GROUNDWATER RESPONSE TO PRECIPITATION EVENTS, KALALOCH, OLYMPIC PENINSULA, WASHINGTON

By

Casey R. Hanell

Accepted in Partial Completion
Of the Requirements for the Degree
Master of Science

Moheb A. Gali, Dean of the Graduate School

ADVISORY COMMITTEE

Chair, Dr. Robert J. Mitchell

Dr. Douglas H. Clark

Mr. Jeffrey D. Grizzel, L.E.G.

GROUNDWATER RESPONSE TO PRECIPITATION EVENTS, KALALOCH, OLYMPIC PENINSUALA, WASHINGTON

A Thesis
Presented to
The Faculty of
Western Washington University

In Partial Fulfillment
Of the Requirements for the Degree
Master of Science

by
Casey R. Hanell
February 2011

ABSTRACT

Tens of thousands of square kilometers of forestland in Washington are managed as working forests, primarily for timber production. The effects of timber harvesting on physical watershed processes continue to be the subject of intense research throughout the Pacific Northwest. Watershed analyses completed in Washington during the mid-1990s resulted in significant modifications to Washington's Forest Practices Act and Rules. These measures mandate rigorous evaluation of potential effects of timber harvesting on slope stability. Although timber harvesting has been linked to an increase in surface erosion and mass wasting in the Pacific Northwest, most studies have focused on shallow landslide processes. The loss of canopy interception and evapotranspiration associated with timber harvesting and the resulting effects on groundwater levels and stability of deep-seated landslides are not well understood. In this study, I use field measurements to analyze subsurface water level rise and attenuation in response to precipitation events, and the Distributed Hydrology Soils Vegetation Model (DHSVM) to model potential changes in hydrology resulting from clear-cut timber harvesting.

The research site is a portion of a moderately steep watershed (2 sq-km) located 6 km southeast of Kalaloch, WA on the coast of the Olympic Peninsula. Slope gradients generally measure between 30 and 50 percent, with localized steeper and gentler slopes. Ten wells at the site are instrumented with pressure transducers that record hourly subsurface water levels. I use onsite and nearby precipitation measurements and pressure transducer data to characterize groundwater level response characteristics at the site between February 2005 and February 2007. This analysis shows subsurface water levels rise and attenuate rapidly in

response to precipitation and usually reach peak levels within hours after the onset of precipitation and attenuate within days, regardless of the magnitude of the event. I also use Kendall's τ correlation analysis (Kendall, 1938) to evaluate the relationship between cumulative precipitation for a given event and peak well water level for the same event. Kendall's τ values were most significant for between 3 hours and 13 hours of cumulative onsite precipitation in 6 of the 10 wells, with all of the most significant correlations falling between 3 hours and 48 hours with the exception of one well which had no significant correlations. Kendall's τ correlation between subsurface water levels and open air precipitation measurements made at the nearby Black Knob Weather Station and linear regression analysis were also most significant with hours of cumulative precipitation as opposed to days or weeks.

The DHSVM results show a 27.4 percent reduction in evapotranspiration when the research basin vegetation is converted from an entirely forested condition to an entirely shrub-covered condition with all other variables constant. This reduction in evapotranspiration is modeled to result in a slight increase in streamflow and a slight increase in soil moisture and groundwater level for the two year period from February 2005 through February 2007. The majority of this decrease in evapotranspiration and increase in streamflow and subsurface water occurs during the spring and early summer when evapotranspiration rates are high and water levels are below modeled maximum peak levels.

ACKNOWLEDGEMENTS

There are several people whom without their contributions, this research and thesis would not have been possible. I would like to acknowledge my thesis chair, Dr. Robert Mitchell, for his willingness to advise me throughout the course of this project and provide helpful insight and discussion relating to this research and life in general. My other two thesis committee members, Dr. Douglas Clark and Jeffrey Grizzel, have also provided important review and discussion of this thesis. The field portion of this research project was originally conceptualized by Wendy Gerstel, who designed the field instrumentation layout, obtained the funding for the monitoring equipment, and led the effort to get the monitoring equipment installed in 2004. Dr. Robin Matthews provided helpful review and advice regarding statistical analysis. My field assistant, Brock Milliern, provided crucial logistical support during trips to the research site to download data recorded by monitoring equipment.

I would like to acknowledge the Washington State Department of Natural Resources and Western Washington University for providing significant funding for this research and thesis. Dr. Jerry Freilich at Olympic National Park has coordinated annual research permits for monitoring equipment installed within the park boundaries. Niki Thane provided invaluable assistance with data compilation. My fellow graduate students and the faculty and staff at Western Washington University have provided helpful discussion, review, and support throughout the research process.

Finally, I would like to acknowledge my family for their continued support of all of my endeavors, including this research and thesis. They are Abigail, Bob, Mary Kay, Megan, Bobby, and Liam.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

1.0 INTRODUCTION

Tens of thousands of square kilometers in Washington are managed for timber production and other forest resources. The effects of timber harvest on Washington's ecosystems are continually being studied to gain a better understanding of the effects of land management. Washington Forest Practices Rules are established in Title 222 of the Washington Administrative Code (WAC) to help minimize and mitigate the effects of forest land management on public resources such as fish and wildlife habitat and water quality. WAC 222-10-030 states, "Specific mitigation measures or conditions must be designed to avoid accelerating rates and magnitudes of mass wasting that could deliver sediment or debris to a public resource or could deliver sediment or debris in a manner that would threaten public safety." These mitigation steps require rigorous evaluation to assess their effectiveness on maintaining slope stability. Although timber harvesting has been linked to increases in surface erosion and mass wasting in the Pacific Northwest, most studies have focused on shallow landslide processes (e.g., Montgomery et al., 2000). The potential effects of the loss of tree canopy interception and evapotranspiration on groundwater recharge and the effect groundwater recharge has on deep-seated landslide movement are not well understood in the Pacific Northwest.

Deep-seated landslides are defined as having a failure plane deeper than the maximum rooting depth of vegetation, generally considered to be greater than three meters, but can be as much as hundreds of meters. Failure planes are usually located in weak geologic materials or at a boundary between more permeable materials over less permeable materials (Washington State Forest Practices Board Manual, 2004). Deep-seated landslides

can be slides, spreads, flows, or any combination of the three. Rates of movement can range from extremely slow to extremely rapid along translational, rotational, or a combination of translational and rotational failure surfaces. Types of movement along with rates of movement are further described by Cruden and Varnes (1996). For this study, the term deep-seated landslide refers to a landslide with a failure plane below the rooting depth of vegetation that exhibits persistent extremely slow to moderate rates of movement either seasonally or annually and can include episodic increases in movement in response to stressing events such as groundwater table fluctuation, removal of material from the landslide toe, and seismic activity.

Moderate temperatures and high annual precipitation on the western Olympic Peninsula along with easily weathered marine sedimentary bedrock results in relatively rapid soil formation. These soils are often subject to high pore water pressures, have low shear strength, and commonly form on slopes with sufficient gradient to deliver sediment to stream and river systems. Areas underlain by these deeply weathered marine sedimentary bedrock units are prone to deep-seated landsliding (Dragovich et al., 1993; Gerstel, 1999). Establishing the relationship between groundwater response to precipitation events and different degrees of canopy removal will enable future research and monitoring to better assess the extent to which timber harvesting may influence deep-seated slope movement.

Currently, there are two schools of thought regarding the potential effects of vegetation removal on deep-seated landslides (De La Fuente, 2002). One view contends the main effect forests have on slope stability is to provide additional soil cohesion through root strength. By definition, deep-seated landslides occur below the rooting depth of vegetation.

Therefore, according to this concept, the removal of vegetation from a deep-seated landslide should have little or no effect on the stability of the landslide. The other position contends that removal of vegetation from a deep-seated landslide can affect the stability of the landslide through an increase in soil water inputs due to the loss of canopy interception and evapotranspiration. Groundwater levels are at their peak on the Olympic Peninsula during the winter months when a majority of the annual precipitation occurs. Even though the rate of evapotranspiration during the winter months is relatively low as a result of lower temperatures, high relative humidity, and shorter day lengths it could potentially decrease recharge. As such, an increase in recharge could potentially increase pore pressures at the failure plane of a deep-seated landslide, accelerating the rate of movement. For example, researchers studying deep-seated landslides in the Lincoln Creek Formation, a sedimentary bedrock unit that underlies much of southwest Washington, found a strong correlation between increased piezometric surface and periodic deep-seated landslide movement for instrumented landslides (Gerstel and Badger, 2002).

In most cases, it is difficult to accurately characterize the groundwater hydrology of a deep-seated landslide because of subsurface heterogeneities that can introduce significant uncertainties related to slope stability. Numerical modeling by Reid (1997) indicates that even small differences in the hydraulic conductivity of hillslope materials can significantly affect groundwater recharge and pore pressures within the soil, thus decreasing slope stability.

Rain gauges are a relatively inexpensive way to collect data needed to estimate potential groundwater recharge to a landslide or hillslope. In most cases, rain gauge data will

indicate maximum potential recharge to the groundwater table because during periods of heavy precipitation, the rate of precipitation can exceed the rate of infiltration and depression storage capacity, resulting in overland flow that will not recharge the local groundwater table (Fetter, 2001). By comparing precipitation data with landslide movement data, the effects of increased landslide water content can be qualitatively assessed. In the San Francisco Bay Area, interferometric synthetic aperture radar (InSAR) has been used to quantify annual landslide movement rates, which have been correlated with precipitation data (Hilley et al., 2004). Another monitoring site where rain gauges, pressure transducers, extensometers, and geophones have been used to examine the relationship between precipitation, groundwater, and slope stability is the Cleveland Corral landslide along U.S. Highway 50 in California (Reid and LaHusen, 1998).

Subsurface hydrology can have significant effects on deep-seated landslide movement. As such, effects of timber removal on groundwater should be carefully evaluated in areas where deep-seated landslides occur, especially in settings where there is significant risk to public safety or resources (e.g. critical salmon habitat). In situations where risks to public safety or resources are low, it is at least important to assess the potential effects of landslide hydrology on deep-seated landslide movement. To gain a better understanding of the relationship between groundwater recharge and forest canopy, I monitored hand drilled wells and rain gauges in a small catchment on the west coast of the Olympic Peninsula. I used these data to determine the response of groundwater levels to throughfall precipitation and to develop baseline methods that future scientists can employ to assess the effect of timber harvesting on groundwater levels following timber harvesting in the catchment.

2.0 BACKGROUND

2.1 Location

The Kalaloch research site is located on the west-central coast of the Olympic Peninsula approximately 40 km southwest of Forks, Washington (Figure 1). It is accessed by driving forest roads east from Highway 101 for 1 km and then hiking 0.1 – 2 km to the research sites.

2.2 Topography

Elevations in the study area vary from sea level to approximately 200 m above sea level (Figure 2). The slopes vary from gentle near the western portion of the study area to moderately steep in the eastern portion with an approximate average slope gradient of 30 percent, although steeper slopes occur locally over short distances. Relief is generally broad and gentle although some streams have incised gullies between 1 – 3 m deep.

2.3 Geology

Large portions of the western Olympic Peninsula, including the study area, are underlain by Miocene-Eocene marine sedimentary bedrock (Tabor and Cady, 1978; Gerstel and Lingley, 2000). The underlying rock units are thick-bedded (1 – 50 m) lithic sandstones and conglomerates; rhythmically bedded (beds – 50 cm thick) very fine- to medium grained sandstones, siltstones, and shales; and tectonic breccias. Several north-south trending thrust faults are also mapped in the area.

2.4 Soils

Soils in the Kalaloch study area are mapped, classified, and displayed on United States Department of Agriculture (USDA) maps as clay, silty clay loam, silt loam, and gravelly silt loam (Soil Survey Staff, 2007). Soils vary from approximately 1 m thick at the top of the slopes to 4 m thick at the base of the slopes. Site-specific field observations and samples collected during augering were used to classify the soil textures at the individual well locations.

2.5 Vegetation

Due to the small size and homogeneity of the study area, plant diversity is relatively low. Vegetation consists of a uniform, second growth, mixed-conifer forest dominated by western hemlock and Douglas fir with scattered Sitka spruce and red alder. These trees are mostly 40-60 years old and form a closed canopy. As a result, very little understory vegetation is present.

2.6 Climate

The western Olympic Peninsula has a moderate climate with high annual precipitation and small fluctuations in intra-annual temperatures. The average annual precipitation in the area for the period 1895 - 2009 is 295 cm, most of which falls between the months of October and March (Desert Research Institute, 2009). Temperatures vary from an average daily low of 1.0^0 C and an average daily high of 7.3^0 C in January to an average daily low of 9.6^0 C and an average daily high of 21.4^0 C in August for the period 1895-2009 (Desert Research Institute, 2009). Because of the low elevation of the research site and its proximity to the

Pacific Ocean, the area receives very little snow. As a result, rain-on-snow precipitation events are not a significant influence on local hydrology.

2.7 Previous Research

Deep-seated landslides and associated hydrologic regimes are often complex and difficult to quantify, with surface vegetation comprising only one component of the complexity. As a result, there are few studies that address the effects of timber harvest on groundwater levels. Most research examining the effects of vegetation removal on hydrologic regimes has involved quantifying differences in water yield either following vegetation manipulation or by studying paired basins with different vegetation characteristics. Summary information from previous studies indicates total annual water yield in a basin increases with a decrease in forest cover and an increase in forest cover leads to a reduction in annual water yield (e.g., Megahan and Hornbeck, 2000; Grant, 2008). The magnitude of this change in water yield is spatially highly variable and depends on many factors including the amount of annual precipitation and local vegetation characteristics.

One of the few studies to attempt to quantify the effect of vegetation on the hydrologic regime of a deep-seated landslide used a spatially distributed hydrological model to examine a deep-seated earthflow in the French Alps (Malet et al., 2005). The researchers examined the modeled effect of planting grass, 20-year old conifer trees, and a mixture of the two on the deep-seated earthflow. They determined that planting grass and a combination of grass and trees on the landslide would have very little effect on the hydrologic regime of the

earthflow, but planting 20-year old conifer trees on the landslide decreased the water table up to 0.8 m.

Forest canopy interception also plays a major role in moderating precipitation delivery, especially during intense precipitation events. The canopy essentially serves as a buffer, slowing delivery of precipitation to the forest floor and storing some precipitation that evaporates directly back out into the atmosphere following the precipitation event. Keim and Skaugset (2003) placed rain gauges under the tree canopy to measure throughfall and compared them with rain gauges placed in the open. They found that in general, rain gauges under the tree canopy measured peak throughfall intensities that lagged in time and dampened in intensity compared to intensities of rainfall measured by gauges located in the open.

The distributed-hydrology-soils-vegetation model (DHSVM) has been used in several studies to examine the relationship between forest vegetation and hydrology in western Washington, Oregon, and British Columbia. The DHSVM is a physically based model that calculates an energy and water budget at the grid scale of an input digital elevation model (DEM). The model has been applied predominantly to mountainous watersheds in the Pacific Northwest to simulate hydrologic responses to weather and land use conditions (e.g., Wigmosta et al., 1994; Storck et al., 1998; Bowling et al., 2000; Bowling and Lettenmaier, 2001; Wigmosta and Perkins, 2001; Whitaker et al. 2002; Wigmosta et al., 2002; Chenault, 2004; Kelleher, 2006; and Donnell, 2007).

Modeled results of deforestation using DHSVM within a catchment show an increase in flood peaks relative to the same entirely forested catchment (Bowling et al., 2000).

Decreases in vegetation also result in a lower leaf-area index in a catchment, decreasing evapotranspiration (VanShaar et al., 2002). The effectiveness of DHSVM in modeling different forest treatments has also been assessed. In a study by Waichler et al. (2005), the model predictions of mean annual streamflow were within ±10 percent of measured streamflows. These studies use streamflow measurements and predictions to evaluate the effects of vegetation on hydrology, however they do not separate groundwater and surface runoff contributions.

The main impact timber harvest may have on the relationship between precipitation events and groundwater levels is a reduction in canopy interception and evapotranspiration. During precipitation events, tree canopies attenuate the delivery of precipitation falling from the atmosphere to the ground surface through interception (Keim and Skaugset, 2003). Some of the intercepted precipitation evaporates directly from leaf surfaces back into the atmosphere while most of the rest reaches the ground surface at a rate slower than falling directly to the ground. Once precipitation infiltrates into the soil, water can be removed from the soil by processes such as direct evaporation or by tree roots via transpiration (Dingman, 2002).

If the reduction in canopy interception and evapotranspiration at the research site produces a measurable difference in well water level response to precipitation events, post-harvest qualitative analysis would be expected to show a more rapid rise in well water level at the onset of a precipitation event compared with the pre-harvest well water level response to a storm of the same magnitude. This effect would result from more precipitation being delivered directly to the ground surface because precipitation would no longer be stored in

the tree canopy and subsequently delivered to the ground surface at a slower rate with a portion evaporating directly back into the atmosphere (Keim and Skaugset, 2003). Post-harvest qualitative analysis may also show increased peak well water levels when compared with pre-harvest peak well water levels during precipitation events of the same magnitude related to the increase in precipitation reaching the ground surface and the reduction in the amount of water being removed from the soil through transpiration. Post-harvest well water level attenuation following precipitation events may take longer following similar magnitude storm events because of a reduction in water removed from the soil through evapotranspiration.

Another potential effect of timber harvest is a reduction in well water levels after logging. Canopy interception can have the effect of intercepting moisture in the air (fog) and collecting enough to deliver it to the ground surface as fog drip (Dingman, 2002), a phenomenon that would not occur in newly clear-cut areas where all overstory vegetation has been removed. Fog drip is not considered to be a significant factor in maximum peak well water levels observed in this study. However, fog drip may contribute to maintaining high soil moisture contents during the summer when much less precipitation occurs. Analysis of fog drip contribution is beyond the scope of this project.

3.0 RESEARCH OBJECTIVES

To better understand the influence of forest cover on groundwater, I examined the relationship between precipitation events and groundwater response in a forested study area overlying deeply weathered marine sedimentary bedrock on the western Olympic Peninsula,

WA using 1) measured groundwater and precipitation data and 2) the distributed-hydrology-soils-vegetation model (DHSVM) to simulate the basin hydrologic response to vegetation change (simulated timber harvest).

The primary objectives of this study are to establish a pre-harvest baseline groundwater level response to precipitation events, to develop a methodology that scientists can use to compare data collected following timber harvest to pre-harvest data, and to model the hydrologic effects of timber harvest using DHSVM. An actual timber harvest in the catchment occurred during the fall of 2009 following several years of pre-harvest data collection.

4.0 METHODS

In order to accomplish these objectives, I collected and analyzed field data using qualitative and statistical methods and parameterized and used the DHSVM to evaluate the effects of timber harvest on local hydrology in the study area. Initial timber harvest in the catchment was completed during the fall of 2009. Data collection following timber harvest in the catchment will allow for a future study to compare pre- and post-timber harvest water level response to precipitation.

4.1 Field Data Collection

During the summer and fall of 2004, a total of 10 wells 6-cm in diameter were drilled with a hand auger by Washington State Department of Natural Resources staff, including myself, on three west aspect planar sites between 2 and 5 km southeast of Kalaloch, WA. For this study, the three slopes are referred to as Alsea, Ruby, and Talus in order from north to south. The

wells were drilled to refusal and vary in depth from 1.0 m to 3.8 m. The Alsea and Ruby slopes each have a well drilled near the ridge top, a mid-slope well, and a well near the bottom of the slope (Figure 2). A slotted pipe with a solid (unslotted) section near the ground surface was inserted into each well and surrounded with sand with grout sealing the top of the well (Figure 3). The Talus slope has the same well configuration as the northern slopes except that a fourth well was installed in a deep-seated landslide south of the well at the base of the slope (Figure 2). The wells are instrumented with MiniTroll pressure transducers that record the water level hourly. Because the wells are relatively shallow and drilled only to bedrock, 8 of the 10 wells do not have water in them during dry periods. It is possible that the water level recorded in these 8 wells (or all 10) represents a perched water table above the soil/bedrock interface that is independent of a deeper aquifer that may control deep-seated landslide stability. Analysis of this possibility is outside the scope of this research project because there are no wells in the bedrock layer to test this hypothesis.

Each slope is instrumented with a single tipping-bucket rain gauge to measure precipitation under the canopy. Data loggers installed in these rain gauges record each time the bucket tips. The rain gauges were placed under the tree canopy approximately equidistant from adjacent trees in order to obtain an estimate of throughfall at a specific point. As a result of their positioning under the tree canopy, the rain gauge funnels have sometimes been clogged by leaf litter. In April 2005, finer screens were placed in the funnel below the original coarse screens and have successfully prevented further clogging to date. Open air rain gauge data were obtained from the Black Knob Remote Automated Weather Station (RAWS) and accessed digitally from the Office of the Washington State

Climatologist (2008). The Black Knob RAWS is located approximately 25 km southeast of the research site at the same elevation and approximately 20 km further inland.

On the southernmost slope, a barometer was installed that records pressure readings every hour. Originally, the barometer was suspended in a well below the ground surface. However, during large precipitation events, the water level in the well containing the barometer rose nearly to the ground surface. As a result, the barometer was submerged and ensuing barometric pressure readings were inaccurate. Subsequently, the barometer was suspended above the ground surface to prevent this problem.

Beginning in February 2005, I made monthly trips to the study sites to download data recorded by the instruments installed at the sites. I compiled a continuous data set from February 2005 through February 2007 to analyze for this study.

4.2 Establishing a Baseline

Using the February 2005 through February 2007 data set for each well, I established a baseline groundwater response to precipitation events recorded by the onsite rain gauges and at the Black Knob RAWS gauge 25 km southeast of the research site. I analyzed both the level and timing of the groundwater response in the wells graphically and statistically to develop consistent, robust techniques that can be used for comparative purposes once data from the timber harvested slopes are collected. For example, in the fall of 2009, a timber harvesting operation was conducted at the site where one of the instrumented slopes was clear-cut, one of the instrumented slopes was thinned to approximately 50 percent of the pre-harvest timber stand, and the slope in the Olympic National Park unaltered. Data collection

will continue from the instruments installed on the three research slopes for a future study and my baseline analysis will be used for comparative purposes.

4.2.1 Data compilation and conversion

I compiled the data from individual monthly downloads from the onsite instruments for the two year period from February 2005 through February 2007 in Microsoft Excel, hereafter referred to as Excel. The pressure transducers onsite take readings in pounds per square inch (PSI) and the barometer onsite takes readings in inches of Hg. The barometer readings were converted to PSI by multiplying by a conversion factor of 0.4912. The barometric pressures were then subtracted from the pressure transducer readings to isolate the pressures caused by water in the well above the pressure transducers. The PSI values representing the water level above the pressure transducer were then converted to inches of water above the instrument by multiplying by a conversion factor of 27.68. Inches of water were then converted to centimeters for analysis and discussion in this thesis. The depth of the pressure transducer below the ground was subtracted from the height of the water column above the instrument resulting in the depth of water below the ground surface with the ground surface being 0 cm and depth below ground surface in negative values.

4.2.2 Qualitative Analysis

I created plots in Excel to evaluate the relationship between water levels in each of the wells and onsite precipitation. I examined relationships between daily, hourly, and cumulative precipitation compared to well water levels. Only two of the ten wells had water levels above the pressure transducers year round. All ten wells recorded a water level during large

precipitation events in the wet months of the year. I used data from these wells to examine the timing of the well water level rise, peak water levels, and water level recession during and following precipitation events. In addition, I plotted soil columns next to the well water level response curves and projected changes in soil characteristics onto the well water level response graphs. This allowed me to visually interpret how subsurface differences in soil characteristics may be influencing well water level response to precipitation events.

4.2.3 Statistical Analysis

I analyzed the relationship between well water level peaks and the cumulative precipitation in specified time intervals preceding a water level peak, allowing all wells to be evaluated using the same process. For example, 1 hour of cumulative precipitation represents the amount of rainfall that was recorded during the hour preceding the peak level, 2 hours of cumulative precipitation represents the sum of the recorded precipitation in the 2 hours preceding the well water level peak, 24 hours of cumulative precipitation represents the sum of hourly rainfall measurements recorded during the 24 hours preceding the well water level peak, and so on. Using these intervals of cumulative precipitation is, in effect, quantifying precipitation intensity but instead of dividing the quantity of precipitation by the amount of time it takes for that precipitation to fall, the numbers are left undivided to allow for a more clear presentation of the data and results. The relationship between peak well water levels and hourly intervals of cumulative precipitation was selected for analysis to establish a baseline for future studies to determine if timber harvest has an effect on the timing of maximum peak water levels. Water level peaks were selected for analysis from visual

examination of Excel plots. For each well, I selected a threshold beyond which peaks needed to rise to yield a sample population of peak values (Table 1). By using the same threshold values for future studies, a relative comparison of pre-timber harvest and post-timber harvest water level response can be made for each individual well.

Two precipitation data sets were used for statistical analysis. One precipitation data set was the maximum hourly rainfall quantity recorded at the three onsite rain gauges. This value represents the maximum throughfall value recorded at the three point locations. The maximum value was used instead of an average of the three onsite rain gauges because there were periods of time when individual rain gauges were not recording data as a result of various technical difficulties including leaf litter clogging, falling trees, computer problems, and a curious bear. The second precipitation data set is hourly precipitation recorded at an open air precipitation gauge at the Black Knob RAWS located approximately 25 km southeast of the well locations. The Black Knob RAWS is the weather station closest to the research site with a complete data set for hourly open air precipitation measurements for the time period analyzed.

Once the sample population of well water level peaks, hourly throughfall, and hourly open air precipitation values were compiled, I used the computer statistical program R to determine if significant correlations between peak water levels and intervals of cumulative precipitation preceding the peak existed (R Development Core Team, 2007). The intervals of cumulative precipitation were hourly from 1 hour preceding the peak value to 36 hours preceding the peak value, as well as 48 hours, 72 hours, 7 days, and 14 days of cumulative precipitation preceding the peak. The intervals of cumulative precipitation were selected

based on the rapid response of well water levels during precipitation events and the rapid attenuation of water levels observed during the qualitative analysis.

The first statistical method I used to establish a quantitative baseline well water level response to precipitation was Kendall's τ correlation analysis (Kendall, 1938). Kendall's τ correlation analysis is a nonparametric statistical method used to determine if any significant correlations were present between peak water levels and the above stated intervals of cumulative precipitation preceding water level peaks. One benefit of using a nonparametric statistical method for correlation analysis is that it does not require the data set to be normally distributed. Kendall's τ correlation analysis compares the number of concordant and discordant data pairs to test for significant correlations. Concordant data pairs have the same sign for the difference between the *x*-coordinate as the difference between the *y*-coordinate, whereas discordant data pairs would have the opposite sign for the difference between the *x*-coordinate and *y*-coordinate. Values for the Kendall's τ correlation coefficient range from -1 to 1, where 0 indicates no correlation and values of -1 or 1 indicate a perfect correlation. Significant correlations were identified with a p-value < 0.05. Kendall's τ values were plotted using R to illustrate the precipitation intervals that had the most significance. The R code I used to calculate Kendall's τ values is located in Appendix A. Post-harvest data analysis using Kendall's τ would be expected to result in the best correlation for an interval of cumulative precipitation to occur in a shorter time period than the pre-harvest data analysis due to more precipitation reaching the ground in a shorter period of time, in theory allowing more water to infiltrate more rapidly presuming the infiltration capacity of the soil is not exceeded. If the effect of a reduction in canopy interception and evapotranspiration has no

measurable effect on timing of peak well water levels at the site, Kendall's τ correlation coefficients would be expected to remain similar for the same interval of cumulative precipitation post-harvest as pre-harvest.

The second statistical method used to establish a quantitative baseline water level response to precipitation was a simple linear regression model using R. I used the same intervals of cumulative precipitation as the Kendall's τ correlation analysis and used each to develop a linear model with the peak water level values. Simple linear regression is used in addition to Kendall's τ to provide another tool for post-harvest data analysis. One advantage of using simple linear regression is that it allows visualization of the cumulative precipitation interval values plotted with the peak water level values. In addition, linear regression models will allow for the assessment of potential effects of timber harvest on peak water level magnitudes when comparing pre-harvest and post-harvest data. Linear regression modeling has the disadvantage of potentially introducing a linear regression bias, which is why two methods of statistical analysis were used to establish a quantitative baseline water level response to precipitation. The linear regression models are not intended for use as a predictive tool, such as expecting a specific peak water level in response to a given interval of cumulative precipitation. The intended use of the linear regression models is to quantitatively assess differences and similarities between pre-harvest and post-harvest data. In addition to the untransformed linear models, I used a log-log transformation to produce a second linear model in an attempt to improve the model and potentially reduce linear regression bias. The R code I used to compute the linear models is located in Appendix A. Adjusted R-squared values were calculated using the computer program R to assess the best

fit linear models. The closer the adjusted R-squared value is to 1, the better fit the linear model represents.

Post-timber harvest linear regression models can be compared to pre-harvest models to help quantify any change in water level response to precipitation. If there is a measurable change in the timing of peak water levels post-harvest, the linear model with the adjusted R-squared value closest to 1 should be a shorter interval of cumulative precipitation preceding water level peaks. If there is a measurable increase in the magnitude of water level peaks post-harvest, then the slope of the linear model will increase. If there is no measureable change in peak water levels, the slope of the linear model with the best adjusted R-squared value should remain the same and if there is a decrease in the magnitude of peak water levels following precipitation events then the slope of the linear model would be expected to decrease.

4.3 DHSVM Modeling

DHSVM is a spatially distributed hydrology-vegetation model that simulates a water and energy balance at the grid scale of a digital elevation model (DEM). The model was developed at the University of Washington and the Pacific Northwest National Laboratory and includes canopy interception, evaporation, transpiration, snow accumulation and melt, and saturation excess runoff generation (Wigmosta et al., 1994). The model has been applied predominantly to mountainous watersheds in the Pacific Northwest to simulate hydrologic responses to changing weather and land cover conditions (e.g., Wigmosta et al., 1994; Storck et al., 1998; Bowling et al., 2000; Bowling and Lettenmaier, 2001; Wigmosta and Perkins,

2001; Whitaker et al. 2002; Wigmosta et al., 2002; Chenault, 2004; Kelleher, 2006; and Donnell, 2007).

For this study, DHSVM was used to model the effects of vegetation cover change on the amount of water available to potentially recharge the groundwater table. Model simulations of the research basin with a mixed-conifer forest land cover and a shrub land cover were run and compared to simulate potential hydrologic effects of logging the research basin. The shrub vegetation land cover was used to simulate a clear-cut timber harvest scenario as opposed to a bare soil land cover because the model predicts a landscape with a shrub cover is the minimum soil water loss scenario (R. Mitchell, personal communication, 2008). The DHSVM predicts a bare soil land cover will lose water directly to the atmosphere due to evaporation and so, according to the model, the maximum amount of water available to recharge the groundwater table will be available when shrubs are covering the ground which usually occurs within the first few years following timber harvest on the western Olympic Peninsula.

4.3.1 DHSVM Basin Setup

Six geographic information system (GIS) data layers are required input for DHSVM. These data layers are: a DEM, watershed boundary, soil texture, soil thickness, land cover, and a stream network. ESRI's ArcGIS software was used to work with, create, and manipulate model input layers. I followed the methodology described in Appendix A of Donnell (2007) for locating and preparing the digital data required to parameterize my research basin for use

in DHSVM. The digital data and where it came from is described briefly in the following paragraphs. For a detailed description, refer to Donnell (2007).

The DEM is a digital representation of the research basin topography. The entire research basin for this study is encompassed by the Queets 7.5 minute quadrangle 10 m DEM. I downloaded the DEM from the University of Washington (2007). The research basin watershed boundary was determined by using the 'hydrology modeling' tool in ArcGIS 9 and is the compilation of several catchments for streams that drain the instrumented slopes at the research site and outlet directly into the Pacific Ocean. The Queets DEM was clipped with the watershed boundary and resampled to a 30 m by 30 m grid resolution. The other GIS layers input into DHSVM to parameterize the research area were also clipped with the watershed boundary to ensure all of the layers had identical overlapping grids and boundaries.

The soil texture layer was created using data downloaded from the U.S. Department of Agriculture Natural Resource Conservation Service website (Soil Survey Staff, 2007). DHSVM assigns soil-dependent hydraulic characteristics to the primary soil texture in each given cell. Soil thickness was modeled using an Arc Macro Language (AML) script written at the University of Washington. Modeled soil thicknesses were compared with field data collected during monitoring well installation to ensure modeled soil thicknesses were reasonable.

The land cover layer was created using digital data from the National Oceanic and Atmospheric Administration (NOAA, 2007). Per Donnell's (2007) methodology, I used ArcGIS to reclassify the vegetation classes in the land cover layer obtained from NOAA to

the vegetation classes used by DHSVM. Each vegetation class in DHSVM is assigned a set of vegetation-dependent hydraulic parameters and each pixel in the land cover layer is assigned the parameters of the dominant overstory vegetation species.

4.3.2 Meteorological Data

The meteorological (met) input data required for DHSVM include hourly precipitation, wind speed, humidity, air temperature, and incoming shortwave solar radiation and longwave radiation. I used met data from the Black Knob RAWS (Office of the Washington State Climatologist, 2008), which was the weather station closest to the research site that had a complete record for the period of this study. Longwave radiation data were not collected at the Black Knob RAWS, so Dr. Robert Mitchell modeled it using the shortwave radiation and other met data from the Black Knob RAWS.

4.3.3 Calibration and Validation

Previous DHSVM work done at Western Washington University has included model calibration and validation using stream gauge data from the basin being researched (Chenault, 2004; Kelleher, 2006; Matthews et al., 2007, and Donnell, 2007). Measured streamflow data are not available for my site, so I did not fully calibrate the model to the field area. Stream-gauge data from the nearby Queets-Clearwater gauging station was used to compare the timing of stream flow peaks to model predictions. The magnitudes of stream flow peaks to model predictions could not be directly compared due to the significantly larger basin size draining to the Queets River near Clearwater gauging station (USGS Gauging Station 12040500). Model simulations may be validated in a future study that

compares actual post-harvest groundwater response to DHSVM predicted values in this study.

4.3.4 Modeling the Effects of Timber Harvest

Once the basin was appropriately parameterized, the land cover layer was modified to simulate vegetation change resulting from timber harvest. The vegetation layer was changed from a mixed conifer forest to a shrub vegetation cover and input back into DHSVM to simulate potential effects of timber harvest on hydrology. Dr. Robert Mitchell ran DHSVM with both land cover input layers and sent the model results to me for comparison and analysis.

5.0 RESULTS

One objective of this study is to establish a baseline water level response to precipitation events in 10 wells located across three hydrologically disconnected slopes within the research basin. Describing and quantifying water level response to precipitation events using robust and consistent methods allows future data collected in the research basin following timber harvest to be analyzed with the same methodology and compared with the established pre-harvest baseline response. Once the effects of timber harvest on groundwater levels are better understood, the risks associated with timber harvest on and near deep-seated landslides can be better characterized.

I present results of the qualitative and quantitative data analysis for each well below. Results for each well are described individually and consist of a qualitative description of observed water level response to precipitation events, results of Kendall's τ correlation

analysis between maximum peak water levels and both onsite and open air precipitation data, and results of simple linear regression modeling of maximum peak water levels and onsite precipitation data. By plotting water level, precipitation, and soil characteristics with depth, qualitative relationships between the three can be defined.

Additional figures supporting the qualitative analysis illustrate six individual week-long periods of well water levels along with cumulative precipitation in order to observe water level response to precipitation at a more detailed scale. Figures supporting the quantitative analysis include the linear regression models with the best R^2 values for each well. Tables supporting the quantitative analysis include Kendall's τ correlation results for all relationships evaluated. Results for each well are described separately because any future analysis will first need to determine if any measurable changes are detected at the individual wells prior to making any attempt to describe changes in the response of the three separate slopes or the entire basin. Summary results of the maximum peak water level observed in each well are presented for comparison with future studies in Table 2.

Following the presentation of the qualitative and quantitative descriptions of water level response to precipitation events, I present DHSVM results for a basin vegetation change from forest to shrub cover. This modeling examines potential hydrologic effects of timber harvest. Actual post-timber harvest data collected in the future from the 10 wells at the research site can be compared with model results to evaluate model predictions.

5.1 Precipitation Data

Two sets of precipitation data were used for comparison with water level data collected from the 10 monitoring wells at the research site. Open air precipitation data were obtained from the Black Knob RAWS approximately 25 km south of the research site and onsite precipitation data were collected under the tree canopy from three tipping-bucket rain gauges, one on each research slope. The three onsite rain gauges provide only a rough estimate of throughfall precipitation values. Throughfall is the portion of precipitation that falls through the vegetation canopy to the ground surface. When all three rain gauges were functioning, they recorded similar daily precipitation values for totals less than 1 cm. For days with higher rainfall totals, the Talus and Ruby slope rain gauges generally recorded similar values with the Alsea slope rain gauge recording approximately 0.5 cm – 1.5 cm less, likely due to differences in the density of the tree canopy above the rain gauges. Numerous maintenance problems occurred with the onsite rain gauges resulting in data gaps at individual gauges. However, there were rarely time periods during the two year study period when all three onsite rain gauges were not functioning. As a result, the maximum hourly precipitation value of the three onsite rain gauges was used to create a single data set representing an estimation of throughfall at the research site.

Throughfall precipitation data collected under the tree canopy are consistent with published values of canopy interception loss. Cumulative throughfall precipitation for the two year period from February 2005 through February 2007 was 487 cm. Open air precipitation recorded at the Black Knob RAWS for the same time period was 643 cm. The majority of this precipitation fell between October and May. Approximately 24 percent of

precipitation was intercepted by the tree canopy, which implies that the collection and analysis methodologies used for the throughfall estimation are reasonable. Published values of interception loss in Pacific Northwest conifer forests vary based on canopy characteristics and climate conditions and range from 10 percent to 30 percent (Moore and Wondzell, 2005). Similar values are reported by Dingman (2002) which are specific to plant communities in the northwestern United States and range from 21 percent to 35 percent.

The total precipitation amount recorded at the Black Knob RAWS was 201.4 cm for water year 2005 and 272.4 cm for water year 2006 (Office of the Washington State Climatologist, 2008). Water years are defined as the 12 month period that starts in October and ends the following September. The water year is labeled by the year in which September falls. The Black Knob RAWS was established in 2003, so it does not have a long historical record for comparison. However, the nearby Clearwater weather station has a partially complete set of monthly precipitation records for the period 1931 through 2006. The Clearwater weather station is approximately 24 km northwest of the Black Knob RAWS and is closer to the research site. Data from the Clearwater weather station was not used for comparison with the data collected at the research site from February 2005 through February 2007 because the Clearwater records are incomplete prior to 2006 and no data were collected after 2006. Mean annual precipitation for the period 1931 through 2006 at the Clearwater weather station is 299.5 cm with a standard deviation of 50.1 cm (Desert Research Institute, 2009). These results indicate that water year 2005 was drier than usual whereas water year 2006 was close to an average water year. Total precipitation for water year 2007 was abnormally high, however part of the total appears to be an error in the data for July 2007

because the data indicate 570.48 mm of precipitation fell on July 16, 2007 which is more precipitation in one day than a majority of the monthly totals for the entire water year. Of the 24 months analyzed for this study six monthly precipitation totals at the Black Knob RAWS were outside the standard deviation of the monthly mean precipitation values for the period of record at the Clearwater weather station (Figure 4). January 2006 and November 2006 were significantly above the monthly mean standard deviation while February 2005, February 2006, April 2006, and October 2006 were all moderately below the monthly mean standard deviation (Figure 4). Since most monthly precipitation totals fall within one standard deviation of the mean, I have reasonable confidence that a baseline groundwater response to precipitation events has been established during water years that were not extremely wet or extremely dry.

5.2 Soils

Soil characteristics were noted in the field as the test wells were hand augered (Gerstel, 2005, personal communication). Additionally, samples were collected when significant changes in soil characteristics were noted at depth during augering. I classified the soil texture of these samples using field methods described by the United States Department of Agriculture Natural Resources Conservation Service (USDA NRCS, 2010). Descriptions of the soils at each well are presented below and are plotted along with groundwater level and precipitation data (Figures 5 - 9). The following soil descriptions are derived from notes taken in the field during initial well installation (Gerstel, 2005, personal communication) and observations of the samples made during soil texture classification.

Soils are categorized into hydrologic soil groups by the USDA to assign general hydrologic response characteristics to soils in the United States (USDA, 1986). All of the wells at the Kalaloch research site are placed into the Snahopish soil group with the exception of the Talus 4 well which is in the Hoko soil group. The Snahopish soil group is placed into hydrologic group B, indicating these soils have moderate infiltration rates when they are wetted and have a moderate rate of water transmission ranging from 0.38-0.76 cm/hr. Hydrologic characteristics of soils in the Hoko soil group are placed into hydrologic group C, indicating these soils have low infiltration rates with low rates of water transmission ranging from 0.13-0.38 cm/hr.

5.2.1 Alsea 1 Soils

The total depth of the Alsea 1 well is 135 cm (Figure 5). Approximately 10 cm of forest litter and duff are on top of the mineral soil. Once the mineral soil was reached, it remained a generally consistent sandy clay loam texture through the profile. Many small rock fragments were observed in the soil. The soil was dry near the top and moisture content increased slightly with depth. The soil parent material is mapped as Miocene to Eocene tectonic breccia (Gerstel and Lingley, 2000).

5.2.2 Alsea 2 Soils

The total depth of the Alsea 2 well is 113 cm (Figure 5). Approximately 15 cm of forest litter and duff are on top of the mineral soil. Once the mineral soil was reached, it remained a generally consistent silty clay loam texture through the profile. Small rock fragments were present in the soil and increased in size and frequency from 98 cm to 113 cm deep. The soil

parent material is mapped as Miocene to Eocene tectonic breccia (Gerstel and Lingley, 2000).

5.2.3 Alsea 3 Soils

The total depth of the Alsea 3 well is 139 cm (Figure 6). Approximately 8 cm of forest litter and duff are on top of the mineral soil. From a depth of 8 cm to 84 cm, the soil has a clay loam texture and it was damp during the augering of the well in August 2004. Moisture content was observed to increase slightly from 84 cm to 99 cm and maintained a clay loam texture. Gravel rock fragments became common from 99 cm to 113 cm in the clay loam as well as a noted decrease in relative soil moisture. The soil parent material is mapped as Miocene to Eocene tectonic breccia (Gerstel and Lingley, 2000).

5.2.4 Ruby 1 Soils

The total depth of the Ruby 1 well is 362 cm (Figure 6). Approximately 8 cm of forest litter and duff are on top of the mineral soil. From a depth of 8 cm to 124 cm, the soil has a silty clay texture that includes angular pebble clasts. Between 124 cm and 139 cm, there is a noted absence of rock fragments and the soil texture changes to silt loam. Below 139 cm, the soil has a loamy sand texture with increasing quantity and size of gravel rock fragments to a depth of 319 cm and was dry although mottling was observed in this layer. From 319 cm to 362 cm, the soil texture is loamy sand with observed iron staining. The soil parent material is mapped as Miocene marine sedimentary bedrock, consisting primarily of rhythmically bedded sandstone, siltstone, and shale or slate (Gerstel and Lingley, 2000).

5.2.5 Ruby 2 Soils

The total depth of the Ruby 2 well is 291 cm (Figure 7). Approximately 20 cm of forest litter and duff overlie the mineral soil. From a depth of 20 cm to 151 cm, the soil has a silty clay loam texture and was moist during the augering of the well in July 2004. Between 151 cm and 172 cm, the soil texture is clay loam and was notably dry when originally augered from the well. The frequency of gravel size rock fragments increases between 172 cm and 243 cm and the soil texture is clay loam. From 243 cm to 291 cm, rock fragments are dominant in a sandy clay loam matrix. The soil parent material is mapped as Miocene marine sedimentary bedrock, consisting primarily of rhythmically bedded sandstone, siltstone, and shale or slate (Gerstel and Lingley, 2000).

5.2.6 Ruby 3 Soils

The total depth of the Ruby 3 well is 252 cm (Figure 7). Approximately 20 cm of forest litter and duff are on top of the mineral soil. From a depth of 20 cm to 63 cm, the soil texture is silty clay. Between 63 cm and 102 cm, the soil texture remains silty clay, however this layer is moist with a higher clay content indicated by a stickier texture. From 102 cm to 194 cm, the soil texture remains silty clay until the bottom of the layer where a thin clay layer is present and the soil moisture content grades from dry to moist and back to dry with mottling observed. Below 194 cm the soil texture is silty clay until the bottom of the well with both the frequency of pebble size rock fragments and soil moisture increasing with depth. The soil parent material is mapped as Miocene marine sedimentary bedrock, consisting primarily of rhythmically bedded sandstone, siltstone, and shale or slate (Gerstel and Lingley, 2000).

5.2.7 Talus 1 Soils

The total depth of the Talus 1 well is 250 cm (Figure 8). Approximately 24 cm of forest litter and duff are on top of the mineral soil. From a depth of 24 cm to 91 cm the soil texture is a clay loam with mottling observed. Between 91 cm and 122 cm, the soil texture becomes a sandy clay loam. From 122 cm to 152 cm below the ground surface, the soil texture changes to sandy loam and was dry during augering on June 30, 2004. From 152 cm to 168 cm, the soil texture is sandy loam with rust staining observed. The soil texture remains a sandy loam from 168 cm to 183 cm with rust staining no longer observed. From 183 cm to 213 cm the soil texture changes to loamy sand with many gravel rock fragments. Between 213 cm and 250 cm, the soil texture remains loamy sand, but the rock fragment content increases to a degree where the clasts appear to be supporting themselves with soil filling in between. The soil parent material is mapped as Miocene marine sedimentary bedrock, consisting primarily of rhythmically bedded sandstone, siltstone, and shale or slate (Gerstel and Lingley, 2000).

5.2.8 Talus 2 Soils

The total depth of the Talus 2 well is 366 cm (Figure 8). Approximately 24 cm of forest litter and duff are on top of the mineral soil. From a depth of 24 cm to 58 cm the soil texture is clay with mottling observed. Between 58 cm and 154 cm the soil texture is sandy clay loam. From 154 cm to 259 cm the soil texture remains sandy clay loam, however there is a significant increase in gravel size rock fragments. From 259 cm to 366 cm the soil texture is still sandy clay loam, but the gravel size rock fragment content notably decreases and the moisture content was high at the time of augering on August 16, 2004. The soil parent

material is mapped as Miocene marine sedimentary bedrock, consisting primarily of rhythmically bedded sandstone, siltstone, and shale or slate (Gerstel and Lingley, 2000).

5.2.9 Talus 3 Soils

The total depth of the Talus 3 well is 304 cm (Figure 9). There was little to no forest litter and duff on top of the mineral soil. From 0 cm to 259 cm the soil texture is silty clay with mottling observed and a moisture content that graded from moist at the top of this zone to dry in the middle to wet at the bottom of this zone during augering on June 16, 2004. Between 259 cm and 304 cm the soil texture is sandy clay loam with gravel rock fragments. The soil parent material is mapped as Miocene marine sedimentary bedrock, consisting primarily of rhythmically bedded sandstone, siltstone, and shale or slate (Gerstel and Lingley, 2000).

5.2.10 Talus 4 Soils

The total depth of the Talus 4 well is 366 cm (Figure 9). From 0 cm to 152 cm the soil texture is clay with observed mottling and samples were moist during augering on June 16, 2004. Between 152 cm and 274 cm the soil texture remains clay, but no mottling was noted and samples were dry during augering on June 16, 2004. From 274 cm to 320 cm the soil texture is clay, but contains a slightly higher sand and silt content. Between 320 cm and 366 cm, the soil texture is clay with observed mottling and samples were moist during augering on June 16, 2004. The soil parent material is mapped as Miocene marine sedimentary bedrock, consisting primarily of rhythmically bedded sandstone, siltstone, and shale or slate; however given the nature of the material observed during augering the parent material is more likely Quaternary alpine glacial outwash which is mapped nearby to the west (Gerstel

and Lingley, 2000). This was the only well where refusal was not reached during augering and the maximum well depth was based on the length of the auger rather than the depth to refusal which was the case with the other 9 wells.

5.3 Alsea Slope Groundwater Level Response

There are three wells installed on the Alsea slope, Alsea 1 at the top of the slope, Alsea 2 midslope, and Alsea 3 at the bottom of the slope (Figure 2). The Alsea slope wells are characterized by rapid water level rise and attenuation during and after high intensity precipitation events. All three wells on this slope are dry for most of the year except following precipitation events. Water levels rise rapidly over the course of 1 to 3 hours during these events. As the duration of a precipitation event continues, water levels continue to rise but at a much slower rate until the precipitation event ends or decreases in intensity. Once the precipitation event ends, well water levels retreat to below the depth of the instruments over the course of 1 to 5 days.

5.3.1 Alsea 1

The Alsea 1 well was dry for a large majority of the study period and rarely did the well water level rise above the pressure transducer (Figure 5). This is likely the result of the shallow depth of the soil over bedrock, the coinciding shallow well depth, and the location of the well near the top of a ridge. The moderate infiltration rate likely allows the water infiltrating into the subsurface to pass to the underlying bedrock which may be fractured enough in this location to allow the infiltrating water to pass through without perching on the bedrock. The location of the well near the ridge top limits the area contributing water to the

well, which likely minimizes the amount of water that accumulates in the soil at this location. Eleven water level peaks above the threshold depth of 120 cm below ground surface were identified during the two year period of record (n = 11). Three of these peaks occurred during a time period when all onsite rain gauges were not functioning, so only eight of the peaks could be compared with onsite precipitation data. On the rare occasion water levels were recorded in this well, the water rapidly rose to a peak in 1 to 2 hours and then rapidly attenuated over the course of 1 to 24 hours (Figures 10, 11, 12). The maximum peak water level reached was -101.7 cm below the ground surface on February 15, 2007 at 08:00 hours (Table 2).

No significant Kendall's τ correlations occurred between the cumulative hourly and daily onsite precipitation or the cumulative hourly and daily precipitation recorded at the Black Knob RAWS station for the intervals of cumulative precipitation evaluated (Table 3). The lack of a significant correlation probably reflects the small sample of water level peaks recorded in this well (n = either 8 or 11). Statistically significant (p-value < 0.05) linear regression models exist between peak levels and 1 and 2 hours of cumulative onsite precipitation. Both regression models had very similar p-values and R-squared values (Figure 13). The log-log transformed linear models did not improve the randomization of residuals or improve p- or R-squared values (Figure 13).

5.3.2 Alsea 2

The Alsea 2 well water level was above the pressure transducer continuously during prolonged periods of precipitation and fell below the pressure transducer during dry periods

for the period from February 2005 through February 2007 (Figure 5). For the Alsea 2 well, 74 peaks above the threshold value of 26 cm below the ground surface were selected for analysis (n = 74). Well water levels reached their peaks approximately 1 to 3 hours after rising above the pressure transducer and attenuated over the course of 3 to 5 days (Figures 10, 11, and 12). The maximum peak water level reached was -9.3 cm below the ground surface on January 12, 2006 at 21:00 hours (Table 2).

Kendall's τ correlation analysis of well water level peaks and cumulative precipitation were all statistically significant with p-values < 0.05 for both onsite precipitation and precipitation recorded at the Black Knob RAWS (Table 3). The most significant correlation occurred after 13 hours of cumulative precipitation. The median quantity for 13 hours of onsite cumulative precipitation is 2.5 cm with a minimum of 0.7 cm and a maximum of 6.8 cm. Kendall's τ correlation values within 0.1 of the most significant value ranged between 7 and 27 hours of cumulative precipitation recorded onsite (Table 3). The most significant correlation between water level peak and precipitation recorded at the Black Knob RAWS occurred after 21 hours of cumulative precipitation (Table 3). The median quantity for 21 hours of cumulative precipitation at the Black Knob RAWS is 4.1 cm with a minimum of 1.3 cm and a maximum of 12.8 cm. Kendall's τ correlation values within 0.1 of the most significant value ranged between 2 and 36 hours of cumulative precipitation recorded at the Black Knob RAWS (Table 3).

The linear regression model with the highest R-squared value was between well water level peaks and 13 hours of cumulative precipitation (Figure 14). Following the log-log transformation, the R-squared value improved slightly and the residuals did become slightly

more random (Figure 14). All of the linear regression models were significant with p-values < 0.05 with the exception of peak levels and 1 hour of cumulative onsite precipitation.

5.3.3 Alsea 3

The Alsea 3 water level was above the pressure transducer in the well during periods of prolonged precipitation and below the level of the pressure transducer during dry periods (Figure 6). For the Alsea 3 well, 58 peaks above the threshold of 26 cm below ground surface were selected for analysis (n = 58). During precipitation events, the well water level rises rapidly over the course of 1 to 3 hours, except following long dry periods (Figures 10, 11, and 12). During precipitation events following prolonged periods without precipitation, the water level in the Alsea 3 well rises at a variable rate from 1 to 36 hours. The maximum peak water level reached was -9.2 cm below the ground surface on March 26, 2005 at 08:00 hours (Table 2).

Almost all Kendall's τ correlations between peak values and onsite cumulative precipitation were significant with only the 72 hour, 7 day, and 14 day cumulative precipitation correlations having p-values > 0.05 (Table 3). The most significant correlation between Alsea 3 peaks and cumulative precipitation occurred after 3 hours. The median quantity for 3 hours of onsite cumulative precipitation is 0.9 cm with a minimum of 0.1 cm and a maximum of 2.84 cm. Kendall's τ correlations within 0.1 of the most significant value ranged between 1 and 18 hours of onsite cumulative precipitation (Table 3). Kendall's τ analysis of peak levels and cumulative precipitation recorded at the Black Knob RAWS had the best correlation following 2 hours of cumulative precipitation. The median quantity for 2

hours of cumulative precipitation at the Black Knob RAWS is 0.8 cm with a minimum of 0.0 cm and a maximum of 2.7 cm. Kendall's τ correlations between peak levels and Black Knob RAWS cumulative precipitation from 1 hour to 27 hours are significant with the range from 1 hour to 12 hours having Kendall's τ values within 0.1 of the most significant value (Table 3).

Linear regression modeling for peak levels and 3 hours of onsite precipitation had the highest R-squared value (Figure 15). The log – log transformation decreased the R-squared value from 0.383 to 0.358, however the residuals did become more random, so the log – log transformation presents a better model in this case (Figure 15). All of the linear regression models were significant with the exception of 48 hours, 72 hours, and 7 days of cumulative onsite precipitation. However, R-squared values decreased as cumulative precipitation increased from 3 hours.

5.3.4 Alsea Summary

The three wells on the Alsea slope only record water levels during periods of high precipitation; none record a continuous water level for the entire year. All three wells at the Alsea site exhibit rapid well water level increases during precipitation events. This rapid water level rise usually occurs over the course of a few hours (Figures 10, 11, and 12). The timing of the well water level response is different between the three wells following dry periods and similar during periods with more frequent precipitation events. Water levels in the Alsea 3 well attenuate at a more rapid rate than water levels in the Alsea 2 well, which may indicate soils around the Alsea 3 well have a locally higher permeability due to the

gravel content of the soil at depth or macropores in the soil at this location (Figures 10, 11, and 12). The Alsea 1 well does not have enough data to make a reliable comparison of water level response characteristics, which is likely the result of the shallow well depth and the location of the well near a ridge top which limits the area contributing water to the location.

Kendall's τ correlation analysis indicates a stronger correlation between cumulative precipitation measured onsite and peak water levels compared with cumulative precipitation measured at the Black Knob RAWS (Table 3) for both the Alsea 2 and the Alsea 3 wells. No significant Kendall's τ correlations were calculated for either precipitation data set and peak well water levels for the Alsea 1 well. Linear regression models for the Alsea 2 and Alsea 3 wells had the best fit for the same onsite cumulative precipitation values as the strongest Kendall's τ correlations, which occurred at 13 hours and 3 hours respectively. Although no Kendall's τ correlations at the Alsea 1 slope were significant, linear regression models for 1 and 2 hours of cumulative onsite precipitation and peak water levels were similarly significant and had high R-squared values of 0.711 and 0.712 respectively (Figure 13).

5.4 Ruby Slope Groundwater Level Response

There are three wells installed on the Ruby slope, Ruby 1 at the top of the slope, Ruby 2 midslope, and Ruby 3 at the bottom of the slope (Figure 2). Well water levels at the Ruby site rise rapidly to peaks during precipitation events. The rapid water level rise generally occurs over a 2 to 10 hour period. Following the period of rapid rise, well water levels in two of the three wells rise only slightly even if the precipitation event continues at a similar intensity (Figures 6 and 7). The water level in the well at the top of the slope appears to

continue to rise until a decrease in precipitation intensity occurs. Peaks usually attenuate between 10 hours and 2 days following a precipitation event. Two of the three wells on this slope have water levels below the recording instrument most of the year and only record water levels during and following precipitation events. The Ruby 3 well has water above the recording instrument all year which provides a continuous water level record at that location.

5.4.1 Ruby 1

The Ruby 1 well is located at the top of the Ruby slope (Figure 2). The water level in the well rises above the recording instrument during precipitation events, but during a majority of the year the water level in the well is not recorded (Figure 6). From February 2005 through February 2007, 23 peaks occurred above the threshold minimum of 195 cm and were selected for analysis (n = 23). Once the water level was above the recording instrument during a precipitation event, it rose steadily to a peak over 4 to 10 hours. As soon as a precipitation event ends, the water level in the Ruby 1 well attenuates over the course of 16 hours to 2 days (Figures 16, 17, and 18). There is a disproportionate water level rise compared with the amount of precipitation that falls. During precipitation events that deliver between 2 and 4 cm of precipitation over a 24-hour period, well water levels rise between 75 and 150 cm (Figures 16, 17, and 18). The maximum peak water level reached was -106.8 cm below the ground surface on December 11, 2006 at 10:00 hours (Table 2).

Kendall's τ correlation analysis had significant correlations between peak water levels and cumulative precipitation for almost half of the time periods analyzed. Kendall's τ values were significant for well water peaks and 3 to 6 hours of cumulative onsite precipitation in

addition to 8 to 23 hours of cumulative onsite precipitation (Table 4). Significant Kendall's τ correlation values were all within 0.1 of the most significant value with the exception of 14 and 20 hours of cumulative onsite precipitation. The most significant Kendall's τ correlation value was for peak well water level and 10 hours of cumulative onsite precipitation (Table 4). The median quantity for 10 hours of onsite cumulative precipitation is 3.6 cm with a minimum of 2.0 cm and a maximum of 5.8 cm. Kendall's τ correlation analysis for peak well water levels and cumulative precipitation recorded at the Black Knob RAWS was significant for 7 through 12, 14, and 17 through 24 hours of cumulative precipitation (Table 4). All significant Kendall's τ correlation values were within 0.1 of the most significant value. The most significant Kendall's τ correlation value is between 10 hours of cumulative precipitation recorded at the Black Knob RAWS and Ruby 1 peak well water levels (Table 4). The median quantity for 10 hours of cumulative precipitation at the Black Knob RAWS is 5.2 cm with a minimum of 1.0 cm and a maximum of 9.7 cm.

Linear regression models for peak water levels and onsite cumulative precipitation were all significant with the exception of 1 and 2 hours of cumulative precipitation, and all values greater than or equal to 30 hours of cumulative precipitation. In addition to the non-significant linear models listed above, log-log transformed linear models using 5, 6, 7, 8, 27, 28, and 29 hours of onsite cumulative precipitation are also insignificant. The most significant linear model was the untransformed linear model between peak water levels and 11 hours of cumulative precipitation with an R-squared value of 0.363 (Figure 19).

5.4.2 Ruby 2

During most of the year, the Ruby 2 water level only rises above the pressure transducer during precipitation events with the exception of periods of frequent precipitation in which the well water level is recorded for a week or two at a time (Figure 7). During the period of time from February 2005 through February 2007, 41 peaks above the threshold of 45 cm below the ground surface were identified and used for analysis (n = 41). Well water levels peak rapidly once they get above the pressure transducer, usually within 2 hours during wet months and between 5 and 9 hours during dry months. Following the period of rapid water level rise, the water level generally plateaus for the duration of the precipitation event prior to attenuation (Figures 16, 17, and 18). The water level attenuates over the course of 8 to 72 hours to pre-rain event levels. Well water level response is disproportionate to the amount of precipitation that falls. A storm that delivers 5 to 10 cm of rain over a 24-hour period produces a 50 cm to 100 cm water level rise in the well (Figures 16, 17, and 18). The maximum peak water level reached was -11.1 cm below the ground surface on January 9, 2006 at 07:00 hours (Table 2).

Kendall's τ correlation analysis indicates a significant correlation between cumulative onsite precipitation and well water level peaks for all cumulative precipitation values with the exception of 7 and 14 days. Kendall's τ values within 0.1 of the most significant value ranged from 7 to 48 hours of cumulative onsite precipitation with the most significant correlation between 32 hours of cumulative onsite precipitation and well water level peaks (Table 4). The median quantity for 32 hours of onsite cumulative precipitation is 4.4 cm with a minimum of 2.1 cm and a maximum of 10.4 cm. Kendall's τ values for well water levels

and precipitation recorded at the Black Knob RAWS were all significant with the exception of 72 hours, 7 days, and 14 days of cumulative precipitation. Kendall's τ correlation values within 0.1 of the most significant value ranged between well water levels and 1 to 35 hours of cumulative precipitation recorded at the Black Knob RAWS. The most significant correlation was between peak well water level and 28 hours of cumulative precipitation recorded at the Black Knob RAWS (Table 4). The median quantity for 28 hours of cumulative precipitation at the Black Knob RAWS is 5.9 cm with a minimum of 2.9 cm and a maximum of 13.3 cm.

Linear regression models for untransformed and log – log transformed peak well water levels and onsite cumulative precipitation were all significant with the exception of 1 hour, 7 days, and 14 days of onsite cumulative precipitation. The linear regression model with the highest R-squared value was between peak water levels and 11 hours of onsite cumulative precipitation, with an R-squared value of 0.412. The log – log transformed linear regression model did not improve the significance of the model nor did it improve the R-squared value (Figure 20).

5.4.3 Ruby 3

The Ruby 3 well is located at the bottom of the Ruby slope (Figure 2). Water levels were above the recording instrument in the well for the entire two year monitoring period resulting in a continuous well water level record at this location from February 2005 to February 2007 (Figure 7). Over the course of the two year period, 81 water level peaks occurred above the 26 cm depth below ground surface threshold value and were the sample set used in statistical

analysis (n = 81). The water level in the Ruby 3 well rises rapidly to a peak during a precipitation event. As a precipitation event continues, the Ruby 3 water level may continue to rise slowly, but at a much slower rate than the initial rise (Figures 16, 17, and 18). Following dry periods, the rapid water level rise is much more dramatic than water level rise during precipitation events occurring during the rainy season (Figure 7). The maximum peak water level reached was -8.6 cm below the ground surface on February 4, 2006 at 16:00 hours (Table 2).

Kendall's τ correlation results were significant for all water level peak and cumulative onsite precipitation intervals with the exception of 2 to 4 hours, 7 days, and 14 days of cumulative precipitation (Table 4). Kendall's τ values within 0.1 of the most significant value ranged between 11 and 36 hours of cumulative onsite precipitation, with the best Kendall's τ correlation between peak water levels and 21 hours of cumulative onsite precipitation. The median quantity for 21 hours of onsite cumulative precipitation is 2.6 cm with a minimum of 0.8 cm and a maximum of 8.3 cm. Kendall's τ correlation values for peak water levels and precipitation recorded at the Black Knob RAWS were significant for all of the intervals analyzed with the exception of 1 hour, 2 hours, 4 hours, 5 hours, 72 hours, 7 days, and 14 days of cumulative precipitation (Table 4). Kendall's τ correlation values within 0.1 of the most significant valued ranged between 10 and 36 hours of cumulative precipitation recorded at the Black Knob RAWS with the best Kendall's τ correlation between 20 hours of cumulative precipitation and peak water levels (Table 4). The median quantity for 20 hours of cumulative precipitation at the Black Knob RAWS is 3.4 cm with a minimum of 0.2 cm and a maximum of 12.8 cm.

Linear regression models for untransformed and log – log transformed peak water levels and cumulative onsite precipitation were all significant with the exception of 7 and 14 days of cumulative onsite precipitation. The linear model with the highest R-squared value was the log – log transformed data for peak water levels and 21 hours of cumulative onsite precipitation, which had an R-squared value of 0.235. The log – log transformation increased the randomization of the residuals in the linear regression model for peak water levels and 21 hours of onsite cumulative precipitation (Figure 21).

5.4.4 Ruby Summary

The water levels in all of the Ruby slope wells respond rapidly to precipitation events. This is likely due in part to the moderate infiltration rate of the soils. Water level peaks are usually reached within hours from the time the water level begins to rise. As precipitation continues to fall, the water level in the Ruby 1 well continues to rise at an almost constant rate until the precipitation event is over at which time the water level attenuates rapidly. In contrast, the water level in the Ruby 2 and Ruby 3 wells rises rapidly over the course of a few hours and then levels off and only rises slowly for the duration of the precipitation event, regardless of the precipitation intensity (Figures 16, 17, and 18). In addition, the water level in the wells rises disproportionately compared to the amount of precipitation that falls during precipitation events. During wet periods, the disproportionate water level rise is much more dramatic than during dry periods in the Ruby 1 well. The opposite is true for the Ruby 2 and Ruby 3 wells. The disproportionate water level rise is more dramatic during dry periods than during wet periods (Figures 16, 17, and 18).

The strongest Kendall's τ correlations between peak water levels and cumulative onsite precipitation are 10 hours of cumulative precipitation for the Ruby 1 well, 32 hours of cumulative precipitation for the Ruby 2 well, and 21 hours of cumulative precipitation for the Ruby 3 well. The strongest Kendall's τ correlations between peak water levels and cumulative precipitation recorded at the Black Knob RAWS are 10 hours of cumulative precipitation for the Ruby 1 well, 28 hours of cumulative precipitation for the Ruby 2 well, and 20 hours of cumulative precipitation for the Ruby 3 well.

Linear models for untransformed well water level peaks and cumulative onsite precipitation had the highest R-squared values for 11 hours of cumulative precipitation at the Ruby 1 well, 11 hours of cumulative precipitation at the Ruby 2 well, and 21 hours of cumulative precipitation at the Ruby 3 well. The log – log transformed linear models did not improve the randomization of residuals or R-squared values for the Ruby 1 or Ruby 2 wells, however the log – log transformation did improve both the randomization of the residuals and R-squared values for the Ruby 3 well.

5.5 Talus Slope Groundwater Level Response

The Talus slope well configuration is similar to the northern two slopes with an additional well at a similar elevation to that of the third well. The Talus 1 well is at the top of the slope, the Talus 2 well is midslope, and the Talus 3 and Talus 4 wells are at the bottom of the slope (Figure 2). Water levels in the Talus slope wells rise rapidly over the course of 2 to 7 hours during precipitation events and generally attenuate over the course of 6 hours to 4 days. Three of the four wells only have water levels above the recording instrument during

precipitation events and during the rainy season. The Talus 4 well recorded a water level for the entire two year period, resulting in a continuous water level record from February 2005 to February 2007.

5.5.1 Talus 1

The water level in the Talus 1 well was above the recording instrument during precipitation events and during the rainy season (Figure 8). During extended dry periods, the Talus 1 well water level was below the recording instrument. Over the two year period of record, 72 peaks occurred above the threshold value of 100 cm below the ground surface and were selected for analysis (n = 72). Water levels in the Talus 1 well rise over the course of 3 to 7 hours during precipitation events and take approximately 3 to 10 days to attenuate. There is a significantly larger water level rise observed in the well in comparison with the amount of precipitation that falls. The magnitude and timing of the disproportionate water level rise depends on the intensity of the precipitation event and the antecedent soil moisture conditions (Figures 22, 23, and 24). The maximum peak water level reached was –29.8 cm below the ground surface on January 9, 2006 at 08:00 hours (Table 2).

Kendall's τ correlation values for peak well water levels and cumulative onsite precipitation are all significant for the intervals evaluated with the exception of 14 days of cumulative precipitation (Table 5). The significant correlation values within 0.1 of the most significant value ranged between 3 and 7 hours of cumulative precipitation with the best correlation value for peak water level and 4 hours of cumulative precipitation. The median quantity for 4 hours of onsite cumulative precipitation is 0.5 cm with a minimum of 0.03 cm

and a maximum of 3.4 cm. Kendall's τ correlation values for peak well water levels and cumulative precipitation recorded at the Black Knob RAWS are all significant for the Talus 1 well (Table 5). The significant correlations within 0.1 of the most significant value ranged between peak water levels and 1 to 5 hours of cumulative precipitation. The best correlation is between peak water levels and 3 hours of cumulative precipitation at the Black Knob RAWS (Table 5). The median quantity for 3 hours of cumulative precipitation at the Black Knob RAWS is 0.5 cm with a minimum of 0.0 cm and a maximum of 3.4 cm.

Linear regression models for peak water levels and cumulative onsite precipitation are all significant with the exception of the model between peak water levels and 14 days of cumulative onsite precipitation. The best linear model is between peak water levels and 5 hours of cumulative precipitation, which has an R-squared value of 0.569 (Figure 25). The log – log transformed linear model did not have an improved R-squared value or p-value and the residuals are similarly random (Figure 25).

5.5.2 Talus 2

The Talus 2 well water level was below the recording instrument for a majority of the period of record except following precipitation events and extended wet periods (Figure 8). Between February 2005 and February 2007, 37 peaks occurred above the threshold value of 100 cm below ground surface and were used for quantitative analysis (n = 37). Well water levels rise to peaks rapidly during high intensity precipitation events and more gradually during low intensity precipitation events. Peak water levels attenuate rapidly following precipitation events that occur during dry periods and attenuate slowly during wet periods

(Figures 22, 23, and 24). There is a significantly greater rise in well water level during a precipitation event in comparison with the amount of precipitation that falls. During precipitation events that occur during dry periods, this water level rise is greater than during precipitation events that occur during wet periods (Figure 8). The maximum peak water level reached was -31.6 cm below the ground surface on November 10, 2006 at 11:00 hours (Table 2).

Kendall's τ correlation values for peak water levels and cumulative onsite precipitation were significant for the intervals evaluated between 13 hours and 7 days of cumulative precipitation (Table 5). The only significant correlation within 0.1 of the most significant value was 72 hours of cumulative onsite precipitation with the best correlation between peak water level and 48 hours of cumulative onsite precipitation. The median quantity for 48 hours of onsite cumulative precipitation is 5.5 cm with a minimum of 2.4 cm and a maximum of 12.0 cm. Kendall's τ correlation values for peak water levels and precipitation recorded at the Black Knob RAWS are all significant with the exception of 1 through 8, 10, and 11 hours of precipitation. The significant correlations within 0.1 of the most significant value were between peak water levels and 22 hours, 48 hours, 72 hours, and 14 days of precipitation with the best correlation between peak water levels and 7 days. The median quantity for 7 days of cumulative precipitation at the Black Knob RAWS is 16.8 cm with a minimum of 7.4 cm and a maximum of 38.3 cm.

Few linear regression models are significant for the Talus 2 well. The most significant linear regression model is between peak water levels and 48 hours of cumulative precipitation with an R-squared value of 0.241 (Figure 26). The log – log transformed linear

regression model improved the R-squared value to 0.299 and increased the randomization of the residuals (Figure 26).

5.5.3 Talus 3

The Talus 3 well water level is above the recording instrument in the well during the rainy season and falls below the recording instrument during extended dry periods (Figure 9). From February 2005 to February 2007, 48 peaks occurred above the threshold depth of 100 cm below ground surface and were used for quantitative analysis (n = 48). The water level in the Talus 3 well rises over the course of several hours and attenuates over the course of several days (Figures 22, 23, and 24). The water level rise observed in the well is disproportionate to the amount and timing of rainfall during precipitation events. The maximum peak water level reached was –29.7 cm below the ground surface on March 26, 2005 at 11:00 hours (Table 2).

Kendall's τ correlation values for peak water levels and onsite cumulative precipitation were all significant with the exception of 1 hour, 48 hours, 72 hours, 7 days, and 14 days of cumulative precipitation (Table 5). The significant correlations within 0.1 of the most significant value are between peak water levels and 4, 6, and 12 to 15 hours of cumulative precipitation with the best correlation between peak water levels and 5 hours of cumulative precipitation. The median quantity for 5 hours of onsite cumulative precipitation is 1.0 cm with a minimum of 0.3 cm and a maximum of 3.0 cm. Kendall's τ correlation values for peak water levels and cumulative precipitation recorded at the Black Knob RAWS are all significant with the exception of 48 hours, 72 hours, 7 days, and 14 days of cumulative

precipitation (Table 5). The significant correlations within 0.1 of the most significant value range from 1 to 5 hours and 10 to 30 hours of cumulative precipitation at the Black Knob RAWS with the best correlation between peak water levels and 2 hours of cumulative precipitation (Table 5). The median quantity for 2 hours of cumulative precipitation at the Black Knob RAWS is 0.3 cm with a minimum of 0.0 cm and a maximum of 1.7 cm.

The most significant linear regression model for peak water levels and cumulative onsite precipitation is between peak water levels and 5 hours of cumulative onsite precipitation, which has an adjusted R-squared value of 0.422 (Figure 27). The log – log transformed linear regression model did not improve the significance or R-squared values and it did not result in improved randomization of residuals (Figure 27).

5.5.4 Talus 4

The water level in the Talus 4 well was above the recording instrument all year resulting in a continuous water level record for the two year period of record. During this period, 156 water level peaks above the threshold value of 50 cm below the ground surface occurred and are used for quantitative analysis (n = 156). The water level in the Talus 4 well responds rapidly during precipitation events rising to a peak level within 1 to 3 hours. This peak level is maintained for the duration of the precipitation event, at which time the water level gradually attenuates (Figures 22, 23, and 24). Water level rise in the Talus 4 well is significantly greater than the amount and timing of precipitation that falls during precipitation events. The maximum peak water level reached was -22.1 cm below the ground surface on January 12, 2006 at 20:00 hours (Table 2).

Kendall's τ correlation values for peak water levels and cumulative onsite precipitation are significant for all precipitation intervals evaluated (Table 5). The significant correlations within 0.1 of the most significant value range between peak water levels and 4 to 36 hours of cumulative onsite precipitation with the best correlation between peak water level and 9 hours of cumulative onsite precipitation. The median quantity for 9 hours of onsite cumulative precipitation is 1.4 cm with a minimum of 0.03 cm and a maximum of 5.3 cm. Kendall's τ correlation values for peak water levels and cumulative precipitation measured at the Black Knob RAWS are also all significant (Table 5). The significant correlations within 0.1 of the most significant value ranged between peak water levels and 3 to 36 hours of cumulative precipitation measured at the Black Knob RAWS, with the best correlation between peak water level and 16 hours of cumulative precipitation. The median quantity for 16 hours of cumulative precipitation at the Black Knob RAWS is 1.9 cm with a minimum of 0.3 cm and a maximum of 12.2 cm.

All of the linear regression models for peak water levels and cumulative onsite precipitation are significant. The linear regression model for peak water levels and 7 hours of cumulative precipitation has the highest R-squared value of 0.535 (Figure 28). The log – log transformed linear regression model did not improve the models' significance or R-squared value, although it did appear to increase randomization of residuals (Figure 28).

5.5.5 Talus Summary

Talus slope well water levels rise and attenuate in a similar pattern during low to moderate precipitation events during wet periods of the year (Figure 23). Water level rise and

attenuation in the Talus 2 well is more rapid and greater in magnitude than the other wells during precipitation events occurring after a dry period (Figures 22 and 24). Talus slope water level peaks generally take multiple days to attenuate with the exception of the Talus 2 well water level which attenuates over several hours during dry period precipitation events. This may be the result of the soils at the Talus 2 well having a higher sand content, and therefore a potentially higher permeability, than the other wells. During prolonged precipitation events, the Talus 4 water level remains relatively constant and does not follow the rise and attenuation pattern of the other wells (Figure 24). The response characteristics of the Talus 4 well are likely different due to the high clay content of the soil, which restricts water flow.

Kendall's τ correlation analysis of peak well water levels and intervals of cumulative precipitation from 1 hour to 36 hours, 48 hours, 72 hours, 7 days, and 14 days had different levels of significance at each well. The best correlation is with 4 hours of cumulative onsite precipitation for the Talus 1 well, 48 hours for the Talus 2 well, 5 hours for the Talus 3 well, and 9 hours for the Talus 4 well. The Talus 2 well is anomalous because there are two distinct groups of peak water levels in this well that make the statistical analysis less significant. These two groups of peaks are best illustrated by the linear regression model plot (Figure 26). The most significant Kendall's τ correlations between peak water levels and cumulative precipitation recorded at the Black Knob RAWS were 3 hours for the Talus 1 well, 7 days for the Talus 2 well, 2 hours for the Talus 3 well, and 16 hours for the Talus 4 well. Again, the anomalous lag for the Talus 2 well reflects its development of two distinct groups of peaks.

Linear regression models for peak water levels and cumulative onsite precipitation have the highest R-squared value for 5 hours at Talus 1, 48 hours at Talus 2, 5 hours at Talus 3, and 7 hours at Talus 4. The Talus 2 linear regression model is again complicated by the apparent separation of two distinct groups of peaks. From visual inspection of Figure 26, 48 hours of cumulative onsite precipitation does not appear to correlate as well with peak water levels as compared to shorter periods of time.

5.6 DHSVM results

The DHSVM-predicted streamflow value for the forested scenario could not be calibrated to actual streamflow data from the basin because no stream gauges are installed in the basin. The closest available stream gauge data is from the Queets River near Clearwater, approximately five kilometers southeast of the study area. The contributing drainage area to the Queets River gauge is approximately 1150 sq-km (USGS, 2009) compared to a study basin area of approximately 2 sq-km. As a result, a direct comparison of discharge values is not reasonable; however the Queets River gauge data were divided by a scaling factor to get flow volumes on the same order of magnitude as DHSVM predicted flows for the study area. In general, DHSVM predicted streamflow peak and recession timing for the study basin is in good agreement with gauge measurements from the Queets River gauge (Figure 29). The agreement between DHSVM-predicted values and Queets River gauge measurements, especially when comparing recession curves, indicates the study basin is reasonably modeled. Once the basin hydrology was reasonably simulated, changes to the land cover

input layer were made in order to model the effects that different vegetation cover might have on basin hydrology.

Two ground cover scenarios were modeled with the DHSVM for the two years from February 2005 through February 2007. The first was a mixed conifer forest-covered basin and the second was an entirely shrub-covered basin. The modeled basin is composed of several smaller basins that encompass the area where the monitoring instruments are installed. The shrub-covered basin was used to simulate basin hydrology following a clear-cut timber harvest. The basin was modeled with a shrub land-cover as opposed to a bare soil land-cover as a result of previous work by Mitchell and Kelleher (personal communication, 2008) that found the minimum DHSVM soil water loss back out to the atmosphere, and therefore the maximum potential recharge to the groundwater table, under shrub land cover conditions. The previous work found model predictions for evapotranspiration in a bare soil condition were higher than in a shrub vegetation cover as a result of high values for modeled evaporation directly out of the bare soil (Mitchell, personal communication, 2008). Results from the model simulations of the forested and shrub-covered basins are summarized for the entire two year period of February 2005 through February 2007 and in the three month time periods February – April, May – July, August – October, and November – January (Table 6). Modeled changes in streamflow output, water table depth, soil moisture, and evapotranspiration resulting from change in vegetation cover are discussed below.

5.6.1 Streamflow Output

In general, simulated increases in streamflow resulting from vegetation cover change were smaller during the rainy season months and larger during the drier months when total streamflow volume is low. When DHSVM was run with a shrub vegetation cover across the entire watershed for the two year period from February 2005 through February 2007, the average streamflow increased by 6 percent compared with a completely forested basin (Table 6). Simulated average streamflow had the greatest percentage increase, at 103 percent, when vegetation cover was changed from forest to shrub cover during the three month period of August 2006 through October 2006 and the smallest percentage increase, at 1 percent, during the three month period of November 2005 through January 2006. Although the 103 percent increase is large as a percentage, the total flow during this three month period was on the order of 30X lower than streamflow volumes during the rainy season.

5.6.2 Groundwater Level

Model results for the forested basin scenario predict a basin wide average groundwater level that is similar to actual measured values. The measured groundwater level response used for comparison to model results is the average of the Ruby 3 and Talus 4 wells. These sites were averaged and used for comparison because they are the only two wells where water was present (and recorded) year round. The modeled forested groundwater level is closest to measured values during periods of prolonged high groundwater levels. Precipitation events occurring when water levels are low produce a much greater water level rise and fall in the instrumented wells relative to the DHSVM results.

The DHSVM results for the shrub vegetation cover, which is used to model a post-timber harvest groundwater level, are almost identical to the modeled forested groundwater level (Figure 30). The modeled shrub-covered basin results in a higher groundwater level during periods when the water level is low during the spring and summer. Over the entire two year period from February 2005 through February 2007, DHSVM results for depth to the water table decreased slightly when basin vegetation cover is changed from a forest condition to a shrub condition.

5.6.3 Soil Moisture

Soil moisture conditions under simulated forested and shrub-covered basin scenarios were very similar. Over the two year period from February 2005 through February 2007, soil moisture was modeled to slightly increase.

5.6.4 Evapotranspiration

Changes in landscape vegetation affects evapotranspiration rates. For the two year period from February 1, 2005 through January 31, 2007, DHSVM results for a shrub vegetation cover show a 27.4 percent decrease in total evapotranspiration relative to the forested basin scenario resulting in approximately 24.6 cm of water remaining in the subsurface that would otherwise be lost through evapotranspiration (Table 6). The decrease in evapotranspiration is greatest as a percentage, at 52.4 percent, during the three month period from November 2006 through January 2007. This 52.4 percent change resulted in an additional 1.8 cm of water remaining in the subsurface. The decrease in evapotranspiration is greatest as a quantity of water, at 5.2 cm, during the three month period from February 2006 through April 2006.

This additional 5.2 cm of water remaining in the subsurface represents a 45.2 percent decrease in evapotranspiration.

6.0 DISCUSSION

The purpose of this thesis is to establish a baseline groundwater response to precipitation events and model potential differences in this response following logging operations in a small basin near Kalaloch, Washington. Both qualitative and quantitative methods are used to describe this response as recorded by instruments in the field. The DHSVM is used to model the differences in basin hydrology between a conifer forest and shrub vegetation cover. The shrub vegetation cover represents basin vegetation following a clear-cut timber harvest.

6.1 Reoccurring Peak Levels

Observed well water levels rise rapidly during precipitation events. This rapid rise generally occurs over the course of several hours and in most of the wells the water level appears to rise to reoccurring discernible peak levels (Figures 5 - 9). Differences in the well water response between the wells are likely the result of localized differences in the hydrologic properties of the soil, differences in the depth of the wells (and therefore differences in the soil depth above bedrock), and the location of the wells on the hillslope. Wells located near the ridge top have a smaller contributing area relative to midslope wells and wells located at the base of the slope and so they generally have lower water levels and shorter recoveries to precipitation events.

The reoccurring peak water levels are likely controlled by subsurface soil characteristics and antecedent moisture conditions. Similar maximum peak water levels are attained over a range of precipitation event magnitudes. When cumulative precipitation and water level are plotted on the same graph, maximum and intermediate peak levels can be observed over a wide range of precipitation timing and quantity (Figures 5 - 9). Perhaps the strongest evidence for subsurface soil characteristics controlling water level peaks is provided by the maximum peak levels among the wells. In most cases, the maximum peak water level corresponds with the contact between forest litter and duff with the underlying mineral soil observed during the boring of the wells (Gerstel, 2005, personal communication).

6.2 Disproportionate Water Level Rise

Another characteristic of the water level response to precipitation events at the Kalaloch site is the disproportionately large water level rise compared to the degree of precipitation and infiltration. This phenomenon is most distinctly pronounced during the months of the year when the majority of the annual precipitation falls. There are several mechanisms that can cause this disproportionate water level rise.

The Lisse effect is a mechanism that can cause a rapid water level rise in a well (Healy and Cook, 2002; Weeks, 2002). In order for this phenomena to take place, installed wells must penetrate the groundwater table and only be screened below the water level. The Lisse effect occurs during a precipitation event when a wetting front traps air in the unsaturated zone and as the wetting front infiltrates into the soil, the downward pressure from

the trapped air forces well water levels to go up. The Lisse effect is not widely documented in field observations and is not thought to be a significant hydrologic process, however it could lead to overestimates of recharge in areas where the Lisse effect is occurring and not documented (Weeks, 2002).

It is unlikely that the wells are experiencing the Lisse effect because one of the prerequisites for this phenomenon is the entire screened portion of the well must be below the water table. At the research site, all of the wells have screened portions above the water table for a majority of the year and definitely during times when the rapid water level rise is observed. During the winter months, some of the wells may have the entire screened section beneath the water table, but macropores in the upper soil layers from tree roots and bioturbation make it unlikely a seal would form that would allow for air compression in the unsaturated zone.

The most likely phenomena responsible for the rapid water table rise observed at the Kalaloch research site is the reverse Wieringermeer effect (Gillham, 1984; Weeks, 2002; Jaber et al., 2006). Water is held by surface tension in the unsaturated zone which extends from near the ground surface to the water table. If the unsaturated soil layer is close to saturation, only a small amount of infiltrated water is required to saturate the soil column. Once saturated, the pore water is liberated from tension allowing groundwater to flow and fill the well (O'Brien, 1982; Dingman, 2002). The silt loam soils at the site likely have pore throats narrow enough to provide strong capillary forces when unsaturated and allow for relatively quick transmission of water when saturated. In addition, the cool, wet climate at the research site maintains a high relative humidity which restricts moisture from evaporating

out of the capillary fringe into the atmosphere. Both the grain size and climate characteristics are ideal conditions for maintaining a capillary fringe that extends close to the ground surface. Similar rapid water level rise has been observed in case studies done by Washington State Department of Transportation geologists in comparable weathered marine sedimentary bedrock geologic units in southwestern Washington (Badger, 2010, personal communication).

Subsurface storm flow can also be responsible for the observed rapid water level rise. Subsurface storm flow occurs when a permeable subsurface layer is underlain by a less permeable subsurface layer and a thin saturated zone forms above the less permeable layer (Scanlon et al., 2000; Smakhtin, 2002; and Dingman, 2002). An example of this is the permeable duff resting on top of the actual mineral soil. Once this zone is saturated, water flows on top of the mineral soil and through the duff and discharges as quick flow to surface water bodies. At the Kalaloch research site, if there is a storm flow layer and it intersects the screened portion of the well (or breaches the grout cap), the storm flow could be intercepted by the well. This could then fill up the well, giving the appearance of a rapid water table rise, but in reality the well would just be filling up with storm flow from a perched saturated layer (Figure 31). In other words, water flowing in the permeable layer above the impermeable layer enters the well, which is screened through the entire section of permeable and impermeable layers, giving the illusion that the water level in the entire subsurface has risen quickly when it is possible the underlying less permeable layer is still unsaturated.

Shallow subsurface storm flow interception by the wells is likely working along with the Wieringermeer effect to produce the observed water level response. Well logs from the

bore hole installation indicate the presence of an organic duff layer with damp, mottled, and oxidized soils immediately underneath (Gerstel, 2005, personal communication). The mottling and oxidation indicate these soils alternate frequently between saturated and unsaturated conditions. At depth, a dry layer of weathered fine-grained sandstone and siltstone is present and the bore logs indicate soils were usually damp near the bottom of the wells at the time when they were installed in the summer and fall of 2004. The thickness of these layers and the depth at which they are encountered varies for the specific well locations. Alternating layers of soils with different textures and moisture contents noted during well installation indicates the presence of subsurface soil layers with different permeabilities. This situation creates a condition for subsurface storm flow to be transmitted at a higher rate horizontally (slope parallel) through the more permeable layers when it cannot continue to infiltrate vertically due to the presence of a less permeable layer below. The less permeable layers are likely holding water in tension in a near saturated condition until precipitation infiltrates the soil. As the wetting front moves vertically downward through the soil layer, it converts the water held in tension to water allowed to flow through a saturated porous media. The effect of layers with different permeabilities may be evidenced in the water level record for a majority of the wells and this effect is conceptually illustrated in Figure 31.

Another possible explanation for the rapid water level rise is that the grouted well caps are being breached by surface water flow entering the well. If this is the case, the water level recorded in the well would not be representative of a subsurface water level. This would also mean that all of the wells were failing in the same manner, a scenario that does

not seem likely due to the quality control measures implemented during well construction. Additionally, the recession curves following water level peaks generally take days to attenuate. This is a response that is more typical of a subsurface water level and not a slug of water introduced into the well with unsaturated soils surrounding it. Furthermore, DHSVM hydrograph recession curves show similar attenuation characteristics, reinforcing the notion that the observed response is an actual phenomenon and not the result of faulty well construction.

6.3 DHSVM Basin Response

The DHSVM was used to investigate how the Kalaloch study site hydrology may change if the conifer forest is converted entirely to shrub vegetation. The shrub vegetation simulation was used to model potential effects of timber harvest on groundwater recharge to the system. By altering the vegetation in this way, evapotranspiration and canopy interception is decreased. This decrease potentially results in more water available to infiltrate into the subsurface and less water being lost from the system.

Because of the relatively small decrease in evapotranspiration losses during periods of peak groundwater levels, the modeled depth to the water table is almost identical for forested and shrub conditions in the wet months (Figure 30). During the drier months when the modeled water table is relatively low, the water table rises in the shrub-covered basin. The DHSVM results indicate that maximum peak annual water levels would not be expected to increase more than a centimeter or two as a result of converting vegetation cover from a conifer forest to shrub-covered basin, although an increase in peak water levels during spring

and summer would be expected for a shrub vegetation cover in the simulated basin (Figure 30).

6.4 Deep Groundwater Recharge

This is the first phase of an ongoing study to investigate the measured effects of timber harvest on peak groundwater levels and water level response to precipitation events in the study area. The motivation for this research is to better inform management decisions regarding proposed timber harvest operations in the groundwater recharge areas of deep-seated landslides. Increased groundwater levels have been associated with increased deep-seated landslide activity (Iverson and Major, 1987; Reid and LaHusen, 1998; Gerstel and Badger, 2002), however the effects of timber harvest on peak groundwater levels are not well understood. Although my study is intended to provide information to improve understanding of the effects of timber harvest on groundwater levels, the heterogeneities of the natural environment may confound direct cause-and-effect relationships.

Well water level observations from February 2005 through February 2007 indicate that there are likely a series of perched sub-surface water lenses that correspond with differences in permeability of the soil layers and marine sedimentary bedrock underlying the research site. In addition, 8 of the 10 wells go dry for large portions of the year, so it is unclear whether water levels recorded in those wells are capturing a subsurface water table response or just the response of a water level in a more permeable layer over a perching layer. In the other two wells, Ruby 3 and Talus 4, water is present year-round. Even though Ruby 3 and Talus 4 record a water level year round, the possibility that they are perched

water levels cannot be eliminated given the limited scope of this investigation. The water level response to precipitation events in the other eight wells exhibit similar response characteristics as the two wells with water in them year round (i.e., a rapid rise and attenuation). These similar response characteristics could indicate that the true water table is being recorded.

Because of the absence of year-round water levels in all wells, the layering of more and less permeable layers, the reverse Wieringermeer effect, and the likelihood of horizontal water movement in the form of subsurface storm flow, accurately characterizing potential recharge to the deep groundwater table is difficult. Accomplishing this is not within the scope of this study, but would be useful information if a methodology was developed to isolate potential recharge to the deep groundwater at this site. In a previous case study, Iverson and Major (1987) demonstrated that the residual friction angle of a deep-seated landslide is insensitive to changes in water table depth less than 1 m. As a result, any estimate of increased recharge to the deep groundwater table resulting from timber harvest in the catchment would need to be significant before potential changes to deep-seated landslide stability would be expected.

6.5 Potential Impacts on Slope Stability

Significant changes in the hydrologic response of a slope following timber harvest have the potential to alter the stability of that slope. Mathematical modeling done by Iverson (2000) to investigate the relationship between infiltrating rain and changes in slope stability indicate that infiltrating rain will have the largest effect on shallow soils over less permeable bedrock.

In this setting, infiltrating rain can decrease the stability of the slope by adding weight and decreasing cohesion and the effective stress resulting in a landslide. This becomes especially problematic as trees roots decay causing a loss in root cohesion.

At the Kalaloch research site, if maximum peak water levels are observed to increase following timber harvest, this could indicate that changes in hydrology due to timber harvest have the potential to decrease shallow slope stability on steeper slopes with similar soil and subsurface characteristics. Of all the wells instrumented as part of this study, the wells at the top of the slopes (Alsea 1, Ruby 1, and Talus 1) are most likely to show an increase in maximum peak water level because peak water levels at the top of the slope generally do not get as close to the ground surface as the mid-slope and bottom slope wells (Figures 5 – 9). Deep-seated landslide stability has been observed and modeled to be influenced more by seasonal and annual fluctuations in water level and less responsive to individual precipitation events or peak water levels (Iverson and Major 1987; Iverson, 2000). Following timber harvest in the catchment, elevated seasonal or annual water levels would only be observable in the Ruby 3 and Talus 4 wells because they are the only wells which record a water level for the entire year.

6.6 Baseline Response

One of the motivations for this study is to establish a baseline response of well water levels to precipitation events at the Kalaloch site. This information will be compared to data collected post-timber harvest in the catchment in an attempt to quantify any measureable changes in hydrologic response resulting from timber harvesting. For this study, the methods

selected to establish a baseline response were Kendall's τ correlation analysis, linear regression analysis, and the maximum water level observed in each individual well (Table 2).

One possibility is that water levels in the wells will rise to a peak above the established threshold level (Table 1) in less time following the onset of a precipitation event post-timber harvest due to the loss of canopy interception. If this occurs, the most significant correlation between water level and cumulative onsite precipitation would decrease and the slope of the linear regression line would increase. However, both statistical analysis methods may be best suited to indicate that in general, onsite well water levels respond within hours of the onset of a precipitation event as opposed to weeks or months, and the statistics may be less useful when trying to analyze specific water level response. Another possibility is that maximum peak water levels will be higher following timber harvest due to the loss of canopy interception and evapotranspiration. Post-harvest maximum peak water levels can be compared with pre-harvest levels to determine if there are any differences in peak water level response. If differences occur, the individual storms that caused the peaks will also need to be compared to determine if differences in storm magnitude and timing can be separated from any potential changes in hydrologic response due to timber harvest.

6.7 Future Work

Timber harvest in the research catchment was completed in the fall of 2009 and monitoring equipment was reinstalled during the winter of 2010. Data continue to be collected at the research site and will be compared to data collected pre-harvest. In addition to the comparisons described above, future work could compare changes in the minimum water

levels observed in the Ruby 3 and Talus 4 wells since they record a water level for the entire year. The annual minimum water level may increase if measureable changes in hydrologic response result from the loss of canopy interception and evapotranspiration at the research site.

Another possible hydrologic change following timber harvest would be an increase in the magnitude and frequency of recorded water levels in the wells that go dry for much of the year. This again would be the result of more water infiltrating into the soil as a result of a reduction in canopy interception and less water being lost from the soil due to a reduction in evapotranspiration.

Other hydrologic response characteristics that may be possible to evaluate using the pre- and post-timber harvest data include seasonal changes in the water level magnitude and seasonal differences in the speed of water level attenuation following peaks.

Detailed soil hydrologic properties for each well could be determined by sampling soils at the research site throughout the year to determine soil moisture contents and site specific hydraulic conductivities during different seasons of the year. This work was outside of the scope of this project, but could potentially add to the understanding of the water level response to precipitation events at the research site.

7.0 CONCLUSIONS

The hydrology of the Kalaloch research site appears to be controlled by the presence of soil layers with variable permeability and weathered bedrock underlying the study area. Rapid water level rise occurs over the course of several hours during precipitation events and

maximum peak water levels generally correlate to antecedent precipitation between 1 and 24 hours. Observed water level rise is disproportionate compared to precipitation amounts falling during storm events. This rapid, disproportionate water level rise appears mainly to be the result of the reverse Wieringermeer effect. In nine out of the ten wells, discrete reoccurring peak levels can be identified and appear to be controlled by differences in subsurface permeability.

The DHSVM evaluation of the hydrologic effects of converting the basin vegetation from forest to shrub cover for the two year period from February 2005 through February 2007 indicates a 27.4 percent decrease in evapotranspiration. The modeled average depth to the water table decreased slightly and the soil moisture content increased slightly for the two year DHSVM simulation when basin vegetation is changed from a forested condition to a shrub-covered condition.

At the Kalaloch research site, pre-timber harvest monitoring of groundwater response to precipitation events indicates that peak groundwater levels are controlled more by characteristics of the subsurface permeability and less by how much water is input to the system. Modeling using the DHSVM to investigate the potential hydrologic changes of clear-cut timber harvest on peak groundwater levels shows very little effect on maximum peak groundwater levels during the rainy months of the year. Estimated recharge to the deep groundwater system is outside of the scope of this study, however evidence suggests that the soil column saturates quickly following the onset of a precipitation event and most, if not all of the water that infiltrates into the subsurface flows horizontally as storm flow through more permeable layers that lie atop less permeable layers. Timber harvest was completed at the

research site in the fall of 2009. Post-timber harvest monitoring will take place at the site and actual post-harvest data will be compared to pre-harvest data as part of a future study to determine if any measurable differences in groundwater response to precipitation events are occurring at the site.

8.0 REFERENCES

Bowling, L.C., Storck, P., and Lettenmaier, D.P., 2000, Hydrologic effects of logging in western Washington, United States: Water Resources Research, v. 36 no. 11, p. 3223-3240.

Bowling, L.C. and Lettenmaier, D.P., 2001, The effect of forest roads and harvest on catchment hydrology in a mountainous maritime environment, in *Land Use and Watersheds: Human Influence on Hydrology and Geomorphology in Urban and Forest Areas*, Water Science and Application, The American Geophysical Union, 2, 145-164.

Chennault, J., 2004, Modeling the contribution of glacial meltwater to streamflow in Thunder Creek, North Cascades National Park, Washington: Western Washington University Geology Master of Science thesis.

Cruden, D.M. and Varnes, D.J., 1996, Landslide Types and Processes, in Turner, A. K., and R.L. Schuster, *Landslides: Investigation and Mitigation*, Transportation Research Board Special Report 247, National Research Council, Washington, D.C.: National Academy Press.

De La Fuente, J., 2002, Does deforestation influence the activity of deep-seated landslides? Observations from the flood of 1997 in the Central Klamath Mountains, Northern California: Geological Society of America Abstracts with Programs, Cordilleran Section – 98th Annual Meeting.

Desert Research Institute, Western Regional Climate Center, 2009, Western U.S. climate historical summaries; Washington climate summaries--Clearwater, Washington (451496): Desert Research Institute Western Regional Climate Center website, accessed Nov. 6, 2009 at http://www.wrcc.dri.edu/cgi-bin/cliMAIN.pl?wa1496

Dingman, S.L., 2002, Physical Hydrology, Prentice Hall, 646 p.

Donnell, C., 2007, Quantifying the glacial meltwater component of streamflow in the Middle fork of the Nooksack River, Whatcom County WA using a distributed hydrology model: Western Washington University Geology Master of Science thesis.

Dragovich, J.D., Brunengo, M.J., and Gerstel, W.J., 1993, Landslide inventory and analysis of the Tilton Creek-Mineral River area, Lewis County, Washington; Part 1--Terrain and geologic factors: Washington Geology, v. 21, no. 3, p. 9-18.

Fetter, C.W., 2001, Applied Hydrology, Prentice Hall, 598 p.

Gerstel, W.J., 1999, Deep-seated landslide inventory of the west-central Olympic Peninsula; Washington Division of Geology and Earth Resources Open-File Report 99-2, 36 p., 2 plates.

Gerstel, W.J., and Badger, T.C., 2002, Hydrologic controls and forest land management implications for deep-seated landslides: examples from the Lincoln Creek Formation, Washington: Geological Society of America Abstracts with Programs, Cordilleran Section – 98th Annual Meeting.

Gerstel, W. J. and Lingley, W. S., Jr., 2000, Geologic map of the Forks 1:100,000 quadrangle, Washington: Washington Division of Geology and Earth Resources Open File Report 2000-4, 36 p.

Gillham, R.W., 1984, The capillary fringe and its effect on water-table response: Journal of Hydrology, v. 67, no. 1-4, p. 307-324.

Grant, G.E., Lewis, S.L., Swanson, F.J., Cissel, J.H., and McDonnell, J.J., 2008, Effects of forest practices on peak flows and consequent channel response – a state-of-science report for western Oregon and Washington: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station, General Technical Report PNW-GTR-760, 76 p.

Healy, R.W., and Cook, P.G., 2002, Using groundwater levels to estimate recharge: Hydrogeology Journal, v. 10, p. 91-109.

Hilley, G.E., Burgmann, R., Ferretti, A., Novali, F., and Rocca, F., 2004, Dynamics of slow-moving landslides from permanent scatterer analysis: Science, v. 304, p. 1952-1955.

Iverson, R.M., 2000, Landslide triggering by rain infiltration: Water Resources Research, v. 36, no. 7, p. 1897-1910.

Iverson, R.M. and Major, J.J., 1987, Rainfall, ground-water flow, and seasonal movement at Minor Creek landslide, northwestern California: Physical interpretation of empirical relations: Geological Society of America Bulletin, v. 99, p. 579-594.

Jaber, F.H., Shukla, S., and Srivastava, S., 2006, Recharge, upflux and water table response for shallow water table conditions in southwest Florida: Hydrological Processes, v. 20, p. 1895-1907.

Kelleher, K., 2006, Streamflow calibration of two sub-basins in the Lake Whatcom Watershed, Washington using a distributed hydrology model: Western Washington University Geology Master of Science thesis.

Kendall, M.G., 1938, A new measure of rank correlation: Biometrika, v. 30, no. 1/2, p. 81-93.

Keim, R.R. and Skaugset, A.E., 2003, Modelling effects of forest canopies on slope stability: Hydrological Processes, v. 17, p. 1457-1467.

Malet, J.P., van Asch, Th. W.J., van Beek, R., and Maquaire, O., 2005, Forecasting the behaviour of complex landslides with a spatially distributed hydrological model: Natural Hazards and Earth Systems Sciences, v. 5, p. 71-85.

Matthews, R., Hilles, M., Vandersypen, J., Mitchell, R., and Matthews, G., Lake Whatcom Monitoring Report 2005-2006, March 2007.

Megahan, W.F. and Hornbeck, J., 2000, Lessons learned in watershed management: a retrospective view: USDA Forest Service Proceedings RMRS-P-13.

Montgomery, D.R., Schimdt, K.M., Greenberg, H.M., and Dietrich, W.E., 2000, Forest clearing and regional landsliding: Geology, v. 28, no. 4, p. 311-314.

Moore, D.R. and Wondzell, S.M., 2005, Physical hydrology and the effects of forest harvesting in the Pacific Northwest: a review: Journal of the American Water Resources Association, v. 41, no. 4, p. 763-784.

National Oceanic and Atmospheric Administration, 2007, Pacific Coast land cover, website accessed August 2007 at: http://www.csc.noaa.gov/crs/lca/pacificcoast.html

O'Brien, A.L., 1982, Rapid water table rise: Water Resources Bulletin, v. 18, no. 4, p. 713-715.

Office of the Washington State Climatologist, 2008, Black Knob RAWS hourly climate data, website accessed March 3, 2008 at: http://www.climate.washington.edu/maps/

R Development Core Team (2007). R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. ISBN 3-900051-07-0, URL http://www.R-project.org.

Reid, M.E., 1997, Slope instability caused by small variations in hydraulic conductivity: Journal of Geotechnical and Geoenvironmental Engineering, v. 123, n. 8, p. 717-725.

Reid, M.E. and LaHusen, R.G., 1998, Real-time monitoring of active landslides along Highway 50, El Dorado County, URL:http://landslides.usgs.gov/monitoring/hwy50/report.php, Accessed: March 14, 2007.

Scanlon, T.M., Raffensperger, J.P., and Hornberger, G.M., 2000, Shallow subsurface storm flow in a forested headwater catchment – observations and modeling using a modified TOPMODEL: Water Resources Research, v. 36, no. 9, p. 2575-2586.

Smakhtin, V.U., 2002, Some early Russian studies of subsurface storm-flow processes: Hydrological Processes, v. 16, p. 2613-2620.

Soil Survey Staff, Natural Resources Conservation Service, United States Department of Agriculture. U.S. General Soil Map (STATSGO2) for Washington. Available online at http://soildatamart.nrcs.usda.gov accessed August 2007.

Storck, P., Bowling, L., Wetherbee, P., and Lettenmaier, D, 1998, Application of a GIS-based hydrology model for prediction of forest harvest effects on peak streamflow in the Pacific Northwest: Hydrologic Processes, v. 12, no. 6, p. 653-658.

Tabor, R.W. and Cady, W.M., 1978, Geologic map of the Olympic Peninsula, Washington: U.S. Geological Survey Miscellaneous Investigations Series Map I-994, 2 sheets, scale 1:125,000.

University of Washington, 2007, Geomorphalogical Research Group, 10 m DEM data, website accessed August 2007 at: http://duff.geology.washington.edu/

U.S. Department of Agriculture, Natural Resources Conservation Service, 2010, Guide to texture by feel, website accessed July 6, 2010 at: http://soils.usda.gov/education/resources/lessons/texture/

U.S. Department of Agriculture, Natural Resources Conservation Service, 1986, Urban Hydrology for Small Watersheds. Technical Release 55, 2nd ed., NTIS PB87-101580, Springfield, VA.

U.S. Geological Survey, 2009, USGS stream gauge: Queets River near Clearwater, WA (12040500), website accessed Nov. 6, 2009 at: http://waterdata.usgs.gov/usa/nwis/uv?site_no=12040500

VanShaar, J.R., Haddeland, I., and Lettenmaier, D.P., 2002, Effects of land-cover changes on the hydrological response of interior Columbia River basin forested catchments: Hydrological Processes, v. 16, p. 2499-2520.

Washington State Forest Practices Board Manual, 2004, Section 16 Guidelines for Evaluating Potentially Unstable Slopes and Landforms, website accessed Dec. 8, 2009 at: http://www.dnr.wa.gov/Publications/fp_board_manual_section16.pdf

Waichler, S.R., Wemple, B.C., and Wigmosta, M.S., 2005, Simulation of water balance and forest treatment effects at the H.J. Andrews Experimental Forest: Hydrological Processes, v. 19, p. 3177-3199.

Weeks, E.P., 2002, The Lisse Effect revisited: Ground Water, v. 40, no. 6, p. 652-656.

Whitaker A., Alila, Y., Beckers, J., and Toews, D., 2002, Evaluating peak flow sensitivity to clear-cutting in different elevation bands of a snowmelt-dominated mountainous catchment: Water Resources Research, v. 38, no. 9, p. 1172.

Wigmosta, M.S., Vail, L.W., and Lettenmaier, D.P., 1994, A distributed hydrology-vegetation model for complex terrain: Water Resources Research, v. 30, no. 6, p. 1665-1679.

Wigmosta, M.S. and Perkins, W.A., 2001, Simulating the effects of forest roads on watershed hydrology: *AGU, Water Science and Application*, v. 2, p. 127-143.

Wigmosta, M.S., Nijssen, B., and Storck, P., 2002, The distributed hydrology soil vegetation model. *In* Singh, V.P., and D. Frevert. *Mathematical models of small watershed hydrology and applications* (7-42). Chelsea, MI: Water Resources Publications.

APPENDIX A: Example code used in the statistics program 'R' to calculate Kendall's τ correlation values and linear regression models.

To run the Kendall's τ correlation tests and linear regression models, a comma separated value (.csv) file was created in Microsoft Excel. The first Excel column contained the peak values selected for analysis and the rest of the row was filled in with the amount of precipitation that fell preceding the peak. Preceding precipitation amounts for 1 through 36 hours of precipitation were used for analysis along with 48 hours, 72 hours, 7 days, and 14 days of precipitation.

Sample 'R' code for Kendall's τ correlations

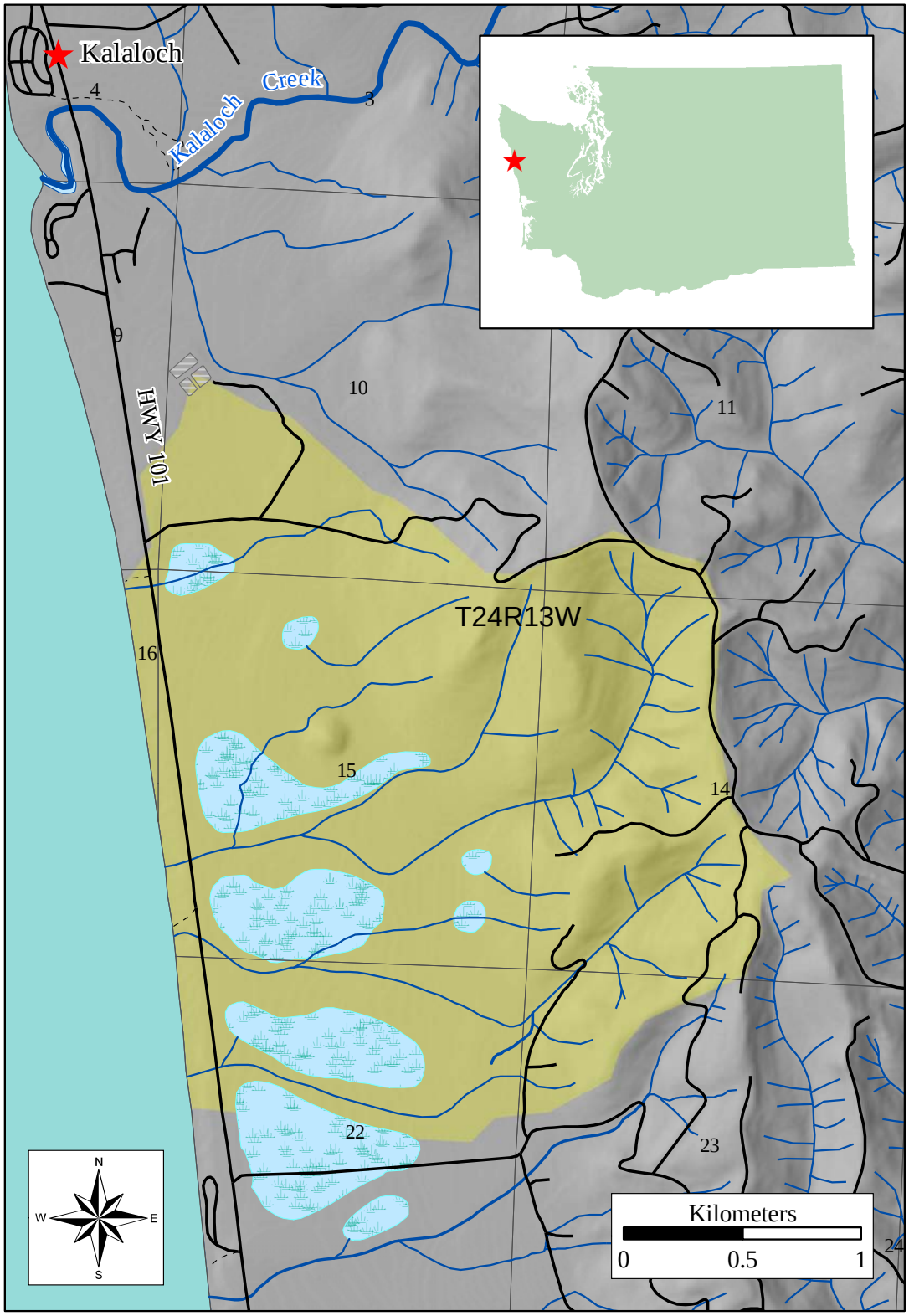
```
## Kendall correlation tests between well peaks and Black Knob
precipitation

well <- read.table("c:/input/peaktrim/csvsmet/bk/bkt4peaks.csv",T,
sep=",")
attach(well)

##  Print correlation commands

print(cor.test(t4peakcm, bkhr1precip, method="kendall"))
print(cor.test(t4peakcm, bkhr2precip, method="kendall"))
print(cor.test(t4peakcm, bkhr3precip, method="kendall"))
print(cor.test(t4peakcm, bkhr4precip, method="kendall"))
print(cor.test(t4peakcm, bkhr5precip, method="kendall"))
print(cor.test(t4peakcm, bkhr6precip, method="kendall"))
print(cor.test(t4peakcm, bkhr7precip, method="kendall"))
print(cor.test(t4peakcm, bkhr8precip, method="kendall"))
print(cor.test(t4peakcm, bkhr9precip, method="kendall"))
```

Print commands continued in the same format to include all precipitation intervals evaluated.

Sample 'R' code for linear regression models

```
well <- read.table("c:/input/peaktrim/csvsmet/r3peaksmet.csv",T, sep=",")
attach(well)


##  Variables for plotting

y<- r3peak
x1<- hr21precip
big1<-"Ruby 3 - 21 hour" ## labels for first plot on 2 by 2
newgraph<-"c:/input/plots/lmplots/ruby3/r3.hour21" ## new saveplot
information


## linear models and log transformations

op <- par(mfrow=c(2,2))
```

```
## Plot x and untransformed Y + residuals

plot(y~x1,main=big1,
xlim=c(0,10),xlab="Precipitation(cm)",
ylim=c(-30,0),ylab="Peak Level (cm)")
abline(lm(y~x1))
yfit<-lm(y~x1)
yfit2<-summary(yfit)

r.lab<-format(yfit2$adj.r.squared,digits=3)
p.lab<-format(yfit2$coef["x1","Pr(>|t|)"],digits=3)
e.lab<-format(yfit2$coef["x1","Estimate"],digits=3)  ## added lm slope to
legend
i.lab<-format(yfit2$coef["(Intercept)","Estimate"],digits=4)## added lm
intercept to legend

legend(x="topright",
c(paste("Adjusted R-squared = ",r.lab),
paste("p-value=",p.lab),
paste("Slope=",e.lab,"Intercept=",i.lab)), ##  added to add equation of
line
bty="n", cex=0.7)

plot(yfit$fitted.values, resid(yfit), main="Untransformed Residuals")
abline(h=0)

##  Plot x and transformed y + residuals

plot(log10(y+30)~log10(x1),main=big1,
xlim=c(0,1),xlab="log10[Precipitation(cm)]",
ylim=c(0,3),ylab="log10[Peak Level (cm)]")
abline(lm(log10(y+30)~log10(x1)))

yfit.trans<-lm(log10(y+30)~log10(x1))
yfit2.trans<-summary(yfit.trans)

r.trans.lab<-format(yfit2.trans$adj.r.squared,digits=3)
p.trans.lab<-format(yfit2.trans$coef["log10(x1)","Pr(>|t|)"],digits=3)
e.trans.lab<-format(yfit2.trans$coef["log10(x1)","Estimate"],digits=3)  ##
added lm slope to legend
i.trans.lab<-format(yfit2.trans$coef["(Intercept)","Estimate"],digits=2)##
added lm intercept to legend

legend(x="topright",
c(paste("Adjusted R-squared = ",r.trans.lab),
paste("p-value=",p.trans.lab),
paste("Slope=",e.trans.lab,"Intercept=",i.trans.lab)),
bty="n", cex=0.7)

plot(yfit.trans$fitted.values, resid(yfit.trans), main="Transformed
Residuals")
abline(h=0)

savePlot(newgraph,type="jpg")
par(op)
```



Kalaloch study area

Figure 1. Kalaloch study area location map.

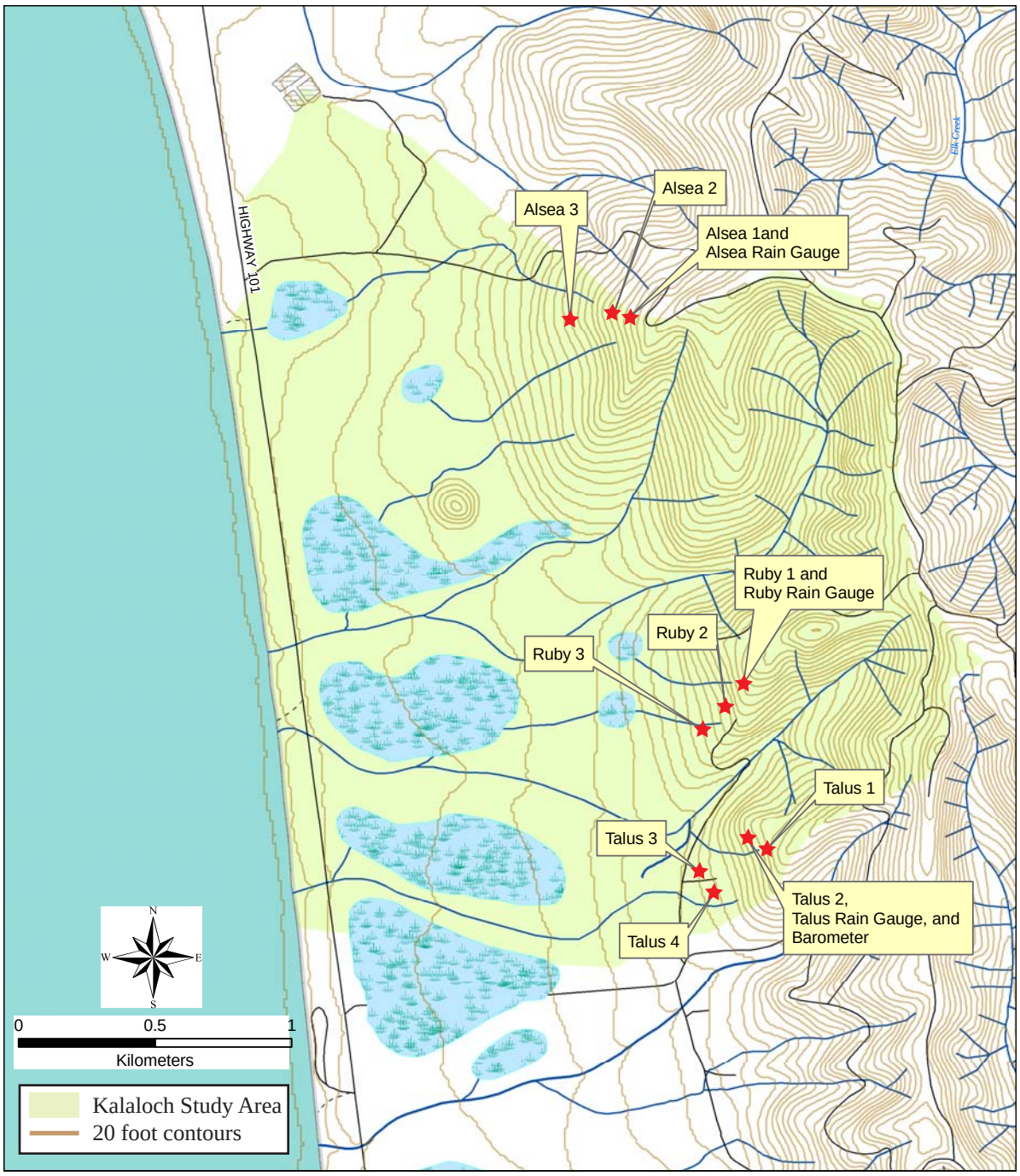


Figure 2. Well and rain gauge configuration at the Kalaloch research site.

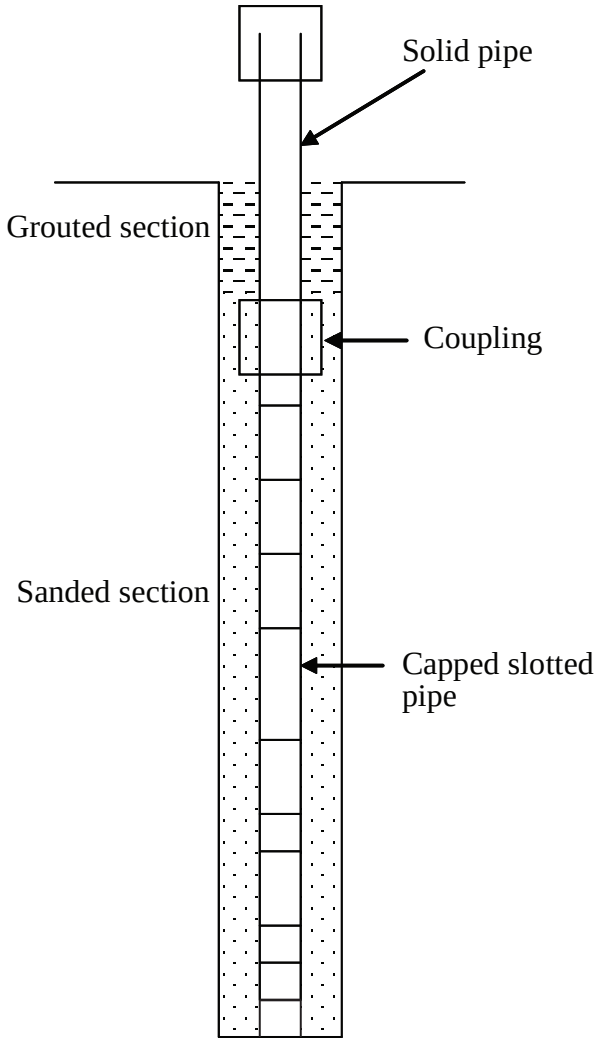


Figure 3. General illustration of monitoring well construction modified from Gerstel, personal communication, 2005.

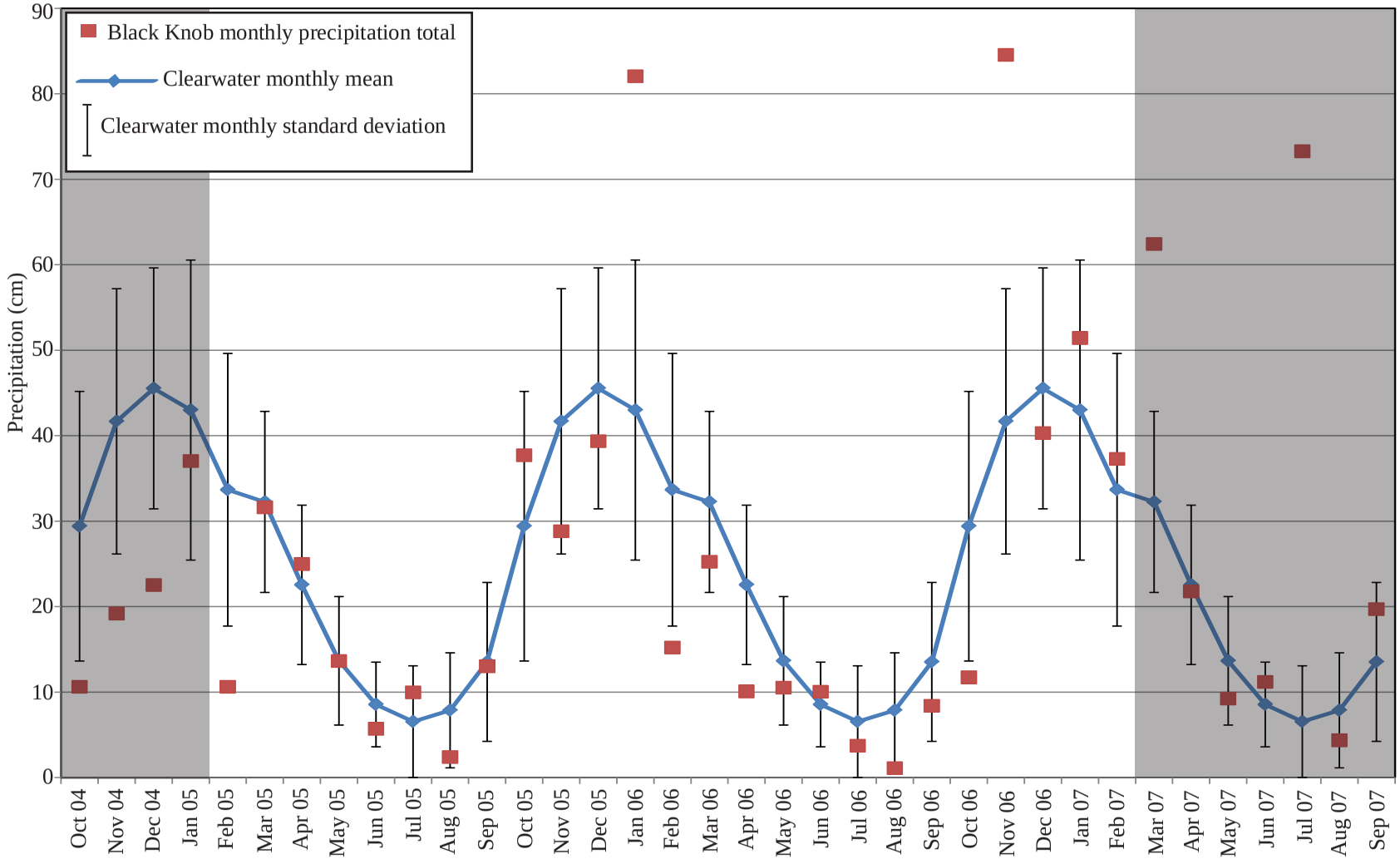


Figure 4. Mean monthly precipitation and standard deviation recorded at the Clearwater weather station for the period of record from 1931 through 2006 plotted with the monthly precipitation recorded at the Black Knob RAWS for water years 2005, 2006, and 2007. Grey boxes represent months outside of the time period analyzed during this study.

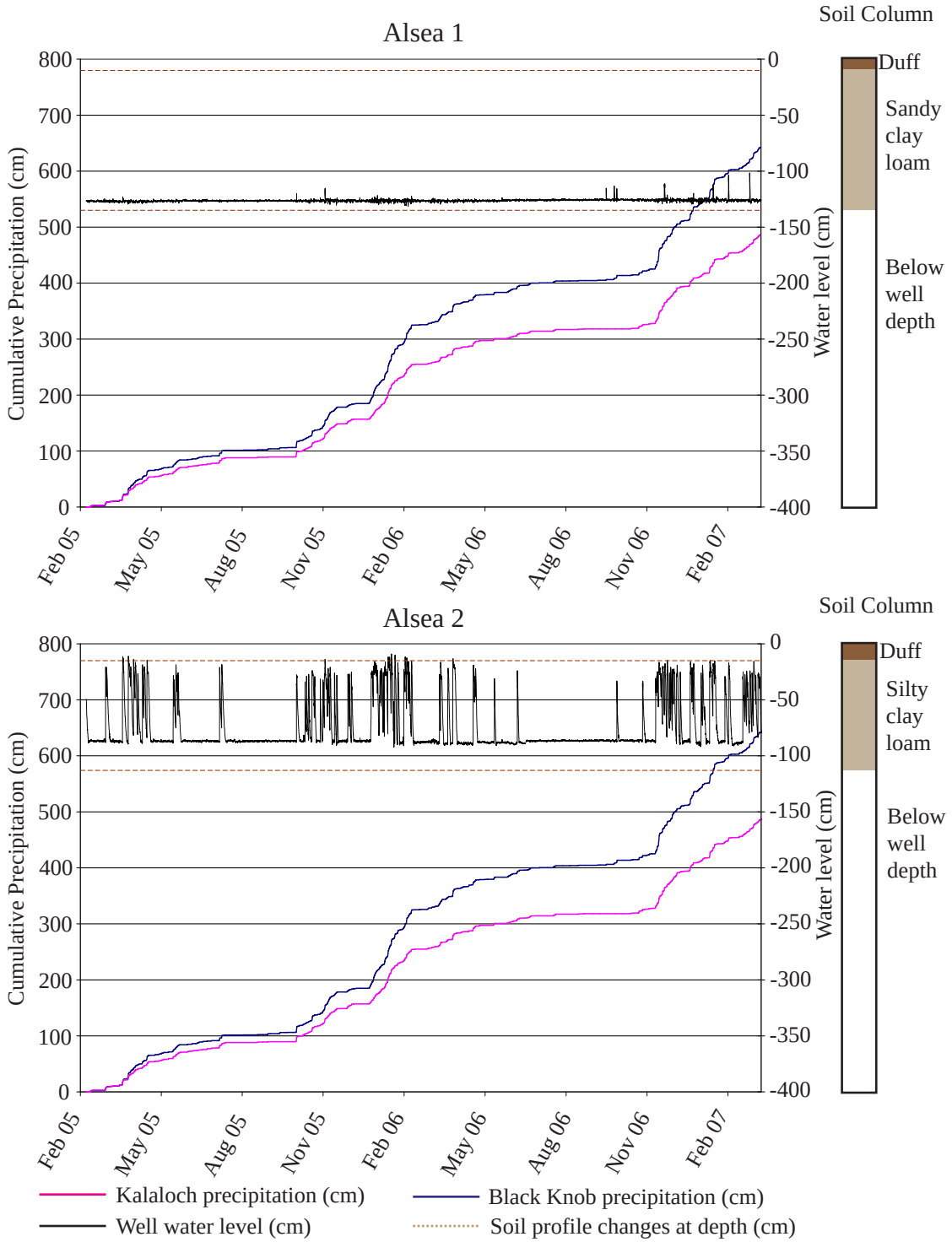


Figure 5. Water level in the Alsea 1 and Alsea 2 wells for the two year period from February 2005 through February of 2007. Also plotted are cumulative precipitation recorded under the tree canopy at the Kalaloch research site and at the Black Knob RAWS along with major changes in soil characteristics. The dotted brown lines represent a change in soil characteristics at depth noted during well installation.

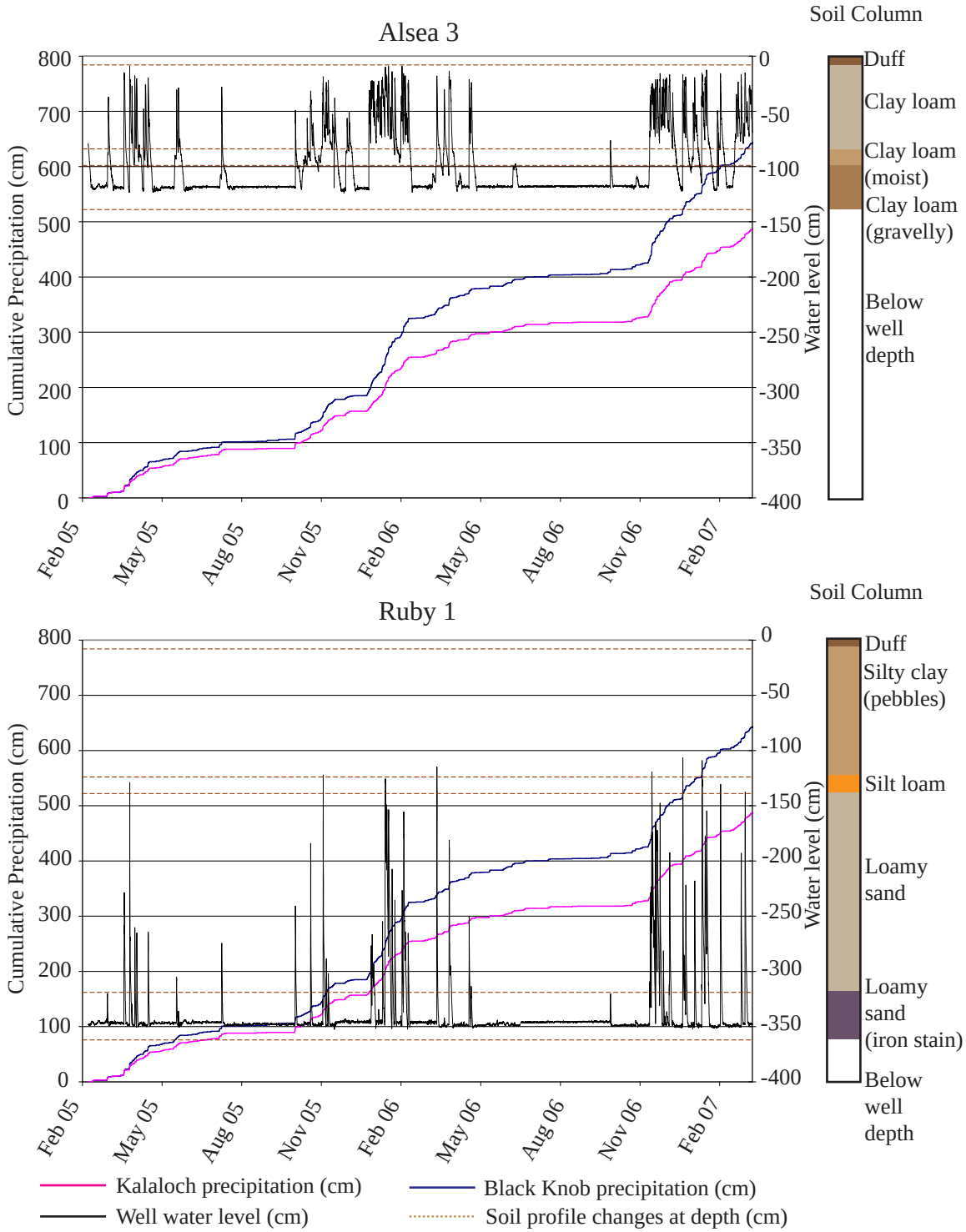


Figure 6. Water level in the Alsea 3 and Ruby 1 wells for the two year period from February 2005 through February of 2007. Also plotted are cumulative precipitation recorded under the tree canopy at the Kalaloch research site and at the Black Knob RAWS along with major changes in soil characteristics. The dotted brown lines represent a change in soil characteristics at depth noted during well installation.

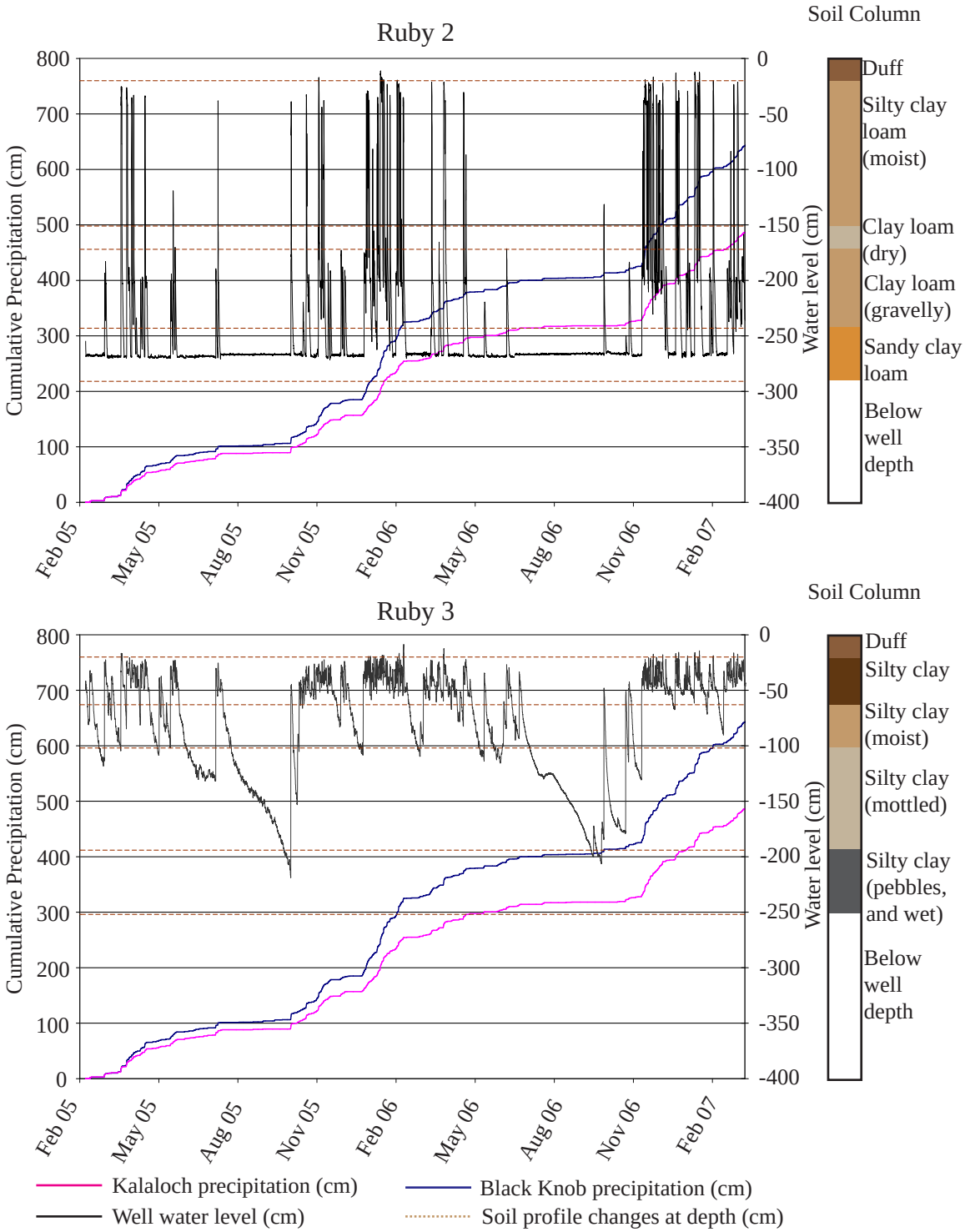


Figure 7. Water level in the Ruby 2 and Ruby 3 wells for the two year period from February 2005 through February of 2007. Also plotted are cumulative precipitation recorded under the tree canopy at the Kalaloch research site and at the Black Knob RAWS along with major changes in soil characteristics. The dotted brown lines represent a change in soil characteristics at depth noted during well installation.

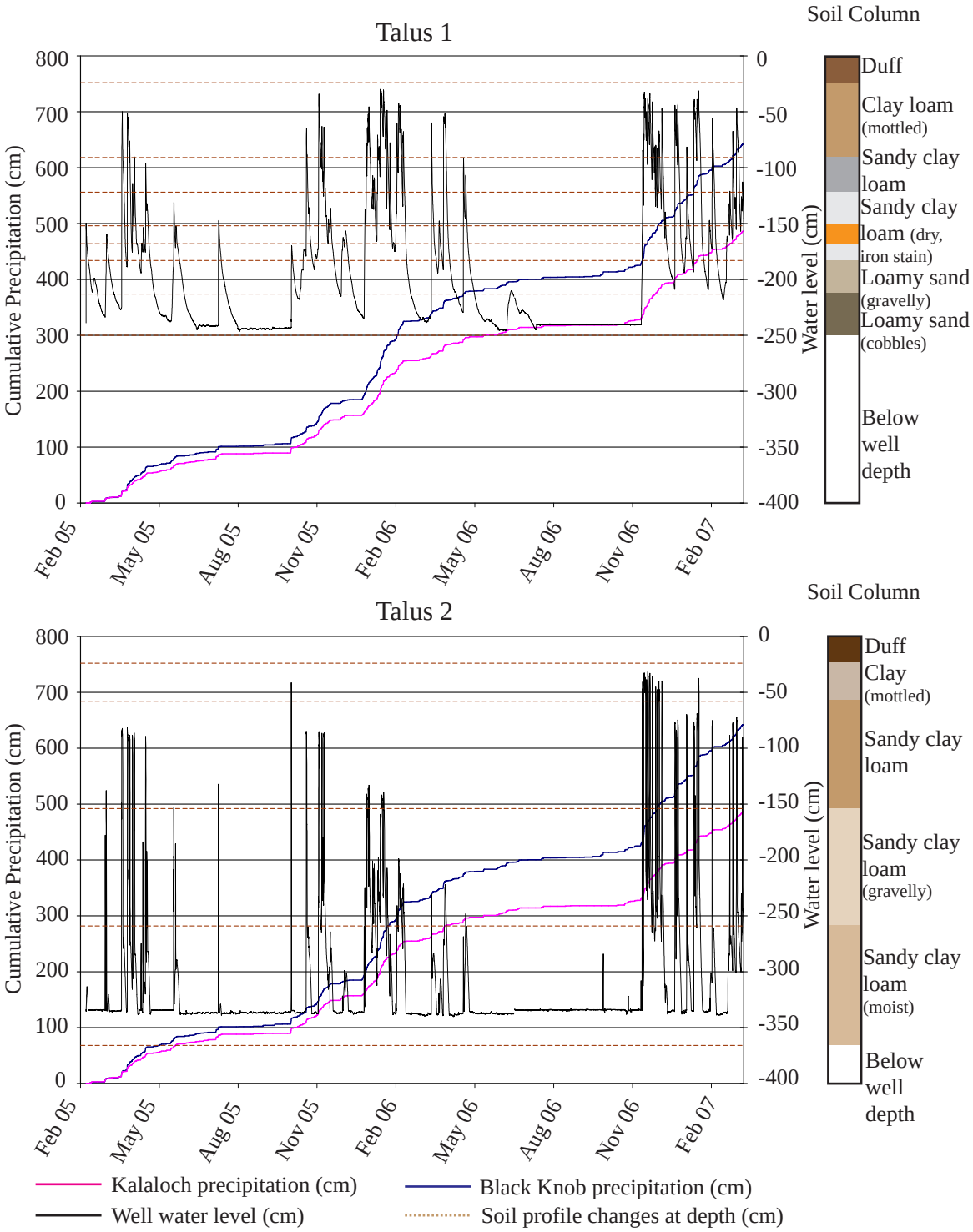


Figure 8. Water level in the Talus 1 and Talus 2 wells for the two year period from February 2005 through February of 2007. Also plotted are cumulative precipitation recorded under the tree canopy at the Kalaloch research site and at the Black Knob RAWS along with major changes in soil characteristics. The dotted brown lines represent a change in soil characteristics at depth noted during well installation.

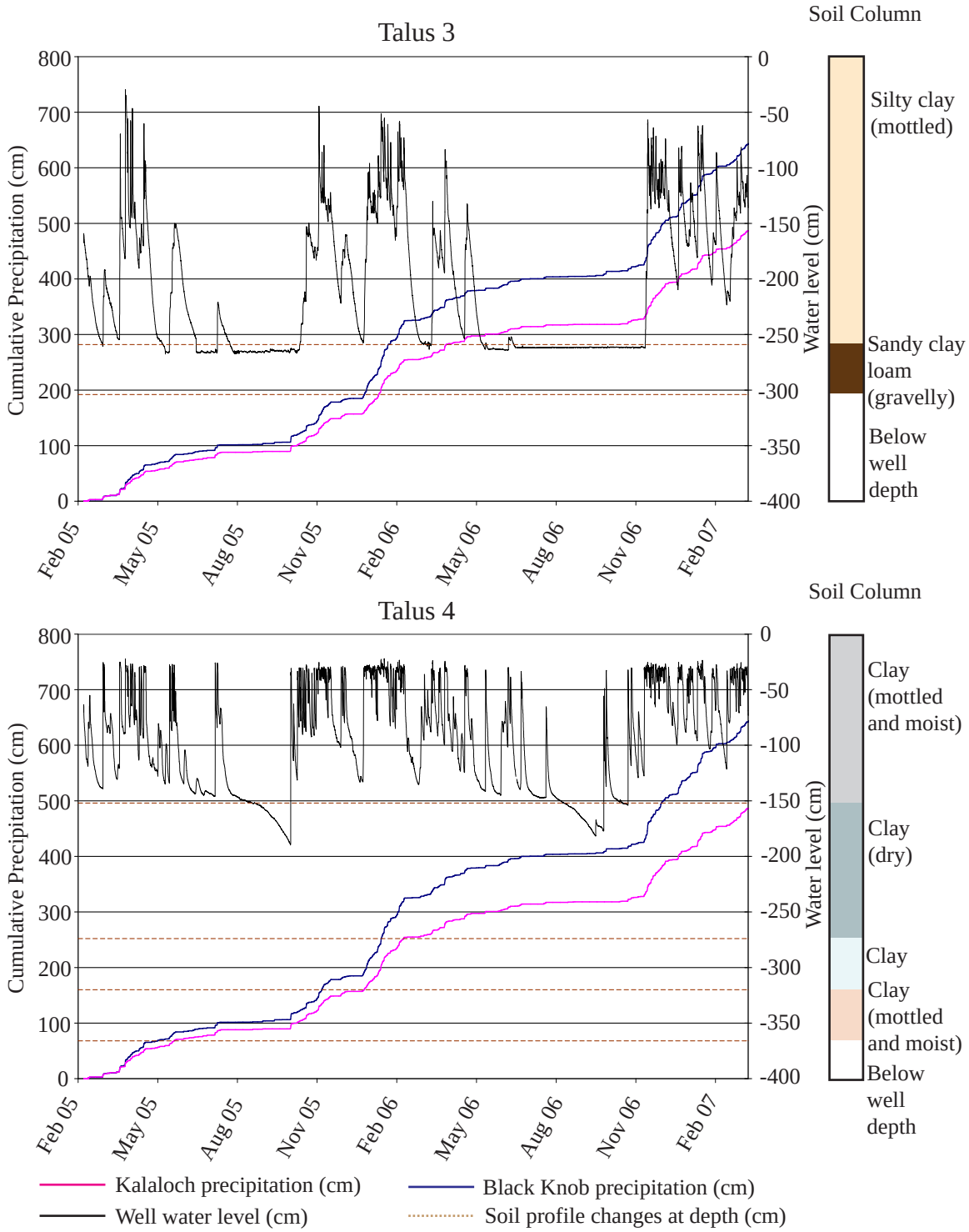


Figure 9. Water level in the Talus 3 and Talus 4 wells for the two year period from February 2005 through February of 2007. Also plotted are cumulative precipitation recorded under the tree canopy at the Kalaloch research site and at the Black Knob RAWS along with major changes in soil characteristics. The dotted brown lines represent a change in soil characteristics at depth noted during well installation.

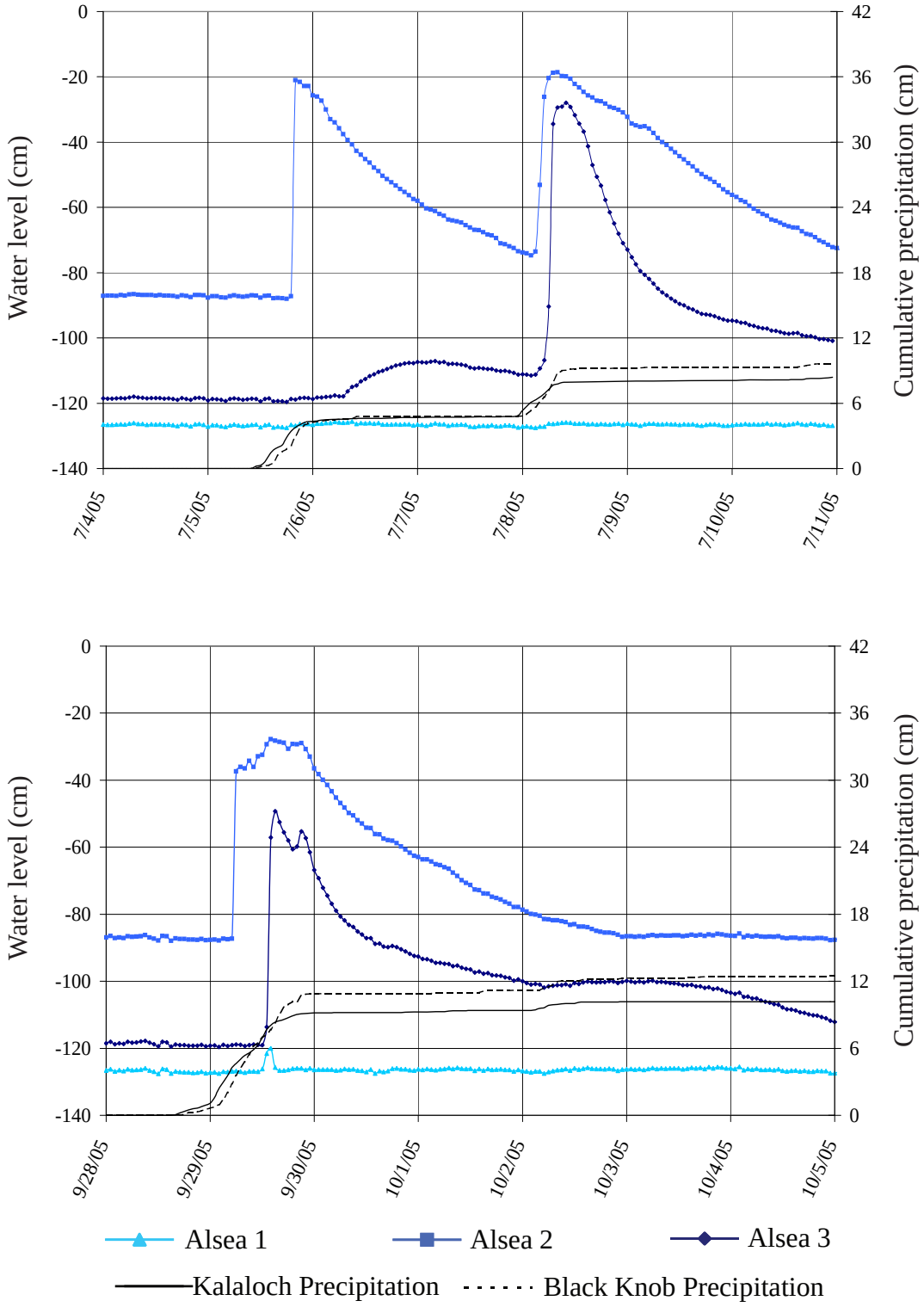


Figure 10. Water level response to precipitation events for the seven day periods from July 4 through July 11, 2005 and September 28 through October 5, 2005 at the Alsea site. Each tick mark on line represents one hour.

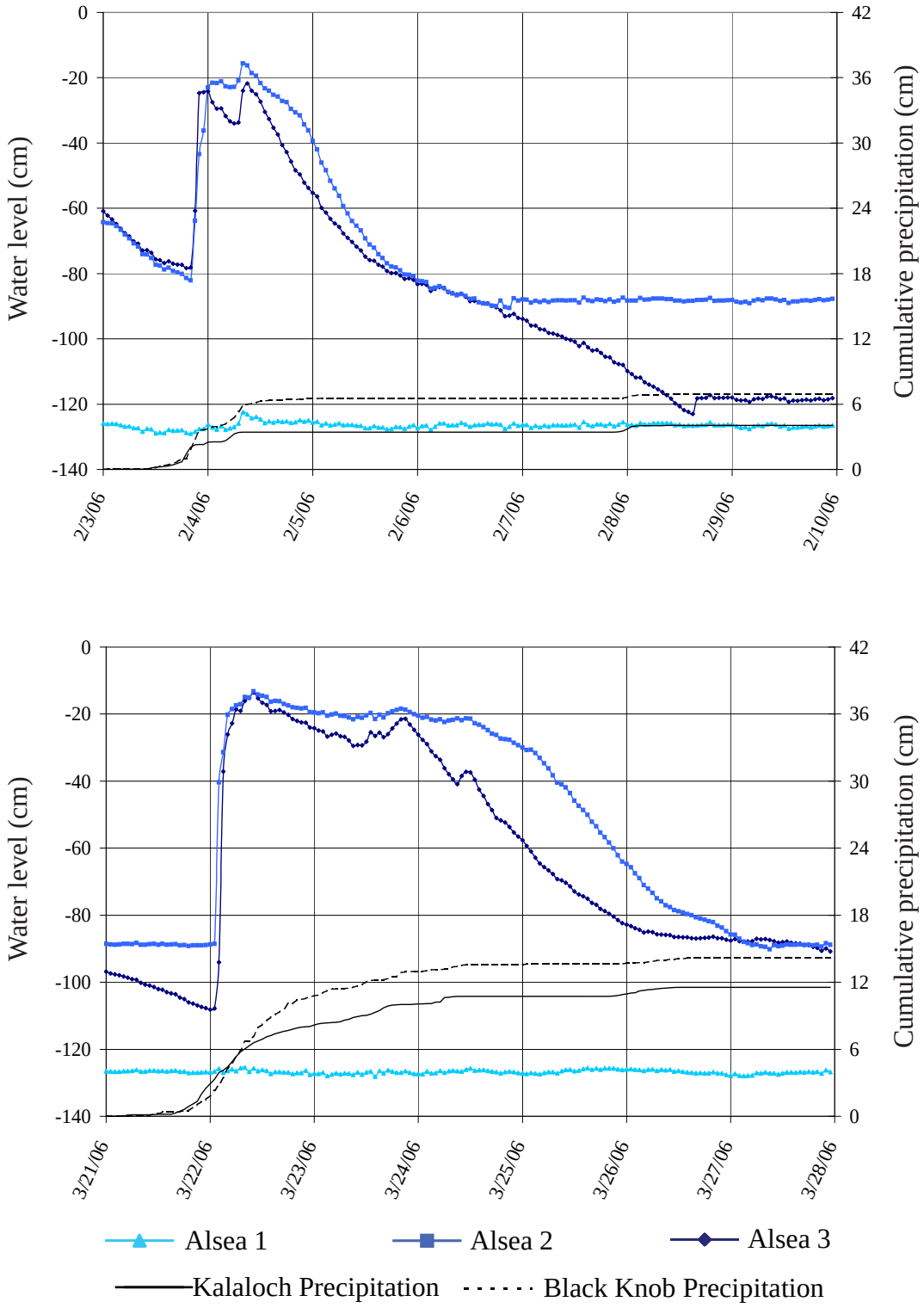


Figure 11. Water level response to precipitation events for the seven day periods from February 3 through February 10, 2006 and March 21 through March 28, 2006 at the Alsea site. Each tick mark on line represents one hour.

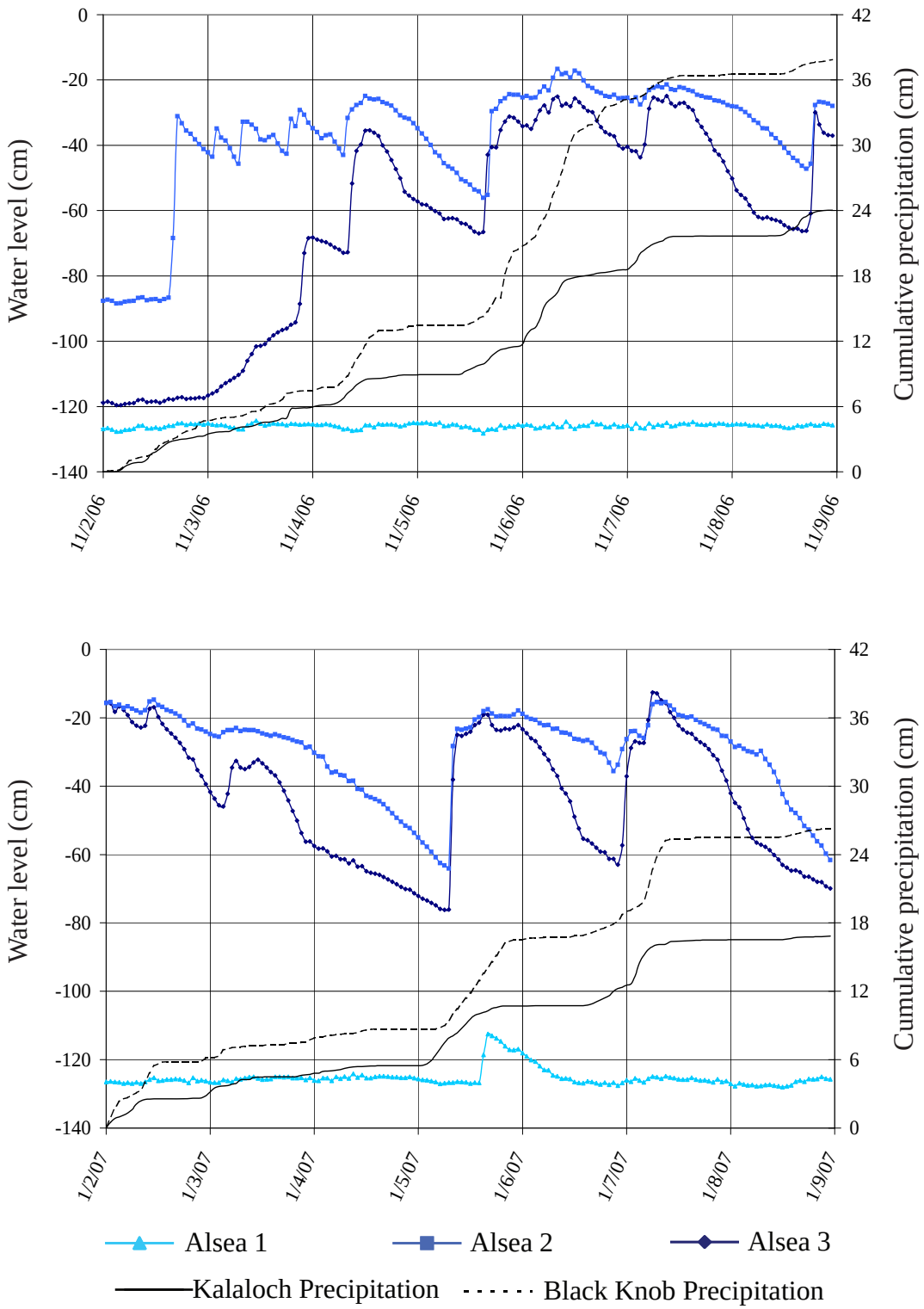


Figure 12. Water level response to precipitation events for the seven day periods from November 2 through November 9, 2006 and January 2 through January 9, 2007 at the Alsea site. Each tick mark on line represents one hour.

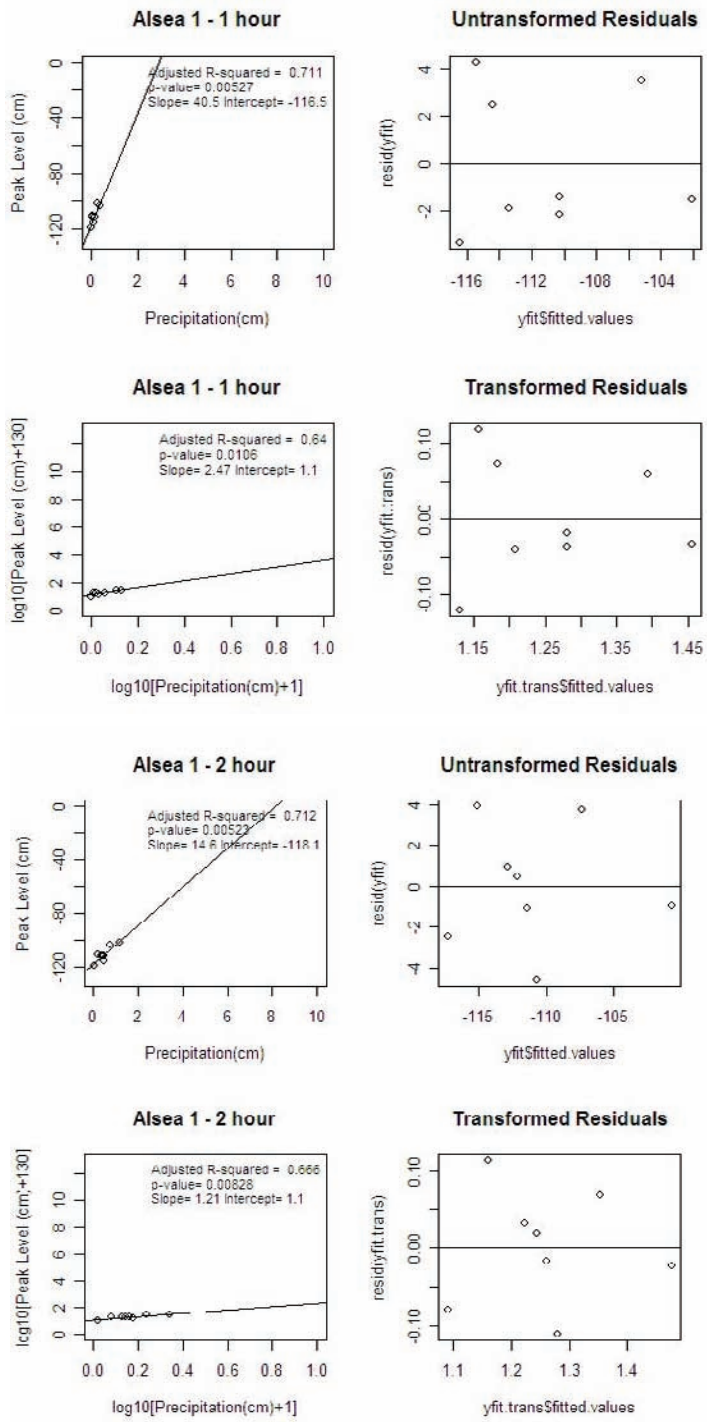


Figure 13. Linear regression models with the best fit for precipitation preceeding peak water levels at the Alsea 1 well. The best fit linear models occured following 1 and 2 hours of precipitation preceeding water level peaks. Log -log transformation graphs for both 1 and 2 hours of precipitation are also shown.

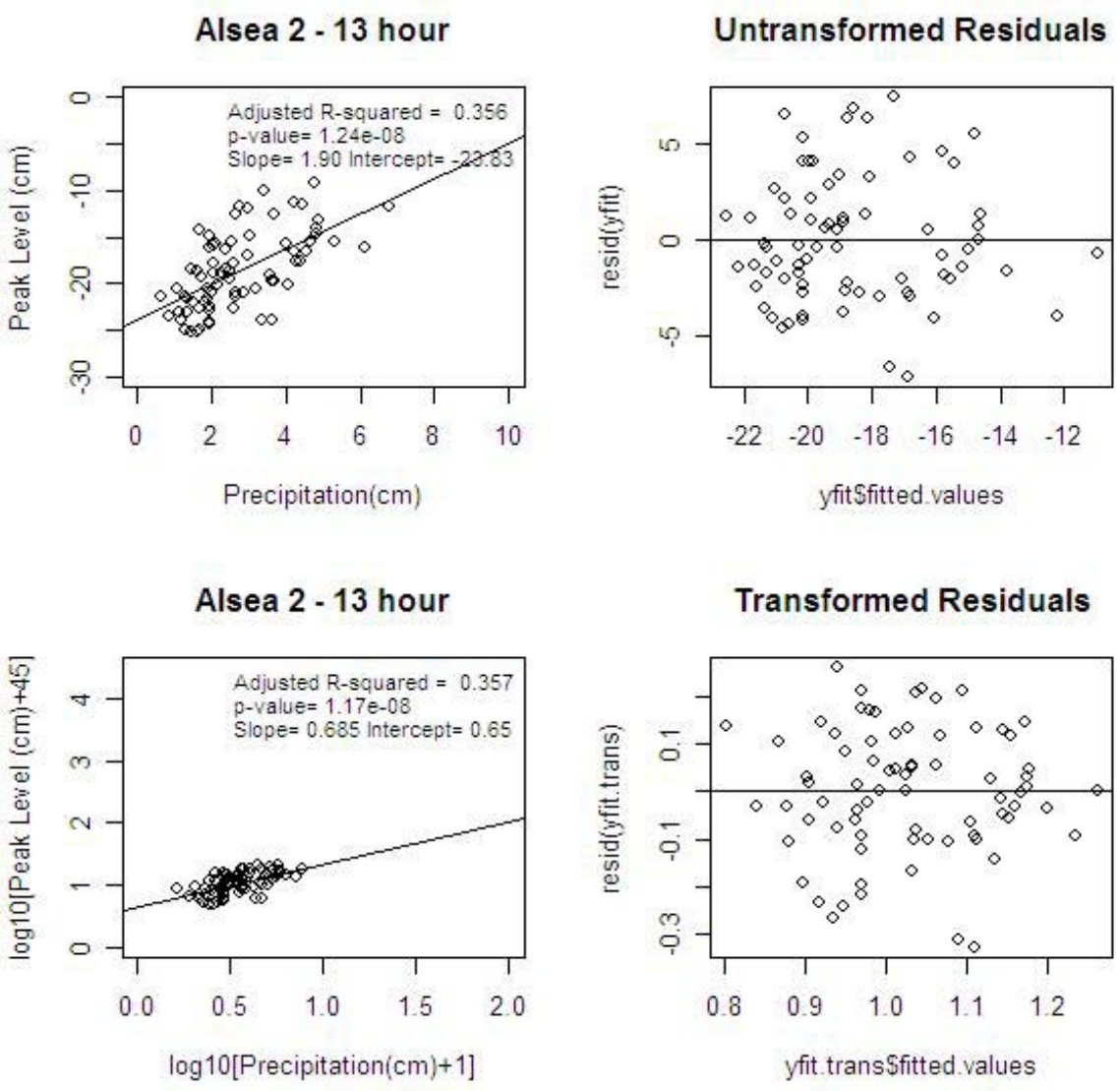


Figure 14. Linear regression model with the best fit for precipitation preceding peak water levels at the Alsea 2 well. The best fit linear regression model is for 13 hours of precipitation preceding peak water levels. Log – log transformation of the data improved the model slightly and results are displayed as well.

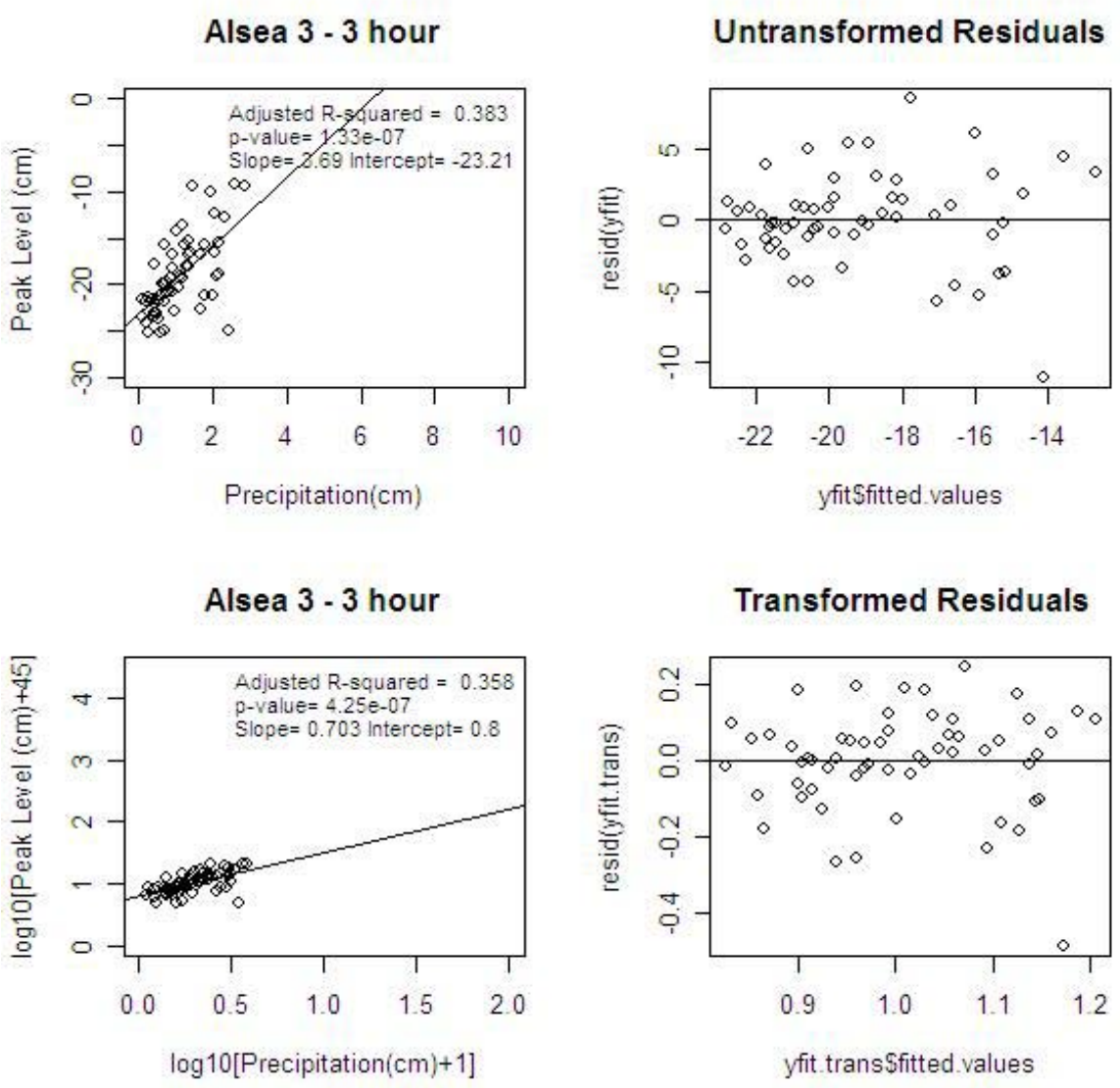


Figure 15. Linear regression model with the best fit for precipitation preceding peak water levels at the Alsea 3 well. The best fit linear regression model is for 3 hours of precipitation preceding peak water levels. Log – log transformation of the data did not improve the R-squared value, however it did make the residuals more random.

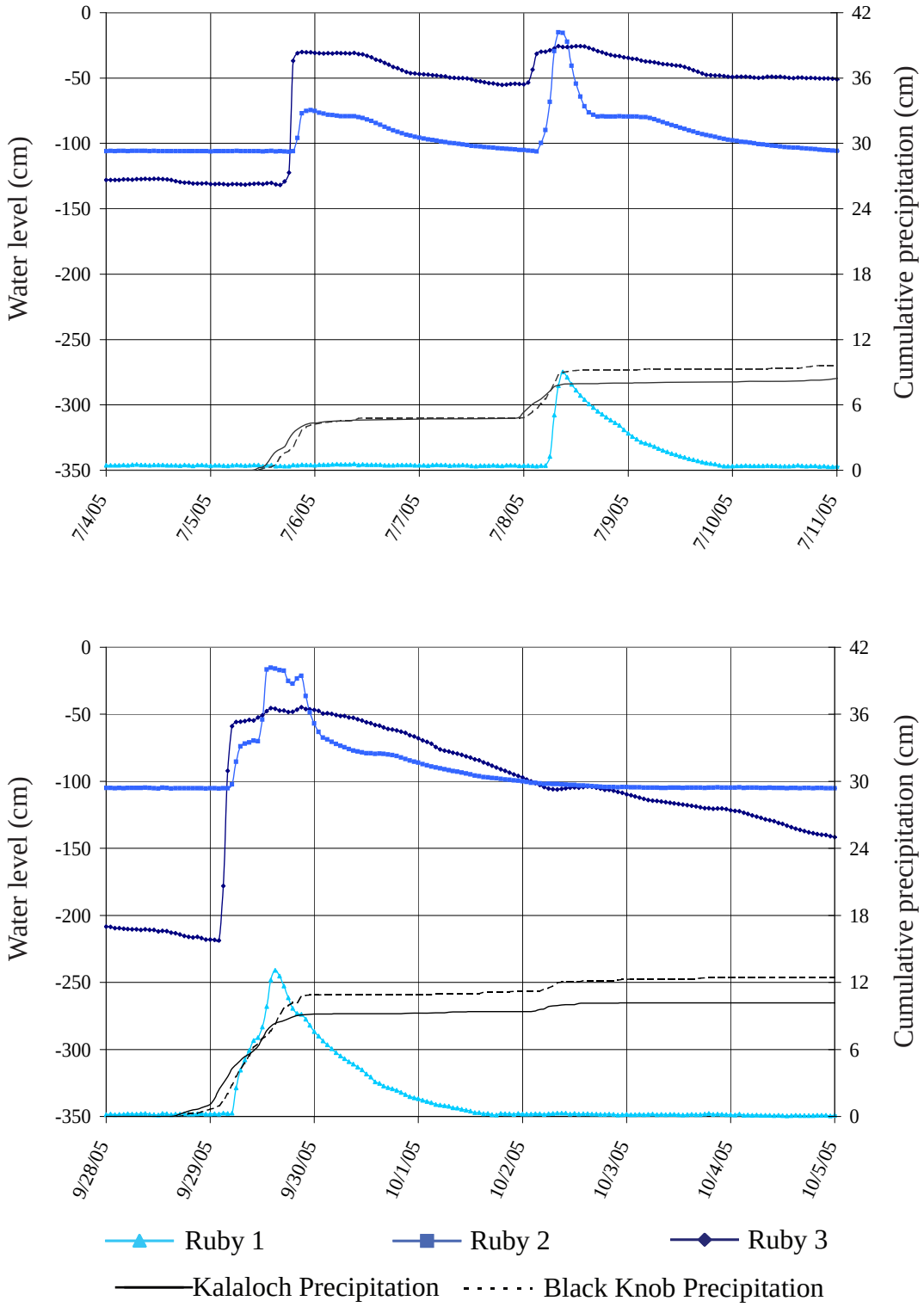


Figure 16. Water level response to precipitation events for the seven day periods from July 4 through July 11, 2005 and September 28 through October 5, 2005. Each tick mark on line represents one hour.

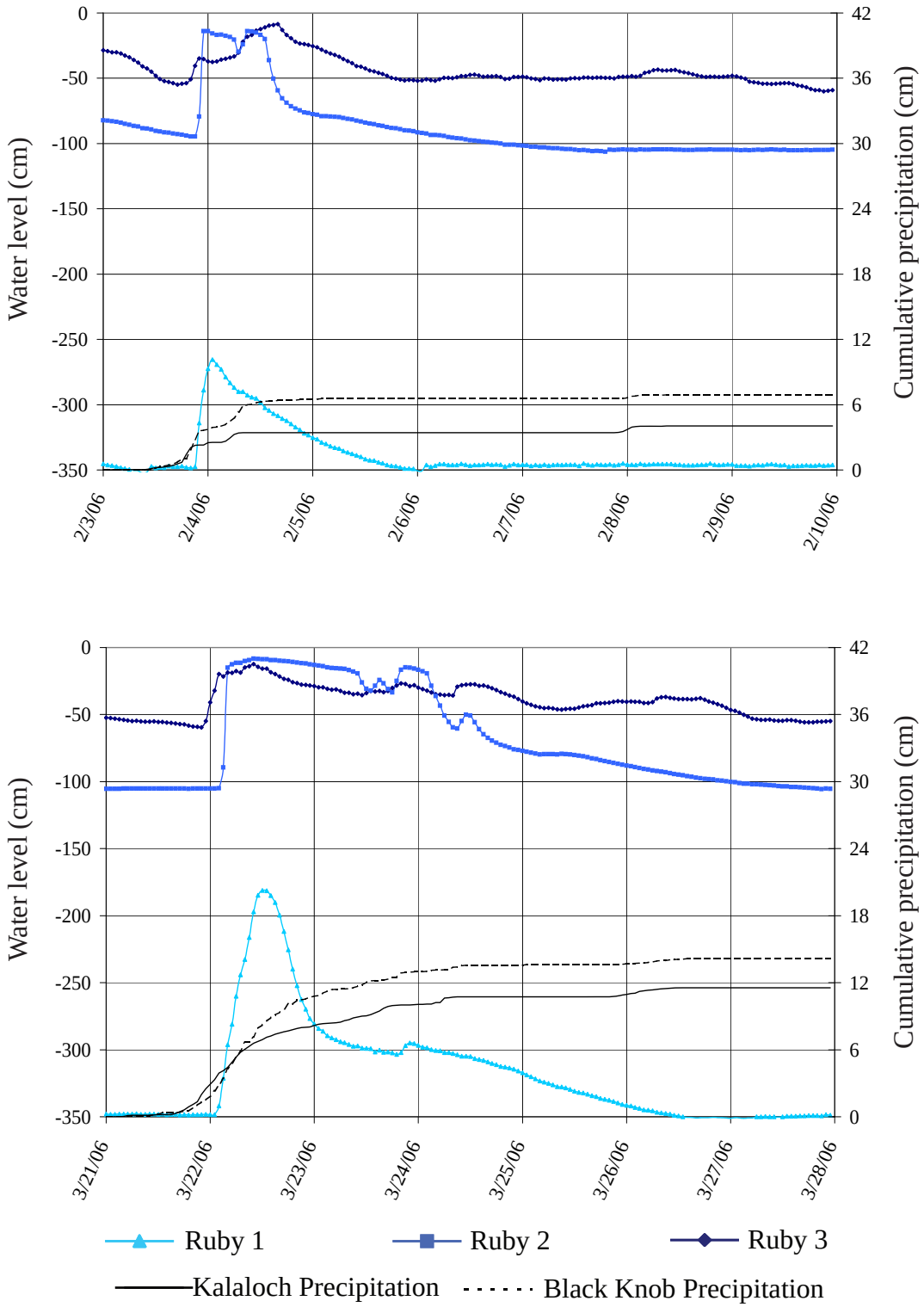


Figure 17. Water level response to precipitation events for the seven day periods from February 3 through February 10, 2006 and March 21 through March 28, 2006 at the Ruby site. Each tick mark on line represents one hour.

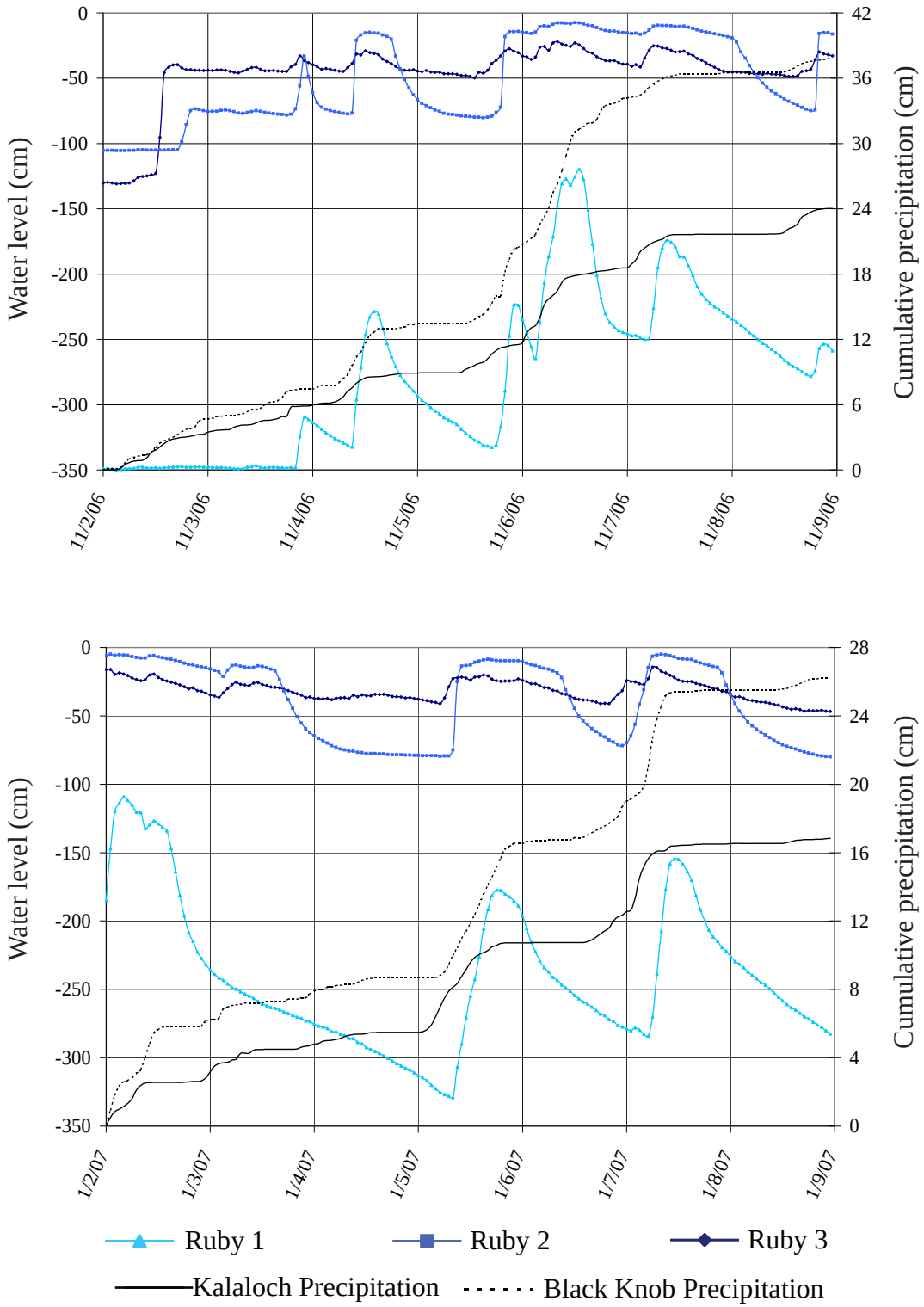


Figure 18. Water level response to precipitation events for the seven day periods from November 2 through November 9, 2006 and January 2 through January 9, 2006 at the Ruby site. Each tick mark on line represents one hour.

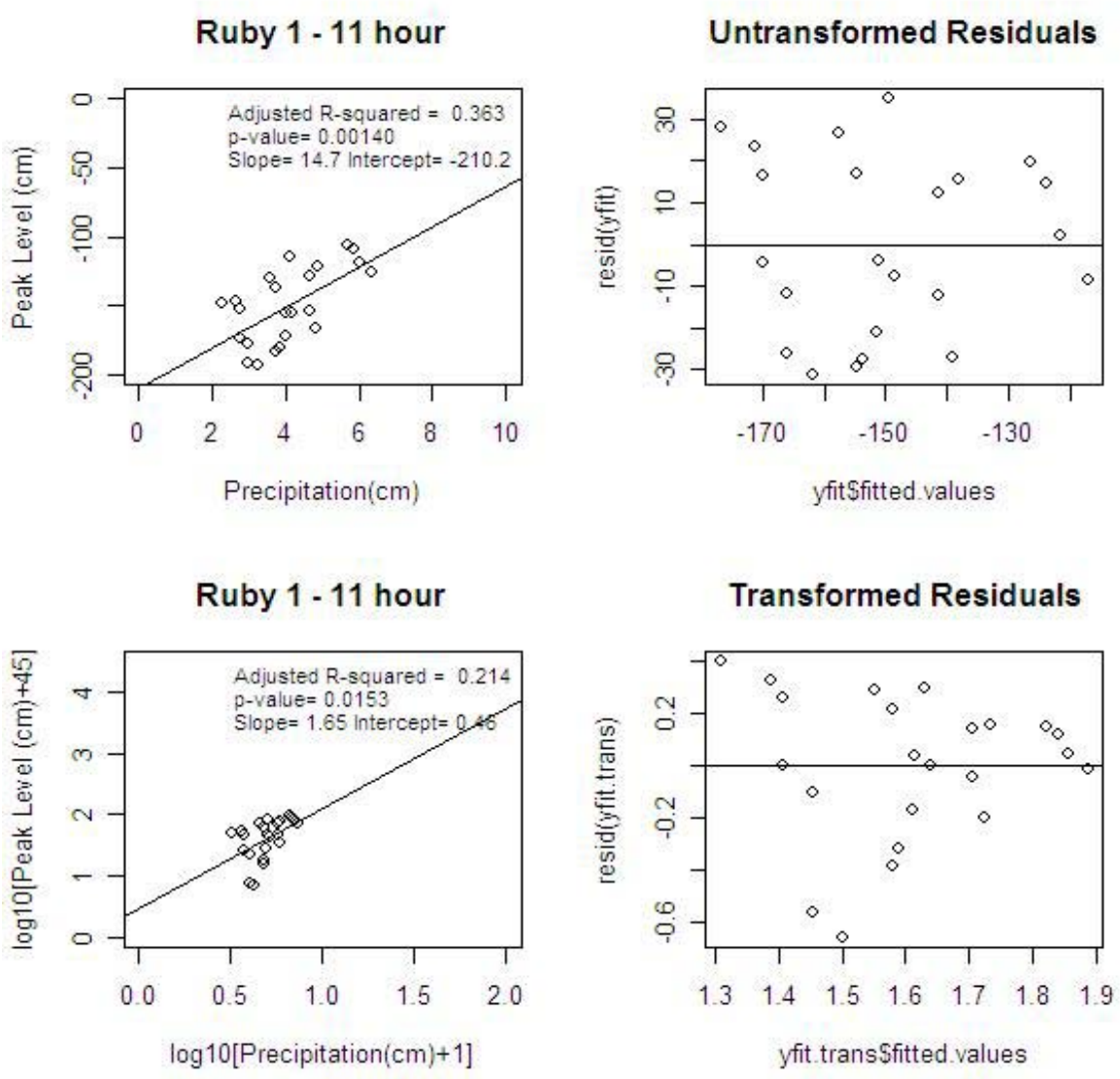


Figure 19. Linear regression model with the best fit for precipitation preceding peak water levels at the Ruby 1 well. The best fit linear regression model is for 11 hours of precipitation preceding peak water levels. Log – log transformation of the data did not improve the R-squared value or improve the randomization of residuals.

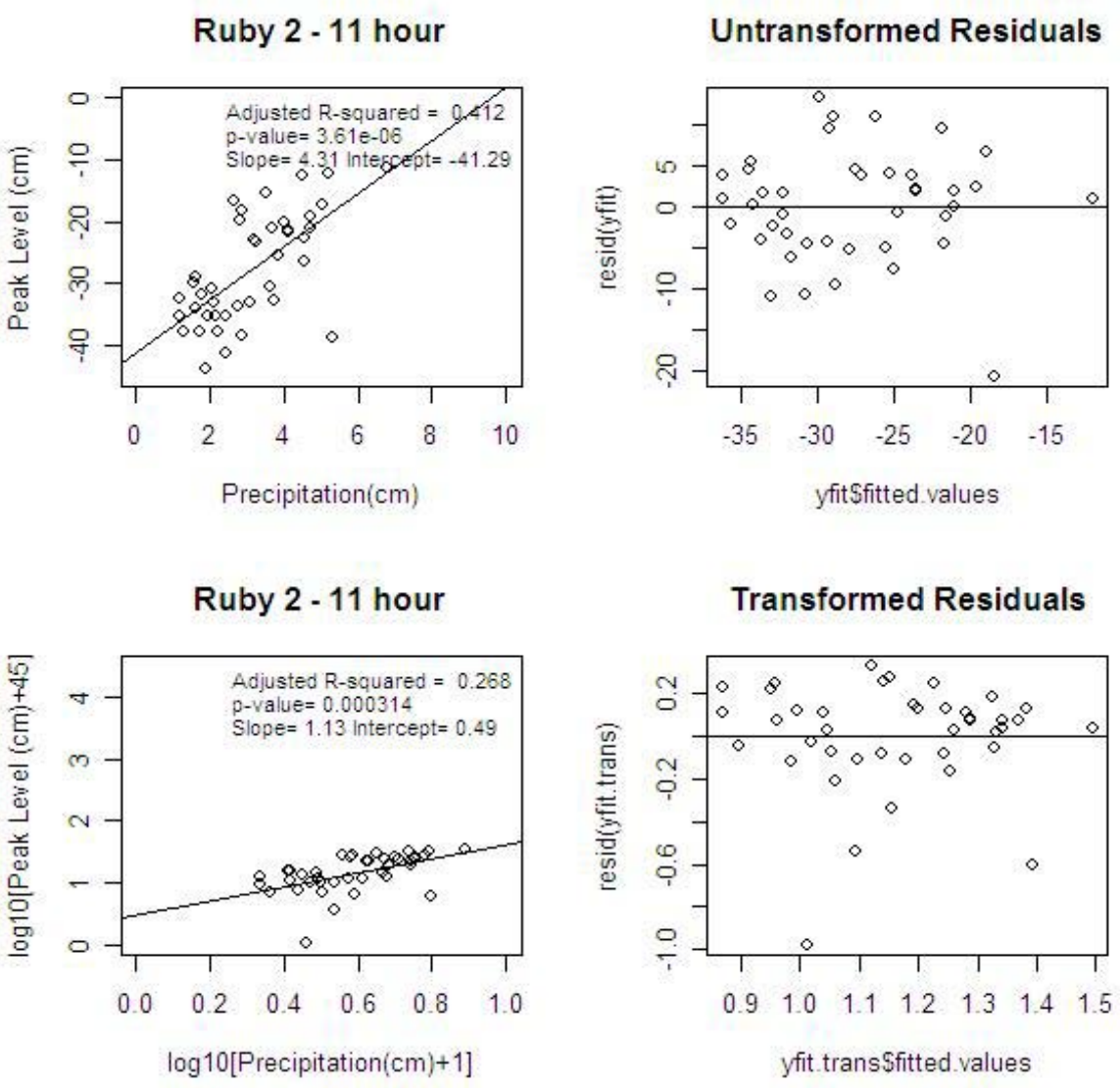


Figure 20. Linear regression model with the best fit for precipitation preceding peak water levels at the Ruby 2 well. The best fit linear regression model is for 11 hours of precipitation preceding peak water levels. Log – log transformation of the data did not improve the R-squared value or improve the randomization of residuals.

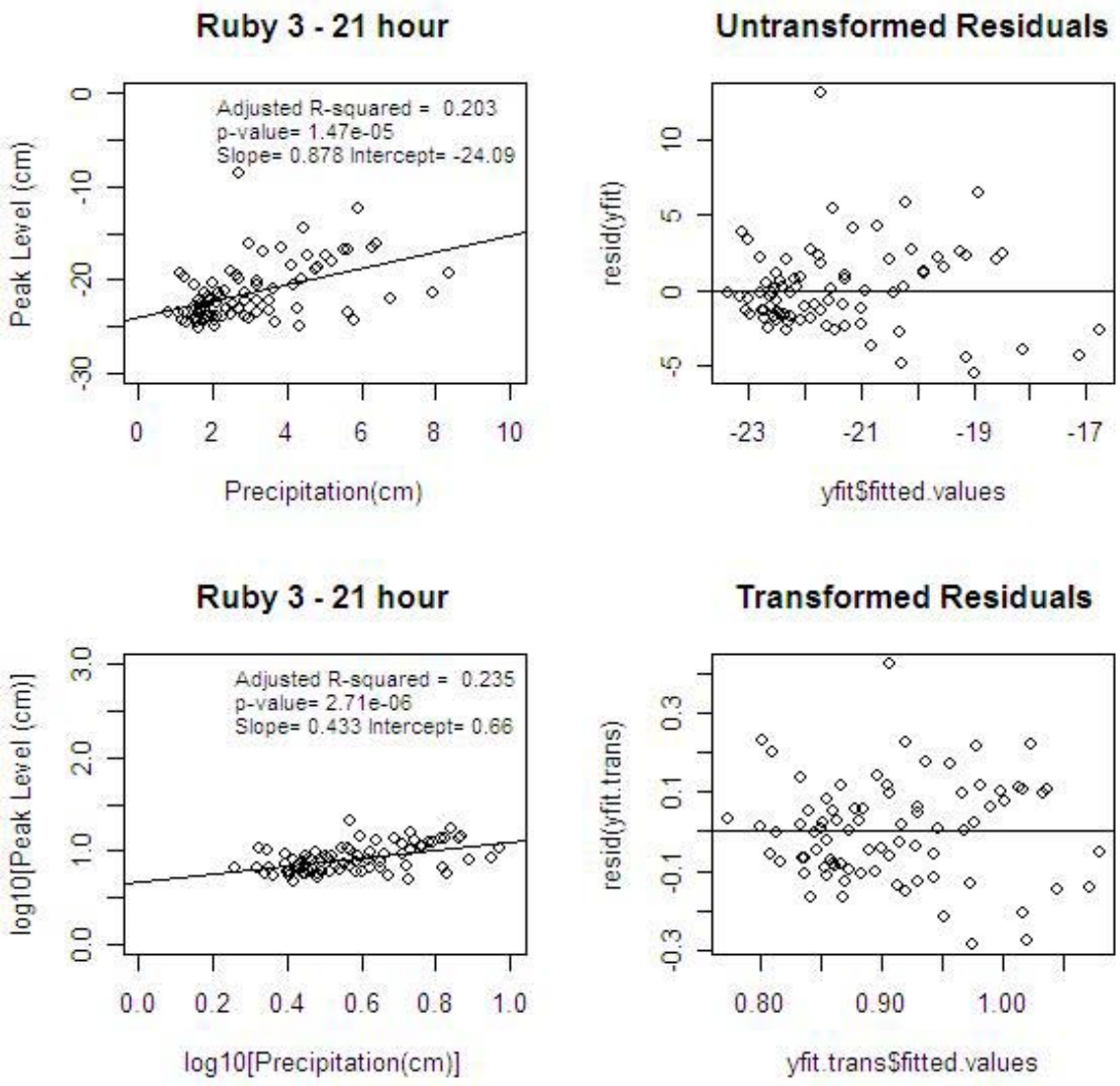


Figure 21. Linear regression model with the best fit for precipitation preceding peak water levels at the Ruby 3 well. The best fit linear regression model is for 21 hours of precipitation preceding peak water levels. Log – log transformation of the data improved the R-squared value and the randomization of residuals.

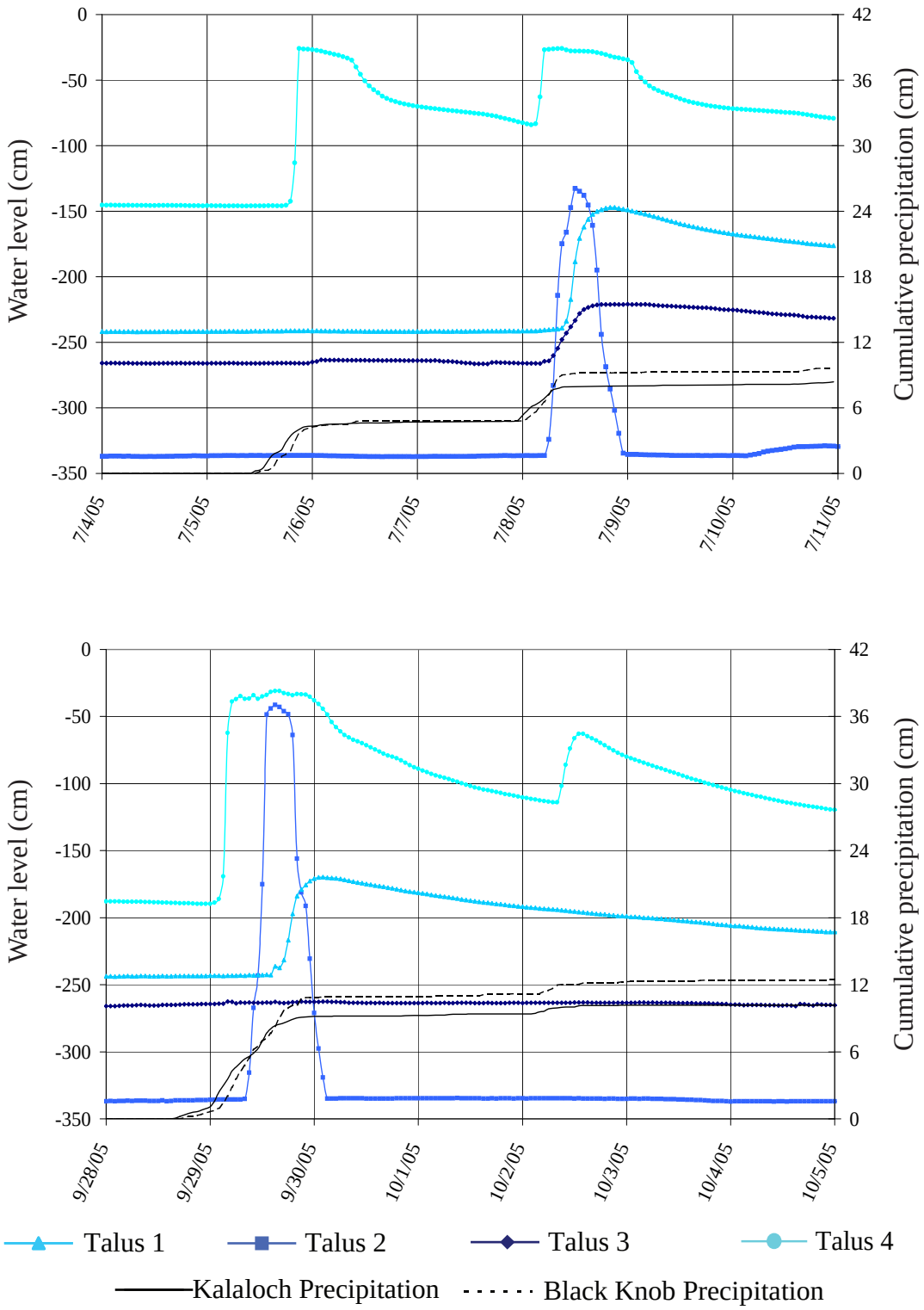


Figure 22. Water level response to precipitation events for the seven day periods from July 4 through July 11, 2005 and September 28 through October 5, 2005 at the Talus site. Each tick mark on line represents one hour.

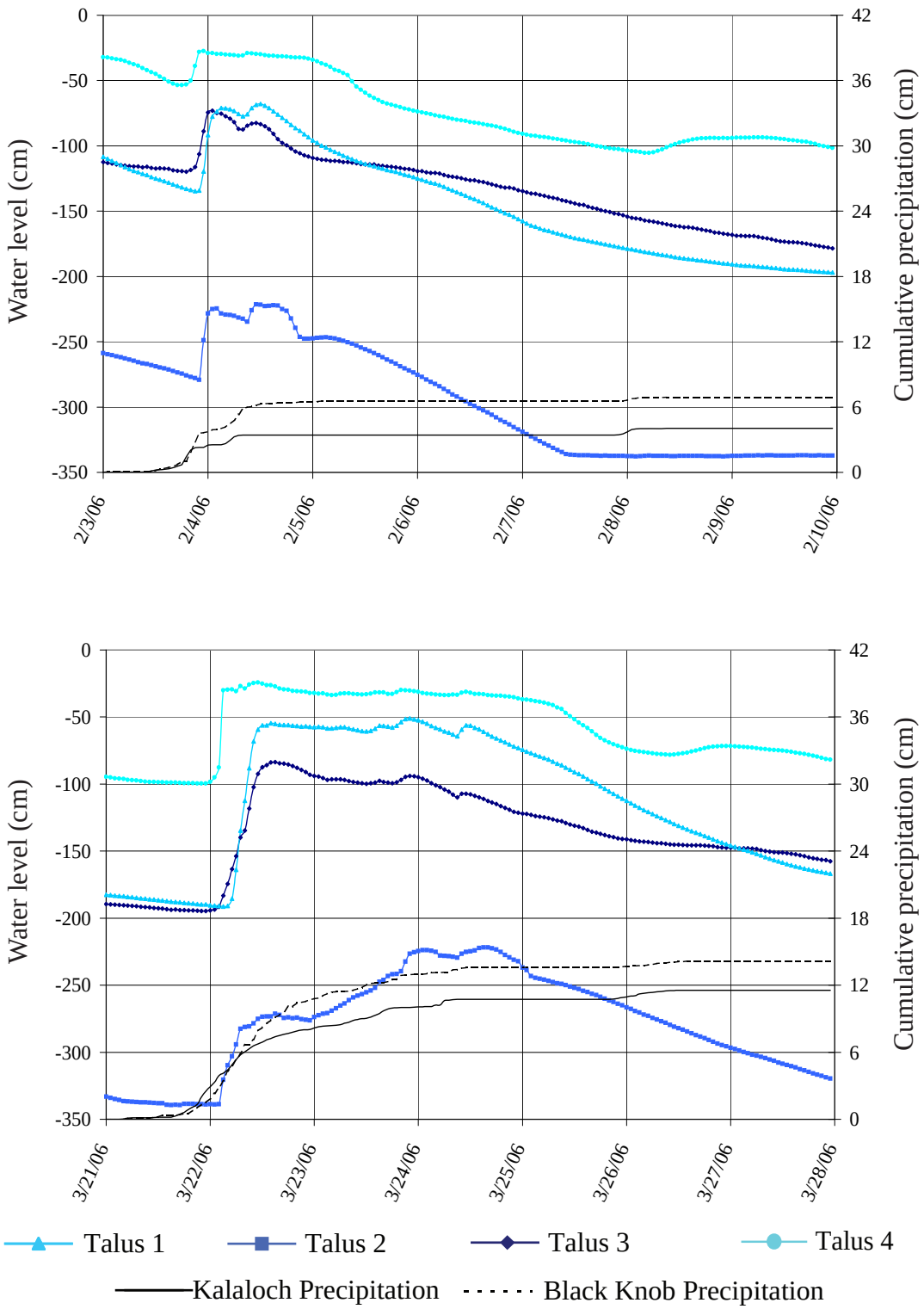


Figure 23. Water level response to precipitation events for the seven day periods from February 3 through February 10, 2006 and March 21 through March 28, 2006 at the Talus site. Each tick mark on line represents one hour.

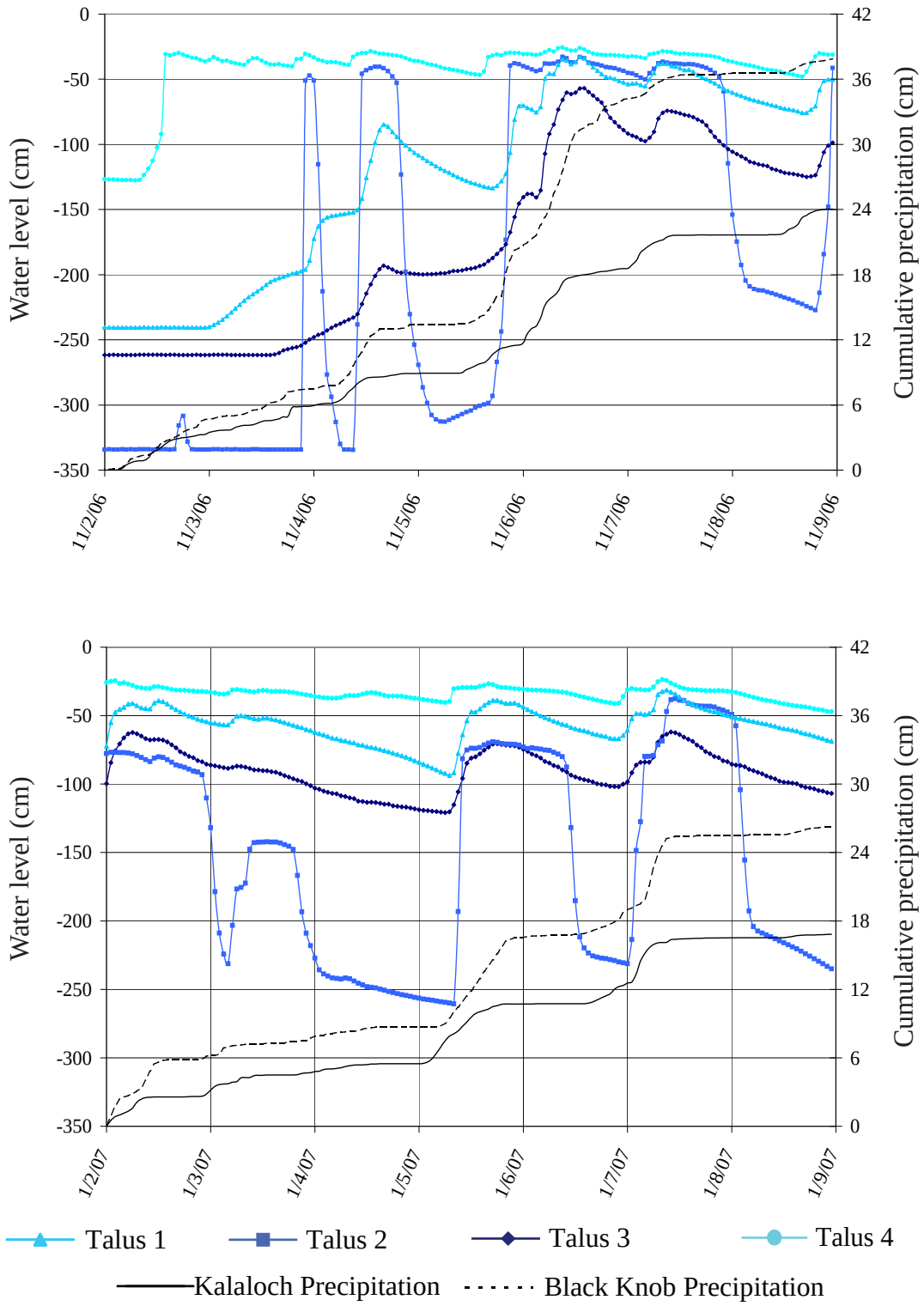


Figure 24. Water level response to precipitation events for the seven day periods from November 2, 2006 through November 9, 2006 and January 2 through January 9, 2007 at the Talus site. Each tick mark on line represents one hour.

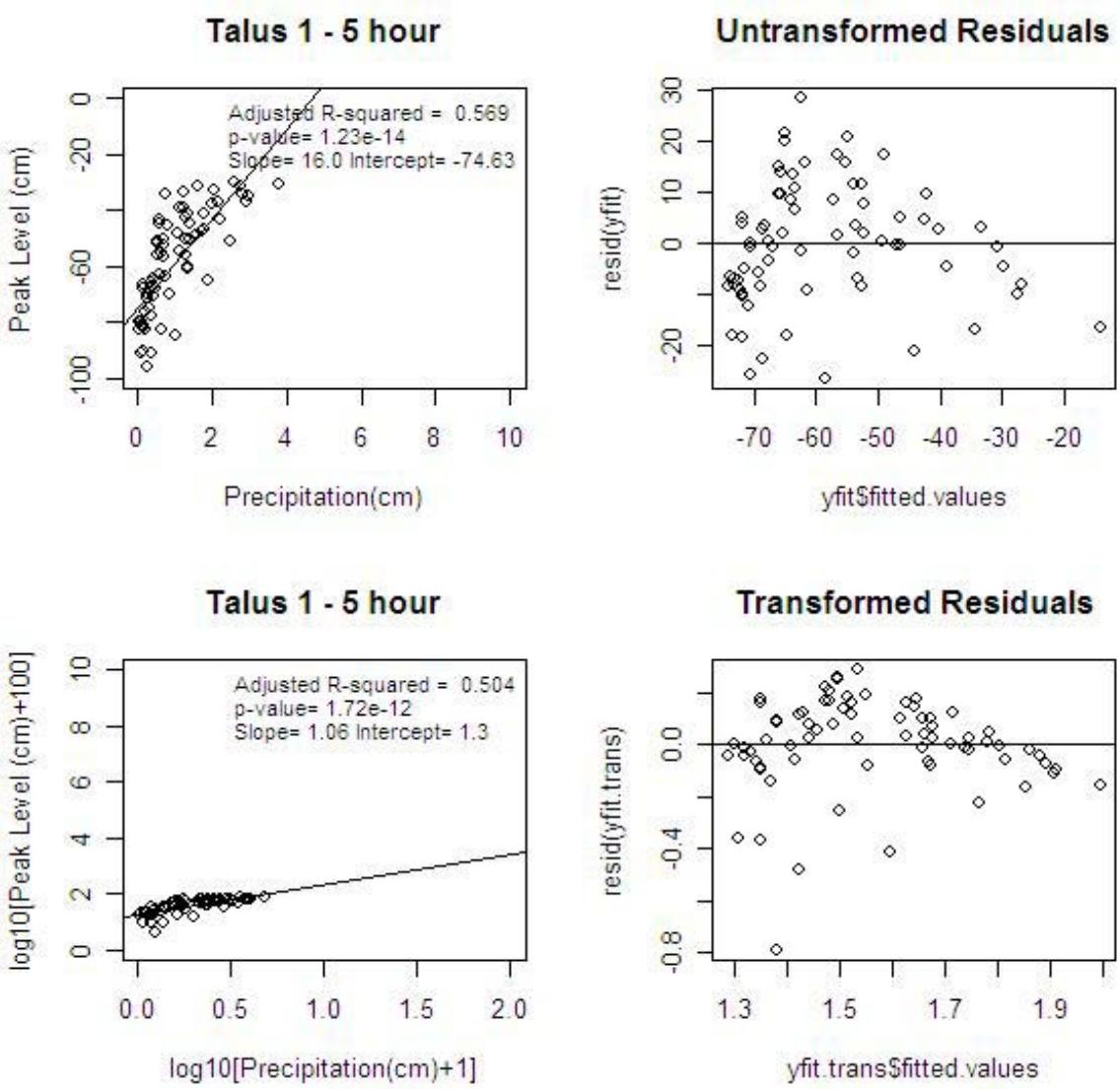


Figure 25. Linear regression model with the best fit for precipitation preceding peak water levels at the Talus 1 well. The best fit linear regression model is for 5 hours of precipitation preceding peak water levels. Log – log transformation of the data did not improve the R-squared value the randomization of residuals appears similar.

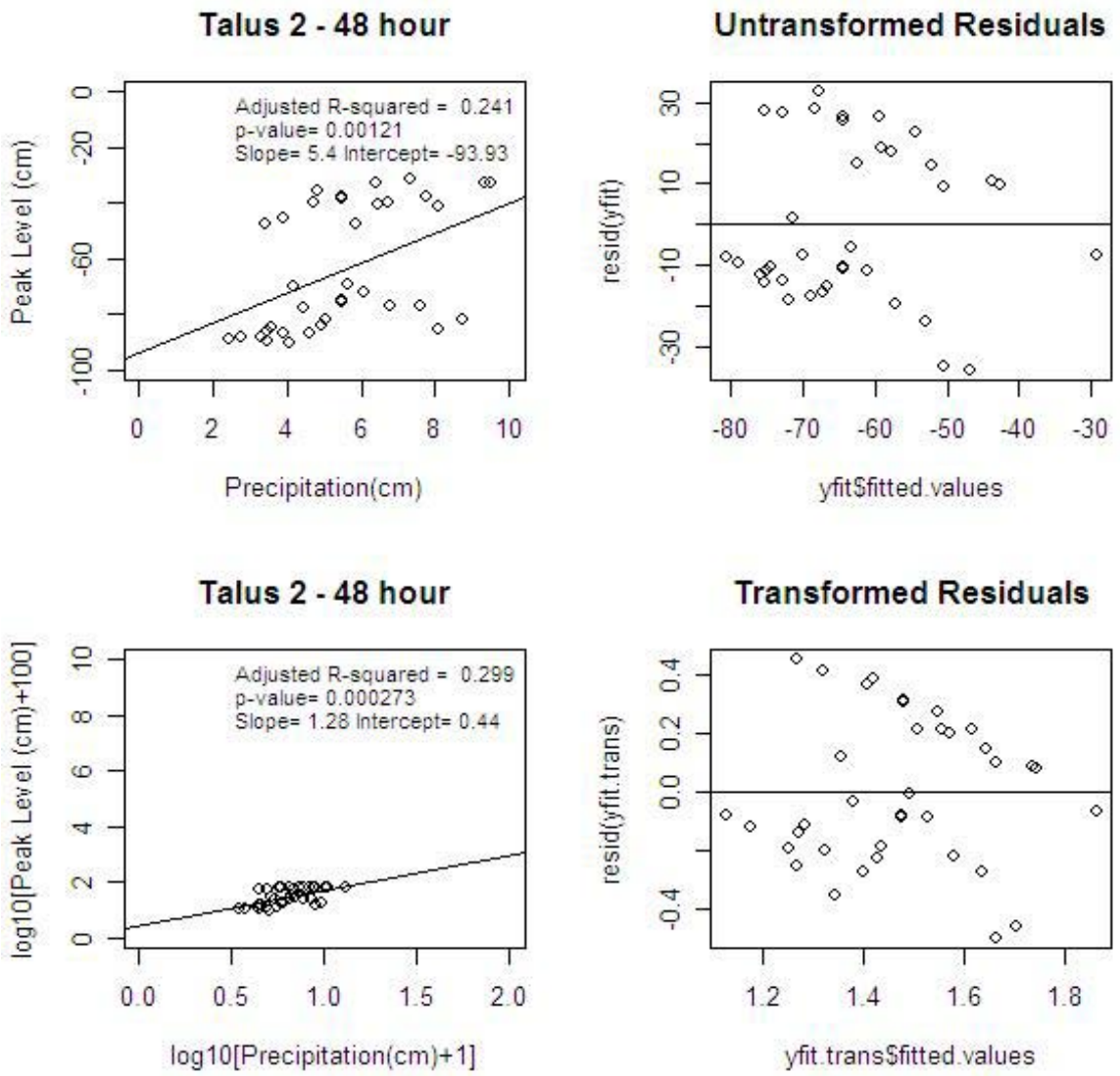


Figure 26. Linear regression model with the best fit for precipitation preceding peak water levels at the Talus 2 well. The best fit linear regression model is for 48 hours of precipitation preceding peak water levels. Log – log transformation of the data improved the R-squared value and the randomization of residuals.

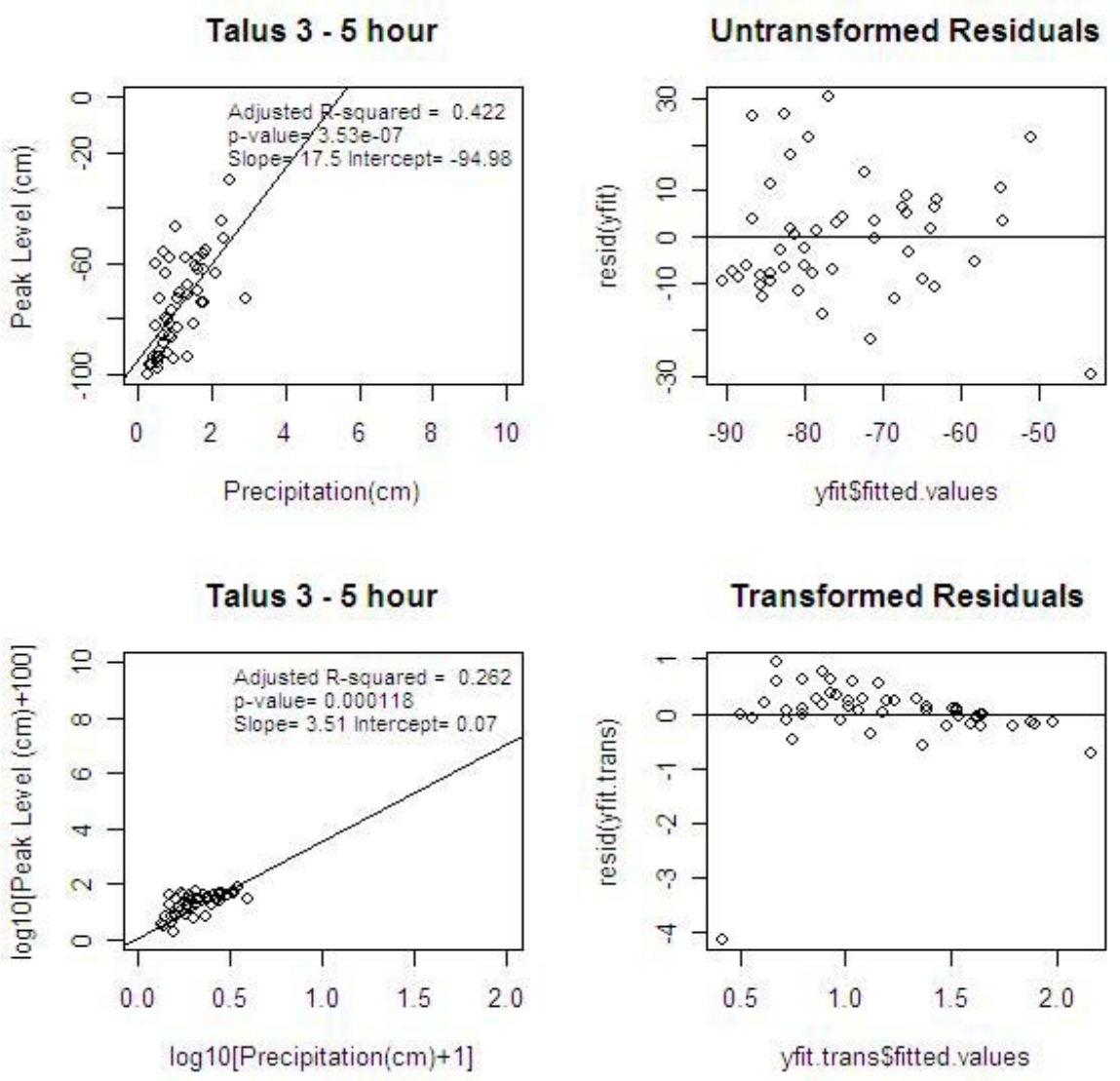


Figure 27. Linear regression model with the best fit for precipitation preceding peak water levels at the Talus 3 well. The best fit linear regression model is for 5 hours of precipitation preceding peak water levels. Log – log transformation of the data did not improve the R-squared value or the randomization of residuals.

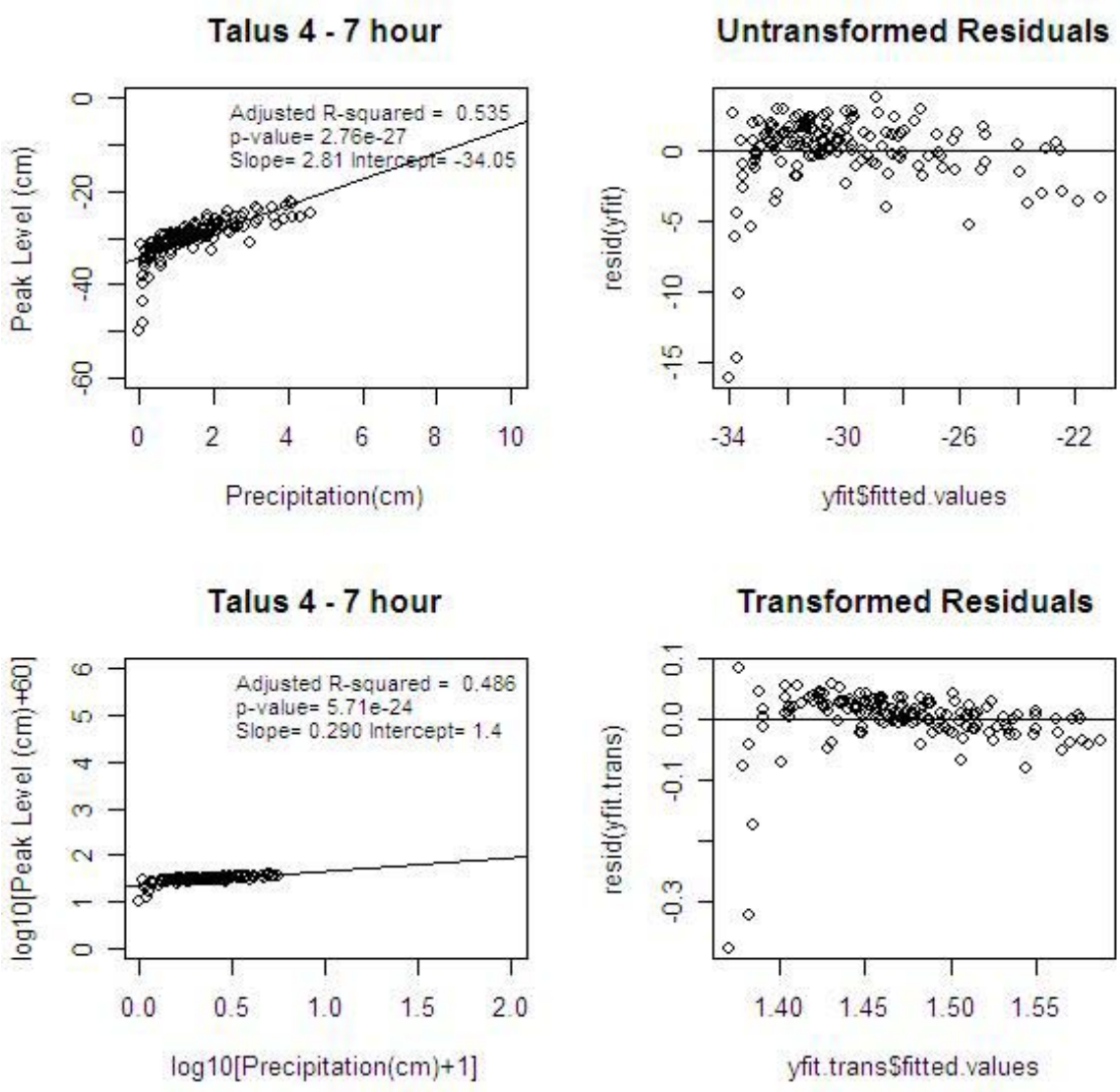


Figure 28. Linear regression model with the best fit for precipitation preceding peak water levels at the Talus 4 well. The best fit linear regression model is for 7 hours of precipitation preceding peak water levels. Log – log transformation of the data did not improve the R-squared value but did improve the randomization of residuals.

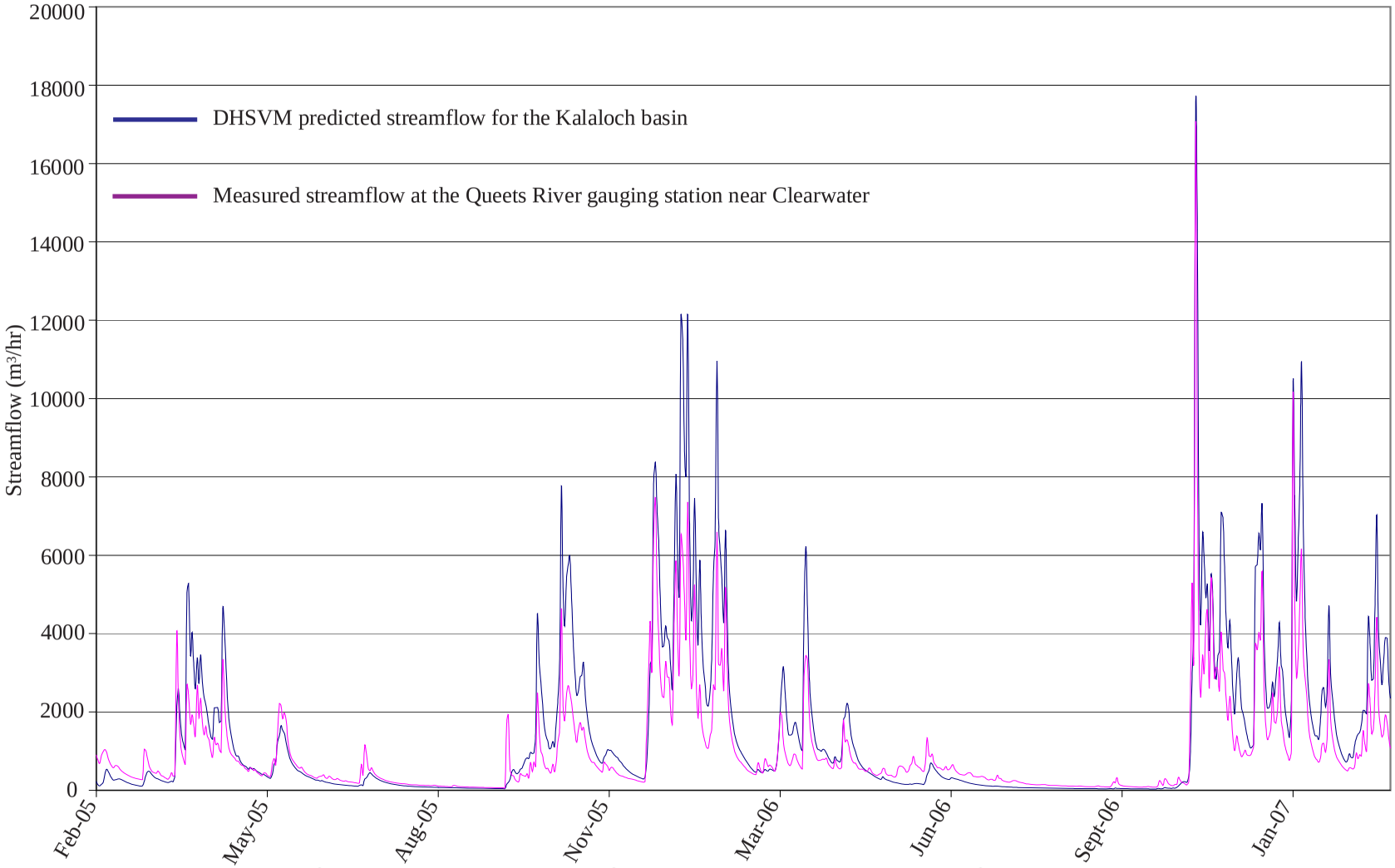


Figure 29. Comparison of DHSVM predicted streamflow output compared with streamflow output measured at the USGS streamgauge on the Queets River near Clearwater. Measured values were adjusted by a constant due to the difference in basin size between the modelled Kalaloch basin and the basin draining to the Clearwater gauge.

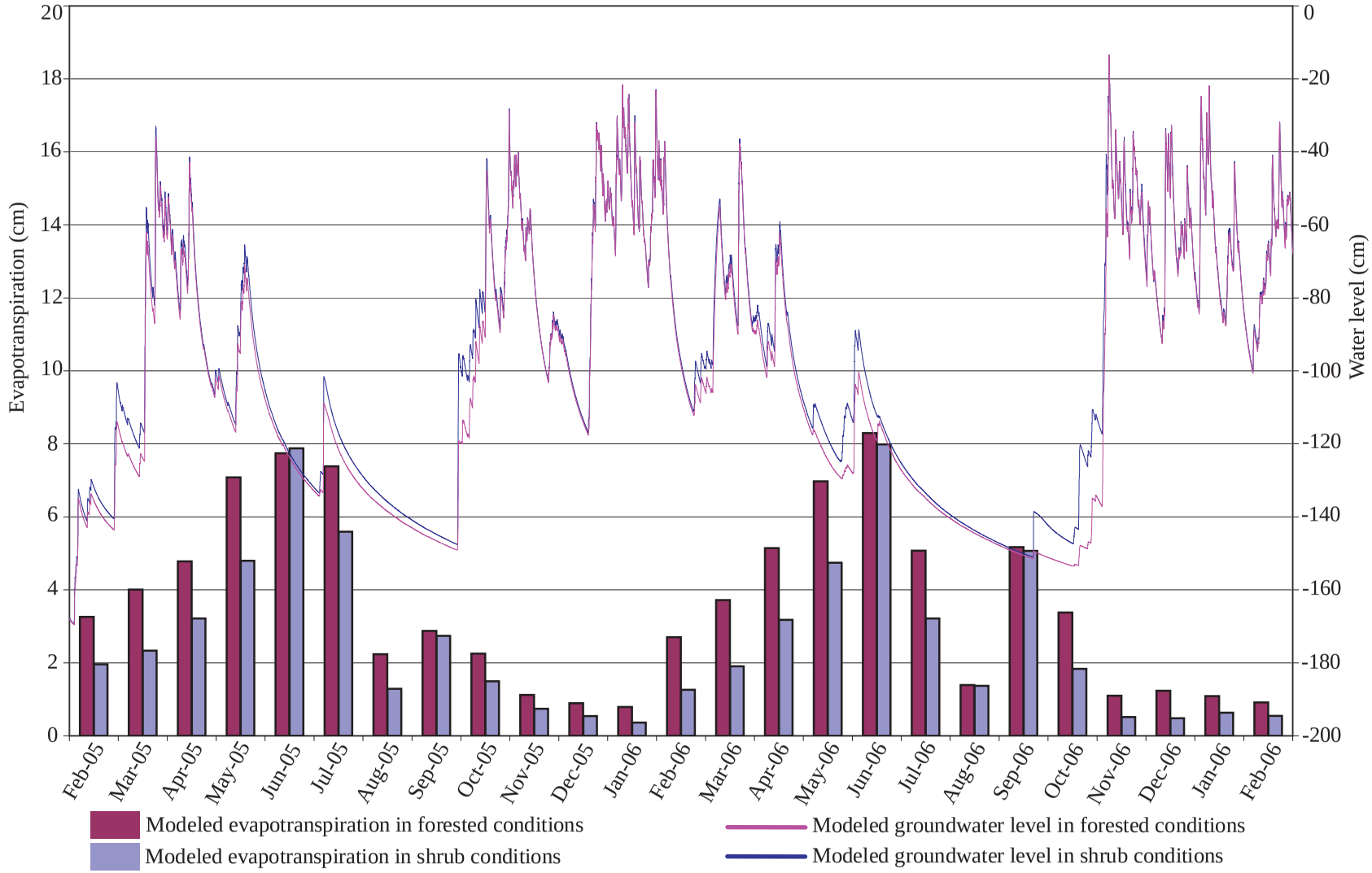


Figure 30. DHSVM predicted groundwater levels and monthly evapotranspiration under a forested basin condition and a shrub covered basin scenario.

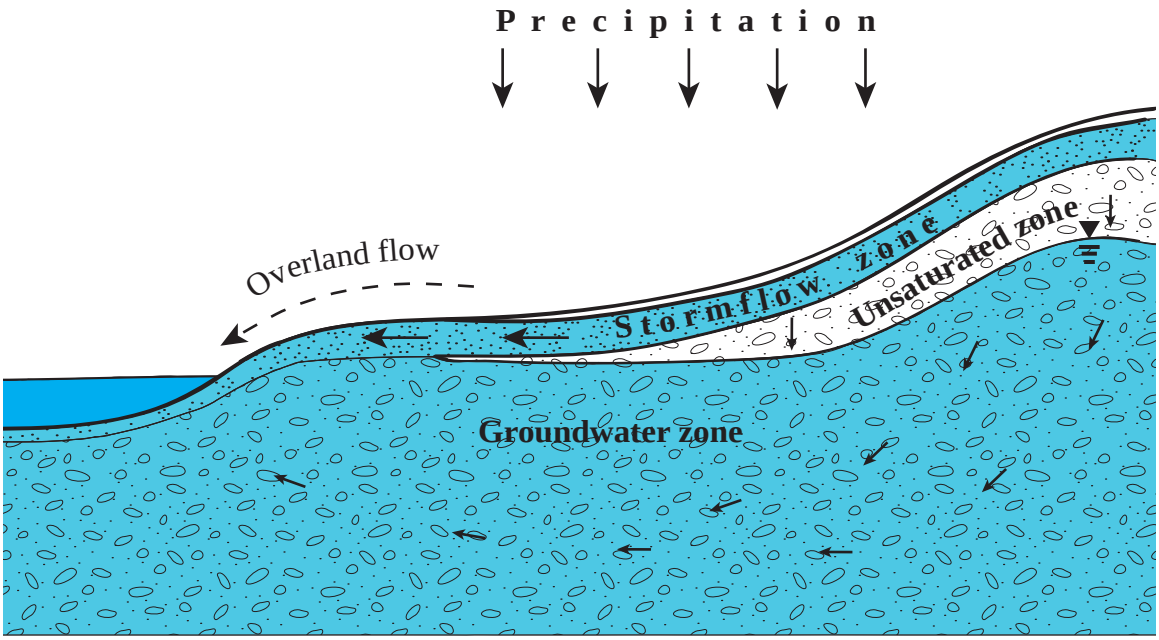


Figure 31. Hillslope cross section illustrating the concept of storm flow. Idealized hydrologic pathways are indicated by the black arrows. Figure modified from Scanlon et al., 2000.

Table 1. Groundwater peak minimum threshold values for the Kalaloch research site wells. Minimum threshold values determined by visual inspection of well data plotted in Microsoft Excel.

Well	Minimum groundwater level (cm below ground surface)
Alsea 1	-120
Alsea 2	-26
Alsea 3	-26
Ruby 1	-195
Ruby 2	-45
Ruby 3	-26
Talus 1	-100
Talus 2	-100
Talus 3	-100
Talus 4	-50

Table 2. Summary of the maximum peak water level observed in each of the 10 onsite wells.

	Maximum groundwater level recorded	
Well	Date and time	Depth below ground surface (cm)
Alsea 1	2/15/2007 8:00	-101.7
Alsea 2	1/12/2006 21:00	-9.3
Alsea 3	3/26/2005 8:00	-9.2
Ruby 1	12/11/2006 10:00	-106.8
Ruby 2	1/9/2006 7:00	-11.1
Ruby 3	2/4/2006 16:00	-8.6
Talus 1	1/9/2006 8:00	-29.8
Talus 2	11/10/2006 11:00	-31.6
Talus 3	3/26/2005 11:00	-29.7
Talus 4	1/12/2006 20:00	-22.1

Table 3. Kendall's τ correlation values between peak groundwater levels and hours of precipitation preceding the peak at the Alsea research site. Precipitation measurements from both on site rain gauges and the Black Knob weather station were used for comparison. For Alsea 1, n = 11; for Alsea 2, n = 74; and for Alsea 3, n = 58.

	Alsea 1 - On site		Alsea 1 - Black Knob		Alsea 2 - On site		Alsea 2 - Black Knob		Alsea 3 - On site		Alsea 3 - Black Knob	
	Kendall's τ	p-value	Kendall's τ	p-value	Kendall's τ	p-value	Kendall's τ	p-value	Kendall's τ	p-value	Kendall's τ	p-value
1 hour	0.473	0.105	0.309	0.218	0.218	8.00E-03	0.295	2.42E-04	0.393	2.06E-05	0.381	2.88E-05
2 hours	0.357	0.275	0.22	0.349	0.275	1.00E-03	0.375	2.59E-06	0.417	4.67E-06	0.394	1.41E-05
3 hours	0.357	0.275	0.127	0.648	0.309	1.13E-04	0.359	6.93E-06	0.452	6.17E-07	0.382	2.57E-05
4 hours	0.429	0.179	0.127	0.648	0.3	1.68E-04	0.353	9.05E-06	0.451	6.36E-07	0.337	1.91E-04
5 hours	0.357	0.275	0.091	0.761	0.31	1.01E-04	0.342	1.72E-05	0.433	1.83E-06	0.318	4.39E-04
6 hours	0.286	0.399	0.091	0.761	0.329	3.47E-05	0.359	6.38E-06	0.423	2.92E-06	0.316	4.62E-04
7 hours	0.286	0.399	0.055	0.879	0.36	6.36E-06	0.336	2.31E-05	0.432	1.83E-06	0.306	1.00E-03
8 hours	0.286	0.399	0.127	0.648	0.377	2.16E-06	0.335	2.45E-05	0.425	2.73E-06	0.305	1.00E-03
9 hours	0.182	0.533	0.091	0.761	0.377	2.21E-06	0.335	2.50E-05	0.417	4.04E-06	0.304	1.00E-03
10 hours	0	1	0.055	0.879	0.386	1.29E-06	0.361	5.60E-06	0.422	3.20E-06	0.326	3.07E-04
11 hours	0	1	0.073	0.755	0.395	7.30E-07	0.385	1.27E-06	0.415	4.69E-06	0.323	3.58E-04
12 hours	-0.182	0.533	0.055	0.879	0.421	1.20E-07	0.396	6.22E-07	0.422	3.21E-06	0.296	1.00E-03
13 hours	-0.286	0.399	-0.018	1	0.452	1.41E-08	0.411	2.38E-07	0.396	1.25E-05	0.289	1.00E-03
14 hours	-0.143	0.72	-0.018	1	0.434	4.73E-08	0.424	9.83E-08	0.404	8.11E-06	0.283	2.00E-03
15 hours	-0.143	0.72	-0.055	0.879	0.437	3.74E-08	0.431	5.85E-08	0.366	5.20E-05	0.272	3.00E-03
16 hours	-0.214	0.548	-0.091	0.761	0.426	8.41E-08	0.424	9.10E-08	0.37	4.26E-05	0.247	6.00E-03
17 hours	-0.214	0.548	-0.091	0.761	0.425	9.04E-08	0.424	9.33E-08	0.366	5.36E-05	0.236	9.00E-03
18 hours	-0.286	0.399	-0.055	0.879	0.41	2.50E-07	0.427	7.79E-08	0.357	7.96E-05	0.243	7.00E-03
19 hours	-0.255	0.383	-0.018	1	0.406	3.37E-07	0.425	8.64E-08	0.345	1.35E-04	0.243	7.00E-03
20 hours	-0.214	0.548	-0.018	1	0.4	4.99E-07	0.43	6.16E-08	0.337	1.96E-04	0.234	1.00E-02
21 hours	-0.214	0.548	-0.018	1	0.408	2.90E-07	0.435	4.50E-08	0.342	1.55E-04	0.225	1.30E-02
22 hours	-0.182	0.533	-0.018	1	0.41	2.57E-07	0.428	7.39E-08	0.331	2.49E-04	0.224	1.30E-02

Table 3 (continued). Kendall's τ correlation values between peak groundwater levels and hours of precipitation preceding the peak at the Alsea research site. Precipitation measurements from both on site rain gauges and the Black Knob weather station were used for comparison. For Alsea 1, n = 11; for Alsea 2, n = 74; and for Alsea 3, n = 58.

	Alsea 1 - On site		Alsea 1 - Black Knob		Alsea 2 - On site		Alsea 2 - Black Knob		Alsea 3 - On site		Alsea 3 - Black Knob	
	Kendall's τ	p-value	Kendall's τ	p-value	Kendall's τ	p-value	Kendall's τ	p-value	Kendall's τ	p-value	Kendall's τ	p-value
23 hours	-0.143	0.72	0.018	1	0.402	4.51E-07	0.422	1.09E-07	0.309	1.00E-03	0.208	2.10E-02
24 hours	-0.143	0.72	0.018	1	0.391	8.86E-07	0.41	2.45E-07	0.31	1.00E-03	0.196	3.00E-02
25 hours	-0.143	0.72	0.018	1	0.387	1.18E-06	0.397	5.78E-07	0.296	1.00E-03	0.182	4.40E-02
26 hours	-0.143	0.72	0.018	1	0.383	1.53E-06	0.395	6.67E-07	0.285	2.00E-03	0.179	4.70E-02
27 hours	-0.143	0.72	0.018	1	0.369	3.57E-06	0.402	4.20E-07	0.288	1.00E-03	0.181	4.60E-02
28 hours	-0.143	0.72	0.018	1	0.351	1.05E-05	0.394	7.17E-07	0.276	2.00E-03	0.172	5.70E-02
29 hours	-0.143	0.72	-0.018	1	0.342	1.65E-05	0.386	1.21E-06	0.265	3.00E-03	0.172	5.70E-02
30 hours	-0.143	0.72	-0.018	1	0.343	1.61E-05	0.379	1.80E-06	0.264	3.00E-03	0.159	7.80E-02
31 hours	-0.143	0.72	-0.018	1	0.341	1.79E-05	0.37	3.27E-06	0.261	4.00E-03	0.161	7.50E-02
32 hours	-0.143	0.72	-0.018	1	0.333	2.72E-05	0.372	2.91E-06	0.249	6.00E-03	0.152	9.20E-02
33 hours	-0.143	0.72	0.018	1	0.324	4.60E-05	0.355	7.95E-06	0.245	7.00E-03	0.143	1.13E-01
34 hours	-0.143	0.72	0.018	1	0.316	7.26E-05	0.36	5.98E-06	0.235	9.00E-03	0.142	1.15E-01
35 hours	-0.143	0.72	0.018	1	0.307	1.13E-04	0.349	1.10E-05	0.216	1.70E-02	0.125	1.67E-01
36 hours	-0.143	0.72	0.018	1	0.305	1.25E-04	0.337	2.17E-05	0.212	1.90E-02	0.117	1.93E-01
2 days	-0.286	0.399	0.018	1	0.27	1.00E-03	0.276	5.07E-04	0.198	2.90E-02	0.079	3.83E-01
3 days	-0.071	0.905	-0.018	1	0.196	1.40E-02	0.214	7.08E-03	0.052	5.69E-01	-0.031	7.32E-01
7 days	0	1	0.2	0.445	0.234	3.00E-03	0.236	2.95E-03	0.022	8.09E-01	-0.088	3.27E-01
14 days	0	1	0.236	0.359	0.2	1.20E-02	0.195	1.41E-02	0.157	8.20E-02	0.055	5.42E-01

Table 4. Kendall's τ correlation values between peak groundwater levels and hours of precipitation preceding the peak at the Ruby research site. Precipitation measurements from both on site rain gauges and the Black Knob weather station were used for comparison. For Ruby 1, n = 23; for Ruby 2, n = 41; for Ruby 3, n = 81.

	Ruby 1 - On site		Ruby 1 - Black Knob		Ruby 2 - On site		Ruby 2 - Black Knob		Ruby 3 - On site		Ruby 3 - Black Knob	
	Kendall's τ	p-value	Kendall's τ	p-value	Kendall's τ	p-value	Kendall's τ	p-value	Kendall's τ	p-value	Kendall's τ	p-value
1 hour	0.106	4.89E-01	0.048	7.51E-01	0.232	3.90E-02	0.372	6.84E-04	0.180	2.24E-02	0.114	1.43E-01
2 hours	0.204	1.77E-01	0.052	7.31E-01	0.287	8.79E-03	0.377	5.39E-04	0.139	7.20E-02	0.120	1.18E-01
3 hours	0.335	2.63E-02	0.178	2.48E-01	0.326	2.80E-03	0.389	3.53E-04	0.142	6.43E-02	0.171	2.53E-02
4 hours	0.402	7.56E-03	0.182	2.24E-01	0.372	6.36E-04	0.362	8.50E-04	0.148	5.25E-02	0.142	6.17E-02
5 hours	0.323	3.22E-02	0.218	1.46E-01	0.393	3.22E-04	0.365	7.84E-04	0.184	1.59E-02	0.143	6.06E-02
6 hours	0.337	2.47E-02	0.273	7.22E-02	0.390	3.39E-04	0.341	1.72E-03	0.182	1.66E-02	0.155	4.14E-02
7 hours	0.290	5.37E-02	0.317	3.46E-02	0.411	1.54E-04	0.328	2.52E-03	0.187	1.42E-02	0.167	2.85E-02
8 hours	0.345	2.15E-02	0.301	4.47E-02	0.414	1.46E-04	0.349	1.32E-03	0.202	8.01E-03	0.166	2.85E-02
9 hours	0.377	1.21E-02	0.337	2.47E-02	0.439	5.49E-05	0.358	9.96E-04	0.199	8.82E-03	0.189	1.30E-02
10 hours	0.404	7.04E-03	0.360	1.62E-02	0.433	6.98E-05	0.387	3.70E-04	0.212	5.33E-03	0.236	1.88E-03
11 hours	0.386	1.03E-02	0.333	2.65E-02	0.426	8.83E-05	0.405	1.36E-04	0.253	8.97E-04	0.223	3.27E-03
12 hours	0.380	1.12E-02	0.312	3.84E-02	0.431	7.32E-05	0.410	1.11E-04	0.294	1.14E-04	0.227	2.79E-03
13 hours	0.388	9.62E-03	0.277	6.44E-02	0.462	2.17E-05	0.373	4.70E-04	0.307	5.55E-05	0.247	1.15E-03
14 hours	0.298	4.75E-02	0.304	4.38E-02	0.441	5.01E-05	0.371	5.14E-04	0.313	3.78E-05	0.267	4.38E-04
15 hours	0.325	3.03E-02	0.289	5.66E-02	0.434	6.66E-05	0.392	3.11E-04	0.321	2.50E-05	0.278	2.53E-04
16 hours	0.306	4.19E-02	0.289	5.66E-02	0.447	3.92E-05	0.397	2.61E-04	0.321	2.50E-05	0.277	2.70E-04
17 hours	0.325	3.03E-02	0.304	4.38E-02	0.455	2.92E-05	0.389	3.39E-04	0.329	1.50E-05	0.280	2.26E-04
18 hours	0.349	2.01E-02	0.312	3.84E-02	0.459	2.52E-05	0.382	4.38E-04	0.329	1.48E-05	0.293	1.16E-04
19 hours	0.336	2.53E-02	0.328	2.92E-02	0.465	1.87E-05	0.388	2.69E-04	0.333	1.18E-05	0.301	7.22E-05
20 hours	0.301	4.47E-02	0.336	2.53E-02	0.469	1.61E-05	0.379	4.77E-04	0.342	6.67E-06	0.303	6.51E-05
21 hours	0.304	4.38E-02	0.320	3.35E-02	0.462	2.17E-05	0.395	2.01E-04	0.348	4.54E-06	0.291	1.28E-04
22 hours	0.325	3.03E-02	0.328	2.92E-02	0.467	1.69E-05	0.390	2.44E-04	0.335	1.03E-05	0.289	1.41E-04

Table 4 (continued). Kendall's τ correlation values between peak groundwater levels and hours of precipitation preceding the peak at the Ruby research site. Precipitation measurements from both on site rain gauges and the Black Knob weather station were used for comparison. For Ruby 1, n = 23; for Ruby 2, n = 41; for Ruby 3, n = 81.

	Ruby 1 - On site		Ruby 1 - Black Knob		Ruby 2 - On site		Ruby 2 - Black Knob		Ruby 3 - On site		Ruby 3 - Black Knob	
	Kendall's τ	p-value	Kendall's τ	p-value	Kendall's τ	p-value	Kendall's τ	p-value	Kendall's τ	p-value	Kendall's τ	p-value
23 hours	0.296	4.98E-02	0.312	3.84E-02	0.462	2.07E-05	0.395	2.01E-04	0.329	1.50E-05	0.290	1.37E-04
24 hours	0.282	6.06E-02	0.304	4.38E-02	0.488	7.01E-06	0.412	1.53E-04	0.328	1.59E-05	0.289	1.39E-04
25 hours	0.258	8.58E-02	0.273	7.22E-02	0.495	1.98E-06	0.415	9.05E-05	0.325	1.94E-05	0.292	1.18E-04
26 hours	0.247	1.01E-01	0.277	6.44E-02	0.487	7.77E-06	0.398	2.50E-04	0.327	1.68E-05	0.293	1.10E-04
27 hours	0.250	9.59E-02	0.273	7.22E-02	0.490	6.97E-06	0.413	1.47E-04	0.327	1.68E-05	0.292	1.16E-04
28 hours	0.246	1.01E-01	0.277	6.44E-02	0.499	4.57E-06	0.418	1.22E-04	0.321	2.33E-05	0.283	1.90E-04
29 hours	0.230	1.25E-01	0.265	8.12E-02	0.495	5.35E-06	0.409	1.68E-04	0.315	3.34E-05	0.274	3.02E-04
30 hours	0.215	1.53E-01	0.266	7.66E-02	0.501	4.10E-06	0.394	2.86E-04	0.309	4.75E-05	0.262	5.42E-04
31 hours	0.199	1.86E-01	0.265	8.12E-02	0.501	4.31E-06	0.379	4.77E-04	0.308	5.02E-05	0.258	6.69E-04
32 hours	0.226	1.32E-01	0.265	8.12E-02	0.510	2.80E-06	0.380	4.76E-04	0.300	7.72E-05	0.251	9.26E-04
33 hours	0.246	1.01E-01	0.265	8.12E-02	0.492	6.27E-06	0.364	8.15E-04	0.297	9.46E-05	0.248	1.07E-03
34 hours	0.269	7.24E-02	0.265	8.12E-02	0.475	1.30E-05	0.345	1.48E-03	0.289	1.44E-04	0.238	1.73E-03
35 hours	0.258	8.58E-02	0.269	7.24E-02	0.456	2.78E-05	0.325	2.81E-03	0.273	3.21E-04	0.226	2.90E-03
36 hours	0.249	1.02E-01	0.277	6.44E-02	0.442	4.99E-05	0.311	4.32E-03	0.268	4.12E-04	0.213	5.01E-03
2 days	0.194	1.95E-01	0.241	1.14E-01	0.422	1.02E-04	0.273	1.16E-02	0.237	1.80E-03	0.199	8.72E-03
3 days	0.115	4.64E-01	0.154	3.19E-01	0.242	2.61E-02	0.195	7.40E-02	0.180	1.76E-02	0.132	8.08E-02
7 days	-0.186	2.27E-01	-0.194	2.07E-01	0.055	6.13E-01	0.072	5.08E-01	0.118	1.19E-01	0.104	1.72E-01
14 days	-0.146	3.46E-01	-0.091	5.65E-01	0.084	4.38E-01	0.054	6.31E-01	0.096	2.08E-01	0.113	1.36E-01

Table 5. Kendall's τ correlation values between peak groundwater levels and hours of precipitation preceding the peak at the Talus research site. Precipitation measurements from both on site rain gauges and the Black Knob weather station were used for comparison. For Talus 1, n = 72; for Talus 2, n = 37; for Talus 3, n = 48; and for Talus 4, n = 156.

	Talus 1 - On site		Talus 1 - Black Knob		Talus 2 - On site		Talus 2 - Black Knob		Talus 3 - On site		Talus 3 - Black Knob	
	Kendall's τ	p-value	Kendall's τ	p-value	Kendall's τ	p-value	Kendall's τ	p-value	Kendall's τ	p-value	Kendall's τ	p-value
1 hour	0.479	2.52E-08	0.473	1.34E-08	0.126	2.94E-01	0.078	5.03E-01	0.206	5.49E-02	0.337	9.63E-04
2 hours	0.525	2.68E-10	0.481	4.26E-09	0.066	5.73E-01	0.119	3.01E-01	0.243	1.75E-02	0.427	2.12E-05
3 hours	0.606	1.20E-13	0.519	1.58E-10	0.141	2.24E-01	0.206	7.31E-02	0.367	2.81E-04	0.367	2.48E-04
4 hours	0.635	5.55E-15	0.487	1.69E-09	0.187	1.05E-01	0.206	7.31E-02	0.451	7.56E-06	0.424	2.31E-05
5 hours	0.632	5.55E-15	0.464	8.82E-09	0.158	1.70E-01	0.220	5.61E-02	0.505	4.61E-07	0.351	4.46E-04
6 hours	0.620	1.73E-14	0.417	2.36E-07	0.170	1.39E-01	0.214	6.32E-02	0.449	7.41E-06	0.291	3.65E-03
7 hours	0.580	7.32E-13	0.364	6.57E-06	0.214	6.32E-02	0.200	8.19E-02	0.385	1.22E-04	0.297	2.99E-03
8 hours	0.519	1.37E-10	0.316	9.09E-05	0.220	5.61E-02	0.215	6.14E-02	0.369	2.25E-04	0.325	1.11E-03
9 hours	0.441	4.87E-08	0.304	1.65E-04	0.205	7.51E-02	0.230	4.54E-02	0.372	1.96E-04	0.318	1.46E-03
10 hours	0.420	2.01E-07	0.314	1.01E-04	0.209	6.90E-02	0.219	5.75E-02	0.377	1.63E-04	0.360	3.08E-04
11 hours	0.433	8.17E-08	0.311	1.16E-04	0.204	7.74E-02	0.206	7.31E-02	0.394	8.47E-05	0.353	4.04E-04
12 hours	0.446	3.24E-08	0.300	1.92E-04	0.215	6.14E-02	0.230	4.54E-02	0.412	3.72E-05	0.352	4.17E-04
13 hours	0.433	8.61E-08	0.301	1.92E-04	0.263	2.21E-02	0.241	3.64E-02	0.425	2.07E-05	0.359	3.19E-04
14 hours	0.443	4.26E-08	0.308	1.33E-04	0.265	2.13E-02	0.248	3.09E-02	0.432	1.50E-05	0.359	3.19E-04
15 hours	0.430	9.62E-08	0.306	1.44E-04	0.299	9.23E-03	0.267	1.99E-02	0.427	1.90E-05	0.360	2.40E-04
16 hours	0.421	1.86E-07	0.303	1.71E-04	0.302	8.86E-03	0.267	1.99E-02	0.400	6.33E-05	0.356	2.79E-04
17 hours	0.417	2.30E-07	0.303	1.68E-04	0.297	9.93E-03	0.249	3.02E-02	0.399	6.55E-05	0.351	3.47E-04
18 hours	0.407	4.50E-07	0.313	1.05E-04	0.271	1.85E-02	0.266	2.06E-02	0.397	7.08E-05	0.365	2.59E-04
19 hours	0.411	3.66E-07	0.311	1.11E-04	0.287	1.25E-02	0.276	1.59E-02	0.387	1.10E-04	0.369	2.18E-04
20 hours	0.399	7.44E-07	0.317	8.22E-05	0.287	1.25E-02	0.273	1.72E-02	0.396	7.60E-05	0.379	1.47E-04
21 hours	0.406	4.73E-07	0.318	7.74E-05	0.284	1.34E-02	0.263	2.21E-02	0.402	6.06E-05	0.399	6.34E-05
22 hours	0.417	2.36E-07	0.339	2.61E-05	0.278	1.55E-02	0.287	1.25E-02	0.388	1.02E-04	0.404	5.25E-05

Table 5 (continued). Kendall's τ correlation values between peak groundwater levels and hours of precipitation preceding the peak at the Talus research site. Precipitation measurements from both on site rain gauges and the Black Knob weather station were used for comparison. For Talus 1, n = 72; for Talus 2, n = 37; for Talus 3, n = 48; and for Talus 4, n = 156.

	Talus 1 - On site		Talus 1 - Black Knob		Talus 2 - On site		Talus 2 - Black Knob		Talus 3 - On site		Talus 3 - Black Knob	
	Kendall's τ	p-value	Kendall's τ	p-value	Kendall's τ	p-value	Kendall's τ	p-value	Kendall's τ	p-value	Kendall's τ	p-value
23 hours	0.425	1.36E-07	0.335	3.23E-05	0.271	1.85E-02	0.270	1.85E-02	0.385	1.14E-04	0.393	8.23E-05
24 hours	0.428	1.10E-07	0.330	4.25E-05	0.268	1.99E-02	0.271	1.85E-02	0.380	1.42E-04	0.383	1.23E-04
25 hours	0.429	9.91E-08	0.325	5.45E-05	0.269	1.92E-02	0.263	2.21E-02	0.369	2.17E-04	0.371	2.03E-04
26 hours	0.429	1.02E-07	0.325	5.57E-05	0.266	2.06E-02	0.250	2.99E-02	0.370	2.17E-04	0.355	3.00E-04
27 hours	0.435	7.16E-08	0.323	6.17E-05	0.274	1.73E-02	0.241	3.64E-02	0.365	2.58E-04	0.349	3.74E-04
28 hours	0.434	7.57E-08	0.326	5.13E-05	0.275	1.67E-02	0.244	3.41E-02	0.360	3.18E-04	0.344	4.63E-04
29 hours	0.432	8.65E-08	0.326	5.13E-05	0.271	1.85E-02	0.246	3.29E-02	0.348	4.93E-04	0.337	7.30E-04
30 hours	0.437	6.10E-08	0.327	4.92E-05	0.277	1.61E-02	0.239	3.76E-02	0.351	4.32E-04	0.334	8.05E-04
31 hours	0.436	6.43E-08	0.330	4.08E-05	0.287	1.25E-02	0.249	3.02E-02	0.336	7.55E-04	0.326	9.27E-04
32 hours	0.443	3.83E-08	0.337	2.90E-05	0.292	1.11E-02	0.248	3.09E-02	0.325	1.14E-03	0.317	1.51E-03
33 hours	0.442	4.39E-08	0.342	2.24E-05	0.292	1.12E-02	0.245	3.30E-02	0.320	1.37E-03	0.306	2.16E-03
34 hours	0.442	4.04E-08	0.346	1.76E-05	0.308	7.33E-03	0.260	2.37E-02	0.307	2.10E-03	0.303	2.44E-03
35 hours	0.449	2.52E-08	0.341	2.34E-05	0.332	3.84E-03	0.269	1.92E-02	0.298	2.82E-03	0.299	2.74E-03
36 hours	0.453	1.86E-08	0.344	1.97E-05	0.337	3.39E-03	0.276	1.59E-02	0.302	2.51E-03	0.289	3.87E-03
2 days	0.518	1.34E-10	0.365	5.87E-06	0.456	7.37E-05	0.326	4.54E-03	0.163	1.02E-01	0.181	6.98E-02
3 days	0.482	2.23E-09	0.326	5.34E-05	0.401	4.79E-04	0.345	2.35E-03	0.194	5.16E-02	0.084	3.98E-01
7 days	0.335	3.30E-05	0.319	7.58E-05	0.327	4.03E-03	0.378	8.06E-04	0.171	8.63E-02	0.158	1.16E-01
14 days	0.146	6.98E-02	0.173	3.20E-02	0.216	6.11E-02	0.348	2.14E-03	0.082	4.21E-01	0.092	3.62E-01

Table 5 (continued). Kendall's τ correlation values between peak groundwater levels and hours of precipitation preceding the peak at the Talus research site. Precipitation measurements from both on site rain gauges and the Black Knob weather station were used for comparison. For Talus 1, n = 72; for Talus 2, n = 37; for Talus 3, n = 48; and for Talus 4, n = 156.

	Talus 4 - On site		Talus 4 - Black Knob	
	Kendall's τ	p-value	Kendall's τ	p-value
1 hour	0.433	3.62E-14	0.346	5.81E-10
2 hours	0.495	< 2.2e-16	0.408	7.99E-14
3 hours	0.592	< 2.2e-16	0.458	< 2.2e-16
4 hours	0.635	< 2.2e-16	0.495	< 2.2e-16
5 hours	0.657	< 2.2e-16	0.506	< 2.2e-16
6 hours	0.678	< 2.2e-16	0.511	< 2.2e-16
7 hours	0.687	< 2.2e-16	0.509	< 2.2e-16
8 hours	0.693	< 2.2e-16	0.507	< 2.2e-16
9 hours	0.694	< 2.2e-16	0.512	< 2.2e-16
10 hours	0.683	< 2.2e-16	0.514	< 2.2e-16
11 hours	0.677	< 2.2e-16	0.517	< 2.2e-16
12 hours	0.678	< 2.2e-16	0.517	< 2.2e-16
13 hours	0.679	< 2.2e-16	0.513	< 2.2e-16
14 hours	0.676	< 2.2e-16	0.517	< 2.2e-16
15 hours	0.674	< 2.2e-16	0.518	< 2.2e-16
16 hours	0.668	< 2.2e-16	0.522	< 2.2e-16
17 hours	0.668	< 2.2e-16	0.517	< 2.2e-16
18 hours	0.674	< 2.2e-16	0.511	< 2.2e-16
19 hours	0.676	< 2.2e-16	0.511	< 2.2e-16
20 hours	0.680	< 2.2e-16	0.515	< 2.2e-16
21 hours	0.677	< 2.2e-16	0.513	< 2.2e-16
22 hours	0.675	< 2.2e-16	0.514	< 2.2e-16
23 hours	0.667	< 2.2e-16	0.513	< 2.2e-16
24 hours	0.665	< 2.2e-16	0.506	< 2.2e-16
25 hours	0.660	< 2.2e-16	0.501	< 2.2e-16
26 hours	0.655	< 2.2e-16	0.496	< 2.2e-16
27 hours	0.648	< 2.2e-16	0.493	< 2.2e-16
28 hours	0.645	< 2.2e-16	0.490	< 2.2e-16
29 hours	0.643	< 2.2e-16	0.494	< 2.2e-16
30 hours	0.637	< 2.2e-16	0.495	< 2.2e-16
31 hours	0.634	< 2.2e-16	0.490	< 2.2e-16
32 hours	0.628	< 2.2e-16	0.488	< 2.2e-16
33 hours	0.629	< 2.2e-16	0.485	< 2.2e-16
34 hours	0.630	< 2.2e-16	0.485	< 2.2e-16
35 hours	0.624	< 2.2e-16	0.482	< 2.2e-16
36 hours	0.614	< 2.2e-16	0.482	< 2.2e-16
2 days	0.491	< 2.2e-16	0.397	2.08E-13
3 days	0.383	1.50E-12	0.331	9.13E-10
7 days	0.273	4.50E-07	0.252	3.11E-06
14 days	0.137	1.11E-02	0.147	6.56E-03

Table 6. Distributed Hydrology Soil Vegetation Model (DHSVM) comparison of the Kalaloch basin with forest vegetation cover and shrub vegetation cover.

	Streamflow Avg. (cu-m/s)	Actual ET (cm)
Forest (Feb 01, 2005 - Apr 30, 2005)	1157.2	12.0
Shrub (Feb 01, 2005 - Apr 30, 2005)	1276.1	7.5
Increase/Decrease (Feb 01, 2005 - Apr 30, 2005)	118.9	-4.5
Percent	10.3	-37.7
Forest (May 01, 2005 - July 31, 2005)	384.6	22.2
Shrub (May 01, 2005 - July 31, 2005)	446.3	18.3
Increase/Decrease (May 01, 2005 - July 31, 2005)	61.7	-3.9
Percent	16.0	-17.8
Forest (Aug 01, 2005 - Oct 31, 2005)	566.7	7.4
Shrub (Aug 01, 2005 - Oct 31, 2005)	662.0	5.5
Increase/Decrease (Aug 01, 2005 - Oct 31, 2005)	95.3	-1.8
Percent	16.8	-25.0
Forest (Nov 01, 2005 - Jan 31, 2006)	3429.3	2.8
Shrub (Nov 01, 2005 - Jan 31, 2006)	3462.7	1.5
Increase/Decrease (Nov 01, 2005 - Jan 31, 2006)	33.4	-1.3
Percent	1.0	-47.9
Forest (Feb 01, 2006 - Apr 30, 2006)	1504.3	11.6
Shrub (Feb 01, 2006 - Apr 30, 2006)	1625.8	6.3
Increase/Decrease (Feb 01, 2006 - Apr 30, 2006)	121.5	-5.2
Percent	8.1	-45.2
Forest (May 01, 2006 - July 31, 2006)	213.9	20.3
Shrub (May 01, 2006 - July 31, 2006)	277.4	15.9
Increase/Decrease (May 01, 2006 - July 31, 2006)	63.6	-4.4
Percent	29.7	-21.6

Table 6 (continued). Distributed Hydrology Soil Vegetation Model (DHSVM) comparison of the Kalaloch basin with forest vegetation cover and shrub vegetation cover.

	Streamflow Avg. (cu-m/s)	Actual ET (cm)
Forest (Aug 01, 2006 - Oct 31, 2006)	54.2	9.9
Shrub (Aug 01, 2006 - Oct 31, 2006)	110.0	8.3
Increase/Decrease (Aug 01, 2006 - Oct 31, 2006)	55.8	-1.7
Percent	103.0	-16.8
Forest (Nov 01, 2006 - Jan 31, 2007)	3718.7	3.4
Shrub (Nov 01, 2006 - Jan 31, 2007)	3828.3	1.6
Increase/Decrease (Nov 01, 2006 - Jan 31, 2007)	109.5	-1.8
Percent	2.9	-52.4
Forest (Feb 01, 2005 - Jan 31, 2007)	1379.0	89.7
Shrub (Feb 01, 2005 - Jan 31, 2007)	1461.2	65.1
Increase/Decrease (Feb 01, 2005 - Jan 31, 2007)	82.1	-24.6
Percent	6.0	-27.4