# *Chehalis Basin Watershed Assessment:*

## *Description of Methods, Models and Analysis for Water Flow Processes*


Final
March 31, 2010, Version 2

Ecology Publication #10-06-006

Written by: Stephen Stanley, Susan Grigsby, Tom Hruby, Patricia Olson
Washington State Department of Ecology

## Publication and Contact Information

This report is available on the Department of Ecology's website at
http://www.ecy.wa.gov/biblio/1006006.html

*If you need this publication in an alternate format, call the SEA Program Publications Coordinator, Shellyne Grisham, at (360) 407-6927. Persons with hearing loss can call 711 for Washington Relay Service. Persons with a speech disability can call 877-833-6341.*

Publications Coordinator
Shorelands and Environmental Assistance Program
P.O. Box 47600
Olympia, WA 98504-7600

E-mail: shellyne.grisham@ecy.wa.gov
Phone: (360) 407-6927

Refer to Publication #10-06-006

This work was funded in part by the U.S. Army Corps of Engineers.

Preferred citation:

Stanley, S., S. Grigsby, T. Hruby, and P. Olson. 2010. Chehalis Basin Watershed Assessment: Description of Methods, Models, and Analysis. Washington State Department of Ecology. Publication #10-06-006. Olympia, WA.

(This page left intentionally blank.)

# Table of Contents

## List of Figures

## List of Tables

# Acknowledgements

We are grateful to Mark Cline and Christine Hempleman of the Department of Ecology, and Marcia Heer and Michael Scuderi of the Corps of Engineers (COE), in supporting this assessment project and recognizing both the value of and need for taking a landscape approach to protecting aquatic ecosystems within the Chehalis Basin.

`

# Executive Summary

Land use management plans and regulations are the main tools we use to protect and restore our lakes, rivers, wetlands and estuaries. The **audience** for this watershed assessment includes Corps of Engineers, Department of Transportation, and Lewis County Planners in locating the best areas for the protection, restoration and development in the Chehalis Basin.

## Purpose

This technical document describes the approach taken to **assessing watershed processes in the upper Chehalis Basin**. Planners can use the information from this assessment to minimize negative impacts from changes in land uses.

> Examples of the most important **watershed process*es*** in Washington State are the movement of water, sediment, nutrients, pathogens, toxic compounds, and wood.

Scientists are developing a consensus that understanding watershed processes at a broad scale is essential to adequately protect and restore aquatic ecosystems. This approach outlines **an assessment methodology** to evaluate the **relative importance** of watershed processes among different analysis units of a watershed, and the **relative impairment** to these processes from human activity. The **goal** is to identify areas of the landscape that are important for maintaining watershed processes, and to characterize to what degree human activity has impaired these processes. This information can identify areas that are:

- important to protect,
- a high priority to restore, and
- less sensitive to impacts from new development and changes in land use.

The assessment results do not characterize functions or processes at the site or reach scale. Instead the assessment methods describes the types of "controls" or important areas on the landscape that govern the movement of water and associated processes and how activities impair each process, and identifies a set of indicators for these activities.

.

## Scale

This approach is best suited to the county or watershed level, but also provides valuable information at a sub-watershed scale. Since it evaluates relationships occurring at a watershed scale, it **does not** establish a direct connection between impairments at the larger scale and resulting impacts at the site scale. Assessment at the watershed scale doesn't identify site-specific needs for restoration or mitigation, though it is essential to informing plans for restoring sites or mitigating for site impacts.

`

For example, the assessment results are not intended to modify the results of salmon enhancement plans, which are based on analysis of site and reach specific functions and processes. The assessment results can be used to improve the success of salmon recovery plans by ensuring that watershed processes critical to sustaining reach scale processes are protected or restored in the contributing watershed.

## Benefits

The analyses from this approach can inform the following planning efforts:

- Mitigation Planning
  - Locating the best areas for protection and restoration of wetland ecosystems to offset the impacts of COE flood levee projects and WSDOT I-5 flood proofing projects.
- Growth Management Act
  - Supports protection of critical areas (for example, Critical Areas Ordinances, and public outreach, education, and incentive programs) by identifying areas important in maintaining watershed processes.
  - Evaluates the effect of future changes in land use on watershed processes.
  - Assists with public works infrastructure planning and maintenance.
- Shoreline Management Act
  - Completes the assessment of ecosystem-wide processes.
  - Identifies areas appropriate for restoration and protection as part of the restoration plan.
  - Informs land use designations and development standards that protect ecosystem-wide processes.
  - Supports "no net loss" requirements while allowing flexibility in mitigation.
- State Environmental Policy Act and National Environmental Policy Act
  - Includes watershed processes in the development of mitigation plans.
  - Provides information to meet the avoidance and minimization steps of "mitigation sequencing."
- Local Regulations
  - Supports predictable permitting by streamlining the permitting process with clearly established mitigation, credits, and fees.
- Resource planning
  - Supports more effective natural resource protection.
  - Informs site-level restoration and protection plans, and strategies for reducing risk of negative effects of land use change.

`

## How to Use this Technical Document

If you are a **planner**, the main document provides an overview of the approach used for the Chehalis Basin, the scientific concepts supporting it, and examples of how it can support various planning needs. If you are a **technical specialist**, the appendices provide the detailed methods and scientific rationale used for completing the analyses. In interpreting and applying the results to planning and permitting decisions it is best to engage a technical team with expertise in hydrology, geology and aquatic ecology.

## Background Documents

The approach and methods presented in this document were originally contained in Version 2 and 2 of Ecology Publication 05-06-027, "Protecting Aquatic Ecosystems by Understanding Watershed Processes: A Guide to Planners." Both versions have been peer reviewed, but the second version has not been published. Since the release of Version 2 in early 2006, local governments have applied variations of the original guidance throughout western Washington. This has included shoreline master program updates for Whatcom, Jefferson, King, and Pierce Counties in addition to the Cities of Issaquah, Olympia, Tumwater, and Lacey. Some of these efforts have resulted in the adoption of local plans and development regulations based on watershed principals. Additionally, the guidance was applied in Clark County to support development of a county-wide mitigation framework, and in Birch Bay to support drafting of a watershed based sub-area plan.

Through these individual planning efforts, we have identified ways to improve the assessment methods and models. **A technical team guiding the Puget Sound Characterization project has made further changes to the water flow models including recommendations on how to analyze and interpret the results of the modeling, which were incorporated into the Chehalis assessment.**

**This technical document reflects these improvements and includes**:

1) **Models for scoring** water flow (**Appendix A and B**). This will allow local governments to prioritize planning actions within a watershed.
2) Detailed steps for conducting GIS analysis.

## What this Approach Does Not Do

This approach does not provide information at a scale that will allow for the design of mitigation (includes restoration, enhancement and protection measures) actions at the reach or site scale.

`

## Definitions

The following key terms occur in this document:

***Watershed Processes:*** The dynamic physical and chemical interactions that form and maintain the landscape and ecosystems on a geographic scale of watersheds to basins (hundreds to thousands of square miles). In Washington State, the most important processes are water, sediment, nutrients, pathogens, toxic compounds, and wood. Each of these are described in detail in the appendices.

***Assessing Watershed Processes:*** The methods presented here for analyzing watershed processes. In this document, 'assessment', 'watershed assessment', or 'assessment of processes' all have the same meaning.

***Method(s)*****:** The analysis of an individual watershed process in one region of the state. Each appendix, B through G, presents the method for one process.

***Model:*** Numeric equations for scoring the relative level of importance and impairment for analysis units within an analysis area. Currently, three of the processes have models: Water Flow, Nitrogen, and Pathogen processes.

***Watershed Management Matrix:*** The matrix to identify the most suitable areas for protection, restoration, and development for a process within the analysis area. It combines the results of the models for importance and impairment for one process.

***Analysis Area:*** The geographic extent of the assessment. It ranges in scale depending on the size of a jurisdiction (city vs. county) and the type of landforms (coastal terrace vs. large river basin). It can include several watersheds. See Step 2.

***Analysis Unit:*** Each analysis area is divided into many smaller analysis units for comparison of model results. These are the units that are ranked as most important to least important for a process, or most impaired to least impaired for a process. The size and number of these units depends on the size of the analysis area, the landform types, and the planning issues a jurisdiction may be addressing. See Step 2.

***Landscape Group:*** A group of analysis units within the analysis area that have similar environmental characteristics, such as precipitation, landform, and geology. A large analysis area may have one landscape group in a coastal terrace consisting of till, with relative low precipitation, and a second landscape group in mountainous bedrock with high precipitation and snow pack. The analysis units within each landscape group are compared to each other and not to analysis units in a different landscape group.

***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.

***Effective Impervious Area (EIA)s:*** Impervious surfaces in a watershed that have a downstream drainage connections which eventually connects to surface water bodies such as streams, lakes, and wetlands. The Effective Impervious Area in a watershed is typically less than the total impervious surface.

`

# Overview

## Importance of Watershed Processes in the Chehalis Basin

### Role of Ecosystem Processes: Process, Structure and Function

"Habitat" is comprised of the biological, physical and chemical conditions of an area that support a particular species or species assemblage" (Ruckelshaus and McClure 2007). Examples of Chehalis Basin habitats include high-elevation glaciers, alpine meadows, mid-elevation mixed forests of fir, hemlock, alder and maple, river floodplains, freshwater wetlands, riparian forests, estuarine and tidal marshes, mudflats, eelgrass beds, and sand and gravel beaches (Kruckeberg 1991; Williams et al. 2001; Ruckelshaus and McClure 2007). These habitats are not formed *de novo* and are not static in their condition, area or availability. Instead, they are part of a complex web of habitats formed and maintained over time by the interaction of physical, chemical and biological processes occurring throughout their watersheds (Spence et al. 1996; Dale et al. 2000; NRC 2001; Roni et al. 2002; Stanley 2005; Simenstad et al. 2006).

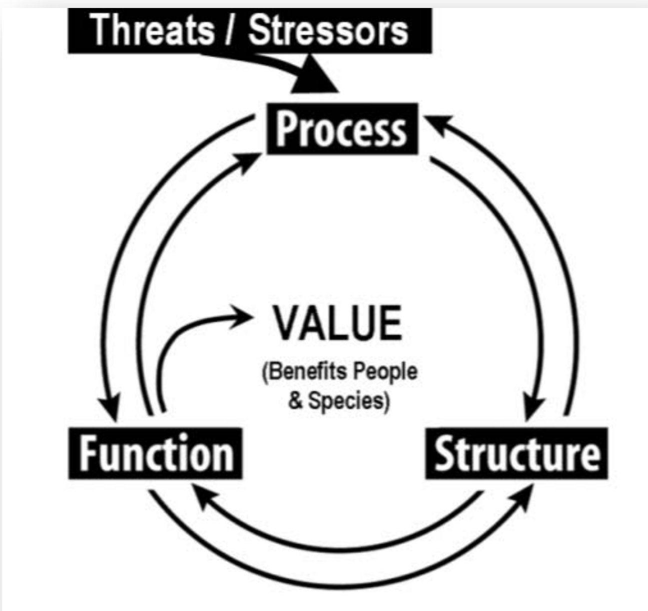



Figure 1. Ecosystem processes are responsible for creating/maintaining habitat structures and the resulting functions. Threats alter components of ecosystem processes, which in turn, affect structure and function and ultimately the values people and species may desire (Fuerstenberg 1998; King County 2007).

Ecosystem processes deliver, move, and transform water, sediment, wood, nutrients, pathogens, and organic matter. These processes are responsible for creating and maintaining the habitats that we see and for the functions that habitats provide (Naiman and Bilby 1998; Beechie & Bolton 1999, Hobbie 2000; Benda 2004; Simenstad et al. 2006; King County 2007). These processes exist in a dynamic state and constantly respond to controlling factors such as precipitation or to episodic disturbance events like landslides, fires, and flooding (NRC 1996).

**Watershed 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 (hundreds to thousands of square miles).

In Washington State, the most important processes are water, sediment, nutrients, pathogens, toxic compounds, and wood.

These processes operate at multiple scales (e.g., regional/large-scale local/landscape-scale, or finite/small-scale) and time scales (e.g., daily versus once a century) and at varying magnitudes (e.g., baseflow or bankfull river flows versus 100-year storm event). Despite adverse short-term impacts to survival, native species are adapted to and ultimately benefit over time from the frequency and magnitude of disturbances in their habitats (Reice et al. 1990). However, when disturbance frequency and magnitude patterns change, for example increase beyond the boundaries of natural variability, then species may not be able to adapt to more frequent disturbances.

## Major Threats to Ecosystem Processes and Habitats

Human activities often alter factors such as land cover, topography and soils that control processes and, in turn, the structure, function and value of a given habitat (Figure 1). Major impairments or "threats" [1] to ecosystem processes include forest clearing, impervious surfaces, draining/diking and filling of wetlands and floodplains, roads and associated storm drainage systems, shoreline armoring, overwater structures, removal of riparian vegetation, and excessive loading of nutrients, sediment, pathogens and toxic materials.

## Using a Watershed Approach to Protect and Restore Ecosystem Processes and Habitats

To protect and restore our lakes, rivers, wetlands, and estuaries, we must consider the ***watershed processes*** that support these ecosystems (National Research Council 2001, Dale et al. 2000, Bedford and Preston 1988, Roni et al. 2002, Poiani et al. 1996, Gersib 2001, Gove et al. 2001). In order to evaluate "threats" to habitats from land use practices we must understand how threats impair ecosystem processes. This also provides an understanding of the level of impairment to water quality, water quantity, and habitat functions.

[1] In this document "threats" are human activities that can alter habitat processes, disturbance regimes, and ultimately the structure and function and value of habitat. It is synonymous with "stressors", a term that is often used in scientific literature.

Unfortunately, up to now, management and regulation of these aquatic ecosystems has typically concentrated on the individual lake, wetland, stream reach or estuary, and not on the larger watershed, that controls these characteristics.

Much of the research concludes that protection, management, and regulatory activities could be more successful if they incorporate an understanding of watershed processes. 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 (Buffington et al. 2003, National Research Council 2001, Reid 1998, Frissell and Ralph 1998, Beechie and Bolton 1999, Kauffman et al. 1997, Roni et al. 2002).
- The design of mitigation projects needs to integrate a watershed perspective (Mitsch and Wilson 1996, Preston and Bedford 1988).
- Land use plans should develop within a framework that first focuses on maintaining or restoring watershed processes (Hidding and Teunissen 2002, Dale et al. 2000, Gove et al. 2001).

## Methods for Mapping & Analyzing Watershed Processes

The methods presented in this document for assessing watershed processes is based on predicting how water moves within a watershed according to the **landscape setting** (Preston and Bedford 1988, Bedford 1996, Winter 1988). This document describes the types of "controls" or important areas on the landscape that govern the movement of water and associated processes and how activities impair each process, and identifies a set of indicators for these activities.

Appendices A through B describe these relationships in detail for the Chehalis Basin and western Washington. The goal of watershed assessment is to inform decisions on where protection and restoration of watershed processes will be most effective, and which areas on the landscape are less sensitive to future disturbance.

A ***watershed management matrix,*** Figure 2, summarizes the information from the assessment. The matrix is a graphical representation used to identify analysis units most suited for protection, restoration, and other land use activities for a watershed process. The matrix results from two factors: 1) the importance of the analysis unit in maintaining watershed processes, 2) and the degree to which the processes in the analysis unit have been impaired by human activities.

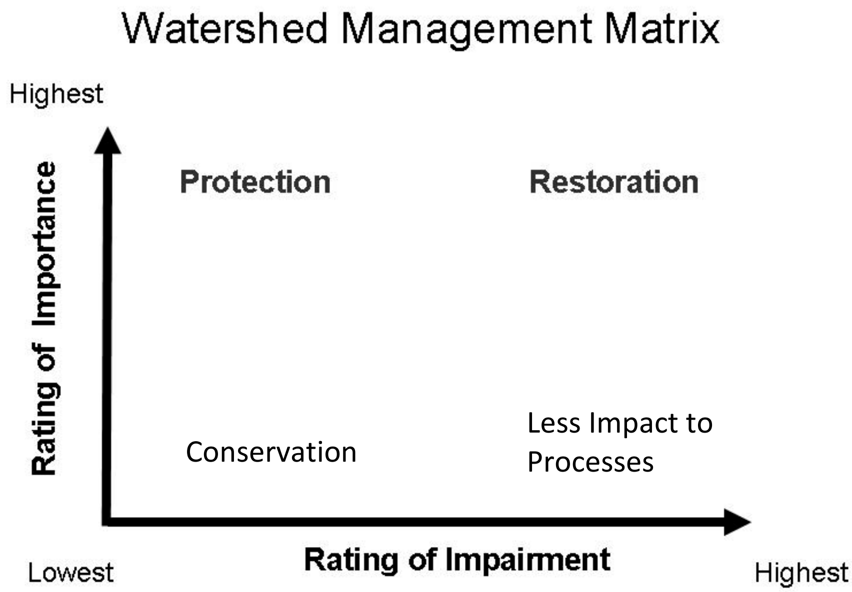



**Figure 2. Watershed Management Matrix.** The matrix summarizes information on the rating of importance and rating of impairment for analysis units within an analysis area. The matrix identifies those analysis units most suitable for protection, and restoration, and those less sensitive to impacts from additional development and changes in land use.

The appendices present the methods for analyzing, ranking, mapping, and interpreting the importance and level of impairment in all analysis units of a watershed. The appendices describe in detail the kinds of information to combine (e.g., soils and geology) and how to select attribute combinations (e.g., hydric rating and permeability) to identify locations where processes are important. This approach also applies when evaluating impairments. We applied the methods described in the appendices to the Chehalis Basin watersheds.

## Incorporating an Understanding of Watershed Processes into Planning

This analysis assesses all analysis units of a watershed in terms of the management matrix described above. Each analysis unit is ranked, relative to the other analysis units, for its potential for restoration, preservation, and development suitability. Policy and resource managers can use this information to assess the potential impact of future development patterns on watershed processes. The results of the analysis can also be used to establish the environmental condition of an analysis unit relative to other analysis units. This approach is most effective when used in the comprehensive planning process applied at the county, subarea, or watershed scale, allowing communities to effectively plan for future development. This approach can identify the actual and potential adverse changes in watershed processes resulting from different patterns and types of land use activities.

**Issues of Scale** – Integrating information on watershed processes into land use plans and policies that deal with individual sites can be difficult. Our understanding of how processes interact at different geographic scales is limited. For example:

| We understand… | But our knowledge is less certain of… |
|---|---|
| Some relationships between landscape conditions and water movement on a watershed scale. | How the movement of water at the large scale affects the movement of water to a single wetland, stream, reach, etc. |
| Which human activities are likely to alter watershed processes (e.g., additional inputs of nutrients or change to nutrient removal mechanisms). | How the addition of nutrients will change the functions of an individual wetland. |

Therefore, the results from analyses for an entire watershed will not be accurate for a specific site. Most hydrologic studies are conducted on the site scale and up-scaling of these processes to the watershed scale is a problem that has not been resolved. Watershed level hydrologic process measurement studies are just beginning to be instituted and results are very preliminary and not conclusive (McDonnell et al 2007). The information, however, can be used to develop standards for protecting and managing aquatic resources through local government plans (i.e. comprehensive plans, shoreline management plans) or state planning documents (e.g. establishing regional restoration priorities). This creates a watershed based management framework that helps inform site specific decisions on the best location of mitigation and restoration actions and future development. See page 45 for more detail on state planning laws.

# Introduction to the Chehalis Basin Assessment Project

The Washington State Department of Ecology (Ecology) received funding from the Corps of Engineers (COE) in 2009 to conduct an assessment of water flow processes in the Chehalis Basin watershed. The purpose was to identify and rank areas for protection and restoration of aquatic ecosystems and thereby provide a mitigation framework for offsetting the impacts of COE flood levee projects and WSDOT I-5 flood proofing projects. In the following section, we describe both the steps used to conduct the assessment and the results.

## Overview of the Basic Steps Used in this Approach

The basic steps used in this approach for assessing watershed processes included:

1. Import the Salmon and Steelhead Habitat Inventory and Assessment Program (SSHIAP) catchments for the upper Chehalis Basin, WRIA 23, and the northeast portion of WRIA 22, lower Chehalis Basin (Satsop watershed) (see Figure 3).
2. Develop landscape groups and identify analysis unit size for each landscape group.
3. Aggregate smaller SSHIAP units into the selected analysis unit size for each landscape group (Figure 4).
4. Apply (water flow) process models and map the relative importance of these analysis units for maintaining the processes in the watershed.
5. Apply process models and map the relative impairment of these analysis units to the watershed processes. For Phase I only the model for water flow processes was run.
6. Identify analysis units for potential restoration and protection actions at the broad scale and those units less sensitive to disturbance. Apply watershed management process outlined in Figure 21 to incorporate assessment results into local plans.

We applied these six steps in assessing water flow processes in the Chehalis Basin. The results of this assessment will assist resource managers to identify areas for protection; restoration; and less sensitive to development (or more resilent).

All six steps use existing environmental data and land use information. This includes data such as surficial geology, soils, topography, land cover, land use, hydrography, and wetlands. Table 1 summarizes some of the key data sources that were used in applying these steps. Appendices A and H provide a complete description of the GIS data sources and methods used for The Chehalis Basin.

| GIS Data | |
|---|---|
| Geology | http://www.dnr.wa.gov/ResearchScience/Topics/GeologicHazardsMapping |
| Soils (SSURGO) | http://soils.usda.gov/survey/geography/ssurgo/ |
| Topography | http://www3.wadnr.gov/dnrapp6/dataweb/dmmatrix.html |
| Rain on snow | http://fortress.wa.gov/dnr/app1/dataweb/dmmatrix.html |
| Stream Confinement (SSHIAP) | http://wdfw.wa.gov/hab/sshiap/ |
| Land Cover (CCAP) | http://www.csc.noaa.gov/crs/lca/pacificcoast.html |
| **Other Useful Sites** | |
| Ecology data | http://www.ecy.wa.gov/services/gis/data/data.htm#p |
| Geospatial One-Stop – Federal GIS Portal | http://www.geodata.gov |
| Pacific North West Hydro Clearinghouse | http://hydro.reo.gov/ |
| Land Use / Land Cover Reference | http://www.wdfw.wa.gov/wlm/gap/dataprod.htm |

**Table 1. Key sources of existing digital data.**

After delineating the area and units for analysis, Steps 4 and 5 describe how to identify both the areas important for maintaining the watershed process and the impairments that may have degraded that process. Step 6 describes how to synthesize the information from Steps 4 and 5 to develop management recommendations. Areas that are important and relatively unimpaired become candidates for protection, while those that are important to the process but more impaired become candidates for restoration. Areas that are both relatively less important for a process and already have severe changes are the areas less sensitive to disturbance. The aquatic ecosystems in these latter areas are expected to change less if human disturbances are increased.

## Step 1: Import the SSHIAP Habitat Catchments

The Salmon and Steelhead Habitat Inventory and Assessment Program (SSHIAP) analysis unit is a reach-scale catchment that represents the immediate drainage unit for a SSHIAP stream habitat segment. The SSHIAP stream habitat segments were originally delineated and developed by the Northwest Indian Fisheries Commission (NWIFC) for the Puget Sound, Strait of Juan De Fuca, and Olympic Coast regions. The SSHIAP stream habitat segmentation is based on channel gradient, channel confinement, and onside channel, slough, wetland, and lake habitat types. As such, they reflect the effect of processes that formed and maintain these individual stream segments. For example, a stream segment that is confined (width of stream valley is less than 2 times the width of the stream channel) and has a gradient of greater than 8% would have only the adjacent watershed delineated that drains directly to that stream segment.

These SSHIAP segment catchments are at a very small scale, with some encompassing only .01 square miles (64 acres) in size. It is the initial finding of the Puget Sound Characterization Project technical committee (i.e. we used the same model and analysis methods in the Chehalis) that the results of the assessment are not accurate at this smaller scale due to the resolution of the assessment data (i.e. 1:24,000 and greater). Instead, the committee set the smallest analysis unit at 1 square mile.

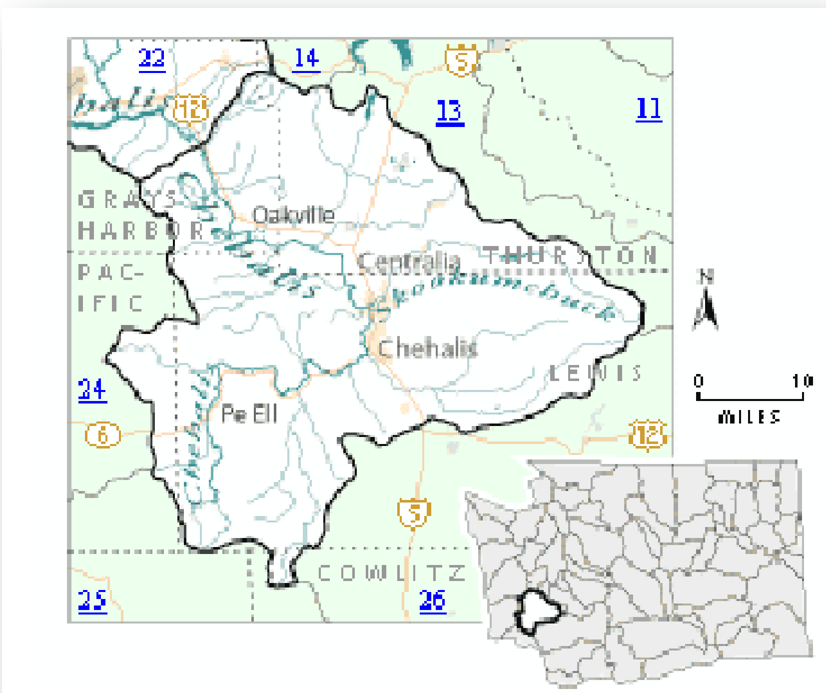



**Figure 3. WRIA 23(Upper Chehalis Basin) and a portion of WRIA 22 (Lower Chehalis Basin, Northeast portion, Satsop) Watersheds Analyzed by The Chehalis Basin Assessment.**

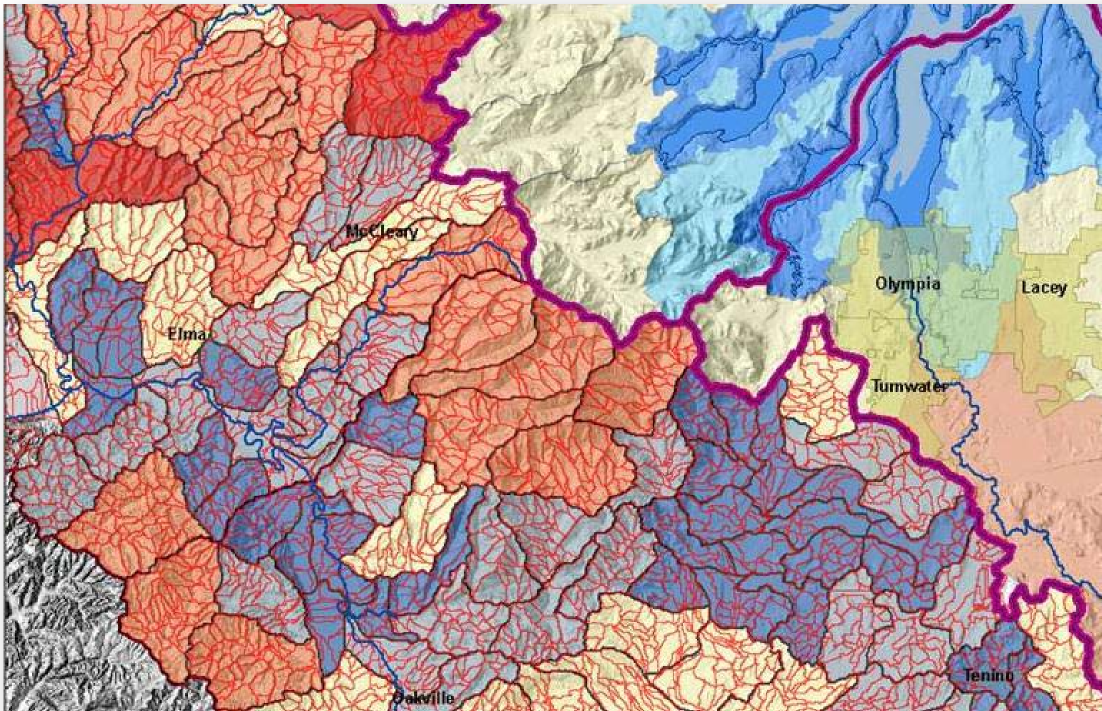



**Figure 4. Imported SSHIAP units for WRIA** 22 and 23. Upper Chehalis Basin. Black outlined watersheds represent the analysis units developed from aggregating the "red" outlined catchments, which are the SSHIAP catchments prior to the aggregation.

Figure 4 depicts the range of sizes of SSHIAP analysis units prior to aggregation, which we discuss in step 3, with an example of aggregation, provided in Figure 7 for WRIA 23 and the northeastern portion of WRIA 22.

## Step 2: Develop Landscape Groups (LG)

***Key Questions***:

Are there significantly different areas of precipitation, landform and geology in the analysis areas?

What size of the analysis units meets local planning and permitting needs?

### *Landscape Groups (LG)*

For each WRIA, the SSHIAP catchments units were grouped or classified into landscape units with similar environmental conditions. This classification system is based on Winter's (2001) "analysis-landscapes" and Bedford (1999 & 1988) hydrogeology framework. This classification considers regional climate, surficial geology, topography (landform), groundwater, and surface flow patterns in relationship to aquatic ecosystems. Based on this classification we developed criteria (Figure 5) for three landscape groups: mountainous, lowland, and the Satsop mountainous. The criteria details are:

Mountainous Group. This higher elevation area is characterized by high precipitation, significant snow cover, bedrock and steep topography with shallow seasonal groundwater and deeper regional groundwater systems. Three discontinuous mountainous groups were created.

Lowland Group. Lower elevation terraces comprised of glacial deposits. Moderate levels of precipitation occurring primarily as rainfall. Groundwater patterns consist of both intermediate and local recharge in the upper terraces and local to regional scale groundwater discharge in broad glacial valleys.

Satsop Mountainous Group. This area was considered separately because the headwaters are in the Olympic mountains, with a distinct geologic formation, and very high precipitation.

Figure 6 and 7 for WRIA 23 and 22, Lewis County illustrates the landscape groups and analysis units.

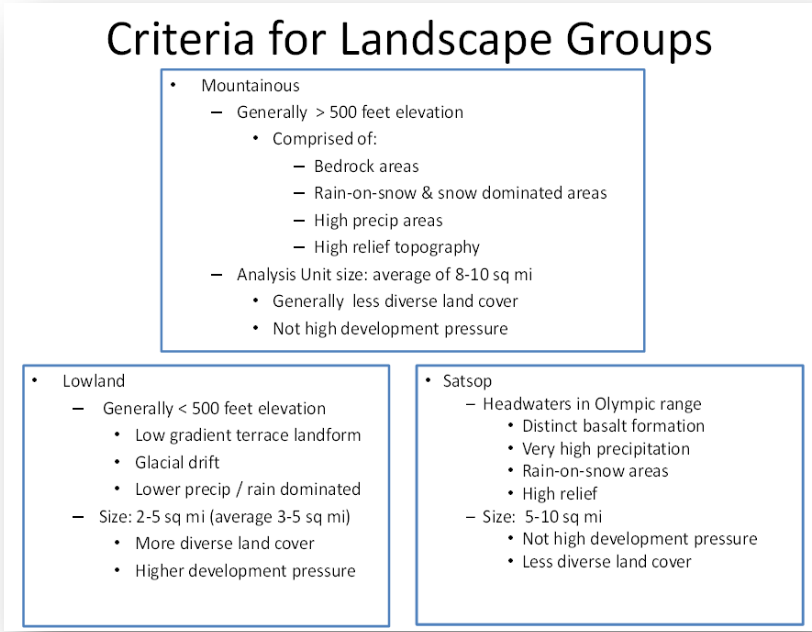



**Figure 5. Criteria for Landscape Groups.** Criteria for the three landscape groups used for the Chehalis water flow assessment.

We created two separate mountainous groups for the analysis area since each drains into the lowland group from distinctly different regions, and therefore have potential for different effects on water flow processes in the lowland group. The northern and western units (green group in Figure 6) may tend to have more rain dominated precipitation relative to the more interior eastern mountainous group (blue group in Figure 6) which has a potential to be dominated by rain-on-snow and snow dominated precipitation. This was an additional basis for creating separate mountainous groups for these two portions of the analysis area.

For these two separate mountainous groups, the western group, and the eastern one, the assessment only evaluated analysis units within each group and not as single combined mountainous group.

## Step 3: Aggregate Units for Each Landscape Groups

> ***Key Questions***:
>
> Does the aggregation generally represent similar landform and geologic conditions?

Once we identified the landscape groups, the smaller SSHIAP catchments were aggregated into larger analysis units. These aggregations were assembled based on similar landform, geologic and water flow characteristics.

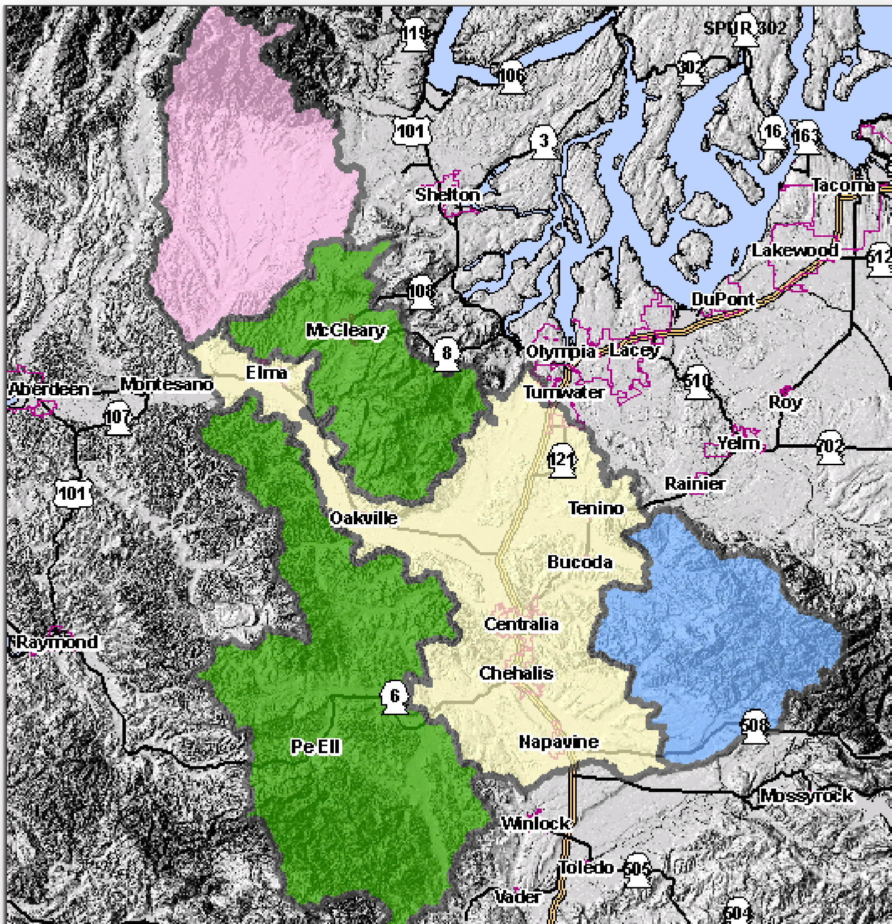



**Figure 6. Landscape Group (LG) for WRIA 22 and 23, Chehalis Basin Watersheds.** The three landscape groups used for the Chehalis Basin assessment Characterization are shown along with the approximate size of each analysis unit within each of those landscape groups. The green area is the Mountainous group for the western and northern portion of the assessment area; the blue area is Mountainous group for the eastern portion of the analysis area; yellow area is the Rain-dominated Lowland group; and the pink area is the Mountainous group for the Satsop watershed.

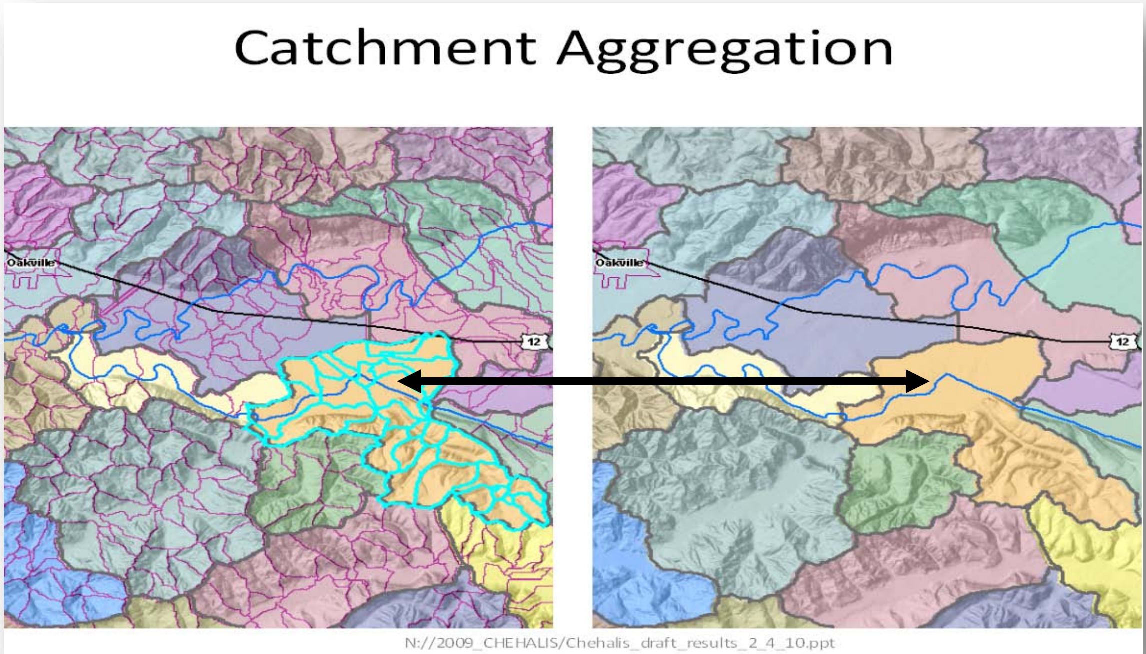



**Figure 7. Example of the Aggregation of SSSHIAP Analysis units into Lowland Units.** Blue outlined area in the left panel shows individual SSHIAP units prior to aggregation. This "blue" grouping of units will form a larger analysis unit, shown in the right panel.

Figure 7 provides an example of the aggregation process for the lowland landscape group. Appendix C (GIS Methods) provides more detail on the aggregation step.

## Step 4: Map 'Important Areas' and Rank Analysis units by Watershed Process

***Key Question:***

In the absence of human impairment*, what areas are important to each watershed process?

Where these areas located and what are their relative importance to each process?

* We address important areas that are impaired in the next section.

***Methods:*** This step maps the physical characteristics that control the natural performance of each watershed process in The Chehalis Basin . In this document, the term "*important areas*" refers to those areas with characteristics that help maintain a watershed process. Step 3 in Appendix, B describes our current understanding (or informed assumptions) regarding these relationships for each process. The numeric model for mapping important areas results in a relative ranking of each analysis unit within the analysis area, from most to least important. Figure 8 shows the results of the water process model for assumed delivery of surface water and ground water components. Individual maps displayed the results of each of these components (Figure 8).

***GIS analyses:*** The section on "Models" in each appendix describes the individual analyses and the scoring methods that make up each model. After combining various layers of digital data, each sub-basin receives a composite score that represents its relative importance to the process within the analysis unit. This final score is grouped into one of four rating categories: High, Moderate to High, Moderate, or Low. These results can then be supplemented with local data. Table 3 lists GIS data sets.

***Products:*** Map of ratings for analysis units (Figure 8): We created a summary map from the GIS analysis work that displays the importance of each analysis unit for the water flow process relative to other analysis units within the analysis area. The darker the color the more important the sub-basin is relative to the others. The results of analysis **within each landscape group**, were used to create a ranking for only that group. We did not combine the scores of landscape groups to create rankings for an entire WRIA or multiple WRIA's.

***Example:*** We analyzed and mapped the water flow process for WRIA 22 and 23, Lewis County (Figures 8 to 12). The analysis units within each landscape group were analyzed separately from those in other landscape groups. In this way, each landscape unit has analysis units that range from high to low.

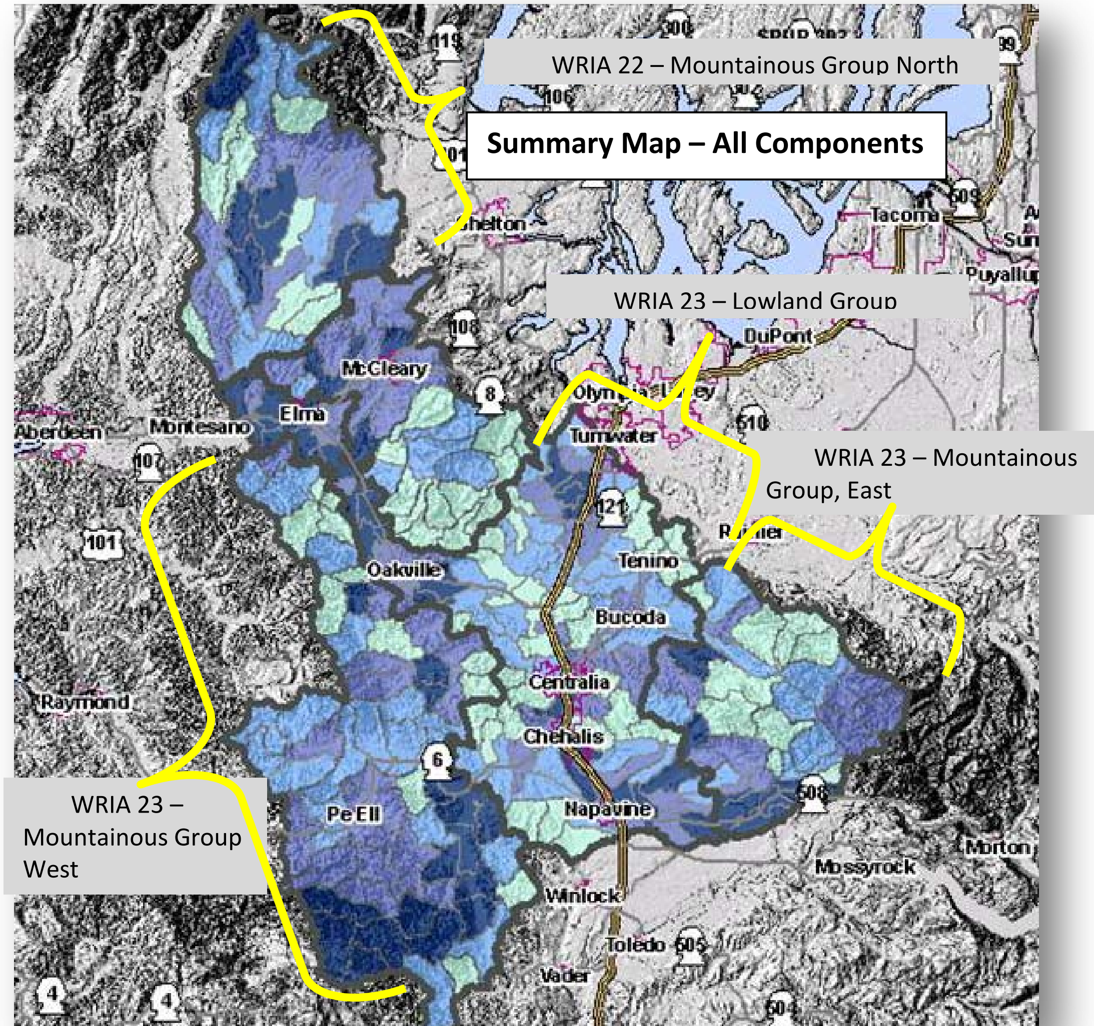



**Figure 8. Example of Summary of Important Areas Map for WRIA 23 (Upper Chehalis Basin) and 22 (Lower Chehalis Basin), Lewis County. [HU_M1] .** This map represents results of all components (delivery, storage, recharge discharge). The black outline delineates the four landscape groups: mountainous east, mountainous west, mountainous north and lowland. Analysis units are evaluated only within their landscape group. Dark blue analysis units are the most important (High rating) and lightest blue analysis units are less important (Low rating) for the water process. This map shows the combined scores for all three components of the importance model - delivery, surface and ground water. Results are shown in quantiles.

We recommend considering both the combined and individual results of the model (i.e. for delivery, surface and groundwater components) when addressing planning or environmental issues. For example, if flooding is a consideration, then using the results from both the delivery and storage components of the model will help address this issue (see Table 2). Two different flooding events can be considered: rain-on-snow events and storms proceeding "up a basin". Figure 8 and 9, the delivery results, show areas more important for generating "rain-on-snow" floods. Figure 10 shows the surface storage areas immediately downstream of "rain-on-snow" and "snow dominated" areas

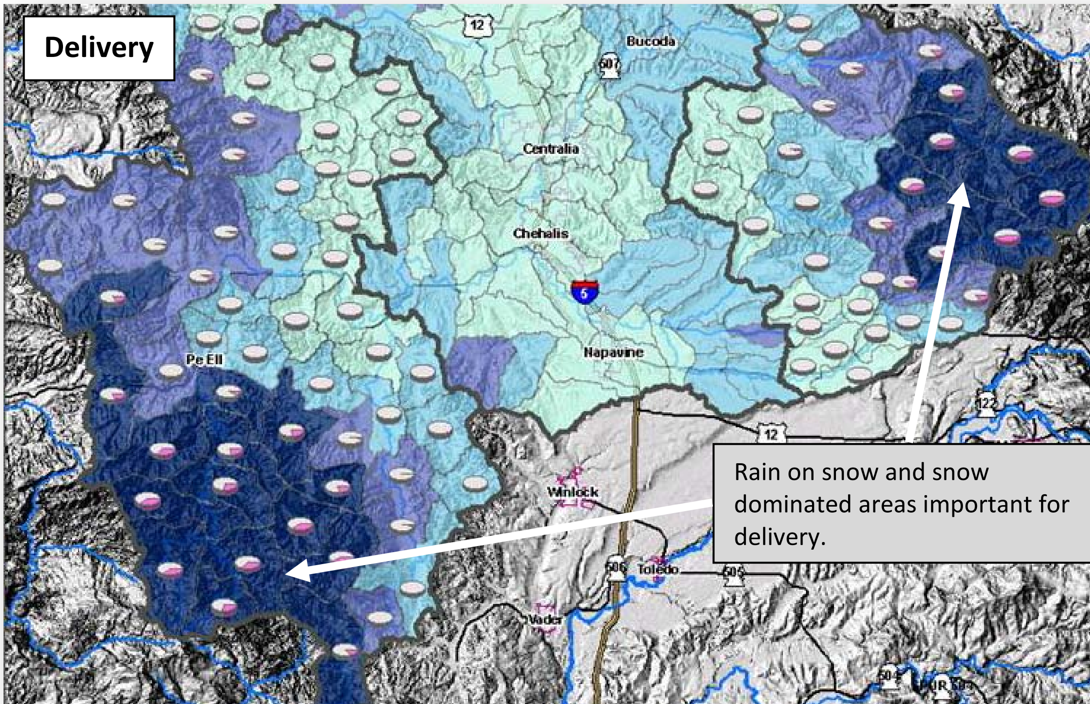



**Figure 9. Example of Important Areas for Delivery for WRIA 23, Upper Chehalis Basin [HUD_Q].** Pink areas in pie charts represent the area of "rain-on-snow" zones relative to the area zone of rain dominated precipitation for an analysis unit. These factors contributed to the high importance designation shown in "dark blue" on the map for the mountainous groups.

that could play an important role in moderating "rain-on-snow" floods. For storms that "come up" a watershed flooding occurs in the lowland first. In these circumstances storage on the mainstem and in lowland is important for moderating flood events.

Figure 10 shows the surface storage areas immediately downstream of these "rain-on-snow" and "snow dominated" areas that would play an important role in moderating flood events generated by them. The higher in the watershed these storage areas are, the greater effect they will have on moderating downstream flooding.

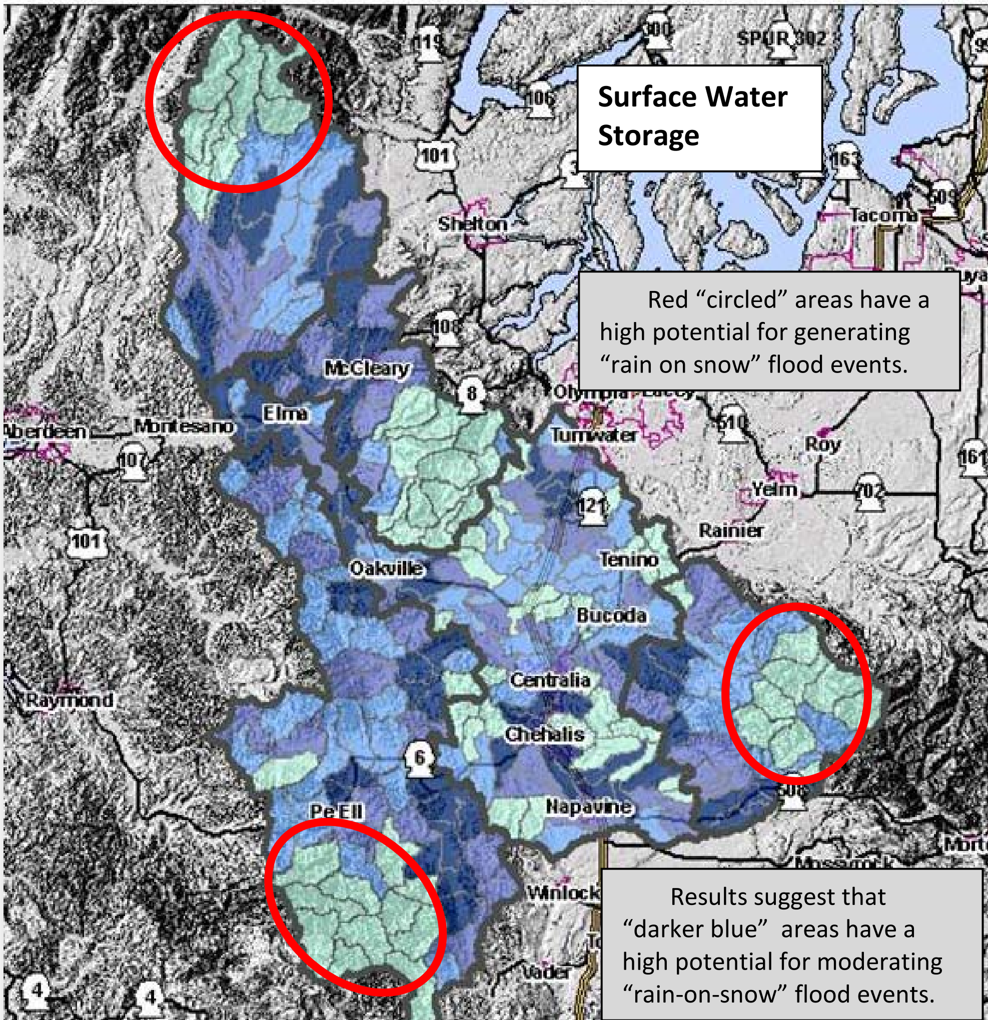



**Figure 10. Example of Important Areas for Storage Relative to Rain on Snow and Snow Dominated Ares. For WRIA 22, Upper Chehalis Basin.** Darkest analysis units are the most important (High rating) and lightest analysis units are the less important (Low rating) for the storage of surface flows. [HUSW_Q]. Results shown in quantiles.

The recharge map (Figure 11) demonstrates that recharge is a significant process throughout the mountainous groups and in the northern or downstream portion of the lowland group of WRIA 23 and 22.

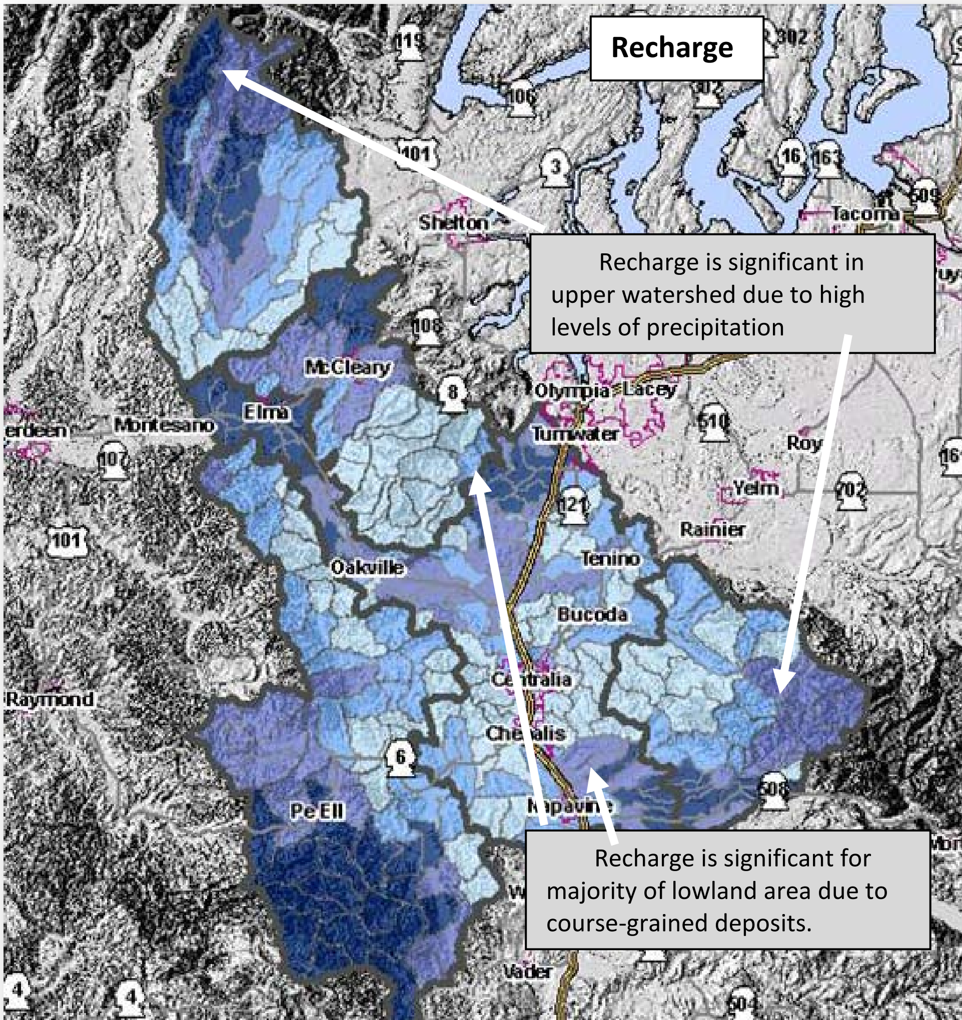



**Figure 11. Example of Important Areas for Recharge For WRIA 23 and northeast portion of WRIA 22, Chehalis Basin [HU5_Q].** Darkest blue analysis units are the most important (High rating) and lightest analysis units are less important (Low rating) for recharge. Results shown in quantiles.

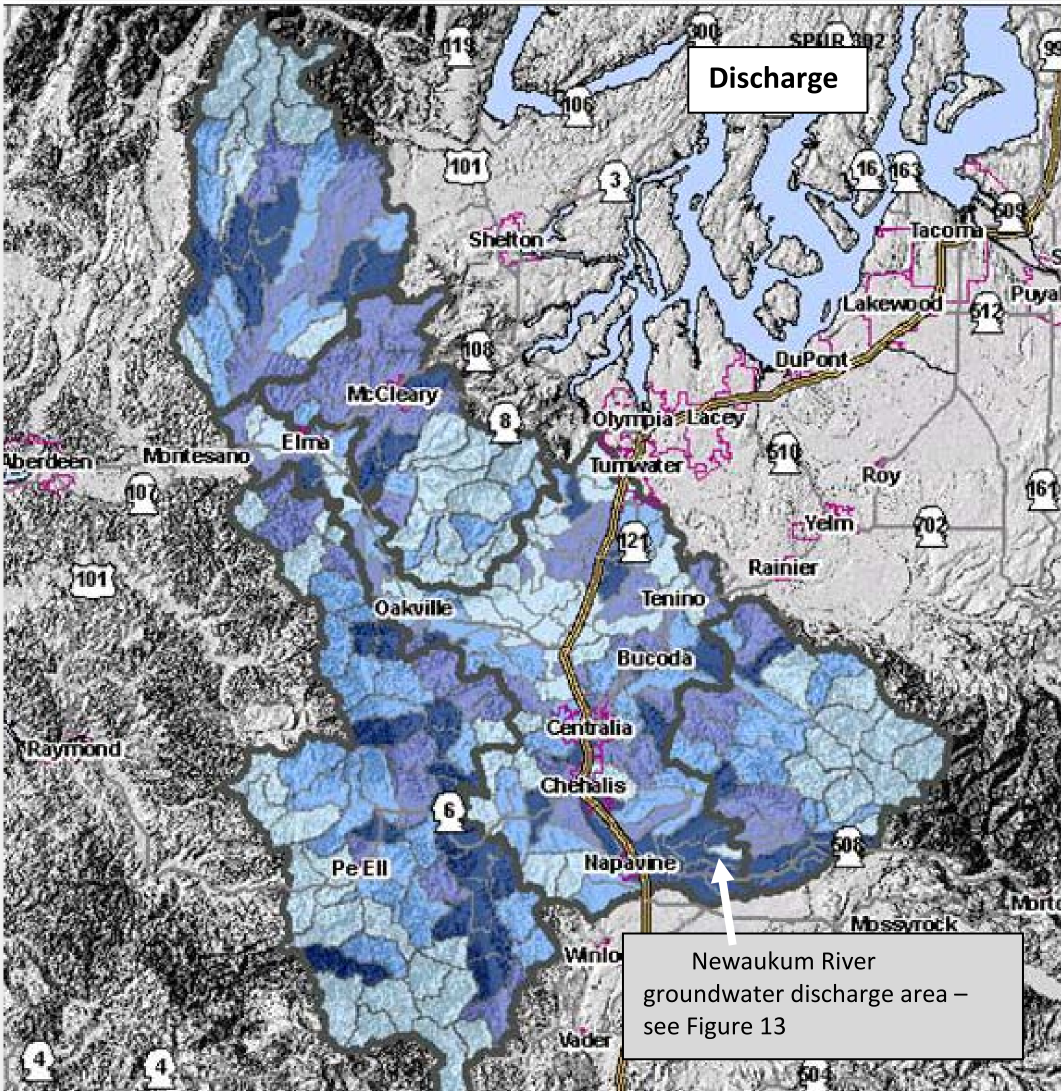



**Figure 12. Example of Important Areas for Discharge, WRIA 23 and northeast portion of WRIA 22, Chehalis Basin [HU_D_Q]** Darkest analysis units are the most important (High rating) and lightest analysis units are less important (Low rating) for groundwater discharge. Results shown in quantiles.

The discharge map (Figure 12) provides more detail on the most important areas for discharge, which includes the south fork of the Chehalis and upper to mid reaches of the Newaukum River. It is interesting to note that Weigle (1962) identified essentially the same area on the Newaukum River as an important groundwater discharge area (i.e. artesian basin).

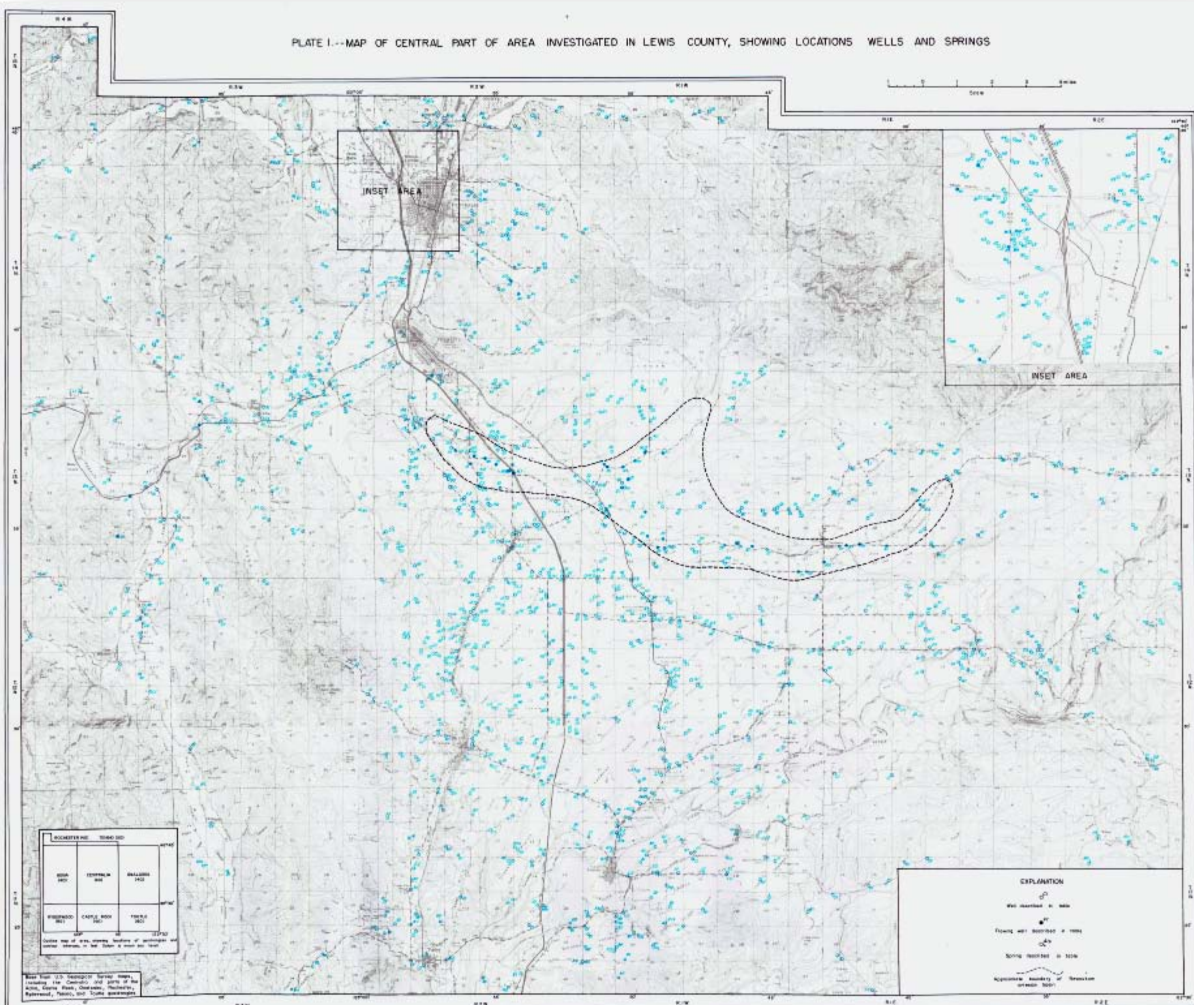



**Figure 13. Example of Important Groundwater Discharge Areas.** Outlined area was identified by Weigle (1962), in Water Supply Bulletin 17, as an important groundwater discharge area (artesian basin) within the Newaukum River floodplain and prairie.

## Step 5: Map Impairment Areas' and Rank Analysis units by Watershed Process

***Key Questions***:

What human activities have impaired each watershed process?
Where do these activities occur and what is the relative severity of the impairment?

***Methods***: This step identifies analysis units where human activities are likely damaging the watershed process. Many human activities affect the physical characteristics of a watershed, and thus, have the potential to impair watershed processes. For example, construction of impervious surfaces, such as roads or buildings, can prevent the recharge of groundwater. This reduces the amount of groundwater available and increases the amount of surface runoff.

In some cases, it is not possible to map the activities that impair the processes. For example, the databases used do not map the specific locations where wetlands are ditched or streams are channelized. In this instance, we use the land use type as an indicator of the probability that these impairments are present. Thus, urban wetlands are rated as having more of these impairments relative to rural wetlands. However, data was not available to assess the specific level of impairment to each wetland. This type of site specific information can be acquired by applying the Department of Ecology Wetland Rating System for Western Washington. http://www.co.san-juan.wa.us/cdp/docs/CAO/WA_Wetland_Rating_System.pdf .

Step four of each Appendix B, describes our current understanding of the relationships between indicators and their effects on each watershed process. The numeric model for identifying impairments results in a relative ranking of each analysis unit within the analysis area from least to most impaired. (Figure 14).

***GIS analyses***: The section on "Models" of each appendix describes the individual analyses and scoring methods for each model of impairments to a process. After combining various layers of digital data, each analysis unit receives a relative score. This score is grouped into one of four ratings: High, Moderate to High, Moderate, or Low. Table 3 lists the datasets used for these analyses in The Chehalis Basin.

***Products:*** The GIS analyses result in a summary map displaying the rating of impairments for each analysis unit relative to other analysis units (Figure 14-17). The darker the color the higher the level of impairment the analysis unit has relative to other analysis units within the analysis unit.

***Example****:* Impairments to the water process were analyzed for WRIA 11 and 13, Thurston County. Units within each landscape group were analyzed separately from those in other landscape groups. Thus, the Snow-dominated Mountainous analysis units were compared to one another, as were the analysis units in the Lowland Group. In this way, each landscape unit has analysis units ranked from high to low impairment.

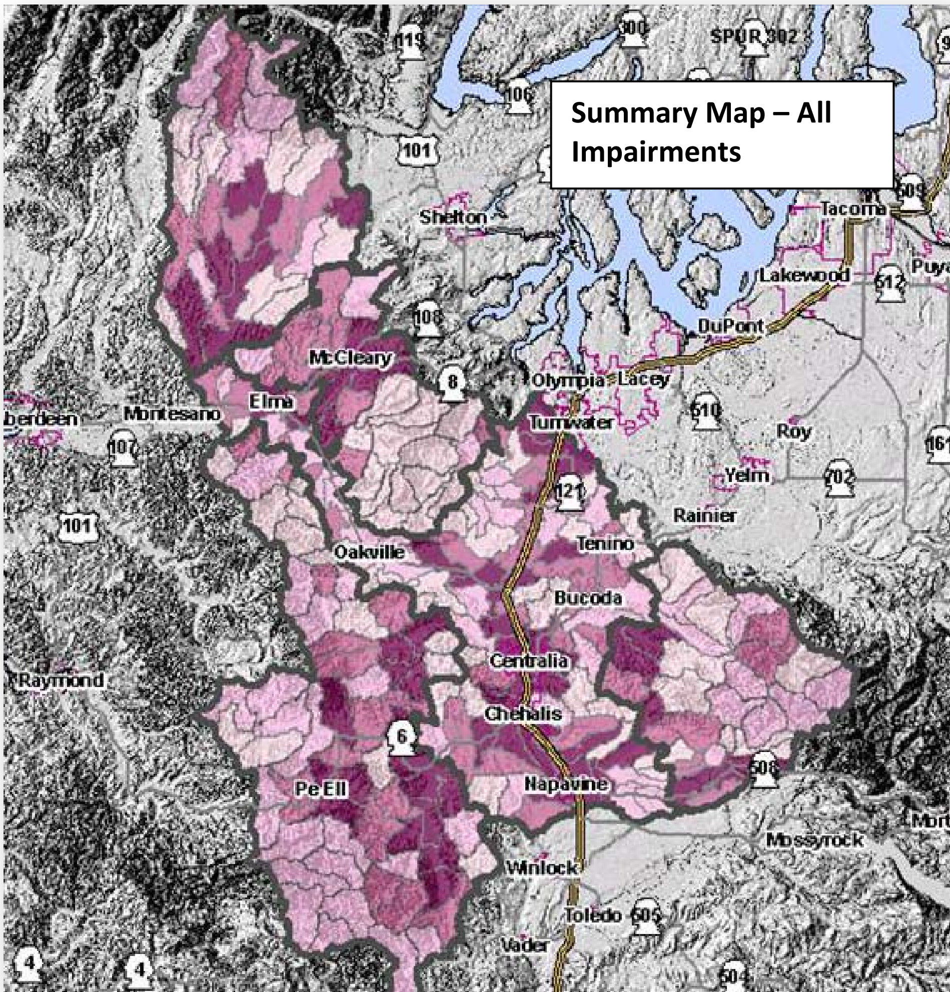



**Figure 14. Example of Overall Impairments Map for Water Flow Processes, WRIA 23 and 22 [HI_M2] The darkest pink areas are the most impaired. Results shown in quantiles.**

Impairments for separate components of the water flow process are displayed as separate components in order to address potential environmental issues within WRIA 21 and 22, including lowland flooding and low flows in streams. Figure 15 and 16 shows the areas that have impaired delivery and surface storage. If impaired surface storage areas are located below areas important for delivery (Figure 8) then restoration actions are recommended. If these same areas have low impairment then protection is recommended. Conversely, if delivery areas are impaired (Figure 14), then restoration is recommended.

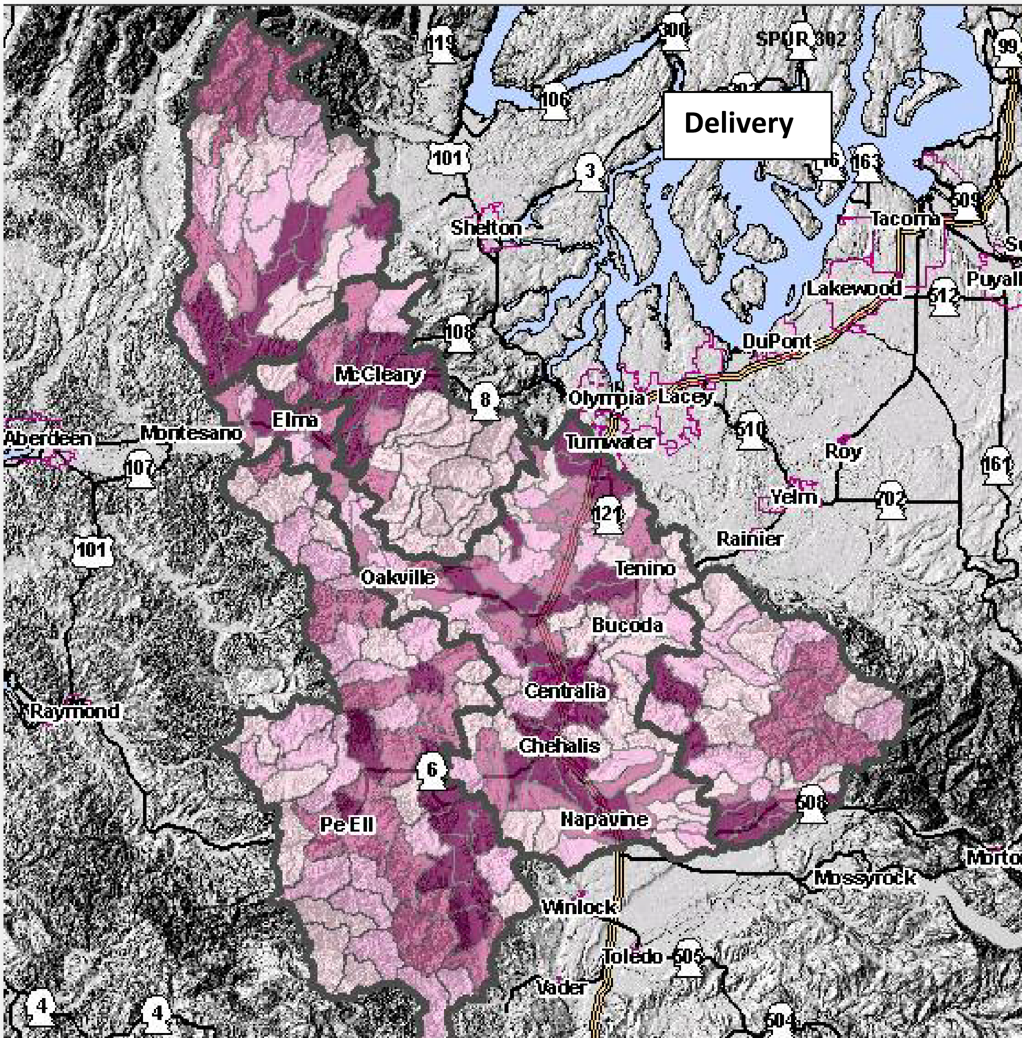



**Figure 15. Example of Impairments Map for Delivery, WRIA 23 and northeast portion of WRIA 22, Chehalis Basin. [HI_D_Q]** The darkest "pink" analysis units are the most impaired.

The delivery map (Figure 15) indicates that the relative degree of impairment is significant for all of the mountain groups. This would suggest that forest clearing is the primary impairment within the "darker pink" analysis units. These impairment conditions could contribute to increased flooding in the lowland areas. Further, Figure 16 indicates that storage areas below these delivery areas (i.e. lowland landscape group) are also significantly impaired, which would also contribute to increased flooding .

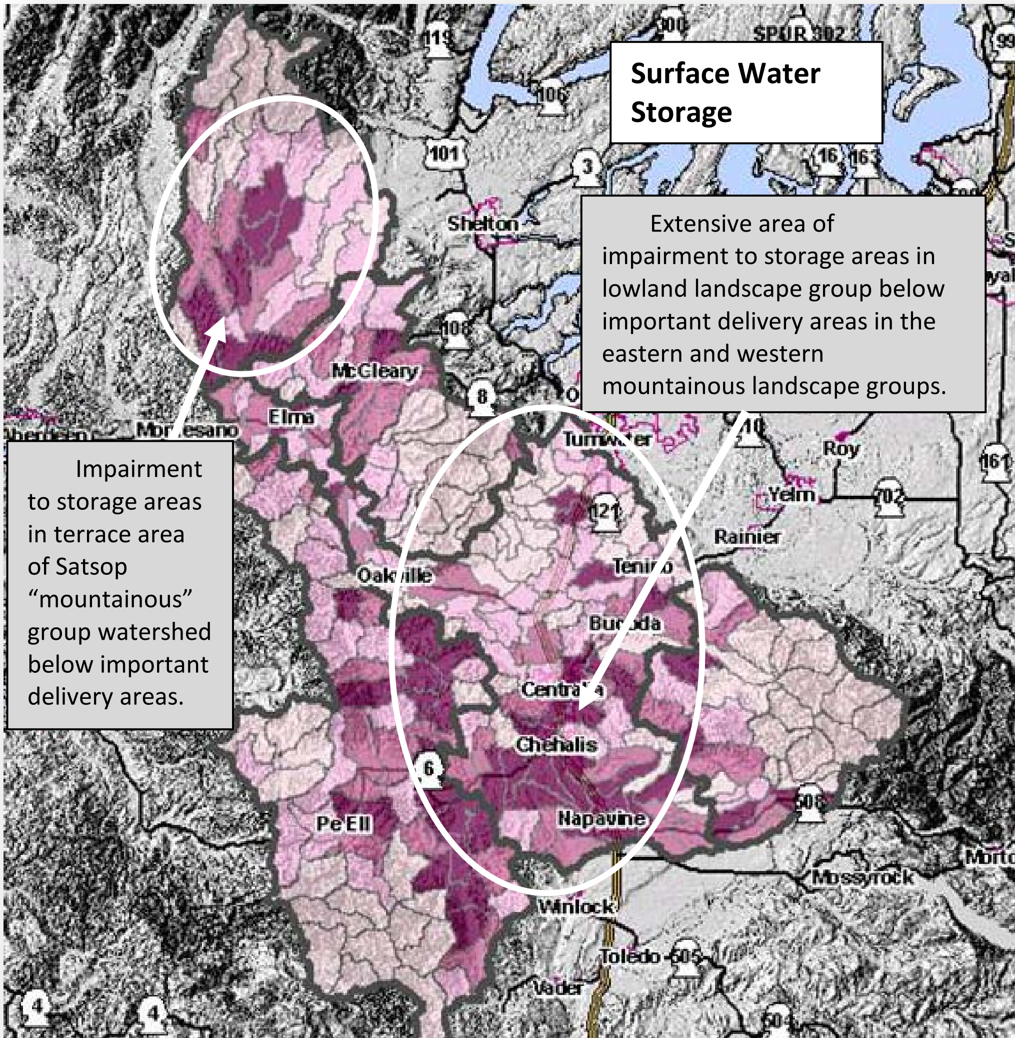



**Figure 16. Example of Impairments Map for Surface Water Storage for WRIA 23 and northeast portion of WRIA 22, Chehalis Basin.** **[HISW_Q]** The darkest "pink" analysis units are the most impaired. The impaired storage areas could contribute to increased flooding in lowland areas since they are all located immediately below important delivery areas.

Impairments to recharge and discharge areas are presented in Figures 17 and 18. The impairments can be compared to the important areas for recharge and discharge shown in Figures 11 and 12 in order to select appropriate land use actions. Table 2 presents the methods for evaluating results from separate components of the water flow assessment.

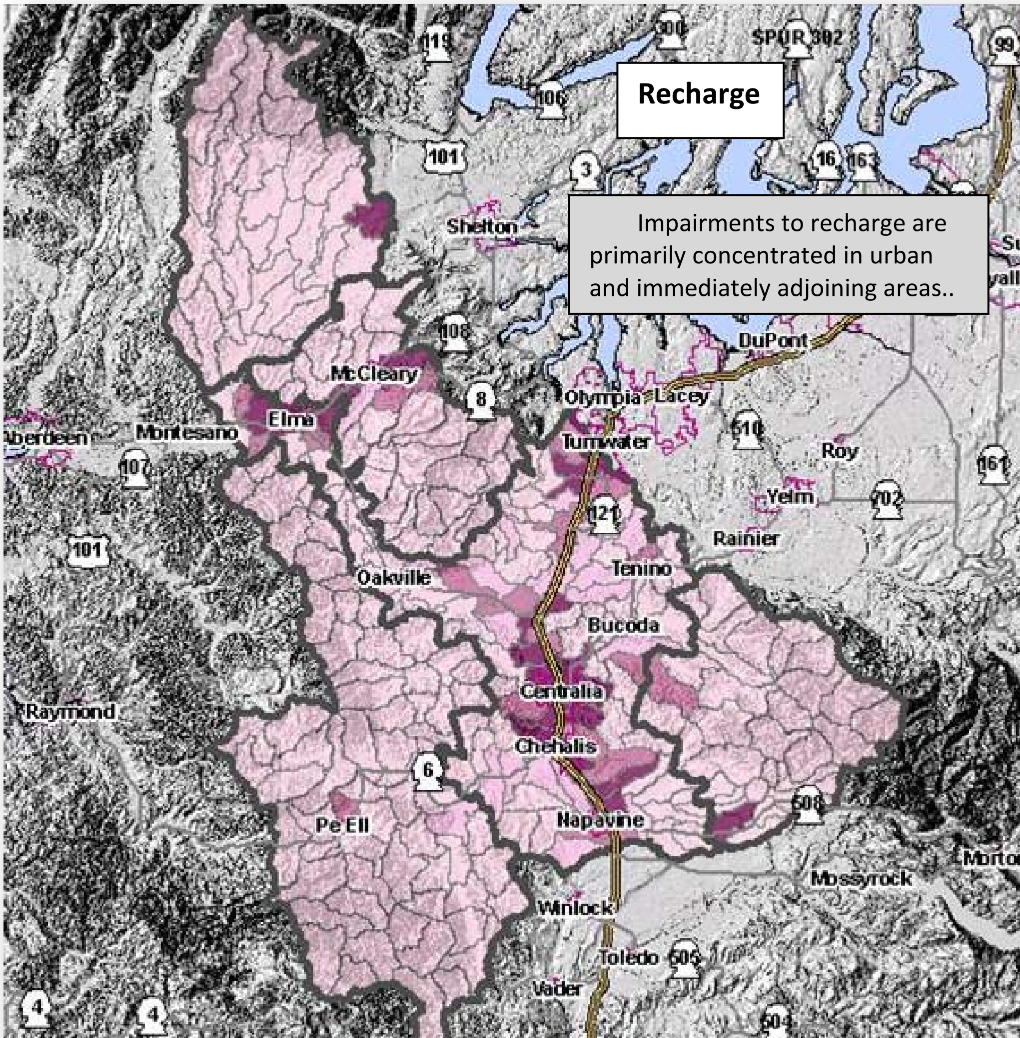



**Figure 17. Example of Impairments to Recharge Areas for WRIA 23 and northeast portion of WRIA 22, Chehalis Basin**. **[HI_R_Q]** The darkest analysis units are the most impaired within the landscape unit, and the lightest analysis units are less impaired. Results shown in quantiles.

The pattern for impairments to recharge (Figure 17) would suggest that the majority of the watershed is not significantly impacted, whereas impairments to discharge (Figure 18) are widespread and a significant issue. Impairments to discharge include pumping of groundwater and urban development within areas of slope wetlands and alluvial floodplains.

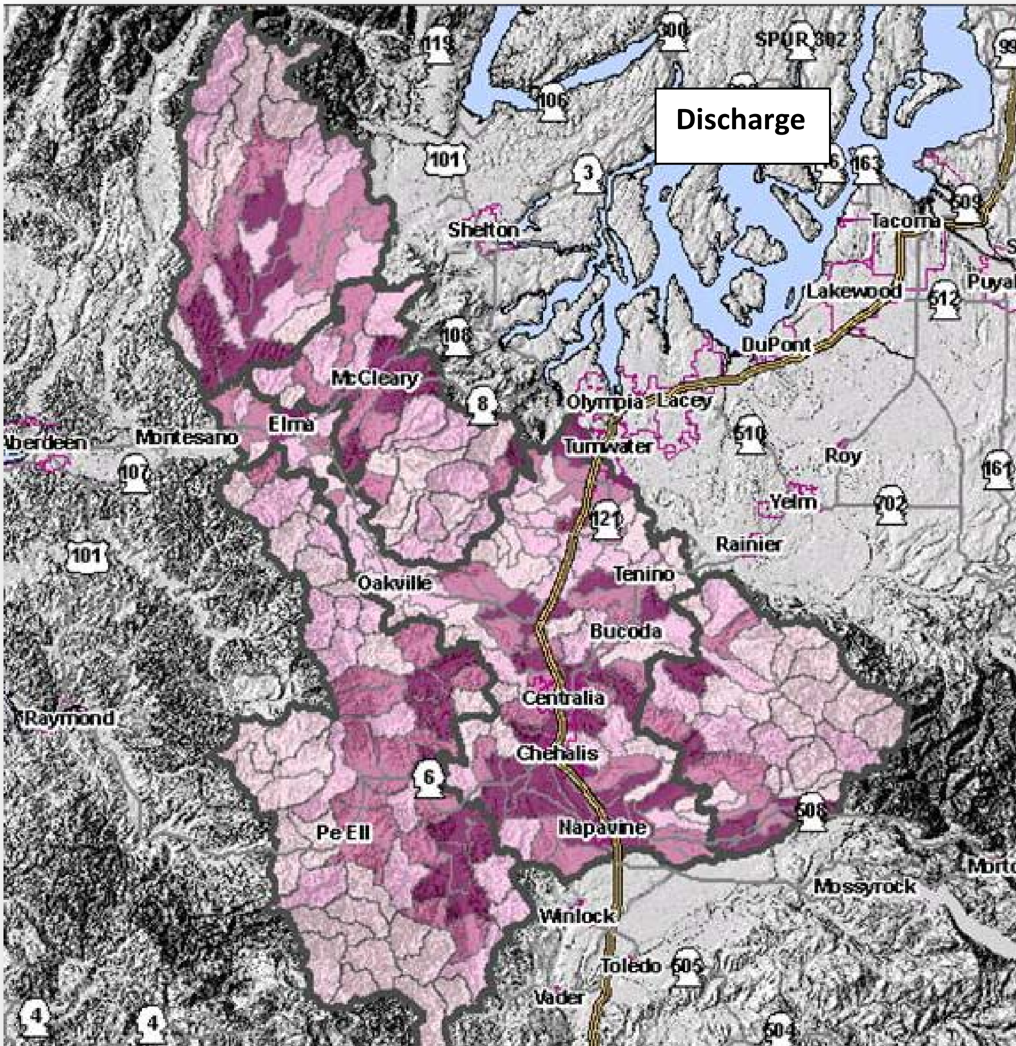



**Figure 18. Example of Impairments to Discharge Areas for WRIA 23 and northeast portion of WRIA 22, Chehalis Basin.** [HI_DI_Q] The darkest analysis units are the most impaired within the landscape unit, and the lightest analysis units are less impaired. Results shown in quantiles.

## Step 6: Identify Analysis units for Protection and Restoration and Recommended Actions

***Key Questions***:

What are the environmental issues within your analysis area?
Where are the most important analysis units for supporting watershed processes related to these issues?
Where are watershed processes still intact or minimally impaired?
Where have watershed processes been impaired?
What actions can be taken to address watershed scale issues by protecting relatively intact processes and repairing impaired processes

This step provides the user with data for initiating the development of a watershed based management framework (Figure 24). The watershed based management framework consists of four parts: characterization, prescribes solutions, take actions, and monitor results. Step 6 addresses the characterization and prescribe solutions portion of the management plan.

A complete characterization requires use of data from landscape assessment of fish and wildlife and other key watershed processes such as delivery and movement of nutrients, sediment and wood.

It is important that the user work with a watershed team, either the Chehalis Basin Technical team or local watershed experts, in interpreting and applying the step 6 data correctly. Tables 2 and 3 provide specific examples of using the data from individual components of the water flow process model to address environmental issues within the watershed. Figures 20 to 24 show the results of that analysis.

***Methods:*** Completion of Steps 4 and 5 produces two sets of maps for each component of a watershed process. For example, the analysis results include individual sets of maps for the delivery, surface water and groundwater components. The first map in each set locates analysis units most important for supporting a watershed process, while the second locates analysis units with relative impairment to these processes. The water flow assessment data were placed into four groups of "high, medium high, medium and low". Data frequency distribution provides the basis for grouping into each category so that the top 25% of the scores were placed in the high, the next 25% in the medium high, the next 25% in the medium and the final 25% in the low.

The final step combines the results of the importance and impairment maps, resulting in recommended watershed management actions. The watershed management matrix can help in selecting both recommended options for each management category (Figure 19) and the appropriate type of action. Each analysis unit has a rating for importance and a rating for impairments that places it into one of the "boxes" in the management matrix.


**Figure 19. Watershed Management Matrix.** The rating for importance is on the vertical axes, and rating for impairment is along the horizontal axes. The combination of these two indicates suitability of the analysis unit for protection, restoration, or development.

Analysis units rating high for importance and low for impairment will be in the upper left corner of the matrix. These analysis units will be the most suitable candidates for protection, ensuring that the associated watershed process will remain intact. Analysis units rating high for importance and high for impairment will be most suitable for restoration. Focusing restoration in these units will increase the likelihood that associated watershed processes will be restored. Based on the color scheme from the Watershed Management Matrix, a general description of the type of land use activities and protection and restoration actions is presented in the text box on page 26.

**TABLE 2 - Interpreting Map Results- Understanding What Important Areas Do and Possible Actions to Offset Impairments Identified**

| Process Component | Description of Component | Important Areas - Look for : and locate the following features within Hydro Unit | Areas of Higher Impairment Look for: and locate the following land cover types with Hydro Unit | How Impairment Affects Process Component | General Actions if Synthesis Maps Show: | General Actions if Synthesis Maps Show: |
|---|---|---|---|---|---|---|
| Delivery Maps – Mountainous Group  | The type of precipitation and timing for its movement across the landscape in a hydro unit. |  Rain-on-snow & Snow Dominated areas |  Loss of Forest Cover in Rain–on-snow and Snow Dominated area. | Increases the rate of snow melt which in turn increases downstream flooding. |  Reforest | Minimize logging in rain-on-snow and snow dominated areas. |
| Delivery Maps – Lowland & Coastal Groups  | The type of precipitation and timing for its movement across the landscape in a hydro unit. | Rainfall dominated areas (which would occur throughout the unit) |  Impervious surfaces | Prevents infiltration and reduces residence time on the surface, thus allowing precipitation to flow overland and reach streams and wetlands more rapidly. |  Re-establish natural cover or use other green infrastructure measures | For new development minimize forest clearing through clustering (approximately 65% or more forest retained) |
| Storage Maps – Mountainous, Lowland and Coastal Group  | The relative amount of surface storage in a hydrologic unit |  Depressional wetlands and floodplains. For Mountainous groups this will primarily be in alluvial valleys. In lowland groups depressional wetlands are located in terraces and floodplains. | Urban and rural development that intersects areas where depressional wetlands and floodplains are located. | Ditching and draining will reduce storage capacity of wetlands. Diking and channelization also reduces storage of floodplains. In urban areas these impacts are usually greater with the filling, diking and draining of wetlands and floodplains. The net result of these impairments is increased channel velocity and greater erosion and flooding downstream. | For wetlands, re-establish natural hydrology by plugging ditches that drain wetland, and restore natural outlet and native vegetation (to slow water). For floodplains, re-establish overbank flooding by removing dikes/levees or raising incised channel. Also, remove any floodplain fill.  | Protect and maintain existing condition by preventing development in floodplains or depressional wetlands and limit sediment transport into depressional wetlands by maintaining adequate buffers. |

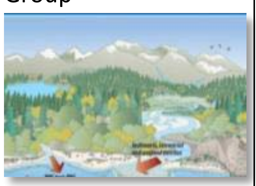
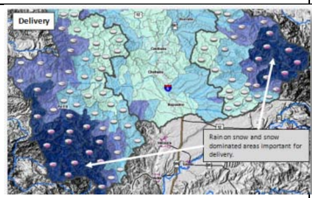
| TABLE 2 - Interpreting Map Results- Understanding What Important Areas Do and Possible Actions to Offset Impairments Identified | | | | | | |
|---|---|---|---|---|---|---|
| **Process Component** | **Description of Component** | **Important Areas - Look for : and locate the following features within Hydro Unit** | **Areas of Higher Impairment Look for: and locate the following land cover types with Hydro Unit** | **How Impairment Affects Process Component** | **General Actions if Synthesis Maps Show:** | **General Actions if Synthesis Maps Show:** |
| Recharge Maps– Mountainous, Lowland and Coastal Group  | The infiltration of surface water into the ground. | Coarse and fine grained surface deposits. Generally, the rate and quantity is greater in coarse grained deposits which include alluvium (valley bottoms) and outwash deposits.  |  The amount of impervious surface. | Greater cover and intensity of development (impervious surfaces) significantly reduces the amount of infiltration and recharge that would otherwise occur. |  Avoid or minimize impacts to recharge areas through clustering and provide native cover on balance of site to facilitate infiltration. Existing urban development can be retrofitted using green infrastructure measures (replace paving with perme-able surfaces & native cover). | Locate higher intensity development in areas with lower permeability. Otherwise, select land use activities that minimize the use of impervious surfaces. This includes agriculture and clustered low density residential development. |
| Discharge Maps – Mountainous, Lowland and Coastal Group  | Areas on the landscape where groundwater moves to the surface in the form of springs, seeps and in floodplains of streams and wetlands. | Slope wetlands in all landscape groups. Alluvial valleys in mountainous areas and broad floodplains in lowland group.  | Urban and rural development that intersects areas where alluvial valleys are located and slope wetlands. Location and quantity of wells. | Well pumping can lower groundwater table and reduce quantity of subsurface water that moves towards and discharges in slope wetlands (usually lower part of hillslopes) and alluvial valleys. Rural and urban development can change the location of where groundwater discharges by installation of roads, ditches, foundations and fill. | Reduce pumping levels in areas that are important recharge areas. Restore natural discharge patterns by plugging/removing ditches and fill. | Protect and maintain discharge areas by preventing development that will permanently alter natural discharge patterns (impervious surfaces and structures). Other uses such as agriculture should avoid use of ditches in discharge zones. |

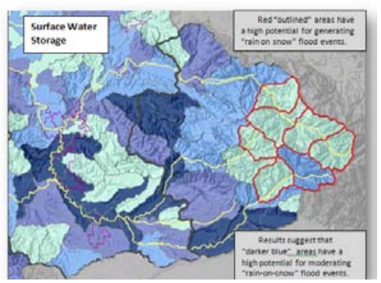
**Table 3. Examples of Interpreting Results from Water Flow Assessment**

| Watershed Issue | Process Component & Landscape Group | Process Component & Landscape Group | Impairment | Actions |
|---|---|---|---|---|
| Lowland Flooding: Rain-on-Snow events | Delivery in Mountainous Group | Storage in Lowland Group | | |
| Look for: | Analysis Units ranking high for delivery + greatest area of "rain-on-snow" and "snow dominated" zones.<br><br>See Figure 8 and 9 | Analysis units ranking high for storage in upper and mid portions of watershed and located downstream of delivery areas in column 2.<br><br>See Figure 10 | High impairment for delivery areas and low for storage areas<br><br>See Figure 15 and 16 | Protect floodplain and depression areas throughout watershed and restore forested cover in mountainous group.<br><br>See Figure 21 |
| | | | High impairment for storage and low for delivery areas<br>See Fig. 15 and 16 | Restore depressional and wetland storage throughout watershed. See Figure 21 |

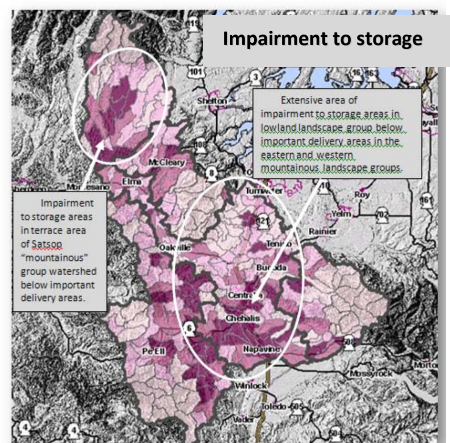



Important areas for rain on snow and snow dominated processes in upper watershed of WRIA 22

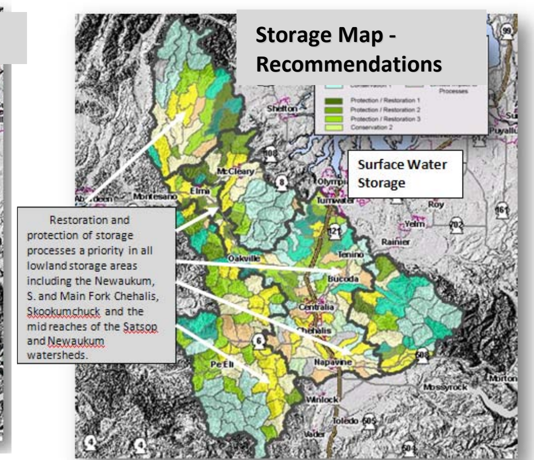
I




Example of important areas downstream (darker blue) of rain on snow and snow areas (red outline) that could contribute to storage of surface flows and reduce downstream flooding and erosion and flooding.

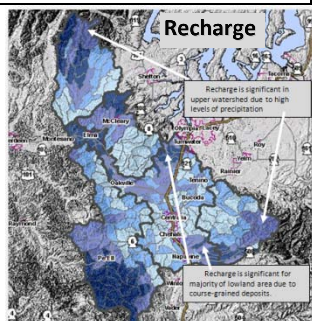
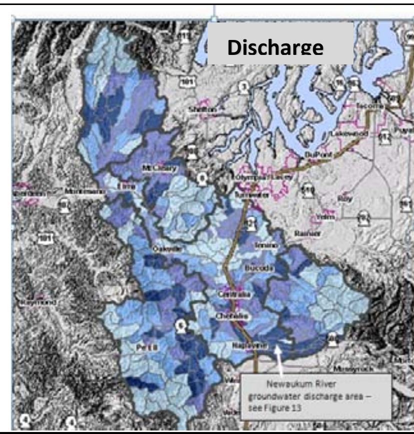
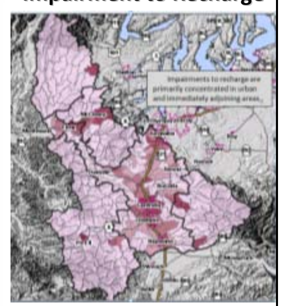
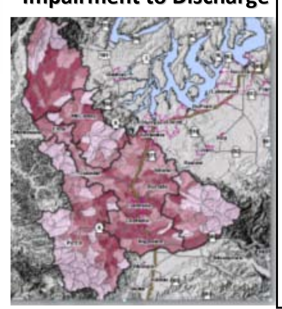
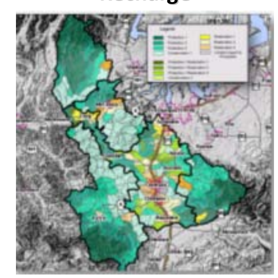
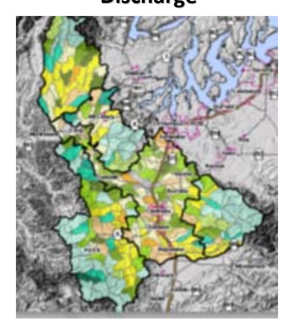



The impairment map for storage shows relatively low impairment for the upper watersheds but high impairment for the mid and lower watersheds of all three landscape groups..




Restoration and protection of storage processes a priority in all lowland areas (South and Main Fork of Chehalis, Newaukum, Skookumchuck) and mid reaches of the Satsop and Newaukum watersheds.

Table 3

| Watershed Issue | Process Component & Landscape Group | Process Component & Landscape Group | Impairment | Actions |
|---|---|---|---|---|
| Reduced Base Flows in Streams | Recharge, all Landscape Groups | Discharge, all Landscape Groups | | |
| Look for: | Analysis Units ranking high for recharge in Mountainous Group or in upper and mid watershed of Lowland or Coastal Group.<br><br>See Figure 11 | Analysis units ranking high for discharge in floodplains and slope wetlands, and located downgradient of recharge areas in column 2.<br><br>See Figure 12 | High impairment to recharge areas, and low impairment to discharge areas.<br><br>See Figure 17 & 18 | Restore recharge in rural areas through low impact development measures, including reforestation and elimination of drainage systems (ditches, drain tiles) and stormwater retrofit programs in urban areas. Protect discharge areas.<br>See Figure 22 and 23 |
| | | | High impairment to discharge areas, low impairment to recharge areas.<br><br>See Fig 17 & 18 | Restore floodplain & slope discharge areas by eliminating diversions of discharge flows by drainage systems on slopes and in floodplains. Protect recharge areas. See Figure 22 and 23. |
|  |  <br>Darker blue areas are important for recharge. The results suggest that all three mountainous areas, play a significant role in providing recharge. |  <br>Darker blue areas are more important for discharge. The discharge areas are located primarily in lowland or valley areas below areas important for recharge | Impairment to Recharge<br><br>Impairment to Discharge<br><br>Overall, the maps suggest that impairment to recharge is focused in urban areas. However, impairments to discharge are occurring in mid reaches of mountainous landscape groups (Satsop, Newaukum, Skookumchuck, and S. Fork of Chehalis.) Additionally, impairments to discharge are more widespread. | Recharge<br><br>Discharge<br><br>Overall, the maps suggest that restoration of discharge is the more important priority for maintaining low flows in the analysis area. Discharge restoration efforts should be prioritized in the mid reaches of the Satsop, S. Fork of the Chehalis, Newaukum and Skookumchuck. |

***Analysis units where <u>protection</u> is a priority (green)*:** Development may be suitable in analysis units that rate high for importance but have not yet been impaired (dark green). Extra care should be taken, however, to establish land use patterns (i.e. land use types, activities, development policies, standards and regulations) that protect and maintain watershed processes. Analysis units with a lighter green color in the matrix may have a lower rating of relative importance but also play an important role in sustaining down-gradient aquatic ecosystems. In these analysis units the management of land use can include traditional measures for protecting land from human activities (e.g., open space, conservation easements) as well as environmentally friendly infrastructure (clustering, rain gardens, and permeable pavement).

***Analysis units best suited for <u>restoration</u> (yellow):*** These analysis units have some impairments of a process but also rated high for importance. Zoning and regulations in these analysis units should promote development that restores areas important to watershed processes (excluding heavily urbanized areas). This could include specific measures that allow impacts in analysis units identified as suitable for development to be mitigated in restoration areas. Restoration in "dark yellow" analysis units will have the most significant benefit in restoring watershed processes and aiding in sustaining down-gradient aquatic ecosystems. Restoration activities can involve restoring the natural condition of the site or focus on restoring the process. For instance, restoring the recharge component could involve increasing surface water retention through restoring depressional wetlands or floodplain areas or replacing impervious surfaces with permeable pavement and recharge ponds.

***Analysis units where further disturbance will have less impact on watershed processes (orange and red):*** Orange and red analysis units have lower levels of importance for watershed processes and higher levels of impairment, and should be considered less sensitive to future impairment. Measures should still be applied at the site scale that protects water quality and quantity functions and significant habitat functions.

***GIS display****:* Combine the final ratings for importance and level of impairment for each analysis unit and represent them using the following scheme:

Green – Analysis units' best suited for Protection
Yellow - Analysis units' best suited for Restoration
Orange to Gray – Analysis units where future disturbance have less impact.

***Product****:* A map showing management recommendations (or option) for each analysis unit.

***Example****:* The information presented in Figure 20 can be used to identify priorities for each analysis unit in WRIA 23 and 22, Chehalis Basin. A planner using this approach would be able to identify which areas to prioritize for protection or restoration of watershed processes. The maps also provide information to prioritize restoration for aquatic ecosystems and locate areas for more intense land use activities.

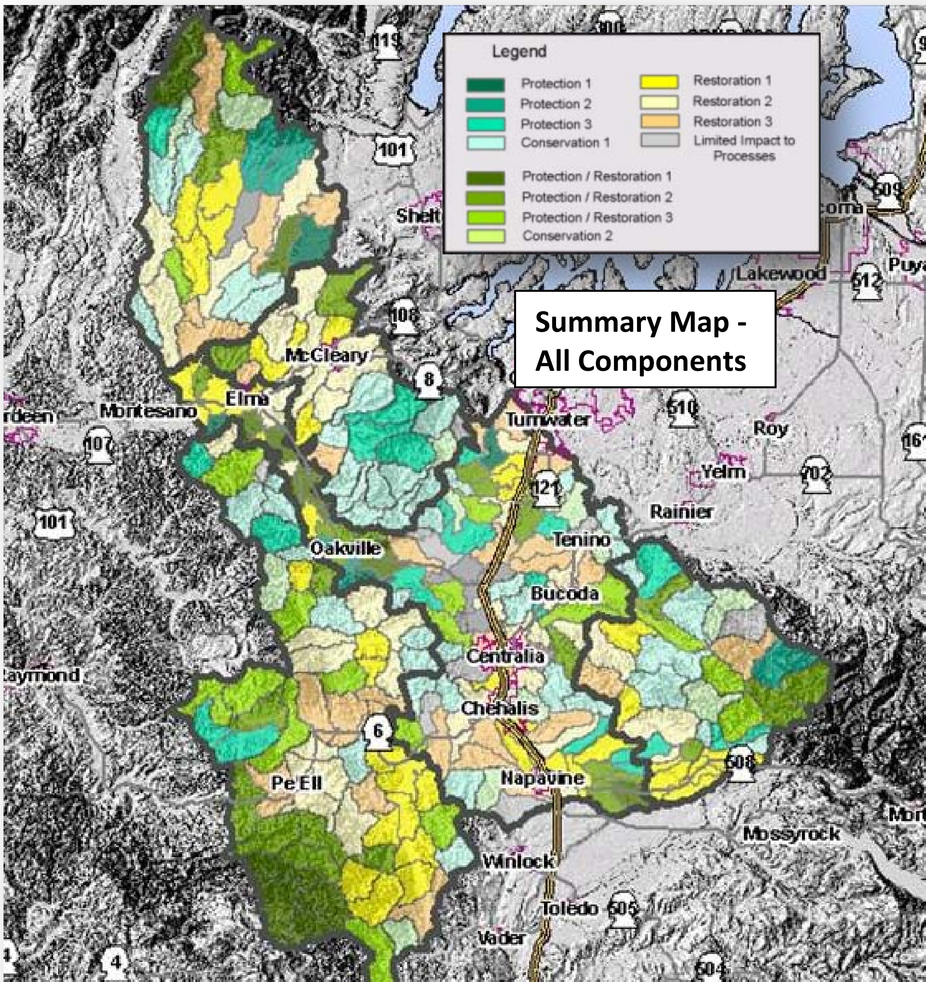



**Figure 20. Example of Restoration and Protection [WF_RP] (All Components of Water Flow Model)** Combining the ratings of "importance" and "impairment" identifies a potential overall management approach for each analysis unit. Darker green indicates that an analysis unit is most suitable for protection of processes; darker yellow is most suitable for restoration of processes; orange to gray indicates analysis units where future disturbance will probably have less impact on watershed processes.

Protection and restoration priorities for specific planning and environmental issues can be determined by looking at the individual components of the water flow process. Examples of this type of evaluation are set forth in Table 2 and 3. The areas for protection and restoration for surface water storage are depicted in Figure 22; for groundwater recharge and discharge in Figures 23 and 24.

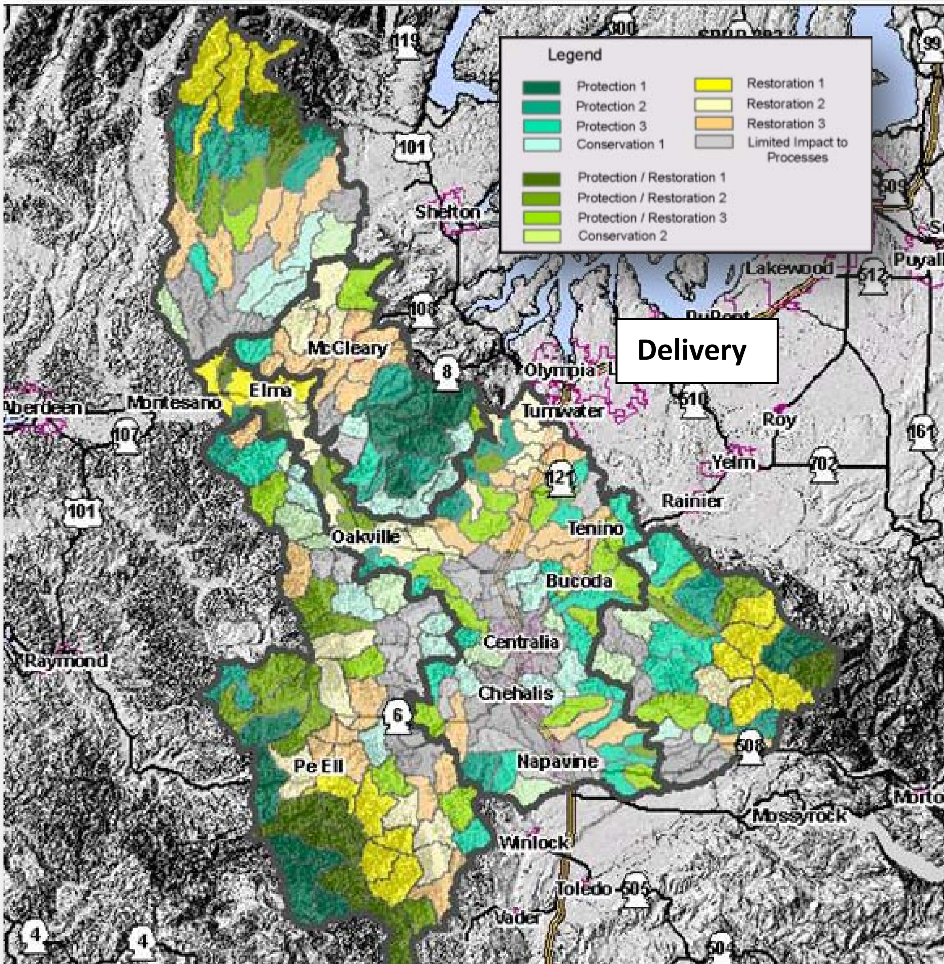



**Figure 21. Example of Restoration and Protection (Delivery).** [D_RP] Combining the ratings of "importance" and "impairment" identifies the most suitable management approach for each analysis unit. Darker green is most suitable for protection of processes; light blue/green is suitable for conservation of processes; darker yellow is most suitable for restoration of processes; orange to gray indicates analysis units where future disturbance will probably have less impact on watershed processes.

Figures 21 to 24 show a somewhat different pattern of restoration and protection for delivery, surface water storage and groundwater recharge and discharge relative to Figure 20. The delivery map indicates that all of the upper mountainous groups have significant areas of restoration relative to the lowland areas.

Relative to the delivery map, areas identified for restoration and protection for storage (Figure 22) are located primarily in the mid to lower reaches of the watershed.

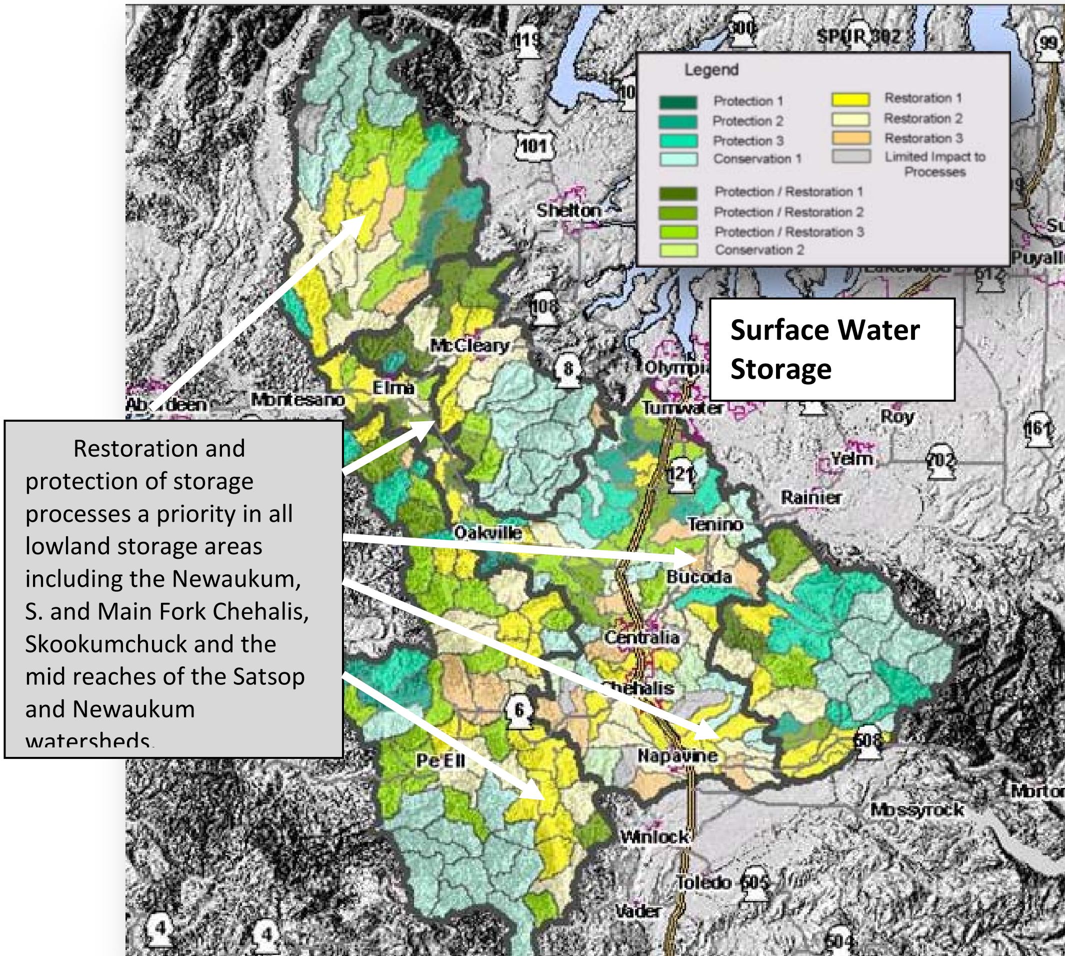



**Figure 22. Example of Restoration and Protection (Surface Water Storage).** [SW_RP] Combining the ratings of "importance" and "impairment" identifies the most suitable management approach for each analysis unit. Darker green is most suitable for protection of processes; light blue/green is suitable for conservation of processes; darker yellow is most suitable for restoration of processes; orange to gray indicates analysis units where future disturbance will probably have less impact on watershed processes. Results shown in quantiles.

This includes the floodplains of the South Fork of the Chehalis, the Newaukum, Skookumchuck and the mainstem of the Chehalis including the towns of Chehalis, Centralia, Oakville and Elma. These results would suggest that local plans and policies promote restoration of storage capacity in these areas, which in turn should reduce flooding and erosion.

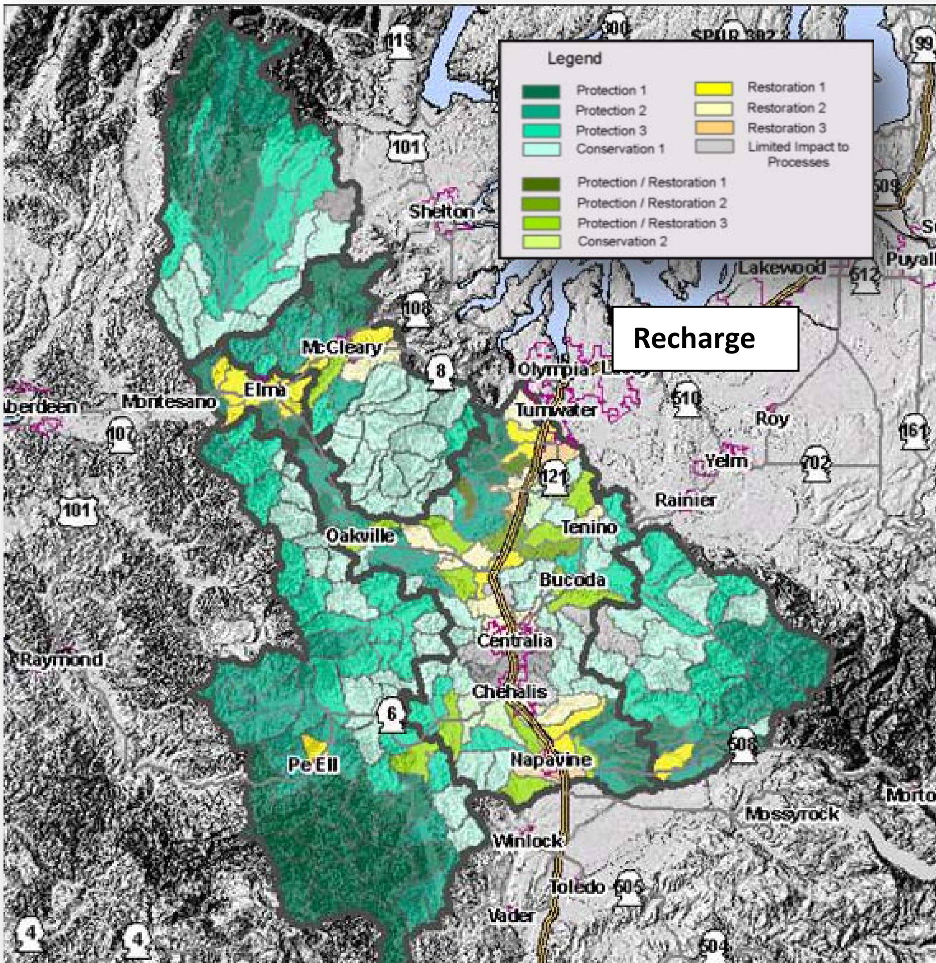



**Figure 23. Example of Restoration and Protection for Groundwater Recharge.** [R_RP] Combining the ratings of "importance" and "impairment" identifies the most suitable management approach for each analysis unit. Darker green is most suitable for protection of processes; darker yellow is most suitable for restoration of processes; orange to gray indicates analysis units where future disturbance will probably have less impact on watershed processes. Results shown in quantiles.

Protection of recharge (dark green, Figure 23) is the highest priority for all of the upper watersheds (mountainous groups), and the floodplain of the lowland group from Oakville downstream. High priority restoration of recharge processes is limited primarily to Elma, Pe Ell, Napavine and south of Tumwater. Future protection and restoration measures could include clustering of development to reduce loss of forest, increase forest cover and reduce the amount of hard surfaces within these recharge areas.

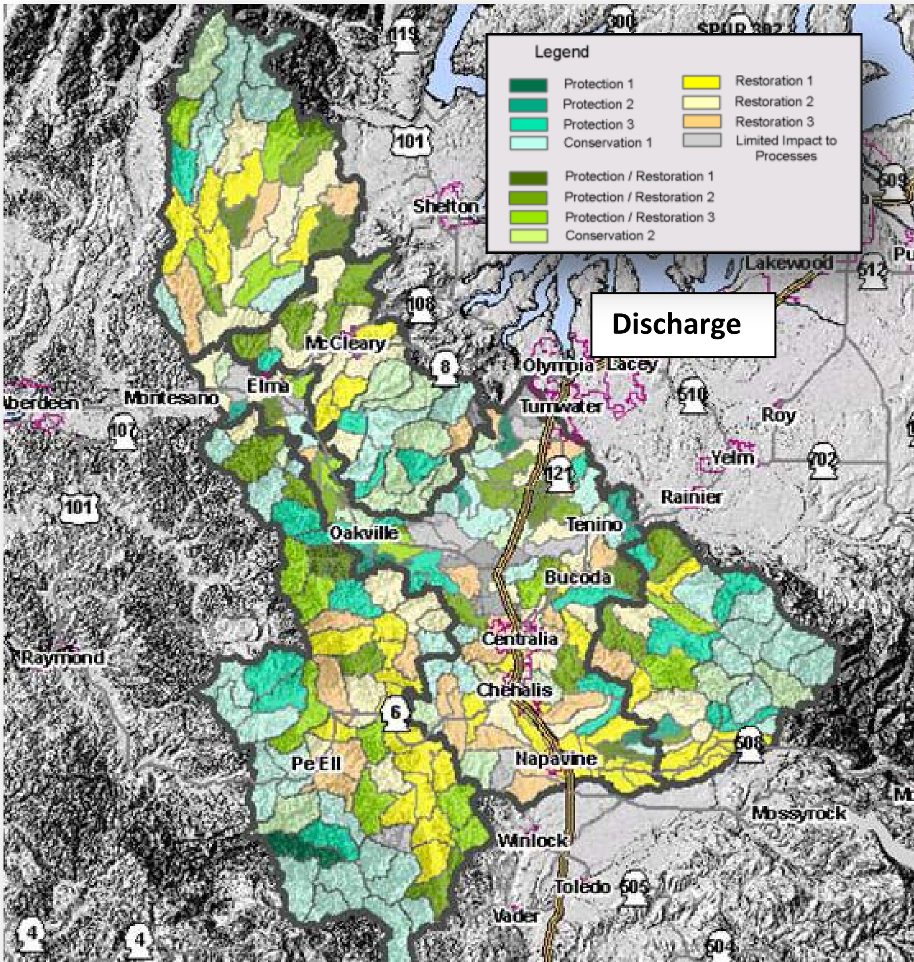



**Figure 24. Example of Restoration and Protection for Groundwater Discharge.** [DI_RP] Combining the ratings of "importance" and "impairment" identifies the most suitable management approach for each analysis unit. Darker green is most suitable for protection of processes; darker yellow is most suitable for restoration of processes; orange to gray indicates analysis units where future disturbance will probably have less impact on watershed processes. Results shown in quantiles.

Overall, Figure 24 indicates restoration of discharge is a priority issue in the mid reaches of the Satsop, South Fork of the Lewis, Newaukum and Skookumchuck watersheds. Impairments to discharge areas include surface water diversions, groundwater pumping, and interruption of shallow groundwater flow by roads and ditching, and diking and filling in floodplains. In general, restoration measures can include the re-establishment of natural hydrologic patterns in these areas. For addressing potential low flow issues, the maps suggest that discharge restoration actions are a higher priority to address than recharge issues. This would assume that impervious cover is not increased within important recharge areas.

## Incorporating Results into Existing Planning Efforts

### Framework for Planning

The information generated by this assessment is most useful when applied to a watershed based planning framework incorporating adaptive management principles (Figure 25). A more detailed discussion of this planning framework is presented in Guidance for Protecting and Managing Wetlands in Western Washington, Volume 2, Chapters 4 and 5 (Granger et al. 2005).

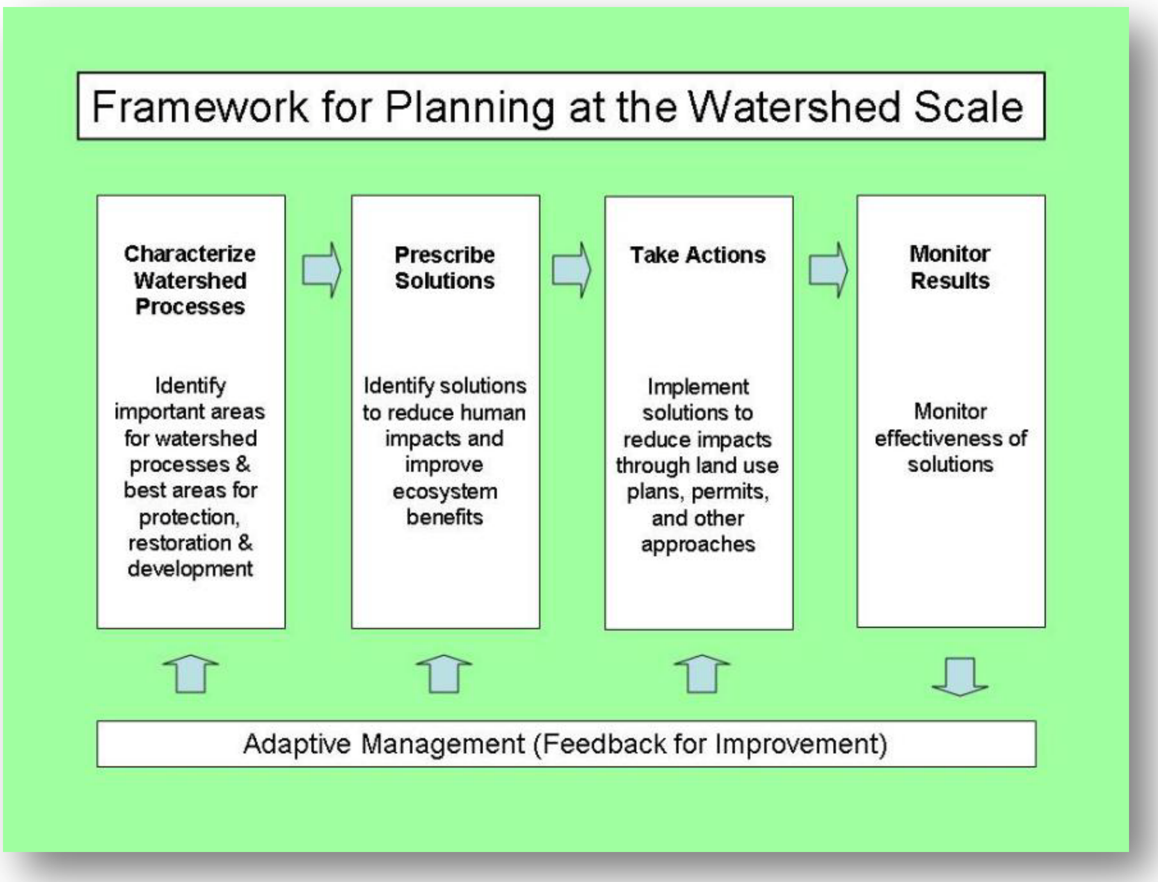



**Figure 25. A general framework for planning at the landscape scale.** This represents a suggested framework that local governments could use in protecting and managing aquatic ecosystems through land use planning.

The methods described here for mapping important areas and relative impairments to watershed processes address the first box of Figure 25, "Characterize Watershed Processes." Planners can then use this information to develop preliminary solutions (box 2, "Prescribe Solutions") including alternative scenarios for development/ management. Examples include:

- Selecting the appropriate types and intensity of development for different locations
- Changing zoning to better protect the ecological services provided by the environment
- Identifying the best locations for mitigation
- Identifying the types of mitigation needed in different areas
- Locating the best areas for cost-effective restoration

The "Take Actions" step in Figure 25 implements solutions when scenarios for future development and management are analyzed, locally reviewed, and accepted. Actions could include adopting updates for comprehensive plans or Shoreline Master Programs with specific provisions based on the analyses.

The final, and most important step in the framework, is monitoring the results of the adopted plan. This determines if the provisions of the plan are effectively protecting and/or restoring aquatic ecosystems. Feedback from this monitoring effort can be used to modify or "adapt" the plan to correct those aspects that are not meeting the objectives of protection and restoration.

| **Scale** | **Tool** | **Information Provided** |
|---|---|---|
| Broad Scale– Multiple analysis units | Assessment, using our approach, or another similar watershed analysis method. | Identify and map important areas within an analysis area. |
| Mid Scale– Analysis unit | Rating of subunits using scoring models – Appendix B | Identify best areas for protection, restoration, and types of land use activities. Helps evaluate existing restoration projects within a watershed context. |
| Fine Scale– Reach, catchment or project site within analysis unit | Synthesis Table (see table 4) and site assessment tools including rating of wetland functions, wetland delineation, groundwater monitoring, | Identify specific planning solution at fine scale based on broad and mid-scale information. |

**Table 4– Integrating information across scales to identify planning solutions**

Successful watershed planning uses larger scale information (i.e. the assessment) to help identify planning solutions at smaller scales. We suggest the use of three planning scales: broad, mid, and fine when developing watershed plans. Table 4 suggests the type of tool appropriate at each scale. Planners should also be aware of both the resolution of the data and the time it was collected since this can affect the accuracy of results. For example, this assessment of water flow processes uses land cover data from the 2006 Coastal Change Analysis Program. As a result, more recent land use activities could change the assessment results presented in this document.

## Using the Watershed Planning Framework with Existing State Planning Laws

The methods described in this document can assist **planners** in meeting the planning goals for resource protection contained in state and local environmental laws and regulations. This includes the Growth Management Act (Chapter 36.70A.060) the Shoreline Management Act (Chapter 90.58), and the State Environmental Policy Act (Chapter 43.21C). Furthermore, these methods are an acceptable approach to completing an "assessment of functions and ecosystem wide processes" as specified in WAC 173-26-201(3)(d)(i).

Additionally, this framework for watershed planning is useful to **non-profit organizations** and other governmental entities that restore, manage, or conserve aquatic resources. A detailed discussion of the application of landscape planning to the protection of wetland ecosystems is presented in chapters 2, 6 and 7 of Granger et al. (2005).

Growth Management Act. The Growth Management Act (GMA) requires local governments to develop comprehensive plans and to adopt critical area regulations in order to meet the fourteen GMA planning goals. Comprehensive plans are intended to conserve the state's resource lands protect our environment, and promote economic development that is sustainable (RCW 36.70A.010). Comprehensive plans are intended to be a cooperative and coordinated approach amongst jurisdictions and private parties. The methods presented in this document are ideally suited for helping local governments meet these goals in a cooperative manner because they:

- Identify watershed processes operating across jurisdictional boundaries.
- Support protection of critical areas by considering important areas for watershed processes, and identify those areas where development will have the less impact.
- Evaluate the effect of future land use on watershed processes.

- Identify watershed processes operating across jurisdictional boundaries.
- Support protection of critical areas by considering important areas for watershed processes, and identify those areas where development will have less impacts (location of Urban Growth Areas).
- Evaluate the effect of future land use on watershed processes.

This type of information will provide an understanding of the most appropriate areas for effective protection and restoration, and how existing or future land uses, both within and outside particular jurisdictional boundaries, may impair watershed processes.

Additionally, this guidance will allow local governments to develop Critical Area Ordinances (CAO's) that are tailored to their specific landscape. Ecologists have known for some time that natural resources require management at the watershed scale (Dale et al. 2000). Presently, however, many local governments have adopted a generalized set of regulations for critical areas using guidance developed by Ecology for use statewide, which can make watershed-based permit decisions difficult. New federal mitigation rules require a watershed analysis to determine appropriate mitigation sites. The Department of Commerce is updating its administrative rules in 2009 to guide local governments in implementing the GMA, including recommendations to use watershed-based mitigation schemes consistent with the best available science.

Application of this framework to the development or revision of CAO's would allow jurisdictions to identify:

- both existing and future environmental problems that would affect aquatic resources; and
- areas where actions would be most effective in addressing these local/regional environmental problems. This could include identification of areas where specific types mitigation would be most effective in addressing ecosystem problems and areas of lower importance where standard regulatory measures could be relaxed such as buffer widths.

The information can also be used to identify areas best suited for using innovative measures such as mitigation banks and fee-in-lieu programs.

Shoreline Management Act. The Shoreline Management Act (SMA) states that "shorelines of the state are among the most valuable and fragile of its natural resources and that there is great concern throughout the state relating to their utilization, protection, restoration, and preservation." Similar to the stated purpose of the GMA, the SMA goes on to state that there is "a clear and urgent demand for a planned, rational, and concerted effort, jointly performed by federal, state, and local governments, to prevent the inherent harm in an uncoordinated and piecemeal development of the state's shorelines."

Ecology adopted new Shoreline Master Program Guidelines in 2003 that require jurisdictions to incorporate information on the physical, chemical, and biological processes and functions that drive shoreline resources.

The new guidelines implement the policy of the Shoreline Management Act for the protection of shoreline natural resources through the protection and restoration of ecological functions and ecosystem-wide processes necessary to sustain these natural resources. The guidelines specifically state that effective management of shorelines depends on sustaining the functions provided by: (1) **ecosystem-wide processes** (i.e., flow and movement of water, sediment, and organic materials and movement of fish and wildlife); and (2) individual components and localized processes such as those associated with shoreline vegetation, soils, and water movement through the soil and across the land (WAC 173.26.201(2)(c)).

Further, the new guidelines require that SMP policies and regulations ensure "no net loss" of ecological functions necessary to sustain shoreline ecosystems. Updated SMPs must regulate new development in a manner that is protective of existing ecological functions and provide policies that "promote restoration of impaired ecological functions" (WAC 173.26.201(2)(c) and (f)).

Because the shoreline guidelines contain many of the same landscape principles that are addressed in this document, the methods presented for describing and mapping important areas for watershed processes can be useful to local governments updating their SMP. Specifically, under the new guidelines these methods can be used to:

- Conduct the assessment of ecosystem-wide processes (WAC 173.26.201(3)(d)(i)).
- Identify areas appropriate for restoration and protection as part of the restoration plan element (WAC.173.26.201(2)(f)).
- Identify land use designations and development standards that protect ecosystem-wide processes (WAC 173.26.201(3)(f)).
- Meet "no net loss" requirements while allowing for mitigation flexibility (WAC 173-26-186(8) and 173.26.201(3)(d)(i)(E).
- Address cumulative impacts in developing master programs (WAC 173.26.201(3)(d)(iii).

For more information on the updated SMP guidelines, see: http://www.ecy.wa.gov/programs/sea/SMA/index.html

## Other Approaches

Various methods have been developed to analyze individual aquatic resources and the nearby landscape in which they occur. Battelle developed a method for characterizing and assessing marine shorelines to identify the best areas for restoration (Diefenderfer 2007). Those marine methods were applied in conjunction with the freshwater methods presented in this document for shoreline planning in Jefferson County.

The methods for analyzing the functions and characteristics of individual wetlands have been extensively tested in the State (Hruby et al. 1999, 2000, Hruby 2004a, b). Appendix A-2 of Granger et al. (2005) also discusses other methods that have been used to analyze individual wetland sites. Methods for analyzing specific stream reaches have been developed by natural resources agencies (e.g., NOAA's properly functioning conditions). However, methods for analyzing the larger geographic scales are only starting to be developed and applied in Washington.

## Influencing Human Behavior

The following section is excerpted from the Puget Sound Partnership Habitat Issues Paper, 2008.

Washington currently has a long list of incentives, education and stewardship programs, which may influence human activities in a way that results in positive outcomes for the environment. A summary of those programs is set forth in Appendix P1-2 of the Habitat Issues Paper. It should be noted that this is not an exhaustive list and there may be programs, which should be added to it. With regard to incentive programs, these activities provide landowners with benefits that in turn, induce them to protect or restore the ecosystem processes, structures and functions on their land.

*Landowner Incentives Programs* include:

(1) Direct Financial Incentives (grants, subsidized loans, cost-shares, leases);

(2) Indirect Financial Incentives (property tax or sales tax relief, such as Public Benefit Rating System programs);

(3) Acquisition of Property and/or Conservation Easements;

(4) Technical Assistance (referrals, education, training, design assistance programs); and

(5) Recognition and certification for products or operations.

Puget Sound has a history of success with landowner incentive programs. For example, many Conservation Districts throughout Puget Sound have been quite successful in working with rural landowners and farmers to create and implement individual farm plans. As a result, landowners and farmers have planted and fenced stream buffers and reduced the introduction of nutrients and pathogens to downstream aquatic ecosystems.

Another successful tool is the Public Benefit Rating System program (PBRS), a form of indirect financial incentive.   This tool is available today under state law, and has been proven effective in protecting critical habitats in urban and rural areas.  For example, King, Clark and Whatcom counties have used the voluntary PBRS program to reduce property taxes in exchange for a landowner granting protective habitat easements and/or restoring habitat on private property.

**Conservation Markets** encourage the sale of conservation products or credits from private land. Few examples exist for these types of incentives outside of wetland banking, although interest in these programs in growing.  (See, e.g., the Ecosystem Services Marketplace program, an innovative water quality trading program designed to reduce stream temperatures in the Willamette Basin; and Green House Gases (GHG) emission cap and trade programs being discussed across the nation).

**Stewardship Programs** include land sales or exchanges, conservation easements, transfer or purchase of development rights.  Acquiring property has the potential to provide long-term protection to habitat resources from a variety of risks.  Public agencies, as well as non-governmental organizations such as land trusts and conservancies, often acquire property in one of two ways: acquire the entire property through a fee simple transaction, or, acquire a portion of a property's rights by either stripping the property of its development rights or acquiring a conservation easement with associated long-term deed restrictions and covenants. Successful examples of such stewardship programs include the Cascade Land Conservancy's acquisition efforts through its long-term protection plan known as the Cascade Agenda, and the King County and Snohomish County Transfer of Development Rights/Purchase of Development Rights Programs.

**Education Programs** include public and private outreach and education programs, which are either passive in nature (where a resident simply receives information in the mail or at an event), or active (where training occurs with the expectation that a person will volunteer to protect or monitor some portion of the ecosystem or the health of a species).  There are many natural resource education programs designed to be taught in K-12 schools (e.g., education programs designed by state agencies such as WDFW or counties under their NPDES permit programs, and private programs such as Salish Sea Expeditions).  There are programs for adults, as well, such as beach-watcher and beach seining volunteer organizations for salmon recovery,  watershed-keeper education programs and similar.  These programs may result in long-term volunteer engagement in efforts to protect and restore local aquatic systems; however, their effectiveness has yet to be measured on a comprehensive scale.

## References


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 S. Bolton. 1999. An approach to restoring salmonid habitat-forming processes in Pacific Northwest watersheds. Fisheries Habitat 24:6-15.

Beechie, T.J., G. Pess, E. Beamer, G. Lucchetti, and R.E. Bilby. 2003. Chap 8: Role of watershed assessment in recovery planning for salmon. In: Restoration of Puget Sound Rivers. Eds: D.R. Montgomery, S. Bolton, D.B. Booth, and L. Wall. University of Washington Press. 194-225 pp.

Benda, L., N.L. Poff, D. Miller, T. Dunne, G. Reeves, G. Pess, and M. Pollock. 2004. The newwork 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.

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.

Diefenderfer, H.L., K.L. Sobocinski, R.M. Thom, C.W. May, S.L. Southard, A.B. Borde, J. Vavrinec, and N.K. Sather, Multi-scale analysis of restoration priorities for marine shoreline planning. Environmental Management. Submitted December, 2007, In Revision

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.

Gersib, R. 2001. The need for process-driven, watershed-based wetland restoration in Washington State. Proceedings of the Puget Sound Research Conference 2001.

Glasoe, S. and A. Christy. 2004. Literature Review and Analysis: Coastal Urbanization and Microbial Contamination of Shellfish Growing Areas. Puget Sound Action Team Publication #PSAT04-09.

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.

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.

Hobbie, J.E. (ed). 2000. Estuarine Science: A Synthetic approach to Research and Practice. Island Press, Washington D.C. 539 p.

Hruby, T. 2004a. Washington State Wetland Rating System for Eastern Washington – Revised. Washington State Department of Ecology Publication #04-06-015. Olympia, WA.

Hruby, T. 2004b. Washington State Wetland Rating System for Western Washington – Revised. Washington State Department of Ecology Publication #04-06-025. Olympia, WA.

Hruby, T., S. Stanley, T. Granger, T. Duebendorfer, R. Friesz, B. Lang, B. Leonard, K. March and A. Wald. 2000. Methods for Assessing Wetland Functions Volume II: Depressional Wetlands in the Columbia Basin of Eastern Washington. Washington State Department of Ecology Publication #00-06-47. Available at: http://www.ecy.wa.gov/biblio/0006047.html

Hruby, T., T. Granger, K. Brunner, S. Cooke, K. Dublonica, R. Gersib, L. Reinelt, K. Richter, D. Sheldon, E. Teachout, A. Wald and F. Weinmann. 1999. Methods for Assessing Wetland Functions Volume 1: Riverine and Depressional Wetlands in the Lowlands of Western Washington Part 1 Assessment Methods. Washington State Department of Ecology Publication #99-115. Available at: http://www.ecy.wa.gov/programs/sea/wfap/westernwfapmethods.html#Download

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

Kruckeberg,A.R., 1991. Natural history of Puget Sound country. University of Washington Press, Seattle Washington. 480 p.

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

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.

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.

Naiman, Robert J., and Robert E. Bilby, editors. 1998. River ecology and management: lessons from the Pacific coastal ecoregion. Springer-Verlag, New York.

Naiman, R.J., T.J. Beechie, L.E. Benda, D.R. Berg, P.A. Bisson, L.H. MacDonald, M.D. O'Connor, P.L. Olson, and E.A. Steel. 1992. Fundamental elements of ecologically healthy watersheds in the Pacific Northwest Coastal Ecoregion. In:

Watershed Management: Balancing Sustainability and Environmental Change. Eds R.J. Naiman. New York: Springer Verlag. 27-188 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 p.

National Research Council. 2001. Committee on Mitigating Wetland Losses. Compensating for wetland losses under the Clean Water Act. Washington, D.C.: National Academy Press. 348 pp.

Poiani, K.A., B.D. Richter, M.G. Anderson, and H.E. Richter. 1996. Biodiversity conservation at multiple scales: Functional sites, landscapes, and networks. Bioscience 50(2): 133-146.

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.

Reice, S.R.,R. Wissmar, R. Naiman. 1990. Disturbance regimes, resilience and recovery of animal communities and habitat in lotic ecosystems. Environmental Management 14(5):647-659

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.

Shreffler, D.K. and R.M. Thom. 1993. Restoration of urban estuaries: new approaches for site location and design. Prepared for: Washington State Department of Natural Resources, Aquatic Lands Division, Olympia Washington. Battelle Laboratories. 107 pp.

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.

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

Vaccaro, J.J., A.J. Hansen Jr., and M.A. Jones. 1998. Landscape Framework of the Puget Sound Aquifer System, Washington and British Columbia. Part of the Regional Aquifer-System Analysis – Puget- Willamette Lowland. U.S. Geological Survey Professional Paper 1424 – D, 77 pp.

Weigle, J.M. and B.L. Foxworthy. 1962. Geology and groundwater resources of west-central Lewis county, Washington. U.S. Geological Survey, Ground Water Branch.

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 analysis 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 R.M. Thom. 2001. Marine and Estuarine Shoreline Modification Issues. Prepared by Battelle Marine Science Laboratory. Prepared 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.

# Appendix A: Overview of Appendices B and C

Characteristics of the landscape within a watershed can predict which geographic areas are more likely to be important to each of the watershed processes.

For each process the discussion in the appendix is divided into five sections describing:

1. The watershed process and each of its components.
2. For *unimpaired* conditions, the controls and important areas for each of the components of the watershed process (corresponding to Step 4 in the guidance).
3. For *impaired* conditions, the human impairments to the controls and important areas (corresponding to Step 5 in the guidance).
4. *Models for unimpaired* conditions for scoring the relative importance of sub-units within an analysis area for a watershed process.
5. *Models for impaired* conditions for scoring the relative level of impairment to important areas for a watershed process, at the sub-unit scale.

## Description of the Process

For Appendix B we diagram (Figure A-1) and describe the delivery, movement, and loss of each watershed process. These processes include water, nitrogen, pathogens, sediment, phosphorous and toxins, and large woody debris. The appendices present methods and supporting rationale for identifying important areas in the watershed that support the **components** of each watershed process.

***Main Component–*** Delivery, movement and loss.

***Sub-Component*** - The individual mechanisms of each main component that make up a process. For example, infiltration, percolation, recharge, and discharge are all sub-components of the movement of water, which is a main component.

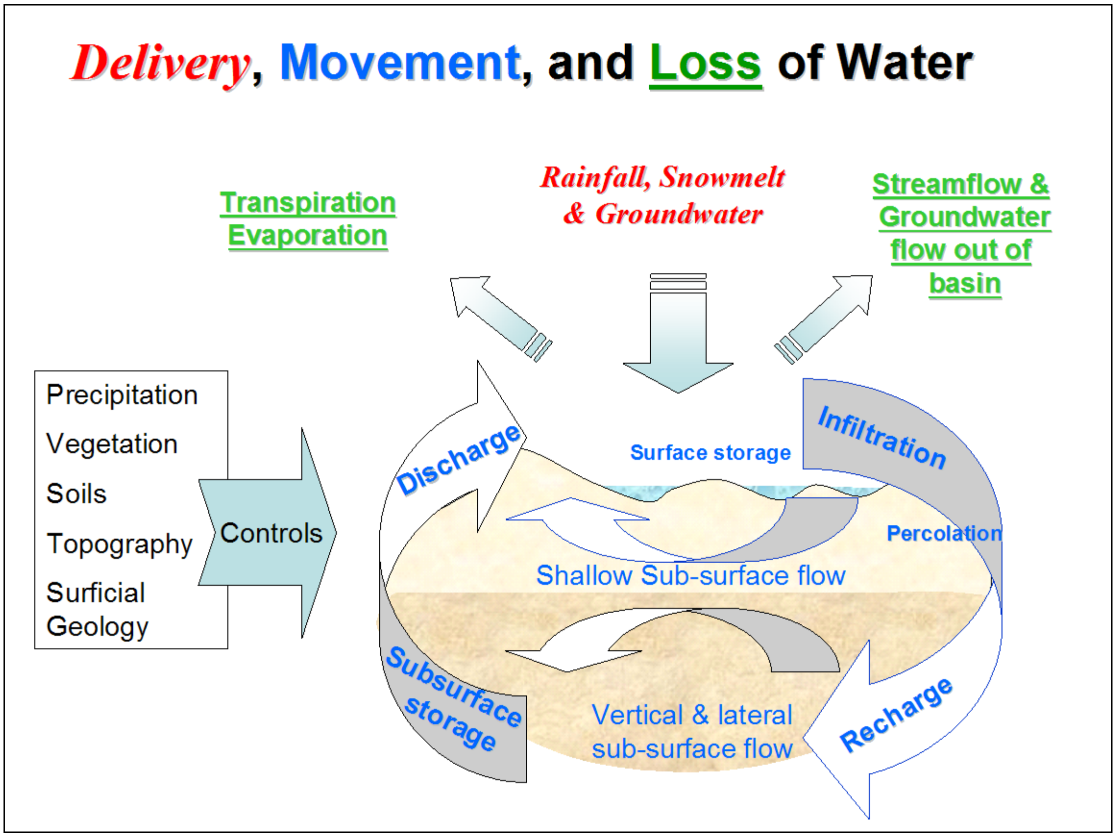



**Figure A-1: Example of the components for a watershed process.** This diagram illustrates the main components of delivery, movement and loss of *water* in watersheds in western Washington. The sub-components of delivery are in red italics, sub-components of movement are in blue, and sub-components of loss are in green and underlined. The light brown area indicates near-surface material; darker brown indicates deeper material; and controls of the process are shown in black to the left of the diagram.

Mapping methods are in Appendix C for those important areas and impairments that you can identify by using regionally available GIS data. We also provide suggestions for using local data to map important areas when regional data is not available.

## Unimpaired Conditions - Step 4 of the Guidance

Following the description of the process, we provide a table for identifying the major controls and important areas (e.g., Table A-1) of each watershed process.

We discuss the supporting rationale for each of the major natural controls and their important areas. Important areas shown in bold type in the Table Cave regionally available data for analysis and mapping. Each of these has a corresponding "variable" that is an analysis step in the overall model. An introduction to the models is below and the details of the models are discussed in each appendix.

Important areas shown without bold type are not readily identified with existing data. Sometimes they can be analyzed if local data exists or additional data is collected. Including them in the table provides both completeness and transparency of the models.

**Major controls and important areas for the delivery, movement, and loss of water in Western Washington.**

| Main Component and Sub-components of Process | | | Major Natural Controls | Important Areas | Variable for Scoring Importance |
|---|---|---|---|---|---|
| *Delivery* | | | Precipitation patterns | **Recharge areas with higher amounts of precipitation** | **P** |
| | | | Timing of snowmelt | **Rain-on-snow zones**<br>**Snow-dominated zones** | **HU1** |
| *Movement* | *At the surface* | Overland flow | Precipitation patterns<br>Soils | Saturated areas | |
| | | Surface storage | Topography<br>Surficial geology<br>Soils | **Areas of low gradient**<br><br>**Floodplains** | **HU2**<br><br>**HU3, HU4** |

**Table A-1. Example of a portion of the table presenting major controls for important areas** for the delivery and movement of a process (i.e., water process, in this example). The components of the process are color coded to correspond to the diagram (Figure A-1).

## Impaired Conditions - Step 5 of the Guidance

Following descriptions of the controls and important areas, we present the type of impairments likely to affect the processes. Appendix B provides a set of GIS indicators that can identify activities that are likely to produce these impairments (Table A-2). We include a detailed discussion of the technical rationale for the use of each of these indicators. These indicators apply to watersheds in Western Washington.

The indicators in bold type represent variables included in the models. Those not in bold type are not included in the models since existing data is not currently available. All indicators are listed for model completeness and transparency.

| Component of Process | Major | Important | Variable for |
|---|---|---|---|

| | | | Natural Controls | Areas | Scoring Importance |
|---|---|---|---|---|---|
| *Delivery* | | | Precipitation patterns | **Recharge areas with higher amounts of precipitation** | **P** |
| | | | Timing of snowmelt | **Rain-on-snow zones**<br>**Snow-dominated zones** | **HU1** |
| *Movement* | *At the surface* | Overland flow | Precipitation patterns & Soils | Saturated areas | |
| | | Surface storage | Topography, Surface geology<br>Soils | **Areas of low gradient**<br>**Floodplains** | **HU2**<br>**HU3, HU4** |
| | *Below surface* | Shallow subsurface flow | Topography<br>Surface geology | **Low permeability deposits** | **HU5** |
| | | Recharge | | **High permeability deposits** | **HU5** |
| | | Vertical and lateral subsurface flow | | Entire watershed | |
| | | Subsurface storage | Surface geology | Deep permeable deposits | |
| | *Return to surface* | Discharge | Topography<br>Surface geology | **Floodplains intersecting permeable deposits**<br>**Slope breaks intersecting area of hydric soils extending into lower gradient area**<br>Stratigraphic pinchouts<br>Contact areas between geologic deposits of different permeabilities | **HU6, HU7** |
| *Loss* | | Evaporation/ Transpiration | Vegetation<br>Climate | Entire watershed | Addressed in impairments |
| | | Stream or sub-surface flow out of basin | Topography<br>Surface geology | | |

**Table A-2. Example of a portion of the table presenting indicators of impairments to the delivery and movement of a process** (i.e., water process, in this example). The components of the process are color coded to correspond to the diagram (Figure A-1).

This list of indicators is not all-inclusive. The literature and scientific studies supporting these indicators are relative to the larger Puget Sound region. It does not include many of the national indicators identified by the Heinz Report (Heinz Center 2002) for biological components, but it has adapted some of the physical and chemical indicators. Users of this guidance should ensure that these indicators seem reasonable for their specific planning area. Other indicators may be added that are supported by local studies or data.

## Introduction to Models

> The purpose of these numeric models is to effectively display watershed characteristics to inform land use decisions. The information developed from the models can identify sub-units where:
> - future development could significantly impact watershed processes
> - new development would have the least impacts
> - the hydrologic process might best be protected or restored.

Numeric models have been developed for the water flow process.

These numeric models (equations) can identify the areas in a watershed that are most suitable for protection, restoration or development. They provide a transparent, repeatable method to analyze watershed processes and represent the "how" of the methods described in this guidance document.

There are two models or equations developed to analyze each of three watershed processes (water, nutrients, and pathogens). The first model scores the **relative importance** of sub-units in maintaining a process in an unimpaired setting. The second scores the **relative severity of impairments** to the process in those sub-units.

The general form of the models is:

Importance of Process = Importance of *Delivery* +
Importance of Movement +
Importance of Loss

Impairment of Process = Impairment of *Delivery* +
Impairment of Movement +
Impairment of Loss

These general equations are then adapted for each process using components and variables in the model diagram and tables (e.g. Figure A-1 and Table A-1 and A2). Figure A-2 below provides a summary of the process of adapting the general equations.

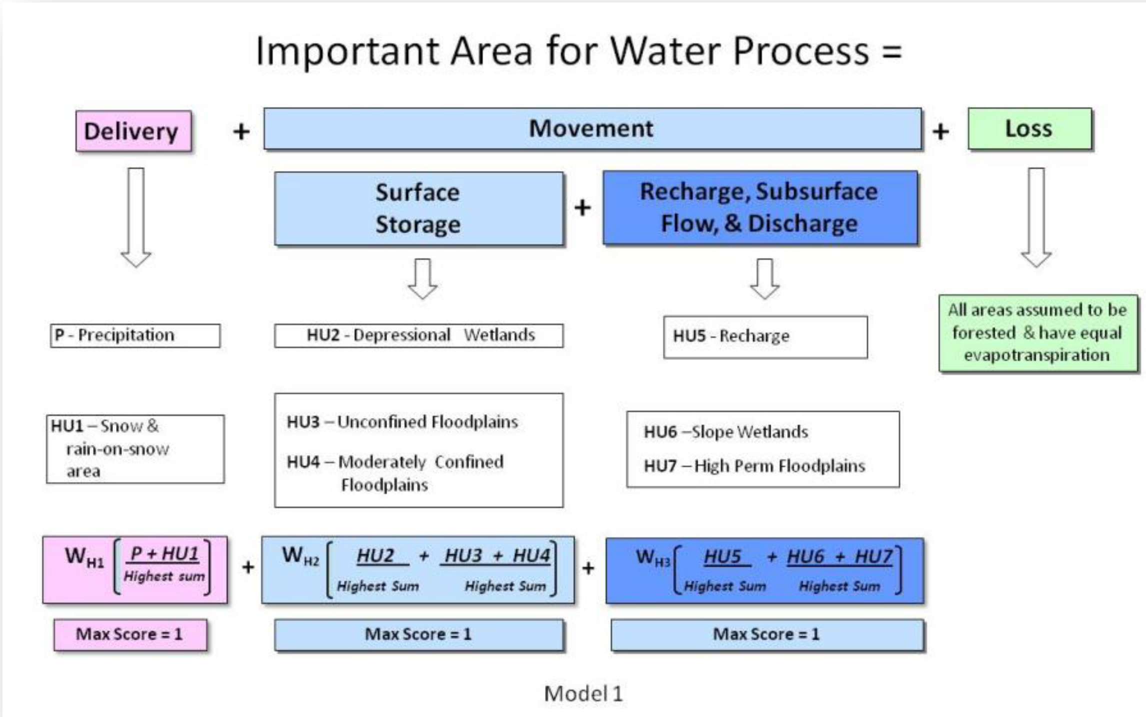



**Figure A-2. Example of numeric model for scoring important areas for the water process.**

Evapotranspiration, or **loss**, is assumed to be equal in importance for all sub-units (with forest cover in an unimpaired state), so it is not included in the model for importance. However, it is included in the model for impairments.

## Summary of Scoring

Numeric models use the variables in each table to determine a score for each environmental characteristic. The model for the importance in the unimpaired condition uses variables that start with "HU" (Hydrologic Unimpaired). The model for the impairments to the process uses variables that start with "HI" (Hydrologic Impairment). A graphic of the model and its variables is presented at the beginning of each section on models.

In general, variables are scored from "0 to 1" with the final score derived from a ratio of the area over which a control for a process operates relative to the area of the watershed. The models are constructed so that higher total scores represent basins of greater importance for supporting a process in a watershed, or one with a higher degree of impairment to that process.

We normalize the sum of variables for each component so they have equal weighting. Scoring is normalized by the maximum value within the analysis area. In this way, the models provide a comparison of the **relative level** of importance and impairment of process components. The scores do not represent a specific rate (e.g., rate of removal of sediment or nitrogen) or specific level of impairment of a process that can be compared to scores outside of the analysis area. We do not have enough information at this time to calibrate models to conditions throughout the state and establish relative importance of processes and impairments among different watersheds.

## Process for Calculating the Models

Below are the recommended steps for calculating the models.

1. Calculate the values for each variable and normalize (scores for each variable will be from 0 to 1).
2. Total all variables from each component (see introduction to models above) within the specific equation for the process.
3. Normalize the total scores for each component to "one" [1] so that final values are from 0 – 1. Therefore, all scores become a percentage of the highest score. For the water flow process (importance model), this would be: delivery = 0-1; and movement = 0-1.
4. Calculate the final score for a process (hydrologic unimpaired) by summing the normalized scores of each component. (delivery + movement = 0-2)
5. Calibrate the **final** scores for a process to zero by subtracting the lowest score for an analysis area from all other scores, then divide all scores by the highest remaining value. This calibrates all scores from zero to one.
6. Divide the final range of scores into 4 equal buckets and assign a rating to the final score calculated above for both the importance and impairment models. The four ratings are High (H), Moderate High (MH), Moderate (M), and Low (L).

Since the final scores for both the importance model and the impairment model are calibrated from zero to one, the four ratings can either be represented as quantiles (i.e. top 25% of the scores; then the next 25%...) or four equal ranges of the total score (0 to 1):

| Rating | Range of Total Scores |
|---|---|
| High (H) | .75 - 1 |
| Moderate High (MH) | .5 - .75 |
| Moderate (M) | .25 - .5 |
| Low (L) | 0 - .25 |

Synthesize the results of the importance and impairment models. The synthesis matrix (Figure A-3) uses these two final ratings (H, MH, M, L for importance on the vertical axis, and H, MH, M, L for impairment on the horizontal axis) to indicate the most suitable application of protection, restoration, or development for each sub-unit.

## Process for Running the Models

The process for running the models for the Chehalis Watershed Assessment Project was designed to account for the variation in geology, precipitation and landform within this large geographic area.  In order to provide modeling results that represent a relative analysis of areas with comparable environmental conditions a watershed can be divided into landscape groups (see main guidance step 2).

For Puget Sound, we calculate Step 4 above using the landscape group as the "watershed."  Thus, scores are normalized to the highest analysis unit score within the landscape group, and the rankings are based on the range of scores within that landscape group.

When the purpose is to identify specific areas for restoration based on ecological systems that have similar geologic, geomorphic and hydrologic (surface and subsurface) conditions.  This information can be used to develop watershed based mitigation plans, including mitigation banks, advanced mitigation, in-lieu mitigation or other such projects.

The ratings for a process and its impairment are the information that is carried forward into the next step in the analysis.

## Analyzing the Results of the Models.

The two ratings for each sub-unit, the H, M, or L for importance and impairment, can be combined into a "4 x 4" matrix as shown in Figure A-3.  The matrix allows for synthesis of the results of the importance and impairment models into management categories or recommendations.  Each box in the matrix has a management recommendation that applies to all sub-units with the corresponding ratings.

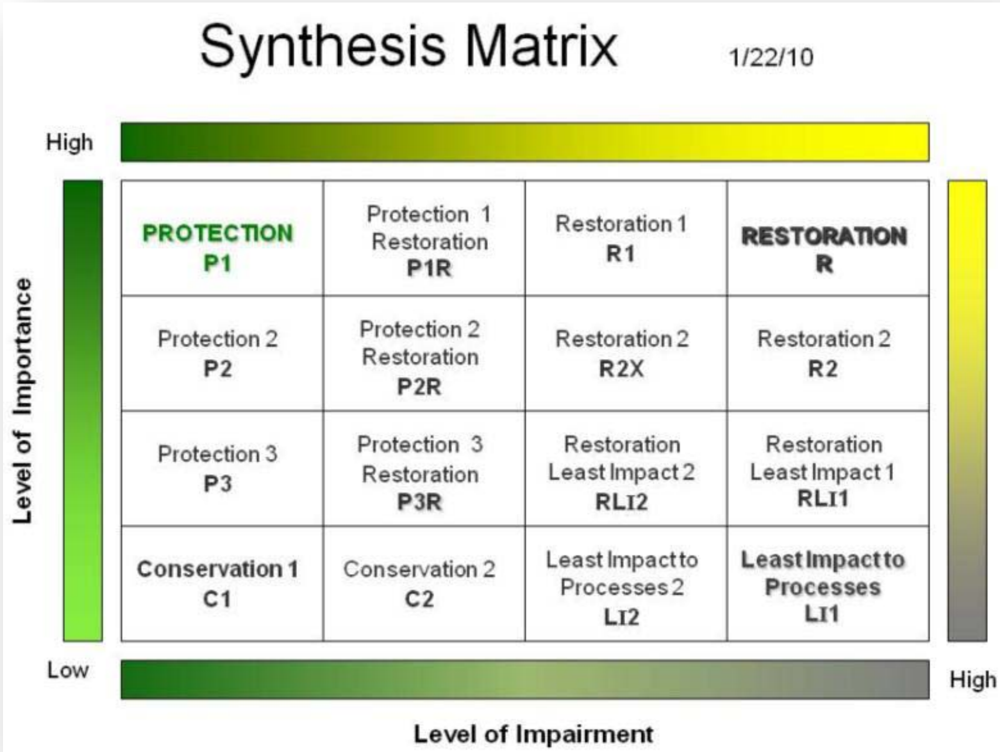



**Figure A-3: A suggested matrix for synthesizing the results of the importance and impairment models into management categories.** The colors correspond to colors used on a GIS map to represent areas most appropriate for restoration (yellow), protection (green) and less impact to processes (gray).

The synthesis matrix allows for a range of protection, restoration, and conservation options to be depicted on planning maps, which generally represent the following types of management recommendations:

(1) Protection areas have higher levels of importance for watershed processes and limited impairment. Protection of functioning processes should be a high priority. When development is proposed in these areas, extra care should be taken to establish land use patterns (i.e. land use types, activities, development policies, standards and regulations) that protect and maintain watershed processes. Protection 2 areas may have a lower level of importance but may play an important role in sustaining down-gradient aquatic resources.

(2) Restoration areas, including "restoration/development," still have a high level of importance for watershed processes, but also have a higher level of impairment. Restoration of watershed processes should be considered a high priority unless all watershed processes and aquatic functions are permanently impaired by urban development. Restoration in "Restoration 1" areas will have the most significant

benefit, relative to other rated sub-units, in restoring watershed processes and aiding in sustaining down-gradient aquatic resources. Again, care should be taken in establishing land use patterns that protect and maintain areas for important watershed processes.

(3) Conservation areas have a lower level of relative importance in supporting watershed processes, but also have a low level of impairment. As such, these areas have an intact suite of processes and functions that support existing aquatic ecosystems and would require considerable time to restore elsewhere on the landscape. Management strategies in these areas may rely more heavily on wildlife assessments and the need to protect critical habitats. Higher intensity land use activities may be appropriate in these areas relative to protection areas, but care should be taken to establish land use patterns (i.e. land use types, activities, development policies, standards and regulations) that protect and maintain watershed processes

(4) Areas "less sensitive to disturbance" have lower levels of importance for watershed processes and higher levels of impairment. These areas can be considered as more suitable for urban land use activities. Planning measures employing protection of critical aquatic resources and appropriately sited development should be considered. However, offsite mitigation in other areas suitable for restoration should be evaluated as a higher priority.

Definitions of watershed protection and restoration and further examples of how they can be interpreted are presented below.

***Protection***: Any activity that ensures that the watershed process supported by an important area is relatively unimpaired. This can include traditional efforts of protecting land from human activities (e.g., open space, conservation easements), or it can also mean designing development in a way that allows the watershed process to continue with minimal impairment. For instance, an area important for recharge could be set aside from any development, or new development could be sited and designed to ensure recharge of the additional surface runoff generated by the development.

***Restoration:*** Any activity that ensures that the watershed process associated with an important area is reinstated. This can involve restoring the natural condition of the site, but it can also include activities that restore the capacity of the important area to support the process. For instance, an area important for recharge that is covered with impervious surfaces could be modified to accommodate recharge or it could be restored to natural conditions.

The specific design of any of these activities requires further site-level analysis.

## Redundancy of Indicators

Several indicators of important areas and impairments to important areas are used multiple times. For example, depressional wetlands are indicators in Step 4 for important areas for providing storage of surface water, adsorption and removal of pathogens, and loss of nitrogen. For Step 5, impervious cover is an indicator of impairment to groundwater recharge, overland flow, evapotranspiration. Despite this overlap, we have chosen to maintain the redundancy within this document for two reasons:

The science underlying the link between indicators and a process is constantly changing. As a result, it is likely that at some point in the near future, there will be solid evidence that different indicators should be identified for one of the processes but not for all. Maintaining the redundancy within this document allows for transparency of the rationale for each process separately and for updating this rationale with new scientific research and findings as appropriate.

Despite the need to maintain these redundancies for the purposes of this document, the results of one analysis can inform several of the models. This supports more efficient analysis and display of results.

## Testing and Review of Model Results

The validity of the model results were reviewed and tested using an iterative process that consisted of the following steps for each WRIA:

1) Results of the runs that characterized the Importance, Impairment and Protection/Restoration subunits of the model were reviewed with staff scientists (e.g. hydrogeologist, aquatic ecologists) to determine if the ratings (i.e. high, medium and low) were generally consistent with their knowledge of processes in the area. The review involved the analysis of the individual results of the model components (e.g. delivery, surface storage, recharge, discharge and evapotranspiration).
2) When the results from the model were inconsistent with the local knowledge of processes, the data tables and calculations were first examined for errors. If no errors were found then applicable scientific research and information was sought to justify changes to individual variables. Changes to specific variables were made when the scientific information suggested different issues were present in that watershed. For example, the permeability variable was originally based on the relative area of high permeability deposits; this was modified to include a regression equation from USGS research in Puget Sound that considered both precipitation and permeability for discrete spacial units within a

watershed. This resulted in more accurate results for the groundwater recharge component of the model. If results for a new variable were not acceptable then the variable was eliminated.

*3)* Results were presented to the Puget Sound Technical Committee and Tribal Scientists for review and comment. The same process outlined in #2 above was followed for this step. The input from this group also resulted in changes to the presentation of the data (e.g. groups for display- quantiles vs. quartiles)

Sensitivity analyses were attempted initially but these did not prove to be a very effective tool to understand the system better. The modeling uses a mechanistic approach to combining variables and indicators. The sensitivity of the results in these types of models is based strictly on the importance assigned to each variable by the model builder. For example our initial model assigned one variable – precipitation – once third of the overall score in the "importance sub-model. This resulted in an overall change to the model structure, which gave equal weighting to each of the model components (i.e. delivery, surface storage, ground water recharge and discharge). This was done because the model was not intended to compare the actual rates and quantities of one component of a process with another (precipitation amount vs. total storage in a sub-basin) but the individual importance of each component for individual watersheds or analysis units. Furthermore, mechanistic models of this type use indicators/variables can represent different types of numeric scales (e.g. nominal, ordinal, interval and ratio (Stevens 1946). Because different types of scales are used, the standard statistical analyses are also not valid.

# References

Bedford, B.L. 1999. Cumulative effect on wetland landscapes: links to wetland restoration in the United States and Southern Canada. Wetlands 19(4):775-788

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.

Heinz Center. 2003. The State of the Nation's Ecosystems – Measuring the Lands, Waters and Living Resources of the United States. John Heinz III Center for Science, Economics and the Environment. Available at: http://www.heinzctr.org/ecosystems/intro/toc.shtml

Mundorff, M.J. 1964 Geology and ground-water conditions of Clark County Washington, with a description a major alluvial aquifer along the Columbia River. U.S. Geological Survey Water-Supply Paper 1600, 268 p.

Stevens, S. S. (1946). "On the Theory of Scales of Measurement". Science 103: 677–680)

Winter, T.C. 2001. The concept of hydrologic landscapes. Journal of the American Water Resources Association 37(2):335-348.

# Appendix B: Assessing the Water Process in Chehalis Watershed and Western Washington

## Methods for Assessing the Water Process

This section on Methods explains the rationale used in Assessing the water process. It describes

- what indicators we use.
- the rationale for that indicator.
- the literature support for the indicator.

For an explanation of **"how"** to do this analysis, go to the section on Models.

### Description of the Water Process

The water process is defined as the delivery, movement, and loss of water in a watershed in Western Washington. This is the most important watershed process for aquatic resources because it also plays a critical role in assessing many of the other processes. Figure B-1 outlines some of the dynamic relationships among the different components of the process. The following sections describe each of these components in more detail.

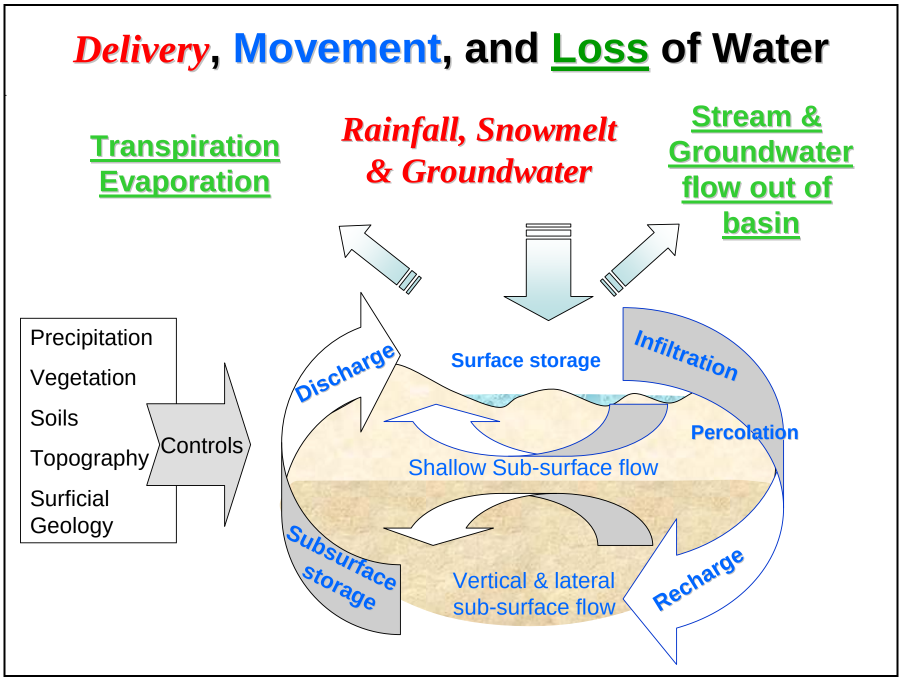



**Figure B-1: Illustration of the delivery, movement, and loss of water in watersheds of Western Washington.** Controls of the process are in black to the left of the diagram; components of delivery are in red italics, components of movement are in blue, and components of loss are in green and underlined. The light brown area indicates near-surface material; darker brown indicates deeper material.

## Delivery of Water

Delivery of water describes how water, in the form of rain, snowmelt, or groundwater, reaches a watershed. Precipitation patterns and temperature control the delivery of water to a watershed. The regional climate, including the quantity, type (snow vs. rain), and timing of precipitation and the timing of snowmelt, determines these patterns.

In certain watersheds, water may enter a watershed as groundwater from adjacent watersheds. Surface geology and topography determine these groundwater flow patterns. This method does not include such regional flow patterns because they are difficult to characterize using existing data.

## Movement of Water

The movement of water begins when precipitation sinks into, or infiltrates, the soil column and underlying geologic deposits. In the Western Washington, the ability of soils to allow water to sink in, its infiltrative capacity or permeability, greatly exceeds precipitation rates except in the most severe storms (Booth et al. 2003). As a result, water generally infiltrates into the soil, rather than remaining at the ground surface and moving down slope as overland flow (Harr 1977, Figure B-2). All but the most restrictive soil types in Western Washington allow for the complete infiltration of water in most storm events if they have relatively undisturbed natural cover (e.g., forest, scrub-shrub).

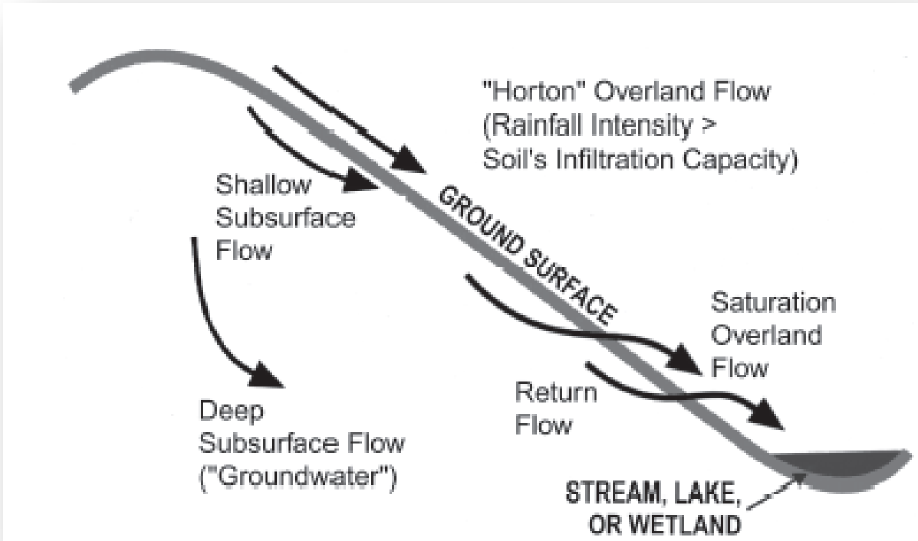



**Figure B-2: Components of water movement after precipitation and snow melt reach the ground surface.** Adapted from Booth et al. 2003.

Saturated areas form on the surface where water cannot infiltrate easily. These are wet areas where the water table is at or near the surface. These saturated areas can also form when subsurface flow reaches the surface and becomes surface flow. This is called return flow and is typically found in valley bottoms. Precipitation falling on saturated areas cannot infiltrate, and instead moves down slope, on the surface as overland flow. In general, however, saturated areas occupy a relatively small portion of a watershed. Most of the water infiltrates as described above. Another factor involved with saturated areas is their variability. The size of saturated areas will change depending storms or snowmelt that can change soil moisture conditions (Dunne et al. 1975).

Once water enters the soil, the topography and the permeability of surface deposits control the path water takes.

- In steeper areas that overlie permeable surface deposits, some portion of this water percolates downward to recharge the groundwater, while a smaller portion continues to move laterally as shallow subsurface flow (Figure B-3).
- In steeper topography that overlies less permeable surface deposits, the lateral movement of water as shallow, subsurface flow dominates and there is less recharge of groundwater (Figure B-4).
- In low gradient areas overlying less permeable deposits, water can move laterally, but only under high soil moisture conditions (Weiler et al. 2005). As a result, these areas can provide surface storage of water.

- In low gradient areas surface ponding can occur is the soil surface is fine grained (or organic) and has low permeability regardless of the permeability of deeper deposits. These areas, often depressional wetlands, provide surface storage of water.

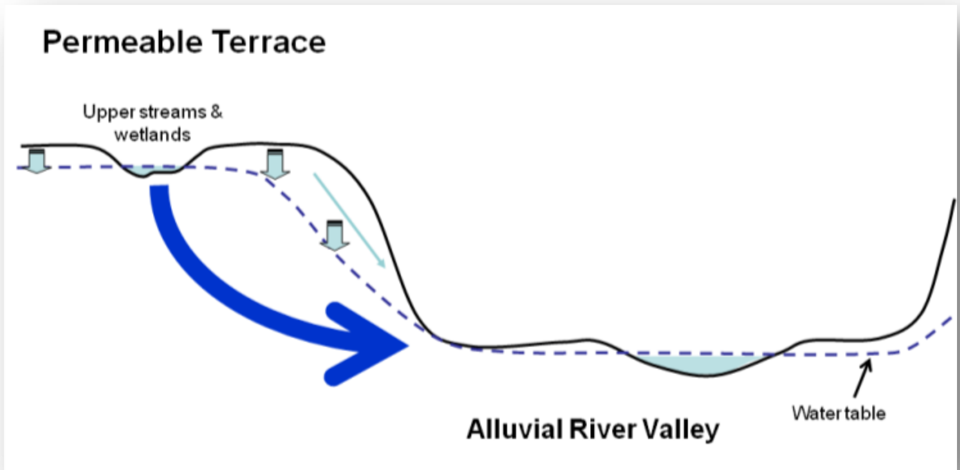



**Figure B-3: Relationship of topography to water movement on permeable deposits** adjacent to a river valley of Puget Sound. Blue arrows indicate movement and relative volume of water. Flows are dominated by vertical and lateral flows in deeper deposits. High groundwater level at base of slope of valley walls indicates discharge areas, which may have wetlands with organic soils.

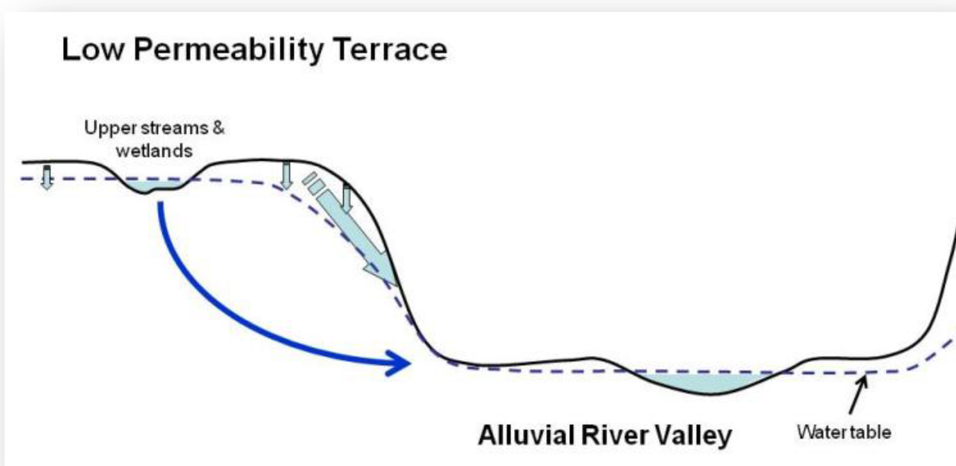



**Figure B-4: Relationship of topography to water movement on low permeability deposits** adjacent to a river valley of Puget Sound. Blue arrows indicate movement and relative volume of water. Shallow subsurface flows dominate in this setting. High groundwater level at base of slope of valley walls indicates discharge areas, which may have wetlands with mineral soils.

During rainfall or snowfall, water stored in the soil column is forced to move down slope as subsurface flow, eventually reaching aquatic ecosystems such as streams, lakes, and wetlands (Weiler et al. 2005). Surface water in streams can be temporarily stored in floodplains, wetlands, or lakes. Once in surface storage areas, water can begin the entire cycle again by infiltrating and percolating into the soil column and underlying geologic deposits or returning to streams.

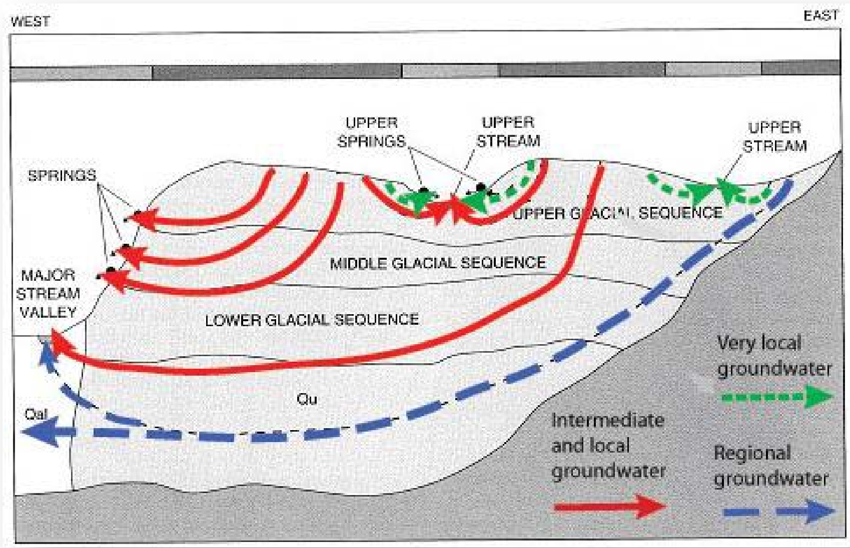



**Figure B-5. Generalized cross section through typical basin in the Puget Sound Lowland**, showing recharge (dark area on top bar) and discharge areas (light areas on top bar) and generalized directions of groundwater flow paths (taken from Morgan and Jones 1999).

Water that percolates deeper into the surface geologic deposits eventually reaches the water table, providing recharge to groundwater. The scale of vertical and lateral flow of groundwater is usually described hierarchically in three levels, each with longer flow distances and therefore longer residence time: local flow, intermediate flow, and regional flow (Figure B-5).

In the Puget Sound basin, regional groundwater flow follows deep flow paths defined by large topographic features such as the Puget trough and the Cascade Range. Intermediate and local groundwater flow follows shallower flow paths defined by topography, the presence of confining layers in the surface deposits, and the extent of salt water (Morgan and Jones 1999, Vaccaro et al. 1998). The subsurface storage of water that occurs in deep, permeable surface deposits, often provides the primary aquifers used by humans.

In some landscape settings, groundwater comes back to the surface. This occurs as springs or seeps that are often visible at the ground surface, but it can also occur directly as surface water. For example, many lakes in southern Puget Sound are actually intersecting the upper surface elevation of groundwater. Water that "reaches" the surface in this way re-enters the cycle described earlier for movement of water above ground.

### Loss of Water

Water is lost from a watershed in one of two ways: (1) it flows out of the basin on the surface as a stream or as groundwater continuing into another basin or directly to marine waters, or (2) it returns to the atmosphere by evaporation or transpiration in plants. There is a net conservation of water. All the water coming into a basin eventually leaves as groundwater, surface water or evapotranspiration.

## Identifying Important Areas to the Water Process – Step 3

In this section, we discuss the environmental controls of the movement and loss of water in a basin. This information can be used to map the important areas for each component of the water process for watersheds in Western Washington.

Table B-1 summarizes these relationships. Each component, their controls, important areas and variables are color coded in the table according to the colors presented in Figure B-1 for delivery, movement, and loss (red, blue, and green respectively). Important areas in **bold** type are those that you can map using regionally available data. The table also lists the variable used for "scoring" each component. See the section 5.0 on **"Models"** for the methods on scoring these variables. If we do not know of a reasonable method for analyzing an important area with existing data, the box for the important area is not in bold type and the box for the variable is empty. However, you may be able to map these areas if you have local data or knowledge.

*Table B-1: Variables for "scoring" the importance of the delivery, movement, and loss of water* **in Western Washington based on the major environmental controls, and the important areas**

| Component of Process | | | Major Natural Controls | Important Areas | Variable for Scoring Importance |
|---|---|---|---|---|---|
| *Delivery* | | | Precipitation patterns | **Recharge areas with higher amounts of precipitation** | **P** |
| | | | Timing of snowmelt | **Rain-on-snow zones**<br>**Snow-dominated zones** | **HU1** |
| *Movement* | *At the surface* | Overland flow | Precipitation patterns & Soils | Saturated areas | |
| | | Surface storage | Topography,Sur-face geology<br>Soils | **Areas of low gradient**<br>**Floodplains** | **HU2**<br>**HU3, HU4** |
| | *Below surface* | Shallow subsurface flow | Topography<br>Surface geology | **Low permeability deposits** | **HU5** |
| | | Recharge | | **High permeability deposits** | **HU5** |
| | | Vertical and lateral subsurface flow | | Entire watershed | |
| | | Subsurface storage | Surface geology | Deep permeable deposits | |
| | *Return to surface* | Discharge | Topography<br>Surface geology | **Floodplains intersecting permeable deposits**<br>**Slope breaks intersecting area of hydric soils extending into lower gradient area**<br>Stratigraphic pinchouts<br>Contact areas between geologic deposits of different permeabilities | **HU6, HU7,** |
| *Loss* | | Evaporation/ Transpiration | Vegetation<br>Climate | Entire watershed | Addressed in impairments |
| | | Stream or sub-surface flow out of basin | Topography<br>Surface geology | | |

## Delivery of Water

Precipitation and groundwater flow patterns primarily control the delivery of water to a watershed. We discuss the quantity of water available for recharge and the timing of snowmelt. We do not address groundwater coming in from other basins because we lack data and methods to characterize it. The relevant section of Table B-1 is below.

| Component of Process | Major Natural Controls | Important areas | Variables for Scoring | GIS Data |
|---|---|---|---|---|
| ***Delivery*** | Precipitation patterns | **Areas with higher amounts of precipitation** | **P** | **Precipitation** |
| | Timing of snowmelt | **Rain-on-snow zones<br>Snow-dominated areas** | **HU1** | **Rain on Snow<br>Snow dominated** |

### *Precipitation patterns [P]*

The amount of water available to supply surface water and groundwater will be greater in areas with higher precipitation. Variation in rainfall (Figure B-6) can have a significant effect on both surface flows and groundwater recharge. For example, the estimated rates of mean annual groundwater recharge in Whatcom County range from 11 to 50 inches, which corresponds to the rainfall gradient (Cox and Kahle 1999). In models of groundwater recharge in the Western Washington, Vaccaro et al. (1998) estimated the recharge of the groundwater aquifer by first examining the geologic deposit and then overlaying precipitation patterns. In coarse-grained deposits, recharge related linearly to precipitation. In finer-grained deposits, recharge was initially a linear response to precipitation but eventually leveled off indicating that even increased precipitation did not produce greater recharge or groundwater flow. This pattern occurs as finer-grained materials and the overlying deposits become saturated, preventing water from moving downward to support groundwater recharge.

***Identifying Important areas for precipitation:*** *Areas in a watershed that have relatively larger rates of precipitation.*

### *Timing of snowmelt [HU1]*

Snowmelt provides an important source of water that can support groundwater recharge and baseflow[2], depending upon the landscape group setting of a watershed. Snowmelt, however has different characteristics for two distinct zones: rain-on-snow and snow dominated zones. For rain-on-snow zones, major changes to the timing of

[2] Streamflow coming from groundwater seepage into a stream or river.

snow melt results when warm rains occur.  These warmer conditions cause the snow to melt at a faster rate at the same time that runoff from the rain is occurring (Brunengo et al. 1992).  This can increase the amount of surface water flowing in the watershed to the extent that many of the largest flooding events in Western Washington are associated with these rain-on-snow storms.

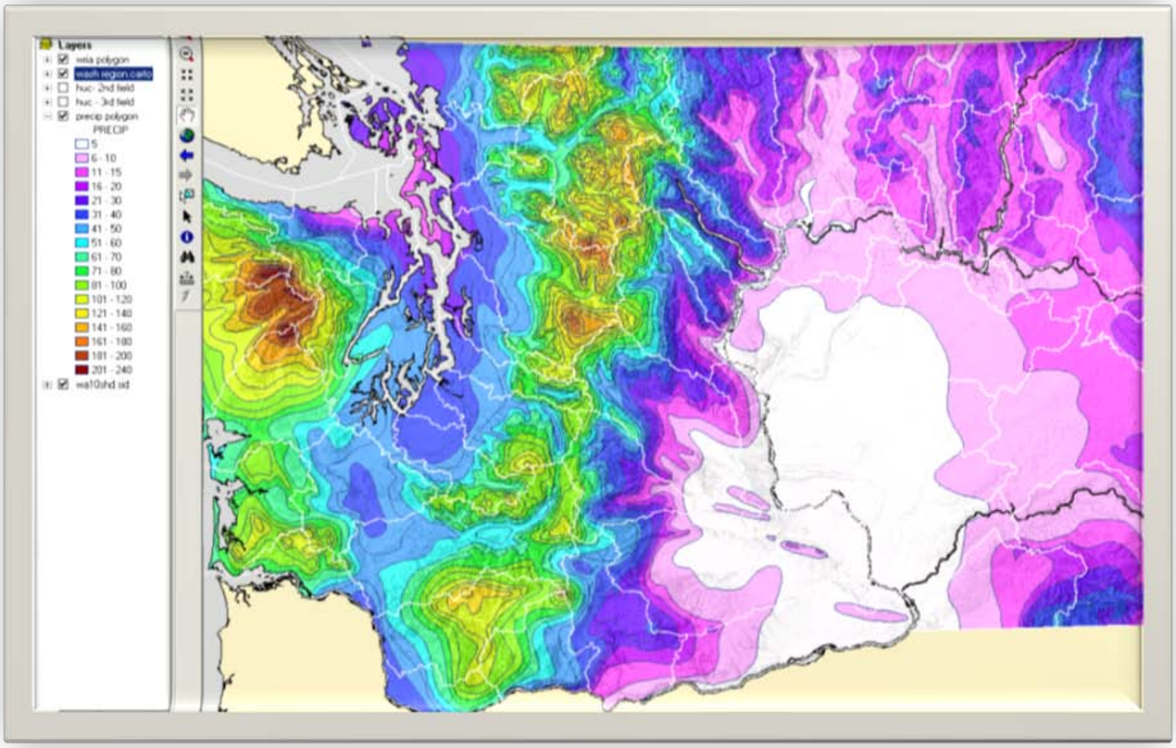



Figure B-6: Precipitation patterns across Washington State**.** Different colors indicate isohyetals of annual precipitation (inches). The white lines delineate WRIA's.

Snowmelt, in snow-dominated zones, is also an important component of surface flows in the spring to late-summer . Snow melt is also an important source of base flow and will affect groundwater recharge and groundwater levels in streams at lower elevations. (P. Olson, personal communication, Sep 2005.)

***Identifying Important areas for snowmelt:*** *Zones mapped as Rain-on-snow and snow-dominated by the Washington State Department of Natural Resources.*

## Movement of Water

The movement of water is divided by the location of water in the geomorphic setting: a) at the surface, b) below the surface, and c) emerging to the surface.

### *At the surface:*

It is not possible to identify saturated areas accurately, where overland flow is likely to occur at the scale of a watershed and using regionally available data. However, it is possible to identify the places where water is likely to become subsurface flow, percolate to recharge groundwater, or be stored on the surface. Subsurface flow, recharge, and surface storage occur in all areas of the landscape to varying degrees. The discussion following the relevant section of Table B-1, shown below, highlights those areas in which one or more of these components dominates.

### *Overland flow*

Overland flow occurs when the precipitation rate exceeds the infiltration rate in seasonally saturated areas. These seasonally saturated areas are variable in size depending upon storm or snowmelt events. They commonly occur when shallow subsurface flow accumulates in topographic depressions or in areas with decreasing hillslope gradient (Ziemer and Lisle 1998). These areas often play an important role in the delivery of nutrients and pathogens to aquatic resources, and should be mapped if data are available for you watershed.

***Identifying Important areas for overland flow:*** *Not possible unless local data exists.*

| Component of Process | | | Major Natural Controls | Important areas | Variables for Scoring | GIS Data Layers |
|---|---|---|---|---|---|---|
| *Movement* | ***At the surface*** | Overland flow | Precipitation patterns<br>Soils | Seasonally saturated areas | | Not generally available |
| | | Surface storage | Topography<br>Surface geology<br>Soils | **Areas of low gradient**<br><br>**Floodplains** | **HU2**<br><br>**HU3, HU4** | **Wetlands**<br>**Hydric soils**<br><br>SSHIAP **confinement data** |

### *Surface storage* *[HU2, HU3, HU4]*

Depressional wetlands, lakes, and floodplains are all areas with the highest potential to store water during high-flow events. Specifically:

(a) Depressional Wetlands: The cumulative role of depressional wetlands in storing surface water has been demonstrated in numerous locations around the world.  By storing water, depressional wetlands delay the release of surface waters during storms, thereby reducing downstream peak flows in rivers and streams (Adamus et al. 1991).  Studies of depressional wetlands in other parts of the world also conclude that they can reduce or delay peak downstream flows (Bullock and Acreman 2003).

In King County the percentage of a watershed that contains wetlands has been found to relate to the flashiness or variability of runoff events.  For example, Reinelt and Taylor (1997) found that watersheds with less than 4.5% of their area in wetlands produced a greater range of surface water level fluctuations in depressional wetlands than did those with a higher percentage of area in wetlands.

(b)  Lakes:  Lakes are important for storing surface water because of the large volumes of water they can hold.  For example, Lake Washington holds 2,350,000 acre feet of water about half of which is flushed out every year (DNR King County, July 29, 2008).  Thus, the annual storage in Lake Washington is equivalent to every drop of rain that falls on about 400 square miles of the region in a year (assuming an average rainfall of 48"/yr).

(c)  Floodplains:  Floodplains and their associated wetlands play an important role in reducing flood peaks and shifting the timing of peaks.  In a review of studies from around the world, Bullock and Acreman (2003) found that 23 out of the 28 floodplain wetlands that were examined reduced or delayed flooding.  In Western Washington, river valleys formed by continental glaciers and those formed by recent river action provide different levels of surface water storage and can be identified using different GIS methods.

***Identifying Important areas for surface storage:*** *Areas in the watershed with depressional wetlands, lakes, and floodplains.*

### *Below the surface:*

Data are available on a regional basis to characterize the important areas for shallow subsurface flow and recharge. You will have to use locally available data, however, to identify important areas for vertical and lateral subsurface flow and subsurface storage.

| Component of Process | | | Major Natural Controls | Important areas | Variables for Scoring | GIS Data Layers |
|---|---|---|---|---|---|---|
| *Movement* | ***Below surface*** | Shallow subsurface flow | Topography Surface geology | **Areas on deposits with low permeability** | **HU5** | **Geology & Soils** |
| | | Recharge | | **Areas on deposits with high permeability** | **HU5** | **Geology & Soils** |
| | | Vertical and lateral subsurface flow | | Entire watershed | | Not generally available |
| | | Subsurface storage | Surface geology | Deep permeable geologic deposits | | Not generally available |

### *Shallow subsurface flow*

Under natural conditions, after infiltrating the soil column, some water is likely to move down slope as shallow subsurface flow, particularly in areas with underlying geologic deposits with low permeability (Booth et al. 2003).

***Identifying important areas for shallow subsurface flow:*** *Areas with surface deposits of low permeability.*

### *Recharge [HU5]*

In the Pacific Northwest, areas with surface geologic deposits of high permeability or large grain size allow precipitation to percolate directly into the groundwater (Dinicola 1990, Winter 1988). Soils are not the controlling factor for recharge in the Pacific Northwest because their infiltration rate generally exceeds the rainfall intensity (Vaccaro 1998). In a glaciated landscape, there is good correlation between the grain size of the surface geology deposit and the permeability of that deposit (Table B-2, Vaccaro et al. 1998, Jones 1998). Typically, alluvium in lowland areas and glacial outwash (especially recessional outwash) are composed of coarse-grained sediment and support high levels of percolation.

The USGS developed regression equations for recharge on course and fine grained deposits as part of the Hydrogeologic Framework of the Puget Sound Aquifer System.

These equations represent the relationship between water budget components that contribute to recharge. This includes:

Recharge (course grained deposits) = 0.838 * P – 9.77

Recharge (fine grained deposits) – 0.497 * P – 5.03

Where P = average precipitation for area over which the deposit extends

***Identifying Important areas for recharge:*** *Areas where surface deposits have a high permeability and high rainfall.*

*Table B-2: Generalized relationship between surface geology and permeability* in a glaciated landscape. 1Vaccaro et al. 1998; 2 Jones 1998

| Surface Geology | Sediment Size | Permeability | Hydraulic conductivity[2] (ft/day) |
|---|---|---|---|
| Recessional Outwash Alluvium in lowland | Coarse Gravel/ Sand | High[1,2] | >100 |
| Advance Outwash | Moderate Sands | Moderate[2] | 15-50 |
| Organic Deposits | Not applicable | Low to Moderate | |
| Moraine, Till | Varied | Low to Very Low[2] | 0.005-22 ~0.0001 ft/d [1] |
| Lacustrine, Glacial Marine Drift, Mudflows | Fine Silts | Very Low | <10 |
| Finer Alluvium (lower reaches of major river valleys) | Fine | Very Low[2] | 1-15 |
| Bedrock | Consolidated Deposit | Very Low | |

## *Vertical and lateral flow*

The movement of water below the surface can be vertical or lateral in response to the gradient of water levels. It typically occurs in deeper deposits (Figure B-1) but can become shallow subsurface flows in the vicinity discharge areas (see section 2.2.7). These flows are an expression of both the elevation of groundwater and the pressure it exerts. In upland terrain with unconfined aquifers, surface topography is the dominant controller of these gradients and can be used as an indicator of likely water movement paths (McDonnell 2003). It is important to note that there are exceptions where other factors may control water movement patterns below the surface. For example, McDonnell (2003) notes that water movement on steep slopes with thin soils overlying impermeable surface deposits may be controlled more by bedrock topography than surface topography.

Although specific data in GIS layers do not exist, it is possible to develop a description of groundwater flow patterns in Puget Sound watersheds that can be helpful in modeling the water process. A diagram of groundwater flow patterns can be useful for understanding the likely relationship between recharge and discharge areas and for identifying potential impairments to these patterns from human activities.

Some assumptions or rules that you can apply developing a diagram of groundwater flows are:

- In general, topography, the shape or geometry of the aquifer system, and the locations and amount of discharge and recharge control the movement of the uppermost layers of groundwater (Vaccaro et al. 1998).
- In general, groundwater flow follows major topographic gradients. Groundwater movement will tend to be from higher areas to lower areas (Vaccaro et al. 1998). Lows in Western Washington or Puget Sound itself are generally surface water drainages.
- On slopes with little permeability, water will move downslope as shallow subsurface flow. If it reaches more permeable deposits when the topography flattens, this water will then move vertically downward to recharge groundwater.
- Lakes and large wetland areas and perennial streams are an expression of the water table or the emergence of groundwater at the surface, unless you can document that they sit on perched water tables.

***Identifying areas important for vertical and lateral flows****: Not possible unless local data exists.* *Needs to be based on local information.*

### *Subsurface storage*

Permeable surface deposits or aquifers that are deep provide for greater storage of groundwater. You can use local information on the depth and extent of aquifers to identify important areas for subsurface storage.

***Identifying areas of subsurface storage***: *Not possible unless local data exists.*

### *Return to the surface:*

In the Pacific Northwest, groundwater is generally an important contributor to annual streamflow (Winter et al. 1998). However, researchers have noted the difficulty of identifying, without actual measurements on a local scale, whether larger-scale groundwater is discharging in a particular reach of a stream (Christensen et al. 1998). Despite these difficulties, it is possible, using locally available data and the GIS layers of geology and topography to identify some indicators of places where groundwater discharges to the surface.

| Component of Process | | | Major Natural Controls | Important areas | Variables for Scoring | GIS Data |
|---|---|---|---|---|---|---|
| *Movement* | ***Return to the surface*** | Discharge | Topography<br>Surface geology | **Floodplains (low gradient) intersecting permeable deposits**<br>**Slope breaks intersecting area of hydric soils extending into lower gradient area**<br><br>Stratigraphic pinchouts<br>Contact areas between geologic deposits of different permeabilities | **HU6**<br><br>**HU7** | **Geology, soils, topography**<br><br>Local information |

*Discharge [HU6, HU7]*

Water moves from below ground to above ground at locations that are predictable based on their landscape group setting. Generally, discharge occurs at slope breaks or areas where the topographic slope shifts from being quite steep to being far more gentle Groundwater is often discharged to the surface on the shallow slope side of the intersection (Winter et al. 1998, Figure B-5) . These areas can include the intersection of a valley wall with the valley floor, the valley floor (e.g. alluvial deposits in floodplains) and depressional wetlands.

Using local data in conjunction with the geology and topographic layers in your GIS, you may be able to identify general areas of discharge:

(a) Permeable geologic deposits adjacent to and within river valleys: USGS field investigations of groundwater discharge zones in the south fork of the

Nooksack, suggest that coarse grained geologic deposits (outwash, some alluvial fans and landslides) adjacent to and within stream valleys contribute to groundwater discharge and support localized stream/river flow (Cox et al. 2005).

(b) Area of hydric soils intersects a slope break and extends into a lower gradient area below the slope break (e.g. valley, terrace). Hydric soils on a slope and beneath a slope break are typically the result of groundwater discharging to the surface. Hydric soils form under saturated conditions indicating the presence of water at or near the surface. This can include both hydric mineral and hydric organic soils. For example, in a portion of Whatcom County, organic soils have been found to be reliable locations of groundwater discharge (Cox and Kahle 1999). Organic soils form when the decomposition of vegetative material is prevented or slowed. Conditions that produce this change occur with consistent, continuous, waterlogged conditions (Mitsch and Gosselink 2000), low pH, or low temperatures (A. Aldous, personal communication).

(c) Stratigraphic pinchouts: Areas where the top of impermeable layers intersect the ground surface. These areas can become areas of groundwater discharge.

(d) Areas where the boundary between permeable and impermeable surface deposits intersect the surface. As groundwater flows down through a fairly permeable deposit and intersects a deposit of less permeability, it can be forced laterally along the boundary between deposits. The water will emerge when the boundary intersects the surface (Winter et al. 1998).

## Loss of Water

Water is lost from a watershed by:

- Surface flow out of the basin (streams and rivers)
- Groundwater flow out of the hydrologic unit
- Evaporation
- Transpiration by plants

Loss of water is not modeled in Western Washington because we consider all hydrologic units in a watershed equally important for these components. All hydrologic units have similar relationships between surface outflow and groundwater outflow that are related to the rainfall. In addition, we assume that evaporation and transpiration rates similar in the different hydrologic units across the Puget Sound area. All hydrologic units are considered to have been forested before human land uses changed this pattern.  These indicators however, will have to be modeled in eastern Washington. There are significant differences between hydrologic units relative to outflow, evaporation, and transpiration.

| Component of Process | | Major Natural Controls | Important areas |
|---|---|---|---|
| ***Loss*** | Evaporation/ Transpiration | Vegetation<br>Climate | Entire watershed |
| | Stream- or subsurface flow out of basin | Topography<br>Surface geology | |

# Identifying Impairments to the Water Process - Step 4

Human activity has impaired the natural condition of the lowland areas of Puget Sound. However, the intensity of impairments varies significantly. Where impairment is minimal, processes are still primarily intact and functioning. Where impairments have been significant, processes are no longer providing the functions on which we rely. We can characterize the current condition of the important areas identified in the previous section by mapping the locations and impacts of various activities. This section describes the relationships between a suite of human activities and the delivery, movement and loss of water (Figure B-7) that are used in the model for the Western Washington and Puget Sound.

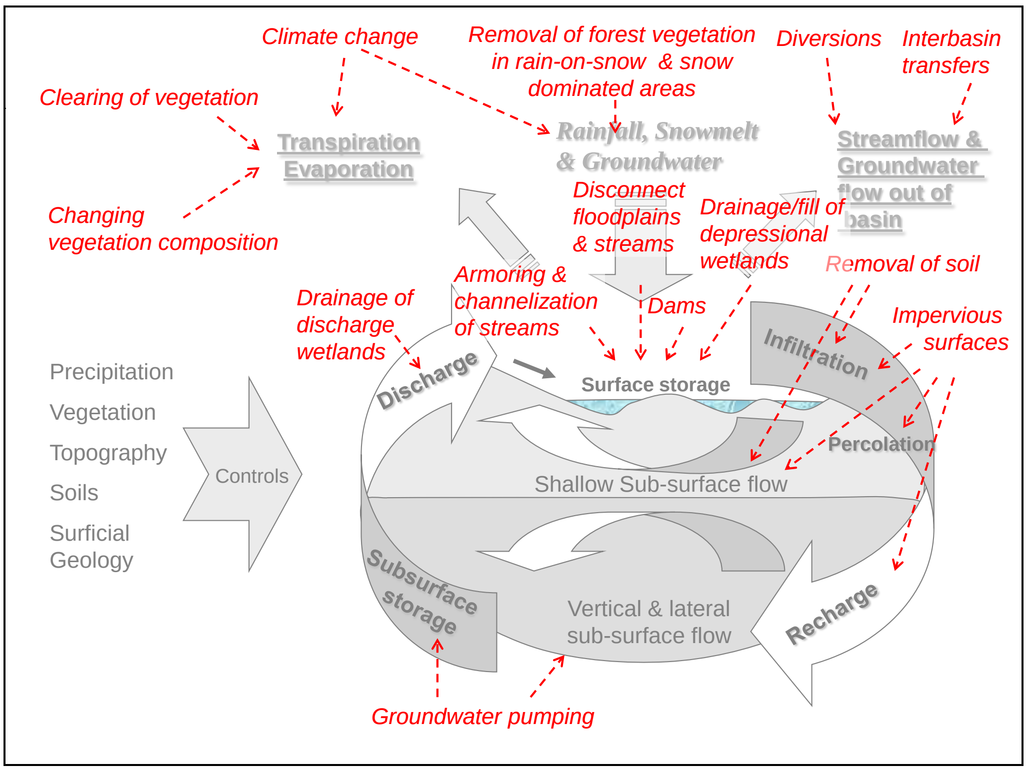



Figure B-7: Illustration of how human activities alter the delivery, movement and loss of water.

Indicators of the impairments are summarized in Table B-3. Indicators in **bold** type are those that you can map using regionally available data. See the section on "Models" for how to quantify these variables. Changes to the process that are not in bold type may be mapped if you have local data or knowledge. If we do not know of a reasonable method for assessing an impairment, the box for the variable is empty. Each component, their controls, and important areas are color coded in the table according to the colors presented in Figure B-1 for delivery, movement, and loss (red, blue, and green respectively).

*Table B-3: Indicators of impairment to the delivery, movement, and loss of water* **for the Western Washington and Puget Sound.**

| Component of process | | | Major natural controls | Change to process | Cause of change | Indicators of impairment | Variable for scoring in model |
|---|---|---|---|---|---|---|---|
| *Delivery* | | | Precipitation patterns | Changes in runoff quantity & timing | Climate change | | |
| *Delivery* | | | Timing of snowmelt | Increase streamflow | Removal of forest vegetation | **Reduction of forest cover in rain-on-snow and snow dominated zones** | **HI-1** |
| *Delivery* | *Overland flow* | | Precipitation patterns<br>Soils | Change timing of surface runoff<br>Decreased infiltration | Impervious areas<br><br>Channelization of flows<br>Filling and draining of seasonally saturated areas | **Watershed imperviousness**<br><br>Stormwater discharge pipes<br>Drainage ditches in seasonally saturated areas<br>Loss of seasonally saturated areas | **HI-2** |
| *Movement* | *Avove surface* | Surface storage | Topography<br>Surface geology<br>Soils | Increase streamflow<br>Decrease storage capacity<br>Increase velocity of surface flows | Drainage or filling of depressional wetlands | **Rural & urban land use**<br>**Loss of depressional wetlands** | **HI-3, HI-4** |
| *Movement* | *Avove surface* | Surface storage | Floodplain width | Increase water storage capacity & decrease downstream flow | Channelization of streams | **Miles of impaired stream through unconfined & moderately confined floodplains** | **HI-5, HI-6** |
| *Movement* | *Avove surface* | Surface storage | Floodplain width | Increase water storage capacity & decrease downstream flow | Disconnection of stream from floodplain | Dikes and levees on stream reaches with floodplains | |
| *Movement* | *Avove surface* | Surface storage | Floodplain width | Increase water storage capacity & decrease downstream flow | Dam operation | Dams | |

**Table B-3 continued**

| Component of process | | | Major natural controls | Change to process | Cause of change | Indicators of impairment | Variable for scoring |
|---|---|---|---|---|---|---|---|
| *Movement* | *Below surface* | Shallow subsurface flow | Topography<br>Surface geology | Reduce recharge and increase surface runoff | Removal or compaction of soil | New construction | |
| | | | | | Impervious surfaces | **Land uses with impervious cover on geologic deposits of low permeability** | **HI-7** |
| | | | | | Loss of forest cover | **Non-forested vegetation on geologic deposits of low permeability** | **HI-7** |
| | | Recharge | Topography<br>Surface geology | Reduce recharge and increase surface runoff | Loss of forest cover | **Non-forested vegetation on geologic deposits of high permeability** | **HI-7** |
| | | | | Reduce groundwater recharge | Impervious surfaces | **Land uses with impervious cover on areas of high permeability** | **HI-7** |
| | | | | Shift location of groundwater recharge<br>Losses from water supply pipes or sewer lines, or septic drainfield discharges | Leaky pipes or irrigation canals<br>Water supply and wastewater management | Utility lines<br>Septic systems<br>Unlined irrigation canals | |

**Table B-3 continued**

| Component of process | | | Major natural controls | Change to process | Cause of change | Indicators of impairment | Variable for scoring |
|---|---|---|---|---|---|---|---|
| *Movement-* | *Below surface* | Vertical and lateral subsurface flow | Topography<br>Surface geology | Change location of groundwater discharge | Interception of subsurface flow by ditches and roads | **Roads** | **H-8** |
| | | | | Decrease quantity of groundwater available for discharge | Groundwater pumping | **Well locations and density**, Drawdown patterns<br>Reduced Baseflow | **HI-9** |
| | | Subsurface storage | Surface geology | Decrease quantity of groundwater available for discharge | Groundwater pumping | **Well locations and density**, pumping rates and volumes | **H-9** |
| | *Return to surface* | Discharge | Topography<br>Surface geology | Decrease groundwater inputs to aquatic resources | Loss of groundwater discharge areas | **Land use type (urban/rural) in floodplains and wetlands** | **HI-10, HI-11, HI-12, HI-13** |
| *Loss* | | Evaporation | Climate | Alter evaporation rates | Change temperature and precipitation patterns | | |
| | | Transpiration | Vegetation<br>Climate | Alter evapotranspiration rates | Clearing vegetation<br>Shifting vegetation composition | **Land cover** | **HI-14** |
| | | Streamflow out of basin | Topography | Change streamflow direction | Diversions<br>Interbasin transfers | Diversion structures | |
| | | Groundwater flow out of basin | Topography<br>Geology | Altering quantity and pattern of groundwater flow | Interbasin transfers<br>Groundwater pumping<br>Impervious surfaces<br>Interception of subsurface flows | Baseflow trends<br>Well locations, pumping rates and volumes | |

## Delivery of Water - Impairments

| Component of process | | Major natural controls | Change to process | Cause of change | Indicators of impairment | Variable for scoring |
|---|---|---|---|---|---|---|
| ***Delivery*** | | Precipitation patterns | Change in runoff quantity & timing | Climate change | | |
| ***Delivery*** | | Timing of snowmelt | Increased streamflow | Removal of forest vegetation in rain-on-snow zones | **Loss of forest in rain-on-snow and snow dominated zones** | **HI-1** |
| ***Delivery*** | **Overland Flow** | Precipitation patterns<br><br>Soils | Change timing of surface runoff<br><br>Decreased infiltration | Impervious areas<br><br>Rerouted drainage<br><br>Filling and drainage of seasonally saturated areas | **Watershed imperviousness**<br><br>Stormwater discharge pipes<br>Drainage ditches in seasonally saturated areas<br>Loss of seasonally saturated areas | **HI-2** |

### *Precipitation patterns*

An analysis of eight climate models, conducted by the U.S. Global Change Research Program (2000), predicts that global climate change will alter precipitation patterns in the Pacific Northwest. All eight models concur that winters are likely to be wetter and warmer. However, the models do not provide consensus for summer precipitation patterns. We do not address these effects in this guidance because the source of this potential change, emission of greenhouse gases, is global in scale and cannot be addressed at a watershed scale.

### *Timing of snowmelt [HI-1]*

Removal of forest cover in rain-on-snow zones: During rain-on-snow events, areas in the rain-on-snow zone that have been cleared can produce 50 to 400% greater outflow from snow packs than do similar areas that are still forested (Coffin and Harr 1992). The absence of vegetation during rain-on-snow events results in more snow accumulation due to reduced interception and a higher rate of snowmelt (Brunengo et al. 1992, Coffin and Harr 1992). Both of these factors result in increased peak outflow from snow packs.

In rain-on-snow zones that are cleared of vegetation but are still in forestry land use, the increased flow will occur in response to rain-on-snow events until more mature forest vegetation re-establishes. However, if land cover is permanently shifted out of forest cover (i.e., through conversion to agriculture or impervious surfaces) increased outflow is a permanent response to rain-on-snow events.

Removal of forest vegetation in snow dominated zones: This can alter spring to late-summer runoff patterns and can affect groundwater recharge and base flow for streams at lower elevation. (P. Olson, personal communication, Sep 2005.)

***Identifying areas of impaired timing of snow melt:*** *Non-forested land cover in rain-on-snow and snow-dominated zones.*

### *Timing of runoff in "rain dominated" zones*

Removal of forest cover in "rain-dominated" zones. Removal of forest in "rain-dominated" zones (outside the snow zones) also alters runoff patterns by decreasing recharge and increasing surface flow (Booth et al. 2002).

***Identifying areas of impaired timing of runoff:*** *Non-forested land cover in "rain-dominated" zones.*

### *Overland flow [HI-2]*

Impervious cover within a watershed decreases infiltration and increases overland flow. Seasonally saturated areas are impaired by increased surface flows from upland development and by filling or drainage activities within their boundaries. Upland development decreases infiltration and increases surface flows, which is usually routed into seasonally saturated areas. As a result seasonally saturated areas can expand in size. Draining and filling activities are common within these impaired seasonally saturated areas. Determining impairment within saturated areas requires local data.

***Identifying areas of impaired overland flow:*** *Percent impervious cover within a watershed*

## Movement of Water - Impairments

### *At the Surface :*

*Surface storage [HI-3, HI-4, HI-5, HI-6]*

Floodplains and depressional wetlands can be important areas for the storage of surface water runoff. Activities that reduce the spatial extent or storage capacity of these areas during peak flow events can increase the volume of water and the rate at which it reaches aquatic ecosystems (Sheldon et al. 2005, Gosselink et al. 1981, Reinelt and Taylor 1997)

| Component of process | | | Major natural controls | Change to process | Cause of change | Indicators of impairment | Variable for scoring |
|---|---|---|---|---|---|---|---|
| *Movement* | ***At the surface*** | Surface storage | Topography<br><br>Surface geology | Increased streamflow<br><br>Decrease storage capacity<br><br>Increase surface water velocity | Drainage or filling of depressional wetlands | **Depressional wetlands in areas of rural and urban land uses** | **HI-3, HI-4** |
| | | | | | Channelization of streams | **Miles of stream in urban areas & rural areas** | **HI-5, HI-6** |
| | | | | | Disconnection of stream from floodplain | **Dikes and levees on stream reaches with floodplains** | **HI-5, HI-6** |
| | | | | Increase water storage capacity<br>Decrease downstream flow | Dam operation | Dams | |

<u>Drainage or filling of depressional wetlands (HI-3, HI-4):</u> In various parts of the country there is evidence reducing the amount of wetlands in a watershed results in a larger quantity of water being delivered to downgradient aquatic ecosystems in a shorter period of time. As a result, water level fluctuations in aquatic ecosystems are greater. In King County, the fluctuation of surface water levels in response to runoff

events was statistically greater where less than 4.5% of the watershed area was wetland (Reinelt and Taylor 1997).

Straight channels associated with depressional wetlands or historic depressional wetlands can indicate drainage of these aquatic resources. In addition, the type of land use associated with these wetlands can indicate the degree of impairment to wetland water regime.

***Identifying areas of impaired surface storage (loss of depressional wetlands):*** *Urban and agricultural land use adjacent to depressional wetland areas. Land use type associated with depressional wetlands can provide a general but consistent assessment of the potential degree of impairment to wetlands.*

<u>Channelization of streams (HI-5, HI-6):</u> The capacity of streams to store water within the channel is reduced when streams are channelized or straightened. This can also result in disconnection of a stream from its floodplain (see below).

***Identifying areas of impaired surface storage (channelization of streams):*** *Streams with adjacent urban and agricultural land cover will have a greater relative degree of impairment than streams with rural or natural land cover. Use analysis below for "disconnection of stream from floodplain."*

<u>Disconnection of stream from floodplains (HI-5, HI-6):</u> Dikes and levees directly disconnect the river water from the floodplain, thus removing flood storage capacity at high water levels. (Sheldon et al. 2005). No regionally available data layer exists showing the locations of dikes or levees. However, by intersecting land use with degree of floodplain confinement (SSHIAP data) a relative rating of impairment to floodplain storage can be attained. Section 5, Models for Impairment, discusses this method of analysis further.

***Identifying areas of impaired surface storage (disconnection from floodplain):*** *Streams within unconfined floodplains with adjacent urban and agricultural land cover will have a greater relative degree of impairment than streams within unconfined floodplains with natural land cover.*

<u>Dams:</u> The presence of dams that form reservoirs increases the surface storage of water above the dam but reduces the surface flow downstream of the dam. Local data will have to be used in order to quantify the impact of a dam to downstream aquatic ecosystems.

***Identifying areas of impaired surface storage (dams):*** *Presence of dams.*

### *Below the Surface:*

Impairments to recharge are addressed by one variable, HI-7, which considers land cover type, permeability of the surficial deposits and precipitation. The specific impairments recharge are discussed in the following sections of shallow subsurface flow and recharge. Coefficients for the reduction in recharge can be based on land cover type (Vacarro 1998). Vacarro used Landsat satellite data to categorize land cover type. Three categories, with corresponding recharge reduction coefficients were created: urban (95% impervious – no recharge); built up (75% developed – 0.75 reduction); and residential (50% developed – 0.50 reduction). We recommend the use of Coastal Change Analysis Program satellite data. Because different catergories of land cover are available relative to the Landsat data the following categories and reduction coefficients are suggested:

High Intensity = 0.9 (80 to 100% impervious)
Medium Intensity = 0.7 (51 to 79% impervious)
Low Intensity = 0.35 (20 to 50% impervious)

### *Shallow subsurface flow [HI-7]*

Three factors are likely to alter the quantity of water that flows subsurface on less permeable deposits: removal of soils, construction of impervious surfaces, and removal of forest vegetation. Each of these activities will prevent water from infiltrating into the soil and produce surface runoff instead (Figure B-8).

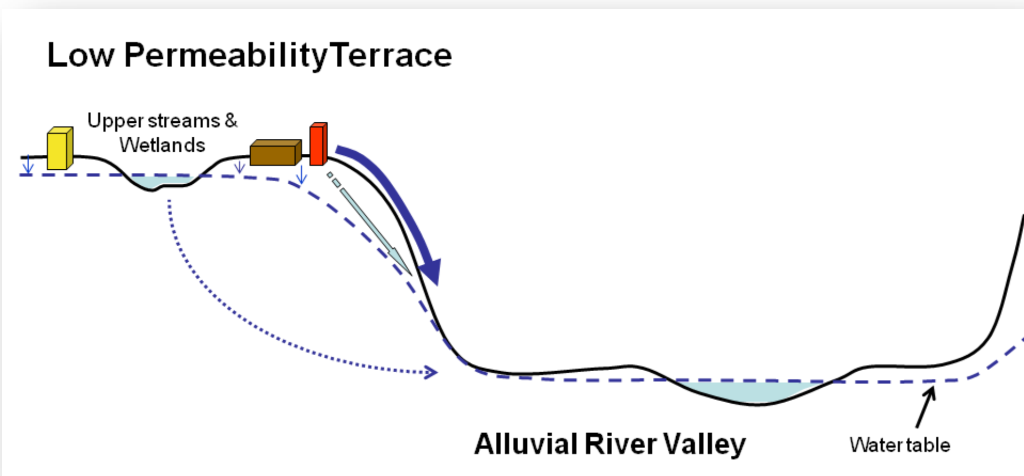



Figure B-8: The effect of impervious surfaces on a terrace with low permeability deposits: removal of soil and forest vegetation reduces subsurface flow and increases surface runoff.

| Component of process | | | Major natural controls | Change to process | Cause of change | Indicators of impairment | Variable for scoring |
|---|---|---|---|---|---|---|---|
| *Movement* | ***Below surface*** | Shallow subsurface flow | Topography<br><br>Surface geology | Convert to surface runoff | Removal or compaction of soil | New construction | |
| | | | | | Impervious surfaces | **Land uses with impervious cover on geologic deposits of low permeability** | **HI-7** |
| | | | | | Removal of forest cover | **Non-forested vegetation on geologic deposits of low permeability** | **HI-7** |

Removal of soil: Urbanization and development typically result in the removal and compaction of soils. In areas of low permeability, soil removal results in surface runoff since the precipitation rate usually exceeds the infiltration rate of the underlying surface deposit (Dunne and Leopold 1978). Local data are needed to identify these impairments.

Impervious surfaces on permeable surface deposits: (HI- 7) Impairment of aquatic ecosystems has been documented to occur with virtually any level of impervious cover in a watershed. Furthermore, this decline progresses as the portion of the watershed with impervious cover increases (Booth et al. 2002). In the Puget Lowland, readily observable damage to stream resources (i.e., unstable channels) occurs if the effective impervious area (EIA) of a watershed is greater than 10% (Booth et al. 2002) (Table B-4). Impervious surfaces on areas with deposits of lower permeability are judged to result in a lower level of impact relative to areas with deposits of higher permeability (See HI-10).

*Table B-4: Summary of thresholds associated with visible degradation of stream channels* **in Western Washington.**

| Permeability of surface deposits | Percent of watershed with: | |
|---|---|---|
| | Impervious cover (EIA) | Non-forest vegetation |
| Permeable | 10 | 0 |
| Impermeable | 10 | 35 |

***Identifying areas of impaired shallow sub-surface flows::*** *Land cover with impervious surfaces on areas with geologic deposits of low permeability.*

Removal of forest cover on low permeability deposits (HI-7): There is growing evidence that simply clearing forest vegetation, even in rural areas that have little impervious cover, can produce increased streamflow as subsurface flow is converted to surface runoff (Booth et al. 2002). In the Western Washington, visibly impaired (or unstable) stream channels are associated with watersheds in which the 2-year peak flow that occurs under current conditions ($Q_{2\ developed}$) is greater than the 10-year peak flow ($Q_{10\ forested}$) that occurs under natural conditions (Booth et al. 2002). While the precise reason for this equivalency is not yet understood, the relationship has been confirmed in numerous watersheds in King County.

Modeling efforts have found that on the most common, impermeable deposits (i.e. glacial till), the $Q_{2\ developed}$ discharge can be maintained at less than the $Q_{10\ forested}$ discharge if less than 35% of the forested cover in a watershed has been removed (Booth et al. 2002). The modeling also demonstrated that the conversion of forest to suburban development (primarily lawns) affected peak discharges more significantly than small increases in impermeable cover associated with low-density rural development (i.e., 4% EIA).

***Identifying areas of impaired shallow sub-surface flows:*** *Non-forested vegetation on areas with geologic deposits of low permeability*

*Recharge [HI-7 continued]*

| Component of process | | | Major natural controls | Change to process | Cause of change | Indicators of impairment | Variable for scoring |
|---|---|---|---|---|---|---|---|
| *Movement* | ***Below surface*** | Recharge | Topography<br><br>Surface geology | Convert to surface runoff – reduce recharge | Removal of forest cover | **Non-forested vegetation on geologic deposits of high permeability** | **HI-7** |
| | | | | Reduce groundwater recharge | Impervious surfaces | **Land uses with impervious cover on areas of high permeability** | **HI-7** |
| | | | | Shift location of groundwater recharge<br>Losses from water supply pipes or sewer lines, or septic drainfield discharges | Leaky pipes or irrigation canals<br><br>Water supply & waste-water manage-ment | Utility lines<br><br>Septic systems<br><br>Unlined irrigation canals | |

Removal of forest cover on high permeability deposits (HI-7): The $Q_{2\ developed}$ can be maintained at less than the $Q_{10\ forested}$ on deposits with lower permeabilityif less than 35% of the forested cover in a watershed has been removed. However, this relationship cannot be maintained with any forest clearing on permeable deposits because so little surface runoff occurred naturally (Booth et al. 2002). As a result, the threshold of forest clearing at which aquatic resources are impaired is likely much lower for the permeable deposits than impermeable. The modeling also demonstrated that the conversion of forest to suburban development (primarily lawns) affected peak discharges more significantly than small increases in impermeable cover associated with low density rural development (i.e., 4% EIA) (Booth et al. 2002).

***Identifying areas of impaired recharge:*** *Non-forested vegetation on areas with geologic deposits of high permeability*

Impervious surfaces (HI-7): The construction of impervious surfaces on areas that are important for recharge (high permeability) can reduce the quantity of recharge as well as increase surface runoff (Table B-4, Figure B-9). Studies of the Western Washington indicate that recharge in "built-up areas" (appx. 95% impervious surfaces) is reduced by 75% while that of residential areas (appx. 50% impervious surfaces) is reduced by 50% (Vaccaro et al. 1998).

A given amount of impervious cover can produce a greater percentage increase in runoff if it is located on permeable surface deposits than if it is on lower permeability surface deposits (Booth et al. 2002). However, in such areas with permeable deposits, development designs that include measures to increase infiltration are also most effective at reducing the amount of surface runoff (U.S. EPA 1999, Washington State Department of Ecology 2005).

***Identifying areas of impaired recharge:*** *Land uses with impervious cover on areas with geologic deposits of high permeability*

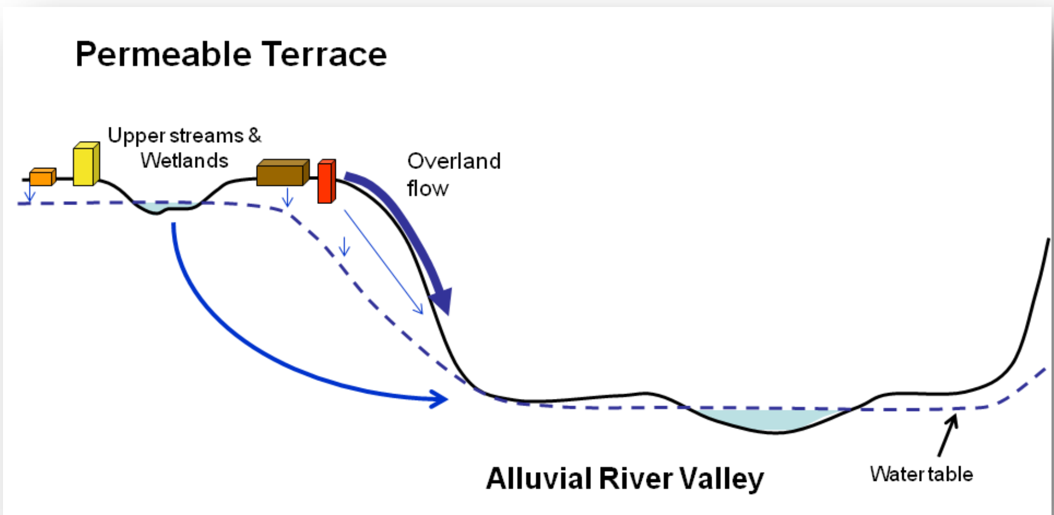



Figure B-9: Permeable deposits and impervious surfaces: recharge is reduced and surface runoff is increased.

Leaky utility lines, septic systems or irrigation canals: The location of recharge areas can be shifted by the presence of utility lines, septic systems or irrigation canals that leak water. Local information will be needed to locate these situations and to evaluate their significance.

### *Vertical and lateral subsurface flow [HI-8]*

| Component of process | | | Major natural controls | Change to process | Cause of change | Indicators of impairment | Variable for scoring |
|---|---|---|---|---|---|---|---|
| *Movement-* | ***Below surface*** | Vertical and lateral subsurface flow | Topography Surface geology | Change location of groundwater discharge | Interception of subsurface flow by ditches and roads | **Road density** | **HI-8** |

<u>Interception of subsurface flow by ditches and roads: (HI-8):</u> Research suggests that forest roads may intercept subsurface flows, alter the timing of runoff, and increase peak flows within those basins (Luce et al. 2001). This interception can convert water to surface runoff and alter the location at which it discharges into aquatic ecosystems. Correlations between road densities and hydrologic changes at the sub-watershed scale were observed in several studies in the Puget Lowlands. Road densities exceeding 3 miles/mile$^2$ in the Skagit watershed were found to correlate with changes to the hydrologic regime (Beamer et al. 2002). For Snohomish County, hydrologic units in the Stillaguamish watershed with peak flow problems had road densities exceeding 3 km/km2 and vegetative cover consisting of >50% immature vegetation (Beamer 2000).

***Identifying areas of impaired vertical and lateral flows:*** *Roads and their associated drainage system (ditches and culverts) which intercept sub-surface flow and convert it to surface flow.*

### *Subsurface storage [HI-9]*

| Component of process | | | Major natural controls | Change to process | Cause of change | Indicators of impairment | Variable for scoring |
|---|---|---|---|---|---|---|---|
| *Movement* | ***Below surface*** | Lateral Flow & Sub-surface storage | Surface geology | Decrease quantity of groundwater available for discharge | Groundwater pumping | **Well locations & density,** pumping rates and volumes | **HI-9** |

Groundwater pumping: The pumping of groundwater wells can, depending upon the subsurface stratigraphy, have a significant effect upon the flow patterns of groundwater. Well location and density can provide a general relative indicator of the potential impact of groundwater pumping on vertical and lateral subsurface flows. However, quantifying the impact of groundwater pumping typically requires local data. Local studies of the effects of large groundwater extraction projects may provide useful information for conducting this assessment. Additionally, local information suggesting that trends in baseflow are declining can suggest that up-gradient activities have reduced the amount of groundwater reaching streams, possibly as a result of impairments to the subsurface flow patterns.

The volume of water stored below the surface can be reduced by groundwater pumping and this can affect the amount of water available for discharge to aquatic resources. Local patterns of the volume of water pumped by wells, using relative density of wells and water right allocations, can help to identify areas where groundwater pumping may be altering the quantity of groundwater stored.

### *Discharge [HI-10, HI-11, HI-12, HI-13]*

| Component of process | | | Major natural controls | Change to process | Cause of change | Indicators of impairment | Variable for scoring |
|---|---|---|---|---|---|---|---|
| *Movement* | ***Return to surface*** | Discharge | Topography Surface geology | Decrease groundwater inputs to aquatic resources | Alteration of groundwater discharge areas | **Land use type (urban/rural) within wetlands and floodplains** | **HI-10, HI-11, HI-12 HI-13** |

Impairment of groundwater discharge areas: In Puget Sound, areas of wetlands and floodplains are probable locations for groundwater discharge. This is due to a combination of topography and geology and upslope recharge areas (Winter et al 1998). Development can impair these discharge areas differently through land clearing, ditching and draining in rural settings and through more extensive draining and subsequent filling and construction of buildings, roads, parking lots and stormwater systems in urban areas. These impairments can change the way groundwater moves into aquatic ecosystems, potentially altering water quality characteristics such as temperature. Additionally, it can alter the amount of groundwater that discharges at a particular location as the water table is lowered and the piezometric gradient is shifted.

This in turn has the potential to affect the hydroperiod of wetlands and hydrograph of rivers and streams which ultimately affects their biological systems.

***Identifying areas of impaired discharge:*** *The extent of urban and rural development within or adjacent to wetlands and floodplains.*

## Loss of Water

| Component of process | | Major natural controls | Change to process | Cause of change | Indicators of impairment | Variable for scoring |
|---|---|---|---|---|---|---|
| *Loss* | Evaporation | Climate | Alter evaporation rates | Change temperature and precipitation patterns | | |
| | Transpiration | Vegetation<br>Climate | Alter transpiration rates | Clearing vegetation<br>Shifting vegetation composition | **Land cover** | **HI-14** |
| | Streamflow out of basin | Topography | Change streamflow direction | Diversions<br>Interbasin transfers | Diversion structures | |
| | Groundwater flow out of basin | Topography<br>Geology | Alter quantity and pattern of groundwater flow | Interbasin transfers<br>Groundwater pumping<br>Impervious surfaces<br>Interception of subsurface flows | Baseflow trends<br><br>Well locations, pumping rates and volumes | |

### *Evaporation and transpiration*

Evaporation and transpiration are impaired by human activities. While it is difficult to quantify the exact change to evaporation and transpiration, impervious cover is an acceptable indicator of elimination of this water flow component.

***Identifying areas of impaired evaporation and transpiration:*** *Impervious surface cover within a watershed.*

### *Streamflow out of basin*

Natural patterns of water loss from a watershed can be impaired with inter-basin transfers or diversions that transfer water to a different watershed. Diversions and transfers can have a greater impact than wells upon downstream resources, since a portion of that water is not being returned after use (i.e. agriculture, rural residential) to the same watershed. Local data and the Department of Ecology Water Right Tracking System (http://www.ecy.wa.gov/PROGRAMS/wr/rights/tracking-apps.html) can help identify these activities and determine the relative quantity of water being diverted or transferred.

### *Groundwater flow out of basin*

Impairments from human activities can change natural patterns of water loss from a watershed. This starts with impervious surfaces, which reduces recharge and groundwater storage and flow. Groundwater pumping removes groundwater and in many cases moves water directly to sewer plants and discharges to marine waters. Inter-basin transfers, derived from groundwater wells, can also reduce change groundwater flow patterns out of a basin. You will need local data to identify these activities.

# *Models for Assessing the Water Process*

This section explains the **"how"** of this method. For the GIS analyst, it describes

- The individual analyses that make up each model.
- The scoring method for each analysis.

Model 1 scores the **relative importance** of hydrologic or analysis units in maintaining a process in an unimpaired setting. Model 2 scores the **relative severity of impairments** to the process in those analysis units.

The section on Methods explains **"why"** we use these analyses.

## Model 1 : Important Areas for the Water Process

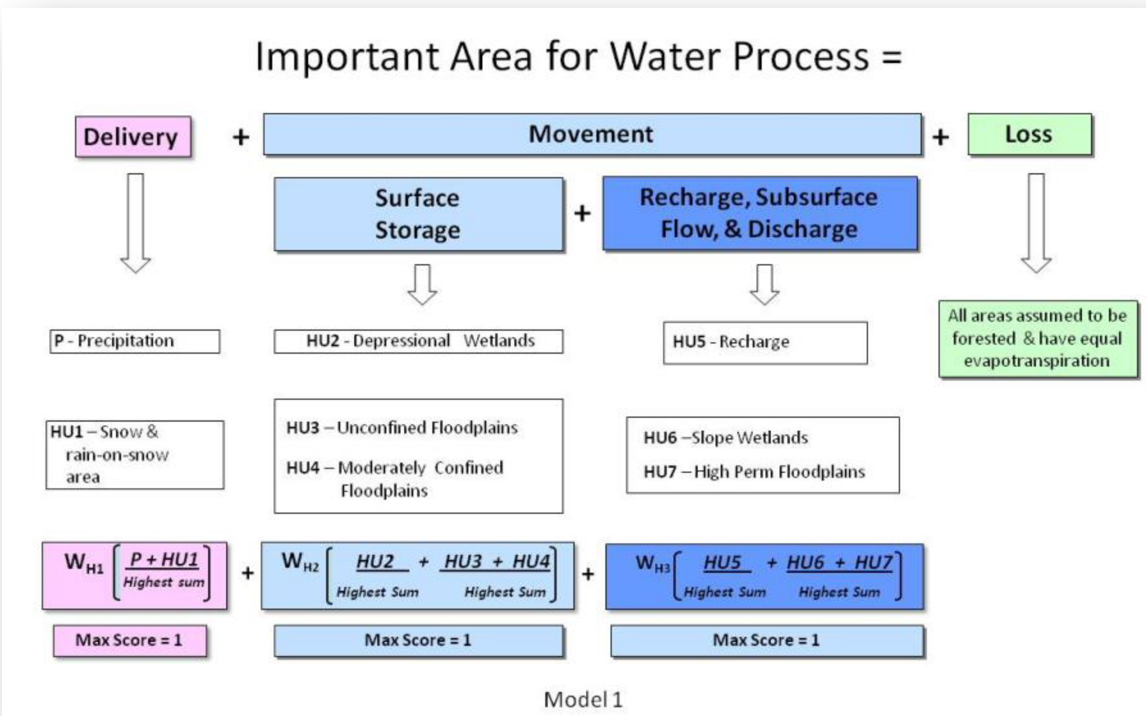



**Figure B-10. Diagram of the equation for calculating the importance of the water flow process** for analysis units across a watershed. Each component (i.e. delivery, surface storage, groundwater) requires analysis for several variables. We have grouped them together and discuss each in detail below.

Important areas for the water flow process are modeled as: important areas for delivery + important areas for movement + important areas for loss. For delivery the model considers the relative volume of water falling on the hydrologic unit as precipitation and the timing of the delivery of that precipitation (e.g. rain-on-snow). For movement the model considers the relative area of surface storage and the relative area contributing to subsurface flow, recharge and discharge.

*Model 1 = [(Precipitation + Timing of Water Delivery] + [(Surface storage +Sub-surface flow + Recharge +Discharge)] + (Evapotranspiration)*

In Western Washington the assumption is that all hydrologic units have approximately the same rate of evapotranspiration in unimpaired conditions because they were all generally forested. The equation for Model 1 can then be simplified to:

*Model 1 = [(Precipitation + Timing of Water Delivery] + [(Surface storage +Sub-surface flow + Recharge +Discharge)]*

It cannot be assumed, however, that the amount of surface water is always equal to the amount of groundwater (Olson 2008, personal communication). For example, in East King County the water balance estimates (Turney et al. 1995) indicate that there is substantially more groundwater moving through the Snoqualmie watershed than surface water (e.g. shallow groundwater and surface water is 5% and groundwater 54% of total rainfall). The USGS Aquifer Systems Analysis for the Puget Lowlands estimates that runoff constitutes 20%, recharge 37% and evapotranspiration 44%. For the Puget Sound Characterization Project the weighting factors were all kept at "1" since the technical team concluded that there was insufficient data at this time to apply different weighting factor to all analysis areas. At finer scales of analysis, however, it may be appropriate to use local data in order to adjust the weighting factors.

*Model 1 = [*$W_{H1}$ *(Precipitation + Timing of Water Delivery] + [*$W_{H2}$*(Surface storage) +* $W_{H3}$ *(Sub-surface flow + Recharge +Discharge)]*

## Water Delivery

$$W_{H1}\ (P + HU1) \; + \; W_{H2}\ (HU2 + HU3 + HU4) \; + \; W_{H3}\ (HU5 + HU6 + HU7)$$

Variables in Model 1

Water delivery is modeled as the relative amount of precipitation for each analysis unit and the area important for rain-on-snow and snow dominated zones. The equation is: Water delivery = P + $HU_1$.

Total possible score is 2.

### *P – Score for Precipitation*

Total possible score is 1.

Precipitation (**P**) is the average yearly amount of precipitation per unit area that falls within a analysis unit. This can involve one or several distinct areas of precipitation bands within an individual analysis unit. The average rainfall in each analysis unit is determined by calculating the area within each precipitation band, and then adding those values to obtain the average precipitation per unit area for the analysis unit. The equation for the precipitation variable is:

$$P = \sum PA_n \Big/ \text{Hydrologic Unit Area}$$

Where $PA_n$ = Average annual precipitation * area of analysis unit over which this precipitation falls and where "n" equals the individual areas of different precipitation within a analysis unit.

We normalize the results of **P** for all analysis units within a landscape group as follows:

$$P_{normalized} = HU1_{subunit} \Big/ \text{Maximum Value for hydrologic units}$$

### *HU1 – Score for Timing of Water Delivery*

Total possible score is 1.

The model for timing water delivery is the importance of the relative area of rain-on-snow zone plus the importance of the relative area of the snow-dominated zone in a analysis unit.

The rain-on-snow and snow-dominated zones change the timing of the delivery of precipitation to a watershed. Though rain-on-snow events and snow dominated zones have different effects on hydrologic processes at different times of the year, they were judged to be equal in importance. We address the delivery of precipitation in lowland rain zones in the impairments section (HI-1). The equation for the timing of water delivery variable is:

$$\mathbf{HU_1}\ \textit{(Importance of Rain-on-Snow \& Snow-Dominated Zone)} = \frac{\text{(Area of RS + Area of SD)}}{\text{Area of analysis unit}}$$

We use data layers from DNR to estimate the Rain-on-Snow (RS) and Snow-Dominated (SD) zones.

We normalize the results of $\mathbf{HU_1}$ for all analysis units within a landscape group as follows:

$HU_{1Normalized}$ = $HU_1$ hydro unit/Maximum value for analysis units

## Surface Storage

$$W_{H1}\ (P + HU1) \; + \; W_{H2}\ (HU2 + HU3 + HU4) \; + \; W_{H3}\ (HU5 + HU6 + HU7)$$

Variables in Model 1

Surface storage is modeled as the importance of the relative area of depressional wetlands ($HU_2$) in a analysis unit + the importance of the relative miles of different widths of the floodplains in a analysis unit ($HU_3$ and $HU_4$). The equation is: Surface Storage = $HU_2 + (HU_3 + HU_4)$. Depressional wetlands and floodplains play a significant role in reducing or delaying peak downstream flows (Bullock and Acreman 2003, Adamus et al. 1991, Reinelt and Taylor 1997). Floodplain storage is important because it reduces or delays flooding (Bullock and Acreman 2003).

Total possible score is 2.

### *HU2, - Score for Wetland Storage*

Total possible score is 1.

**$HU_2$** (Relative Importance of Wetland Storage) is based on the percentage of analysis unit covered with depressional wetlands (both upland and riverine). The percentage of possible wetlands is estimated for all analysis units using the topographic layer and the hydric soil layer. Areas with hydric soils on slopes that are less than 2% are considered to be areas where storage wetlands exist or have existed in the past. The equation for the wetland storage variable is:

$$HU_2 = \frac{\text{Area of Depressional Wetland in analysis unit}}{\text{Total area of analysis unit}}$$

We normalize the results of **$HU_2$** for all analysis units within a landscape group as follows:

$HU_{2Normalized} = HU_2$ hydro unit/Maximum value for analysis units

### *HU3, HU4- Score for Floodplain Storage*

Total possible score is 1.

Floodplain storage is based on the percentage of the analysis unit covered with unconfined and moderately confined floodplains. Floodplain types are determined using SSHIAP data for floodplain confinement. An unconfined floodplain is 4 times the width of the stream and a moderately confined floodplain is 2-4 times width of stream. Both of these floodplain types allow a significant degree of overbank flooding to occur, relative to confined floodplains, and are able to store surface waters during a flooding event.

**$HU_3$**for unconfined floodplains has an importance factor of 3 because they have the highest relative degree of surface storage capacity. The equation for the **$HU_3$** variable is:

$$HU_3 = \frac{\text{Miles of Stream in Unconfined Floodplain in analysis unit * (3)}}{\text{Area of analysis unit}}$$

**$HU_4$** has an importance factor of 2 because it has a moderate level of floodplain confinement and therefore has a moderate amount of surface storage capacity. The equation for the **$HU_4$** variable is:

$$HU_4 = \frac{\text{Miles of Stream in Mod Conf floodplain in analysis unit } *(2)}{\text{Area in analysis unit}}$$

We normalize the results of $\mathbf{HU_3}$ and $HU_4$ for all analysis units within a landscape group as follows:

$$\text{Floodplain Storage}_{\text{Normalized}} = \frac{HU_3 + HU_4}{\text{Maximum value all analysis units}}$$

## Recharge and Discharge

$W_{H1}$ *(P + HU1)* **+** $W_{H2}$ *(HU2 + HU3 + HU4 )* **+** $W_{H3}$ *(HU5 + HU6 + HU7 )*

Variables in Model 1

The importance of groundwater processes is modeled as the relative areas important for recharge and discharge. The equation for recharge and discharge = HU5 + (HU6 + HU7) .

Total possible score is 2.

### *HU5 - Score for Recharge*

Total possible score is 1.

The importance of recharge in a analysis unit is modeled as the relative area of higher and lower permeability times the average precipitation for that area. The equation for the recharge variable is as follows:

$$HU_5 = \frac{\text{Recharge for Course Grained Deposits + Recharge for Fine Grained Deposits}}{\text{Area in Analysis Unit}}$$

Where:

Recharge Course Grain Deposits = [(aver_prec ip x Area of high perm) x .838] - 9.77

Recharge Fine Grained Deposits =[(aver_precip x Area of low perm) x .497] - 5.03

The equations for recharge in both course grained and fine grained deposits are based on a recharge analysis presented in the Hydrogeologic Framework for Puget Sound (Vacarro, 1998)

Areas of higher permeability are determined by looking at the permeability of surface deposits. Deposits with coarse grains, such as recessional and advance outwash and alluvium in lowland areas, were placed in a " high permeability" category relative to bedrock such as till, basalt, and granite which were placed in a "low permeability" category . Table B-2 "Protecting Aquatic Ecosystems" summarizes these deposits and their relationship to sediment size, permeability, and hydraulic conductivity.

We normalize the results of $\mathbf{HU_5}$ for all analysis units within a landscape group as follows:

$HU_{5Normalized}$ = $HU_5$ value for hydro unit/Maximum value for analysis units

### HU6, HU7 - Score for Floodplains and Wetlands (Discharge)

Total possible score is 1.

Importance of discharge is modeled based on two types of indicators: stream and river floodplains and wetlands. The equation for the importance of discharge is:

$$\text{Importance of Discharge} = \frac{HU_6 + HU_7}{\text{Area of analysis units}}$$

For discharge within floodplains, we model the relative miles of streams and rivers with different types of confinement that intersect deposits of higher permeability in a analysis unit. Permeable geologic deposits adjacent to and within stream and river valleys are important because they appear to contribute to groundwater discharge and support localized stream/river flow (Cox et al. 2005). For discharge areas associated with wetlands, wetlands associated with slopes and depressional areas are modeled.

Note that the score can be "zero" if an entire basin consists of deposits of low permeability.

The equation for the floodplain discharge variable is as follows:

$$\mathbf{HU_6}\ \text{Permeable deposits intersect unconfined floodplain} = \frac{\text{Miles of streams \& rivers in permeable deposits of unconfined floodplains}}{\text{Total area in analysis unit}}$$

Streams and rivers crossing permeable deposits in unconfined floodplains were judged to have greater importance for discharge, relative to moderately and confined floodplains, since they represent the largest relative area for discharge to potentially occur.

We normalize the results of $\mathbf{HU_6}$ for all analysis units within a landscape group as follows:

Discharge $_{Normalized}$ = $\underline{HU_6}$/Maximum value all hydro units

$\mathbf{HU_7}$ – Relative Importance of Wetland Discharge is based on percentage of analysis unit covered by slope wetlands. These are areas of potential discharge, especially wetlands below slope breaks. The percentage of possible wetlands is estimated for all analysis units using the topographic layer and the hydric soil layer. Areas with hydric soils on all gradients are assumed to be areas where wetlands exist or have existed in the past.

The equation for slope wetland discharge

$$\mathbf{HU_7}\text{ Wetland Discharge} = \frac{\text{area of potential slope wetlands}}{\text{Total area of analysis unit}}$$

We normalize the results of $\mathbf{HU_7}$ for all analysis units within a landscape group as follows:

Wetland Discharge $_{Normalized}$ = $HU_7$/Maximum value all hydro units

## Model 2 : Impairments to Water Process

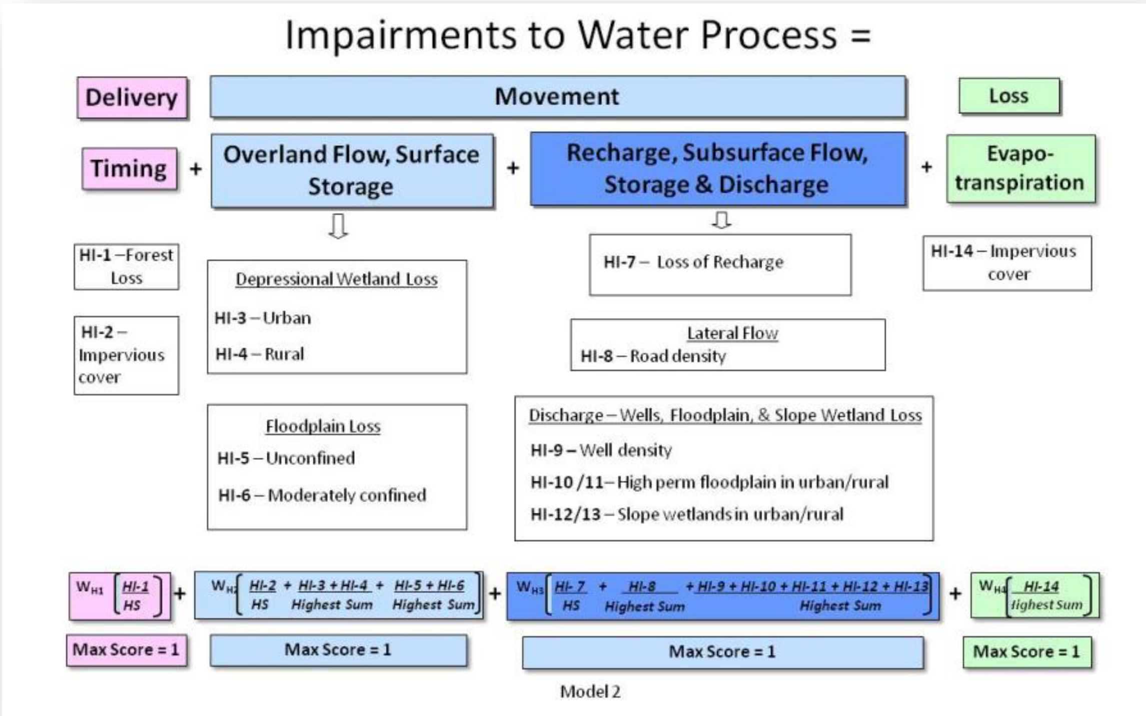



**Figure B-11. Diagram of the equation for calculating the level of impairment to the water flow process** for analysis units across a watershed. Each component (i.e. delivery, surface water, groundwater) requires analysis for several variables. We have grouped them together and discuss each in detail below.

Impairments to water processes are modeled as:

Impairments to Delivery + Impairment to Movement + Impairments to Loss

Impairments to delivery addresses changes to areas that control the timing of snow melt. Impairments to movement is modeled as the relative area of impervious surface (overland flow), the relative area of wetland and floodplain loss, and the changes to areas that contribute to subsurface flow, recharge and discharge. Impairments to loss are modeled by the amount of impervious surface in the analysis unit. Precipitation is not included in the impairment model because it is assumed that this component has not been changed by land uses.

*Model 2 =(impairment of timing of delivery)+ [(impairment of overland flow + impairment of surface storage)+(impairment of areas for recharge + impairment of subsurface flow+impairment of discharge areas)] +(impairment of evapotranspiration)*

It is recommended that the same weighting factors applied for unimpaired conditions be applied to model 2. For the Puget Sound Characterization Project the weighting factors were all kept at "1" since the technical team concluded that there was insufficient data at this time to apply a different weighting factor to all analysis areas. At finer scales of analysis, however, it may be appropriate to use local data in order to adjust the weighting factors. With weighting factors, model 2 is expressed as follows:

*Model 2 =* $W_{H1}$*(Impairments to Timing of Water Delivery) + [*$W_{H2}$*(Impairments to Overland Flow +Impairments to Surface Storage) +* $W_{H3}$*(Impairments to Recharge +Impairments to Subsurface flow+Impairments to Discharge)] +* $W_{H4}$*(Impairments to Evapotranspiration)*

## Impairments to Water Delivery

$W_{H1}$ *HI-1+HI-2* + $W_{H2}$ *( HI-3 + HI-4 + HI-5 + HI-6)* + $W_{H3}$ *(HI-7 + HI-8 + HI-9 + HI-10 + HI-11 + HI-12 + HI-13 )* + $W_{H4}$ *HI-14*

Variables in Model

### *HI-1- Score for Impairments toTiming of Delivery*

Total possible score is 1.

The severity of impairment to water delivery is modeled as the relative loss of forest (HI-1). The equation is:

**HI-$_1$** [Severity of Loss of Forest] $= \frac{\text{Area of non-forest vegetation in analysis unit}}{\text{Area of analysis unit}}$

HI-$_1$ is the score for the relative importance of forested areas to the timing of surface flows for all landscape groups in an analysis area. Forest vegetation includes forested classes only.

We normalize the results of **$HI_1$** for all analysis units within a landscape group as follows:

$HI_{1Normalized}$ = $HI_1$ hydro unit/Maximum value for analysis units.

### *HI-2– Score for Impairments to Overland Flow*

Total possible score is 1

The severity of impairments to overland flow (i.e. change in timing of surface flows) is modeled as the percent impervious surface within a analysis unit. The equation is:

$$\textit{HI-2 (Severity of Impairment to Overland Flow)} = \frac{\textit{Impervious Area}}{\textit{Area of Analysis Unit}}$$

We normalize the results of $\mathbf{HI_2}$ for all analysis units within a landscape group as follows:

$HI_{2Normalized}$ = $HI_2$ hydro unit/Maximum value for analysis units.

## Impairments to Overland Flow and Surface Storage

$$W_{H1}\ \textit{HI-1+HI-2} + W_{H2}\ (\textit{HI-3 + HI-4 + HI-5 + HI-6}) + W_{H3}\ (\textit{HI-7 + HI-8 + HI-9 + HI-10 + HI-11 + HI-12 + HI-13}) + W_{H4}\ \textit{HI-14}$$

Variables in Model

We model the impairment to overland and surface storage as the amount of impervious area and loss of storage in wetlands and streams.

### *HI-2– Score for Impairments to Overland Flow*

Total possible score is 1 prior to normalization.

The severity of impairments to overland flow (i.e. change in timing of surface flows) is modeled as the percent impervious surface within a analysis unit. The equation is:

$$\textit{HI-2 (Severity of Impairment to Overland Flow)} = \frac{\textit{Impervious Area}}{\textit{Area of Analysis Unit}}$$

We normalize the results of $\mathbf{HI_2}$ for all analysis units within a landscape group as follows:

$HI_{2Normalized}$ = $HI_2$ hydro unit/Maximum value for analysis units.

### *HI-3, HI-4 – Score for Impairments to Storage in Wetlands*

Total possible score is 3 prior to normalization.

Impairment to surface storage for wetlands is modeled as the relative loss of surface storage of wetlands in a analysis unit. The potential of historic surface storage for depressional wetlands is based on hydric soils cover intersected with topographic depressions (< 2% slope). The equation is:

*$HI_{-3}+HI_{-4}$ ( Severity of Impairment in Surface Storage) = relative loss of storage in wetlands*

The severity of wetland storage loss is characterized in terms of wetlands that are permanently impaired due to urbanization, and those temporarily impaired due to extensive ditching/tiling in agricultural and rural areas.

An impairment factor of [3] was assigned to impaired wetlands within areas that have urban land uses (i.e. moderate and high density residential, commercial and industrial land cover) since these areas have a higher relative probability of being partially or completely filled. When depressional wetlands are filled, that area no longer provides surface storage. The losses of wetlands in rural and agricultural areas are most likely to be a result of draining and to a lesser extent from filling. Drained wetlands can be restored. Therefore, rural and agricultural wetlands are judged to provide a greater degree of existing and potential surface storage relative to urban wetlands. These impairments are assigned an importance value of [2].

$$\mathbf{HI_{-3}}\ \text{(loss of storage wetlands in urban areas)} = \frac{\text{Area of storage wetlands lost in urban areas *3}}{\text{Total area analysis unit}}$$

$$\mathbf{HI_{-4}}\ \text{(loss of storage wetlands in rural areas)} = \frac{\text{Area of wetlands lost in agricultural and rural area *2}}{\text{Total area in analysis unit}}$$

We normalize the results of $\mathbf{HI_3} + \mathbf{HI_4}$ for all analysis units within a landscape group as follows:

Wetland Storage Impairment$_{\text{Normalized}}$ = $\mathbf{HI_3} + \mathbf{HI_4}$ hydro unit/Maximum value for analysis units.

## HI-5, HI-6 – Score for Impairments to Storage in Floodplains

Total possible score is 3

Impairment to surface storage is modeled as the relative loss of surface storage of floodplains in a analysis unit and the relative loss of storage in the floodplain because of channelized streams and rivers. The potential or historic storage for floodplains is based on the degree of floodplain confinement. The equation is:

*$HI\text{-}_5 + HI\text{-}_6$ ( Severity of Impairment in Surface Storage) = relative loss of storage in floodplains*

<u>Modeling the severity of loss of storage in floodplains</u> ($HI\text{-}_5 + HI\text{-}_6$)

$$\mathbf{HI\text{-}_5} = \frac{\text{Miles of channelized}^{3}\text{ stream in } \textbf{unconfined} \text{ floodplain} * (3)}{\text{Total area in analysis unit}}$$

$$\mathbf{HI\text{-}_6} = \frac{\text{Miles of channelized stream in } \textbf{moderately confined} \text{ floodplain} * (2)}{\text{Total area in analysis unit}}$$

Impairments to streams and rivers, such as dikes, levees, and channelization (including incised channels), have a more significant impact on water storage in floodplains with greater surface storage (i.e., unconfined) relative to more confined floodplains. Dikes and levees of sufficient height can prevent yearly overbank flooding into the adjacent floodplain. Channelization can result in incised channels (i.e., channels that erode significantly below the historic surface elevation of the riverbed) which also prevents overbank flooding.

We normalize the results of $\mathbf{HI_5} + \mathbf{HI_6}$ for all analysis units within a landscape group as follows:

Floodplain Storage $\text{Impairment}_{\text{Normalized}} = \mathbf{HI_5} + \mathbf{HI_6}$ hydro unit/Maximum value for analysis units.

> The effect of dikes on overbank flooding should be confirmed with local experts and/or data because some dikes no longer disconnect the river from its floodplain. These dikes may be overtopped so that the actual floodplain regains some of its former functions.

---

[3] We identify channelized streams as those reaches passing through urban or agricultural land uses. These areas have a higher likelihood of channelization than rural or natural areas.

## Impairments to Recharge

$W_{H1}$ HI-1+ HI-2 + $W_{H2}$ ( HI-3 + HI-4 + HI-5 + HI-6) + $W_{H3}$ (HI-7 + HI-8 + HI-9 + HI-10 + HI-11 + HI-12 + HI-13 ) + $W_{H4}$ HI-14

Variables in Model

### *HI-7– Score for Impairments to Recharge*

Total possible score is 1

*HI-$_7$ (Severity of Impairments to Recharge) = Loss of recharge*

Loss in Recharge = Recharge Coefficient x Total Recharge

Where:

Total Recharge = $HU_5$

Recharge Coefficient = $\frac{\text{Area of Land Use Cover Type x Reduction Coefficient}}{\text{Total area of analysis unit}}$

Land Cover Types (Coastal Change Analysis Program) & Reduction Coefficient:

- High Intensity = 0.9 (80 to 100% impervious)
- Medium Intensity = 0.7 (51 to 79% impervious)
- Low Intensity = 0.35 (20 to 50% impervious)

We normalize the results of **$HI_7$** for all analysis units within a landscape group as follows:

Recharge Impairment$_{\text{Normalized}}$ = **$HI_7$** hydro unit/Maximum value for analysis units.

## Impairments to Subsurface Flow

$W_{H1}$ HI-1 + HI-2 + $W_{H2}$ ( HI-3 + HI-4 + HI-5 + HI-6) + $W_{H3}$ (HI-7 + HI-8 + HI-9 + HI-10 + HI-11 + HI-12 + HI-13 ) + $W_{H4}$ HI-14

Variables in Model

### *HI-8 – Score for Impairments from Roads*

Total possible score is 3.

*Severity of Impairment to Subsurface Flow = Impairments from roads (HI-$_{11}$ )*

**HI-8** is the severity of impairment resulting from roads and their associated drainage system (ditches and culverts) which intercept subsurface flow and convert it to surface flow. HI-8 applies to roads of all classes. The maximum score for HI-8 is 3.

$$HI_8 = \frac{\text{miles of roads}}{\text{analysis unit in sq. miles}}$$

We normalize the results of **HI8** for all analysis units within a landscape group as follows:

Impairment to Subsurface Flow$_{Normalized}$ = **HI8** hydro unit/Maximum value for analysis units.

## Impairments to Discharge

$W_{H1}$ HI-1 + HI-2 + $W_{H2}$ ( HI-3 + HI-4 + HI-5 + HI-6) + $W_{H3}$ (HI-7 + HI-8 + HI-9 + HI-10 + HI-11 + HI-12 + HI-13 ) + $W_{H4}$ HI-14

Variables in Model

Impairment to discharge is modeled as the relative impairment from wells (decreasing discharge through groundwater pumping) and the impairment from urban and rural land use activities on floodplains and slope wetlands (areas of groundwater discharge).

### *HI-9 Score for Impairments from Wells,*

Total possible score is 1 prior to normalization.

Impairment to discharge due to groundwater extraction, is modeled as the relative density of wells within an analysis unit.

*Severity of Impairment to Discharge by Wells = HI-9*

$$HI\text{-}_9 = \frac{\text{Density of Class A and B wells}}{\text{Area of analysis unit}}$$

We normalize the results of **Impairments to Discharge by wells** for all analysis units within a landscape group as follows:

Impairment to Discharge by Wells$_{Normalized}$ = HI-9 / Maximum value for analysis units.

## *HI -10 and HI - 11 Score for Impairments to Floodplains*

Impairment to discharge in floodplains with deposits of high permeability, is modeled as the miles of unconfined streams or rivers within either areas of urban or rural land use.

*Severity of Impairment to Discharge in Floodplains = (HI-$_{10}$ + HI-$_{11}$ )*

**HI-$_{10}$** (Higher permeable deposits intersect unconfined urban floodplain ) =

$$\frac{\text{Miles of unconfined streams or rivers in higher perm deposits * (3)}}{\text{Total area of analysis unit}}$$

Higher permeable deposits within unconfined **urban** floodplains are assigned an impairment factor of [3]. This higher factor was applied since urban floodplains typically have a greater degree of impairment including floodplain fill and development, channelization of streams and isolation from adjoining floodplain. Unconfined floodplains also have the largest area, relative to more confined floodplains, for groundwater discharge to occur in and are usually located in the lower portion of a watershed where groundwater discharge is more likely to occur.

**HI-$_{11}$** (Higher permeable deposits intersecting unconfined **rural** floodplain) =

$$\frac{\text{Miles of modified streams in higher perm deposits of unconfined rural floodplains * (2)}}{\text{Total area of analysis unit}}$$

Deposits of higher permeability within unconfined **rural** floodplains are assigned an impairment factor of [2]. This factor was applied since rural floodplains typically have a lesser degree of impairment relative to urban floodplains. Impairment can include activities such as agriculture, limited fill and development, levees and dikes and draining of floodplain wetlands. These activities can alter the pathways of discharged groundwater do not always permanently eliminate groundwater discharge areas.

We normalize the results of **Impairments to Discharge** in Floodplains for all analysis units within a landscape group as follows:

$$\text{Impairment to Discharge in Floodplains}_{\text{Normalized}} = \frac{(\text{HI-}_{10} + \text{HI-}_{11})}{\text{Maximum value for analysis units.}}$$

## *HI -12 and HI – 13 Score for Impairments to Slope Wetlands*

Impairment to discharge in slope wetlands, is modeled as the area of potential slope wetlands within either areas of urban or rural land use.

*Severity of Impairment to Discharge in Slope Wetlands = (HI-$_{12}$ + HI-$_{13}$ )*

$$\textbf{HI-}_{\mathbf{12}} \text{ (Slope wetlands in urban landuse)} = \frac{\text{Area of slope wetlands within urban land use } * (3)}{\text{Total area of analysis unit}}$$

Slope wetlands within areas of **urban** landuse are assigned an impairment factor of [3]. This higher factor was applied since urban slope wetlands typically have a greater degree of impairment including a dense network of roads, ditches, drains and building foundations and fill that intercept and re-route groundwater discharge to stormdrain systems or directly to aquatic resources.

$$\textbf{HI-}_{\mathbf{13}} \text{ (Slope wetlands in rural landuse )} = \frac{\text{Area of slope wetlands within rural land use } * (2)}{\text{Total area of analysis unit}}$$

Slope wetlands within areas of **rural** land use are assigned an impairment factor of [2]. This factor was applied since rural slope wetlands typically have a lower degree of impairment relative to urban areas. This can include roads and building foundations associated with lower density rural residential and commercial development and roads, ditches and drain systems for agriculture. These activities intercept and re-route groundwater discharge to wetlands, streams and rivers.

We normalize the results of **Impairments to Discharge for slope wetlands** for all analysis units within a landscape group as follows:

$$\text{Impairment to Discharge for slope wetlands}_{\text{Normalized}} = \frac{(\text{HI-}_{12} + \text{HI-}_{13})}{\text{Maximum value for analysis units.}}$$

## Impairments to Loss

$$W_{H1}\ \text{HI-1} + \text{HI-2} + W_{H2}(\text{HI-3} + \text{HI-4} + \text{HI-5} + \text{HI-6}) + W_{H3}(\text{HI-7} + \text{HI-8} + \text{HI-9} + \text{HI-10} + \text{HI-11} + \text{HI-12} + \text{HI-13}) + W_{H4}\ \text{HI-14}$$

Variables in Model

### *HI-14 – Score for Impairments to Evapotranspiration*

Total possible score is 1.

Impairments to evapotranspiration are modeled as the relative amount of total impervious surface present in the analysis unit.

*Change in ET = $HI\text{-}_{14}$*

$HI\text{-}_{14}$ = 0-1 based on percentage of analysis unit covered with impervious surface

The percent of total impervious surface in each analysis unit is estimated by the percent of urban land use. Impervious surface, therefore, becomes a surrogate for the loss of evapotranspiration in a basin relative to unimpaired conditions. The score is based on the assumptions that: the basin was 100% forested prior to human impairments; that maximum evapotranspiration occurred during these unimpaired conditions relative to impaired conditions; and that the loss of evapotranspiration is proportional to the area or percentage of the basin lost. Based on these assumptions, the equation for calculating the score for evapotranspiration is as follows:

$$HI\text{-}_{14} = \frac{\text{Acres of impervious cover}}{\text{Total area of analysis unit}}$$

We normalize the results of **Impairments to Evapotranspiration** for all analysis units within a landscape group as follows:

Impairment to $\text{Evapotranspiration}_{\text{Normalized}}$ = HI-14/Maximum value for analysis units.

# References


Adamus, P.R., E.J. Clairain, Jr., M.E. Morrow, L.P. Rozas, and R.D. Smith. 1991. Wetland Evaluation Technique (WET), Volume I: Literature Review and Evaluation. WRP-DE-2. Vicksburg MS: U.S. Army Corps of Engineers Waterways Experiment Station.

Aldous, A. 2005. Wetland Ecologist, The Nature Conservancy, Portland Oregon. Personal communication.

Booth, D.B., D.Hartley, and R. Jackson. 2002. Forest cover, impervious-surface area, and the mitigation of stormwater impacts. Journal of the American Water Resources Association. 38(3):835-845.

Booth, D.B., R. Haugerud and K.G. Troost. 2003. The geology of Puget Sound rivers. In: Restoration of Puget Sound Rivers. Eds: D.R. Montgomery, S. Bolton, D.B. Booth, and L. Wall. University of Washington Press. 194-225.

Brunengo, M.J., S.D. Smith, and S.C. Bernath. 1992. Screening for Watershed Analysis – A GIS-based method of Modeling the Water Input from Rain-on-Snow Storms, for Management and Regulation of Clearcut Forest Harvest. WA DNR, Forest Practices Division, Open-File Report 92-2.

Bullock, A. and M. Acreman. 2003. The role of wetlands in the hydrological cycle. Hydrology and Earth System Sciences. 7(3):358-389.

Christensen, S., K.R. Rasmussen, and K. Moller. 1998. Prediction of regional groundwater flow to streams. Groundwater 36(2):351 – 360.

Coffin, B. A. and R. D. Harr. 1992. Effects of Forest Cover on Volume of Water Delivery to Soil During Rain-on-snow. Final Report #TFW-SH1-92-001 to the Timber Fish and Wildlife Sediment, Hydrology and Mass Wasting Steering Committee. 131 pp.

Cox, S. E. and S.C. Kahle. 1999. Hydrogeology, Ground-water quality, and Sources of Nitrate in Lowland Glacial Aquifers of Whatcom County, Washington and British Columbia, Canada. USGS Water-Resources Investigations Report 98-4195. 251 pp.

Cox, S.E., F.W. Simonds, L. Doremus, R.L. Huffman, and R.M. Defawe. 2005. Ground water/surface water interactions and quality of discharging ground water in streams of the lower Nooksack River Basin, Whatcom County, Washington: U.S. Geological Survey Scientific Investigations Report 2005-5255, 46 p.

Dinicola, R.S., 1990, Characterization and Simulation of Rainfall-runoff Relations for Headwater Basins in Western King and Snohomish Counties, Washington. U.S. Geological Survey Water-Resources Investigations Report 89-4052, 52 p.

Dunne, T. and L.B. Leopold. 1978. Water in environmental planning. W.H. Freeman and company, New York. 818 pp.

Dunne, T., T.R. Moore, and C.H. Taylor. 1975. Recognition and prediction of runoff-producing zones in humid regions. Hydrological Sciences Bulletin 3: 305-327.

Gosselink, J.G., S.E. Bayley, W.H. Conner, and R.E. Turner. 1981. Ecological factors in the determination of riparian wetland boundaries. In: J.R. Clark and J. Benforado, eds, Wetlands of Bottomland Hardwood Forests. Elsevier, Amsterdam, pp 197-219.

Harr, R.D. 1977. Water flux in soils and subsoil on a steep forested slope. Journal of Hydrology 33:37-58.

Hruby, T., T. Granger, K. Brunner, S. Cooke, K. Dublonica, R. Gersib, L. Reinelt, K. Richter, D. Sheldon, E. Teachout, A. Wald and F. Weinmann. 1999. Methods for Assessing Wetland Functions Volume 1: Riverine and Depressional Wetlands in the Lowlands of Western Washington Part 1 Assessment Methods. Washington State Department of Ecology Publication #99-115. Available at: http://www.ecy.wa.gov/programs/sea/wfap/westernwfapmethods.html#Download

Jones, M.A. 1998. Geologic Framework for the Puget Sound Aquifer System, Washington and British Columbia. Part of the Regional Aquifer-System Analysis – Puget-Willamette Lowland. U.S. Geological Survey Professional Paper 1424 – C. 31 pp.

McDonnell, J.J. 2003. Where does water go when it rains? Moving beyond the variable source area concept of rainfall-runoff response. Hydrological Processes 17:1869-1875.

Mitsch, W.J. and J.G. Gosselink. 2000. Wetlands. New York: Van Nostrand Reinhold. 920 pp.

Morgan, D.S. and J.L. Jones. 1999. Numerical Model Analysis of the Effects of Ground-Water Withdrawals on Discharge to Streams and Springs in Small Basins Typical of the Puget Sound Lowland, Washington. U.S. Geological Survey Water-Supply Paper 2492. 73 pp.

Olson, P.L. 2005. Hydrogeologist, Washington State Department of Ecology, Lacey, Washington. Personal communication.

Olson, P.L. 2008. Hydrogeologist, Washington State Department of Ecology, Lacey, Washington. Personal communication 6-23-08.

Reinelt, L.E. and B.L. Taylor. 1997. Effects of watershed development on hydrology. In: A.L. Azous and R.R. Horner, Eds. Wetlands and Urbanization: Implications for the Future. Report of the Puget Sound Wetlands and Stormwater Management

Research Program. Available at: http://splash.metrokc.gov/wlr/basins/weturban.htm

Sheldon, D.T., T. Hruby, P. Johnson, K. Harper, A. McMillan, T. Granger, S. Stanley, E. Stockdale. 2005. Freshwater Wetlands in Washington State Volume I: A Synthesis of the Science. Washington State Department of Ecology Publication #05-06-006. Available at:. http://www.ecy.wa.gov/programs/sea/bas_wetlands/volume1final.html

Turney, G.L., S.C. Kahle, and N.P. Dion. 1995. Geohydrology and Ground-Water Quality of East King County, Washington. U.S. Geological survey Water Resources Investigations Report 94-4082.

U.S. Environmental Protection Agency. 1999. Preliminary Data Summary of Urban Stormwater Best Management Practices. EPA-821-R-99-012. 216 pp

U.S. Global Change Research Program, National Assessment Synthesis Team. 2000. Climate Change Impacts on the United States. The potential consequences of climate variability and change. Overview: Pacific Northwest. Published on line at: http://www.usgcrp.gov/usgcrp/Library/nationalassessment/overviewpnw.htm

Vaccaro, J.J., A.J. Hansen Jr., and M.A. Jones. 1998. Landscape group Framework of the Puget Sound Aquifer System, Washington and British Columbia. Part of the Regional Aquifer-System Analysis – Puget- Willamette Lowland. U.S. Geological Survey Professional Paper 1424 – D. 77 pp. Published on line at:

http://pubs.er.usgs.gov/usgspubs/pp/pp1424D

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

Weiler, M., J. McDonnell, I. Tromp-van Meerveld, and T. Uchida. 2005. Subsurface streamflow. Encyclopedia of Hydrological Sciences. Ed: M. Anderson. John Wiley and sons, Ltd. 18 pp. (in press). Available at: http://faculty.forestry.ubc.ca/weiler/pdfs/hsa119.pdf

Winter, T.C. 1988. A conceptual framework for assessing cumulative impacts on the hydrology of nontidal wetlands. Environmental Management 12(5):605-620.

Winter, T.C., J.W. Harvey, O.L. Franke, and W.M. Alley. 1998. Groundwater and Surface Water: A Single Resource. U.S. Geological Survey Circular 1139. 79 pp.

Ziemer, R.R. and T.E. Lisle, 1998. Chap 3: Hydrology. In: R.J. Naiman and R.E. Bilby (Eds). River Ecology and Management: Lessons from the Pacific Northwest. New York: Springer-Verlag Press, New York, Inc.

# *Appendix C: Mapping Methods*

The previous two appendices (Appendices A and B) identified important areas (Step 4 of the assessment) for the water flow process and human activities that impair (Step 5) this process . This appendix provides details on the GIS analysis for identifying important areas and their impairments.

## Analyses for important areas for watershed processes (Step 3)

### Overview

Methods for mapping important areas for each watershed process are based upon the relationships described in the previous appendices. We mapped these important areas using a suite of GIS analyses with regionally available datasets. We provide details for conducting the analyses in Table C-1.

**Table C-1: GIS analyses for variables for important areas for the water process. The results of these analyses provide a simple way of displaying areas that are more important in the water process relative to others within the analysis area. These variables are appropriate for use in Western Washington.**

| Water Process Important Areas Analysis by LG (Landscape Group) | | Field | Calculation | values | Max | Description |
|---|---|---|---|---|---|---|
| | | AU_ID | number | | | Analysis Unit ID number |
| | | LG | L-lowland, M-mountainous, ME-eastern mtns, S-Satsop | | | Landscape Group |
| | | acres | acres in AU | | | acres in AU |
| | | sqmi | acres / 640 | | | sq mi in AU |
| Delivery | Precipitation patterns | aver_prec | inches (in x area / total acre inches for AU) | | | average precipitation for AU |
| | | ***P*** | aver_prec / max value BY LG | 0-1 | 1 | value for precipitation |
| | Timing of Precipitation | SRS_ac | acres | | | acres of AU in snow dominated (SD), rain-on-snow (ROS) area, & highlands (HL) |
| | | SRS_pct | SRS_ac / acres | 0-1 | | % cover for rain-on-snow & snow dominated zone |
| | | ***HU1*** | SRS_pct / max value BY LG | 0-1 | 1 | value for PRECIP TIMING |
| | | ***HUD*** | ( P + HU1 ) / max value BY LG | 0-2 | **0-1** | **SUM & NORMALIZE DELIVERY BY LG** |
| | | *HUD_Q* | *quartile ranking **by landscape group*** | | | |
| Movement | Surface storage | depwet_ac | acres | | | **all depressional wetlands (hydric, NWI, LC_wet, marsh on ≤2% slope)** |
| | | depwet_pct | depwet_ac / acres (in AU) | | | percent of **all depressional** wetlands |
| | | ***HU2*** | depwet_pct / max value BY LG | 0-1 | 1 | score for wetland storage |
| | | uc_mi | UNCONFINED stream miles | | | miles of UNconfined floodplain/streams |
| | | mc_mi | MODERATELY CONFINED stream miles | | | miles of Moderately Confined floodplain/streams |
| | | ***HU3*** | uc_mi / **sqmi x 3** | 0-? | | value for UNconfined floodplain/streams |
| | | ***HU4*** | mc_mi / **sqmi x 2** | 0-? | | valuer for Moderately Confined floodplain/streams |
| | | ***HU_S*** | (HU3 + HU4) | 0-3 | | value for streams |
| | | ***HU_SS*** | HU_S / max value BY LG | 0-1 | 1 | score for stream storage |
| | Surface Water | ***HUSW*** | ( HU2 + HU_SS) / max value BY LG | 0-2 | **0-1** | **SUM & NORMALIZE SURFACE WATER BY LG** |
| | | *HUSW_Q* | *quartile ranking **by landscape group*** | | | |
| | Recharge | PermH | acres | | | acres of AU in high/moderate permeable deposits |
| | | PermL | acres - PermH | | | acres for low perm - geology- fine grained (bedrock, till, etc) |
| | | **rechH** | **[(aver_prec x PermH) x .838] - 9.77** | | | Hydrogeologic Framework of the Puget Sound Aquifer System - Vaccaro |
| | | **rechL** | **[(aver_prec x PermL) x .497] - 5.03** | | | http://pubs.er.usgs.gov/usgspubs/pp/pp1424D |
| | | RechT | (rechH + rechL) / acres | | | value for total recharge |
| | | ***HU5*** | RechT / max value BY LG | 0-1 | 1 | value for area in high/moderate permeable deposit |
| | | *HU5_Q* | *quartile ranking **by landscape group*** | | | |

| | | | | | | |
|---|---|---|---|---|---|---|
| | | ucHp_mi | miles | | | miles of Unconfined streams in High perm deposits |
| | Discharge | ucHp_area | ucHp_mi / sqmi | | | area value within AU for Unconfined streams in High perm deposits |
| | | ***HU6*** | ucHp_area / max value BY LG | 0-1 | 1 | value for UNconfined floodplain/stream discharge |
| | | slpwet_ac | acres | | | acres of slope wetlands >2% (compliment to depressinal wetlands ≤2% slope) |
| | | slpwet_pct | slpwet_ac / acres | 0-1 | | % of AU with slope wetland (>2%) |
| | | ***HU7*** | slpwet_pct / max value BY LG | 0-1 | 1 | value for slope wetland discharge areas |
| | | ***HU_D*** | (HU_6 + HU_7 ) / max value BY LG | 0-1 | 1 | total discharge areas |
| | | *HU_D_Q* | *quartile ranking **by landscape group*** | | | |
| | Groundwater | ***HUGW*** | ( HU5 + HU_D) / max value BY LG | 0-2 | **0-1** | **SUM & NORMALIZE GROUNDWATER BY LG** |
| | | *HUGW_Q* | *quartile ranking **by landscape group*** | | | |
| **Model 1** | | ***HU_N*** | **HUD + HUSW + HUGW** | | 0-2 | **SUM OF NORMALIZED SCORES FOR MODEL 1 ACROSS ALL Aus** |
| **Model 1 by LG** | | ***HU_N_LG*** | **HU_N / max value BY LG** | | **0-1** | **SCORES FOR MODEL 1 BY EACH LG** |
| | | ***HU_CAL*** | **HU_N_LG shifting all values to zero to one scale** | | | **CALIBRATE DATA RANGE TO ZERO TO ONE (1) FOR MANAGEMENT UNITS - for each LG, subtract lowest value from highest, then divide all values by highest remaining value; then all values can be grouped into 4 buckets at once for HU_M1** |
| Management Units | | **HU_M1** | **Model 1 - Importance for Water BY LG** | | **H,MH M,L** | **HU_CAL by QUANTILES BY LANDSCAPE GROUP** |

**Model 1 = ( P + HU1 ) N + [ ( HU2 + HU_SS ) N ] + [ ( HU5 + HU_D ) N ] --> CALIBRATE VALUES FROM ZERO TO ONE**

HUD + HUSW + HUGW

## Analyses for impairments to watershed processes - (Step 4)

### Overview

Methods for mapping impairments to the important areas for each watershed process are based upon the relationships described in the previous appendices (A-B). The GIS Analysis steps are described in Table C-2.

**Table C-2: GIS analyses for variables for impairments to the water process. The results of these analyses provide a simple way of displaying areas that are more impaired in the water process relative to others within the analysis area. These variables are appropriate for use in Western Washington.**

| Water Process Alterations Analysis by LG (Landscape Group) | | Field | Calculation | values | Max | Description |
|---|---|---|---|---|---|---|
| | | **LC_ac** | acres (minus NA areas - snow/ice, bare, tundra) | | | acres in AU for LC calculation |
| | | LC_sqmi | sq miles | | | sq miles of above |
| Timing of Delivery | | forloss_ac | acres (excLCde NA areas: snow,bare rock, etc.) | | | acres of landuse that are no longer forested due to LC alteration |
| | | forloss_pct | forloss_ac / LC_ac | 0-1 | | percent of loss of forest within AU |
| | | ***HI_1*** | forloss_pct / max value by LG | 0-1 | **1** | **NORMALIZE IMPAIRMENT TO DELIVERY BY LG** |
| | | imp_ac | acres | | | acres of urban (indicator of impervious) area in AU |
| | | imp_pct | imp_ac / LC_ac | 0-1 | | % of urban (indicator of impervious) area in AU |
| | | ***HI_2*** | imp_pct / max value BY LG; where imp_pcnt >50% = 1 | 0-1 | **1** | value for urban (indicator of impervious) surface |
| | | ***HI_D*** | HI_1 + HI_2 / max value by LG | | | value for impairment to timing of delivery |
| | | *HI_D_Q* | *quartile ranking* ***by landscape group*** | | | |
| | | *D_RP* | *RP for Delivery* | | | *Restoration_Protection for Delivery* |
| | Surface Storage | wet_ur_ac | acres | | | acres of depressional wetlands impaired by urban land use |
| | | ***HI_3*** | (wet_ur_ac / depwet_ac) x 3 | 0-3 | | value for depressional wetlands impaired by urban land use |
| | | wet_ru_ac | acres | | | acres of depressional wetlands impaired by rural /ag landuse |
| | | ***HI_4*** | (wet_ru_ac / depwet_ac) x 2 | 0-2 | | value for depressional wetlands impaired by rural /ag |
| | | ***HI_W*** | HI3 + HI4 | 0-3 | | total value for wetlands on altered LC (urban & rural) |
| | | ***HI_WS*** | HI_W / max value BY LG | 0-1 | 1 | value for impairment to DEPRESSIONAL WETLANDS |
| | | uc_alt_mi | miles | | | miles of impaired UNconfined streams |
| | | mc_alt_mi | miles | | | miles of impaired Moderately Confined streams |
| | | ***HI_5*** | (uc_alt_mi / **LC_sqmi** ) **x** 3 | 0-? | | value for impaired UNconfined streams |
| | | ***HI_6*** | (mc_alt_mi / **LC_Sqmi**) x 2 | 0-? | | value for impaired Moderately Confined streams |
| | | ***HI_S*** | (HI5 + HI6) | 0-? | | total value for impaired streams |
| | | ***HI_SS*** | HI_S / max value BY LG | 0-1 | 1 | value FOR STREAM STORAGE IMPAIRMENT |
| | | ***HI_TS*** | (HI_WS + HI_SS) | 0-2 | **1** | value FOR TOTAL STORAGE IMPAIRMENT |
| | Surface Water | ***HISW*** | HI_TS / max value BY LG | 0-2 | **0-1** | **SUM & NORMALIZE IMPAIRMENT TO SURFACE WATER BY LG** |
| | | *HISW_Q* | *quartile ranking* ***by landscape group*** | | | |
| | | *SW_RP* | *RP for Surface Water* | | | *Restoration_Protection for Surface Storage* |
| | | ***u_ac*** | ac x .9 | | | urban (value = 2) |

| | | | | | | |
|---|---|---|---|---|---|---|
| | | ***bu_ac*** | ac x .7 | | | built up (value = 3) |
| | | ***LI_ac*** | ac x .35 | | | low intensity (value = 4) |
| | | ***RRC*** | (u_ac + bu_ac + LI_ac) / LC_ac | | | reduction recharge coefficient; |
| | | ***HI_7*** | RRC x RechT | 0-1 | | score for impaired recharge |
| | | ***HI_R*** | HI_7 / max value by LG | 0-1 | | value for total impairments to recharge |
| | | *HI_R_Q* | *quantile ranking **by landscape group*** | | | |
| | | *R_RP* | *RP of Recharge* | | | *Restoration_Protection for Recharge* |
| | Lateral subsurface flow | rd_mi | mi | | | road miles on Low perm deposits **(poor drainage**) (geology & soils) |
| | | rd_den | rd_mi / sqmi | | | density of road miles |
| | | ***HI_8*** | rd_den / max value BY LG | 0-1 | **1** | score for impairment from roads on Low perm/poor drainage deposits |
| Movement | Subsurface storage | well_cnt | number of wells | | | number of wells |
| | | well_den | well_cnt / sqmi | | | number of wells per unit area (dept of health well data base) |
| | | ***HI_9*** | {number of wells/ sqmi] x 1/max value BY LG ?? | 0-1 | **1** | score for impairment from roads on Low perm/poor drainage deposits |
| | Discharge | ucHp_u | miles | | | Unconfined stream miles in High perm in Urban land cover |
| | | ***HI_10*** | (ucHp_u / **LC_sqmi**) x 3 | 0-3 | | value for unconfined streams in high perm in Urban land cover |
| | | ucHp_r | miles | | | Unconfined stream miles in High perm in Rural land cover |
| | | ***HI_11*** | (ucHp_r / **LC_sqmi**) x 2 | 0-2 | | value for unconfined streams in high perm in rural land cover |
| | | ***HI_SD*** | ( HI10 + HI11) / max value BY LG | 0-1 | 1 | alterations to stream discharge |
| | | slpw_u | slpwet_ac intersect with urban | | | urban LC on slope wetlands (>2%) |
| | | ***HI_12*** | slpw_u / LC_ac x 3 | 0-3 | | value for urban LC on slope wetlands |
| | | slpw_r | slpwet_ac intersect with rural | | | rural LC on slope wetlands (>2%) |
| | | ***HI_13*** | slpw_r / LC_ac x 2 | 0-2 | | value for rural LC on slope wetlands |
| | | ***HI_HD*** | (HI12 + HI13 ) / max value BY LG | 0-1 | 1 | value for alterations onwetland/hydric slopes - hydric discharge |
| | | ***HI_DI*** | HI_9 + HI_SD + HI_HD / max value BY LG | 0-1 | **1** | alteration to discharge from loss of wetland/hydric slope to LC |
| | | *HI_DI_Q* | *quartile ranking **by landscape group*** | | | |
| | | *DI_RP* | *RP for Discharge* | | | *Restoration_Protection for Discharge* |
| | Groundwater | ***HIGW*** | **(HI_R + HI_8 + HI_HD ) / max value BY LG** | 0-3 | **0-1** | **SUM & NORMALIZE** IMPAIRMENT TO GROUNDWATER **BY LG** |
| | | *HIGW_Q* | *quartile ranking **by landscape group*** | | | H, MH, M, L |
| | | *GW_RP* | *RP for Groundwater* | | | *Restoration_Protection for Groundwater* |
| Loss | Transpiration | ***HI_14*** | imp_pcnt | | | loss of transpiration from loss of forest |
| | | ***HIL*** | **HI_14 / max value BY LG** | | **0-1** | **NORMALIZE** LOSS OF ET **BY LG** |
| Model 2 | | ***HI_N*** | **HI_D + HISW + HIGW + HI_L** | | **0-3** | **SUM OF NORMALIZED SCORES FOR MODEL 2 ACROSS ALL AU's** |

| | | | | | |
|---|---|---|---|---|---|
| **Model 2 by LG** | ***HI_N_LG*** | **HI_N / max value BY LG** | | **0-1** | **SCORES FOR MODEL 2 BY EACH LG** |
| | ***HI_CAL*** | **HI_N_LG shifting all values to zero to one scale** | | | **CALIBRATE DATA RANGE TO ZERO TO ONE (1) FOR MANAGEMENT UNITS - for each LG, subtract lowest value from highest, then divide all values by highest remaining value; then all values can be grouped into 4 buckets at once for HI_M2** |
| **Management Units** | **HI_M2** | **Model 2 - IMPAIRMENT to Water by LG** | **H, MH, M, L** | | **HI_CAL by QUANTILES BY LANDSCAPE GROUP** |
| | **Model 2 = ( HI1 ) N + ( HI2 + HI_WS + HI_SS ) N + ( HI7 + HI8 + HI9 + HI10 + HI11 + HI_SD ) N + ( HIL )** | | | | |
| | HID + HISW + HIGW + HIL | | | | |
| | **WF_RP** | **Synthesis - Restoration/Protection Matrix** | | | COMBINATION OF HU_M1 & HI_M2 Using Management Matrix By LG |