A multi-temporal scale look at the origins and storage of water in headwater watersheds in a small forested basin of the Western Cascades, Oregon

Ben M. Dawson[1]

[1] *Department of Biolgical and Ecological Engineering, Oregon State University, Corvallis, OR 97331, USA*

Abstract:

The origins, storage and transport of water in headwater watersheds is an important aspect of understanding the future of the Pacific Northwest's water resources. With the dynamic changes in climate we are loosing snowpack and increasing our spring/fall Mediterranean rainfall in the Pacific Northwest, which some say may jeopardize our precious sources of water. To better understand these headwaters a spreadsheet scale model was developed to investigate the effects of discharge on a second order stream. The focus was on three major inputs of water: (a) snowmelt, (b) precipitation, and (c) discharge from groundwater sources, mean while accounting for water storage, and various water losses. The snowmelt and precipitation data are coming from the LTER database of the HJ Andrews Experimental Forest, which have been paired with soil moisture and knocking pole data to look at soil depth and groundwater discharge sources. As well, water isotope data was analyzed from various water sources throughout the watershed to get a more comprehensive look at the "old" and "new" water origins of the stream. Working from these analysis' an attempt is made to get a better understanding of the Pacific Northwest water resources, and what effects a changing water year could do to the discharge of such headwater streams.

1. Introduction

This study examined the origins, storage and transport of water within headwater watersheds using an excel based spreadsheet model, accounting for three major inputs, (1) precipitation, (2) snowmelt, and (3) groundwater. The mass balance has been run out over an eleven-day period for six peak discharge events from 1990 to 2008.

The method of mass balance is no new technique in the field of watershed hydrology, however this study incorporates two potentially novel features. First, water samples were taken throughout the watershed varying spatially and temporally, and were then analyzed isotopically to return an isotopic signature helping to understand and validate speculated origins of water within the watershed. Secondly, the mapped structure of the bedrock within the watershed was achieved through the implementation of the knocking pole, this device will be described later. The soil/bedrock mapping was used to examine the volume of soil within the studied watershed and develop another portion to the model centered on water storage within soil moisture. The two new aspects of analysis have helped develop a better understanding of storage and transport within the watershed.

The premise of this paper is to examine all the given inputs, understand the origins, and through these methods gain a better understanding of the hydrologic transport and storage in the Pacific Northwest. Then proceeding with the findings, gain a greater understanding of the potential changes that will be experience in the reported changing water year.

1.1 Changing water year

With the short temporal span that humans have quantitatively monitored the environment it has been noticed that great changes are occurring. This paper discusses the possible effects in water storage and transport with the reported changing water year. While it is premature to assume that these effects are anthropogenic, it is important that the occurred changes are noted and addressed.

Average annual temperature has increased 0.7-0.8 ^{0}C since 1920 (Mote 2003), and daily minimum temperature from January to March have rose much faster than the maximum daily temperature (Hamlet and Lettenmaier 2007). Cool season precipitation has become more variable (Hamlet and Lettenmaier 2007). April 1 snow water equivalent (SWE) has declined by 40% in almost all sites in the PNW lower elevations (<1600 m) between 1950 and 2000, see figure 1, (Mote et al. 2005). Lastly, timing of peak runoff has shifted; the centroidal timing of the mass annual river runoff in snowmelt basins has shifted 0-20 days earlier in much of the PNW from 1948 to 2002 (Stewart et al. 2005). These are the changes that have already been observed.

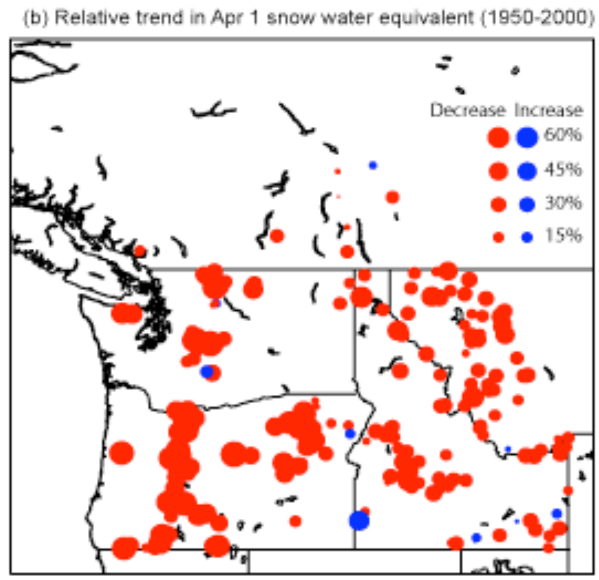

Figure 1 – (Mote et al., 2005)

Projected to still come in the 21st century is an increase in temperature of 0.3 ^{0}C per decade, and small changes in precipitation timing. Precipitations is projected to increase during the winter, and lessen in the summer (Salathé 2006). These projections could have an effect on storage and transport of water, which we will discuss later.

1.2 Stable Isotopes

To give a little background to isotopic analysis, the following information has been included: Within a watershed there exists two forms of water, water introduced within that water year, or water that was already present within the watershed. These two forms of water will respectively be called "new" and "old" water (Pilgrim et al., 1979). Using stable water isotopes a hydrograph separation can be preformed to separate new and old water compositionally as components of a stream. The form of isotopic analysis used returns differentials of the forms of hydrogen (^{1}H and

^{2}H [or D]) and oxygen (^{16}O and ^{18}O), which will be described in section 3.2.

This paper will use this method of isotopic analysis to determine the origins of water throughout March to May of 2009 to better understand the role of precipitation, snowmelt, and soil and groundwater contributions to the hydrograph. The separation is achieved by determining the ratios between the two stable isotopes throughout various locations and input points (which we will call endmembers) within the watershed. Then comparing the endmembers to the composition of the stream. With these values the separation is then a done through computing a dilution problem where the isotopic ratios are treated as concentrations. The full hydrograph separation will not be present in this paper, the data will only be used to get a general understanding of origins.

2. Site Description

The study catchment is located in the central western cascade of Oregon at the HJ Andrews (HJA) Experimental Forest. The main drainage within HJA is Lookout Creek, which is a drainage of the Blue River watershed and eventually the McKenzie River. The HJA is a National Science Foundation Long Term Ecological Research Site (LTER), and has been extensively described and monitored over the last five decades. The description and monitoring of ecological data has facilitated much research and been a major contributor in large legislation such as the Northwest Forest Plan.

The study catchment will be watershed 07 (WS07), and is a small high elevation (~1000m) headwater watershed. WS07 is 21 hectares in area (Jones, 2000), and low gradient with a mean slope angle of 15 degrees. It was partially cut in 1974, removing 50% of the basal area, and the remaining overstory was removed in 1984. A unique feature of WS07 is that it is a climatic transition zone, meaning that it receives both snow and rain throughout the catchment. This is an important feature for studying large discharge events in the western cascade because large discharge events occur following a rain on snow event.

The soils within the HJA are mainly a poorly developed Inceptisol containing thick organic layers over highly weathered parent material. The soils are a clay loam that is exhibit a massive and well-aggregated structure highly effecting the hydrologic process: infiltration rates are typically >500 cm/h (McGuire et al., 2005), with highly drainable porosities from 40% to 50%. Overland flow has not been observed in any of the catchments. This becomes an important in developing an understanding of water transport within WS07.

The HJA has a maritime climate dominated by frontal systems form the Pacific Ocean during November – April, at which over 80% of the 2300 mm – 3550 mm of rain falls (McGuire et al., 2005). In WS07 snow may persist up to six months and may exceed 1.5 meters of depth (Jones, 2000).

3. Methods

3.1 Field Measurements

With the implementation of the knocking pole, the goal was to develop a three dimensional map of the soil within WS07. A knocking pole location map was developed in a grid like fashion to survey soil depths every 40 meters of channel length, and at each channel point further points were taken 40 meters in each perpendicular direction from the channel to the edge of the catchment.

The knocking pole is a dynamic penetrometer consisting of sever 0.5 meter flights of 15 mm stainless steel rod with etched graduations every 5 cm. A 20 mm long, 24 mm diameter cone is attached to the end of the flights, and a 5 kg sliding weight is attached and dropped on an exposed platform on the flights from 50 cm. The data is recorded as the number of "knocks" or drops to go every 5 cm, and this is continued until it took 20 to 25 knocks to go 5 cm. It was assumed, and noticed, that at this point no forward progress was being made, the flights were sliding sideways with the slope of the bedrock. It was initially anecdotally found that the soil averaged to be two meters thick, so if approximately the two meter mark was not met the knocking pole would be redone at that site. As well, if the flights hit a tree root (this could be observed by the noise made by the knocker) or some other obstruction the experiment would be redone. Knocking was continued throughout the watershed until all points had been successfully "knocked".

With the points taken the depth measurements were entered into an existing layer of WS07 in ArcGIS. With the entered points the program was used to create two surfaces, from which was then appropriately considered bedrock (see figure 5) and soil surface. The creation the bedrock layer was done with the method of kringing, which created a surface from points in three-space. With the bedrock surface and the soil surface, the volume between the two was achieved through integration. This will later be used within the mass balance to achieve changes in soil moisture as a method of water storage during the peak discharge events.

3.2 Storm Event Selection

The selection of the six storm events was a visual process, where discharge data was acquired for WS07 from 1990 to 2008 from the HJ Andrews MS001 database on meteorological data. The data was taken from the USGS gauging station for WS07. The discharge data was then plotted over time, and six large discharge events were selected. The selections were designed to select over the full 20-year period to achieve a more complete summary of discharge events in the last two decades.

From the selected six events data was then retrieved for temperature, precipitation, snow water equivalent (SWE) and snowmelt, all on a one-hour time step. All of the data was taken from the Hi-15 Meteorological Station (922 m), which lies at the base of WS07. It has been found for such high elevation watersheds in the Western Cascades that the centroid lag time for peak precipitation events with its corresponding peak discharge event is approximately 12 hours (Perkins and Jones, 2008). With 12-hour lag times in such low angle headwater watersheds the data was selected to be ± five days from the selected event, totaling with an 11 day window.

From the selected six events, the data was plotted and visually analyzed for many factors to classify the event. Such factors included position and magnitude of peak snowmelt, precipitation and discharge events. As well, change in SWE and temperature were visually assessed to determine whether it was a snow on rain event, a precipitation event, or a massive snowmelt event. As seen in figure 2, 3 and 4 it can be visually deduced that the December 13, 2001 event was a rain on snow event. This was deduced my observing that there was a large precipitation event closely followed by a large snowmelt event at which the temperatures were above 0^0C. Therefore the large precipitation and snowmelts with the above freezing temperatures lead you to believe this event was a rain on snow event.

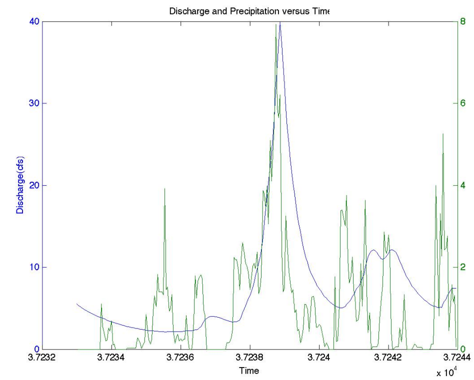

Figure 2

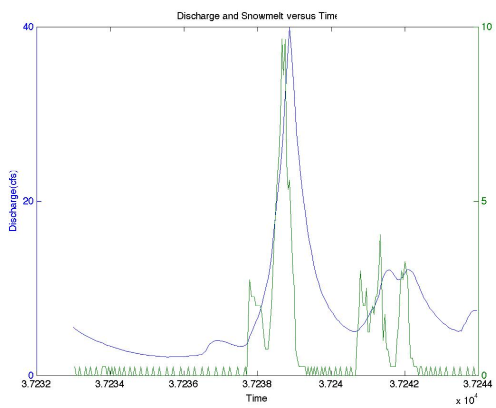

Figure 3

All of the events have been analyzed for these traits and are summarized in table 1. With the understanding of these events it can help later to understand the origins of these events and the water within the stream.

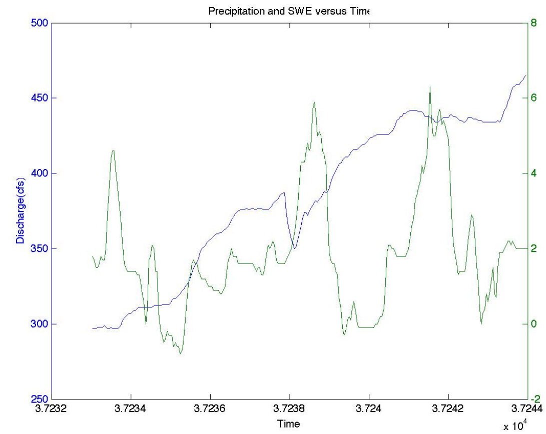

Figure 4

3.2 Isotopic Analysis

A total of 344 samples (188 automated stream sampler, 66 well, 59 stream, 10 snow, 11 rain, 10 snowmelt lysimeter) were collected for isotopic analysis from late March to late May. Sampling frequency was determined by hydrologic events throughout the melting season. Stream isotopic composition was monitored throughout the full period with an automated sampler (ISCO) with intervals no greater than 420 minutes. As well, throughout the full period samples were taken at the other locations to monitor fluctuations of isotopic composition spatially as well as temporally.

Date	Rain on Snow (Y or N)	Comments
11/26/91	Y	Almost all snow melted, SWE decreased with precipitation
2/24/94	N	Peak Q on precip. event, SWE increased through peak Q
2/6/96	Y	Cold snow followed by warm temps. and rain, peak snowmelt and precip. hours before peak Q
12/27/98	N	Precip. event 2 days before event, wet snow, then warm air event
12/13/01	Y	Snowmelt and precip. event hours before peak Q event
12/30/05	Y	Rain on snow ½ day before Q event, then warm temps for peak Q

The samples were then decanted into polyethylene bottles and brought to an isotopic analysis laboratory at Oregon State University. The samples were then measured for their permille content of deuterium and ^{18}O using standardized equilibration methods [IAEA, 1981]. The analysis then outputs a relationship between the two stable isotopes of hydrogen and oxygen using the following equation:

$$\delta_x = 1000\,\frac{R_x - R_{std}}{R_{std}}$$

where the R, for deuterium, is the D/H ratios. Since 'δ' values are typically small the function is then multiplied by 1000 to represent the permille ratio. The precision of the analysis is ±1% for deuterium and ±0.1% for oxygen (Hooper and Shoemaker, 1986).

3.3 Water Balance

The water balance is to be an assessment of water origins during peak discharge events, thus it must assess short-term changes in storage (S) components and various inputs (I) and outputs (O):

$$\Delta Q = I - O - \Delta S$$

Which then the various components must be broken down further, assessing each state variable of the water balance model. Inputs include precipitation (P) and snowmelt (N), outputs include solely Evapotranspiration (ET) and storage includes snow (SWE), regolith (which we will call soil moisture, SM) and groundwater (GW).

$$I = P + N$$

$$O = ET$$

$$\Delta S = SWE > 0 + GW + SM$$

Now combining and rearranging the equations so unknown values are on the left, and known values on the right:

Since snowmelt is recorded by the snowmelt lysimeter only an increase in storage needs to be assessed with the SWE measurements.

Each of these variables will then be quantified and assessed from a combination of field measurements and meteorological data. The precipitation, snowmelt and discharge data sets are all composed of one hour time-steps over the 11-day assessment period, therefore the volumes of water were determined by a trapezoidal approximation of integration using the built-in Matlab algorithm. These values then returned volumes of water moving through the system for the 11-day period.

The storage variables were derived a variety of ways. Since groundwater is an unknown it was left to be determined through the application of the water balance model. Storage within the snowpack was determined by addressing the starting and ending values of the SWE measurements over the 11-day period. If the values were negative, it was to be assumed the quantity was recorded by the snowmelt lysimeter, if the value was positive, the volumetric change was then removed from the integrated precipitation value. Change in storage by the regolith was determined by a series of steps, which the validation of this method will be discussed later.

Only soil moisture data existed for depths of 10, 20, 50 and 100 cm for two of the discharge events (2001 and 2005). As stated earlier the mean depth of soil is 200 cm, so the moisture content had to be extrapolated to the full depth. This was done by evaluating the changes in soil moisture, then plotting the changes, regressing the change to return an equation of soil moisture change as a function of depth. This equation was then used as a concentration of soil moisture change for each event, and could be integrated along the full soil profile to output change in soil moisture. The outputted value was then multiplied by 0.50 to represent soil porosity and then used to quantify change in soil moisture for the given event.

Lastly evapotranspiration was determined by the publication "Simulation of Water Balance…" by Waichler et al. 2002 where sapflow measurements were taken to determine volumetric uptake of water in various watersheds. They found for given winter months the uptake was 1-2 mm of water/day in a unit area (Waichler et al., 2002)

All these combined values were then input into the water balance model to achieve values of accounted water by various know inputs and outputs, and get a better look at importance of groundwater during these peak events.

4. Results

4.1 Knocking Pole

Once the knocking pole data was analyzed in ArcGIS, it was found that there was 420,000 m^3 of soil in the 21-hectare watershed. The average depth was two meters over the full watershed, the map in figure 1 is the created soil depth map.

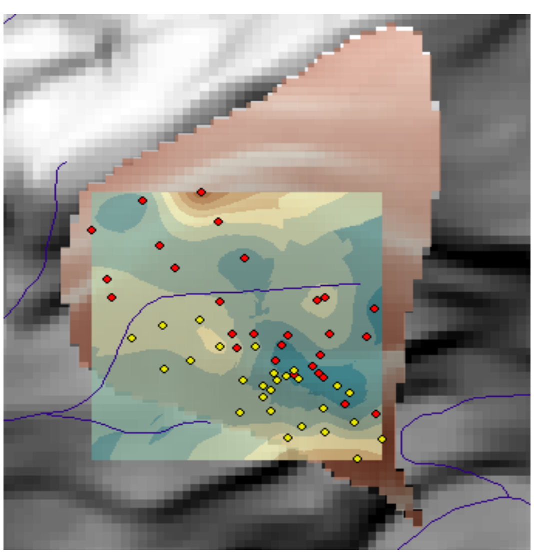

Figure 5 –

Red (0.8 m) -Blue (3.5 m)

4.2 Isotopic Analysis

The following analysis will cover two methods of looking at the data, (a) a low resolution perspective of changing isotopic composition for snow, rain and the stream, and (b) a higher resolution look the trends of change with the high-resolution analysis of the ISCO measurements.

To qualitatively separate the hydrograph using stable isotopes we shall look at isotopic readings for the stream, snow and rain over a three-month time period. This time period will allow for trends in snowmelt and seasonal changes of rain composition to be better revealed. Figure 6 summarizes the $\delta^{18}O$ ratios for the two endmembers (snow and rain) and the stream. It is important to notice that neither of the endmember's $\delta^{18}O$ ratios overlap with the ratio of the stream, and that the stream permille values are not between either of the endmembers. This is important because it shows the stream's primary components must have some other source that isn't either of the "new" water endmembers (rain or snow). If the stream was a combination of the rain and the snow the $\delta^{18}O$ ratio for the stream would be between the two endmembers and it would be a function of volume and $\delta^{18}O$ ratio to determine the composition of the stream.

Another important feature of figure 6 is that both the endmembers are becoming lighter throughout the three-month period, while the stream is becoming heavier. This trend is another indication that the snow or the rain does not dominate the composition of the stream. Thus compositionally speaking the contributor with the greatest volume doesn't have the composition of either the stream or the rain, the endmembers.

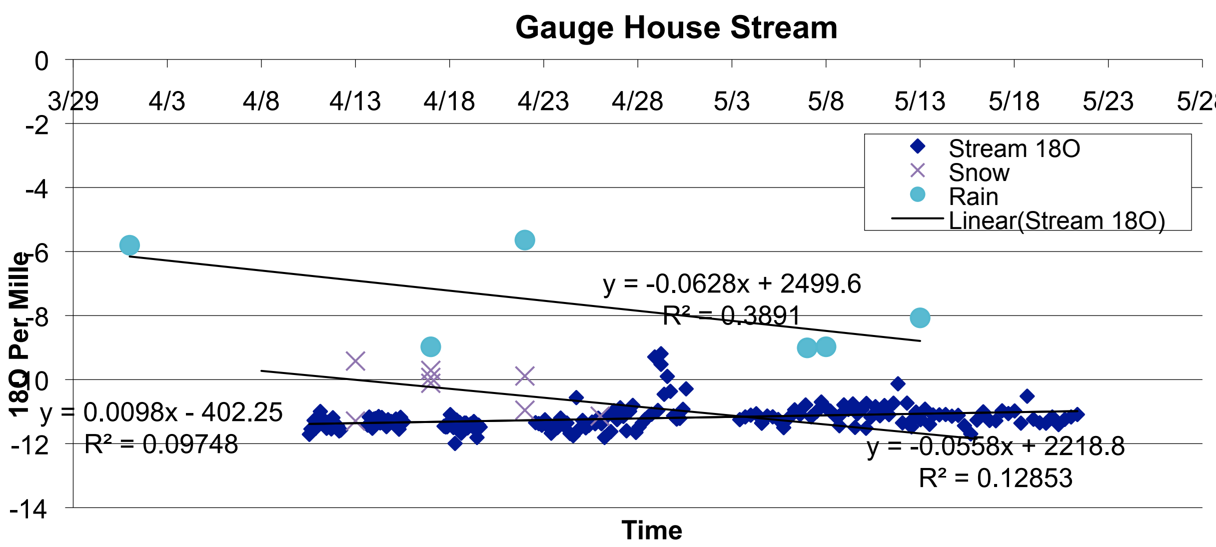

Figure 6

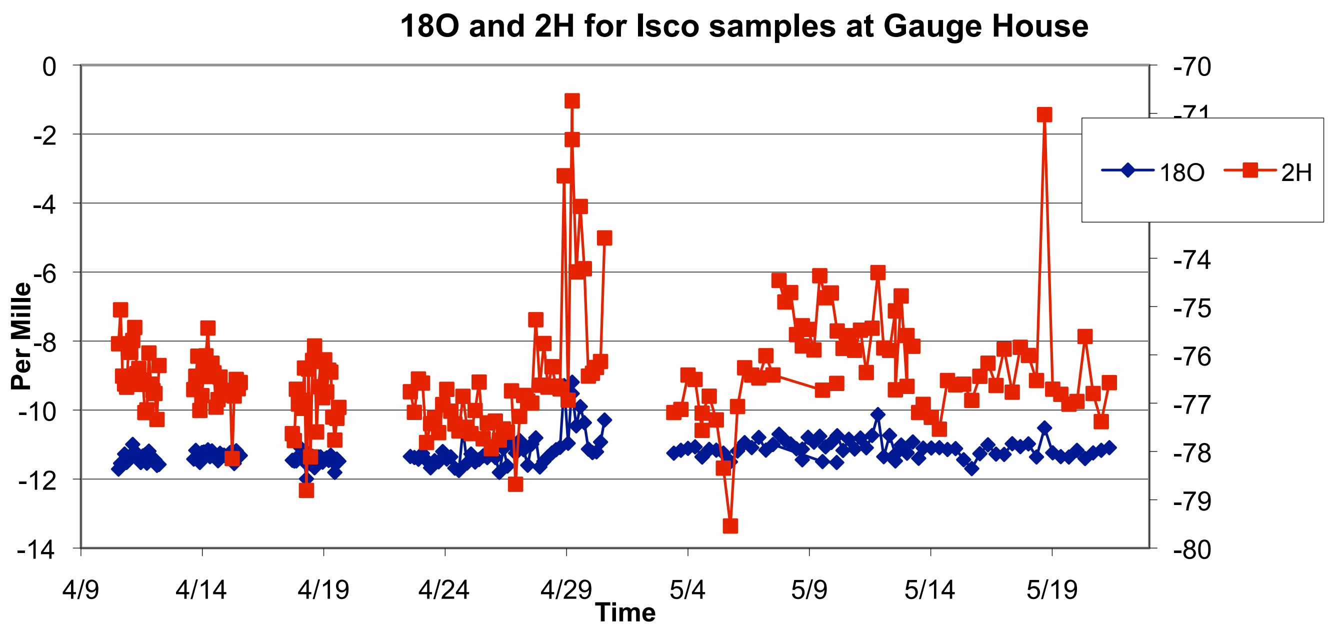

Figure 7

To look at the changes of composition closer figure 7 is the high-resolution readings of the ISCO. This figure is important to be analyzed for over all changing trends. In early May there was a large rain event, which can be noticed, because the δD values become heavier. The increase is an indication of a new source of water, and since the composition became heavier, it can be inferred that a new source of water was introduced as rain because rain has a heavier signature, and because of the overlapping rain event.

4.3 Water Balance

Using the water balance model it was found that during the six storm events approximately 60 percent of the water wasn't accounted for within the model, therefore leaving that 60 percent to be accounted for as groundwater contributions. The groundwater contributions varied from 53.1 % to 68.8 % in 1994 and 1996.

Table 1 summarizes the water balance for each event. The major contributor to these events behind groundwater is snowmelt and precipitation, which we will discuss in more detail later. Table 2 summarizes values of discharge in terms of the derived values of groundwater exchange and combined inputs and outputs. The trends of these tables will be discussed later.

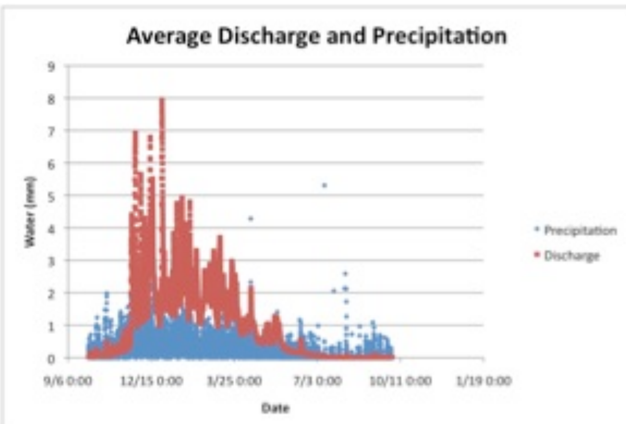

Figure 7

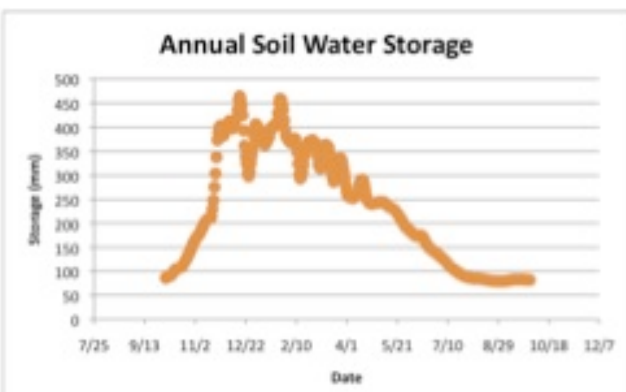

Figure 8

To assist in answering the ultimate question of what could be the ultimate effects of a changing water year, refer to figures 8 and 9. The patterns of precipitation, discharge and soil moisture all follow similar patterns of annual fluctuations. These results and patterns of soil moisture, precipitation and discharge will be discussed later.

5. Discussion

The behavior of the six storm events within the water balance model demonstrates that there are only a few major contributing factors to which effect the discharge of headwater streams, however to understand the major contributors is a complex issue. This paper doesn't address the complex issues of water transport, but advocates through water balance modeling that a better understanding of these contributors could lead to further understandings of fate and transport of water in these headwater watersheds. However, by viewing streamflow as these varying components will bring to light the response and importance of soil moisture, groundwater exchange, precipitation, evapotranspiration and snowpack. All of which are expected to change in the future according to predictive climate change models (Hamlet and Lettenmaier, 1999).

5.1 Knocking Pole

The knocking pole was a great method of obtaining a comprehensive representation of the subsurface, which in turn was used to determine a three-dimensional model of soil thickness. The knocking pole could be a valuable tool for potentially new work in hydraulic flowpaths within watersheds, however in this paper was not used past the capacity of bedrock depth.

5.2 Stable Water Isotopes

Having the stable isotope data greatly helped add to the understanding of the origins of water during high flow, but not during peak discharge events. In many works it has been

Year	Groundwater (mm)	Precipitation (mm)	Δ SWE (mm)	Snowmelt (mm)	ET (mm)	Δ SM (mm)	Discharge (mm)
1991	881.9	177.3	-4	153.945	22		1191.2
1994	887.8	201	-114	172.3	22		1239
1996	3227.7	340.7	210	438.685	22		3775.2
1998	1781	397.5	-65	368.46	11		2535.9
2001	1419.8	246.4	-137	192.99	11	-2.75	1850.9
2005	1848.6	197.9	-35	379.74	11	-30	2445.3

Table 1 –Water Balance Summary

Year	Discharge (mm)	Inputs/Outputs (mm)	Missing Water (mm)	Missing (%)
1991	809.6	353.3	456.3	56.4
1994	842.1	395.3	446.8	53.1
1996	2565.6	801.4	1764.2	68.8
1998	1723.4	776.9	946.5	54.9
2001	1257.9	447.6	810.3	64.4
2005	1661.8	558.7	1103.1	66.4
Average				60.6

Table 2 – Water Balance Results

cited that overland flow, or direct additions of "new" water are not the major contributors to discharge in streams. As cited by Hooper and Shoemaker, 1986, during small events in the melting season, 75% of the water within the stream is old water (Hooper and Shoemaker, 1986). As well it has been found that in low-angle watersheds that the mean residence times of water are approximately 3.3 years (McGuire et al. 2005). These key values, paired with the visual analysis done with the isotopic data for WS07 illustrates the importance of groundwater within small headwater stream systems.

With a residence time of 3.3 years in WS07, this allows for great build-ups of varied water origins within the system, which is why we could be left with significantly different isotopic signatures than that of either of the endmembers. A curious aspect of figure 6 is that the stream's signature is not between rain and snow, which is the only two endmembers of WS07, but rather is lighter than both the endmember signatures. There has been little work concerning such effects, but some controlling variables to this may be annual or multi-annual fluctuation of isotopic ratios, or preferential selection of given isotopes by evapotranspiration. Preferential selection of certain isotopes is a great potential because it has been cited that the $\delta^{18}O$ and δD tend to be a little heavier in the CO_2 release of tree species in the HJ Andrews (Bowling et al., 2003). These potential controlling variables to the groundwater allow for the varied isotopic signature that is seen in WS07.

Contributing factors to residence time are slope, spatial variability, flowpath length and groundwater exchange. With the average mean residence time of water at the HJ Andrews being one to two years (McGuire et al. 2005), WS07 must have an intricate subsurface spatial variability, which increases the length of flowpath. The increase of flowpath, spatial variability and residence time allows for increased groundwater exchange and thus importance of groundwater as a contributing factor to the headwater stream system.

Understanding the origins, residence times and knowing that there are complex flowpaths that exist in WS07 help with the understanding and validation of the water balance, and the contribution of 60% groundwater in the peak discharge events.

5.3 Water Balance

With a more complete understanding of water origins and transport in WS07 over large time periods lets move to the smaller scale of peak discharge events. It was found from a water balance that during the peak discharge events 60% of the water is a contributed from groundwater.

Table 1 displays all the inputs, outputs and changes in storage during these six events. Since these events occurred during the winter it was cited that trees only transpire water at a rate of 1mm/day per unit area during December and January, while during February they transpire 2 mm/day per unit area (Waichler et al., 2002). Therefore the values of evapotranspiration were calculated by multiplying the 11-day period of study to the appropriate value of ET. However in the grand scheme of things these values are negligible, it was important to validate these values to account for them during the event for the mass balance.

Precipitation and snowmelt were the major contributors to the water balance, and each variable contributed approximately 19% to the water balance. Both these values are integral parts of the mass balance and regardless of whether the event was a direct rain on snow event, precipitation within the 11-day window of study contributed to 19% of the water balance.

Soil moisture is an important feature and factor of storage in transport of water in the HJ Andrews. The soil is an aggregate structure of a clay loam texture, which highly affects the hydraulic properties: high infiltration rates (generally >500 cm/h) and high drainable porosity (40%-50%). Soil moisture was a key feature of the study since soil depth was known throughout WS07. Having quantified soil moisture, and thus soil moisture changes throughout the storm events, allowed for a more comprehensive model to determine storage capacity and changes during the discharge events. Through the analysis it was found that change in soil moisture is not an important feature of the water balance, however again it was important to quantify soil moisture to return better values within the model.

Lastly a feature of the catchment that was not monitored, and could not be quantitatively addressed was the volume and storage of pooled water at the soil/bedrock interface. Since this water was deeper than our soil moisture sensing capability, this volume of water was then treated as contribution from groundwater. There has been citation that pooling exists at the bedrock and soil interface because bedrock being much less permeable doesn't allow for the water to infiltrate at high rates, thus saturating the soil and creating pooling of water at the interface. This pooling could be an explanation of why such large volumes of water were readily available during such storm events. With a pool of water existing at the bedrock/soil interface, the extreme pressures exerted on the pool from massive introductions of new water would force the water out of the pool through down-slope transport to a point of pressure release (the stream). This release of water from the pool, and the increase in discharge within the stream would indicate that large volumes of water are being released form the groundwater, when they are not. This introduction of water is coming from the pooling of saturated soil at the bedrock/soil interface. This is a transport mechanism that needs further quantification and analysis, however it is a potential reason that such large discharge events were seen even with the catchment having a 3.3 year hydraulic residence time.

The water balance was a good model to investigate various parameters and state variables that are important within the storage and transport of water in a high elevation watershed.

5.4 Implications on Two Scales

The mass balance was directly created for the short-term, eleven day, scale. However, when addressing the implications with the model on an extended time period there arise some further parameters that should be considered, such as cloud water interception (Jones, 2000). Although there was such a parameter overlooked, the suggestions from the model show that water is not stored during these extreme peak discharge events. The large pressure forces created from the precipitation and snowmelt push out more water than is input into the system, therefore depleting subsurface storage, likely the majority of the water at the pooling near the soil/bedrock interface.

Ecosystems are resilient and dynamic, so one large seasonal loss may not be a problem, although when addressing human needs and changing climate there could be serious groundwater depletion issues. It has been reported that there will be increased daily minimums, and varying precipitation patterns, these of which aren't as serious to storage issues. The citation of reduced SWE values of 40% by April 1st and peak run off occurring up to 20 days earlier could put serious stressors on our water resources. This means there will be less time for slowly storing the water, potentially causing more peak discharge events, and extreme soil moisture pressure events which displace water from the system and thus don't facilitate water storage. On larger scales we will likely see less water stored, and larger varying discharge events. If water doesn't become stored during these wet months, we will see a direct impact upon the water availability late summer.

6. Conclusion

Water balances may not be a novel method of a watershed dynamics analyses, however this study offered ideas on soil moisture content using a three-dimensional model of the soil thickness. With such highly drained soils, soil moisture in the first meter of soil has an insignificant role in water storage or contribution during peak discharge events. This finding could be an enlightening matter when further investigating the potential water resource effects in the PNW with a changing water year. As well, the finding that 60% of the water within the stream during peak discharge events is from groundwater will be important to help the scientific community better understand the effects of large events, such as the ones studied. However the matter of soil/bedrock water pooling was not directly addressed in this paper, it and isotopic analysis during peak discharge events would be potential further research that could lead to developing our understanding of water dynamics in extreme situations such as the February 1996 flood.

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