# Appendix B: Assessing the Water Process in Puget Sound and Western Washington

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# 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.



# **Delivery, Movement, and Loss of Water**

**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.

The following sections describe each of these components in more detail.

### 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.

We	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	Areas with higher amounts of precipitation	Ρ			
			Timing of snowmelt	Rain-on-snow zones Snow-dominated zones	RS		
	A I	Overland flow	Precipitation patterns & Soils	Saturated areas			
ent	surface	Surface storage	Topography, Sur- face geology	Areas of low gradient	WLS		
	Below surface	Shallow subsurface flow	Topography	Low permeability deposits	PermL		
		Recharge	Surface geology	High permeability deposits	PermH		
lovem		Vertical and lateral subsurface flow		Entire watershed			
2		Subsurface storage	Surface geology	Deep permeable deposits			
	Return to surface	Discharge	Topography Surface geology	Floodplains intersecting permeable deposits Slopes intersecting area of hydric soils extending into lower gradient area Stratigraphic pinchouts Contact areas between geologic deposits of different permeabilities	SD SWD		
		Evaporation/ Transpiration	Vegetation Climate	Entire watershed	Addressed in Degradation		
Loss		Stream or sub- surface flow out of basin	Topography 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	GIS Data	Variables for Scoring
	Precipitation patterns	Higher precipitation	Precipitation	Ρ
Delivery	Timing of snowmelt	Rain-on-snow zones Snow-dominated areas	Rain on Snow Snow dominated	RS

# 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 [RS]

Snowmelt provides an important source of water that can support groundwater recharge and baseflow<sup>1</sup>, 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 snow melt results when warm rains occur. These warmer conditions cause the snow to

<sup>&</sup>lt;sup>1</sup> Streamflow coming from groundwater seepage into a stream or river.

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) return to the surface.

### At the surface:

It is not possible to accurately identify saturated areas 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.

Component of Process		Component of Process Natural areas		Important areas	GIS Data Layers	Variables for Scoring
t	At the surface	Overland flow	Not generally available	Precipitation patterns Soils	Saturated areas	
Movemen		Surface storage	Wetlands Hydric soils <u>SSHIAP</u> confinement data	Topography Surface geology Soils	Areas of low gradient Floodplains	WLS UNSS, MCSS

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

# Surface storage [WLS, UNSS, MCSS]

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 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 (<u>DNR King</u> <u>County</u>, 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		MajorComponent of ProcessNaturalImportant areasControls		GIS Data Layers	Variables for Scoring	
		Shallow	Geology & Soils		High permeability	PermH
ment	Below surface	flow & Recharge	Geology & Soils	Topography Surface geology	Low permeability deposits	PermL
Mover		Vertical and lateral subsurface flow	Not generally available		Entire watershed	
		Subsurface storage	Not generally available	Surface geology	Deep permeable deposits	

# 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 [I\_R]

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.

Surface Geology	Sediment Size	Permeability	Hydraulic conductivity <sup>2</sup> (ft/day)
Recessional Outwash Alluvium in lowland	Coarse Gravel/ Sand	High <sup>1,2</sup>	>100
Advance Outwash	Moderate Sands	Moderate <sup>2</sup>	15-50
Organic Deposits	Not applicable	Low to Moderate	
Moraine, Till	Varied	Low to Very Low <sup>2</sup>	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 <sup>2</sup>	1-15
Bedrock	Consolidated Deposit	Very Low	

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

# 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 degradation 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 whether larger-scale groundwater is discharging in a particular reach of a stream, without actual measurements on a local scale (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	GIS Data	Variables for Scoring	
Movement	Return to the surface	Discharge	Topography Surface geology	Floodplains intersecting permeable deposits Slope breaks intersecting area of hydric soils extending into lower gradient area Stratigraphic pinchouts Contact areas between geologic deposits of different permeabilities	Geology, soils, topography Local information	SD SWD

### Discharge [SD, SWD]

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
	Evaporation/ Transpiration	Vegetation Climate	Entire watershed
Loss	Stream- or subsurface flow out of basin	Topography Surface geology	

# Identifying Degradation to the Water Process - Step 4

Human activity has degraded the natural condition of the lowland areas of Puget Sound. However, the intensity of degradation varies significantly. Where degradation is minimal, processes are still primarily intact and functioning. Where degradation has 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 Western Washington and Puget Sound.





Indicators of the degradation 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 degradation, 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).

Component of process		onent of ocess	Major natural controls	Change to process	Cause of change	Indicators of degradation	Variable for scoring in model	
			Precipitation patterns	Changes in runoff quantity & timing	Climate change			
Delivery	<b>k</b> i		Timing of snowmelt	Increase streamflow	Removal of forest vegetation	Loss of forest cover in rain- on-snow and snow dominated zones	FL	
		Overland flow	Precipitation patterns Soils	Change timing of surface runoff Decreased infiltration	Impervious areas Channelization of flows Filling and draining of seasonally saturated areas	Watershed imperviousness Stormwater discharge pipes Drainage ditches in seasonally saturated areas Loss of seasonally saturated areas	IMP	
Movement	At the surface	Verticity Surface storage storageTopography Surface geology SoilsDecrease storage capacity Increase velocity of surface flowsDrainage or filling of depressional wetlandsLoss of depressional wetlands from urban rural land useSurface storageFloodplain widthDecrease water storage capacity Increase surface water velocityChannelization of streams and storage capacity floodplainMiles of degraded streat through unconfined & moderately confined floodplainTopography GeologyIncrease storage & change timing of downstream flowsDamsDam storage capacity re to size of watershed	Topography Surface geology Soils	Decrease storage capacity Increase velocity of surface flows	Drainage or filling of depressional wetlands	Loss of depressional wetlands from urban & rural land use	UW, RW	
			estarage	Floodplain	Decrease water storage capacity	Channelization of streams and stream	Miles of degraded streams through unconfined & moderately confined floodplains	UDS, MDS
			Dikes and levees on stream reaches with floodplains					
			Topography Geology	Increase storage & change timing of downstream flows	Dams	Dam storage capacity relative to size of watershed	dam_score	

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

### Table B-3 continued

(	Component of process controls		Major natural controls	Change to process	Cause of change	Indicators of degradation	Variable for scoring
		Recharge	Topography e Surface	Reduce recharge and increase surface runoff		High intensity development, degree of permeability and amount of rainfall	U_AC
nt	ıce				Loss of forest cover & increase in impervious surface	Moderate intensity development, degree of permeability and amount of rainfall	BU_AC
Movemen	elow surfo					Low intensity development, degree of permeability and amount of rainfall	LI_AC
M			geology	Shift location of groundwater recharge Losses from water supply pipes, sewer lines, or septic drainfield discharges	Leaky pipes or irrigation canals Water supply and wastewater management	Utility lines Septic systems Unlined irrigation canals	

### Table B-3 continued

	Cor	nponent of	Major natural	Change to process	Cause of change	Indicators of degradation	Variable for
	0.	<u>p. 00000</u>		Change location of groundwater discharge	Interception of subsurface flow by ditches and roads	Road density	rd_den
Aovement	Below surface	Discharge & Sub-surface storage	Topography Surface geology	Decrease quantity of groundwater available for discharge	Groundwater pumping	Well locations and density, pumping rates and volumes	well_den
				Decrease groundwater inputs to aquatic resources	Loss of groundwater discharge areas	Land use type (urban/rural) in floodplains and wetlands	UUS, URS, SWU, SWR
		Evaporation	Climate	Alter evaporation rates	Change temperature and precipitation patterns		
		Transpiration	Vegetation Climate	Alter evapotranspiration rates	Land cover Clearing vegetation Shifting vegetation composition	Watershed imperviousness	IMP
Loss	s	Streamflow out of basin	Topography	Change streamflow direction	Diversions Interbasin transfers	Diversion structures	
		Groundwater flow out of basin	Topography Geology	Altering quantity and pattern of groundwater flow	Interbasin transfers Groundwater pumping Impervious surfaces Interception of subsurface flows	Baseflow trends Well locations, pumping rates and volumes	

### Delivery of Water - Degradation

Comp of pr	onent	Major natural controls	Change to process	Cause of change	Indicators of degradation	Variable for scoring
		Precipitation patterns	Change in runoff quantity & timing	Climate change		
Delive	ery	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	FL
Delivery Overland Flow		Precipitation patterns Soils	Change timing of surface runoff Decreased infiltration	Impervious areas Channelization of flows Filling and drainage of seasonally saturated areas	Watershed imperviousness Stormwater discharge pipes Drainage ditches in seasonally saturated areas Loss of seasonally saturated areas	IMP

### Precipitation patterns

A recent analysis of regional climate models (Rosenberg et al. 2010) found that although simulations generally predict increases in extreme rainfall magnitudes, the range of these projections is too large at present to provide a basis for engineering design. 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 [FL]

<u>Removal of forest cover in rain-on-snow zones:</u> 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.

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

*Identifying areas of degraded timing of snow melt:* Non-forested land cover in rainon-snow and snow-dominated zones.

## Timing of runoff in "rain dominated" zones

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

*Identifying areas of degraded timing of runoff:* Non-forested land cover in "raindominated" zones.

# Overland flow [IMP]

Impervious cover within a watershed decreases infiltration and increases overland flow. Seasonally saturated areas are degraded 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 degraded seasonally saturated areas. Determining degradation within saturated areas requires local data.

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

## At the Surface :

### Surface storage [UW, RW, UDS, MDS]

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)

С	Component of Major natural process controls		Change to process	Cause of change	Indicators of degradation	Variable for scoring	
					Draining or filling of depressional wetlands	Loss of depressional wetlands from rural and urban land use	UW, RW
ovement	he surface	Surface storage	Topography Surface	Decrease storage capacity Increase surface water velocity	Channelization of streams	Miles of degraded streams through unconfined & moderately confined floodplains	UDS, MDS
Mo	At		geology		Disconnection of stream from floodplain	Dikes and levees on stream reaches with floodplains	
				Increase storage & change timing of downstream flows	Dams	Dam storage capacity relative to size of watershed	dam_score

Drainage or filling of depressional wetlands (UW, RW): 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 degradation to wetland water regime.

**Identifying areas of degraded 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 degradation to wetlands.

<u>Channelization of streams (UDS, MDS)</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 degraded surface storage (channelization of streams):** Streams with adjacent urban and agricultural land cover will have a greater relative degree of degradation than streams with rural or natural land cover. Use analysis below for "disconnection of stream from floodplain."

<u>Disconnection of stream from floodplains (UDS, MDS)</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 degradation to floodplain storage can be attained. Section 5, Models for Degradation, discusses this method of analysis further.

*Identifying areas of degraded surface storage (stream disconnected from floodplain):* Streams within unconfined floodplains with adjacent urban and agricultural land cover will have a greater relative degree of degradation 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. Dams alter water flow processes by fundamentally changing the downstream timing and duration of stream flows, including the intra and inter-annual variation of hydrologic regimes

(Richter et al 1996). In turn, this affects other related watershed processes such as the delivery and movement of sediment and wood. Because these processes help form and maintain habitat structure in streams and their floodplains, changes to their natural patterns can impact species dependent on the habitat they sustain. Though dams have attempted to reduce their impacts by increasing water releases during low-flow periods and periodic releases to mimic natural flows, the documented impacts are substantial relative to other stream and floodplain impacts (e.g. channelization, road crossings).

The downstream effect of dams is dependent on: 1) the storage capacity of the dam relative to annual runoff generated by the watershed above a dam, and 2) the amount of runoff contributed to the stream system downstream of the dam. If a dam retains a significant fraction (or multiple) of the annual runoff of a watershed than it is reasonable to assume that dam has a very large effect on downstream processes, since it can theoretically impact the natural flow patterns over the entire year-long life cycle of stream biota. The analysis of potential dam effects, however, does not incorporate the actual operation of the reservoir (which can significantly influence downstream impacts).

Identifying areas of degraded surface storage (dams): Presence of dams.

## **Below the Surface**

Degradation to recharge and shallow subsurface flow are addressed by a series of variables that consider land cover type, permeability of the surficial deposits and precipitation. 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 (CCAP) satellite data to identify these three categories. Because different categories of land cover are available in the CCAP data 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)

The specific ways in which land cover change alters recharge and shallow subsurface flow are discussed below. The recharge coefficients and a recharge equation developed by Vacarro are used to capture the suite of land cover changes that effect recharge.

## Recharge and Shallow subsurface flow [U\_AC, BU\_AC, LI\_AC]

Three factors are likely to alter the quantity of water that flows subsurface through 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.

<u>Removal of soil</u>: 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).

<u>Impervious surfaces on permeable surface deposits</u>: Degradation 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.

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

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

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

<u>Removal of forest cover on low permeability deposits</u>: 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 degraded (or unstable) stream channels are associated with watersheds in which the 2-year peak flow that occurs under current conditions (Q <sub>2 developed</sub>) is greater than the 10-year peak flow (Q<sub>10</sub> forested) that occurs under natural conditions (Booth and Jackson 1997). 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 <sub>2 developed</sub> discharge can be maintained at less than the Q<sub>10 forested</sub> 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 degraded shallow sub-surface flows:* Non-forested vegetation on areas with geologic deposits of low permeability

Component of process		oonent of rocess	Major natural controls	Change to process	Cause of change	Indicators of degradation	Variable for scoring
ovement	iw surface	Recharge	Topography	Reduce recharge and increase	Loss of forest cover &	High intensity development, degree of permeability and amount of rainfall	U_AC
W	Belo		geology	runoff	surface	Moderate intensity development, degree of permeability	BU_AC

# Recharge [continued]

			and amount of rainfall Low intensity development, degree of permeability and amount of rainfall	LI_AC
	Shift location of groundwate r recharge Losses from water supply pipes, sewer lines, or septic drainfield discharges	Leaky pipes or irrigation canals Water supply & waste- water manage- ment	Utility lines Septic systems Unlined irrigation canals	

<u>Removal of forest cover on high-permeability deposits</u>: The Q<sub>2, developed</sub> can be maintained at less than the Q<sub>10, forested</sub> on deposits with lower permeability if 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 degraded 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 degraded recharge:* Non-forested vegetation on areas with geologic deposits of high permeability

<u>Impervious surfaces :</u> 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 degraded 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.

<u>Leaky utility lines, septic systems or irrigation canals</u>: 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 [rd\_den]

Component of Ma process		Major natural controls	Change to process	Cause of change	Indicators of degradation	Variable for scoring
Movement-	Vertical and lateral subsurface flow	Topography Surface geology	Change location of groundwater discharge	Interception of subsurface flow by ditches and roads	Road density	rd_den

Interception of subsurface flow by ditches and roads (rd\_den): 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<sup>2</sup> 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/km<sup>2</sup> and vegetative cover consisting of >50% immature vegetation (Beamer 2000).

*Identifying areas of degraded 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 [well\_den]

	Component of process		Major natural controls	Change to process	Cause of change	Indicators of degradation	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	well_den

<u>Groundwater pumping</u>: 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 degradation 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.

Component of Major nate process control		Major natural controls	Change to process	Cause of change	Indicators of degradation	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	UUS, URS, SWU, SWR

# Discharge [UUS, URS, SWU, SWR]

Degradation 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 degrade 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. The degradation 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 degraded discharge:* The extent of urban and rural development within or adjacent to wetlands and floodplains.

### Loss of Water

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

### Evaporation and transpiration

Evaporation and transpiration are degraded 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 degraded evaporation and transpiration: Impervious surface cover within a watershed.* 

### Streamflow out of basin

Natural patterns of water loss from a watershed can be degraded 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

Degradation 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 a non-degraded setting. Model 2 scores the **relative severity of degradations** to the process in those analysis units.

The section on <u>Methods</u> explains **"why"** we use these analyses.

# Model 1 : Important Areas for the Water Process



# Important Area for 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 +Subsurface flow + Recharge +Discharge)] + (Evapotranspiration)

In Western Washington the assumption is that all hydrologic units have approximately the same rate of evapotranspiration in non-degraded 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 +Subsurface 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, as a regional average, runoff constitutes 20%, recharge 37% and evapotranspiration 44% of the total water balance. 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 =  $[W_{H1} (Precipitation + Timing of Water Delivery] + [W_{H2}(Surface storage) + W_{H3} (Sub-surface flow + Recharge + Discharge)]$ 



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 + RS.

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:

$$P = \sum PA_n / Analysis Unit Area$$

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<sub>normalized</sub> = avr\_prec <sub>subunit</sub>/Maximum Value for analysis units

## RS – 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-onsnow 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 degradation section (HI-1). The equation for the timing of water delivery variable is:

**SRS\_pct** (Importance of Rain-on-Snow & Snow-Dominated Zone) = (<u>Area of RS + Area of SD)</u> \* 100 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 **SRS\_pct** for all analysis units within a landscape group as follows:

RS = SRS\_pct/Maximum value for analysis units



### Surface Storage

Variables in Model 1

Surface storage is modeled as the importance of the relative area of depressional wetlands and Lakes (WLS) in a analysis unit + the importance of the relative miles of different widths of the floodplains in a analysis unit (STS). The equation is: Surface Storage = WLS + STS). Depressional wetlands, lakes 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.

WLS - Score for Wetland/Lake Storage

Total possible score is 1.

**dpwt\_pct**(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:

**dpwt\_pct =** <u>Area of Depressional Wetland in analysis unit</u>\* 100 Total area of analysis unit

**lk\_pct** (Relative Importance of Lake Storage) is based on the percentage of analysis units covered by lakes. The equation for the lake storage variable is:

*lk\_pct = <u>Area of Lakes in analysis unit</u> \* 100* Total area of analysis unit

We sum the results of the two variables together:

wt\_lk = dpwt\_pct + lk\_pct

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

WLS = wt\_lk/Maximum value for analysis units

# STS- 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 at least 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.

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

**UNSS** = <u>Miles of Stream in Unconfined Floodplain in analysis unit/ sqmi</u>\* (3) Area of analysis unit

**MCSS** 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 **MCSS** variable is:

**MCSS** = <u>Miles of Stream in Mod Conf floodplain in analysis unit / sqmi</u>\*(2) Area in analysis unit

We sum the results of the two variables together:

UN\_MC = UNSS + MCSS

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

STS = UN\_MC Maximum value all analysis units

Recharge and Discharge



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 =  $I_R + I_DI$ .

Total possible score is 2.

# I\_R - Score for Recharge

Total possible score is 1.

The importance of recharge (**I\_R**) 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:

IR= <u>Recharge for Course Grained Deposits (rechH) + Recharge for Fine Grained Deposits (rechL)</u> Area in Analysis Unit

Where:

Recharge Course Grain Deposits (rechH) = [(aver\_precip x .838) – 9.77] x Area of high perm

Recharge Fine Grained Deposits (rechL) = [(aver\_precip x .497) - 5.03] x Area of low perm

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 **IR** for all analysis units within a landscape group as follows:

**I\_R** = IR value for analysis unit/Maximum value for analysis units

# I\_DI - Score for Floodplains and Wetlands

(Discharge)

Total possible score is 1.

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.

**ucHp\_mi** is created by the intersection of permeable deposits with unconfined floodplains.

The equation for the floodplain discharge variable is as follows:

ucHp\_area = Miles of streams & rivers in permeable deposits of unconfined floodplains (ucHp\_mi) 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 **ucHp\_area** for all analysis units within a landscape group as follows:

**SD** = ucHp\_area/Maximum value all analysis units

**SWD** – 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

slpwt\_pct = area of potential slope wetlands (slpwt\_ac) \*100
Total area of analysis unit

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

**SWD** = slwt\_pct/Maximum value all analysis units

We sum the results of the two discharge calculations as follows:

**IDI** = SD + SWD

Importance of discharge (I\_DI) is modeled based on two types of indicators: stream and river floodplains (SD) and wetlands (SWD). The equation for the importance of discharge is:

Importance of Discharge (I\_DI) = IDI/ Maximum value of all analysis units

# Model 2 : Degradation to Water Process<sup>2</sup>



**Figure B-11. Diagram of the equation for calculating the level of degradation 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.

Degradation to water processes are modeled as:

Degradation to Delivery + Degradation to Movement + Degradation to Loss

Degradation to delivery addresses changes to areas that control the timing of snow melt. Degradation 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. Degradation to loss is modeled by the amount of impervious surface in the analysis unit. Precipitation is not included in the Degradation model because it is assumed that this component has not been changed by land uses.

Model 2 =(degradation of timing of delivery)+ [(degradation of overland flow + degradation of surface storage)+(degradation of areas for recharge + degradation of

<sup>&</sup>lt;sup>2</sup> Does not include degradation by dams; see Model 3.

subsurface flow + degradation of discharge areas)] + (degradation of evapotranspiration)

It is recommended that the same weighting factors applied in Model 1 be applied to Model 2. For the Puget Sound Characterization, 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 =  $W_{H1}$ (Degradation to Timing of Water Delivery) + [ $W_{H2}$ (Degradation to Overland Flow +Degradation to Surface Storage) +  $W_{H3}$ (Degradation to Recharge +Degradation to Subsurface flow+Degradation to Discharge)] +  $W_{H4}$ (Degradation to Evapotranspiration)

## Degradation to Water Delivery

$W_{H1}\left[\frac{IMP + FL}{Max \ Value}\right]$	$W_{H2} \left[ \frac{D_WS}{Max \ Value} + \frac{D_STS}{Max \ Value} \right] +$	$W_{H3} \left[ \begin{array}{c} \underline{D}_{R} \neq \underline{D}_{DI} \\ Max \ Value  Max \ Value \end{array} \right]$	+ $W_{H4}\left[\frac{IMP}{MV}\right]$

Variables in Model

# FL- Score for Degradation to Timing of Delivery

Total possible score is 1.

The severity of degradation to water delivery is modeled as the relative loss of forest (fl\_pct). The equation is:

Fl\_pct is the score for the relative degradation 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 **fl\_pct** for all analysis units as follows:

FL = fl\_pct/Maximum value for analysis units.

## IMP- Score for Degradation to Overland Flow

Total possible score is 1

The severity of degradation 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:

We normalize the results of **imp\_pct** for all analysis units as follows:

IMP = imp\_pct/Maximum value for analysis units.

### Degradation to Surface Storage





We model the degradation to surface storage as the loss of storage in wetlands and streams.

# *D\_WS – Score for Degradation to Storage in Wetlands*

Total possible score is 3 prior to normalization.

Degradation 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:

UW+RW (Severity of Degradation in Surface Storage) = relative loss of storage in wetlands

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

A degradation factor of 3 was assigned to degraded 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 degradation areas are assigned a degradation value of 2.

UW (loss of storage wetlands in urban areas) = <u>Area of storage wetlands lost in urban</u> \*3 Total area analysis unit

**RW** (loss of storage wetlands in rural areas) = <u>Area of wetlands lost in agricultural and rural area</u> \*2 Total area in analysis unit

We normalize the results of **UW** + **RW** for all analysis units as follows:

**D\_WS** (Wetland Storage Degradation) = **UW** + **RW**/Maximum value for analysis units.

# D\_STS – Score for Degradation to Storage in Floodplains

Total possible score is 3 prior to normalization.

Degradation 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:

## UDS + MDS (Severity of Degradation in Surface Storage) = relative loss of storage in floodplains

Modeling the severity of loss of storage in floodplains (UDS + MDS)

UDS = <u>Miles of channelized stream in **unconfined** floodplain</u> \*3 Total area in analysis unit

MDS = <u>Miles of channelized stream in **moderately confined** floodplain \*2 Total area in analysis unit</u> Degradation 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 **UDS** + **MDS** for all analysis units as follows:

D\_STS = **UDS** + **MDS**/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.

# Degradation to Recharge



Variables in Model

# *D\_R– Score for Degradation to Recharge*

Total possible score is 1

DR (Severity of Degradation to Recharge) = Loss of recharge

Loss in Recharge = Recharge Coefficient x Total Recharge

Where: Total Recharge = R Recharge Coefficient = <u>Area of Land Use Cover Type x Reduction Coefficient</u> 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 **DR** for all analysis units (except for high density urban - > 90% developed- which is automatically assigned the maximum score for degradation) as follows:

D\_R = **DR**/Maximum value for analysis units.



# D\_DI- Score for Degradation to Discharge

Degradation to discharge is modeled as the relative degradation from roads (intercepting shallow groundwater flow), wells (decreasing discharge through groundwater pumping) and the degradation from urban and rural land use activities on floodplains and slope wetlands (areas of groundwater discharge).

Severity of Degradation to Discharge = R\_RD + R\_WEL + R\_STD + R\_WD

**D\_RD** is the severity of degradation resulting from roads and their associated drainage system (ditches and culverts) which intercept subsurface flow and convert it to surface flow. D\_RD applies to roads of all classes. The maximum score for D\_RD is 1.

rd\_den = <u>miles of roads</u> analysis unit in sq. miles

We normalize the results of **rd\_den** for all analysis units as follows:

D\_RD = **rd\_den**/Maximum value for analysis units.

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

Severity of Degradation to Discharge by Wells = D\_WEL

well\_den = <u>Density of Class A and B wells</u> Area of analysis unit

We normalize the results of **Degradation to Discharge by wells** for all analysis units as follows:

D\_WEL = well\_den / Maximum value for analysis units.

**D\_STD** is the severity of degradation to discharge in floodplains with deposits of high permeability resulting from urban and rural development. It is modeled as the miles of unconfined streams or rivers within either areas of urban or rural land use. The maximum score for D\_STD is 1.

Severity of Degradation to Discharge in Floodplains (D\_STD) = (UUS + URS )

UUS (Higher perm deposits intersect =Miles of urban unconfined streams in higher perm deposits \* 3unconfined urban floodplain )Total area of analysis unit

Higher permeable deposits within unconfined **urban** floodplains are assigned a degradation factor of 3. This higher factor was applied since urban floodplains typically have a greater degree of degradation 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.

URS (Higher perm deposits intersect = <u>Miles of rural unconfined streams in higher perm deposits</u> \* 2 unconfined **rural** floodplain) Total area of analysis unit

Deposits of higher permeability within unconfined **rural** floodplains are assigned a degradation factor of 2. This factor was applied since rural floodplains typically have a lesser degree of degradation relative to urban floodplains. Degradation 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 **Degradation to Discharge (D\_STD)** in floodplains for all analysis units as follows:

D\_STD = <u>(UUS + URS)</u> Maximum value for analysis units.

**D\_WD** is the severity of degradation to discharge in slope wetlands. It is modeled as the area of potential slope wetlands within either areas of urban or rural land use. The maximum score for D\_WD is 1.

Severity of Degradation to Discharge in Slope Wetlands = (SWU + SWR )

SWU (Slope wetlands in urban land use) = <u>Area of slope wetlands within urban land use</u> \* 3 Total area of analysis unit

Slope wetlands within areas of **urban** land use are assigned a degradation factor of 3. This higher factor was applied since urban slope wetlands typically have a greater degree of degradation 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.

**SWR** (Slope wetlands in rural land use ) = <u>Area of slope wetlands within rural land</u> \* 2 Total area of analysis unit

Slope wetlands within areas of **rural** land use are assigned a degradation factor of 2. This factor was applied since rural slope wetlands typically have a lower degree of degradation 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 **Degradation to Discharge for slope wetlands (D\_WD)** for all analysis units as follows:

D\_WD = <u>(SWU + SWR)</u> Maximum value for analysis units. Degradation to Loss  $W_{H1}\left[\frac{IMP + FL}{Max \ Value}\right] + W_{H2}\left[\frac{D_{WS} + D_{STS}}{Max \ Value}\right] + W_{H3}\left[\frac{D_{R} + D_{DI}}{Max \ Value}\right] + W_{H4}\left[\frac{IMP}{MV}\right]$ Variables in Model

### IMP – Score for Degradation to Evapotranspiration

Total possible score is 1.

The severity of degradation to evapotranspiration is modeled as the relative amount of total impervious surface present in the analysis unit.

Change in ET = imp\_pct

IMP is calculated as "D\_L":

D\_L = 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 natural conditions (i.e. prior to European settlement). The score is based on the assumptions that: the basin was 100% forested prior to human degradation; that maximum evapotranspiration occurred when natural conditions were present relative to degraded 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:

imp\_pct = Acres of impervious cover \* 100
Total area of analysis unit

We normalize the results of **Degradation to Evapotranspiration (D\_L)** for all analysis units as follows:

D\_L = imp\_pct/Maximum value for analysis units.

# Model 3 : Degradation to the Water Process by Dams

The severity of degradation to water flow processes by dams is modeled as 1) the storage capacity of the dam relative to annual runoff generated by the watershed above a dam; and 2) the amount of unregulated runoff contributed to the stream system downstream of the dam. The AU Dam Score is represented in depth of feet of storage across an AU(s). For Puget Sound this can range from less than a foot to more than 5 feet in depth.

$$AU \ Dam \ Score_n = SD \ \div \left(A \ dam + \sum_n A_{AU}\right)$$

SD = the storage volume of the dam in acre feet.

A<sub>dam</sub> = the watershed area impounded above the dam in acres.

 $A_{AU}$  = the unregulated watershed area in acres for an AU(s) below the dam that drains to the regulated stream. Depending on point downstream that the dam score is calculated, all upstream AUs would be included in this term, except the AUs above the dam.

The AU Dam Score can be calculated for any point downstream (the downstream "pour point" of an AU).

A dam that captures greater than 4 feet of runoff, which is roughly equivalent to 100% of annual precipitation for most parts of the Puget Sound region, has the potential to significantly change downstream hydrologic regimes (Booth, personal communication). A dam that captures between 1 to 4 feet of runoff (equivalent to about 20-100% of annual precipitation in most parts of the Puget Sound region) is represented to have a moderate potential impact. Less than 1 foot of runoff represents a low potential impact. It should be noted that the *actual* downstream consequences will depend largely on the actual operation schedule of the dam, which is not incorporated into this analysis.

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