A Hydrologic Perspective of Implications of Clearcutting on a Forested Slope Wetland

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Abstract

This project seeks to determine the need for wetland protection by indirectly estimating the hydrologic effects of forest harvesting and the resulting rise in the water table level for a forested, slope wetland in western Washington. Differences between large and small storm wetland response will provide insight into what may happen after clearcutting of the basin feeding this wetland. Hourly precipitation and water level changes were recorded from eight wells. Quiver plots indicate that direction of flow in the wetland after large storms was only slightly different than after small storms, suggesting that topography is the dominant factor in determining hydraulic gradients. Travel times of five preferential flow paths of water through the wetland were quantified to estimate the residence time of water after large and small storms by a cross correlation analysis of the timing of water level changes. Velocities were determined by dividing distances between wells by travel times. Only one of the five flow paths indicated a significant difference in velocity following large and small storms, each of the estimated velocities an order of magnitude larger than saturated hydraulic conductivities of similar substrate of other studies. The presence of several inundated wells serves to skew the predicted groundwater direction and velocities allowing for an accurate portrayal of flow through the wetland only in the absence of surface flow. Because groundwater gradients and their corresponding velocities are not significantly different after large and small storm events, the rate of flow through the wetland does not change with different sized. This quick, coordinated groundwater response throughout the wetland further supports the fact that gravitational flow, dictated by elevation gradients, is the main energy gradient for water movement in areas of high relief like the Pacific Northwest.

Table of Contents

List of Figures

List of Tables

Introduction

In the Pacific Northwest, forested wetlands cover a significant part of the landscape. They account for 13.7% of the wetland acreage on the Pacific coast (USDA 1992). These areas and the surrounding lands represent large potential for wood production. In Washington alone, 1,520,000 acres of forested lands are in timber production (WADNR 96-911). Because of the high productivity of the region and the importance of forestry, it is crucial to adequately protect these valuable resources. Further understanding the characteristics and functioning of forested wetlands is important to the continued healthy function of the northwest ecosystem.

Wetlands are often located where there are exchanges between groundwater and surface water. Wetlands form a link between terrestrial upland systems and lotic ecosystems, where groundwater and surface water hydrology are inseparable. Groundwater is often the principle hydrologic component of the wetland if it is influenced by intermediate to regional scale systems (Siegel 1988). Slope wetlands, or seeps, in western Washington can occur in areas of high relief, and are often found in groundwater discharge zones where impermeable substrate layers yield persistent surface saturation. They can be seasonally or permanently saturated depending on the source of groundwater, which is controlled by geology, topography, and material permeability (Freeze and Witherspoon 1967).

When slope wetlands occur as part of the headwaters of streams, they are most important in maintaining seasonal streamflow by detaining stormwater for future discharge (Freeze 1972). The performance of this valuable function may be critical to salmon habitat in fostering variable, bur moderate flows, cool, well-oxygenated water, and relatively sediment-free streambed gravel (Peterson 1982). Other important common wetland functions in the Pacific Northwest include groundwater exchange, sediment trapping, water purification, fish and wildlife habitat, and sources of significant primary productivity. These functions are often compromised when forestry activities remove much of the vegetation from the surrounding upland area feeding these wetlands. The study of wetlands and their changing wetland function is critical in order to provide effective and efficient protection.

Despite a relatively rudimentary understanding of Pacific Northwest wetland hydrology, several studies of the Southeast and Lake States provide pertinent information. Wetlands are a primary part of the permanent soil and groundwater hydrology of forests on many watersheds. Their influence on stream hydrology is well understood. Specifically, wetlands contribute to low flow augmentation by storage of water and subsequent discharge to soil interflow or direct contribution to streams or groundwater (Winter 1988; Waddington et al. 1993). Wetlands additionally serve to dampen stormflow and store the water for future discharge (Richardson 1994).

Jacques and Lorenz (1988) empirically derived equations predicting stream flow and found that storm flood flows are inversely proportional to the amount of the watershed area in wetlands and lakes. In other words, watersheds with few wetlands have a disproportionately large impact on reducing floodflows. In addition, wetlands slow water flow to allow sediments to precipitate or adhere to vegetation.

In most watersheds, wetlands have profound influences on hydrology and water quality, but the hydrologic impacts of clearcutting and other forest management activities are poorly understood, especially in respect to forested wetlands. The responsive rise in the water table is well documented for low relief, or non-mountainous, regional topography after cutting operations in the surrounding upland area (Williams and Lipscomb 1981, Teskey and Hinckley 1977), but it is poorly understood in higher relief areas like the Pacific Northwest. Elevated water tables can cause plants in and nearby the wetland to be stressed, often resulting in decreased growth and even death. The ability of the plant to withstand these rises depends on many factors, including plant species, water level, duration of flooding, and time of year.

Impacts of forest management on forested wetlands from drainage modifications, like rutting of soil from ground traffic and skidding of logs, and reductions in vegetation result in increased total runoff and shorter residence time for the water in the watershed (Skagg et al. 1991). Clearcutting removes the entire tree canopy in a single operation and creates a dramatic decrease in evapotranspiration (ET) and canopy interception. This often causes the water table to rise substantially, resulting in increased total and peak flows (McCarthy and Skaggs 1992).

Western Washington receives an annual average of close to 100 inches of precipitation, 80 % if which happens in December and January. Frequent floods combined with higher water tables can contribute greatly to drainage channelization. In wetlands, channelization of outflow often results in more rapid storm discharge resulting in the increased potential for channel eroding events downstream, which causes reductions in water storage and discharge during critical summer low flow stream periods.

Despite the lack of understanding of these systems, protection for them must be implemented in the face of increased demand for wood products. Wetlands are most often protected by buffers, which serve important functions such as filtration from sedimentation and the regulation of flow velocity. They also serve to maintain wetland hydrology, protect habitat, and regulate the microclimate temperature and moisture fluctuations by providing windbreaks and shading. Brinson (1993) states that riparian buffer strips adjacent to headwater sources are a critical first step in the movement of water from uplands to streams. The erosion resistance of the above and below ground portions of buffers help stabilize the saturated soils of the wetland from possible slope failures and other soil movement.

Currently, in the state of Washington the Forest Practice Rules (WAC 222-016-010) and the Habitat Conservation Plan (HCP 96-911) describe the protection of forested wetlands. Wetlands larger than 1 acre shall have a buffer width approximately equal to the site potential height of trees in a mature conifer stand or 100 feet, whichever is greater. This protection was chosen without any scientific support detailing the hydrology of forested wetlands or the success of buffer strips. It will never be known if this protection is appropriate without a firm understanding of the hydrologic characteristics of forested wetlands.

This project will provide information about the hydrology of forested wetlands that will be useful in determining the need for wetland protection. The effects of forest harvesting, namely derived form the increase in water table level, will be estimated indirectly for a forested wetland in Washington. It is the preliminary portion of a long-term project conducted by the Washington State Department of Natural Resources to determine how the hydrology of this forested wetland changed with an intensive clear-cut around the wetland. This study serves as the pre-treatment study in order to estimate the normal direction and velocity of water flow through the wetland. Magnitude of the flow will be estimated from travel times through the wetland. The reaction of the wetland to small storms will be compared to large storms by examining water level changes, which allow for the determination of differences in water velocity and travel time. Differences between large and small storm wetland response will provide insight into what may happen after clearclutting of the basin feeding this wetland. If groundwater increases are significant enough, small storms could be interpreted as large storms by the wetland. The hypothesis is that the rate of water from different sized storms travels differently through this forested, slope wetland, in turn providing insight into how increases in the groundwater level from losses in evapotranspiration will affect the wetland.

Methods

Site Description

The forested wetland study site is located in the headwater area of the Bockman Creek Basin in the Soleduck River Watershed on the northwest part of the Olympic Peninsula of Washington state (48° 02’ N, 124° 14’ W, elevation 1,150 feet as estimated by 15’ USGS topographic map). The mini-basin feeding the wetland site in approximately 0.15 km^2; the canopy dominated by Sitka Spruce (*Picea sitchensis*), Douglas-fir (*Pseudotsuga menziesii*), and Western Hemlock (*Tsuga heterophylla*), with some Western Red Cedar (*Thuja plicata*). The same community is found in the wetland, however Western Red Cedar and Western Hemlock, despite being stunted by inundated soils, are in highest abundance. The upland soil is primarily glacial till and characterized as Ozette silt loam (Medial, mesic Andaquic Haplumbrepts). According to the Clallam County Soil Survey, it is a deep, moderately well drained soil on hills with permeability between 0.6 and 2.0 in/hr, available water capacity between 0.12 and 0.21 in/in, and organic matter between 5 and 15 %.

The forested wetland site is approximately 1.25 acres; the top two feet of substrate consisting of partially decomposed organic matter characterized as a peaty histosol underlain by an impermeable clay layer. The wetland and nearby upland area can be seen in Figure 1, which was surveyed at 2 meter increments by an Impulse laser rangefinder from Laser Tech, Inc. The survey was done along eight parallel transects following a southwest to northeast orientation that is aligned with the transverse axis in Figure 1. One transect through the middle of the wetland was done that followed the longitudinal axis in Figure 1, or from the northwest to the southeast. The upland slopes approach 30 % above the wetland, meeting the wetland at the southwest edge. After becoming roughly horizontal at the wetland site, the slopes continue downhill after a lip of about 1.5 meters higher than the lowest point in the wetland with the same relief beginning at the northeast edge. Water is delivered to the wetland by two seeps at the southwest (uphill) edge where groundwater becomes surface flow. The water stored here is released by surface flow when present at two outlets on the north and east sides. These two surface outlets drain the water in the wetland to two first order streams running downhill towards the northeast.

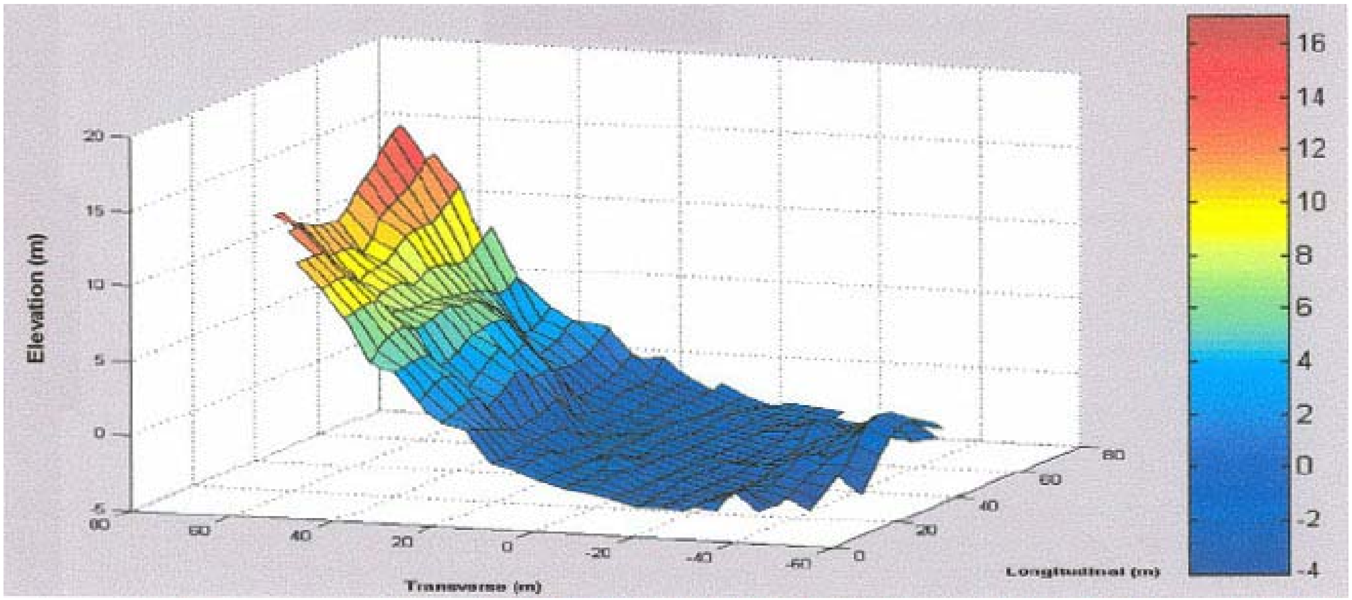

Figure 1. Wetland study site and surrounding upland area. The wetland lies at the foot of the 30 % slope, below 3 meters on the upland side and below 1 meter on the lower side. The color bar units are in meters relative to the first transect surveyed along the longitudinal axis at 0 on the transverse axis.

Eight temporary groundwater wells made of slotted 3 inch PVC pipe were monitored to determine maximum and minimum water levels from June 14, 1999 through August 4, 1999. No well indicated water levels to be greater than 10 inches from the soil surface during this time, and water was fluctuating up to 8 inches. As a result of this high water table, eight automated WL-40 groundwater wells from Remote Data Systems, Inc. were installed throughout the wetland at least 24 inches into the soil. The locations of the wells are labeled in Figure 2, which indicates the seeps at wells 1 and 8 on the uphill side and the seasonal surface flow outlets at wells 2 and 6. The wells recorded hourly groundwater levels to 0.1 inch from October 7, 1999 through January 31, 2000 and were downloaded by infrared every two weeks with a HP48 calculator.

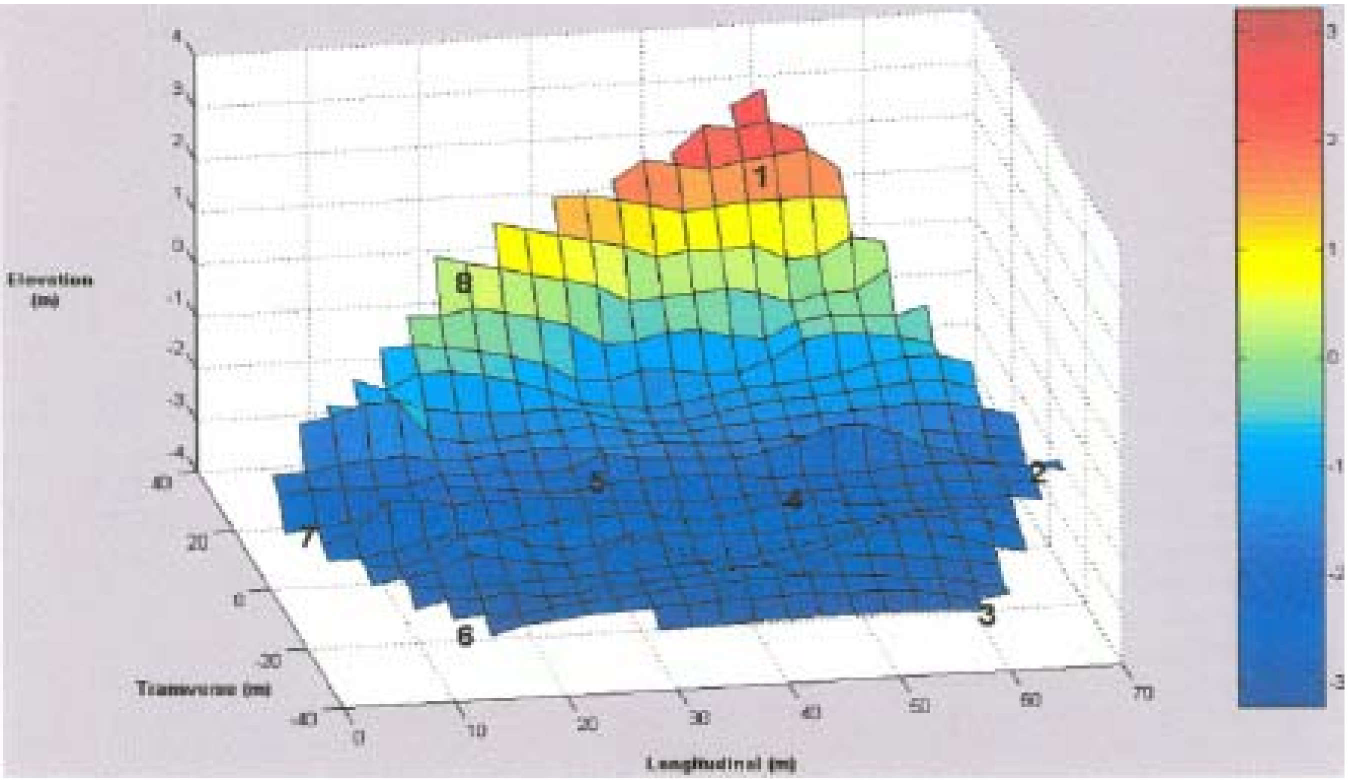

Figure 2. Vertically exaggerated topographic map of the wetland site. Wells 2 and 6 are seasonal surface outlets, and wells 1 and 8 are seeps.

Precipitation

The climate is greatly tempered by winds from the Pacific Ocean. Table 1 shows precipitation data for Sappho weather station located 1.4 miles northeast of the study site (48° 04' N, 124° 15' W, elevation 750 feet as estimated by 15' USGS topographic map) and Quillayute weather station located 24 miles east of the study site (47° 57' N, 124° 33' W, elevation 250 feet as estimated by 15' USGS topographic map). Hourly rainfall data from October 7, 1999 through February 1, 2000 to the 0.01 inch was used from the Quillayute weather station because Sappho weather station stopped collecting data in 1997. To assess whether a bias may occur, a double mass analysis was performed and is described next.

Table 1. Periods of record average monthly precipitation for Sappho 8E, Washington (NOAA station # 457319, period of record 1941-1997) and Quillayute WSCMO AP, Washington (NOAA station # 456858, period of record 1966-2000).

Sappho	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Average total precipitation (cm)	33.4	30.2	24.3	18.0	10.1	6.6	4.9	5.8	10.1	23.9	35.3	39.1	241.6
Average total snowfall (cm)	21.8	6.6	8.6	0.3	0	0	0	0	0	0	2.0	9.1	48.8
Quillayute													
Average total precipitation (cm)	37.0	31.2	28.0	19.7	13.2	8.3	5.7	6.7	11.7	26.5	37.1	38.6	263.8
Average total snowfall (cm)	12.4	7.1	3.8	0.8	0	0	0	0	0	0	2.5	6.9	33.8

The cumulative records and daily totals, especially when considered during the time of the study, for Quillayute and Sappho weather stations were not excessively different. According to Table 1, 54.5 % of the total annual rainfall on average occurred in October, November, December, and January at Sappho weather station while 52.8 % if the total annual rainfall occurred in the same time period at Quillayute weather station. Cumulative rainfall data was calculated for Quillayute and Sappho weather stations for their shared periods of records from August 1996 to June 1997, as seen in Figure 3. Quillayute received 304,293 inches while Sappho received 288,247 inches for the same record. These cumulative records combined with total daily records indicated no distinct difference in the amount or timing of rainfall records between the two weather stations.

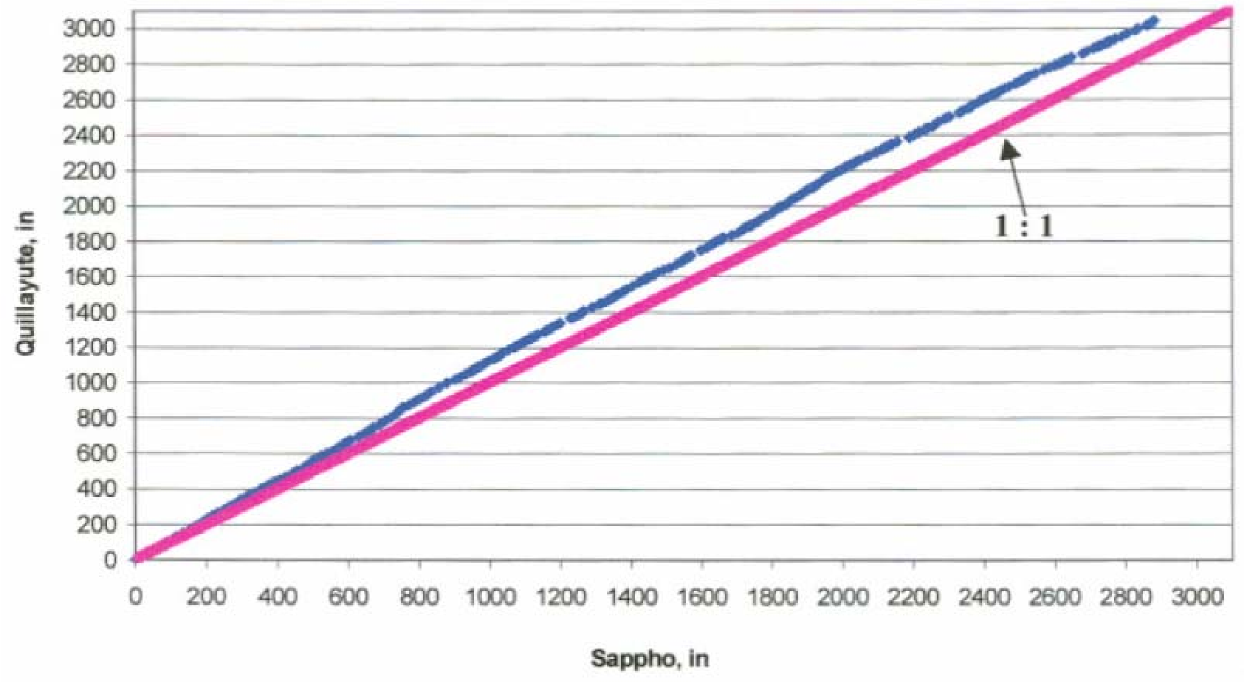

Figure 3. August 1996 to June 1997 cumulative rainfall records for Sappho and Quillayute weather stations.

Results

Groundwater and Precipitation

Figure 4 indicates groundwater hydrographs for each of the eight wells installed in the wetland for the period of December 3 at 14:00 until February 1 at 10:00. Figure 5 indicates the precipitation hydrograph from Quillayute weather station for the same period.

Data Preparation

Storms were partitioned by maximum intensity instead of by total precipitation per storm because of the widespread frequency of long, drawn out, low intensity storms, especially in the winter. Groundwater response was aligned with each storm, and storms were broken up into large and small events, according to a 0.5 cm/hr intensity threshold, estimated to be the

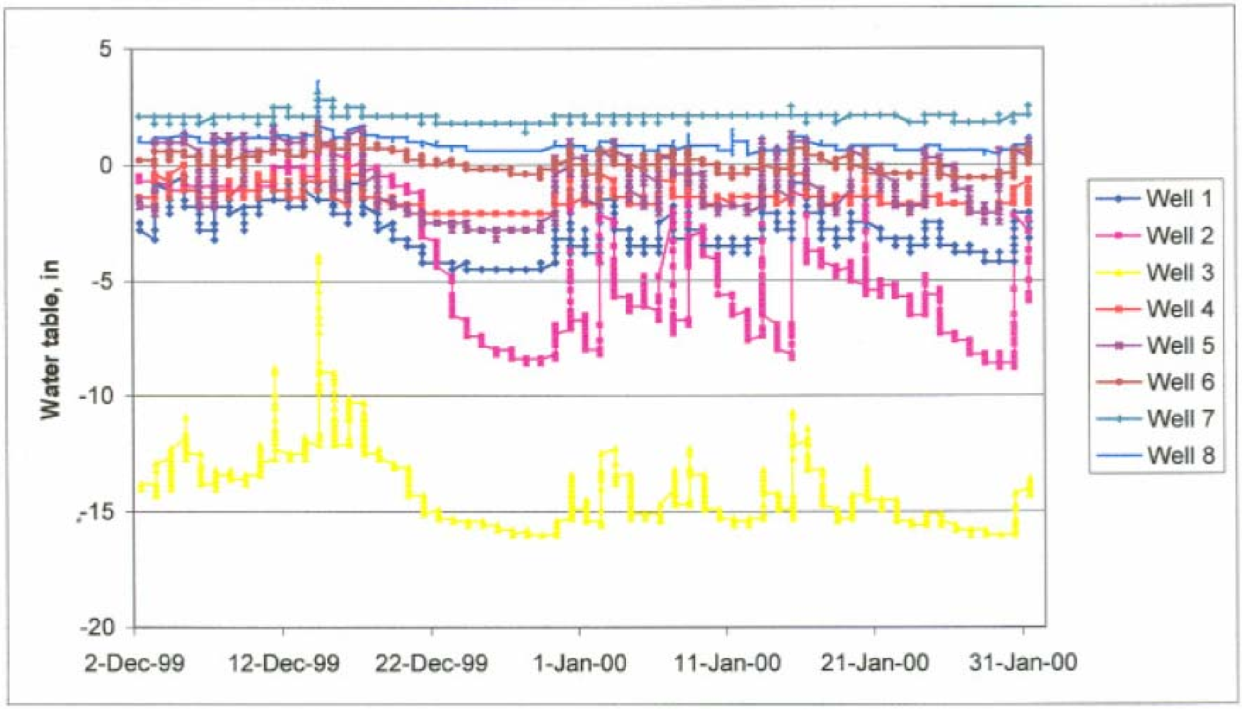

Figure 4. Groundwater hydrographs fore each of the eight wells from December 3 at 14:00 until February 1 at 10:00.

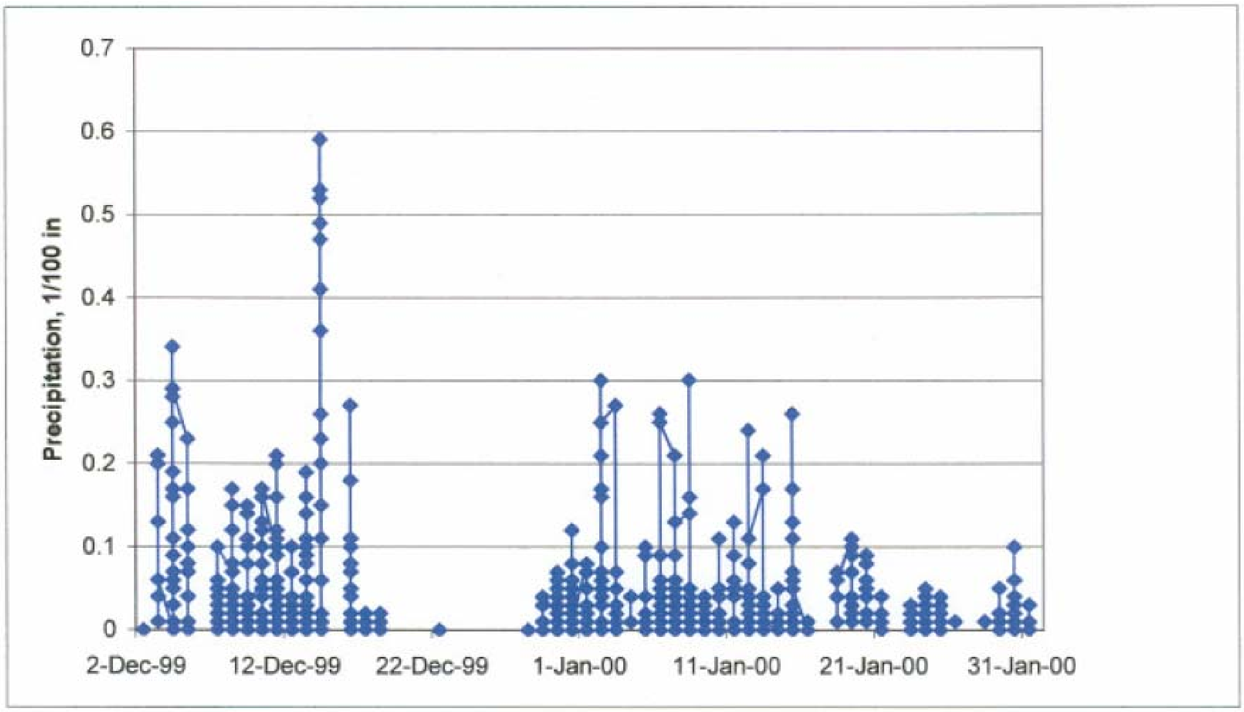

Figure 5. Precipitation time series for Quillayute weather station from December 3 at 14:00 until February 1 at 10:00.

maximum likelihood value of 0.5 of maximum precipitation intensity per storm. Table 2 indicates statistics of storms and water table responses for large and small storms. Storms between large storm events were considered to be small because of the nature of small storms. This method allows for the observation of the rising water table, or "watering up", as well as the falling water table, or "drying down". The composition of large and small storms is significantly different, as are the responses of the water table to each type of storm. Because water is delivered in greater amount and intensity with large storms, greater responses of the water table occur in terms of average rise, percentage of wells flooded, and number of wells newly flooded with each storm. In terms of duration flooding, five wells flooded at one time or another. From December 3 at 14:00 until February 1 at 10:00, well 2 was flooded for 50 hours, well 5 for 502 hours, well 6 for 927 hours, and wells 7 and 8 each for all 1,417 hours that data was reliably collected for all wells.

Table 2. Precipitation even and water table statistics of large and small storms.

	Large	Small
Storms, cm/hr	> 0.50	< 0.50
Events	17	12
Average maximum intensity, cm/hr	0.75 ($p<0.001$)	0.15
Water table rise, cm	4.20 ($p<0.001$)	0.73
Wells flooded, %	50.2 ($p<0.001$)	44.3
New wells flooded with each storm	0.96 ($p<0.001$)	0.28

Qualitative Analysis

After each storm, groundwater levels were interpolated between wells at 625 points throughout the wetlands, spaced 2.19 m on the longitudinal axis and 2.58 m on the transverse axis. From these water levels, vector plots indicating direction and magnitude of water flow were determined at each point by estimating a three dimensional gradient with Darcy's Law, comparing the adjacent water levels in the longitudinal and transverse direction. Figure 4 is a vector plot for typical large and small storms. Groundwater flow is generally toward well 3 after both large and small storms. It is important to note that the wider the contours, the shallower the gradient and the shorter the vectors. Small storms typically cause shallower gradients to occur in the wetland. The difference from large storms can be determined by examining the coincidence of the same contour looping between wells 1 and 2 as that between wells 4 and 5. Well 1 is

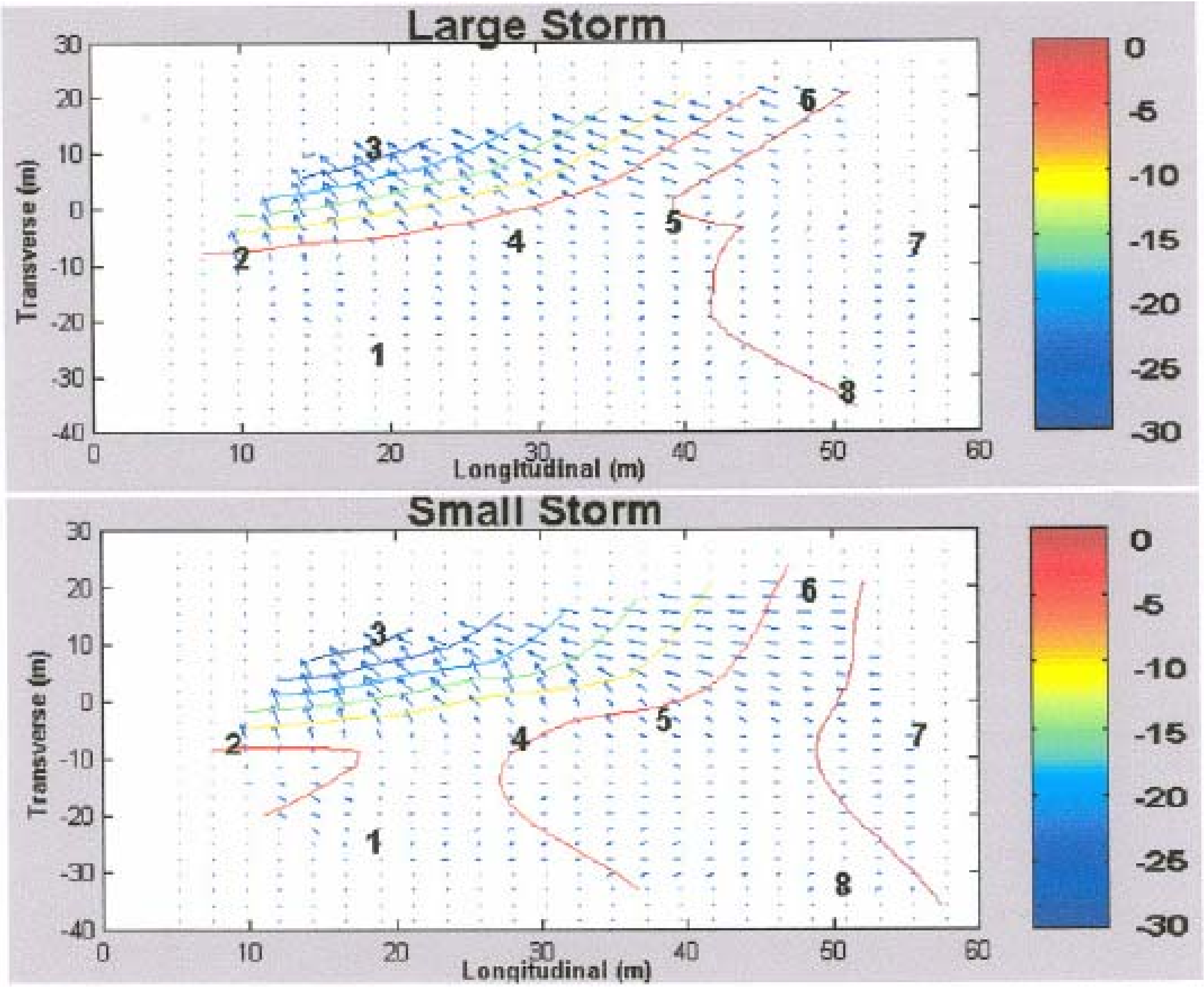

Figure 3. Quiver plots for typical large and small storms with well locations. Contours indicate water levels, and vectors indicate magnitude and direction of flow. Longer vectors indicate larger flux.

located near the low point in relation to the surrounding water levels, indicating a stagnant area with minimal flow near well 1. A similar area of low flow develops near well 1 after large storms, but there is no development of the trough phenomenon as develops after small storms.

Quantitative Analysis

Aside from demonstrating differences in large and small storm response, the vector plots indicate preferential flow paths in the wetland. Examining the general direction of the vectors throughout the wetland between wells, it was determined that five routes are important to examine to estimate travel time: well 1 to well 2, well 4 to well 3, well 5 to well 4, well 5 to well 3, and well 7 to well 5. We will quantify the travel times within the wetland to further investigate the residence time of water. The longer the travel time, the longer the residence time of water molecules in the wetland.

Travel time is determined by examining the timing of water level changes in response to a storm. If the water is known to flow from one well to another and the level in the first well begins to change before the level in the other well, there is a lag in the response. Cross correlation (*CC*) analysis was used to determine lag time between wells for each of the above five routes for each storm using the following equation:

$$CC(\tau) = \frac{\overline{y_1'(t_i+\tau)\cdot y_2'(t_i)}}{\sigma_{y1}\cdot\sigma_{y2}}$$

The maximum cross correlation was determined for hourly intervals where y_1 and y_2 are two variables, t_i is time, primes denote fluctuation from the mean state, and overbar denotes averaging, with $y_1' = y_2' = 0$, and σ is the standard deviation across paths identified from Figure 3. The routes were examined for numerous storms, as indicated by the subscripted primes.

Table 3 illustrates the composite lag, or travel times for each route for the period of record for which all eight wells were fully functional, from December 4 through February 1. It also lists the travel velocity of water traveling the same route, computed by dividing well distance by the appropriate composite lag time. The only significant difference in lag time and velocity between large and small storms is the route from well 5 to well 3. All other differences between either lags or velocities are insignificant.

Table 3. Composite lag times and Darcian velocities for all five groundwater flow routes after large and small storms. P-values are listed for each route, which apply to lag time and velocity; only route 5 → 3 is significantly different for large and small storms.

	1 → 2	5 → 3	7 → 5	5 → 4	4 → 3
Large storm travel time, hrs	1.12	1.50	1.57	1.00	2.41
Small storm travel time, hrs	1.00	3.86	2.00	1.25	2.91
p-value	0.08	***0.01***	0.29	0.09	0.12
Large storm velocity, cm/s	0.15	0.15	0.10	0.12	0.07
Small storm velocity, cm/s	0.17	0.06	0.08	0.09	0.06

Discussion

Interpretation

Few studies have been conducted to determine the wetland-groundwater linkage (*cf.* Carter 1986; Siege1 1988; Roulet 1990) and the hydrologic response to various sized precipitation events. Forested, slope wetland systems of the Pacific Northwest are even less studied. The results of this study show that the rate of flow through the wetland does not change with different sized storms despite the fact that there is more water delivered with larger storms. In order for minimal variability in the rate of flow to occur, the gradient must not be changing significantly with various sized storms. This may be due to the fact that gravitational flow, dictated by elevation gradients, is the main energy gradient for water movement. For this to happen there must be a quick, coordinated groundwater response throughout the wetland. All wells detect similar groundwater level changes within one or two hours of the beginning of the precipitation went, as estimated by the cross correlation analysis.

Such a rapid, synchronized response results from the fact that there is significant surface flow in this wetland and that the water is provided by two seeps yielding water hailing from steep slopes. The 50.2 % of the wells flooded after large storms and 44.3 % after small storms probably allow for short-cuts in the flow through the wetland, at least to the wells defining the five routes examined in this study. About 28% of the wells were newly flooded after small storms which creates temporary short-cuts that allow for water to move just as quickly as after large storms when 96% of the wells were newly flooded. The short-cuts are then lost as water drains from the wetland and allows a quick recession of the surface water at relatively the same rate as the local water table.

The seeps providing the wetland with groundwater at two points is discharging relatively quickly. Groundwater is generally a subdued replica of topography, driven by the relief of the region (Freeze and Witherspoon 1967). Because the water discharges from the water table beneath 30 % slopes, the gradient is relatively high compared to that of the wetland, yielding relatively faster velocities. This water quickly seeping into the wetland is conveyed throughout the wetland by flow associated with both large and small storms.

The conveyance of the faster velocities from the seep can serve to boost the velocities in the wetland. Those estimated from the calculated lag times range from 0.06 cm/s to 0.17 cm/s. These velocities are m order of magnitude larger than any other saturated hydraulic conductivities estimated in the literature. For instance, Romanov (1968) found the hydraulic conductivity of a slightly decomposed fen in the U.S.S.R. to be 0.005 cm/s, a moderately decomposed fen to be 0.0008 cm/s, and a highly decomposed fen to be 0.00001 cm/s. Veny and Boelter (1979) found North American fibric peatlands to generally have a hydraulic conductivity greater than 0.0015 cm/s. Surface flow inevitably serves to increase velocities, and it is possible that this surface flow skews the vectors constructed to predict groundwater movements. It is not reliable to indicate that surface flow follows the routing of the groundwater.

This can be investigated by examining the location of the flooded wells and the period of inundation. Well 8 was flooded for the whole period (1,417 hours) due to the fact it is located at one of the seeps. Well 7 was flooded for the whole period (1,417 hours), probably in direct response to the seep, and well 6 and well 2 were flooded for the period (927 and 50 hours, respectively) where surface flow exited from the wetland. Because well 8 and well 7 were more often flooded than well 6 and well 5, there was standing water unable to discharge from the well 6 outlet due to microtopographic complexity. When the outlet at well 6 was flooded, however, water was freely flowing and exiting from the southwest half of the wetland. Because this half of the wetland is flooded and the northeast half is rarely flooded, the gradient is always indicating that water is flowing generally towards well 3. Well 5 was flooded for 502 hours, which when coincident with wells 7 and 6 flows toward well 6 to the outlet. The vector plot therefore is only accurate when there is minimal surface flow, or at least the outlet wells are not inundated. The lack of distinctly predictive vectors in this wetland half may be attributed to the inability to use hydraulic head alone to predict groundwater flow because flow is above the surface, allowing for short-circuits.

Therefore, because the outlet at well 2 leads to one stream and the other outlet leads to another stream, the groundwater in the wetland may take divergent paths, part of the water towards one stream, the remaining portion towards the other stream. Because wells 3 and 4 never become inundated and they register the lowest average water levels in the wetland, it is a reliable estimate to believe water flows in the general direction towards well 3 from well 4, and sometimes 5. Constant inundation between wells 7 and 8, and prevalent inundation of well 5 and

6, forces the vectors constructed during periods of inundation to skew the groundwater movement predictions. This could be the most discriminating reason that predicted groundwater velocities are not different after large and small storms, in addition to why the gradients and resulting velocities are so inflated compared to other studies.

Furthermore, several inconsistencies exist between the vectors of the quiver plots and the estimated lag times and velocities. In the quiver plots, vectors between wells 4 and 3 are distinctly larger than the vectors between wells 5 and 4 and between wells 1 and 2. Velocities along these larger vectors between wells 4 and 3 should be faster than those between wells 5 and 4 and wells 1 and 2, however, the velocities are the slowest of all five routes between wells 4 and 3 and fastest between wells 1 and 2. Faster velocities between wells 1 and 2 can be explained by the fact that both wells are receiving water from the upland system. Well 1 is receiving water that drains from the seep, but because well 2 lies near the seep and on the border between the upland and wetland systems, it is probably receiving water draining from the upland slope. This causes both wells to react relatively quickly to each precipitation event and yields a shorter lag time.

Explanations of the disparity between the slow velocities of the route between wells 4 and 3 and its corresponding longer vectors are more complex. Water levels in well 3 are much lower than in well 4 yielding a steep gradient, but velocities are much slower than expected. Hence, it is conceivable that the hydraulic conductivities between these two paths is very different than the rest. This point needs further investigation.

Conclusion

Groundwater flow in this forested, slope wetland can be predicted from groundwater levels. The direction of groundwater flow is an accurate portrayal of flow through the wetland only in the absence of surface flow. Travel times of water through the wetland were quantified to estimate the residence time of water after large and small storms. Because groundwater gradients and their corresponding velocities are not significantly different after large and small storm events, the rate of flow through the wetland does not change with different sized storms despite the fact that there is more water delivered with larger storms. This quick, coordinated groundwater response throughout the wetland may be attributed to the fact that gravitational flow, dictated by elevational gradients, is the main energy gradient for water movement in areas of high relief like the Pacific Northwest.

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