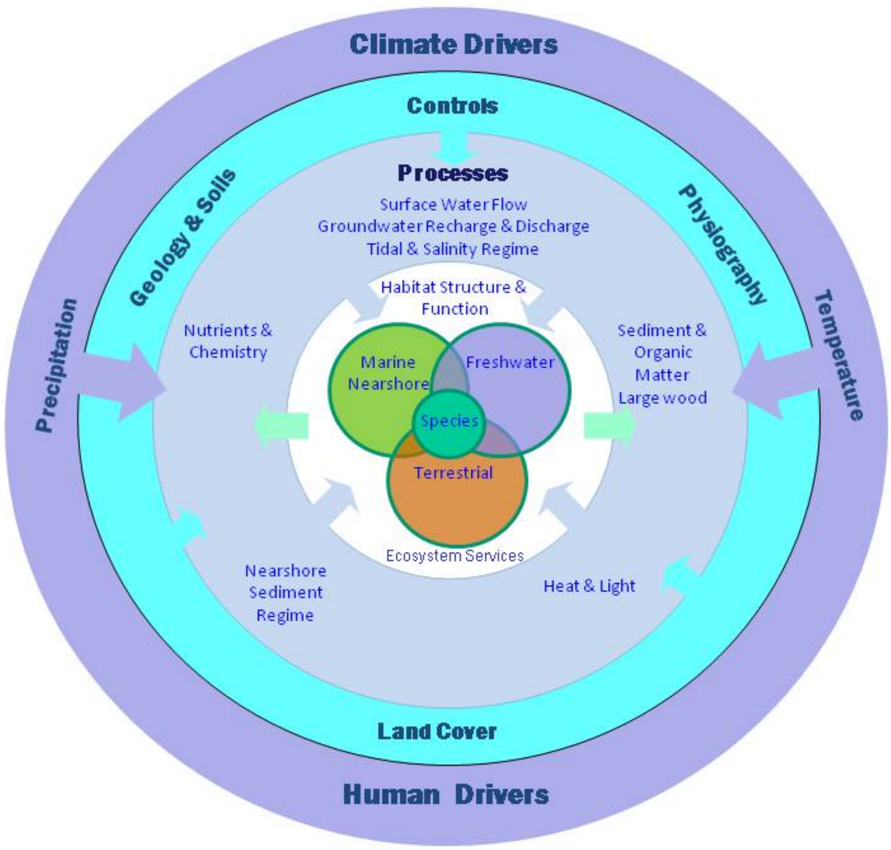


Figure 1. Conceptual model for the Puget Sound ecosystem, illustrating relationships between drivers, controls, processes, and habitat structure and function for freshwater, terrestrial and marine nearshore environments. Large-scale drivers (such as climate) regulate the type and amount of precipitation. Controls, such as geology and land cover, in turn govern processes such as the movement of water, sediment, wood, nutrients and other chemicals. The processes shown do not equally affect each of the environment types. Human impacts, such as forest clearing, construction of impervious surfaces, fill in floodplains and wetlands, occur at all scales and are represented most fundamentally in the outer ring (adapted from Healthy Watersheds Integrated Assessments Workshop, USEPA, in review).

[1] In this document, "degradation" encompasses human activities or structures that alter habitat processes, disturbance regimes, and ultimately the structure and function of habitat. It is synonymous with "stressors" or "pressures," other terms commonly used in scientific literature.

Description of Three Environments in Puget Sound

The Puget Sound basin has three major ecological environments: freshwater, terrestrial, and marine (Figure 1). This simplification is coarse but useful, because many of the ecological processes, anthropogenic drivers, and ecosystem functions of each environment are unique to each environment, and hence can be studied or assessed separately. However, interactions between these environments are also critical to their health, and many anthropogenic drivers act directly upon these interactions. The principal interactions among these three environments occur through the movement of materials, both abiotic and biotic (the "Processes" of Figure 1). Those processes (i.e., the movement of water, sediment, nutrients and wood) transport materials from terrestrial environments to both freshwater and marine environments. In the Puget Sound region, for example, the primary biotic movers between the marine and freshwater ecosystem are anadromous fish—salmon and other species. Salmon carcasses can have profound influence on the health of both freshwater and terrestrial ecosystems through the provision of energy-rich food and marine-derived nutrients (Cederholm et al. 1999).

Land-use activities directly affect these interactions in a number of ways. For instance, timber harvest may reduce the amount of wood entering steams, and large woody debris is an essential component of salmon habitat structure. Shoreline armoring can reduce sediment input from bluffs and alter the erosion, movement, and deposition of sediments along beaches; beach sediments are essential for the spawning of forage fish, such as herring and smelt, which are key components of the marine food web. Residential development can greatly increase the magnitude of stormwater runoff, which damages in-stream salmon habitat and pollutes urban bays and shellfish beds in Puget Sound.

The Freshwater Environment

The freshwater environment includes streams, wetlands and lakes, and the watersheds that contribute to these systems. As such it plays an important role in interacting with and influencing the terrestrial and marine environments. Due to its areal extent and interconnectivity, processes can be located many miles distant from the freshwater environments that they influence. For example, areas high in the watershed of the Cascades, such as rain-on-snow zones, can govern the type and intensity of flooding in lowland streams. Activities within these important "control" areas, such as the clearing of forest, can have significant effects on downstream aquatic areas. It is important that these relationships are recognized when making decisions regarding land use or restoration actions.

The Terrestrial Environment

Prior to European settlement, fire was one of the most important landscape-scale terrestrial processes in the Puget Sound basin. The moist western hemlock forests of the western Cascades had a fire return interval of 200 to 500 years (Agee 1993). Stand-replacing fires occurred after periods of prolonged drought and burned over many thousands of acres. Over the past century, however, wildfire has been controlled to protect property and valuable forest resources, and so fire has been effectively eliminated from the Puget Sound lowlands and Cascades foothills. Smaller (on the order of ¼ to 100 acres) natural disturbances caused by wind or landslides still occur, but the dominant large-scale disturbances now result from human land uses (Figure 2).

Figure 2. The dominant process in terrestrial landscapes of Puget Sound basin, namely the conversion of once-vegetative lands to more developed land uses. These aerial photographs were taken in Lacey, Washington and span a period of about 20 years.

Commercial forest lands are an exception to the pervasive fragmentation that occurs through most typical land-use conversions. Although they lack much of the key structural components of late-successional forests that historically dominated the Puget Sound lowlands and Cascades foothills (such as large trees, large snags, and large logs), they do support a wide variety of native wildlife.

The terrestrial ecosystem has profound influence on both freshwater and marine nearshore ecosystems. It is the medium over which water reaches aquatic ecosystems and the source of wood and sediment, which in turn provide habitat structure and function. The interface between terrestrial and aquatic ecosystems, the riparian zone, is particularly important because it encompasses "…physical processes that shape valley-floor landscapes, the succession of terrestrial plant communities on these geomorphic surfaces, the formation of habitat, and the production of nutritional resources for aquatic ecosystems" (Gregory et al. 1991). Thus, the protection or restoration of aquatic ecosystems also depends on the protection or conservation of the terrestrial ecosystem, and, in particular, riparian areas.

The Marine Environment

Within the marine environment of Puget Sound, the shorelines are the zone of greatest human activity and influence. Along much of the marine shorelines, the most important physical process is the movement of sediment. Sediment movement occurs within spatially distinct littoral drift cells. Littoral drift cells are established by geomorphological features (e.g., sandy bluffs) and energy sources (e.g., wind, waves) along the shoreline, and they generally include the source, transport zone, and accretion areas of sediment along the coast (Figure 3). Puget Sound's shorelines comprise 812 drifts cells with lengths that average 3.3 miles but range from as little as 225 feet to over 40 miles (70 meters to >60 km).

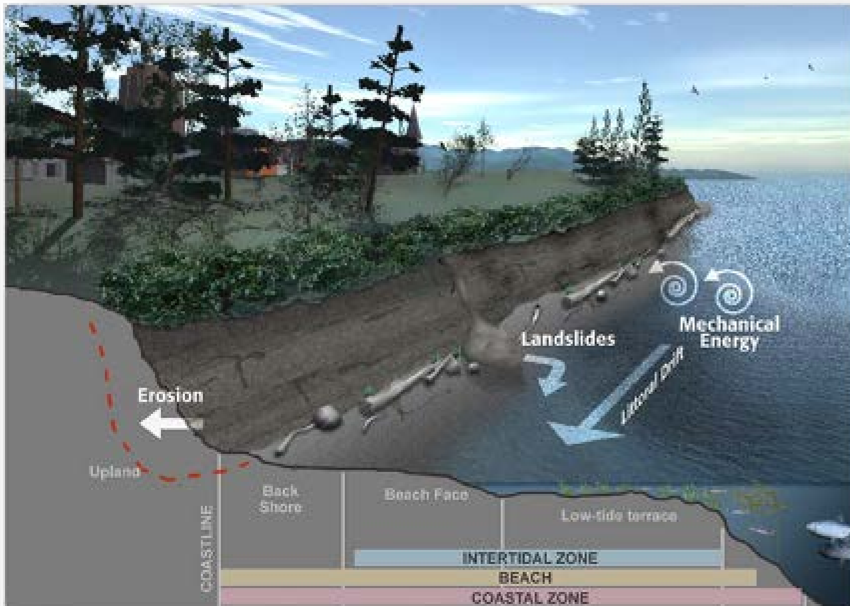


Figure 3. The movement of sediment within a littoral drift cell (from Simenstad et al. 2006).

Within drift cells, variation in wave exposure, sediment sources, and local geomorphology have created a variety of structures, such as bluff-backed beach, barrier beach, pocket beach, barrier estuary, open coastal inlet, closed lagoon, closed lagoon marsh, rocky shore, and river delta (collectively known as "shoreforms"; Shipman 2008). Bluff-backed beaches are sediment sources; barrier beaches, barrier estuaries are sediment sinks; and all beaches play some sort of role in sediment transport. Littoral drift is the process that shapes and maintains most shoreforms and the habitats associated with them. Therefore, in order to protect or restore nearshore habitats for shellfish and fish, such as herring and salmon, the essential processes within drift cells must be protected or restored.

Activities within the upland "freshwater" environment can also significantly affect nearshore processes. For example, clearing of bluff tops and subsequent construction can destabilize bluffs and increase landslides and erosion. A common response is the installation of shoreline stabilization structures, which interrupt and degrade nearshore sediment processes. Shoreline development can also remove marine riparian vegetation, which affects nearshore biotic processes. These interactions require the integration of nearshore and adjacent freshwater and terrestrial areas for management to be effective.

Why Use a Multi-Scale Framework for Analysis of Aquatic Systems?

Management and regulation of aquatic systems have historically concentrated on the individual lake, wetland, stream reach, beach, or estuary. This is a single-scale approach. In contrast, a multi-scale approach also considers larger watershed or shoreline processes, which are ultimately responsible for the creation and maintenance of these habitat types.

Why a Multi-Scale Approach is Important

Research has demonstrated that the protection, management, and regulation of natural resources could be more successful if they incorporate an understanding of the relationship between ecosystem processes, structure, and function. Conclusions from the research are:

- Many restoration efforts fail when they do not consider watershed processes; success would improve with consideration of the watershed context in site-level restoration (Kauffman et al. 1997, Frissell and Ralph 1998, Reid 1998, Beechie and Bolton 1999, NRC 2001, Roni et al. 2002, Buffington et al. 2003).
- The design of successful mitigation projects needs to integrate a whole-watershed or drift-cell perspective (Preston and Bedford 1988, Mitsch and Wilson 1996, NRC 2001, Cereghino 2010)
- Land-use plans should develop within a framework that first focuses on maintaining or restoring watershed and drift-cell processes (Dale et al. 2000, Gove et al. 2001, Hidding and Teunissen 2002, Cereghino 2010).
- Lakes, streams, rivers, wetlands and other aquatic features are interconnected parts of larger landscapes that exert controls on these elements (NRC 1992).

Since the passage of the Clean Water Act and Coastal Zone Management Act in the 1970's, states have followed with similar laws and regulations to protect sensitive resources. These laws and regulations sought to avoid impacts at the site level. If project impacts could not be avoided after considering project alternatives and redesign, impacts were "mitigated" onsite by attempting to replace area and function of the damaged resource. The concept of "no net loss" of area and function, particularly for wetlands, was added over the following decades.

However, subsequent research has demonstrated that, at both the state and national level, net losses in resources do occur under this approach. The most complete evaluations have been made for wetland loss. For example, after reviewing numerous mitigation projects for several states, Turner et al. (2001) concluded that mitigation was resulting in only 0.2 acres of wetlands for every acre of wetland impacted. Johnson et al. (2000, 2002) examined a randomly selected number of mitigation projects in Washington State and found that only 29% were implemented in accordance with project design and permit requirements. Overall, they found significant net loss of wetland acreage, with only 13% of the projects successfully replacing impacted wetland acreage. More generally, it is increasingly evident that the mitigation of project impacts at the site scale is failing to replace aquatic ecosystems, either in area or in function. In addition, most on-site in-kind mitigation generally fails to account for landscape position or overall watershed conditions, both of which are important considerations in the design and success of mitigation projects.

There are multiple reasons for past ineffective application of landscape-scale information, including:

- Conflicting, inconsistent, or simply inadequate local, state and federal laws regulating land use;
- No analytical framework that incorporates an understanding of ecological conditions and processes as the basis for local land-use planning, or that articulate watershed-based ecological and objectives;
- Inadequate interpretation and application of regional data and information, even where that information exists; and
- Lack of follow-up monitoring to determine if the mitigation has been successful, and if not to compel further efforts.

The Puget Sound Characterization cannot correct all of these deficiencies, but it is an explicit effort to correct the second and third elements of this list. The details of its structure and implementation are described in the following sections.

Framework for the Watershed-Based Assessments

The Puget Sound Characterization incorporates the multi-scale framework described in the previous section, emphasizing integration of abiotic and biotic assessments and data interpreted at the larger scales in support of management needs. In describing the details of the framework, we distinguish between those with an explicitly *water resources* focus (those of water flow and water quality) and those that, in part, depend on the movement of materials and energy across watershed boundaries (particularly those of the terrestrial and marine nearshore environments). The multi-scale framework for the watershed-based assessment of freshwater environments is described and presented through a series of interrelated figures and tables:

- A conceptual model illustrating "levels" of information and analysis across a range of spatial scales (Figure 4).
- Description of those levels of information and analysis, relative to the components of the conceptual model and the type of application of results to planning and permitting actions (Table 1).
- Illustration of the specific steps needed to integrate abiotic and biotic assessments and apply their results to planning and permitting actions across a range of scales (Figure 9).
- Description of steps illustrated in Figure 9, plus examples of application in the Gorst Creek watershed (beginning on page 27).

The framework will continue to be refined as subsequent assessments for the three environments are completed and applied in conjunction with the assessments described in this volume. Although the results of the current assessment can be directly applied only at appropriately coarse spatial scales, they also can provide a context for more detailed evaluation by a watershed technical team (which ideally would be composed of experts from a variety of pertinent disciplines, including geomorphology, hydrology, ecology, wildlife biology, fisheries biology, and water quality) to assist in the interpretation and application of assessment results at finer scales.

Watersheds are useful units for considering the relationship between human actions and freshwater environments. Watersheds can also be useful for integrating proposed aquatic conservation with terrestrial and marine nearshore environments. There is no single watershed size suitable for all planning or management activities—multiple scales of watersheds will be required in almost any planning and management effort.

Our conceptual model for a watershed-based framework for freshwater ecosystems is illustrated in Figure 4, using the basic framework illustrated earlier (Figure 1), and is further described in Table 1. In Figure 4, "levels" of assessments and associated information are superimposed across the components of the conceptual model. Table 1 illustrates the types of data and assessment efforts that may be available at a range of levels, and how the information may be applied to planning efforts. More detailed conceptual models of the three environments are being developed for Volume 2 of the Characterization.

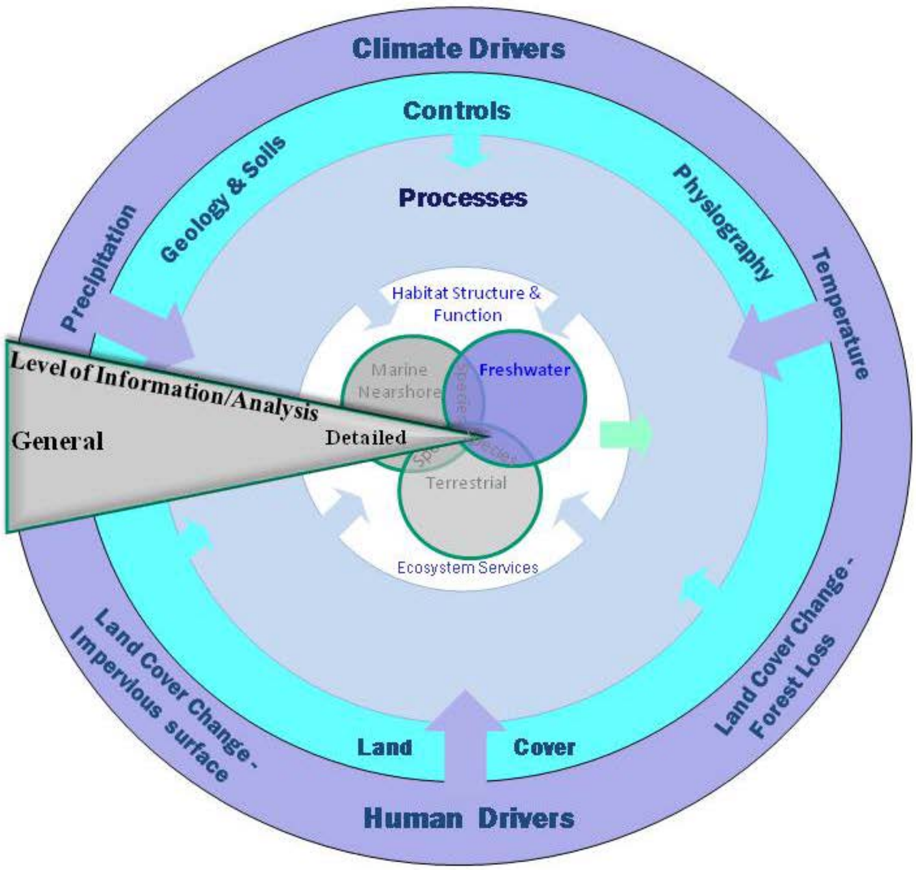


Figure 4. The conceptual model for the approach used in the Characterization, with the "levels" of information and analysis superimposed onto the components of the model. Applying these results at different scales to address specific planning and permitting issues are further outlined in Table 1 and detailed in the steps beginning on page 27.

Table 1. Relationships between the level of information and analysis at different spatial scales to both the type of data, required and type of application of results to planning and permitting. Further detail on the steps required to apply assessments and data from this multiple scales is presented beginning on page 27 (adapted from Healthy Watersheds Integrated Assessments Workshop, USEPA, in review).

Level of Information and Analysis	**Coarse/General → Fine/Detailed**			
Unit of Organization	Basin (WRIA)/ Sub-basin	Sub-basin / Valley segment/drift cell	Reaches / Waterbodies	Segments / Sites
Typical spatial scale (area)	>100 mi^2	1–100 mi^2	100 acres–1 mi^2	<100 acres
Type of Data Acquisition	Existing GIS data layers from Puget Sound Characterization	Existing GIS data layers from Puget Sound Characterization	Using existing data or field collection of new data on biological, physical and chemical conditions at these scales.	Usually requires field collection of new data on biological, physical and chemical conditions at these scales.
Type of Application at Each Level	Land-use planning and zoning, such as the location, type, and/or intensity of new development to avoid and to buffer mapped watershed features.	Refinements of coarse-level assessment for application to land- use planning and zoning to protect existing, mapped watershed features serving important watershed process and function.	Reach- and watershed-scale strategies for land and water protection & restoration. Reach-specific actions & BMPs to protect and restore conditions.	Adaptive management; (bio) feedback and site- and reach- scale project designs for the specific BMPs to remediate stressors to restore and protect healthy water bodies.
How the Puget Sound Characterization results could be applied	Water-flow and water-quality assessments are most applicable at this scale, integrating sub-basin information on conditions of importance to each of these processes.	The water-flow and water quality assessments provide information at a sub-basin scale	The Characterization does not provide results at these scales. However, characterization results should be used to confirm whether actions at these scales are appropriate. For example, installation of wood at the site or reach scale should not be undertaken if upper water delivery and storage processes are highly degraded.	

The purpose of defining the levels explicitly is to guide the proper collection and application of information by following the admonition to *consider and evaluate the effects (at least) one level of organization above and below the level of the action or effect.* Therefore, the conceptual framework of Figure 4 and their associated assessment levels define a nested "hierarchical" framework.

For example, questions regarding stream community structure (a fine level) cannot be answered directly by information acquired and analyzed from coarser levels. However, coarse-level information addresses issues about landscape features that control the movement of water, such as the type of geology and areas of water storage. These landscape features influence stream community structure indirectly, but profoundly. Because processes at a coarse level influence conditions at finer levels, one should always make decisions at a finer spatial scale (for example) only within an understanding of the ecological context of the broader landscape conditions.

The Water-Flow Assessment

The Puget Sound Characterization encompasses a set of GIS-based analyses that integrate multiple data sources, covering the entire contributing watershed area of Puget Sound, that represent the physical, hydrologic, and human attributes of this landscape. These representations are of necessity generalized, because they cover a very large area and express information collected by remote sensing (e.g., satellite) or broad-scale field reconnaissance for an original purpose not connected with this current application. Nonetheless, the chosen data sets, and the manner in which they are combined in the Characterization, provide a valuable regional-scale perspective on the spatial distribution of watershed resources and impacts that is not generally provided by other available tools.

The Puget Sound Characterization can inform a wide range of planning efforts. Potential applications include appropriate siting of wetland mitigation banks or in-lieu-fee approaches by identifying the highest priority areas for restoration on a landscape or ecosystem scale. For local governments planning under the Growth Management act, the Characterization can be used as 'best available science' as they update their Comprehensive Plans, Critical Areas Ordinances, or Shoreline Master Programs. Similarly, once completed by the Department of Fish and Wildlife, the Wildlife Habitat Assessment model and approach could be used by local governments to inform their land-use zoning and critical areas ordinances.

This section describes the integrative results of the water-flow assessment, which combines two separate analyses: one that evaluates the "importance" of an AU for each of three water-flow processes (delivery, surface storage, recharge/discharge), and the other that evaluates the "degradation" of that AU with respect to those same three processes. The next section describes a method for identifying potential solutions to a range of identified natural resource problems, making use of the integrative results. For additional detail, the individual results of these two submodels (importance and degradation) are presented below, and the details of each submodel are presented in Appendix B.

The Watershed Management Matrix

Results from the water-flow assessment can be used in several ways. Both the individual water-flow processes (delivery, surface storage, recharge/discharge) and the integrated condition of these three processes yield independent rankings of “importance” and “degradation” across the region or within a WRIA. Most planning decisions, however, will benefit from integrating the results of the importance and degradation submodels, and so we present those results here first.

This integration is made by combining the results for the importance and degradation submodels into a matrix that defines broad resource-management strategies for each combination of importance and degradation within any given AU. This approach permits varying degrees of discrimination between AU’s, depending on the chosen application. The online geographic database divides the results for both importance and degradation into quartile-grouped[2] results, and so up to 16 unique combinations can be defined (Figure 5a).

Figure 5a:

IMPORTANCE				
HIGH	Protection 1	Protection 1 Restoration	Restoration 1	Restoration
MED-HIGH	Protection 2	Protection 2 Restoration	Restoration 2b	Restoration 2a
MEDIUM	Conservation 1	Protection with Conservation	Restoration 1 with Development	Restoration with Development
LOW	Conservation 2a	Conservation 2b	Development 1	Development
	LOW	MEDIUM	MED-HIGH	HIGH
	DEGRADATION			

The greatest level of management action (broadly denoted “Restoration”) applies to the most important areas with the greatest existing degradation. Conversely, areas of low importance but also low degradation likely require a much lower level of management attention (here termed “Conservation”). Those with high importance and low existing degradation may need little or no active management but warrant a high level of protection to maintain high functional conditions; and those with low importance and significant human impact should be lowest in priority ranking for active management. These are thus tagged “Development,” indicating that development in this AU will have the lowest overall impact relative to others with respect to water-flow processes.

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[2] Evenly divided quartile results were judged to provide the best depiction of existing conditions on the landscape. The groupings are relative comparisons from “high to low” but do not reflect presumptive thresholds or absolute quality for the ecological processes being modeled.

This 16-element matrix implies a relatively fine level of discrimination of management actions, however, that may not always be warranted or necessary. For example, maps that display Sound-wide results (such as Figures 6–8) are usefully summarized into only eight categories (Figure 5b); and if only the most broad characterization is desired, they can be further condensed into just four quadrants (Figure 5c) that define the major management strategies of restoration, protection, conservation, and development.

Figure 5b:

IMPORTANCE	DEGRADATION: LOW	DEGRADATION: MEDIUM	DEGRADATION: MED-HIGH	DEGRADATION: HIGH
HIGH	Protection 1		Restoration 1	
MED-HIGH	Protection 2		Restoration 2	
MEDIUM	Conservation 1		Restoration with Development	
LOW	Conservation 2		Development	

Figure 5c:

IMPORTANCE	DEGRADATION: LOW	DEGRADATION: MEDIUM	DEGRADATION: MED-HIGH	DEGRADATION: HIGH
HIGH	Protection		Restoration	
MED-HIGH				
MEDIUM	Conservation		Development	
LOW				

Figure 5. The Management Matrix, displaying 3 alternatives with different levels of discrimination. In all tables, the rating for importance is on the vertical axis, and rating for degradation is along the horizontal axis; the combination of these two indicates suitability of the assessment unit for various combinations of protection, restoration, conservation, or development. The categories in each of the sixteen boxes in Figure 5a express the range of outcomes generated by the combined importance and degradation submodels, and they provide an initial framework for evaluating management actions. In the following maps, the legends follow Figure 5b; for the solution templates (pp. 36–39), these categories are further condensed as shown in Figure 5c.

Combining the results of the importance and degradation submodels can yield two (related) sets of maps. One set of maps suggests the appropriate management strategy for each *individual* water-flow process (i.e., delivery, storage, and recharge/discharge) used in the analysis, for each AU. The second set is a single map, displaying the *integration* of all processes into an appropriate strategy based on the combined importance and degradation results for all of the water-flow processes. This integrated result for the entire Puget Sound basin is displayed in Figure 6; with Figures 7 and 8 focus on the results from a single WRIA (#11).

Interpreting the Results

Figure 6 presents the Puget Sound-wide map for the water-flow assessment, suggesting a regional picture of recommended management approaches. For example, one of the largest areas indicating a need for restoration of water-flow processes is located in Whatcom County in WRIA 1, in the far northern end of Puget Sound. WRIA's 4 (Skagit) and 7 (Snohomish) include the largest contiguous areas with a priority for protection. Both of these watersheds retain significant tracts of undeveloped floodplains in their lower (western) reaches; although these areas are ecologically degraded, they could be valuable focus areas for restoration efforts to sustain intact water-flow processes in the upper watershed over the long term. Farther south in the more urbanized portions of Puget Sound, areas for restoration become more fragmented and smaller in size.

Overall, the results suggest that whereas we have been relatively successful in protecting water-flow processes in the mountain landscape group, lowland land-use activities have significantly altered processes. These have significant impacted the mid- and lower reaches of nearly every Puget Sound watershed, providing an abundance of restoration opportunities but the corresponding necessity to embark strategically on such a potentially massive undertaking.

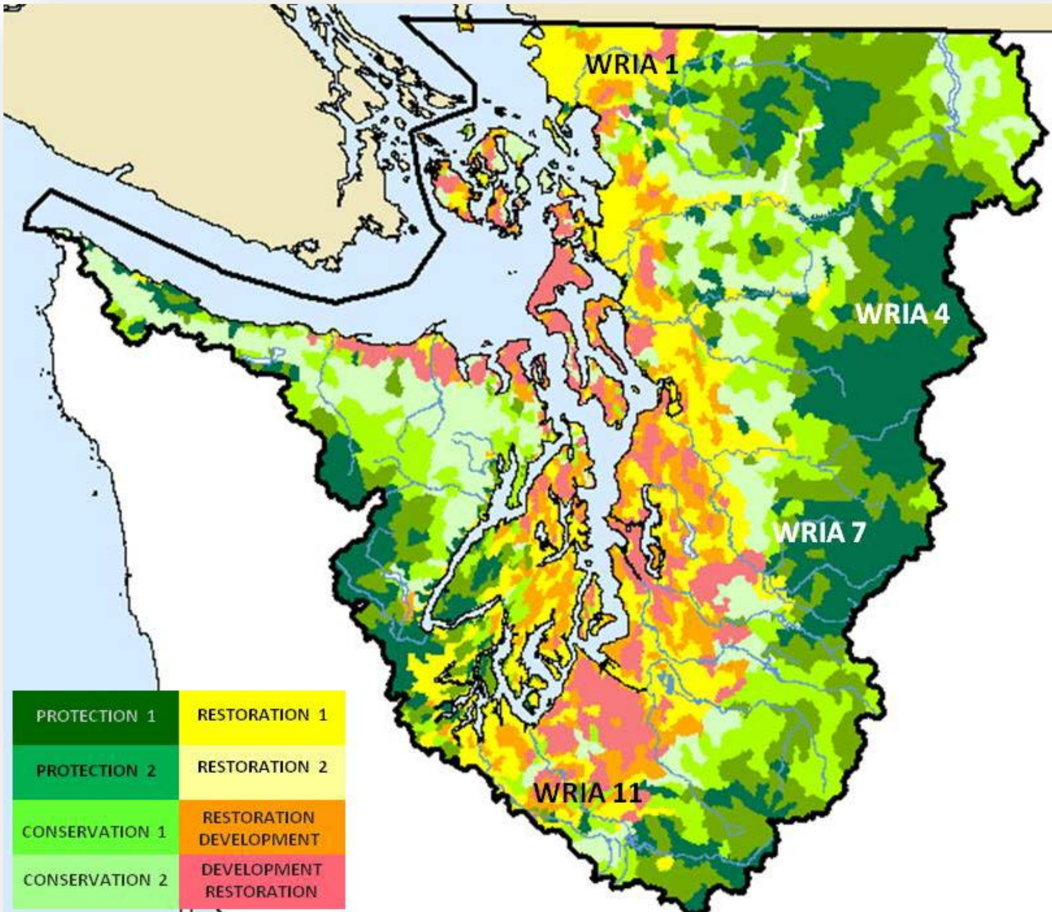


Figure 6. Integrated results of the water-flow assessments for Puget Sound basin. This map displays the results of the Management Matrix (using the 8-fold categories of Figure 5b) across the entire Puget Sound basin. "Protection" is emphasized in the high-mountain areas, and "development" is denoted where much degradation has already occurred. Areas inferred to be most highly suited for "restoration" (yellow and orange shades) are scattered throughout the region but show a particular concentration in many of the lowland areas lying just outside of the areas of greatest urban development.

Where AU's are ranked and categorized based only on the scores within a specific WRIA, however, assessment results can reveal a different, watershed-specific pattern of restoration, protection, conservation, and development. This is particularly evident in WRIA 11, whose lowland areas are dominated by the "development" category when assessed in the context of the entire Puget Sound basin (Figure 6), but which shows a large area suitable for restoration when considered in a more local context (Figure 7), as might be most appropriate for a single municipality, county, or tribe.

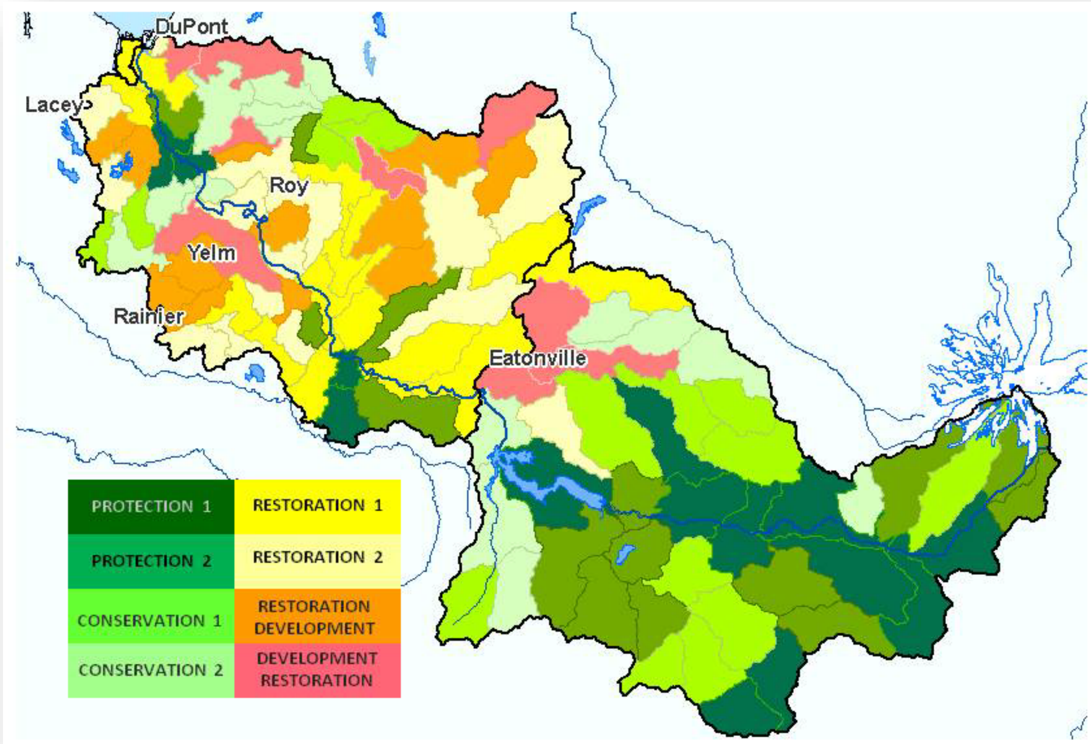


Figure 7. Integrated results of the water-flow assessments for WRIA 11 (Nisqually River watershed). This map displays the results of the Management Matrix (using the categories of Figure 5b) based only on the range of conditions found within WRIA 11. "Protection" is emphasized in the high-mountain areas and "development" (which can include commercial forestry) where much degradation in areas of relatively low importance has already occurred. Note that relative to the Puget Sound-wide results presented in Figure 6, however, the lowland areas show larger areas of "restoration." WRIA-based assessment results will likely prove most useful in developing plans, policies and restoration/protection priorities for local governments considering the area under their jurisdiction.

In working at a single-WRIA scale, both the combined and individual results of the submodels (i.e., delivery, surface storage, and recharge/discharge components) can be useful for planning or environmental problem-solving. For example, if flooding is an issue, then the results from both the delivery and storage components of the model can inform this problem. In a rain-on-snow flood event, areas identified as important for delivery have attributes that contribute to generating "rain-on-snow" floods; similarly, areas high in surface storage downstream of "rain-on-snow" and "snow-dominated" areas can play an important role in moderating "rain-on-snow" floods (e.g., Figure 8). For storms that begin with heavy rain in the lowlands, flooding may occur at low elevations first. In these circumstances storage on the main stem and in lowland areas is likely to be more important for moderating flood events.

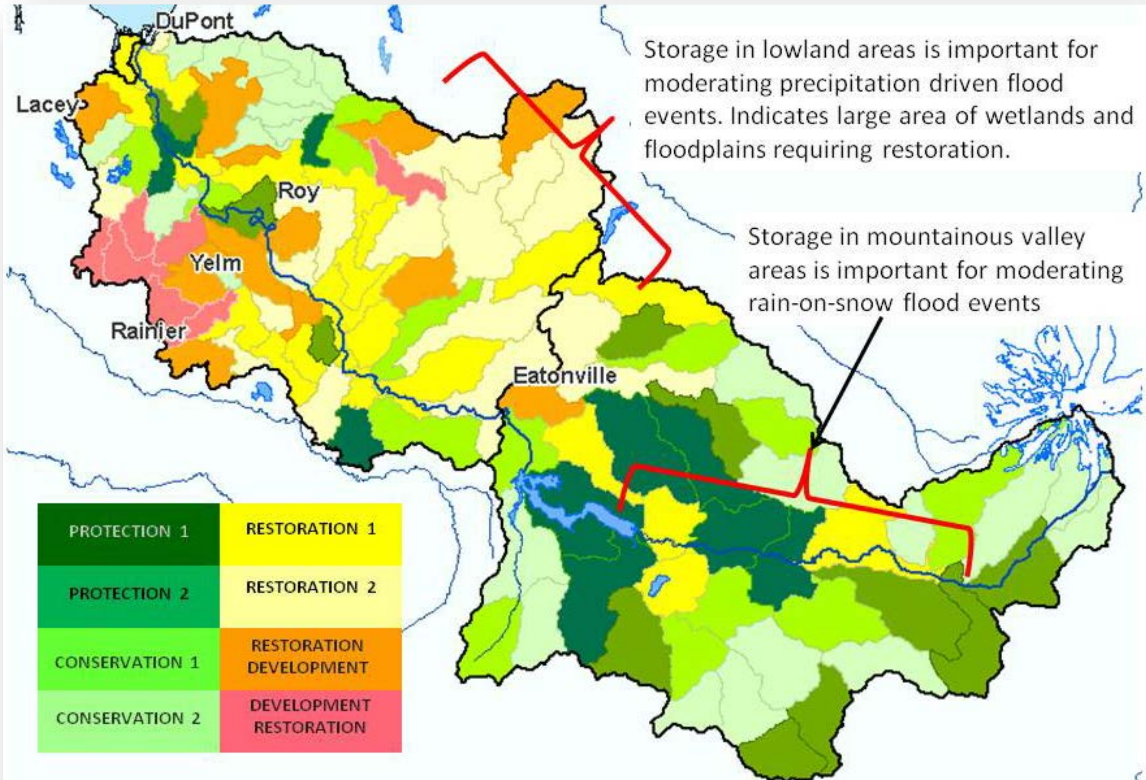


Figure 8. Results of the "Storage" analysis of the water-flow assessments for WRIA 11. This map displays the results from the Management Matrix for areas important for surface storage in WRIA 11. Areas for protection and restoration immediately below Mount Rainier (at extreme right of the watershed) along the Nisqually River are important for moderating rain-on-snow events. Storage in lowland areas shown as bright yellow "restoration" is important for moderating precipitation-driven events.

These maps display the guidance appropriate at the scale of an AU, displayed as a homogenous unit. Of course, at finer scales than this analysis these units will almost all contain a multiplicity of land uses and a range of resource values and threats. The Characterization will not be able to resolve these details because the scale of the data, and thus that of the GIS-based analyses, is too coarse. However, local sub-area or basin plans can be brought to bear to illuminate specific problems and solutions in support of Characterization results.

The next section shows how to use the Characterization results to provide the greatest benefits for the particular environmental and land-use setting. It also provides a framework to incorporate additional information that may be available to identify likely beneficial actions (such as the use of basin plans noted above).

Using the Characterization Results

Results of the Characterization provide a readily accessible spatial integration of the condition(s) of watershed processes across a selected watershed, a WRIA, or the entire region (e.g., Figure 6). These results can then be used to address two fundamental questions: (1) ***where on the landscape or within a watershed*** should management actions be focused, and (2) ***what types of actions*** will likely be most appropriate, be they restoration, protection, conservation, or development, given the historical ecological functions and likely current state of those functions given the environmental constraints and problems[3] already present?

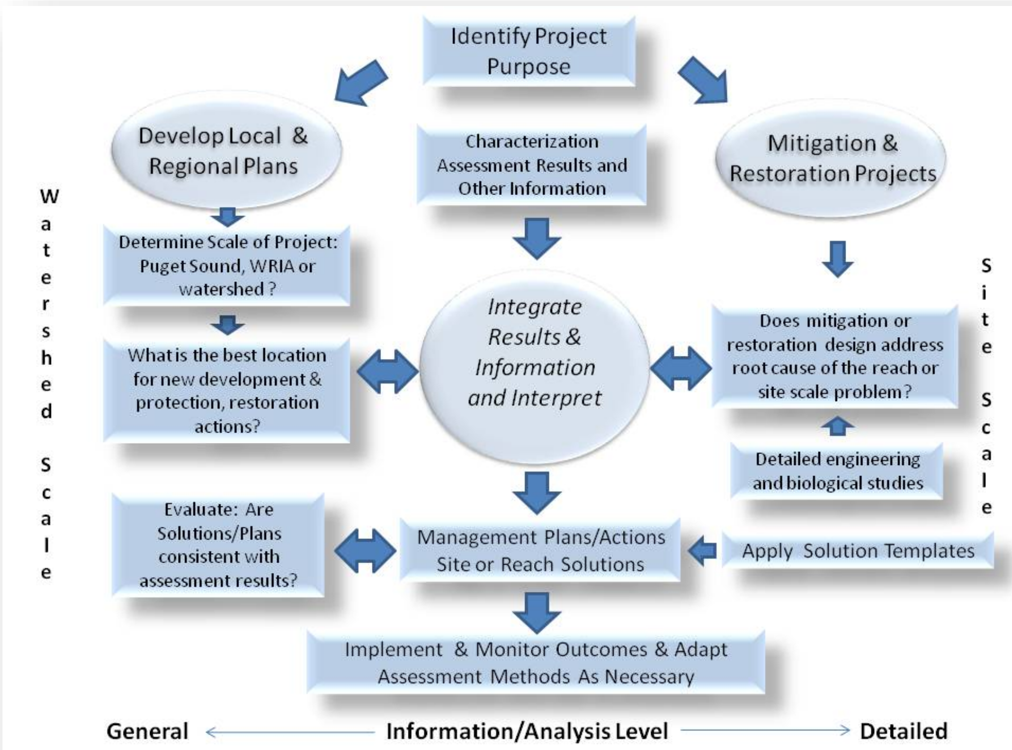


Figure 9. Flow diagram for applying assessment results within the analysis framework. The primary use of information from the assessments is to guide projects such as comprehensive planning, which occur at the watershed scale and require a "general level" of information and analysis (the left hand side of the diagram). At these spatial scales, the assessments indicate where it is most appropriate to restore, protect, conserve, or develop. The assessments can also inform decisions regarding site-level projects (the right-hand side of the diagram) involving mitigation and restoration projects, by providing essential information on landscape context. Site-level projects must take into account conditions at larger spatial scales and determine the "root cause" of environmental problems/impacts being addressed at the site or reach scale.

[3] For example, in a heavily urbanized watershed, removal of existing impervious surface (a constraint) to address erosive flows (the problem) in a potential stream restoration project may not be feasible.

Because the individual assessment units are typically several square miles in area, “where to focus” cannot be defined more precisely without additional information. Similarly, guidance on “what to do” will commonly require additional site-specific information that is not included in the Characterization datasets. The analysis framework provided here, however, offers a systematic approach to reduce the universe of “do all things, everywhere” to a more tractable set of actions that have a high likelihood of improving watershed health.

The following steps, following the framework illustrated in Figure 9, are recommended for making use of the Characterization results. We illustrate these steps using the example of the Gorst Creek watershed, located in Kitsap County, within the City of Bremerton’s Urban Growth Area (UGA).

1. **Identify the project’s purpose(s).** The Characterization results are most useful in two broad arenas: identifying priority areas for management attention (be it active restoration, proactive management through land-use planning, or designation for future population growth given relative resource insensitivity to land-use change); and identifying likely beneficial actions for particular areas already selected by other decision-making processes. A typical example of the former is how to allocate regional restoration funds; of the latter, framing the range of likely effective actions to be subsequently developed in a sub-watershed plan in response to regulatory or citizen concerns.

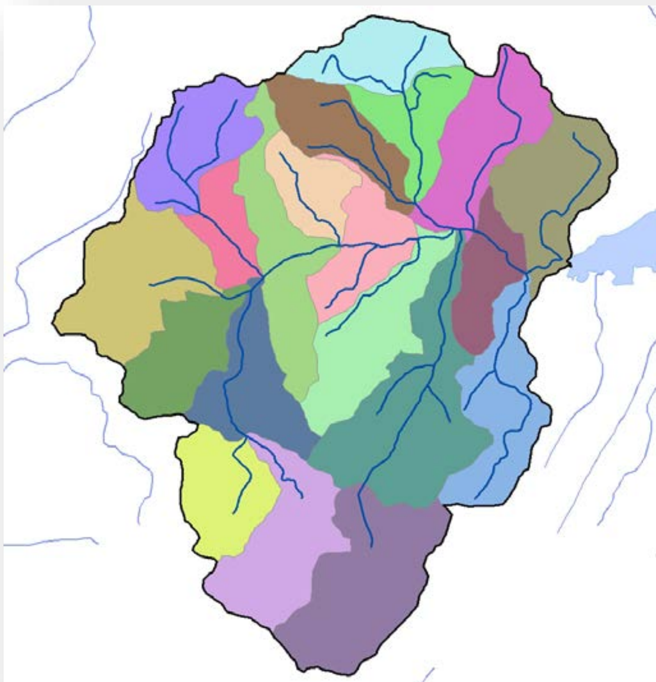
   In addition, the Characterization results can be used by site-scale projects (mitigation and restoration) to help evaluate whether the project is addressing “root causes” of environmental problems. Of course, such an evaluation also requires more detailed analysis and information at the site scale, which is not provided by the assessment results.

   Example: The primary motivation for the Gorst Creek Watershed Characterization (WRIA 15, City of Bremerton) was:

   (1) Assist in developing a watershed-based management plan for the freshwater and terrestrial portions of the watershed;
   (2) Identify the best areas for protection, conservation, restoration, and development.

   The intent was to use the Characterization results to provide science-based information to the City of Bremerton and Kitsap County’s land-use plans and regulations. The specific objectives were to identify areas within the watershed to restore, protect, and conserve, and on which development can be focused with the least amount of additional environmental impact. The results will also be used to guide the types of protective and mitigation strategies that are likely to be most appropriate and most effective in each of these areas.

2. **<u>Choose the primary level of information and analysis</u>**. If the project purpose is for developing local or regional plans (left side of Figure 9) then it must be determined if the work being done is within a WRIA context, a single jurisdiction, or part of a whole-region initiative? In the case of the first (and commonly the second) scale, the WRIA-specific results (e.g., Figures 7-8) are most appropriate; project-specific analysis boundaries may also be required. If the latter scale (i.e., whole region) is appropriate, then the results from the entire Puget Sound region (Figure 6) are more relevant.



If, however, the purpose of the project is to develop mitigation or restoration plans at the site or reach scale (right side of Figure 9), then the scale of analysis must reflect the size of the watershed associated with the mitigation or restoration sites.

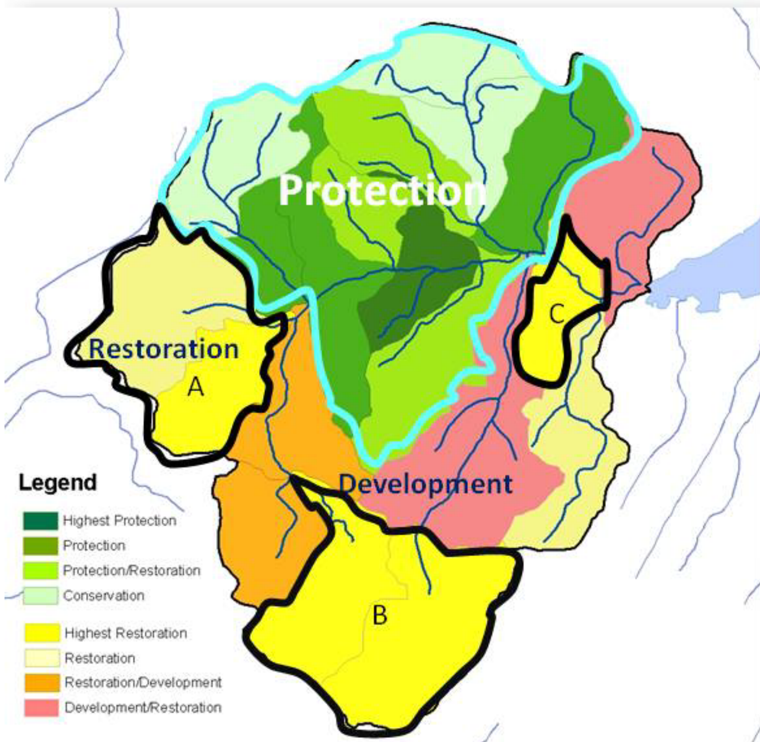
In all cases, the scale of analysis (including any larger spatial scales that should be considered to provide adequate context) must be determined by the scale of the issue(s) and the availability of sufficient (and sufficiently detailed) data.

Figure 10. Assessment Units for Gorst Creek watershed.

Example: The City of Bremerton requires information on the best places to develop, protect and restore for only a single watershed. Therefore the analysis was scaled to this single watershed, which is 11 square miles in area (Figure 10). This required 20 newly defined assessment units (i.e., smaller than those already available through the Characterization), following the procedures described in Appendix B of DOE (2009).

3. **<u>Evaluate the integrated results of the water-flow processes</u>.** The overarching recommendations provided by the water-flow assessments are expressed through the mapped results of applying the management matrix (Figure 5). Collectively, they answer the question “what is the most appropriate management strategy for an AU?” This step requires identifying broad and spatially coherent management “zones,” based on the mapped results of integrated water-flow assessments.

Example: Based on the assessment results for the individual water flow components (delivery, storage, recharge and discharge) in the Gorst watershed, assessment units display spatial patterns that suggest an overall distribution of regions broadly suited for restoration, protection, and development. Figure 11 presents those results, and the broadly defined management zones that were revealed by the Characterization results in the Gorst watershed.



1. Protection Zone (Green). This area is key to recharge and discharge processes for Gorst Creek. Permitted uses preserve forest cover and do not result in conversion

2. Restoration Zone (Yellow & Orange)
   A – Restore wetland storage functions, limit urban development, maintain in open space uses.
   B – Residential uses but restore storage functions of wetlands
   C – Restore recharge/discharge functions using LID measures.

3. Development Zone (Pink & Orange). Residential and commercial uses employing clustering and LID.

Figure 11. Watershed management areas based on water-flow assessment results, and the broad categories of actions suggested by these results (further refined in subsequent steps).

At this point in making use of Characterization results, the *purpose* (Step 1) of the analysis determines the next step(s) to be taken. If the primary purpose is to develop local and regional plans, then the product of Step 3 may be all that is required. Elements of the following steps (Step 4, identify predominant land use, and Step 5, solution templates) may provide some additional guidance, but the primary contribution of the Characterization to planning is largely complete at this point. If, however, the purpose of the analysis is not only to define but also to address environmental problems, then following the following steps in their entirety will normally provide additional value.

4. **Identify the predominant land use(s) within each AU or management zones (from Step 3)**. This can be done by reference to the land-cover maps that are part of the underlying Characterization data (available from this LINK) or by common knowledge. For purposes

of using the Characterization results, the recommended categories are quite broad (termed “forest lands,” “rural lands,” “agricultural lands,” and “urban/suburban” in Step 5 below), reflecting an equally broad discrimination of both the types of typical degradation conditions associated with these human activities and the types of remedial actions that are most suited to the associated land uses. Analogous to Step 3, any single AU almost always encompasses multiple land uses. Particular management actions should always be targeted to specific land uses at whatever scale they actually exist, but the Characterization results are too coarse to reflect this common fact.

Example: In the Gorst Creek watershed, forests predominate in the northern portion of the watershed and a combination of forest and rural residential predominates in the southern portion of the watershed. Agriculture is not a significant land use within the watershed. Thus, the list of solutions (next step) emphasizes forestry and rural residential land-use types.

5. **Apply results of the water-quality assessments.** Although water flow is presumed to be the fundamental driver of watershed conditions and processes, the Characterization’s assessment of water-quality processes can be used to guide more refined choices for specific priority actions. In particular, where the Characterization is being used to identify specific potential water-quality concerns (e.g., downstream contamination of shellfish beds from pathogens), results of the specific water-quality assessment(s) should indicate the greatest potential problems that likely need to be addressed (for example, see Figure 12).

   Further development of the Characterization methodology is anticipated to result in better integration of water-flow and water-quality findings and model outputs. The primacy of the water-flow results in determining overall management strategies, however, reflects the overall importance of these processes and is unlikely to change in any subsequent versions of the method.

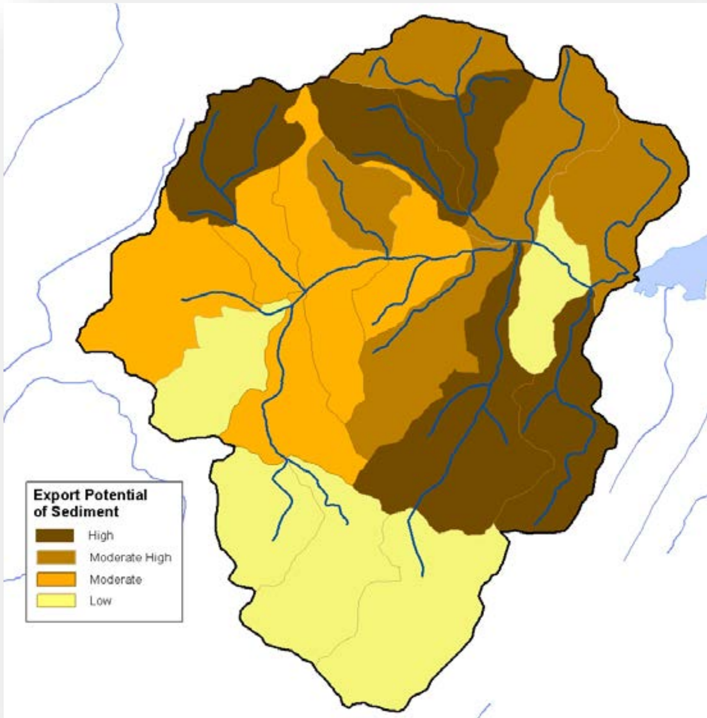


Figure 12. Results of sediment export model for Gorst Creek watershed. Dark brown colors represent areas of highest potential sediment export, and light yellow colors the least.

Example. Figure 12 presents the results of thea sediment export assessment for the Gorst Creek watershed, which can be used to refine management of the development zones presented in Figure 11. The results suggest that the dark brown AU's, in the lower right of the watershed, have a high potential for exporting sediment, which would argue for protecting this area. However, the water-flow assessment shows this area as appropriate for higher intensity development, leading to an integrated conclusion that would likely modify the final location of most intensive development or else emphasize careful mitigation of potential erosion-causing activities.

6. **Refine the recommendations with additional site-specific information, technical expertise, and other considerations relevant to the project's scale**. The Characterization is a *decision-support* tool, not a *decision-making* tool. It is structured to provide an overview of likely conditions, problems, and opportunities based on GIS information, organized and analyzed in accord with well-established scientific principles (and common sense). Therefore, carrying these analyses forward (as either final decisions on priority efforts or specific on-the-ground actions) will normally require further levels of information and expertise not provided by regional-scale maps or tables or lists of generic management actions, or by information restricted only to water-flow processes. Combining a regional structure with local understanding, however, can achieve benefits that are otherwise unattainable.

   Some of these additional levels of information and expertise that can help refine decisions include:

   - Habitat assessments. These will be critical to identify the most important AU's to protect for fish and wildlife.

- Stream network and lateral connectivity. A limitation of the Characterization is that each AU is considered independent of adjacent AU's In a watershed context this obviously ignores the consequences of upstream degradation on downstream systems; in a landscape context it also ignores the movement of materials and biota within and between upland and nearshore habitats. At this stage of the Characterization method, this step is simply a reminder that any credible landscape-scale assessment needs to expand its scope of attention beyond the conditions of a single assessment unit, both geographically and thematically. Figure 9 provides some basic guidance on the kinds of questions that should be asked in addressing conditions *within* an AU that are possibly the result of processes *outside* of the AU. In addition, the results from other regional assessments, where appropriate, should be given consideration along with AU-specific results.
- Biological assessments and other regulatory information. Assessment of biological conditions can also help refine the initial management zones developed in Step 3 (Figure 13). For example, the presence of anadromous fish-bearing waters or TMDL requirements may not change recommended management actions but will commonly alter the implementation priority or the overall priority of actions within the AU relative to others in the analysis area

To achieve these benefits, the assessment results should be examined both individually (by process) and collectively. When examined individually, both the water-flow and water-quality assessments can indicate the most important AU's to protect for water resources. However, the most appropriate places for development are AU's that have the least importance for all processes. Therefore, the assessment results must be integrated at multiple scales and from multiple perspectives. The integration of assessments can also indicate the highest priority AU's for protection, i.e., AU's where all assessments indicate high importance for natural resources.

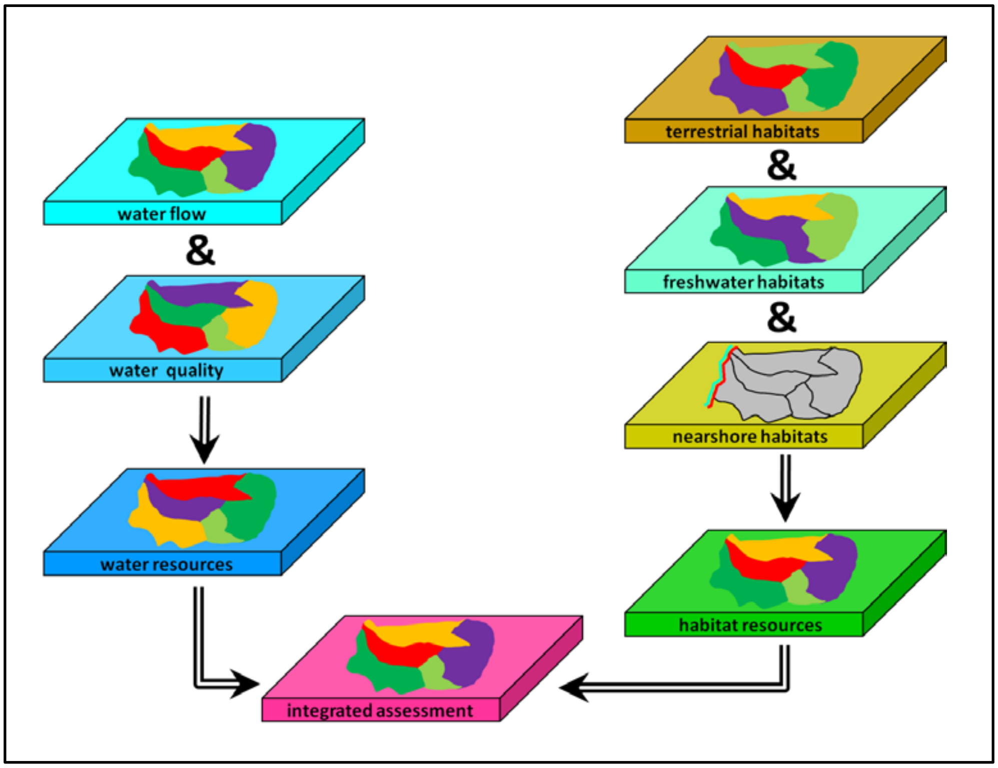


Figure 13. An idealized integration of water resources assessments. Water-flow and water-quality assessments are integrated into an overall "water resources" assessment (Steps 3–5, above). As additional terrestrial, freshwater, and nearshore habitats assessments are developed for the region or implemented in a particular watershed, they should be included as part of an overall assessment (Step 6). However, such integrated assessments can always be decomposed into their components in order to more fully understand the resource conditions and values in each AU.

Example: In addition to the Characterization data sets, much is known about Gorst Creek anadromous fish runs (as well as other conditions relevant to the watershed). Gorst Creek supports Chinook, Chum, Coho, Steelhead and Cutthroat (WDFW 2009). Thirteen Type F tributary streams including Parish Creek, Heins Creek, and an unnamed stream (LMK 122) are located within the watershed. The upper reaches of these tributaries are of high ecological function and generally undisturbed by development; the lower reaches of Gorst Creek are significantly altered by development and highways. The floodplain in lower Gorst Creek is mostly hardened and confined. The lower reaches lack riparian vegetation and large woody debris (LWD). A number of culverts/passage barriers affect the lower reaches, and there is a long history of flooding within the Gorst Creek watershed.

Solution Templates

“Solution templates” is the term used in the Characterization for lists of generic management strategies and actions that can be applied at a variety of spatial scales (e.g., rezoning or development conditions that may apply over large areas, or restoration of a wetland that would occur at a very specific location in a watershed). The templates are stratified by forest lands, rural lands, agricultural lands, and urban/suburban land. Within each land-use category, actions are further identified as to their suitability to the four overarching management strategies identified in the management matrix—protection, restoration, conservation, or development For example, AU’s that fall in the “protection” or “restoration” fields have the most complete suite of recommended actions, because these areas have attributes associated with greater importance to water-flow processes than those that fall into the “conservation” or “development” fields. Recommended management strategies have been identified to correspond to the conditions of the water-flow processes most common in each land use.

Every part of the landscape can contribute to healthy watersheds. Similarly, certain management measures are so fundamental that they should be used in *every* part of a watershed regardless of land use, AU importance, or level of degradation. The specifics of implementation will of course vary depending on whether the area in question is a steep mountainside or a flat urban lowland—but the principles underlying the need for these measures are the same regardless of landscape position or current condition. These uniformly applicable measures, whose overall goal is to protect or restore the ecological integrity of aquatic systems throughout the landscape (Ward 1998), are:

1. Maintain the physical processes within wetlands, stream and riparian zones
2. Restore floodplains (reconnect streams, reduce channelization)
3. Reduce surface-water diversions
4. Restore depressional wetlands and their adjacent riparian zones
5. Restore/replant riparian zones
6. Identify and protect aquifer recharge areas

Several of these are already part of existing state or local development regulations, and as such they should require no further emphasis here, except to note that the Characterization results may be used to support changes to local development regulations as ‘best available science’: changes to Critical Areas Ordinances and Shoreline Master Programs are supported by the water-flow assessment, while changes to mapping of Fish and Wildlife Habitat Conservation Areas and their management could be supported by upcoming habitat assessments as part of the Characterization framework. Others measures, even if not currently mandated, are so fundamental to the attainment of healthy aquatic systems that they should be implemented whenever and wherever possible. The priority of individual actions is generally in the rank order listed above, although many of the constraints already present in the highly developed areas of the Puget Sound basin may limit the potential benefits of such actions.

In each of the land-use-specific solution templates, the first several rows of recommended management strategies apply for the given land use regardless of the assessment results. In other words, these are virtually always worthwhile efforts, but they do not apply to all land uses uniformly. For example, source control for nitrogen and pathogens is beneficial in agricultural areas regardless of the particular AU's importance or level of degradation, because these pollutants are commonly delivered to Puget Sound. Similarly, dispersive/infiltrative stormwater management strategies ("Low Impact Development," or LID in common usage) achieve such demonstrable improvements in stormwater that they should be in widespread use in developed (and developing) areas regardless of other considerations.

Each land-use-specific solution template also has several management strategies that are recommended only for AU's with a particular combination of importance and degradation. Most of these measures are recommended only for those with high importance (i.e., those that fall into the "protection" or "restoration" quadrants of the Management Matrix). In most cases they represent more expensive, justified in the pursuit of healthy watersheds but beyond current regulations or common practice. As such, they probably will not be immediately feasible or affordable everywhere.

THE SOLUTION TEMPLATES

Abbreviations common to all templates:
Management matrix results: "P" = Protection, "R" = Restoration, "C" = Conservation, "D" = Development.
Water-flow processes addressed by recommended actions: "DE" = Delivery, "SS" = Surface Storage, "RD" = Recharge/Discharge.
Light blue rows indicate solutions common to all management matrix categories; medium blue rows indicate solutions applicable to protection and restoration categories; and dark blue rows indicate restoration categories only.

ALL LAND USES	P	R	C	D
Maintain the physical integrity of stream and wetland riparian zones (DE, SS, RD)	☑	☑	☑	☑
Restore floodplains (reconnect streams, reduce channelization) (SS, RD)	☑	☑	☑	☑
Reduce surface-water diversions (RD)	☑	☑	☑	☑
Restore depressional wetlands and their adjacent riparian zones	☑	☑	☑	☑
Restore/replant riparian zones (RD)	☑	☑	☑	☑
Identify and protect aquifer recharge areas (DE, RD)	☑	☑	☑	☑
For relevant literature see: http://www.ecy.wa.gov/biblio/wetlands.html				

FOREST LANDS	P	R	C	D
Common issues: widespread loss of vegetative cover, particularly in high-elevation snow and rain-on-snow areas, high in watersheds and so affecting many reaches downstream. Creation of new impervious surfaces is rare, although a dense forest road network can greatly alter flow paths and sediment production.				
Reduce number of stream crossings by roads (SS)	☑	☑	☑	☑
Reduce interception of shallow GW in channels and road ditches (RD)	☑	☑	☑	☑
Replant deforested areas (DE)	☑	☑		
Ensure zoning is consistent with long-term protection of resources (e.g., large parcel size; stable urban growth boundary) (DE, SS, RD)	☑	☑		
Decommission and remove unneeded forest roads (SS, RD)	☑	☑		
Increase size of protected areas around streams/wetlands (DE, SS, RD)	☑	☑		

RURAL LANDS	P	R	C	D
Common issues: Rural land use can drain key headwater wetlands, with potentially great effect on downstream flooding and erosion. Septic systems can be a source of nutrients and pathogens. Forest clearing increases overland flows, affecting stream/wetland structure and function. Groundwater withdrawal in rural residential areas can affect downstream discharge areas. For relevant literature see: http://www.ecy.wa.gov/biblio/wq.html				
Require [properly functioning] septic systems (RD)	☑	☑	☑	☑
Emphasize dispersive/infiltrative stormwater management (DE)	☑	☑	☑	☑
Ensure zoning is consistent with long-term protection of resources (e.g., clustered development, stable urban growth boundary) (DE, SS, RD)	☑	☑		
Increase size of protected areas around streams/wetlands (DE, SS, RD)	☑	☑		
Reduce drainage density of artificial channels (SS, RD)	☑	☑		
Revegetate upland areas (DE, SS)	☑	☑		
Reduce GW withdrawals (RD)	☑	☑		
Reduce interception of shallow GW in channels and road ditches (RD)	☑	☑		
Replant deforested areas (DE)	☑	☑		
Set back dikes/levees in key areas to restore overbank flooding (SS)		☑		
Restore stream reaches, floodplains, or wetlands to recover lost processes and functions (SS, RD)		☑		

AGRICULTURAL LANDS	P	R	C	D
Common issues: Extensive drainage system reduces residence time of water on landscape and increases downstream delivery of water, and also compromises water-quality functions of wetlands and floodplains. Potential source of nutrients, pathogens and sediment that impact downstream aquatic area; lack of vegetated buffers increases delivery and transport. Floodplains disconnected from overbank flooding and tidal processes. Groundwater withdrawals and diversions can significantly affect low-flow regimes and wetland hydrology.				
Apply source controls for nitrogen and pathogens (SS)	☑	☑	☑	☑
Allow greater residence time of water on fields and ditches outside of growing season (SS, RD)	☑	☑	☑	☑
Encourage [properly functioning] septic systems (RD)	☑	☑	☑	☑
Ensure zoning is consistent with long-term protection of agriculture and resources (e.g., large parcel size; stable urban growth boundary) (DE, SS, RD)	☑	☑		
Reduce GW withdrawals (RD)	☑	☑		
Reduce drainage density of artificial channels (SS, RD)	☑	☑		
Establish buffers for water-quality improvement in strategic areas (DE, RD)	☑	☑		
Reduce interception of shallow GW in channels and road ditches (RD)	☑	☑		
Revegetate upland areas (DE, SS)	☑	☑		
Set back dikes/levees in key areas to restore overbank flooding (SS)		☑		
Restore degraded stream reaches, floodplains, or wetlands to recover lost processes and functions (SS, RD)		☑		
Restore highly infiltrative soils (RD)		☑		

URBAN & SUBURBAN	P	R	C	D
Common issues: Areas of impervious surface impair multiple water-flow processes, resulting in simplification of habitat structure and functions, and compromising effective restoration of structure and function of aquatic habitat. Significant transport of pollutants generated by urban uses to aquatic areas. Note that development regulations will preempt/supersede some of these recommendations.				
Emphasize dispersive/infiltrative stormwater management (DE, SS, RD)	☑	☑	☑	☑
Increase widths of protected wetland, stream, and marine riparian zones (DE)	☑	☑		
Reduce GW withdrawals (RD)	☑	☑		
Reduce interception of shallow GW in channels and road ditches (RD)	☑	☑		
Revegetate upland areas (DE, SS)	☑	☑		
Retrofit structures and roads for greater infiltration (DE, RD)		☑		
Construct stream reaches or artificial wetlands to recover lost processes and functions if/as feasible (SS, RD)		☑		

Although the Characterization provides a useful basis for identifying priority areas for management actions, together with guidance for the types of actions that will be most constructive for improving watershed health, it cannot address two fundamental issues:

- First, it cannot resolve the trade-off between (1) the benefits of working in less-disturbed areas, where the costs are typically low and the likelihood of successful outcomes is high; and (2) the benefits of working in already degraded areas, where the potential for improvement may be great but the uncertainty of achieving that outcome (and the certainty of cost in just making the effort) is high.
- Second, the Characterization cannot resolve the specific types and locations of actions within particular AU's being considered. As noted in the Introduction, the GIS data on which the Characterization is developed are aggregated into assessment units of several square miles, and most of the determinations of "importance" and "degradation" are based on inferences using these data, not on actual measurements themselves. Therefore, applying the data at the site level, solely on the basis of AU characterization, would be a misuse of the tool and its results.

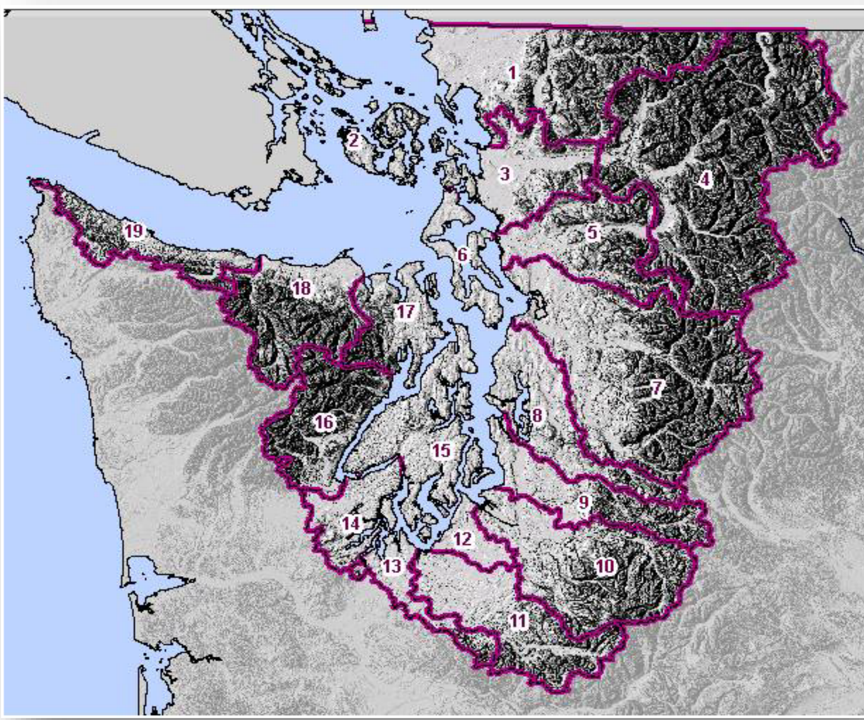
Thus, the Characterization can neither resolve one of the vexing policy issues faced in the science of restoration nor specify the specific actions (or their locations) that need to be taken to make substantive improvements to watershed health. It does, however, offer the land manager a systematic tool to look in the right places to ask the right questions, and to move forward with confidence that the overall context relative to the region as a whole is better understood.

Description of the Water Resources Assessment Models and Submodels

This section summarizes the individual components of the watershed-based assessment models, namely those for water flow and water quality, that together constitute the water resource assessment models of the Characterization.

Defining and Subdividing the Watersheds of Puget Sound

Puget Sound drains over 15,000 mi^2 (>40,000 km^2) of land extending from the crest of the Olympic Mountains to the ridges of the Cascade Range. This area encompasses a tremendous diversity of physical features, a legacy of tectonic activity, volcanism, multiple ice-sheet advances, and riverine erosion and sedimentation. This complexity of geologic processes has yielded an equally diverse landscape.



1-Nooksack
2- San Juan
3- Skagit
4- Skagit Upper
5- Stillaguamish
6- Island
7- Snohomish
8- Cedar/Sammamish
9-Duwamish/Green
10- Puyallup/White
11-Nisqually
12-Chambers Clover
13- Deschutes
14- Kennedy/Goldsborough
15- Kitsap
16- Skokomish/Dosewallups
17- Quilcene/Snow
18-Elwha/Dungeness
19-Lyre/Hoko

Figure 14. The 19 WRIA watersheds of Puget Sound (and their numeric identifiers).

This landscape is divided most broadly into nineteen Water Resource Inventory Areas (WRIA's; Figure 14) that each encompass the contributing drainage area of one of the major rivers of the region (such as the Skagit or the Nisqually), or that include multiple smaller streams that discharge directly to the Sound. The WRIA's range in area from about 200 mi^2 (500 km^2) to more than ten times that size, and they nearly all span a broad range of topography and land uses.

At the other end of the spectrum of watershed scales lies the contributing area of any given stream segment, pond, or wetland. Small catchment boundaries across all of Puget Sound are available through the Salmon and Steelhead Habitat Inventory and Assessment Program (SSHIAP; Figure 15). Based on hydrography, topography, and habitat, these units range from 5 acres to about 5 square miles (0.02–13 km^2); they are at a much finer scale than the nationwide "HUC-12" watershed divisions assigned by the US Geological Survey, which (for example) in the area shown in Figure 15 range from about 20–80 square miles in area (http://watersgeo.epa.gov/mwm/).

For the present application of the Characterization as described in this document, SSHIAP catchments were aggregated to create analysis units that were appropriate for the scale of our source data and for the intended application of the Characterization results. The final "Assessment Units" (AU's) generally range from a few coastal units as small as one square mile, to mountainous units more than 40 square miles, with a median size of 3.4 square miles (8.8 km^2). The size of the AU's represent a tradeoff between increased resolution, analytical complexity, availability of other data at appropriate scale, and the intended uses of the results. As demonstrated in the example of the Gorst Creek watershed, however, the analytical approach of the Characterization can be applied on assessment units of any size, as long as appropriate GIS data are available at the necessary resolution.

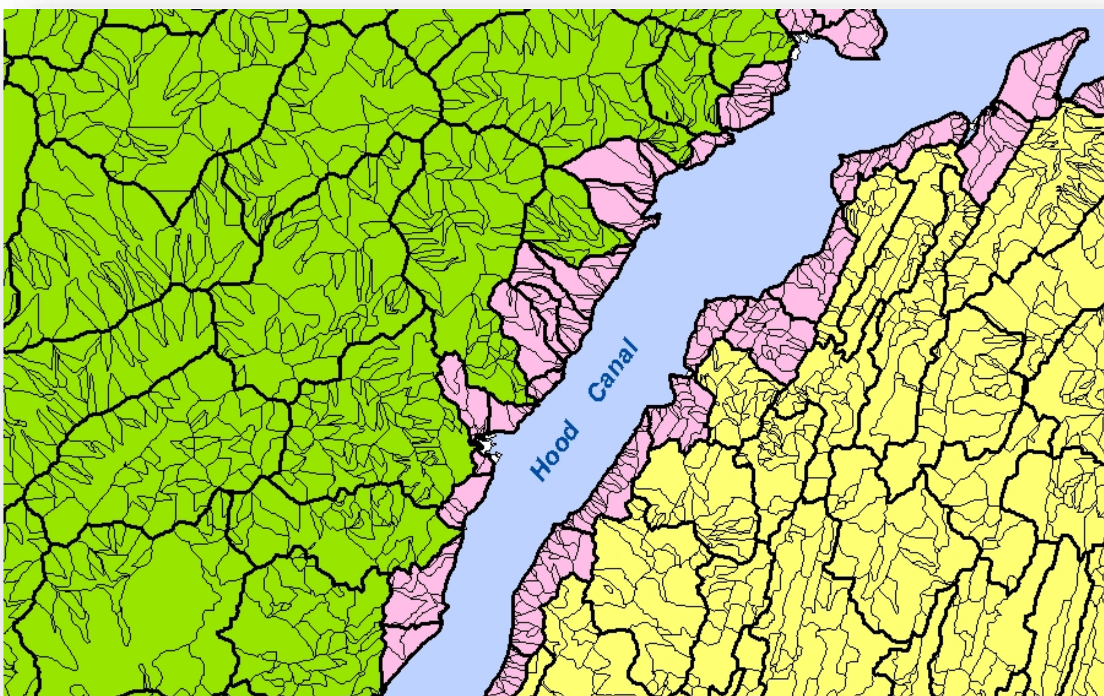


Figure 15. SSHIAP catchments and Assessment Units (southern Hood Canal area in Mason, Kitsap, and Pierce counties). Areas with thin black outlines are the individual SSHIAP catchments; those in heavy black outlines are the final Assessment Units used by the Characterization.

The Water-Flow Assessment

The water-flow assessment provides a landscape-level, integrated view (Figure 6) of the likely status of the processes that impact water quantity. The water-flow model integrates two distinct submodels, one for “importance” and one for “degradation,” that are both applied to every Assessment Unit (AU) across the Puget Sound region. A third submodel is applied only to those AU’s whose water-flow processes are affected by upstream dams (see also Appendix B and DOE 2010 for more detail on the development of and specific steps constituting each submodel).

The **importance submodel** evaluates each AU in its “unaltered” state—that is, based on its physical attributes of topography, soils, geology, and hydrology, and without any consideration of land-use changes or human modifications that may have occurred. It considers four fundamental groups of water-flow processes: *delivery*, *surface storage*, *movement* (separated into *recharge* and *discharge*), and *loss* of water in each AU. The fundamental assumption is that different parts of the landscape have intrinsic differences in their importance to supporting natural volumes, rates, and timing of delivery, storage, movement, and loss. Those areas that are most essential to maintaining natural flow regimes will presumably be those areas most critical to the support of aquatic biota that have evolved in concert with these natural conditions.

In the importance submodel, water delivery is evaluated by the quantity and type of precipitation including rain-on-snow zones, which affect the timing of water movement. Surface storage is estimated by the amount of potential depressional wetlands, lakes, and stream floodplains, using data on soil types, topography, and stream confinement (note that these features also affect the timing of water delivery). Water movement, which is important for understanding the processes of recharge and discharge, is evaluated using data on precipitation, coarse- and fine-grained soil deposits, slope wetlands, and alluvial floodplains. Loss of water through evapotranspiration is considered relatively uniform across a watershed in an unaltered state (at least in comparison to the range of variability of the other processes), and so it is not included as a variable in the importance submodel.

The importance submodel have been conducted *within each landscape group*, whose division are based on the region’s physiography (i.e., coastal, lowland, and mountain; the lowland group is further subdivided to identify those areas draining into the region’s four largest lakes) (Figure 16). The importance submodel thus results in four independent rankings of AU’s, one for each landscape group. The scores of individual landscape groups are not combined in generating the rankings for an entire WRIA or multiple WRIA’s. This reflects the judgment that *all* parts of a watershed, from headwaters to mouth, contribute to the overall health of the system, and so the AU’s within each landscape group should be evaluated for relative importance individually.

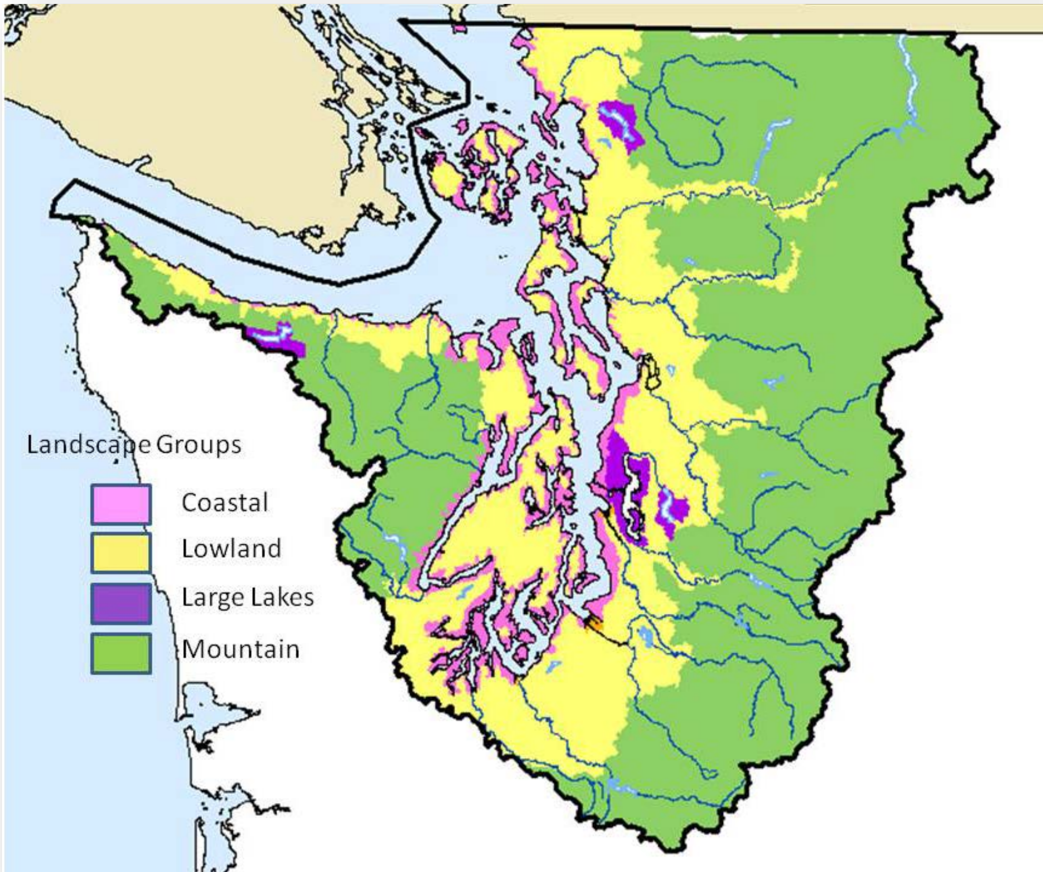


Figure 16. The four landscape groups for analysis in the Puget Sound basin: coastal, lowland, large lakes and mountain.

The **degradation submodel** 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. This evaluation is based on the magnitude of human-affected land cover (for the Puget Sound region, this is assumed to be all non-forest land, except those limited areas that are natural grassland), constructed infrastructure (roads and rooftops), and measures of consumptive water extraction and use.

By themselves, neither submodel offers clear guidance for watershed management. For example, an AU with high "importance" will benefit from different treatment if it is heavily degraded by human activity than if it is largely untouched. Similarly, the funding priorities for active restoration may benefit from considering the significance of the degraded area for supporting key watershed processes. Thus, results from the first two submodels for each AU are combined to create a "Management Matrix" (Figure 5) that provides broad-scale guidance for moving forward to improving water resources in a coherent, logical fashion.

The two submodels do not include all potentially relevant attributes of a watershed for determining management actions. The location of a particular area of concern (or an entire AU) within the watershed should also be considered, because degradation occurring high in a channel network may affect a much greater amount of aquatic resources than one near the mouth. The quality and biological importance of those resources are also likely to influence the priority of upstream actions. Therefore, the results of the Management Matrix (which can be displayed readily on a map) will normally require additional interpretation and context-setting. Although some generalized guidance is provided in this document, recommendations that apply to a particular locale or an individual site cannot be provided by the Characterization methodology without additional site-specific information and the expertise necessary to make use of it. These more detailed scales of management actions are not addressed in this document.

A third submodel that is applied only to certain AU's evaluates the effect of dams on the hydrologic regime of rivers and streams they regulate. It considers the storage capacity of the dam relative to annual runoff generated by the watershed above a dam and the amount of runoff contributed to the stream system downstream of the dam. Results of the dam submodel are not incorporated into the Management Matrix, but its score can be used to evaluate the downstream extent of degradation to the hydrologic regime of the regulated stream system. This information can help inform the best location for instream restoration projects.

The Water-Quality Assessments

Within the overall approach of the watershed-based assessments, water quality is a key element to inform management decisions. The approach used here to characterize the conditions for a suite of water-quality constituents is largely analogous to the approach used to assess water-flow processes. The significant differences from the water-flow modeling are highlighted here and detailed in Appendix C. As with the water-flow model, the water-quality models can provide a valuable regional-scale perspective on the spatial distribution of watershed resources and impacts, specifically related to water quality, that is not generally provided by other available tools.

Water quality is evaluated in five individual models, addressing sediment, metals, pathogens, phosphorus, and nitrogen. These constituents were chosen because, in excess quantities (and for toxins, in any amounts), they degrade the beneficial uses of the state's aquatic ecosystems. Each of the water-quality models parallels the structure of the water-flow model, having two distinct submodels: one for "export potential" (analogous to the "importance" submodel for water flow) and one for "degradation." Both submodels are applied to every AU across the Puget Sound basin.

The **export potential submodel** evaluates each AU without any consideration of land-use changes or human modifications. It considers four fundamental groups of processes that together describe delivery, storage, movement, and loss of a particular water-quality constituent in any given watershed. “Export potential” is a measure of an AU’s relative capacity (if it were disturbed) to generate and transport contaminants to aquatic areas downstream and ultimately to Puget Sound,

The **degradation submodel**, in contrast to the water-flow model, evaluates the watershed in its “altered” state by use of a numerical model, N-SPECT (the “Nonpoint-Source Pollution and Erosion Comparison Tool”), to assess the degree of existing degradation to sediment processes based on compiled GIS land-use data together with a compilation of “typical” contaminant loadings for various land uses. N-SPECT uses pollutant export coefficients to quantify the relationship between land use/land cover and pollutant amounts, and it is applied pixel-by-pixel across the entire Puget Sound basin. For use within the Characterization framework these results are summed by AU, but the raw results on a pixel-by-pixel (i.e., 30×30 meter) basis are also available here for other applications.

As with the water-flow model, none of the water-quality models in isolation offers clear guidance for watershed management. Water-quality conditions differ from those of water flow, however, by being subject to regulatory thresholds and, locally, TMDL requirements that must be followed in any management strategy. Conversely, the water-quality components that are considered in the watershed-based assessments are transported by the water flow, and so they are a consequence of, not a driver of, water-flow conditions. Because Characterization is a planning tool, not a regulatory tool, it makes use of water-quality results only in the latter context—namely, as “modifiers” of the primary strategy recommendations of the water-flow model.

Results of the Water Resources Assessments

At the present stage of the Puget Sound Characterization, the best-developed assessments are those that focus on water resources—namely, the water-flow assessment and the water-quality assessment. Both share the same spatial organization (the multi-square-mile Assessment Units (AU's), divided into individual WRIA's or grouped Puget Sound-wide); they also have the same model structure, with the "importance" (termed "export potential" for water quality) and the "degradation" of each individual AU determined separately.

This section describes the basic methodology and key results of these analyses by focusing on a few specific locations; comprehensive results are available for viewing or downloading from the Characterization website (LINK).

Water-Flow Assessment Results

As previously outlined, each AU has two sets of analyses for water flow: one for **importance** and the other for **degradation**. We will explore the results of each in turn.

The "Importance" submodel is based on an assessment of the physical characteristics that control the natural performance of each watershed process in its unaltered state without any consideration of land-use changes or human modifications; thus, "*important areas*" have characteristics that maintain one (or more) of the key watershed processes (delivery, surface storage, recharge, discharge). For the delivery subcomponent this would include mapping of average annual precipitation and the location of other areas, such as rain-on-snow zones, that regulate the timing of delivery of water (i.e., greater total annual precipitation and/or a greater proportion of an AU in the rain-on-snow zone rates greater importance for delivery). For storage of surface waters, depressional wetlands and floodplains are mapped since they strongly influence the magnitude of downstream discharges. For recharge, the permeability of surface deposits and precipitation are primary determinants on the amount. For discharge, areas of slope wetlands and permeable floodplains are considered primary indicators since they represent the most likely areas where groundwater resurfaces. Appendix B further describes our current understanding (and assumptions) regarding these relationships for each process, and Figure 17 presents a summary of the model.

***Key Questions**:*

- In the absence of human degradation, what areas are important to each watershed process?
- Where are these areas and what are their relative importance to each process?

The scoring for the **importance submodel** generates a *relative* ranking of AU's within each landscape group across the selected analysis area, from most to least important, by ordering the sum of the individual component scores that assess the importance of each AU for each process: delivery, surface storage, and recharge/discharge of water ("loss" is not included in the submodel insofar as it is assumed not to vary significantly between different AU's of the Puget Sound basin). Summary maps display these rankings for each individual water-flow process for either a single WRIA or the entire Puget Sound basin. Although the submodel generates "importance scores" along a continuous range, for purposes of a map display the AU's are grouped into evenly distributed quartiles (labeled high, medium-high, medium-low, and low), with the darkest colors indicating the most important quartile relative to the others.

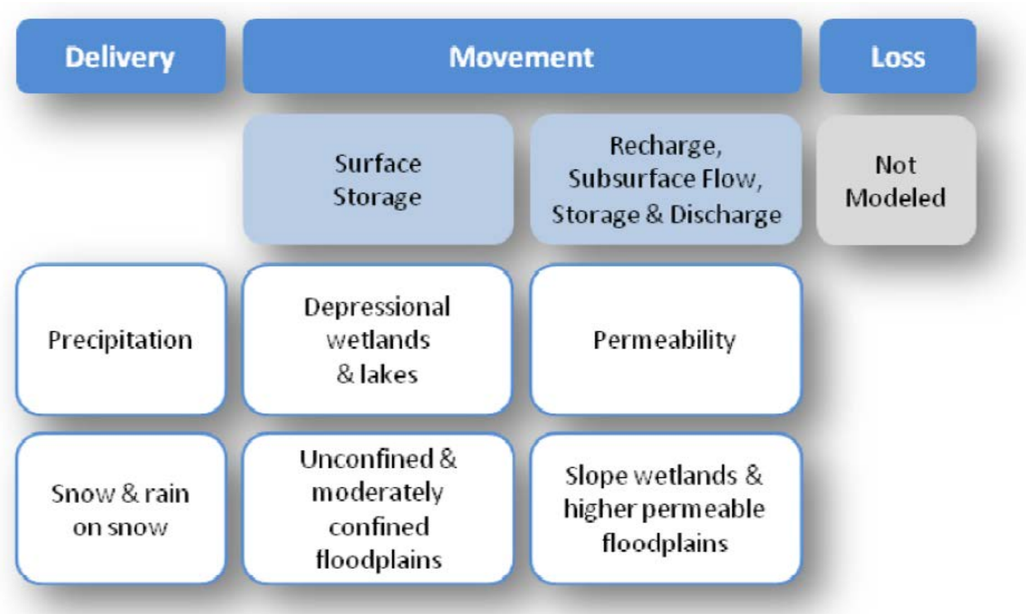


Figure 17. Summary of the importance submodel for water-flow assessment. Sub-components are indicated in blue boxes and indicators are in white boxes.

The **degradation submodel** is largely analogous to the importance submodel in both execution and display (Figure 18). It represent the *relative* ranking of AU's based on where human activities are likely disrupting or degrading watershed process(es). Thus, "*degraded areas*" have characteristics inferred to significantly impair one (or more) of the key watershed processes used in the importance submodel (i.e., delivery, surface storage, recharge, discharge). For example, the clearing of forest affects the delivery of precipitation to streams and wetlands by decreasing the distance that water would follow in unaltered conditions. Construction of impervious surfaces, such as roads or buildings, can prevent the recharge of groundwater. Wells can add to this impact by withdrawing water from shallow groundwater supplies. These activities may reduce the amount of groundwater available for discharge to streams and wetlands. Channelization in streams and draining/filling of wetlands decreases the amount of natural storage in an AU. This can, in turn, increase the degree of downstream flooding and erosion.

> ***Key Questions*:**
>
> - What human alterations have degraded each watershed process?
> - Where do these alterations occur and what is the relative severity of the degradation?

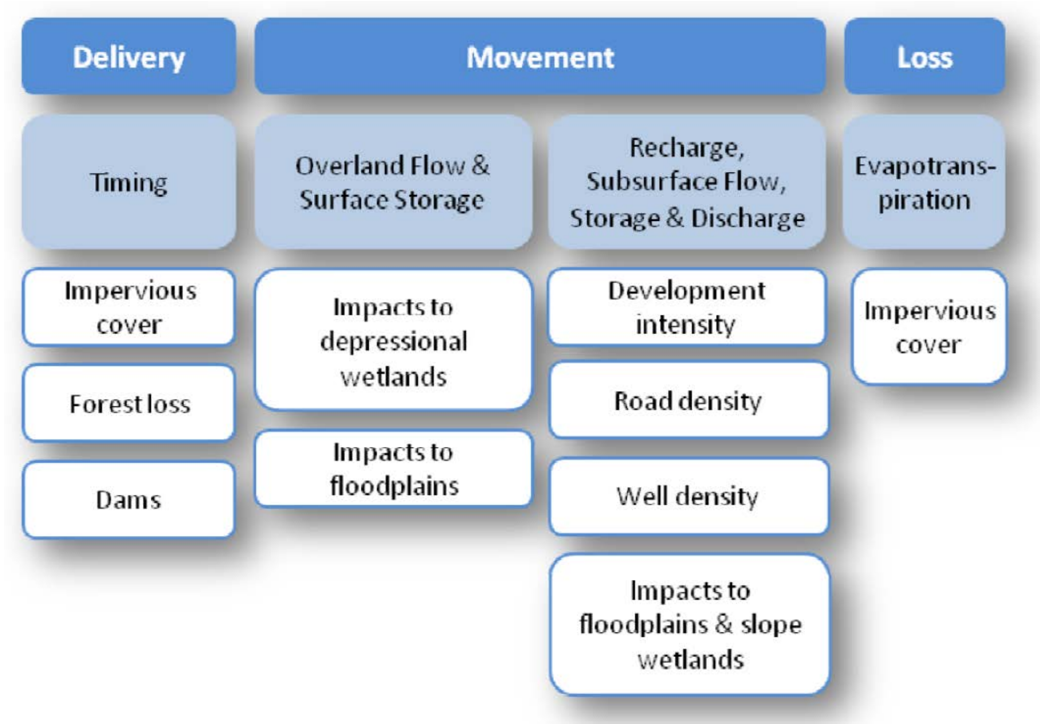


Figure 18. Summary of the degradation submodel for water-flow assessment. Sub-components are in blue boxes and indicators are in white boxes.

Unlike the importance submodels, degradation results are not stratified by landscape group. This reflects the judgment that the severity of degradation is not related to location in the watershed. In other respects, however, these two submodels[4] are executed and displayed using identical approaches. Appendix B describes our assumptions regarding the relationships between GIS data, landscape conditions, and water-flow degradation for each process.

Puget Sound-Wide Results

The submodels for the water-flow processes based on all AU's in the region offer the broadest view of water-flow conditions across the entire Puget Sound basin. Ultimately, the accuracy of AU scores is limited by the availability of comprehensive GIS data and the model

[4] A third submodel, that for assessing the effects of dams, is discussed separately (see below).

uncertainties. Nonetheless, such a synoptic view cannot be obtained by any other means, and the perspective is a useful one.

Because the importance submodel treats each landscape group (coastal, lowland, large lake, and mountains) independently, the results are most appropriately understood by group. At the scale of the entire Puget Sound basin, the AU's composing the coastal landscape group are too small to see in figures. The broad patterns displayed by the lowland and mountain groups, however, can be readily seen even on a page-size printed map (Figure 19a and 19b).

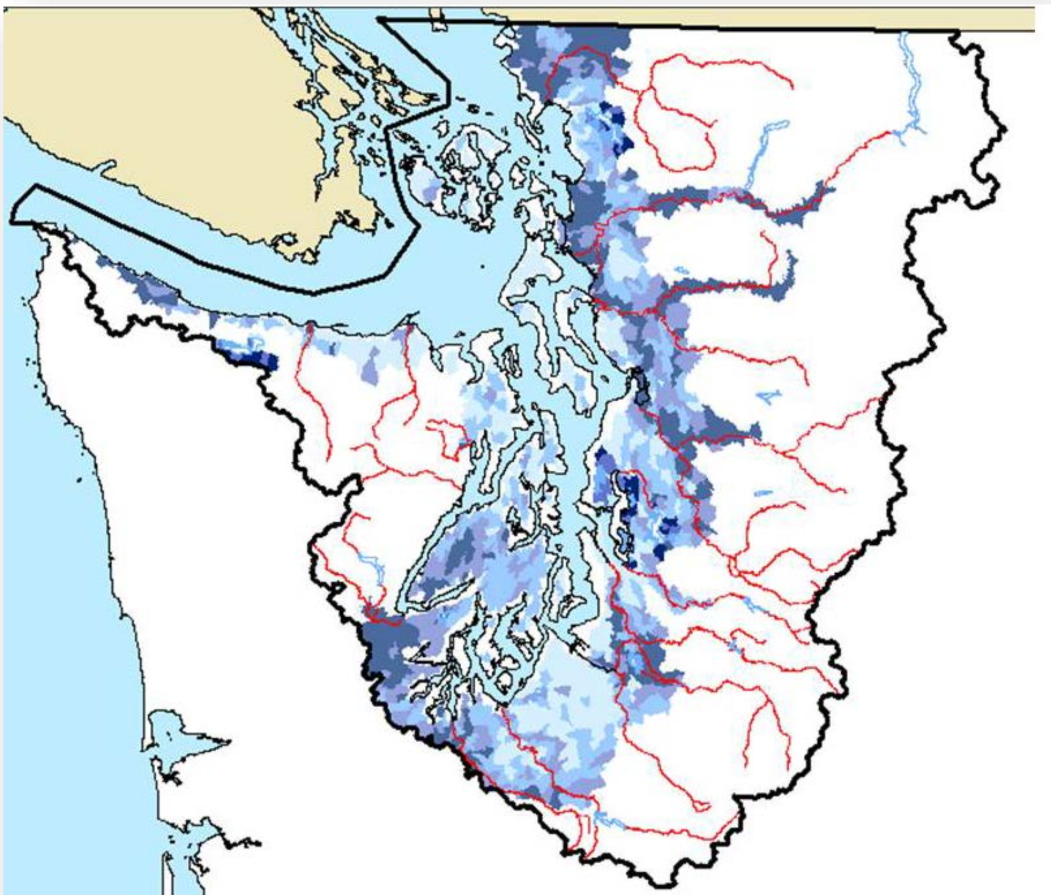


Figure 19a. The "importance" map for the water-flow assessment, lowland landscape group. Dark blue AU's are the most important (i.e., have the highest combined score for importance); lightest blue AU's are the least important for the water process. Major rivers highlighted in red. This map displays only the *combined* scores for the three components, but each can also be displayed individually. In this and the following figures, results are shaded in four groups ("High," "Medium-high," "Medium," and "Low). Note the predominance of high-importance AU's along the floodplains of many of the region's major rivers, and in deltas and some estuaries.

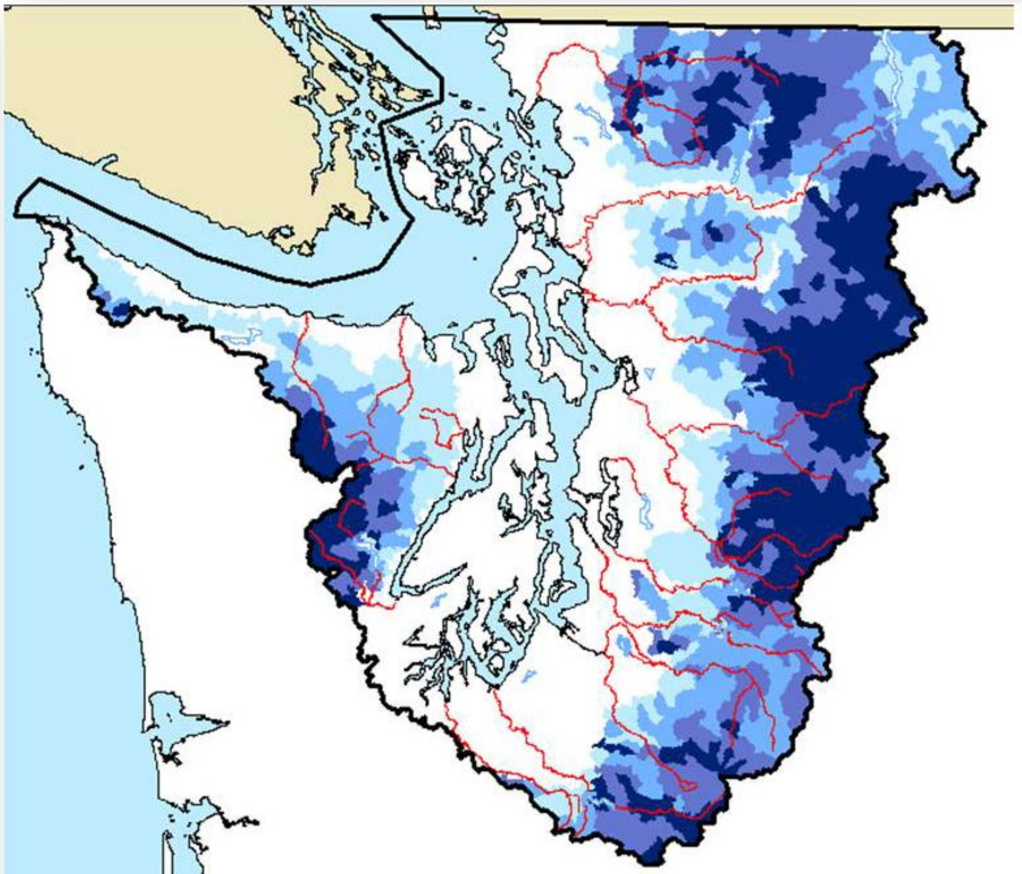


Figure 19b. The "importance" map for the water-flow assessment, mountain landscape group. Colors are as in Figure 19a. Note the predominance of high-importance AU's along much, but not all, of the crest of the Cascade Range, particularly north of the Snoqualmie River; and almost uniformly at high elevations of the Olympic Mountains.

The degradation submodel does not analyze each landscape group separately, and so the results can be displayed on a single map (Figure 20). The pattern of degradation is particularly clear from this perspective: degradation follows population density almost precisely, reflecting the overarching effects of impervious surfaces on virtually every water-flow process. Non-urban areas with extensive forest clearing also can be discerned, but except for the heavily agricultural parts of the lower Skagit and Nooksack rivers, virtually all are of a lower category of degradation and are more widely scattered across the mountainous areas and much of the immediately adjacent lowlands. Coastal areas, with the exception of Hood Canal and the western Juan de Fuca, broadly display the inferred consequences of many decades of urban and suburban development.

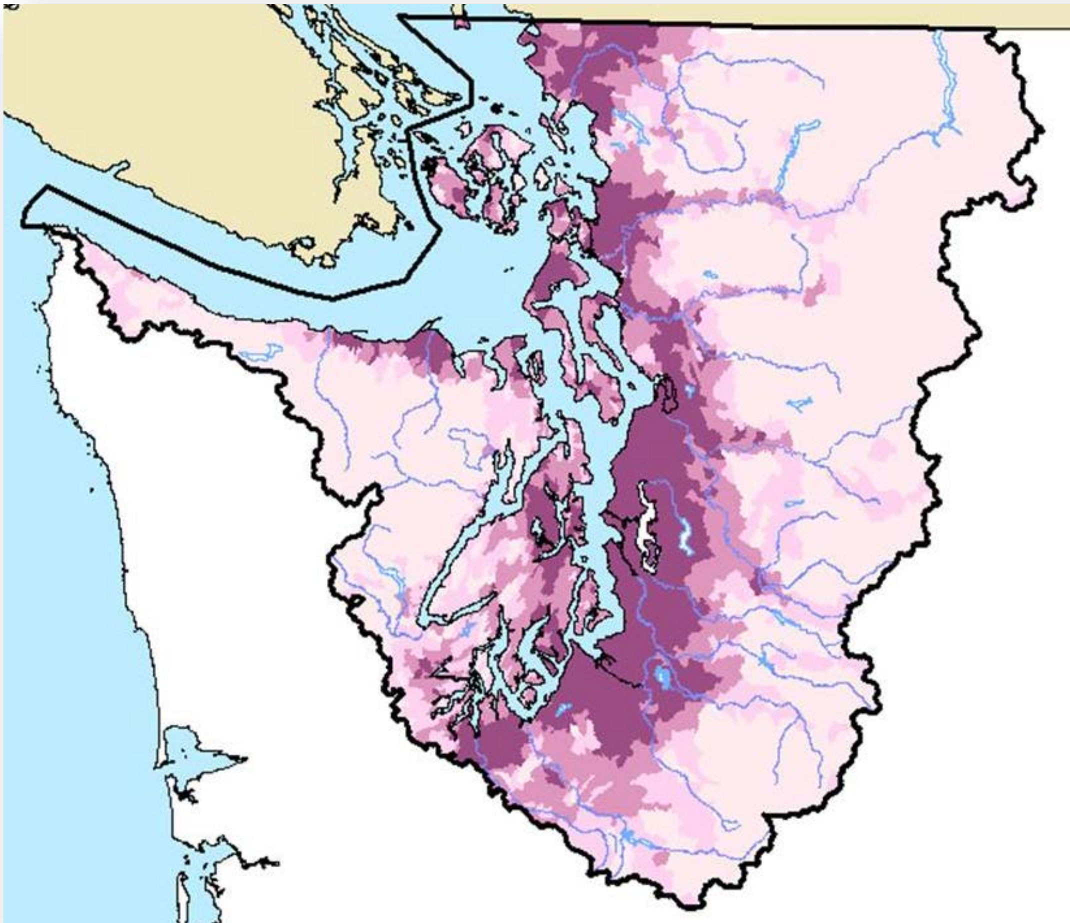


Figure 20. The "degradation" map for the water-flow assessment across the Puget Sound basin. The darkest pink shading indicates the highest quartile of degradation. Note the predominance of greatest degradation in urban areas and a few zones of intensive lowland agriculture; in contrast, the forested uplands, even in non-protected working lands, are generally in the lowest category of impairment.

WRIA-Specific Results

The water-flow model can also be run on at a WRIA-by-WRIA basis, with AU scores only compared to other AU's within a single WRIA. This would be the most appropriate scale of analysis for watershed-management groups, where the focus is not on addressing the needs of the entire Puget Sound basin but rather a somewhat smaller area of concern.

Because there are 19 WRIA's in the Puget Sound basin, there are 19 such analyses. We present here one example, namely the analysis and mapping of the water-flow processes for WRIA 11 (Nisqually) in the southeast part of the basin (Figures 21a-21b).

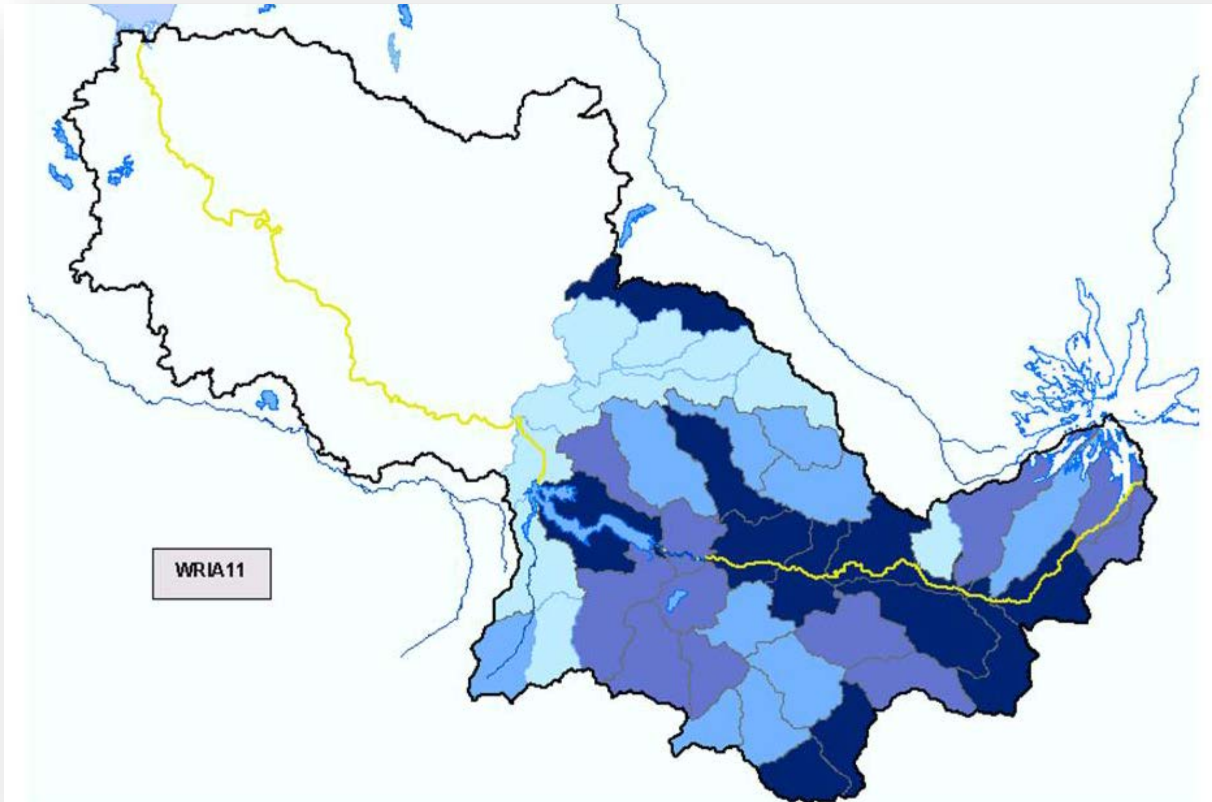


Figure 21a. Important areas for water flow processes, mountain landscape group, WRIA 11 (Nisqually River basin,, Thurston County). This map presents the overall results of the water-flow assessment for the mountain landscape group. Darker blue watershed units represent areas of greater importance to water-flow processes.

Several differences are apparent between this WRIA-specific analysis (Figures 21a-b) and the Sound-wide results (Figure 19a-b). Most importantly, the WRIA-specific analysis will always identify a nearly even distribution of "high," "medium-high," "medium," and "low" importance areas. However, relative to all AU's across Puget Sound, any given WRIA may not have proportional representation in each category.

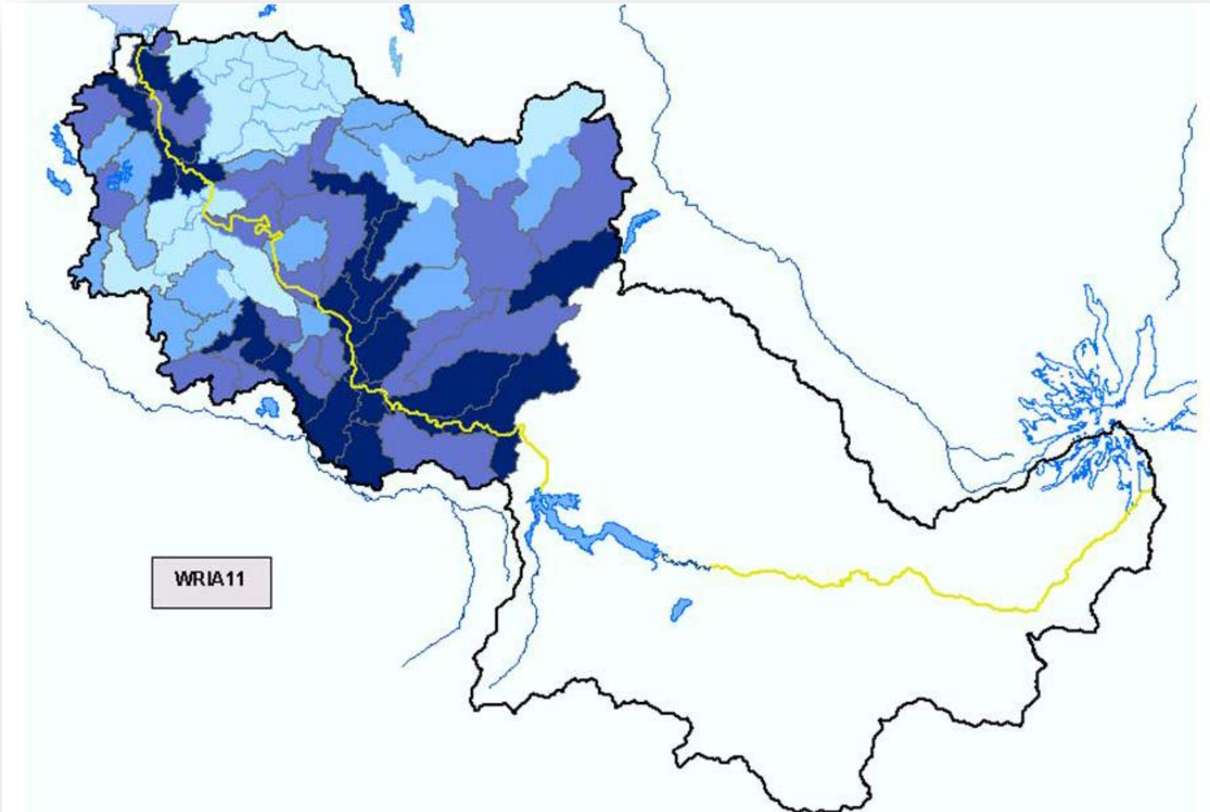


Figure 21b. Important areas for water flow processes, lowland landscape group WRIA 11. Darkest assessment units are the most important (High rating) and lightest assessment units are the least important (Low rating) for water-flow processes. Results are shown in quartiles.

For example, in Figure 19a the lowland landscape group for WRIA 11 shows limited areas of high importance—the major river valleys farther north have a much greater proportion of their area in features (particularly wetlands and unconfined floodplains) important for water-flow processes. On the other hand, the WRIA 11 assessment for the lowland (Figure 21b) recognizes regionally high-importance areas for this watershed along much of the Nisqually River.

Degradation of the water-flow processes for WRIA 11 is displayed in Figure 22, which shows the results of combining all of the water-flow process results into a single ranking. As noted above, rankings for degradation are made across all landscape groups and so the results can be shown in a single figure. The areas of highest relative degradation (e.g., Lacey, Yelm, Fort Lewis) are clustered within a single landscape group because the distribution of disturbance (commonly forest clearing and impervious surfaces) is also unevenly distributed.

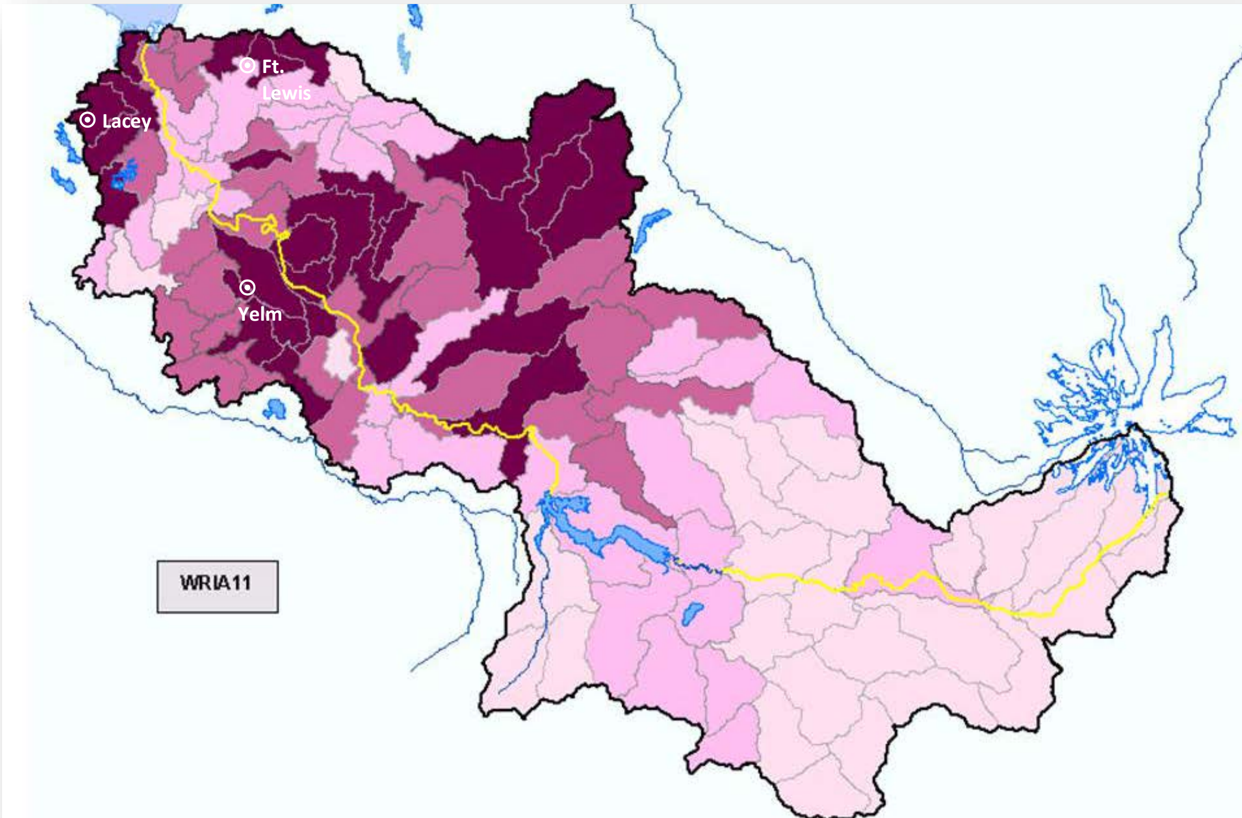


Figure 22. Overall degradation map for water-flow processes, WRIA 11. The darkest pink areas are the most degraded, with urban areas (in the northwest and west-central areas) showing the highest level of degradation.

Submodel for the Effects of Dams

The downstream effect of dams is dependent on: 1) the storage capacity of the dam relative to annual runoff generated by the watershed above a dam, and 2) the amount of runoff contributed to the stream system downstream of the dam. For example, if a reservoir can hold the entire annual runoff volume of a watershed then we assume that dam has a very large effect on downstream processes (since it could potentially impact the natural flow patterns over the entire year-long life cycle of stream biota).

The results of the dam analysis are presented in Figure 23 for WRIA 7, Snohomish River basin. Three colors are shown to depict the individual effect of each dam, repeating the analysis for each river segment in a downstream progression. Red represents a "high" effect upon downstream processes, yellow a "moderate" and light blue a "low" impact. The range of values for each color represent the depth of storage in feet of water across the watershed that the dam captures and regulates (i.e., upstream of the dam). This value can then be directly compared to the average precipitation value for the regulated watershed in order to assess its impact. For instance, the reservoir behind Culmback Dam on the Sultan River can retain over 4.6 feet (54”) of runoff from the regulated watershed. This is represented as having a *high* potential impact upon downstream flows, as is any reservoir that retains more than 4 feet (1.2 m) of watershed runoff. Note that the annual precipitation in this area is approximately 70” to 90”, and so the dam is capturing more than half of the annual precipitation. A dam that captures between 1 to 4 feet (0.3–1.2 m) of runoff (which, depending on specific location, is equivalent to a range of about one-fifth to nearly all of the annual precipitation) is represented to have a *moderate* potential impact (darker yellow to tan color). Less than 1 foot of runoff storage is presumed to imply *low* potential impact.

However, the actual downstream consequences also depends on the actual operation schedule of the dam, which is not incorporated into the Characterization analysis. This is another example for which additional, site-specific information is critical before any final management decisions can be made.

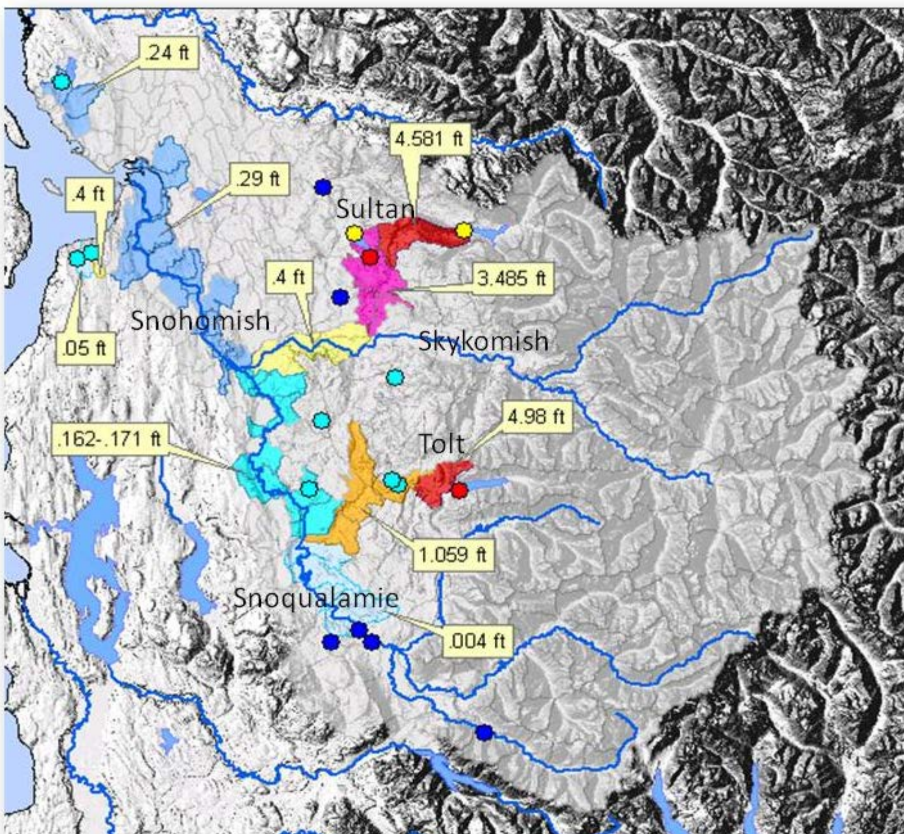


Figure 23. Dam analysis for WRIA 7, Snohomish basin. Dams included in this analysis are shown by colored dots. Numeric values represent the amount of storage in feet of the total annual runoff from the watershed above the AU (not just above the dam itself). Thus, the storage is greatest for the AU containing the dam and is reduced moving downstream away from the dam as runoff from unregulated watersheds contribute to flows for the stream affected by the dam. The downstream AU’s are shown as “red” for relatively high potential impact, (>4’ upstream storage), yellow for moderate (1 to 4’ storage) and shades of blue for low (<1’ storage).

Because of frequent and commonly voluminous precipitation in the Puget Sound basin, the downstream effects of dams on watershed processes attenuate more quickly relative to watersheds characterized by snow in upper elevations and limited precipitation in lower elevations (e.g., the Rocky Mountains of Colorado). For dams on both the Sultan and Tolt rivers, for example, the most significant effects are on the reaches in AU's immediately below the dam and decrease to negligible at the confluence with the next major unregulated drainage (for these examples, the Skykomish and Snoqualmie rivers).

Water-Quality Assessment Results

Analogous to the water-flow assessment, the water-quality model is composed of two submodels, applied to each AU and then combined to display the final results using a management matrix. For each water-quality parameter, submodels for **export potential** and **degradation** are evaluated by AU and mapped either by individual WRIA or Puget Sound-wide.

For simplicity, the results presented in this section are limited to the "sediment" water-quality model and its component submodels. Both the individual submodel results and the management matrix are equivalent for the other water-quality parameters evaluated by Watershed Characterization (metals, pathogens, phosphorous and nitrogen). As with the water-flow results, WRIA 11 is used to display the results for both the "export-potential" (Figure 24) and "degradation" submodels (Figure 25). The export-potential submodel for sediment assesses how readily a given AU can deliver sediment to downstream AU's based on the density of streams and connected wetlands, the relative area of sources of sediment (soil erosivity and landslides) and relative area of sinks that can remove sediment from the transport system. In contrast, the degradation submodel uses the direct output from N-SPECT to characterize the degree of existing degradation to sediment processes based on land-use type.

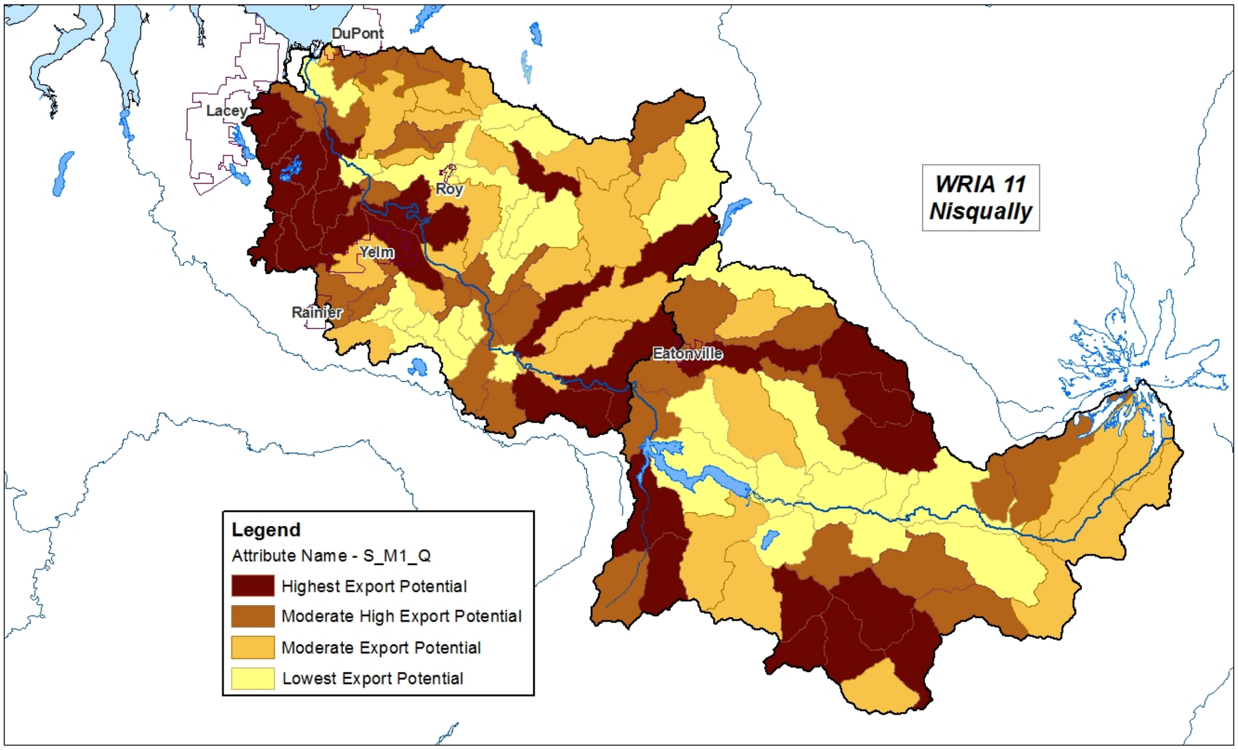


Figure 24. Sediment export potential for WRIA 11. Depicted are the submodel results for sediment export potential, without consideration of existing land uses. The dark brown and light brown AU's represent areas with the highest relative potential, if disturbed, for exporting sediment; tan and pale tan AU's have progressively lower potential. The upper watershed has a moderate to high potential for sediment export, as do areas southwest and east of Eatonville, north to northwest of Yelm, and in the City of DuPont.

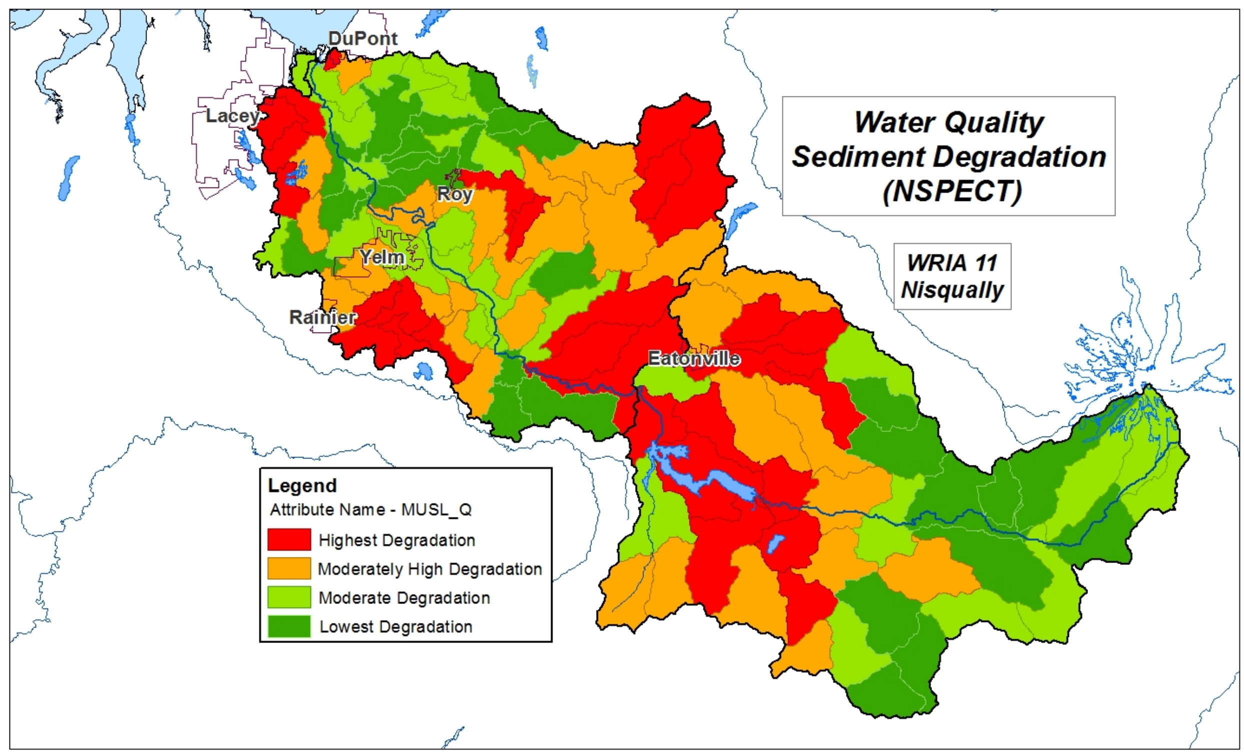


Figure 25. Degradation to sediment processes. Results of the N-SPECT submodel that assesses the relative level of degradation to sediment processes given existing land use. Red AU's followed by orange AU's represent the highest level of degradation, with dark green and light green showing the least. Some of the most extensive degradation is occurring within the central watershed around Eatonville, which includes rural agricultural activities to the west and north and commercial forestry activities to the east and south.

The management matrix for sediment, which combines the results of the two submodels on an AU-by-AU basis into integrated recommendations for management strategies, is presented in Figure 26. AU's that have a high score for export potential (i.e., high stream/wetland density, many sources of sediment), fewer areas to remove sediment (depressional wetlands and floodplains), and low levels of existing degradation constitute the areas least suited for high-intensity land-use activities (such as forest clearing or urban development) that would increase erosion and transport of sediment. These are actual or potential "source" areas for sediment. If presently un-degraded, they fall into the dark green "protection" quadrant of the matrix and would yield the greatest benefits from management approaches that protected the underlying "source" processes and conditions. Source areas that have already been degraded (yellow quadrant) should be the highest priority for restoration.

In contrast, areas with fewer sources of sediment, a poorly connected sediment-transport system, and many sinks (e.g., wetlands and floodplains) that can remove sediment are less sensitive to the impacts of land-use-change, assuming that the wetlands and floodplains themselves were adequately protected. These AU's plot in the lower half of the matrix, with those at a presently low level of degradation (light blue quadrant) warranting the protection of sinks, whereas those with high existing degradation suggest the value of restoring those sinks in the context of existing land-use activities.

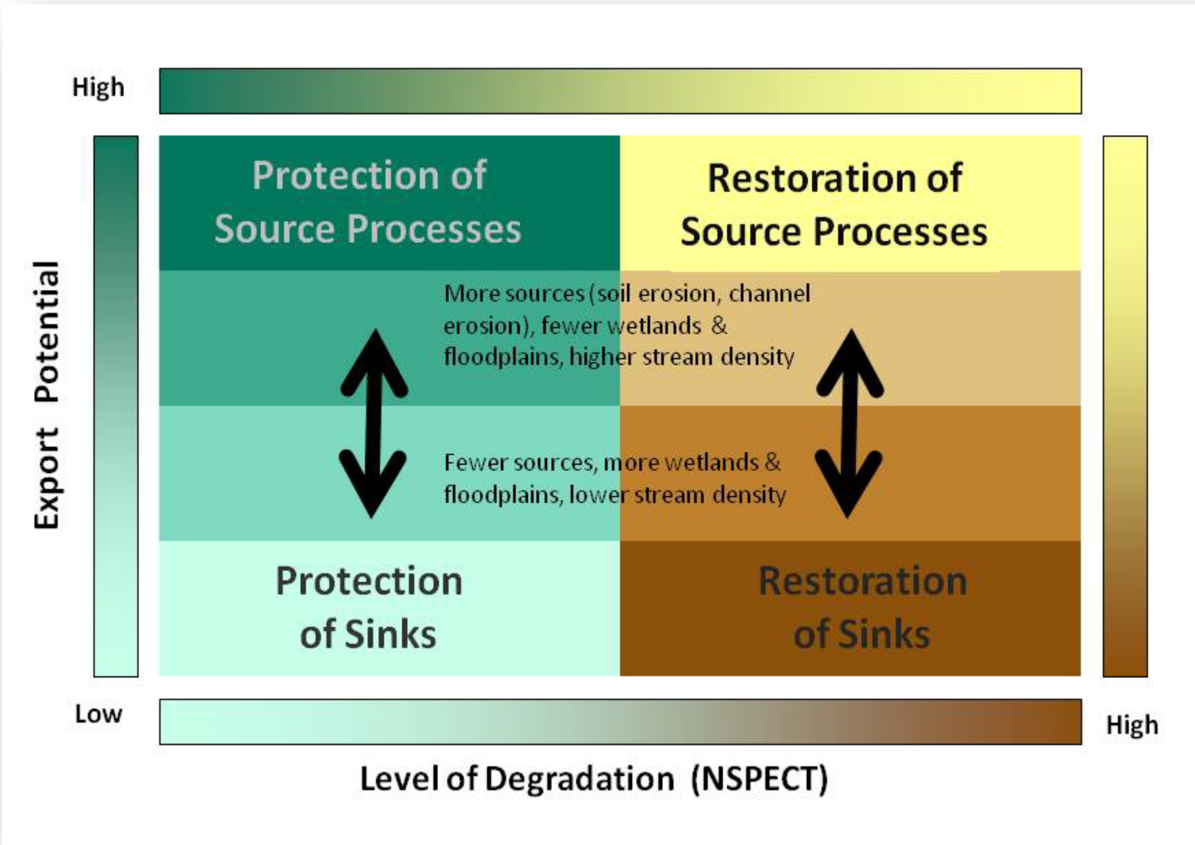


Figure 26. Management Matrix for the Sediment Model. Dark green areas have the greatest potential to transport sediment and the lowest level of degradation; yellow "restoration" areas have similar export potential but a higher degree of existing degradation. Future high-intensity development should be avoided in "protection" areas. whereas active measures to restore source processes should be undertaken in "restoration" areas. AU's plotting in the lower portion of the matrix (light blue and brown) have fewer sources of sediment and less capability to transport sediment due to more wetlands and floodplains, which typically function as pollutant sinks, and lower stream density. The land management should focus on the protection of those sinks where existing degradation is low (lower left corner), but where degradation is already present (lower right) then restoration of sinks would be needed to reduce the export of sediment.

Figure 27 displays the integrated results of the two submodels for sediment in WRIA 11. Further development activities, such as forestry and road-building, are not indicated on the basis of this analysis with respect to sediment generation in the upper watershed. These are areas of high rainfall and erosion, frequent landslides, a well-connected stream network to transport sediment, and few sinks to remove sediment. The dark brown and light blue-green areas immediately below the upper watershed have a lower export potential, however, and so are likely to be more appropriate for forestry activities.

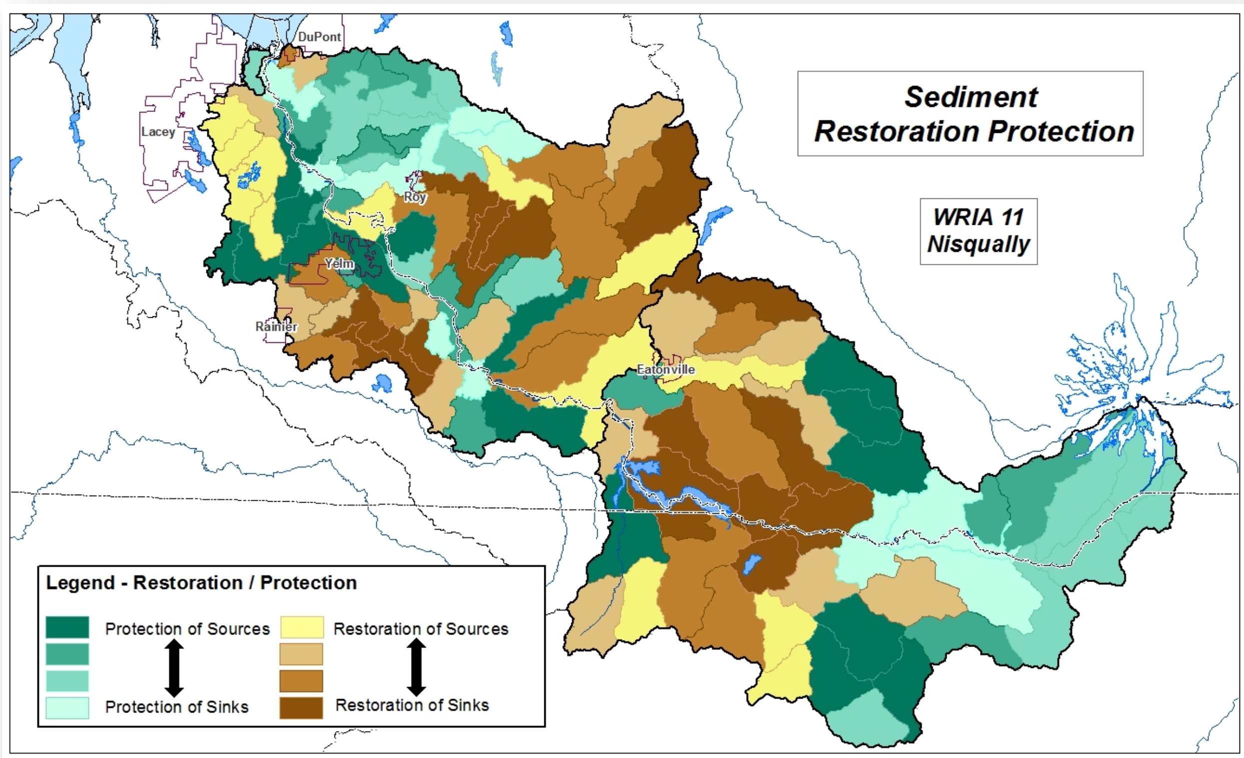
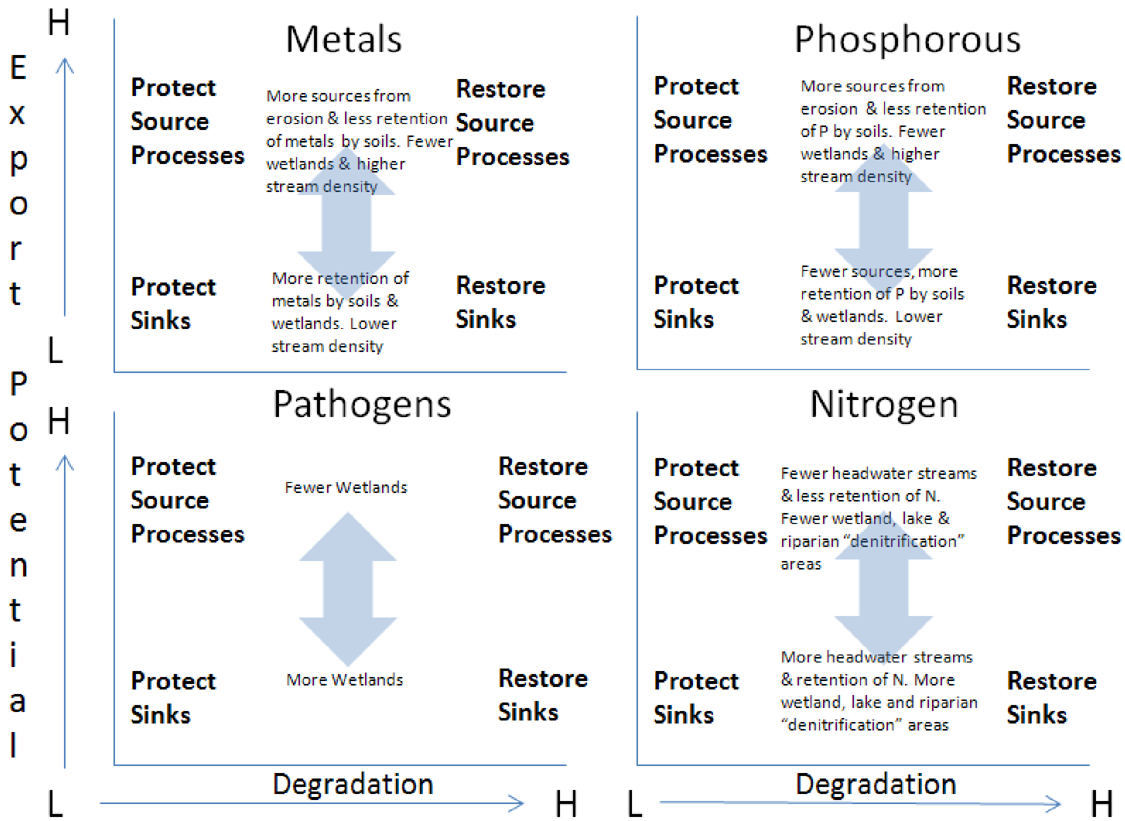


Figure 27. Integrated results for the sediment water-quality model, WRIA 11. Using the management matrix in Figure 26, eight management categories are suggested. The dark blue-green areas represent locations that have the greatest potential to transport sediment and the lowest level of degradation. These areas require protection of the sources of sediment. The light blue-green areas require protection of sinks. The yellow areas indicate a need for restoration of processes controlling erosion of sources, since they have the highest potential to transport sediment but are also the most altered. The dark brown areas are least likely to transport sediment provided altered sinks (wetlands and floodplains) are restored. The results suggest that areas presently contributing to sediment transport (yellow category) should modify ongoing practices to minimize erosion and transport of sediment, including forest practices northeast of Eatonville and agricultural practices to the west.

The results also indicate areas where existing development is probably contributing to the transport of sediment above naturally occurring levels. A band of yellow AU's (Restoration) is located west and southwest of Eatonville, reflecting current land-use practices (agriculture, in this area) that are likely to be contributing to degradation. Depending on the importance of sediment pollution to downstream waterbodies, these results more broadly suggest that this area may not be well-suited for urban expansion by the City of Eatonville. Yellow AU's east of

Eatonville are areas where commercial forest activities are probably contributing to higher sediment loads. The location of several source restoration (yellow) AU's immediately upstream of the Nisqually Delta (just southeast of the city of Lacey) also suggest a high priority for restoration of these processes, since existing activities may be directly contributing higher sediment loads into the delta wetlands.

Equivalent display maps, and the underlying analyses, have been developed for each of the other water-quality parameters (metals, pathogens, phosphorus, and nitrogen) and are being posted on the Characterization website as final maps are completed. Each parameter has slightly different considerations for determining their export potential, but the results from the parameter-specific submodel are combined with the results from the parameter-specific N-SPECT results in analogous management matrices (Figure 28).



Management Actions

Sediment, Metals, & Phosphorous:

Protect Source Processes = Prevent activities that remove vegetation cover & increase channel erosion

Restore Source Processes = Restore natural cover and control existing sources

Protect Sinks = Protect wetlands, lakes, floodplains

Restore Sinks = Restore wetland and floodplains

Pathogens:

Protect Source Processes = Limit new sources of pathogens

Restore Source Processes = Control existing sources of pathogens and restore wetlands

Protect Sinks = Protect wetlands

Restore Sinks = Restore wetlands

Nitrogen:

Protect Source Processes = Limit new sources of N & prevent impacts to headwater streams, wetland, lake and riparian denitrification areas

Restore Source Processes = Control existing sources of N

Protect Sinks = Protect headwater streams and areas of denitrification

Restore Sinks = Restore headwater streams and areas of denitrification

Figure 28. Management matrices for the other four water-quality assessments. The blue arrows indicate the landscape conditions that control the export of pollutants to aquatic areas. The four quadrants, relative to export potential and degradation, indicate whether "protection" or "restoration" of sinks or source processes should occur. Management actions are identified for each protection and restoration category.

In Closing

At the present stage of development of the Puget Sound Characterization, its multiple models for water flow and water quality (and pending models for freshwater, terrestrial, and marine habitats) are not fully integrated. The early history of this project focused exclusively on water-flow processes and conditions, reflecting the widespread understanding of their critical importance on the overall health of Puget Sound and its contributing landscape. The judgment of this overarching importance remains unchanged, but the increasing range of challenges (together with the increasing sophistication of both scientific understanding and analytical tools) has motivated a significant expansion of the Characterization's scope. This volume has presented one such step forward, namely the development of the water-quality models, together with more systematic guidance of how to apply the water-flow results to management issues confronting the region. The next steps—completion of the habitat models; decision-support tools for management application; and full integration into a single, coherent framework for direct agency and public access—are all in progress and are anticipated to bring the Puget Sound Characterization to full implementation over the next two years.

References

Agee, J.K. 1993. Fire ecology of Pacific Northwest forests. Island Press, Washington, DC. 493 pp.

Bedford, B.L. 1996. The need to define analysis equivalence at the landscape scale for freshwater wetland mitigation. Ecological Applications 6:57-68.

Bedford, B.L. and E.M. Preston. 1988. Developing the scientific basis for assessing cumulative effects of wetland loss and degradation on landscape functions: Status, perspectives and prospects. Environmental Management 12(5): 751-771.

Beechie, T., and Bolton, S. 1999. An approach to restoring salmonid habitat-forming processes in Pacific Northwest watersheds. Fisheries, 24 (4), pp. 6-15.

Beechie, T.J., D.A. Sear, J.D. Olden, G.R. Pess, J.M. Buffington, H. Moir, P. Roni, M.M. Pollock, 2010. Process-based principles for restoring river ecosystems.: BioScience 60(3): 209 – 222.

Benda, L., N.L. Poff, D. Miller, T. Dunne, G. Reeves, G. Pess, and M. Pollock. 2004. The network dynamics hypothesis: how channel networks structure riverine habitats. BioScience 54: 412-427.

Booth, D.B., J.R. Karr, S. Schauman, C.R. Konrad, S.A. Morley, M.G. Larson, and S.J. Burges. 2004. Reviving urban streams: land use, hydrology, biology, and human behavior. Journal of the American Water Resources Association 40(5): 1351-1364

Buffington, J.M., R.D. Woodsmith, D.B. Booth, and D.R. Montgomery. 2003. Fluvial processes in Puget Sound rivers and the Pacific Northwest. In: Restoration of Puget Sound Rivers. Eds: D.R. Montgomery, S. Bolton, D.B. Booth, and L. Wall. University of Washington Press. 46-78 pp.

Cederholm, C.J., Kunze, M.D., Murota, T., Sibatani, A., 1999. Pacific salmon carcasses: Essential contributions of nutrients and energy for aquatic and terrestrial ecosystems: Fisheries, 24 (10), pp. 6-15.

Cereghino, P.R., 2010. Considerations for Puget Sound restoration programs that restore beach ecosystems. pp. 213-220 in Shipman, H, Dethier, M.N., Gelfenbaum, G., Fresh, K.L., and Dinicola, R.S. eds. 2010. Puget Sound Shorelines and the Impacts of Armoring: Proceedings of a State of the Science Workshop, May 2009; U.S. Geological Survey Scientific Investigations Report 2010-5254.

Dale, V.H., S. Brown, R.A. Haeuber, N.T. Hobbs, N. Huntly, R.J. Naiman, W.E. Riebsame, M.G. Turner, and T.J. Valone. 2000. Ecological principles and guidelines for managing the use of land. Ecological Applications 10(3): 639-670.

Department of Ecology Water Quality Program. 2005. Stormwater management manual for western Washington, Volumes I – V. Publication # 05-10-029 to 05-10-033.

Fuerstenberg, R. 1998. Needs of salmon in the city: Habitat in the urban landscape. In: Proceedings of the 1st Salmon in the City Conference, May 20-21, 1998. Mt. Vernon, WA.

Frankenstein, G. 2000. Blooms of Ulvoids in Puget Sound. Puget Sound Water Quality Action Team Publication, Office of the Governor. 22 pp.

Frissell, C.A. and S.C. Ralph. 1998. Stream and watershed restoration. In: Naiman, R.J. and R.E. Bilby. River Ecology and Management: Lessons from the Pacific Coastal Ecoregion. Springer, New York, New York. 599-624 pp.

Gove, N.E., R.T. Edwards, and L.L. Conquest. 2001. Effects of scale on land use and water quality relationships: A longitudinal basin-wide perspective. Journal of the American Water Resources Association 37(6):1721 – 1734.

Granger, T., T. Hruby, A. McMillan, D. Peters, J. Rubey, D. Sheldon, S. Stanley, E. Stockdale. April 2005. Wetlands in Washington State – Volume 2: Guidance for Protecting and Managing Wetlands. Washington State Department of Ecology. Publication #05-06-008. Olympia, WA.

Gregory, S.V., F.J. Swanson, W.A. McKee, and K.W. Curnmins. 1991. An ecosystem perspective of. riparian zones." BioScience, Vol. 41, No. 8. pp.540-551

Hidding, M.C. and A.T.J. Teunissen. 2002. Beyond fragmentation: new concepts for urban-rural development. Landscape and Urban Planning 58(2/4): 297-308.

Johnson, P.A., D.L. Mock, A. McMillan, L. Driscoll, and T. Hruby. 2002. Washington State Wetland Mitigation Evaluation Study, Phase 2: Evaluating Success. Washington State Department of Ecology, Publication No. 02-06-009, 146 pp. (http://www.ecy.wa.gov/pubs/0206009.pdf).

Johnson, P.A., D.L. Mock, E.J. Teachout, and A. McMillan. 2000. Washington State Wetland Mitigation Evaluation Study, Phase 1: Compliance. Washington State Department of Ecology, Publication No. 00-06-016, 84 pp. (http://www.ecy.wa.gov/pubs/0006016.pdf).

Kauffman, J.B., R.L. Beschta, N. Otting, and D. Lytjen. 1997. An ecological perspective of riparian and stream restoration in the western United States. Fisheries (5):12-24.

King County. 2007. King County Shoreline Master Program, Appendix E: Technical Appendix (Shoreline Inventory and Characterization: Methodology and Results). Available at: http://www.metrokc.gov/shorelines/shoreline-master-program-plan.aspx

McClain, M.E., E.W. Boyer, C.L. Dent, S.E. Gergel, N.B. Grimm, P.M. Groffman, S.C. Hart, J.W. Harvey, C.A. Johnston, E. Mayorga, W.H. McDowell, and G. Pinay. 2003. Biogeochemical hot spots and hot moments at the interface of terrestrial and aquatic ecosystems. Ecosystems 6:301-312.

McDonnell, J. J., et al. (2007), Moving beyond heterogeneity and process complexity: A new vision for watershed hydrology, Water Resources Research, 43.

Mitsch, W.J. and R.F. Wilson. 1996. Improving the success of wetland creation and restoration with know-how, time, and self-design. Ecological Applications (6): 77-83.

National Research Council (NRC). 1992. Restoration of aquatic ecosystems: Science, technology, and public policy. Washington D.C. National Academy Press. 576 pp.

National Research Council (NRC). 1996. Committee on Protection and Management of Pacific Northwest Anadromous Salmonids. Upstream: Salmon and Society in the Pacific Northwest. Washington D.C. National Academy Press. 472 pp.

National Research Council. 2001. Compensating for wetland losses under the Clean Water Act. Washington, D.C. National Academy Press. 348 pp.

Preston, E.M. and B.L. Bedford. 1988. Evaluating cumulative effects on wetland functions: A conceptual overview and generic framework. Environmental Management 12(5): 565-583.

Reid, L.M. 1998. Cumulative watershed effects and watershed analysis. In River Ecology and Management. Lessons from the Pacific Coastal Ecoregion. Springer, New York. 705 pp.

Roni, P., T.J. Beechie, R.E. Bilby, F.E. Leonetti, M.M. Pollock, and G.R. Pess. 2002. A review of stream restoration techniques and a hierarchical strategy for prioritizing restoration in Pacific Northwest watersheds. North American Journal of Fisheries Management 22. 1-20 pp.

Ruckelshaus, M.H. and M.K. McClure (coordinators). 2007. Sound Science: Synthesizing ecological and socioeconomic information about the Puget Sound Ecosystem. Prepared in cooperation with the Sound Science collaborative team. U.S. Department of Commerce, National Oceanic & Atmospheric Administration (NMFS), Northwest Fisheries Science Center, Seattle, Washington. 93 p.

Shipman, H. 2008. A geomorphic classification of Puget Sound nearshore landforms. Puget Sound Nearshore Partnership Report No. 2008-01. Published by Seattle District, U.S. Army Corps of Engineers, Seattle, WA.

Simenstad, C., M. Logsdon, K. Fresh, H. Shipman, M. Detheir, L. Newton. 2006. Conceptual model for assessing restoration of Puget Sound nearshore ecosystems. Puget Sound Nearshore Partnership Report No. 2006-03. Published by the Washington Sea Grant Program, University of Washington, Seattle, Washington. Available at http://pugetsoundnearshore.org.

Spence, B. C., G. A. Lomnicky, R. M. Hughes, and R. P. Novitzki. 1996. An ecosystem approach to salmonid conservation. Draft report No. TR-4501-96-6057. ManTech Environmental Research Services Corporation, Corvallis, Oregon.

Stanley, S., J. Brown, and S. Grigsby. 2005. Protecting aquatic ecosystems: A guide for Puget Sound planners to understand watershed processes. Washington State Department of Ecology. Publication #05-06-027. Olympia, WA.

Stanley, S and S. Grigsby. October 2008. Watershed assessment and analysis of Clark County, Washington. Final. Washington State Department of Ecology Publication. Olympia, Washington.

Turner, R.E., A.M. Redmond, and J.B. Zedler. 2001, Count it by acre of function: mitigation adds up to net loss of wetlands. National Wetlands Newsletter 23:5.

University of Washington (UW) Urban Ecology Research Lab. 2008. Puget sound future scenarios. Draft report, January 2008. Seattle, Washington. 68 p. Available at: http://online.caup.washington.edu/projects/futurewithout/pdfs/scenarios_report.pdf

Ward, J.V. 1998. Riverine landscapes: Biodiversity patterns, disturbance regimes, and aquatic conservation. Biological Conservation, 83(3), pp. 269-278.

Whatcom County Planning and Development Services, 2007. Birch Bay watershed planning pilot study. Available at: http://www.co.whatcom.wa.us/pds/shorelines_critical_areas/workproducts.jsp

Winter, T.C. 1988. Conceptual framework for assessment of cumulative impacts on the hydrology of non-tidal wetlands. Environmental Management 12:605-620.

Winter, T.C. 2001. The concept of hydrologic landscapes. Journal of the American Water Resources Association. 37(2): 335-349.

Winter, T.C., J.W. Harvey, O.L. Franke, and W.M. Alley. 1998. Ground water and surface water: A single resource. U.S. Geological Survey Circular 1139. 79 pp.

Williams, G.D., and Thom, R.M. 2001. Marine and estuarine shoreline modification issues. Prepared by Battelle Marine Science Laboratory for Washington Department of Fish and Wildlife, Washington Department of Ecology, and Washington Department of Transportation. Sequim, WA. 136 p. Available at http://wdfw.wa.gov/hab/ahg/finalsl.pdf.