Climate Variability, Snowmelt Distribution, and Effects on Streamflow in a Cascades Watershed

ANNE JEFFERSON[1], ANNE NOLIN[1], SARAH LEWIS[1], MEREDITH PAYNE[2],
GORDON GRANT[3], AND CHRISTINA TAGUE[4]

EXTENDED ABSTRACT

Cascades Range rivers provide critical water supply for agriculture, ecosystems, and municipalities in the Pacific Northwest, and they derive much of their water from snowmelt filtered through groundwater aquifers. Recent analyses show that this region is particularly sensitive to current and projected climate warming trends, specifically reduced snow accumulation and earlier spring melt (Mote, 2003; Stewart *et al.*, 2005). By 2050, Cascades snowpacks are projected to be less than half of what they are today (Leung *et al.*, 2004), potentially leading to major water shortages. Broad regional-scale characterizations identify climatic gradients as the most important controls on spatial variability in streamflow regimes, but the potential for other hydrological factors, particularly groundwater, to influence this response has received much less attention. Our objective is to develop an understanding of how discharge from a groundwater-dominated watershed is controlled at the event, seasonal, and interannual scales by snowpack dynamics, antecedent conditions, and global climate signals.

The study watershed is that of the McKenzie River at Clear Lake (Figure 1), in the central Oregon Cascades, includes extensive areas of high permeability Quaternary (High Cascade) basalts that result in a substantial groundwater system, as well as runoff-dominated Tertiary (Western Cascades) landscapes (Sherrod and Smith, 2000; Tague and Grant, 2004). This 239 km^2 watershed has long-term records of streamflow from United States Geological Survey gage #14158500. It also has record of precipitation, snow, and temperature from three Natural Resources Conservation Service SNOTEL sites: Hogg Pass (1451 m, 21E05S), Santiam Junction (1143 m, 21E06S) and Jump Off Joe (1067 m, 22E07S). Annual precipitation in the watershed ranges from ~1.8 to 3 m, and 70% falls between November and March. 47% of the watershed lies between 918 and 1200 m, in the transient snow zone. From 1200 m to the peak elevation (2051 m), seasonal snowpacks occur from November through June. Peak snow water equivalent (SWE) occurs around April 1st at Hogg Pass, and around March 1st at Santiam Junction and Jump Off Joe.

In order to examine relationships between hydrological variables in space and time, we performed Pearson's correlations, autocorrelations, and cross-correlations using 42 parameters derived from discharge, precipitation, SWE, and temperature from the stations listed above. We also correlated discharge and SWE with monthly values of the Niño 3.4 index of sea surface

---

[1] Department of Geosciences, Oregon State University, 104 Wilkinson Hall, Corvallis OR 97331.

[2] College of Oceanic and Atmospheric Sciences, Oregon State University, 104 COAS Administration Bldg., Corvallis, OR 97331.

[3] USDA Forest Service, Pacific Northwest Research Station, 3200 SW Jefferson Way, Corvallis, OR 97331.

[4] Bren School of Environmental Science and Management, University of California, Santa Barbara, 93106.

temperature (Trenberth and Stepaniak, 2001). A simple water balance was constructed for the 2001–2004 water years, using values for the average basin elevation (1215 m) interpolated from precipitation and SWE values at Jump Off Joe and Hogg Pass. Basin-averaged evapotranspiration was calulcated in RHESSys (Tague and Band, 2004). Predictive models of September–November minimum discharge were developed using stepwise regression in SAS 9.1.

Fluctuations in discharge are muted relative to daily variability in the recharge (rain plus snowmelt) signal (Figure 2). Summer streamflows are sustained by groundwater, not snowmelt. There is a high degree of discharge auto-correlation for ~2.5 months, and there is a strong cross-correlation between the previous year's precipitation and the current year's discharge at a 1 year lag. The El Niño-Southern Oscillation is a reasonably good predictor of SWE and a moderate predictor of annual discharge. Internanual variability in the 26-year SNOTEL record masks any long-term trends in precipitation or SWE, but the longer discharge records suggests that climate warming is altering the streamflow regime at Clear Lake. The hydrograph temporal center of mass (Stewart *et al.*, 2005) has moved earlier by a statistically significant 15 days since 1950, which is probably a function of relatively more winter rain and earlier snowmelt. This finding is in line with other watersheds throughout the mountainous west (Stewart *et al.*, 2005). September–November minimum flows have declined since 1947, probably as a result of longer summer recession periods resulting from earlier snowmelt.

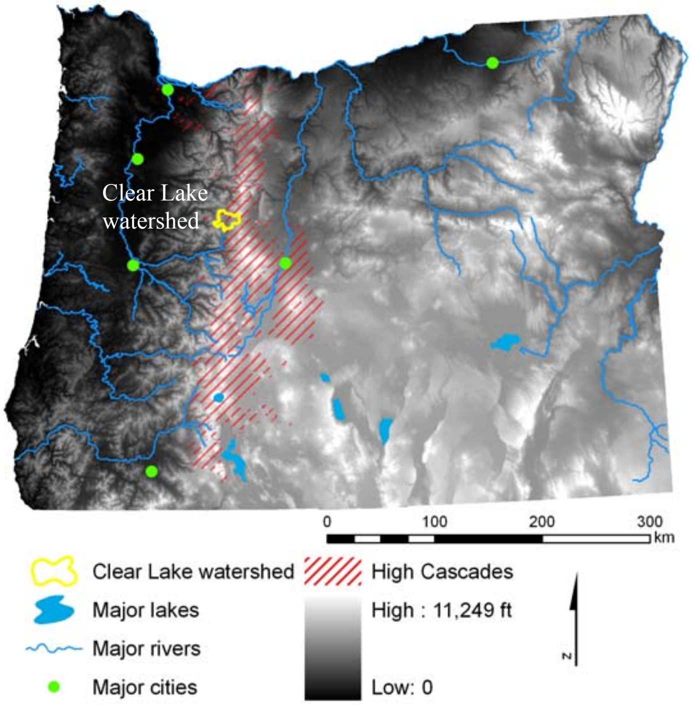

Figure 1. Location map of the study watershed, relative to the topography of Oregon and extent of High Cascades geology.

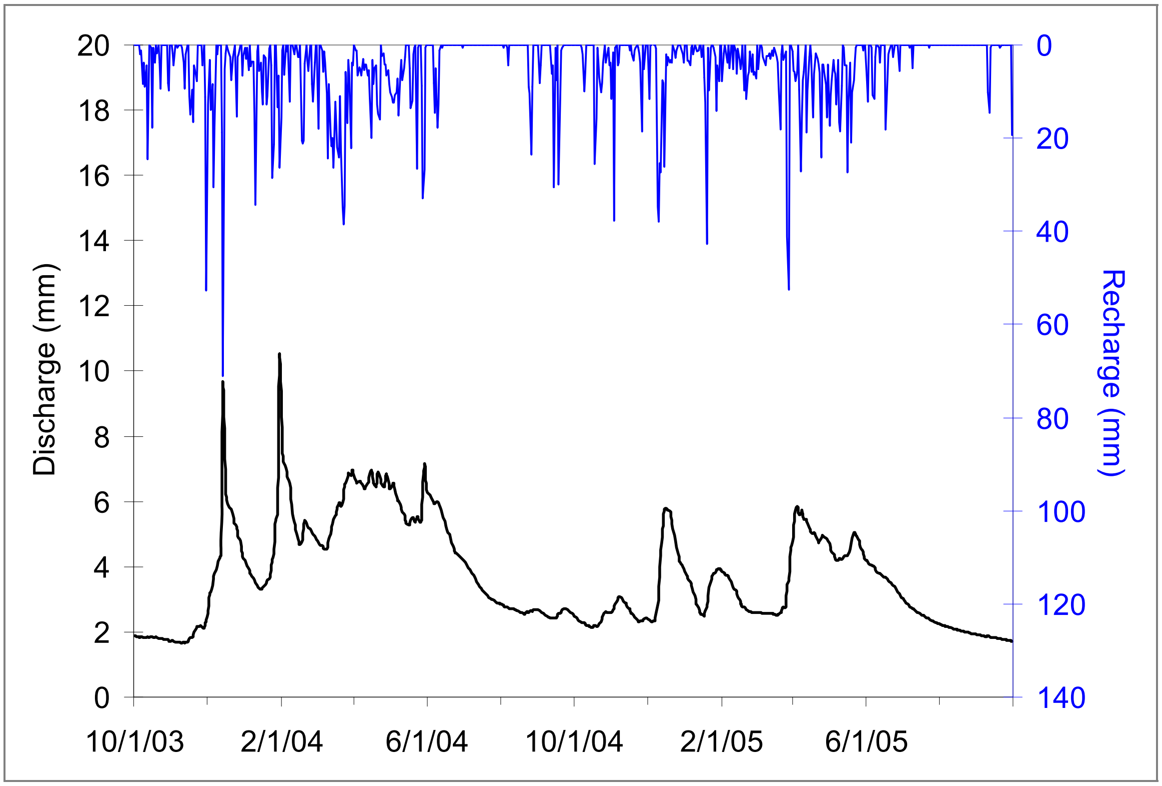

Figure 2. Discharge at Clear Lake for water years 2004 and 2005 (bottom, black line), compared to the interpolated rain + snowmelt time series for the median basin elevation (top, blue line).

The main conclusions of this study are:

1. In the study watershed, pronounced seasonal variability of water inputs is damped by extensive groundwater systems. The study area may serve as a model for other groundwater-dominated watersheds in the mountainous west.
2. Delays between precipitation and discharge are a function of snowpack storage and slow release of groundwater. From July to October, streamflow is sustained by groundwater.
3. Groundwater-dominated watersheds are somewhat buffered from <2-year fluctuations in precipitation, but are susceptible to prolonged droughts or wet periods.
4. Snowpack is more sensitive than discharge to the state of major of climate indices in groundwater-dominated watersheds.
5. Minimum flows are largely controlled by the current year's precipitation, but are also sensitive to the timing of snowmelt and the antecedent conditions in the aquifer.
6. Regional warming of the past several decades has affected the shape of the annual hydrograph, in terms of its temporal center and minimum flows. Continued warming is predicted to lead to loss of snowpack and continued decline in minimum flows.

Keywords: snowmelt, groundwater, climate variability, Oregon, Cascades

ACKNOWLEDGEMENTS

This work was funded by the Institute for Water and Watersheds at Oregon State University, through the USGS water resources research institute program, and by the Eugene Water and Electric Board. This material is based on work supported under a National Science Foundation Fellowship.

REFERENCES

Leung LR, Qian Y, Bian X, Washington W, Han J, Roads JO. 2004. Mid-century ensemble regional climate change scenarios for the western United States. *Climatic Change* **62**: 75–113.

Mote PW. 2003. Trends in snow water equivalent in the Pacific Northwest and their climatic causes. *Geophysical Research Letters* **30**: 1601, doi:10.1029/2003GL017258.

Sherrod DR, Smith JG. 2000. *Geologic Map of Upper Eocene to Holocene Volcanic and Related Rocks of the Cascade Range, Oregon*. U.S. Geological Survey: Washington;

Stewart IT, Cayan DR, Dettinger MD. 2005. Changes toward earlier streamflow timing across western North America. *Journal of Climate* **18**: 1136–1155.

Tague CL, Band LE. 2004. RHESSys: Regional Hydro-Ecologic Simulation System—An object-oriented approach to spatially distributed modeling of carbon, water, and nutrient cycling. *Earth Interactions* **8**: Paper No. 19, p. 1–42.

Tague C, Grant GE. 2004. A geological framework for interpreting the low flow regimes of Cascade streams, Willamette River Basin, Oregon. *Water Resources Research* **40**: W04303 10.1029/2003WR002629.

Trenberth KE, Stepaniak DP. 2001. Indices of El Niño evolution. *Journal of Climate* **14**: 1697–1701.

63^{rd} EASTERN SNOW CONFERENCE
Newark, Delaware USA 2006

Synoptic Patterns Associated with the Record Snowfall of 1960 in the Southern Appalachians

L. BAKER PERRY[1] AND CHARLES E. KONRAD II[2]

ABSTRACT

Record snowfall totals of up to 211 cm blanketed the Southern Appalachians between mid-February and late-March 1960. Snow was reported on average every other day in the higher elevations, and mean temperatures for the period were nearly 6 C below normal. Snow piled up to great depths, with Boone, NC, reporting a maximum depth of 112 cm. Snow drifts buried roads and made travel impossible, requiring food, fuel, and hay to be airlifted into the region. This paper analyzes the synoptic patterns associated with the record snowfall of February and March 1960. Snowfall events are identified using a combination of first order hourly observations and cooperative observer daily snowfall totals. The spatial patterns of snowfall are mapped using a GIS, while mean values for various synoptic fields (e.g. 850 hPa temperature, 500 hPa height) are calculated and compared to 50-year climatological means. Snowfall events during this period are then classified according to the pattern of cyclogenesis and prevailing flow direction.

Keywords: Synoptic patterns, snowfall, 1960, Southern Appalachians

INTRODUCTION

February and March 1960 continue to be remembered as the snowiest period on record in the Southern Appalachians. Snow was nearly a daily occurrence between 13 February and 26 March at higher elevations, with Boone, NC, reporting 211 cm and many other locations in excess of 175 cm. These snowfall totals are considerably greater than the current 30-year mean *annual* snowfall of 102 cm for Boone and approach the mean annual values of nearly 250 cm for the 2,000 m peaks (e.g Mt. Leconte and Mt. Mitchell) of the Southern Appalachians. Mean temperatures for the period were nearly 6 ºC below normal (Hardie 1960). The combination of frequent snowfall and low temperatures allowed the snow to pile up to great depths, with Boone, NC, reporting a maximum depth of 112 cm on 13–14 March (NCDC 2002). Considerable blowing and drifting of snow compounded problems, closing roads and requiring emergency distribution of food, fuel, and hay (Figs. 1 & 2). Although the impacts were greatest in the Southern Appalachians, the entire Eastern U.S. was adversely affected. March alone broke more records for cold and snow across the Eastern U.S. than any other March on record until then (Ludlum 1960a, Ludlum 1960b). It remains the coldest March on record for many locations in the Southern Appalachians (NCDC 2002.

---

[1] Department of Geography and Planning, Box 32066, Appalachian State University, Boone, NC 28608 (perrylb@appstate.edu)

[2] Department of Geography, University of North Carolina, Chapel Hill, NC 27599