Report for 2005OR65B: Influence of Climate Change on Water Supply in the McKenzie River Basin: Analysis of Long-term and Spatial Hydrologic Data.

Publications

- Articles in Refereed Scientific Journals:
  - Jefferson, A., Nolin, A., Lewis, S., Payne, M. and Grant, G., Climate variability, snowmelt distribution and effects on streamflow in a Cascades watershed, to be submitted to Hydrological Processes.
  - Nolin, A.W. and C. Daly, Mapping “at-risk” snow in the Pacific Northwest, U. S. A., Journal of Hydrometeorology, in press.
- Other Publications:
  - Water Supply is on the rocks and that's okay Article in Salem Statesman-Journal, April 4, 2006
  - Global climate change may have a lasting impact on the Lane County landscape. Interview with Eugene Register-Guard, Sunday January 29, 2006.
  - Warmer winters may melt ski spots Article in The Oregonian, March 7, 2006
  - Global warming may melt away fun, study says Article in Seattle Times, March 8, 2006
  - Oregon snow may melt with increased warming Interview with KINK radio, Portland, Oregon, March 8, 2006
  - Warming could douse Oregon ski areas Article in Eugene Register-Guard, March 8, 2006

Report Follows

Influence of Climate Change on Water Supply in the McKenzie River Basin: Analysis of Long-term and Spatial Hydrologic Data

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Abstract

The snowmelt-dominated Cascade mountains provide critical water supply for agriculture, ecosystems, and municipalities. Watersheds draining the Cascades are home to over 3 million Oregonians. Recent analyses show that this region is particularly sensitive to current and projected climate warming trends. The focus of our research is the watershed of Clear Lake in the upper McKenzie River basin. This watershed, with an area of 239 km^2, has long-term records of streamflow, precipitation, and snowpack. Our overarching goal is to determine the timescales and degree of seasonal and inter-annual “memory” between precipitation inputs and streamflow outputs. The specific objectives of this work are therefore to:

1. Examine spatial variability in snow accumulation and melt, precipitation, evapotranspiration, and groundwater recharge in order to be able to quantify seasonal and year-to-year inputs to the hydrologic system;
2. Complete a seasonal and annual water balance for the Clear Lake watershed for wet, dry, and “normal” years;
3. Use long-term datasets to assess time lags between precipitation, snowmelt recharge, and streamflow response.

We use existing and newly compiled data sets to compute water balance, cross-correlations and regression modeling to improve the prediction of annual discharge and mean August discharge. We also analyze the data sets to identify secular trends in discharge in the Clear Lake watershed. Results show that generally, discharge, precipitation and SWE vary together throughout the period of record and among the 3 SNOTEL sites. There are clearly wet years, where all 3 parameters are above average at each of the sites and dry years, where all 3 parameters are below average. Temperature generally varies inversely with the hydrologic parameters, usually a year is cool & wet or warm & dry. For the four-year period of 2001-2004, discharge plus ET equaled 99.8% of precipitation in the Clear Lake watershed. On the annual time-scale, ET was 26% of precipitation. We developed a stepwise regression model for August discharge using four variables: precipitation accumulated at Santiam Junction by April 1st (P_{SJ41}, mm), the previous year’s minimum discharge (Q_{min-1}, m^3/s), the previous year’s winter temperature, and the April 1 SWE at Hogg Pass. When the fitted and validation datasets are combined, the overall R^2 is 0.78. The model predicts an average August discharge of 9.2 m^3/s for 2006, >60% of years in the 62 year period of record at Clear Lake. Both discharge and snow water equivalent show a model level of predictability using an El Niño index. In our examination of secular trends, the historical record suggests that minimum flows are declining as snowmelt occurs earlier. Earlier snowmelt causes the hydrograph to peak sooner in the spring, meaning that the recession from that peak to the beginning of fall rains occurs for a longer period of time and reaches a lower ultimate discharge. Although the declining minimum flows mean difficult management decisions, improved predictability of August streamflows will allow water resources managers to predict average August flow as early as April 1. This allows time to assess consequences of high or low flows and plan mitigation strategies if necessary.

Significance and Justification

The snowmelt-dominated Cascade mountains provide critical water supply for agriculture, ecosystems, and municipalities. Watersheds draining the Cascades are home to over 3 million Oregonians. Recent analyses show that this region is particularly sensitive to current and projected climate warming trends, specifically reduced snow accumulation and earlier spring melt, leading to a decline in summer streamflow (Service, 2004). By 2050, Cascade snowpacks are projected to be less than half of what they are today (Leung et al., 2004), potentially leading to major water shortages during the low-flow summer season. Snowpacks in western North America have declined over the past 50 years, primarily due to an increase in winter (Mote et al., 2005). These broad regional-scale characterizations identify climatic gradients as first-order controls on spatial variability in changing streamflow regimes, but the potential for other landscape controls, notably regional geology, to mediate this response has received much less attention.

This investigation was prompted by our previous research revealing that spatial patterns of summer streamflow in the Cascades exhibit significant differences between the geologically-distinct High and Western Cascade regions (Tague and Grant, 2004). A key control on streamflow differences between these two regions is the partitioning of water input between a fast-draining shallow subsurface flow network (Western Cascades) versus a slow-draining deeper groundwater system (High Cascades). In particular, we hypothesize that for the young volcanic terrains comprising the High Cascades, ground water storage is of sufficient magnitude to buffer potential changes in snowpack volume, hence summer streamflow, due to changing climate, as long as total annual precipitation remains roughly constant. However, we cannot produce accurate models of streamflow response to climate change and variability unless we have a realistic water balance that takes into account snowpack dynamics and spatial variability, and an understanding of time lags in the hydrologic system. Consequently, a necessary first step toward providing realistic model scenarios of future water supplies in Oregon is to understand the past and current behavior of the High Cascades hydrologic system on event, seasonal, and interannual timescales.

This research addresses two critical questions underlying the prediction of hydrologic response to future climate change. First, we identify and quantify key components of the water balance and how they vary across the landscape and through time using remote sensing and historical data. We also examine snowpack and groundwater storage and use time-series analysis to investigate how these reservoirs cause lags in the streamflow response to meteorological inputs.

The focus of our research is the watershed of Clear Lake in the upper McKenzie River basin (Figure 1). This watershed, with an area of 239 km^2, has long-term records of streamflow, precipitation, and snowpack, and is the hub of on-going research on snowmelt response to wildfire (Nolin) and groundwater recharge in young basalts (Jefferson and Grant). Furthermore, the watershed includes substantial areas of typical High Cascades geology, with extensive low-relief lava flows less than 5000 years old, as well as deeply dissected Western Cascades landscapes. Results and methodologies developed from this project may be broadly applicable to the Oregon Cascades.

Clear Lake forms the headwaters of the McKenzie River, which is the source of water and electricity for the city of Eugene, a major recreational economy, and superb salmon and bull trout habitat. Although the Clear Lake watershed occupies only 0.8% of the Willamette basin, it contributes almost 2% of late summer discharge to the entire Willamette River (measured at Portland harbor).

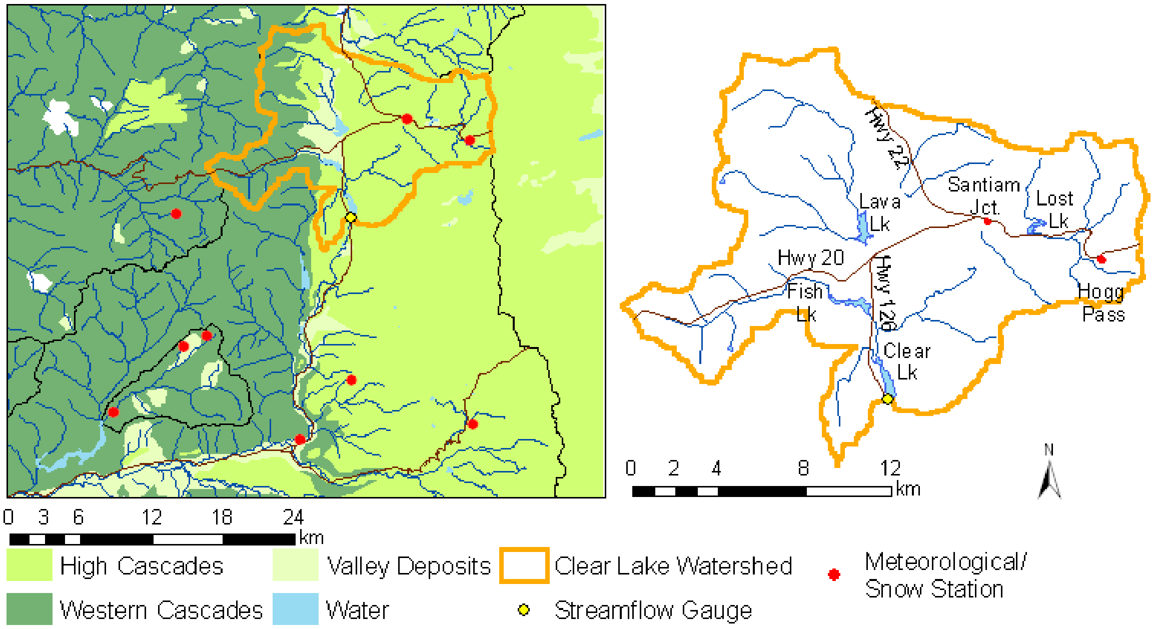

Figure 1. Location map showing Clear Lake watershed, Cascade geology, and meteorological stations.

Nature, scope, and objectives

The goal of this investigation is to analyze historic hydrologic responses to climate variability in the Clear Lake watershed to guide long-term prediction of hydrologic response to climatic change. Our overarching goal is to determine the timescales and degree of seasonal and inter-annual "memory" between precipitation inputs and streamflow outputs. In particular, our aim was to determine whether system memory of wet or dry years persists beyond the year in which the precipitation surplus or deficit occurred. The objectives of this work are therefore to:

4. Examine spatial variability in snow accumulation and melt, precipitation, evapotranspiration, and groundwater recharge in order to be able to quantify seasonal and year-to-year inputs to the hydrologic system;
5. Complete a seasonal and annual water balance for the Clear Lake watershed for wet, dry, and "normal" years;
6. Use long-term datasets to assess time lags between precipitation, snowmelt recharge, and streamflow response.

Methods

Selection and compilation of datasets

Of the available regional meteorological stations, SNOTEL sites provide the longest continuous records of rainfall, snow water equivalent (SWE) and temperature. Since elevations in the Clear Lake watershed range from 918 m at the outlet of Clear Lake to 2051 m on Mount Washington, three sites were selected to be representative of this range. Approximately ~20% of the watershed has an elevation higher than Hogg Pass (1451 m), 63% is higher than Santiam Junction (1143 m), and 83% is higher than Jump Off Joe (1067 m), which lies <3 km west of the Clear Lake watershed. The long-term (>20 year) data sets derived from measurements at SNOTEL sites were used to explore the influence of variation in meteorological parameters on Clear Lake discharge.

For each of the four parameters of interest, annual statistics were compiled from measured daily values as described below. Precipitation and SWE were complied from SNOTEL data for water years 1979-2005 at Santiam Junction and Jump Off Joe and water years 1980-2005 at Hogg Pass. Mean annual precipitation was calculated from measured daily precipitation (includes both rain & snow). Total annual snowfall, reported as snow-water equivalent (SWE), was calculated from measured daily SWE. Temperature was compiled from SNOTEL measured daily temperature maxima and minima for water years 1985-2003 at Santiam Junction and Jump Off Joe and water years 1983-2005 at Hogg Pass. The number of days per year when the maximum temperature remained below zero was used as an index of the "coldness" of the winter. Discharge for the McKenzie River at the outlet of Clear Lake is reported as a daily value by the USGS. An annual mean value was calculated for water years 1978-2005.

To facilitate comparison of the data, the distribution of annual values for each parameter was normalized using the z-score transformation. Discharge, precipitation and SWE were normalized for the period 1980-2005 and temperature was normalized for the period 1985-2003. The z-score for a parameter indicates how far and in what direction the parameter deviates from the distribution's mean, expressed in units of its distribution's standard deviation where:

z-score = (annual value – mean of annual values) / standard deviation of annual values

Plotting z-scores rather than absolute values results in four time series each having a zero mean and unit standard deviation, allowing for easy comparison of the data.

Water Balance

A simplified water balance for the Clear Lake watershed was constructed for the 2001-2004 water years to examine the magnitudes and seasonal variations in water fluxes and stores. Discharge was calculated at the USGS gage, and precipitation and SWE at the median basin elevation (1215 m) were derived by linear interpolation from values at Jump Off Joe and Hogg Pass. Christina Tague (San Diego State University) supplied us with basin-average evapotranspiration (ET) calculated using RHESSys, a physically-based hydro-ecological model previously calibrated for the Clear Lake watershed (Tague and Band, 2004; Tague et al., in review).

Cross-correlations

Daily time-series of discharge, precipitation, snow water equivalent (SWE), and recharge (rain + snowmelt) were normalized to their daily means, and auto- and cross-correlations were computed following the methods described by Box and Jenkins (1976). A similar analysis was conducted for annual time-series.

Modeling

A predictive model of mean August discharge was developed using stepwise regression in SAS 9.1. The model was based on data from the 1984-2003 water years, and 39 parameters were tested as potential predictors (Table 1). Stepwise selection of parameters proceeded until all variables in the model were significant at the 0.05 level and no other variables met the 0.05 significance level for entry into the model. Colinearity was minimized by manual elimination of strongly correlated variables. The resultant model was tested with data from 1979-1983 and 2004-2005.

Correlations with Major Climate Indices

We examined and quantified the relationships between two major climate indices that have been correlated with streamflow in the Pacific Northwest: El Niño/Southern Oscillation Index the Pacific Decadal Oscillation (Beebee and Manga, 2004). We use the Niño 3.4 Index of sea surface temperature (Trenberth and Stepaniak, 2001) and the Southern Oscillation Index of surface pressure (NOAA, 2000) over the period 1978-2004 to explore correlations between El Niño/Southern Oscillation (ENSO) with discharge. The Pacific Decadal Oscillation (PDO) data set is from the University of Washington (Mantua, 2001). We computed correlations between these climate indices and mean annual discharge and mean August discharge using Pearson's linear regression. Individual monthly values of the indices were used rather than seasonal aggregates to better understand the time lags between discharge and the climate indices.

Results

Hydroclimatology

Generally, discharge, precipitation and SWE vary together throughout the period of record and among the 3 SNOTEL sites. There are clearly wet years, where all 3 parameters are above average at each of the sites (1982, 1997, 1999, 2002) and dry years, where all 3 parameters are below average (1987, 1991, 1992, 1994, 2001, 2003, 2005). Temperature generally varies inversely with the hydrologic parameters, usually a year is cool & wet or warm & dry. Years when temperature significantly diverges from the trend, warm wet years such as 1996, or cool dry years such as 1986, may be attributed to larger climate signals such as ENSO or PDO.

The watershed receives a mixture of rain and snow at all elevations. At Hogg Pass, 56% of annual precipitation accumulates as snow, whereas at Santiam Junction it is 37%, and at Jump Off Joe it is 25%. Mean discharge at Clear Lake is strongly correlated with precipitation at all three sites ($r>0.88$), but only at Hogg Pass is there a strong correlation between snow water equivalent (SWE) and mean discharge ($r=0.74$). SWE increases with elevation, and the date peak SWE is reached is later at Hogg Pass than at the lower elevation sites. However, the amount of peak SWE and the date at which it is reached is only poorly correlated for any individual site.

The autocorrelation of Clear Lake discharge shows a slow recession, or the rate at which peak flows diminish to low flows. This slow recession is characteristic of groundwater-fed streams. Discharge is strongly positively auto-correlated ($r>0.5$) for lags of up to 20 days, as opposed to the <7 days typical of streams without extensive groundwater. There are also moderate cross-correlations between Clear Lake discharge and SWE at the 3 SNOTEL sites. The peak cross-correlations occur at 74 to 82 day lags, which probably represents the average time from snowfall to snowmelt. Elevational differences are also apparent in the cross-correlation signal. For short lags, there is a moderate positive correlation between Hogg Pass SWE and discharge, because snow at high elevations may reflect rain at lower elevations, which, in turn, can lead to increasing discharge. There is no correlation between Santiam Junction or Jump-Off Joe SWE and Clear Lake discharge at short lags.

Water Balance

For the four year period of 2001-2004, discharge plus ET equaled 99.8% of precipitation in the Clear Lake watershed (Figure 2). On the annual time-scale, ET was 26% of precipitation, which is almost exactly the same as the ET portion of a 30-year water balance calculated for the adjacent Smith River watershed (Jefferson and Grant, 2003) and within the range of values reported for Western Cascade forests (Jones and Post, 2004). The near perfect match of the annual inputs and outputs and the concordance of ET estimates with regional values lend support to the seasonal water balance calculations despite the simplicity of the methods.

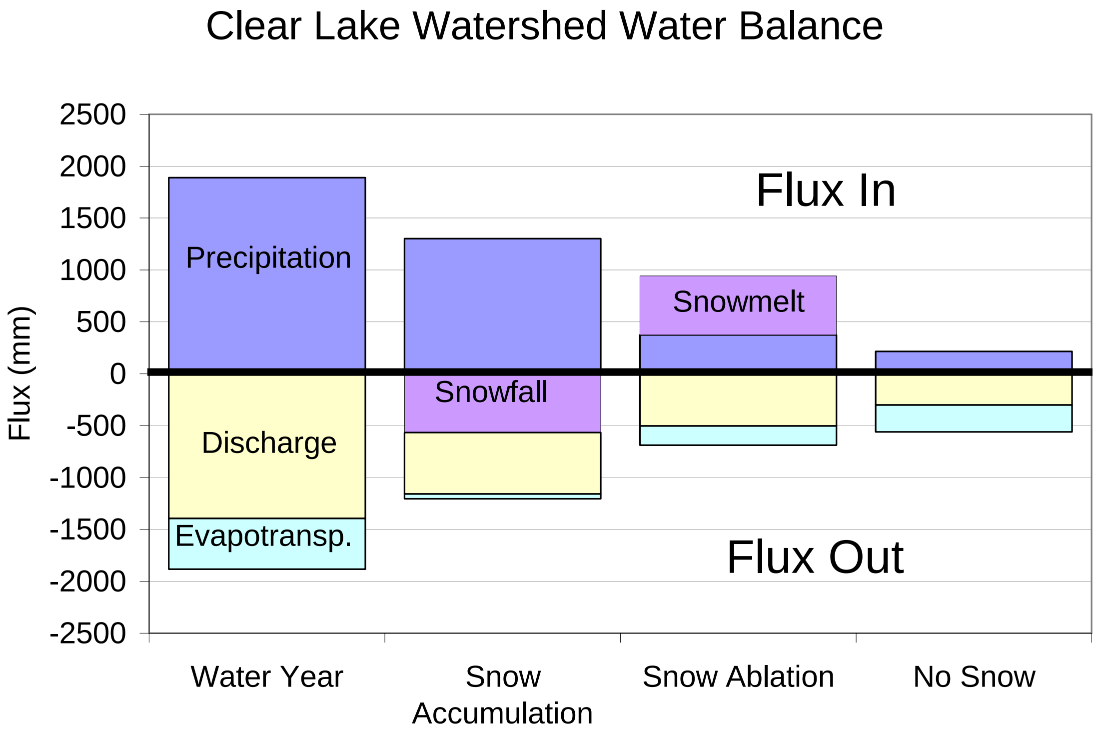

Figure 2. Water balance for the Clear Lake watershed.

We divided the year into three seasons based on the status of the snowpack. November through March constitute the snow accumulation season; April through June are the snow ablation season; and July through October are the no snow season. In the snow accumulation season, 44% of precipitation is stored as snowpack, 46% is accounted for as discharge, and 4% is lost to ET. The remaining 7%, ~100 mm, probably goes to replenishing the soil moisture supply and groundwater storage. In the snow ablation season, ET loss accounts for 49% of incoming precipitation. Abundant snowmelt supplies enough water to account for the discharge and to provide ~250 mm to groundwater storage. In the no snow season, discharge and evapotranspiration are 250% of precipitation, and groundwater storage diminishes to sustain streamflow and supply water to vegetation.

Inter-annual variability

Several analyses indicate an inter-annual memory in the watershed as a result of the High Cascades groundwater system. There are moderate cross-correlations between the previous year's precipitation and discharge at Clear Lake (r_{max}=0.52 for Hogg Pass).

This cross-correlation is higher than either the discharge or precipitation autocorrelation at a 1 year lag. Both the discharge autocorrelation and the cross-correlation are stronger than those for a nearby watershed without an extensive groundwater system.

Plotting z-scores of precipitation versus those for discharge shows that the groundwater system buffers discharge from inter-annual fluctuations in precipitation (Figure 3). This buffering is shown most clearly when a dry year follows several wet years, or vice versa. For example, 1998 was somewhat drier than average, but discharge was above average following two wet years. Similarly, 1995 was wetter than average, but discharge was just below average following a dry year. In the case of persistent drought (1990-1992) or wet years (1982-1984), the z-score of the discharge falls in line with the prevailing precipitation conditions.

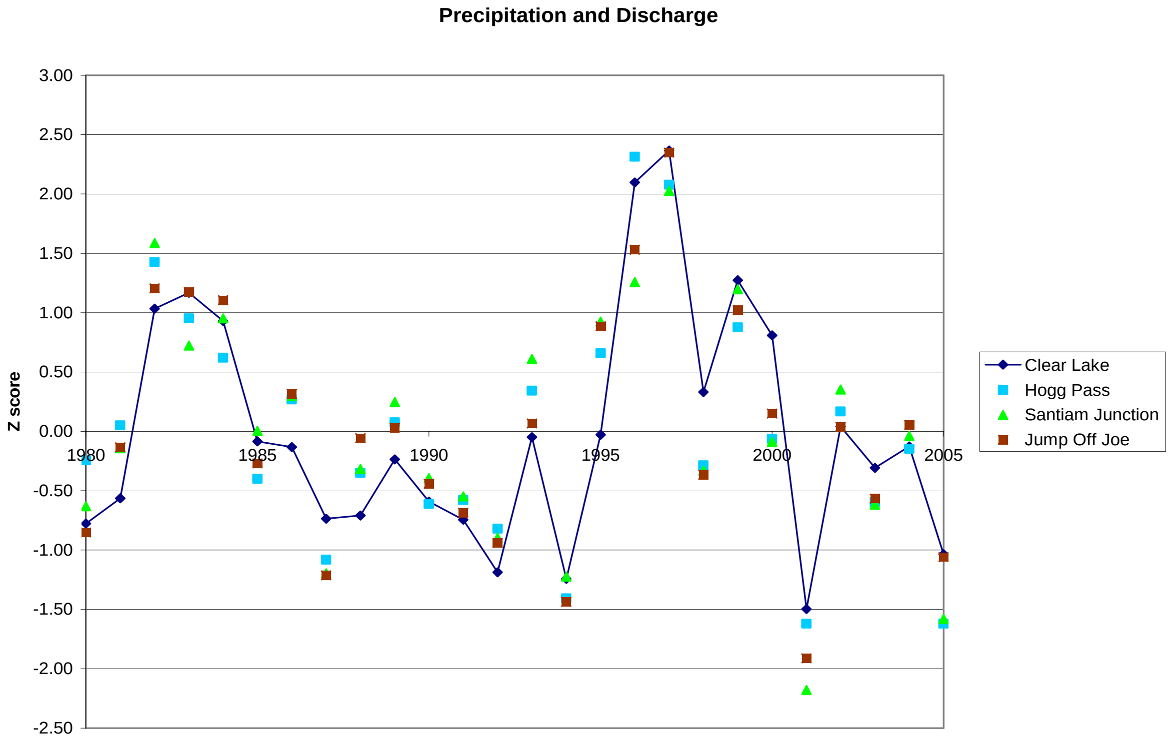

Figure 3. Annual precipitation for the three SNOTel stations and discharge for Clear Lake. Values are shown as z-scores.

Secular trends

Investigation of long-term trends in climatic and hydrograph parameters suggests that inter-annual variability masks potential trends in precipitation and SWE data derived from the <30 year SNOTEL record. The only parameter to exhibit a statistically significant relationship with time was the date of last snow cover at Santiam Junction. There was a weak trend toward earlier loss of snow cover at this site, not exhibited at either the lower or the higher elevation sites. The elevation and temperature regime of Santiam Junction may be particularly susceptible to warming-induced loss of snow as shown in Nolin and Daly (2006) in which such lower elevation snowpacks were shown to be highly temperature sensitive. In these areas, the winter precipitation regime may be shifting from a snow-dominated regime to one that is increasingly dominated by rainfall.

The discharge record for Clear Lake is continuous since 1948 and also has data for 1913-1915. Using only this longer dataset, preliminary analysis suggests that there are some secular trends, although the record is still dominated by inter-annual variability. A trend toward earlier snowmelt is indicated by the hydrograph temporal centroid. The temporal centroid is the day of the water year when half of the annual discharge has occurred, and has been used as an indicator of climate change throughout the mountainous West (Stewart et al., 2005). A best fit line through the data suggests that the temporal centroid has moved earlier in the year by 14-15 days since 1950 and 23-24 days since 1913. This trend is statistically significant at the 95% confidence level.

Earlier snowmelt also seems to be affecting the minimum discharge from Clear Lake. Minimum discharge generally occurs between September and November, and is a function of the year's precipitation, timing of snowmelt, timing of the fall rains, and, possibly, the aquifer storage. There is a slight downward trend in minimum discharge since 1948, potentially as a result of earlier snowmelt in the watershed. This trend is statistically significant at the 95% confidence level. This suggests that as climate warms, minimum flows of the McKenzie River at Clear Lake will decrease.

Modeling

The stepwise model for August discharge used four variables to explain 91% of the variation in the fitted dataset: precipitation accumulated at Santiam Junction by April 1st (P_{SJ41}, mm), the previous year's minimum discharge (Q_{min-1}, m^3/s), the previous year's winter temperature, and the April 1 SWE at Hogg Pass. The first two variables explain 84% of the variation in the fitted dataset and yield a regression equation of: $Q_{Aug} = 0.00573*P_{SJ41} + 0.45384*Q_{min-1} - 3.00216$. This model had an R^2 of 0.60 in the validation dataset, and underpredicts discharge in the validation dataset by an average of 0.6 m^3/s. When the fitted and validation datasets are combined, the overall R^2 is 0.78. The model predicts an average August discharge of 9.2 m^3/s for 2006, >60% of years in the 62 year period of record at Clear Lake.

Correlations with Major Climate Indices

Correlations between the monthly Niño 3.4 index for 1977-2004 and Clear Lake discharge annual discharge were highest for March ENSO with a correlation coefficient of -0.55 (significant at the 0.95 level). Correlation between mean August discharge and the Niño 3.4 index December of the previous year were weakly significant with a correlation coefficient of -0.35. Correlations between Niño 3.4 and SWE had much higher negative correlations. Santiam Junction peak SWE vs. Nino 3.4 from December of the previous year had a correlation of -0.60 (Figure 4). Hogg Pass peak SWE vs. Niño 3.4 from December of the previous year had a correlation of -0.54. Jumpoff Joe peak SWE vs. Niño 3.4 from December of the previous year had a correlation of -0.63. This indicates that ENSO, as explained by the Niño 3.4 index, is a reasonably good predictor of peak SWE and a moderate predictor of annual discharge.

We also explored correlations using the SOI but found that the correlations were much lower than for the Niño 3.4 index. Using the PDO index, we found that there were no significant correlations with annual discharge, August discharge or station SWE.

These results are similar to those of Beebee and Manga (2004) who found correlations between annual discharge, peak runoff and ENSO for eight snowmelt dominated watersheds in Oregon. However, they used the SOI averaged over June-September and Niño 3.4 averaged over September-November. We found lower correlations for seasonally averaged values of both SOI and Niño 3.4. Like Beebee and Manga, we also found no significant correlation with PDO.

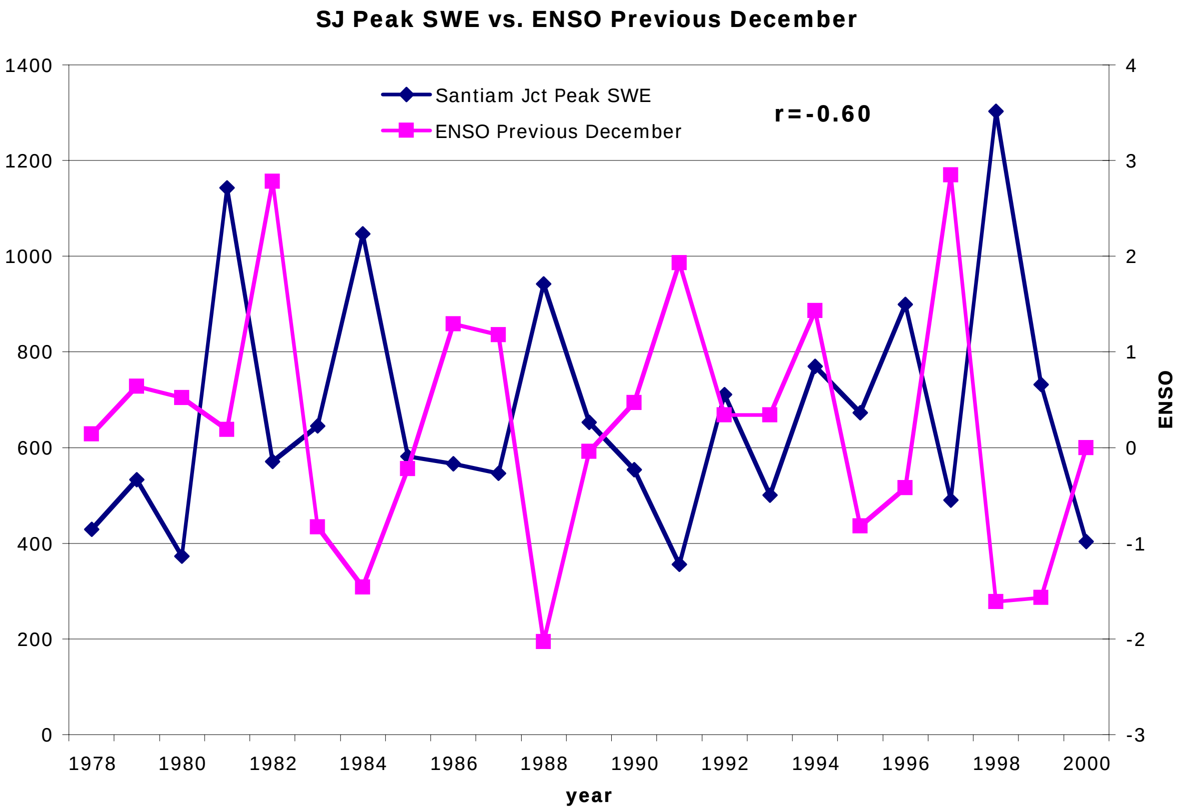

Figure 4. Santiam Junction peak SWE vs previous December Niño 3.4.

Discussion/Conclusions

The extremely permeable nature of the young basalts in the High Cascades leads to extensive groundwater systems, which make High Cascades watersheds, such as that of the McKenzie River at Clear Lake, the dominant sources of summer streamflow in western Oregon (Tague and Grant, 2004). Analyses of the historical datasets clearly highlight the importance of the groundwater system in sustaining summer streamflow. Groundwater storage and the associated slow recession are responsible for sustaining discharge even when the seasonal water balance is negative. Groundwater also helps buffer discharge from year-to-year fluctuations in precipitation, although it cannot fully mitigate a protracted multi-year drought.

The historical record suggests that minimum flows are declining as snowmelt occurs earlier. Earlier snowmelt causes the hydrograph to peak sooner in the spring, meaning that the recession from that peak to the beginning of fall rains occurs for a longer period of time and reaches a lower ultimate discharge. This has direct implications for stream temperatures, which are partly controlled by discharge, and are crucially important for threatened bull-trout that make the upper McKenzie River watershed their home. It is also important for water resources managers concerned with downstream water allocations and for the Eugene Water and Electric Board (EWEB) which generates electricity from a series of reservoirs downstream from Clear Lake. Lower streamflows will restrict junior water rights users and reduce the amount of electricity that EWEB can supply to Eugene.

Fortunately, along with the bad news about declining minimum flows, we report improved predictability of August streamflows. Using the regression equation provided above, water resources managers can predict average August flow as early as April 1. Peak SWE can be predicted as early as the previous December using an ENSO index. This allows time to assess consequences of high or low flows and plan mitigation strategies if necessary.

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