Examining monthly relationships between temperature, precipitation, snowpack, and streamflow in the Upper Klamath Basin over a 26 year SNOTEL record

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Abstract

This investigation aimed to illustrate the relationship between temperature, precipitation, SWE, and water availability on a monthly basis in the Upper Klamath Basin located in southern Oregon and northern California. Understanding the intricacies of climate-snowpack-water relations throughout the year will help create better predictions of how climate change will continue to affect water availability and ecological relationships. Temperature, precipitation, SWE, and streamflow were correlated over a 26 year SNOTEL record in the basin (1982-2008). Trends in these variables were also examined. Snowpack was the most highly correlated variable with streamflow from March through December of the following water year. Decreases in early year SWE were found to be a result of diminishing early snow year precipitation and warming December temperatures. The drier eastern region of the basin experienced temperature increases and diminishing snowpack at a disproportionate rate demonstrating local variability in the effects of climate change. Streamflows were found to be decreasing rapidly, 15.1%/decade, particularly from early-spring to mid-fall. Employing a similar monthly analysis technique on a regional scale would prove helpful towards demonstrating variances in the effects of climate change and preparing for changes in streamflow throughout the west.

Introduction

The Importance of Western Snowpack

The accumulation of snowpack in the mountain ranges of the western United States has been instrumental in supporting the development of the largely arid region, from the pioneer days of the nineteenth century to the boom of the Los Angeles megatropolis in the second half of the 20th century. The majority of yearly precipitation accumulates from mid-fall through the winter to mid-spring and thus much of this precipitation falls as snow in the region's numerous mountain chains. Mountainous snowpacks work as reservoirs, trapping precipitation that falls during the wet winter season and releasing it into the hydrological cycle in the spring and summer when agricultural demand is at its highest. Without snowmelt water, and the of manipulation of this water through extensive reservoirs, canals, and diversions, cities such as Los Angeles, Phoenix and Salt Lake City could not exist and agriculture in what are currently some of the nation's most productive areas would not be possible.

Water management has been, and continues to be, a highly contentious process between agriculturalists, fisheries, environmental advocates and other competing interest groups. Continued population growth and agricultural development have been encouraged by a plethora of governmental water works projects built by the Army Corps of Engineers and the Bureau of Reclamation over the last century. These water works projects, ranging from small scale diversions and irrigation canals to grand projects such as Hoover Dam and the large hydroelectric dams of the Columbia River, have made development possible by providing increased storage for dry summers, producing large amounts of electricity, and diverting water for agriculture and metropolitan use. As the demand for water has continued to grow, the complexity and intricacy of water flow manipulation has also grown.

Today, nearly every drop of western water is spoken for, often leading to conflicts during dry years. For example, the Colorado River which begins in the snow capped peaks of the Rocky Mountains, supplies water to millions of homes in cities such as Phoenix and Los Angeles. Diversions of its waters have turned barren deserts in places like the Imperial Valley of California into some of the most productive farmland in the country. Unfortunately the water diversions of the Colorado River leave it a salty trickle before reaching the Mexican border. Some years the river does not even reach its delta at the northern end of the Sea of Cortez. On the Columbia River, irrigation rights and interests in hydroelectric power production compete for water with interests in salmon and other fish populations. In Utah there is a battle over the right to trap water that falls on one's own rooftop. This simple act is technically illegal because all precipitation that falls in certain watersheds belongs to an irrigation district or a city utility (*High Country News*, November 24th, 2001). These are just a few examples of typical contentious western water issues which demonstrate the delicacy and difficulty of western water management.

Western Snowpack Correlations and Climate Change

Snow accumulation in the mountains of the western United States is highly related to Pacific Ocean climate variability, including El niño-Southern Oscillations (Clark et al 2001), Pacific Decadal Oscillations (Mote 2006) (Knowles et al 2006) (Goodrich 2007), and the Northern Pacific Index (Mote 2006), which is defined as the mean atmospheric sea level pressure over the region 30˚-60˚N, 160˚E-140˚W (Trenberth and Hurrell 1994). These oceanic factors are largely responsible for high annual variability seen in the accumulation of snowpack throughout the west.

While much of the documented variability in western snowpack accumulation and spring runoff can be attributed to oceanic oscillations, consistent decreases in snowpack accumulation observed over the second half of the 20th century are a result of longer term climate shifts (Knowles et al 2006). April 1st snow water equivalents (SWE) is defined as the amount of water in the snowpack at that date. Reductions in April 1st SWE (Hamlet et al 2005; Mote et al 2006), earlier spring runoff and soil moisture peaks (Hamlet et al 2007; Cayan et al 2001; Stewart et al 2005), and increasingly early high rates of evapotranspiration in the beginning of summer and late spring (Hamlet et al 2007), throughout the west are a result of continued atmospheric warming. The majority of snowpack loss has occurred at lower elevations which are more sensitive to warming trends due to generally warmer and more marginal winter temperatures than higher elevations (Mote 2002). As a result, a higher percentage of precipitation is falling as rain instead of snow (Knowles et al 2005). Recent research has suggested that reductions in western snowpack accumulations observed since the mid twentieth century cannot be fully explained by natural climate variability alone and are partially the result of anthropogenic climate changes brought on by the release of greenhouse gases, ozone, and aerosols (Pierce et al 2008).

Significant warming trends are expected to continue in the western United States (Hamlet and Lettenmaier 1999; Mote et al 2003; Leung et al 2004). Forecasts predict that average temperatures will increase by 1-3.2 ˚C by mid century. These conditions paint a disastrous picture for the future of the already stressed water resources of the western United States. Resource managers and planers are largely unprepared for mitigating the ecological and economic impacts of climate change (Mote et al 2003). Consequentially, it is becoming increasingly important to understand how snowpack responds to climate change and how this affects the snowmelt-surfaceflow relationship. Having this understanding will help to prepare for upcoming challenges, including decreased dry season water availability related to climate change.

Much research on snowpack accumulation/melting trends and snowpack/water relations has employed general statistics which are designed to summarize certain variables for a particular year. April 1st snow water equivalent (SWE) is often used because it represents a cumulative and simplified summary of the winter's weather, including the deposition of snow, melting of snow, and rain events which may augment snowmelt or be absorbed in the snowpack (Mote 2006). Winter period average temperature and winter cumulative precipitation are also commonly used as seasonal summaries of temperature and precipitation respectively and their influence on snowpack accumulation and melting. This approach allows for the description of large trends over extensive areas. Nonetheless, the significance of these generic variables is bound to change with continued climate change.

This investigation aimed to elucidate the relationship between climate variables, snowpack, and water availability throughout the year. Specifically, SWE was correlated with temperature and precipitation and stream flow was correlated with temperature, precipitation and SWE on a monthly basis in a western water basin. Increasing our knowledge of these relationships throughout the year will lead to form better predictions of how these variables and the relationships between them respond to seasonal climate variations and how they will continue to transform with climate change. This approach is also important for understanding and predicting the various ecological implications of changing snowpack accumulation and water relations throughout the year.

The Example of the Upper Klamath Basin

This paper examines the Klamath River Basin as a case study of how climate change is currently affecting snowpacks and thus spring and summer water availability in the West. The Klamath River is a classic example of a heavily overburdened western river system. Beginning as snowmelt on the eastern side of the Cascade Mountains in southern Oregon, the Klamath River crosses California and the Cascade and coastal mountains on its way to the Pacific Ocean (figure 1). Historically the river was extremely productive, supporting the third most prolific salmon system on the west coast of the lower forty-eight states, trailing only the Columbia and the Sacramento rivers. It also supported strong populations of other anadromous species, including steelhead, Pacific lamprey as well as sixteen other freshwater fish species (CDFG 2004). The Upper Klamath Basin was composed of a series of large marsh lands and shallow lakes which served and, to a lesser degree, continue to serve as a resting place for large congregations of numerous species of migrating waterfowl on the Pacific Flyway.

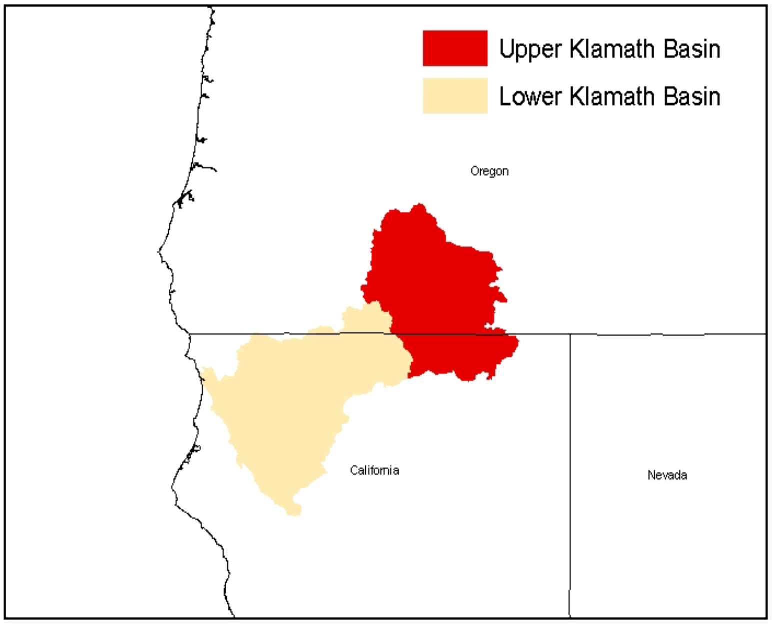

Fig 1: Map of Klamath Basin with the Upper Klamath Basin designated.

As with most western watersheds, the Klamath River basin has been heavily altered to support development. In 1905 the upper Klamath Basin was transformed by the Klamath Reclamation Project from an expansive marshland into a farming region when the Bureau of Reclamation drained most of the area and constructed three water storage dams and an irrigation system of canals and levees. Between 1905 and 1962, a series of hydroelectric projects were built on the main stem of the Klamath River, blocking salmon from nearly half of the basin while manipulating flows and raising average river water temperatures through stagnation. Further diversions from the Trinity River (the largest tributary to the Klamath River) additionally lowered river levels and raised water temperatures. Today, competing water stakeholders in the Klamath Basin include farmers, salmon fishermen, interests in hydroelectric generation, and interest in the five national wildlife refuges which protect much of the area's remaining marsh land that is important to waterfowl and other wildlife.

Due to the heavy alteration of the watershed, the biological productivity of the Klamath River has greatly suffered. Salmon runs and other anadromous fish populations retain a fraction of their historic productivity (CDFG 2004). Waterfowl concentrations have also greatly diminished. Two species of sucker fish in the upper basin were listed as endangered in 1988 (USFWS 2009) and Klamath River Coho salmon have been listed as threatened since 1997 (NMFS 2009).

The upper Klamath Basin, where most of the agriculture is located, is fairly dry due to its position on the east side of the Cascade Mountains. The Cascades run north-south parallel to the Pacific Coast line, from southern British Columbia to northern California. Wet frontal systems generally blow in from the west off of the Pacific Ocean during the winter, hitting the mountain range broadside. Due to the rain shadow effect, these systems drop the majority of their moisture on the western side up to the crest of the mountain range. Snow depths on the order of tens of meters are not uncommon at the crest of the Cascades. The eastern side of the mountain range is significantly dryer. Thus minimal changes in the snowpack may make a more significant difference in water availability.

The effects of climate change have already become apparent in the upper Klamath Basin, resulting in heated debates over water rights as drought years have become more frequent. Following a particularly low snowpack year in 2001, the National Marine Fisheries Service (NMFS) recommended, through a Biological Opinion, maintaining water levels in the river and Upper Klamath Lake to preserve salmon runs in the main stem of the Klamath River as well as two endangered species of sucker fish in Upper Klamath Lake. Biological Opinions are issued when there is a lack of specific scientific research on which to base a management decision. In this case, governmental scientists are asked to use their expertise and knowledge to suggest a management strategy. Due to low water availability, this particular decision meant that no water was to be distributed to farmers. This resulted in millions of dollars in agricultural losses for Klamath Basin farmers during the 2001 growing season (Levy 2003).

Due to controversy stimulated by the economic impact of the NMFS decision, a National Academy of Science (NAS) panel was charged with investigating the science justifying the decision to withhold irrigation water from farmers to protect fish. Their preliminary report produced in 2002 stated that the decision to maintain higher water levels in the river and lake had “no scientific basis” (NAS 2007). The report was implying that there was no scientific study that directly indicated that maintaining water levels in the Klamath River and marshlands would substantially benefit protected suckerfish and salmon. The NAS report instigated a furious uproar by farming advocates and a movement to open the irrigation channels. Under stiff pressure, the recommendations of NMFS fishery biologists were ignored and irrigation channels were opened, lowering lake and river levels.

During the following summer the largest salmon die off in the history of the western United States occurred on the main stem of the Klamath River when at least 33,000 adult salmon went “belly up” before they had the opportunity to spawn (Levy 2003). This event was unprecedented in that it was the first major fish kill recorded in the Klamath River (CDFG 2004). The California Department of Fish and Game (CDFG) undertook an analysis of the causes of the fish kill. In their final report filed in 2004 the agency concluded that low river levels, high water temperatures, and an abnormally large

Chinook salmon run produced the appropriate conditions for a pathogen epidemic which caused gill rot. The report also concluded that “flow is the only controllable factor and tool available in the Klamath Basin (Klamath and Trinity rivers) to manage risks against future epizootics and major adult fish-kills” (CDFG 2004).

After another very low snowpack in 2005 and three consecutive years of what were deemed to be “unsustainable” salmon spawning runs, 700 miles of coastal salmon fishing, from central California to the mouth of the Columbia River, were shutdown to protect Klamath River salmon and maintain the fishery for future production. While other river systems were congruently experiencing sustainable runs, salmon intermingle in the ocean making it impossible to catch salmon without the risk of catching Klamath salmon. This fishing shutdown resulted in millions of dollars in losses for coastal fishermen. The 2008 salmon fishing season was also cancelled, this time as a consequence of threatened salmon on the Sacramento River. As a result of these two cancellations, coastal salmon fishermen in Oregon and California are economically struggling and have repeatedly asked for government aid.

This history demonstrates the need for a better understanding of how water availability is changing in the Klamath Basin, to allow for more foresight and justification for difficult resource management decisions. Having a stronger understanding of snowpack and the hydrologic relation between snowpack and water availability in the Klamath Basin is important for understanding how future climatic changes will affect water availability in the basin and for creating water availability forecasts. Increased knowledge of these relationships could prevent future excessive and unnecessary environmental damage and economic hardship.

The Cascade Mountains of northern California and southern Oregon, where the Upper Klamath Basin is located, have experienced the largest losses of snowpack in the West during the last half of the twentieth century (Mote et al 2005). This is a result of relatively marginal winter temperatures due to lower elevations in the Cascade Mountains compared to other western mountain basins (Mote et al 2006). Consequently, Cascade snowpack is more sensitive to warming which has been shown to cause higher proportions of winter precipitation to fall as rain instead of snow (Knowles et al 2006) and a higher frequency of rain on snow events (Lueng et al 2004). The Pacific Northwest has also experienced decreasing streamflow during the same period (Kalra et al 2008). This has resulted in higher water temperatures and lower flows in the Klamath which have increased the ecological stress on salmon populations (Bartholow 2005).

As in the rest of the West, atmospheric warming is predicted to continue in the Pacific Northwest, producing sustained negative trends in snowpack accumulation and streamflow. Relatively small changes in precipitation and temperature can result in much larger monthly or seasonal changes in snowpack and runoff because the effects of temperature and precipitation are integrated over time and space through various hydrological and land atmosphere feedback processes (Leung et al 2004). Model predictions calculate that average March 1st Columbia River Basin SWE will decrease by 15-25 % by 2025. It is also predicted that by 2045 the reduced snow pack and earlier melt, coupled with higher evapotranspiration in early summer, will lead to reduced runoff volumes of up to 25 % of current conditions between April and September (Hamlet and Lettenmaier 1999). The Columbia River Basin directly borders the Upper Klamath Basin to the north, likely resulting in similar trends in the Klamath. This suggests that by studying the current changes in the snowpack of the Klamath Basin, we could not only better prepare for the management challenges within the basin itself, but use this research to better understand how snowpack may change in other, less marginal basins, which will likely experience similar changing conditions in the future as temperatures continues to rise. Accordingly, the lessons learned from studying the Klamath basin today could help avoid unnecessary environmental and economic losses in other basins in the future.

Study Goals and Methods

This investigation aimed to illustrate the relationship between climatic temperature, precipitation, snowpack SWE accumulation and ablation, and streamflow in the Upper Klamath Basin over a 26 year period (1982-2008). Specific questions which the study attempted to address include; how are SWE in the Upper Klamath Basin and the streamflow related to each other and to temperature and precipitation on a monthly basis? If changes in SWE and surfaceflows are occurring in the Upper Klamath Basin, when are they occurring and how do these changes correlate with each other, as well as changes in precipitation and temperature on a monthly basis? How do trends in these variables vary within a single basin in areas of close physical proximity, but significant climate differences? How can the relationships described in the Klamath be expected to relate to other western basins?

There are numerous factors, most notably groundwater hydrology, which may obscure the relationship between SWE, temperature, precipitation, with surface flows during varying conditions. Bedrock hydrology can have major effects on the timing of streamflow and these effects can differ dramatically depending on varying snowpack accumulations and melting rates (Flerchinger et al 1992). The bedrock hydrology in a basin the size of the Upper Klamath is likely to have many isolated irregularities in the bedrock, differences in soil permeation rates, etc, which affect the response of river discharge to snowmelt. Accordingly, these types of variables were expected to lower the significance of the correlations and trends in snowpack/climate and streamflow data.

Data Source

The basis of this research is data provided by the National Resource Conservation Service's (NRCS) SNOTEL (stands for SNOw TELemetry) system and United States Geological Service (USGS) stream gage data. SNOTEL is a system of automated sensors which measure and record snow accumulation data, SWE, precipitation, and temperature data (NRCS 2009). SNOTEL stations use meteor burst communications technology to collect and communicate data in near-real-time. SNOTEL sites are spatially located throughout western mountain ranges with the intention of creating a general overview of a the West's snow accumulation and melting patterns. The NRCS currently runs 730 SNOTEL stations in 11 western states. Most SNOTEL sites in Oregon were built in the early or mid 1970's creating a more than 30 year data base of snow and precipitation telemetry data. The USGS stream gage system provides stream height and stream velocity measurements as well as discharge calculations at intervals of every 15-60 minutes for sites spread throughout the country (USGS 2009). Most Oregon stream gage sites are significantly older than the SNOTEL stations, allowing for comparisons with the entirety of the SNOTEL data set.

The first SNOTEL stations in the Upper Klamath Basin became operational in 1979. Today, there are 12 SNOTEL sites in the upper Klamath Basin as well as 4 stream gages on the Williamson Rivers and Sprague Rivers (a tributary of the Williamson). The 12 SNOTEL (8 were used in this study) sites are located at varying elevations throughout the basin. The extensive SNOTEL and USGS stream gage coverage in the Upper Klamath Basin makes it a logical place to use SNOTEL data to study snowpack trends and snowpack-water relations.

Data and Methods

Daily and monthly averages of snowpack data and climatic data were extracted from the NRCS website archive (http://www.wcc.nrcs.usda.gov/snotel/) for eight SNOTEL stations located in the Upper Klamath Basin (table 1 and figure 2). Stations becoming operational during or before the year 1982 were analyzed, providing a complete 26 year record for analysis. The altitudes of these eight stations range from 5,030 feet (Taylor Butte) to 7,080 feet (Summer Rim). All stations were operational during the entirety of this 26 year period with the exception of Billy Creek Divide, which became operational before 1982 but produced no snowpack data during the years 1982 and 1984. Billy Creek Divide was included in the analysis because it allowed for an equal number of western and eastern sites and the small amount of missing data was deemed unlikely to alter observed trends.

These eight sites are located in two geographically distinct regions of the Upper Klamath Basin. Four of them are located in the wet western part of the basin near the crest of the Cascade Range while the other four are located in the much drier mountainous areas of the eastern part of the basin. This distribution allowed for statistical comparison between these two geographically distinct areas.

SNOTEL Data gathered and analyzed includes averages for the 26 year period of the monthly mean of climatic variables including snow water equivalent (SWE), precipitation and temperature data from all eight sites. The monthly means for the 26 year study period and the trends over the 26 year period were analyzed for these variables. Characteristics and trends were calculated for each site individually, averaged for all sites in the basin, and averaged and compared for eastern and western sites separately.

Stream discharge data was also gathered from the United States Geological Survey stream gage system for the Williamson River, a free flowing sub-basin of the upper Klamath Basin. Data was gathered for the Williamson River stream gage site located near Chiquiten and below the confluence of the Sprague River from the USGS stream gage website (http://waterdata.usgs.gov/nwis/uv?11501000). Williamson River discharge monthly averages and trends in monthly averages over the 26 year period were calculated as a representation of surface water flows in the basin, allowing for comparison with snowpack data. SWE data was correlated with precipitation and temperature data and Williamson discharge data was correlated with SWE, temperature, and precipitation on a monthly basis. Simple linear regressions were used for all correlation analyses and R^2 values were used to determine the strength of relationships.

SNOTEL Station	Elevation (ft)	Basin Region	Latitude, Longitude
Seven Mile Marsh (SMM)	5700	West	42.69, -122.14
Cold Springs (CS)	5940	West	42.53, -122.17
Fourmile Lake (FML)	5970	West	42.43, -122.22
Billy Creek Divide (BCD)	5280	West	42.40, -122.26
Strawberry Mountain (SM)	5770	East	42.12, -120.83
Quartz Mountain (QM)	5720	East	42.31, -120.82
Taylor Butte (TB)	5030	East	42.69, -121.42
Summer Rim (SR)	7080	East	42.69, -120.80

Table 1: Used SNOTEL sites in the Upper Klamath Basin. Site name, elevation, basin region, and specific location are shown.

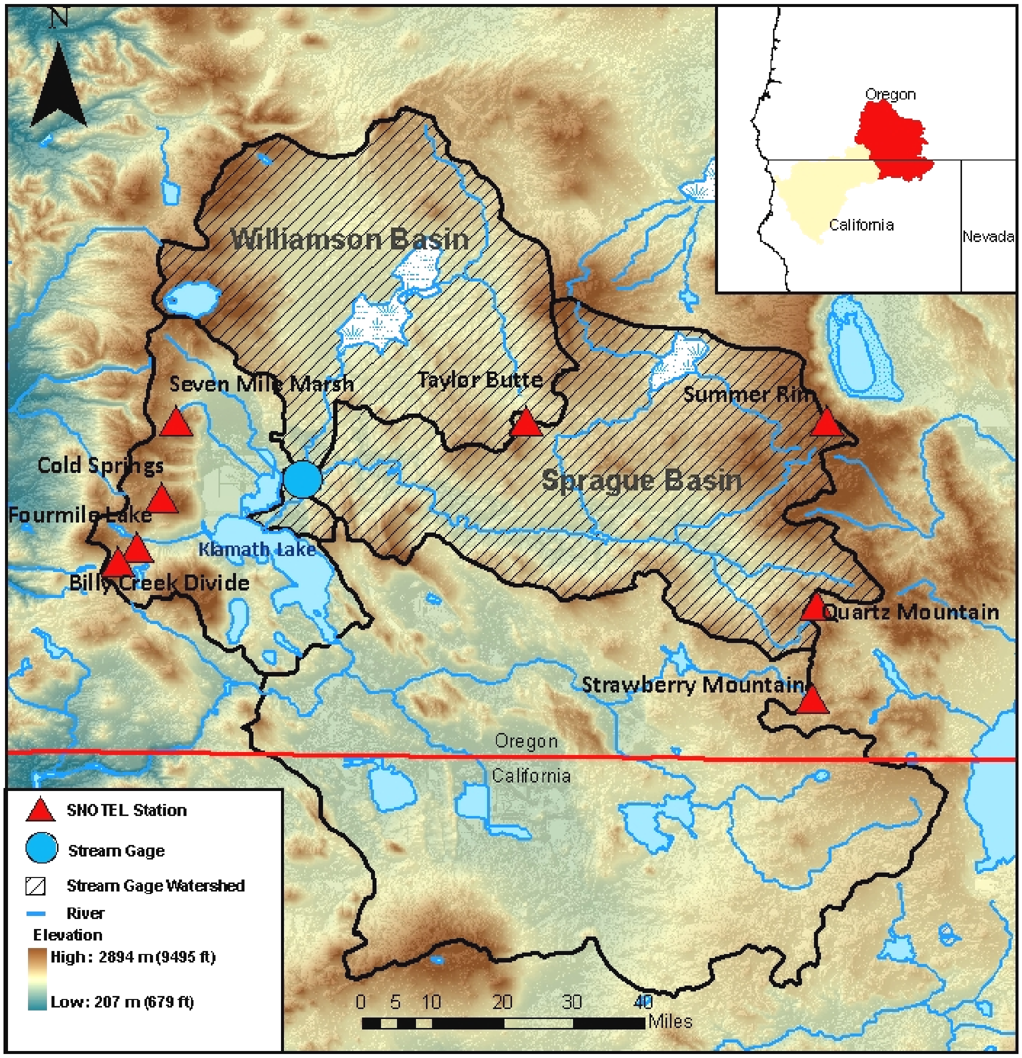

Figure 2: Map of Upper Klamath Basin with studied NRCS Snotel and USGS stream gage sites labeled.

Results and Discussion

Snowpack and Climate Characterization

Precipitation

The wet season in the Upper Klamath Basin was shown to last from November-March (figure 3). Precipitation peaked during the month of December at an average of 7.0 inches before declining throughout the late winter and spring. During the month of March most sites demonstrated less decrease in precipitation. July and August were the driest months of the year. Average low monthly precipitation for all study sites in the basin was 0.54 inches during the month of August. Precipitation was highly variable on a year to year basis during wetter months from October-May.

The rain shadow effect was clearly demonstrated in the yearly precipitation patterns. Western sites located near the crest of the Cascade Mountains averaged 57.0 inches of precipitation per year while eastern sites averaged only 24.1 inches. Western sites averaged significantly more precipitation than eastern sites from September-May. Peak monthly precipitation averaged 10.2 inches in the month of December in western sites while only 3.7 inches in eastern sites. There were no significant differences in precipitation between eastern and western sites during the summer months.

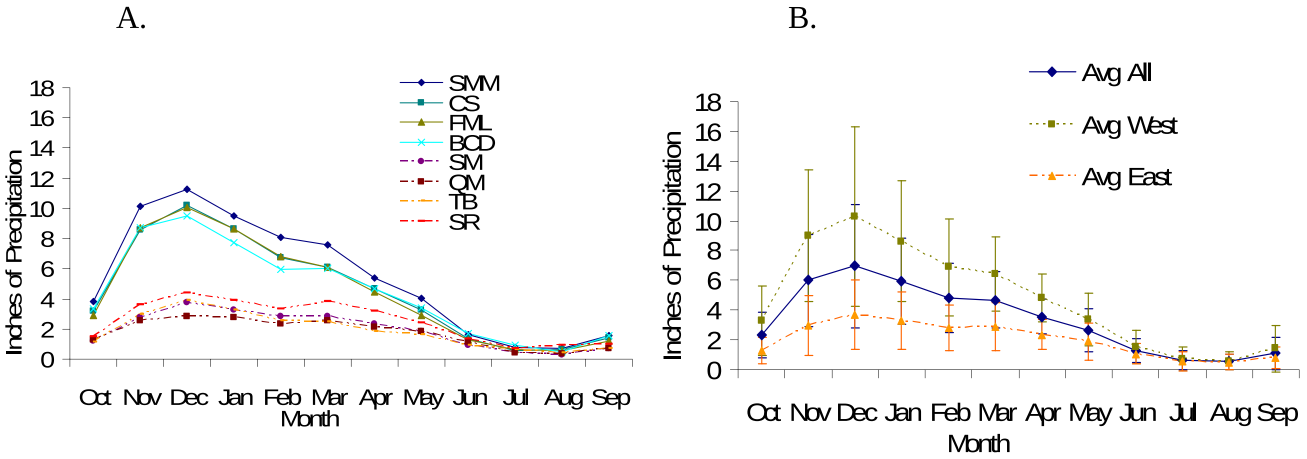

Figure 3: A. Mean monthly precipitation averaged for all study sites in the Upper Klamath Basin averaged for the 26 year study period (1982-2008). B. Mean monthly precipitation averaged over the 26 year study period for western study sites (Avg West), eastern study sites (Avg East), and all study sites in the Upper Klamath Basin (Avg All).

Temperature

Average monthly temperature was very similar at all study sites throughout the Upper Klamath Basin (Figure 4). The yearly low average monthly temperature for all sites was -2.3 C˚ in the month of December while the yearly high average monthly temperature for all sites was 16.2 C˚ during the month of July. Summer Rim was the coldest site throughout the entire year. There were no significant differences in temperature among eastern and western sites in the winter and fall. Eastern sites tended to be slightly warmer during the spring and summer.

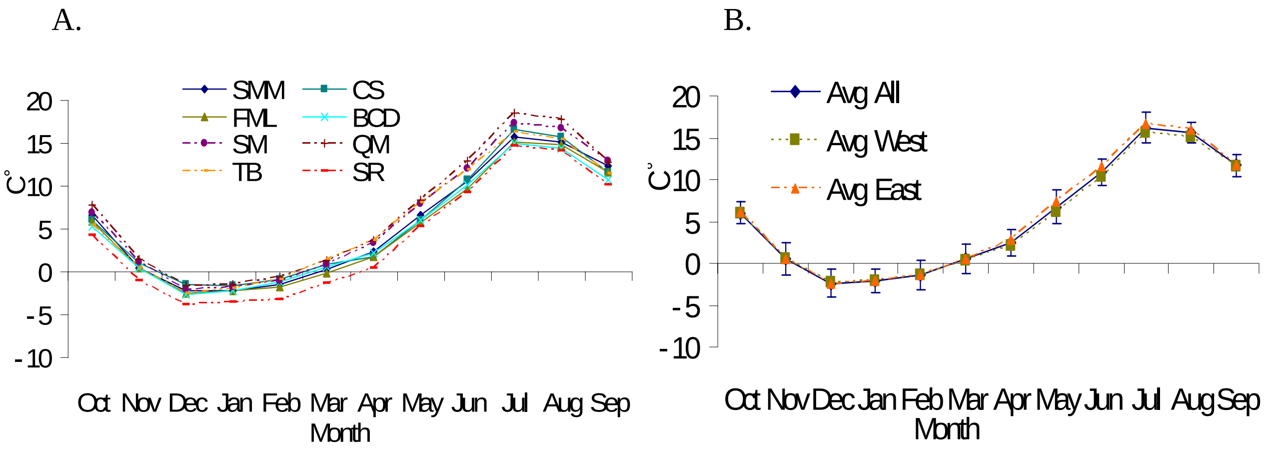

Figure 4: A. Average temperature for SNOTEL sites in the Upper Klamath Basin by month. B. Comparison of western and eastern average monthly temperatures for all SNOTEL sites in the Upper Klamath Basin.

SWE

SWE accumulation varied greatly on a year to year basis. All sites throughout the Upper Klamath Basin reached their average peak SWE for the 26 year period during the months of February or March (Figure 3). The peak mean monthly SWE was 17.4 inches during the month of March. While the magnitude of the SWE accumulation varied greatly among study sites, the shapes of the curves were similar, demonstrating a related pattern of accumulation and melting. Snowpack at all sites tended to accumulate over a 4-6 month period from October/November to February/March before melting at a faster rate during the following 3-4 month period.

Snow accumulation in the western region of the Upper Klamath Basin in the Cascade Mountains was significantly larger than in the eastern region of the watershed, reflecting differences in precipitation. The peak mean monthly SWE averaged over the 26 year study period for western sites is 26.9 inches while only 8.24 inches for eastern sites. Western sites reach their average peak SWE in March while all eastern sites reach their peak SWE a bit earlier during February, with the exception of the Summer Rim, which also reaches its peak SWE in March. While SWE accumulations varied greatly in both the western and eastern regions, they were highly correlated (0.95), maintaining roughly a 3 to 1 ratio, demonstrating a dependence on the same climate variables.

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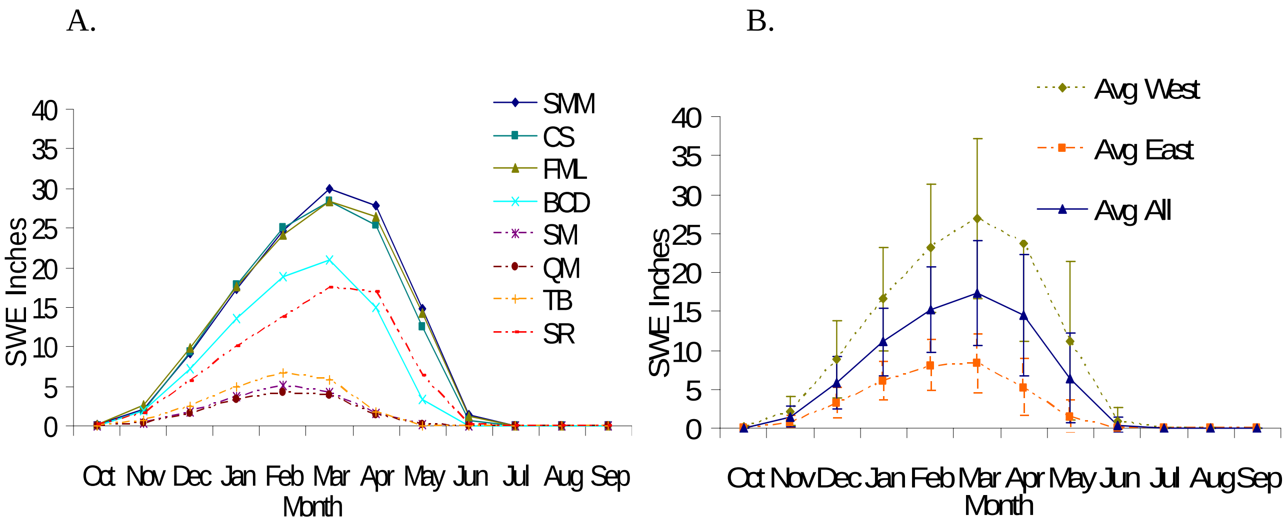

Figure 5. A. Monthly mean SWE for all sites. B. Monthly mean SWE averaged over the 26 year study period for western sites (Avg West), eastern sites (Avg East), and all sites within the Upper Klamath Basin (Avg All).

Williamson River Discharge

When averaged over the 26 year study period, the Williamson Basin monthly discharge peaked during the month of April at an average discharge of 1,622 ft³/sec. The lowest monthly discharge occurred in August at an average of 470 ft³/sec (Figure 6). Average discharge grew over an 8 month period, rapidly from December-March, to its peak in April before declining for a 4 month period towards its minimum in August. The average discharge for the entire year was 1,158 ft³/sec.

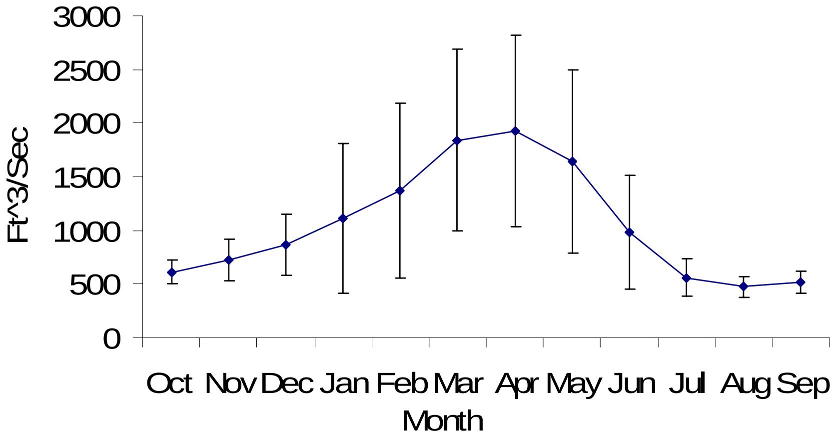

Figure 6: Mean monthly Williamson River discharge as measured by the USGS stream gage near its confluence with the Williamson River for the 26 year study period (1982-2008).

Characterization Summary

By combining the above analyses we can divide the water year (October-Septermber) into four distinct periods with regard to climate, SWE, and stream discharge which will aid further discussion of the relationships between these variables. These periods include a Winter Accumulation Period (WAP), a Spring Melting Period (SMP), a Summer Dry Period (SDP), and a Fall Cooling Period (FCP) (Figure 7). During the Winter Accumulation Period, which lasts from mid-November to mid-March, temperatures average below zero and precipitation is high, resulting in the steady accumulation of snowpack. Stream discharge also progressively increases during the Winter Accumulation Period. The Spring Melting Period, from mid-March to mid-June, is characterized by rapidly increasing temperatures which leads to high rates of snowpack ablation. Streamflow peaks in April before decreasing as a result of diminishing snowmelt and precipitation input. The termination of the snowpack marks the beginning of the Summer Dry Period which lasts from June-September. Persistently high temperatures and minimal precipitation lead to continued diminishing streamflows.

During the Fall Cooling Period, mid-September to mid-November, temperatures progressively drop and precipitation steadily increases. Streamflows begin to increase during this period. While the timing of these periods is bound to vary in different snow-dependent basins, these periods are general and can therefore be applied to other watersheds.

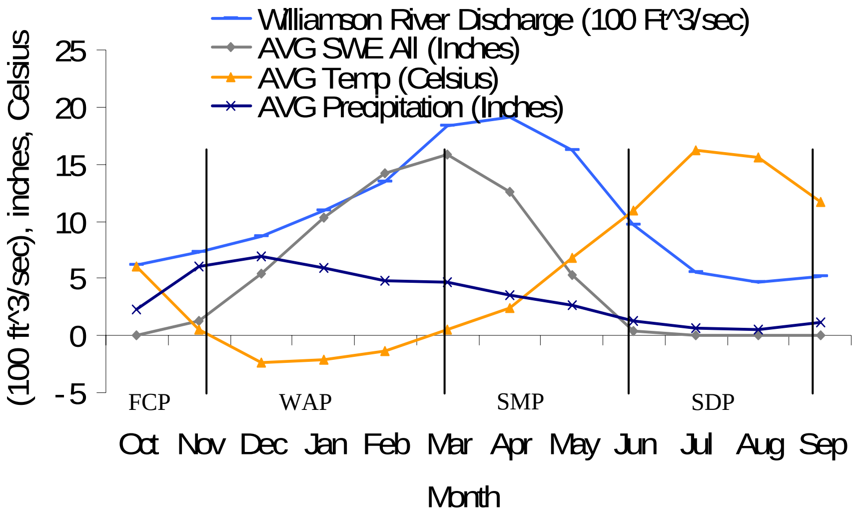

Figure 7: Average monthly SWE, temperature, and precipitation for all SNOTEL study sites in the Upper Klamath Basin and average monthly Williamson River Discharge.

Monthly Correlations of SWE and Streamflow

SWE

The accumulation of SWE was shown to be highly dependent on the cumulative snow year, described here as November-May, precipitation and mean temperature. The accumulation of SWE is highly correlated with cumulative mean temperatures from November and into December (figure 8). This is a result of November temperature averaging marginally above freezing and thus temperatures variations determining whether precipitation falls as rain or snow. As temperatures decrease in December precipitation becomes the driving factor of snowpack accumulation. The significance of the correlations of cumulative precipitation with SWE increases from November through April as more time passes where temperatures average below zero. The significance of the cumulative mean temperature correlations increases after February as temperatures again become more marginal during the late snow year, averaging above freezing starting in March. Predicted temperature increases would lead to an increase in the significance of temperature, specifically in the early and late snow season, resulting in the constriction of the Winter Accumulation Period.

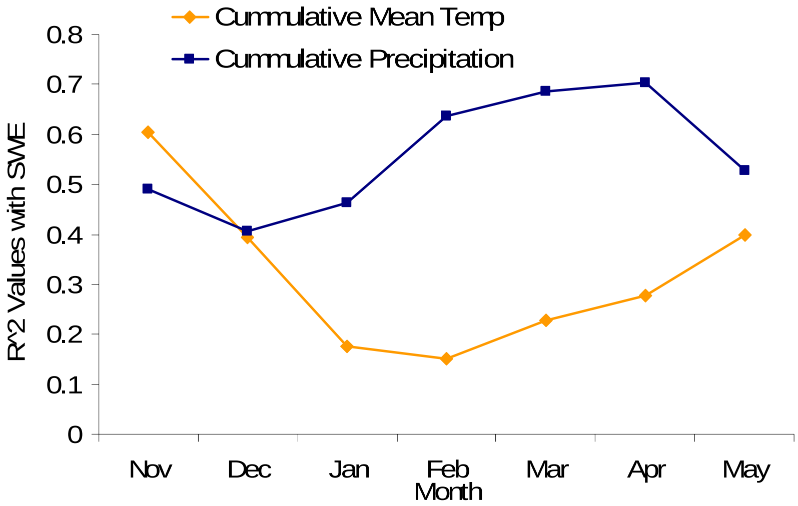

Figure 8: R^2 values for monthly SWE correlated with both cumulative mean temperature and cumulative precipitation during the snow year. The snow year is defined here as November-May.

Williamson River Streamflow

The Summer Dry Period from June-September represented the period of lowest flows (figure 7). The Summer Dry Period is therefore when water resources for agriculture and the environment are most stressed. Salmon are physically stressed by high water temperatures and overcrowding which are more likely to occur during lower flows in the Klamath River (CDFG 2004). Adult fall run Chinook salmon, which were the main species effected in the 2002 fish kill, are often found at high concentrations during their upstream migration during August and September, when water temperatures are high and streamflow is very low (CDFG 2004). The minimum mean monthly summer discharge, which usually occurs during August, is hence the period of time likely to be the most stressful for salmon and thus is considered important in this analysis.

The strength of monthly SWE correlations (R^2 values) with mean Summer Dry Period discharge and minimum yearly mean monthly discharge are shown to increase throughout the snow year (figure 9). The correlation between SWE and Summer Dry Period discharge were the strongest in May ($R^2 = 0.71$). The correlation between SWE and the Minimum Summer Discharge was the strongest in April ($R^2 = 0.61$). This demonstrates that the persistence of late season snow pack during the Spring Melting Period is very important for dry season water availability. As a result, trends toward earlier snowmelt described throughout the west greatly threaten summer water availability and salmon runs.

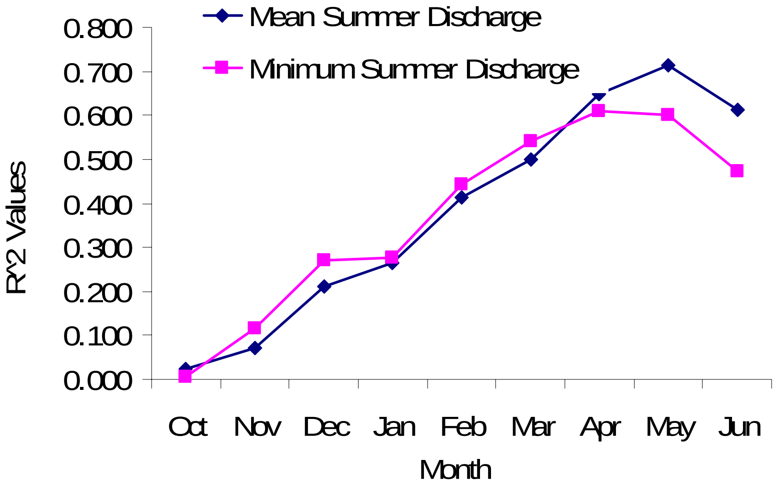

Figure 9: R^2 correlation values for mean monthly SWE values with the minimum average monthly discharge and the mean Summer Dry Period discharge, defined here as June-September.

Streamflow in the Williamson River was highly correlated with snowpack throughout the majority of the water year (figure 10). During the Spring Melting Period, streamflow was highly correlated with SWE from the previous month. This demonstrates that there was a hydrological delay of about a month from snowmelt in the mountains of the Upper Klamath Basin to streamflow at the end of the Williamson River during this time period. Precipitation did not correlate well with flows during the Spring Melting Period, further isolating snowmelt as the main contributing factor. Temperature is negatively correlated with streamflow from March-May, though the significance of these correlations is minimal. This negative correlation demonstrates that colder spring temperatures allow snowpack to endure further into the spring and continue to contribute to streamflows at a higher rate. Colder springs are also likely correlated with colder and snowier winters.

The weak correlation between streamflow and monthly temperature is largely due to the limited variability in temperature throughout the study period (figure 4), and not due to temperatures' lack of influence on streamflow. Increasing temperatures during the Spring Melting Period are the clear driving force behind snowmelt. It should also be noted that temperatures were found to be correlated with the accumulation of SWE which was shown here to correlate with streamflow (figure 8). This suggests that temperature variations had a large delayed effect in streamflow.

The magnitude of SWE was the most highly correlated factor with streamflow during the Summer Dry Period. The magnitude of correlations between discharge and April 1st SWE decreased only marginally from June-September and peaked in August ($R^2 = 0.50$), the lowest flow month. Precipitation was somewhat correlated with late summer flows, also peaking in August ($R^2 = 0.31$), which was the driest month of the year. This demonstrates that while precipitation was minimal and infrequent in August, when it did occur at a substantial magnitude it led to significant increases in late summer streamflows.

During the Fall Cooling Period, SWE remained the most highly correlated factor with streamflow variability. Weak correlations between precipitation and temperature became weaker during this period. This was likely due to decreasing temperatures as the fall progressed, causing higher percentages of precipitation to fall as snow instead of rain leading to storage of this moisture until the Spring Melting Period.

Describing the origins of streamflow during the Winter Accumulation Period becomes more complicated and pushes the limits of this analysis. This likely reflects a complicated relationship between temperature oscillations at lower elevations driving changes between rain/snow and snowmelt/accumulation. In a simplified manner, the Winter Accumulation Period can be seen as having been a transition period between streamflow being driven by the previous year's snowpack to the current year's precipitation and snow accumulation patterns.

While the intricacies of the relationships between temperature, precipitation, SWE, and streamflow may vary in different snow-dependent basins, the described correlations between these variables during the four illustrated seasonal periods are likely to apply generally to other basins throughout the west.

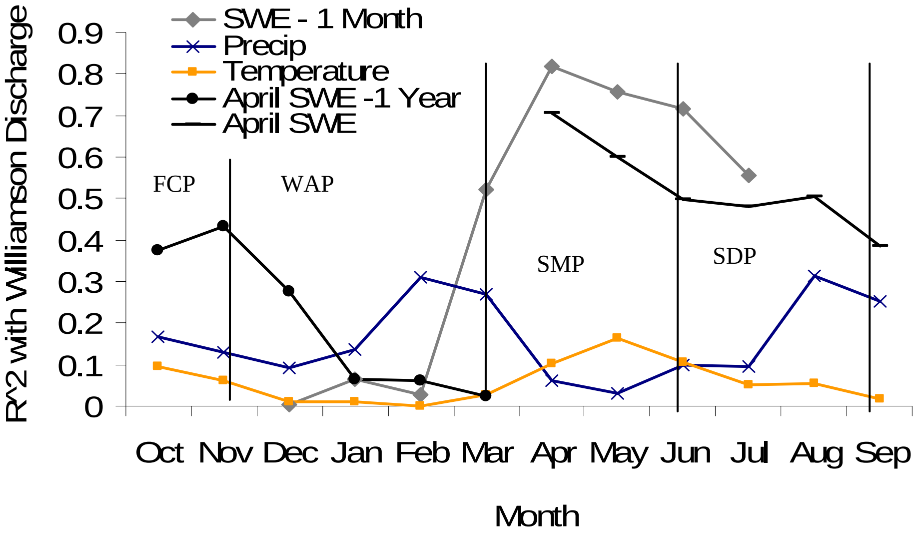

Figure 10: Williamson River discharge correlations with climate and snowpack variables including monthly precipitation, temperature, SWE from the previous month, and April SWE. The year is divided into 4 periods including, the Winter Accumulation Period (WAP), the Spring Melting Period (SPM), the Summer Dry Period (SDP), and the Fall Cooling Period (FCP).

Climatic and Snowpack Trends

Trend Significance

This section describes trends in the changing conditions of temperature, precipitation, SWE, and Williamson discharge in the Upper Klamath Basin over the 26 year study period (1982-2008, temperature 1990-2008). Due to high variability in the climate of the Klamath Basin and the relatively short time period of the study compared to other climate investigations, the correlations analyzed were found to have generally low R^2 values. Accordingly, trends with low R^2 values often represented noteworthy changes. An R^2 value of 0.1 or larger was determined in this study to be noteworthy. The relative size of the R^2 values in the subsequent graphs (figure 12-15) is demonstrated by the size of the data point in the graph (figure 11).

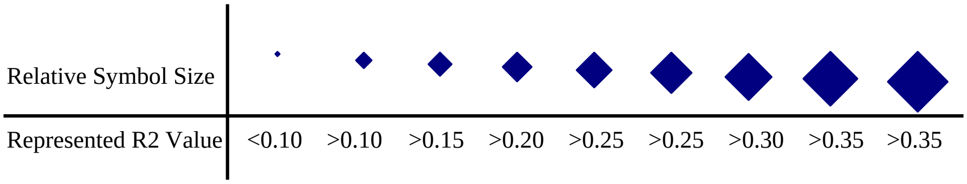

Figure 11: Key demonstrating the R^2 value represented by the relative size of symbols in the following trend graphs (figures 12-15). No trends were found with R^2 values of over 0.45.

Temperature

Analysis of temperature trends in the Upper Klamath Basin demonstrated warming during late fall and early winter, and more prominently during the summer months for the 19 year period of SNOTEL record (1990-2008) (Figure 12). The magnitude of temperature trends varied at different sites though most sites experienced similar changes. Average temperatures for all sites throughout the basin demonstrated a warming trend during all months with the exception of April and September, which experienced minor temperature decreases. Temperatures averaged throughout the entire year increased at a rate of 0.49 C˚/decade ($R^2 = 0.12$). This is a highly significant trend though it falls short of Hamlet and Lettenmair's (1999) forecast of temperature increases in the adjacent Columbia Basin of 0.72-0.84 ˚C/decade between 1999 and 2025. Warming trends peaked in December and July with magnitudes of 1.0 and 1.7 C˚/decade respectively. Summer trends were shown to have the largest magnitude and R^2 values. April and September experienced cooling trends with magnitudes of 0.42 and 0.43 C˚/decade, though the R^2 values of these trends were minimal.

Eastern sites demonstrated higher magnitude warming trends during all months with the exception of August. Average yearly temperature increased by 0.6 C˚/decade ($R^2 = 0.16$) in eastern sites and at a lesser rate of 0.38 C˚/decade ($R^2 = 0.08$) for western sites during the period of SNOTEL record. Heating trends for eastern sites peaked at 1.3 and 1.8 C˚/decade for December and July respectively. For western sites heating trends peaked at a lesser rate, 0.77 and 1.6 C˚/decade in December and July respectively. Western sites also experienced minimal declines in temperatures during the months of October, January, and March which were not experienced by eastern sites. The more substantial warming experienced in the eastern region of the Upper Klamath Basin may have been a result of the western region being more highly influenced by the Pacific Ocean, insulating it somewhat from atmospheric changes relative to the more arid east.

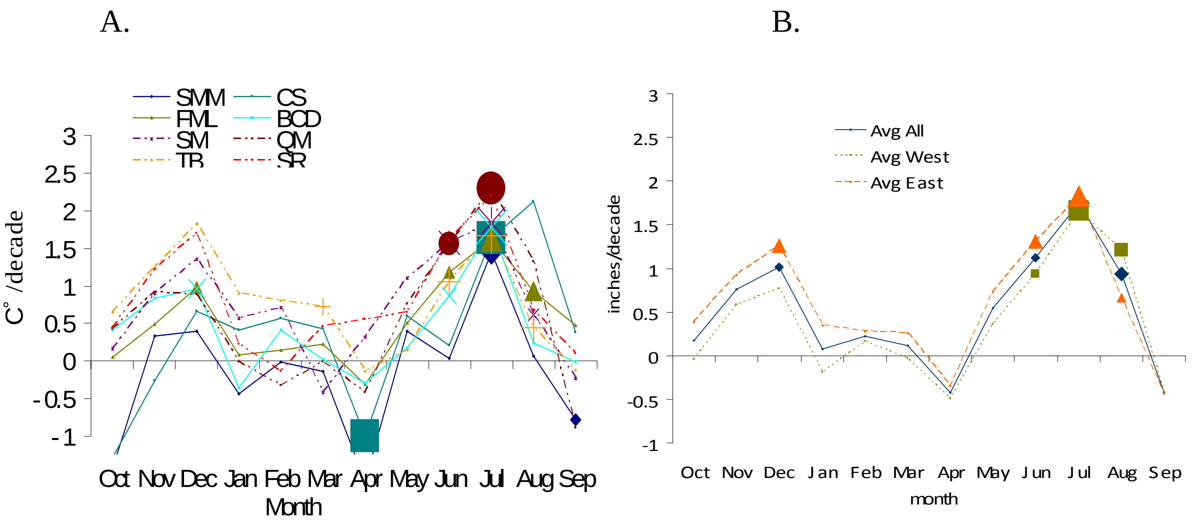

Figure 12: A. Monthly temperature trends during the 19 year period of record (1990-2008) for all study sites in the Upper Klamath Basin. B. Monthly temperature trends for the 19 year period of record averaged for all study sites, western study sites, and eastern study sites in the Upper Klamath Basin. Data point symbol size reflects the significance of the trend.

Precipitation

Monthly trends in precipitation demonstrated similar patterns for most of the study sites in the Upper Klamath Basin over the 26 year study period, with the largest exception being Quartz Mountain, which experienced larger and more highly correlated decreases in precipitation during the winter (Figure 13). Decreasing precipitation trends were found for the months of June-December and in February and March. Trends during April and May were minimal. Increasing precipitation in January averaged a rate of 0.70 inches/decade. Peak decreasing trends averaged a rate of -0.55, -0.68 and -0.71 inches/decade in February, March, and November respectively.

The most notable difference between precipitation trends of eastern and western sites was a much smaller trend of increasing precipitation during the month of January in eastern sites. It should also be noted that trends in precipitation were of similar magnitudes in eastern and western sites despite the much higher rate of precipitation in the western region of the basin. This suggests that changes in precipitation may have occurred at a higher relative rate in the drier eastern region.

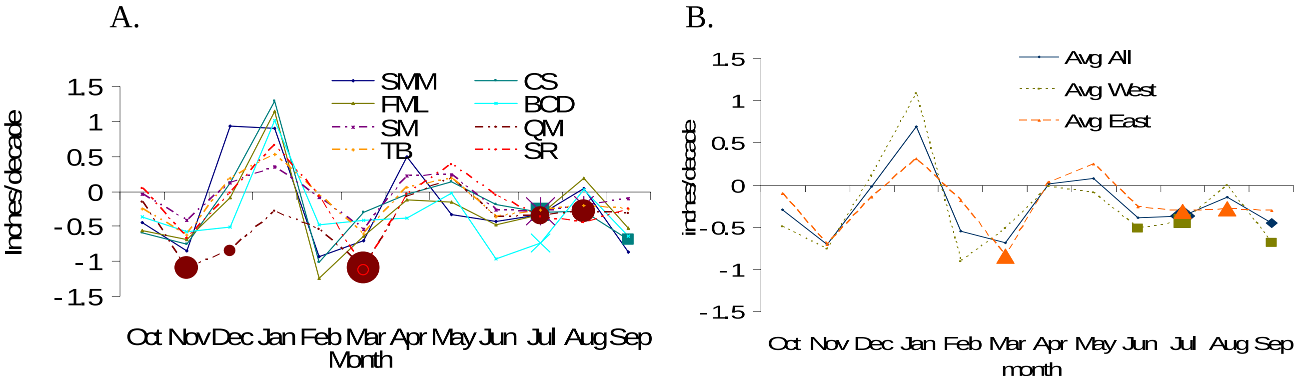

Figure 13: A. Trends in increasing or decreasing mean monthly precipitation for all study sites in the Upper Klamath Basin for the 26 year study period (1982-2008). B. Average trend of increasing or decreasing monthly mean precipitation for all study sites, western study sites, and eastern study sites in the Upper Klamath Basin for the 26 year study period (1982-2008).

SWE

Trends in the monthly mean of aggregate snowpack SWE demonstrated variability between sites though most sites had negative trends in SWE throughout the year (Figure 14). The magnitude and timing of these trends differed and two of the sites, Billy Creek Divide and Taylor Butte, had positive trends by the end of the year. The averaged trend is negative throughout the snow year. This was largely due to a drop in December SWE accumulation. Negative SWE trends decreased in magnitude following the month of December until April before increasing again in magnitude in May. This demonstrated that the accumulation of snowpack increased during February-April; the rate of snowpack melt and/or sublimation decreased, or a mixture of both. Peak SWE values changed at an average rate of 1.2 inches/decade or 5.8% per decade.

When trends in monthly mean SWE were compared between western and eastern sites, the trends were similar though eastern sites demonstrate a smaller magnitude of a negative trend in December and a slight positive trend in November. The lower trend in eastern SWE appears to reflect the lower magnitude of snowfall. While western sites have experienced a larger negative trend in peak SWE accumulation, 2.2 inches/decade compared to 0.95 inches/decade, this represented a larger percentage of percentage of total snowpack in eastern sites (9.0%/decade) compared to western sites (7.1%/decade). This demonstrates that SWE accumulation decreased at a faster relative rate in the dry eastern region than the wetter western region.

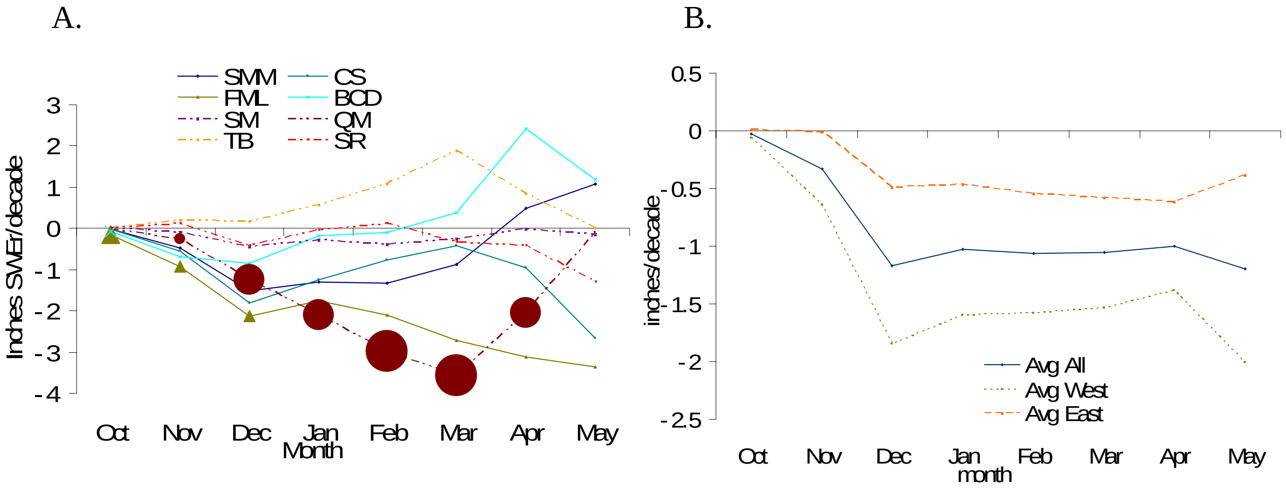

Figure 14: A. Trends in increasing or decreasing mean monthly snowpack SWE for all study sites in the Upper Klamath Basin for the 26 year study period (1982-2008). B. Average trend of increasing or decreasing monthly mean SWE for all study sites, western study sites, and eastern study sites in the Upper Klamath Basin for the 26 year study period (1982-2008).

Williamson River Discharge

The discharge of the Williamson River, as measured from the USGS stream gage station downstream of the River's confluence with the Sprague River, demonstrated a negative trend in all months with the exception of January (Figure 15). Average monthly discharge in the Williamson decreased at a peak rate of (501 ft^3/sec)/decade in March and increased at a peak rate of (69 ft^3/sec)/decade in the month of January. Trends demonstrating decreases in the discharge during late summer months and early fall months of July (101 (ft^3/sec)/decade), August (65 (ft^3/sec)/decade), September (65 (ft^3/sec)/decade), October (74 (ft^3/sec)/decade), and November (131 (ft^3/sec)/decade), demonstrated the strongest correlations ($R^2 = 0.2105, 0.2408, 0.2441, 0.2557$, and 0.2553 respectively).

Model predictions by Hamlet and Lettenmaier (1999) forecast that by 2045 the reduced snowpack and earlier melt, coupled with higher evapotranspiration in early summer, will lead to reduced runoff volumes between April and September of up to 25 % of current conditions in the Columbia River Basin, located directly to the north of the Klamath River Basin. The research for this paper found that over the last quarter century runoff in the Upper Klamath Basin decreased at a faster rate than predicted in the Columbia River Basin. Average flow in the Williamson River for the 26 year study period was found to be 1,158 ft³/sec. Flows were found to have deceased at an average rate of 17.6 (ft³/sec)/year or 176 (ft³/sec)/decade, though the correlation coefficient of this trend was low, demonstrating high yearly variability ($R^2 = 0.0982$). This represents a 15.1% decrease in yearly river discharge per decade. If 1158 ft³/sec is considered the true average flow for the mid year of the study, 1995, and a 15.1% decrease per decade of discharge was assumed to hold constant and continue into the future, average flow of the Williamson River will decrease by 56% to 511 ft³/sec by the year 2045. The correlation of this trend is low, and this analysis takes no account of changing conditions and therefore should not be considered a prediction. Nonetheless, it demonstrates that current decreases in water availability may be occurring faster than model predictions suggest in the Upper Klamath Basin.

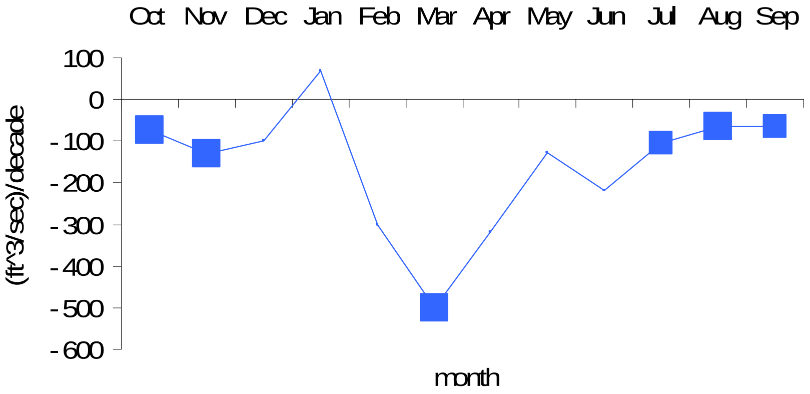

Figure 15: Trends in the monthly mean discharge of the Williamson River over the 26 year study period at the at the USGS stream gage after its confluence with the Williamson River.

Trend Summary

The Winter Accumulation Period experienced a significant increase in temperature, most notably during the month of December over the 26 year study period (figure 15). Early snow season precipitation also declined. These trends aligned with a decrease seen in December SWE accumulation which accounted for the majority decrease in SWE throughout the snow year. Temperature and precipitation were shown above to be highly correlated with the development of early snowpack (figure 8) and thus the decrease in December SWE was likely due to the above described decreases in early snow season precipitation and increases in December temperature.

A slight increase in SWE accumulation during the month of January appeared to be the result of a trend toward increasing precipitation of 0.70 inches/decade during the same month. This increase was followed by another minimal increase in the SWE accumulation during April, which was a result of a decreasing temperature trend of 0.42 C°/decade. Increases in the accumulation of SWE never completely compensate for decreases see in December.

Streamflow in January increased during the study period, likely due to an increase in precipitation during the same month and a rise in December temperatures causing increasing snowmelt at lower elevations. This trend is in accordance to other research which has described increasing winter runoff in the Cascades. In contrast to January, streamflow during the late Winter Accumulation Period and the early Spring Melting Period decreased at a rapid rate. In March this trend reached a peak magnitude of (501 ft^3/sec)/decade, or 27% of the average March discharge per decade ($R^2 = 0.21$). This decrease in late winter and early spring streamflow was surprising since other research has documented increases in early season snowmelt and discharges throughout the west (Hamlet et al 2007; Cayan et al 2001; Stewart et al 2005). The trend appeared to be a result of decreased precipitation during February and March. Precipitation was weakly correlated with streamflow during these months (figure 9). SWE demonstrated the strongest correlations with streamflow during the early Summer Melting Period and thus may also have had an effect on decreasing streamflows. The overall percentage decrease in SWE (5.8%/decade) was much smaller than that of streamflow (15.1%/decade), demonstrating a more complicated scenario.

The most significant trends in decreasing streamflow occurred during the Summer Dry Period and the Fall Cooling Period. This was most likely a result of decreased precipitation during this time period combined with decreases in late season SWE. Both precipitation and April SWE were shown to correlate with summer and fall streamflow (figure 14). Strong trends in increasing temperature also occurred during the Summer Dry Period and may have contributed to trends in streamflow decreases, though summer temperature was not shown to strongly correlate with summer streamflow. Increasing rates of evapotranspiration in the late spring and early summer may also have contributed to this effect (Hamlet et al 2007).

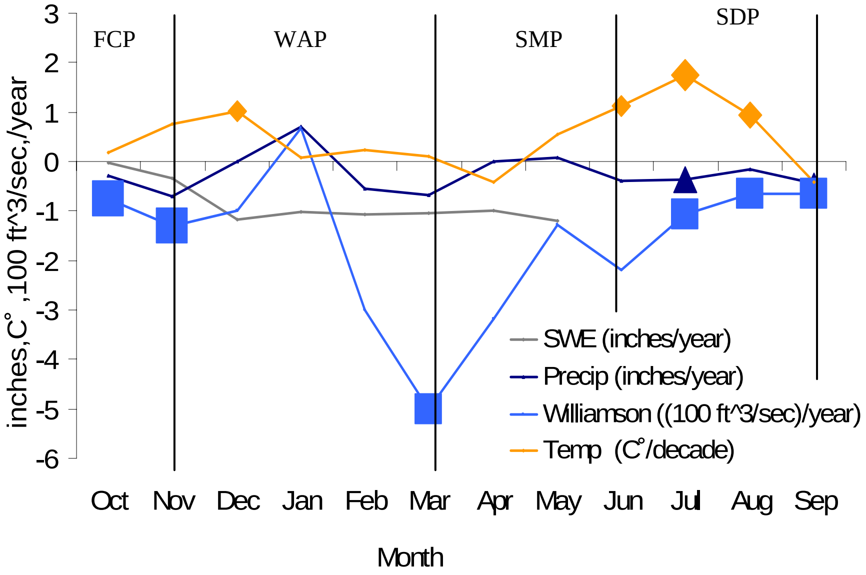

Figure 15: Monthly climatic and snowpack trends including SWE, precipitation, temperature, and Williamson River discharge, is presented on the same graph to visually demonstrate correlations. The year is divided into 4 periods including, the Winter Accumulation Period (WAP), the Spring Melting Period (SPM), the Summer Dry Period (SDP), and the Fall Cooling Period (FCP).

Conclusion

The monthly analysis technique used in this investigation proved successful in describing some of the nuances of how climate-snowpack-streamflow relations are changing throughout the water year as a result of climate change. The relationships described in the Upper Klamath Basin are likely to be similar in other snowpack dependent basins throughout the western United States and therefore generally applicable. Employing a similar technique in a large scale regional investigation would likely produce many new findings with regard to regional differences in monthly climate-snowpack-streamflow relations. This data would help predict regional variations in the effects of climate change.

The Cascade Mountains are a relatively low elevation range in the western United States with marginally cold temperatures for snow accumulation throughout the winter. As a result, the Cascades are currently being affected by climate change at a faster rate than most other mountain ranges. Other ranges will likely be similarly affected by climate change in the near future as warming continues. It would therefore be beneficial to focus attention on the details of how basins, such as the Upper Klamath Basin, in the Cascades are currently responding to climate change to better understand and prepare for future effects in other ranges.

Winter temperatures in the mountains of the Upper Klamath Basin were shown to be relatively mild and marginal, averaging -2.0 C˚ (1990-2008) at all study SNOTEL sites for the three coldest months of year, December, January, and February. SWE accumulation is highly dependent on temperature during the early and late snowseason. Accordingly, an increasing temperature trend of 1.0 C˚/decade during the month of December highly threatens the accumulation of early year snowpack. If this trend continues, December temperatures will average above freezing at the study sites by the year 2025, causing the majority of precipitation to fall as rain well into the current Winter Accumulation Period. While the statistical significance of this prediction is low due the short period of temperature record and the high variability inherent in the local climate, it is in accordance with most other climate studies which have described warming trends in the area and predict that they will continue.

Warming appears to occur at a faster rate in the drier eastern side of the Upper Klamath Basin when compared to the wetter western side. As a result, the eastern region has experienced larger proportional decreases in snowpack. This demonstrates that there is high variability in snowpack trends on the small basin scale, suggesting that there may be more local differences in the effects of atmospheric warming than have previously been recognized. This phenomenon may be a result of the wet western side of the basin being more influenced by oceanic oscillations relative to the more arid eastern region, which is more responsive to atmospheric temperature changes. Further correlations with Pacific Ocean variability, including Pacific Decadal Oscillations, El-niño Southern Oscillations, and the Northern Pacific Index, could help describe this phenomenon.

The results of this investigation reiterate the important role that snowpack in western water basins plays in determining the magnitude and timing of streamflow. In the Upper Klamath Basin, the degree of SWE accumulation was found to be the main factor in determining the magnitude of stream discharge from April through December of the following water year. With continued warming, streamflow timing will become increasingly weighted towards higher winter flows with lower spring-fall flows as snowpack storage decreases.

This analysis revealed that streamflows have decreased significantly in the Upper Klamath Basin throughout the spring, summer and fall. This trend is likely to continue or accelerate as temperatures increase, isolating snowpack accumulation to higher elevations. This was shown to already be causing higher proportions of yearly streamflow to occur during the early wet winter season at the expense of summer dry season flows. Due to the high dependence of diverse wildlife and human economic activities on the Klamath River system, the ecological and financial impacts of this change are bound to expand. Salmon runs are particularly threatened by low flows and increasing water temperatures in the Klamath Basin.

Western resource managers must account for future changes in water availability. The current water management status quo greatly threatens a variety of ecological and economic activities throughout the West. We have already begun to see the environmental and economic costs of atmospheric warming in lower elevation snowpack dependent basins such as the Klamath. These effects are bound to increase and spread as warming persists. Continued delays in preparing for eminent changes in climate-snowpack-water relations, most notably decreases in spring and summer water availability, will greatly augment the environmental and economic costs of climate change.

Literature Cited

Bartholow, John M. "Recent Water Temperature Trends in the Lower Klamath River, California." North American Journal of Fisheries Management 25 (2005): 152-62.

Bedford, D and Doaglass, A. “Changing properties in snowpack in the Great Salt Lake Basin, western United States, from a 26 year Snotel record.” The Professional Geographer 60 (2008) 374-386.

Cayan, D. R., Krammerdiene, S. A., Dettinger, M. D. , Caprio, J. M., and Peterson, D. H. “Changes in the Onset of Spring in the Western United States.” Bulletin of the American Meteorological Society (2001) 399-415**.**

Clark, M. P., M. C. Serreze, and G. J. McCabe. "Historical effects of El nino and La nina events on seasonal evolution of snowpack in the Columbia and Colorodo River Basins." Water Resources Research 37 (2001): 741-57.

Flerchinger, G. N., K. R. Cooley, and Ralston, D. R. "Groundwater Response to Snowmelt in a Mountainous Watershed." Journal of Hydrology 133 (1992): 293-311.

Flug, Marshall, and Sharon G. Cambell. "Drought allocations using the systems impact assessment model: Klamath River." Journal of Water Resources and Management (2005): 110-15.

Friederict, Peter. "A good idea - if you can get away with it; Rain water harvesting saves water, breaks the law." High Country News (HCN) 13 Oct. 2008: 9.

Goodrich, Gregory B. "Influence of the Pacific Decadal Oscillation on winter precipitation and drought during years of nuetral ENSO in the western United States." Weather and Forcasting 22 (2007): 116-12.

Hamlet, Alan F., and Dennis P. Lettenmaier. "Effects of climate change on hydrology and water resources in the Columbia River Basin." Journal of the American Water Resource Association 35 (1999): 1597-623.

Hamlet, Alan F., Philip W. Mote, Martyn P. Clark, and Dennis P. Lettenmaier. "Effects of temperature and precipitation variability on snowpack trends in the western United States." Journal of Climate 18 (2005): 4545-562.

Hamlet, Alan F., Philip W. Mote, Martyn P. Clark, and Dennis P. Lettenmaier. "Twentieth-centurty trends in runoff, evapotranspiration, and soil moisture in the western United States." Journal of Climate 20 (2007): 1468-485.

Hessl, Amy E., Don Mckenzie, and Richard Schellhaas. "Drought and Pacific Decadal Oscillation linked to fire occurance in the inland Pacific Northwest." Ecological Applications 14 (2004): 425-42.

Kalra, Ajay, Thomas C. Piechota, Rob Davies, and Glenn A. Tootle. "Changes in U.S. streamflow and western U.S. Snowpack." Journal of Hydrologic Engineering (2008): 156-63.

"Klamath River Basin Ecosystem, Endangered Species; U.S. Fish & Wildlife Service." U.S. Fish and Wildlife Service Home. USFWS. 24 Apr. 2009 <http://www.fws.gov/endangered/klamath.html>.

Knowles, Noah, Michael D. Dettinger, and Daniel R. Cayan. "Trends in snowfall versus rainfall in the western United State." Journal of Climate 15th ser. 19 (2006): 4545-559.

Leung, L. R., Yun Qian, Xindi Bian, Warren M. Washington, Jongil Han, and John O. Woods. "Mid-century ensemble regional climate change scenarios for the western United States." Climate Change 62 (2004): 75-113.

Levy, Sharon. "Turbulance in the Klamath River Basin." BioScience 53 (2003): 315-20.

Lopez-Moreno, J. I., and D. Nogues-Bravo. "A generalized additive model for the spatial distribution of snowpack in the Spanish Pyrenees." Hydrological Processes 19 (2005): 3167-176.

Marshall, H. P., H. Conway, and L. A. Rasmussen. "Snow densification during rain." Cold Regions Science and Technology 30 (1999): 35-41.

Mote, Philip W., Edward A. Parson, Alan F. Hamlet, William S. Keeton, Dennis Lettenmaier, Nathan Mantua, Edward L. Miles, David W. Peterson, David L. Peterson, Richard Slaughter, and Amy K. Snover. "Preparing for climatic change: the water, salmon, and forests of the Pacific Northwest." Climatic Change 61 (2003): 45-88.

Mote, Philip W., Alan F. Hamlet, MArtyn P. Clark, and Dennis P. Lettenmair. "Declining Mountain Snowpack in Western North America." American Meteorlogical Society 86 (2005): 39-51.

Mote, Philip W. "Climate-driven variability and trends in mountain snowpack in western North America." Journal of Climate 19 (2006): 6209-220.

Pierce, David W., Tim P. Barnett, Hugo G. Hidalgo, Tapash Das, Celine Bonfils, Benjamin D. Santer, Govindasamy Bala, Michael D. Dettinger, Daniel R. Cayan, Art Mirin, Andrew W. Wood, and Toru Nozawa. "Attribution of declining US snowpack to human effects." Journal of Climate 21 (2008): 6425-444.

Scientific Evaluation of Biological Opinions on Endangered Species and Threatened Fishes i nthe Klamath River Basin: Interim Report. Rep.No. National Acadamy of Sciences (NAS). 2002.

Serreze, Mark C., Martyn P. Clark, and Richard L. Armstrong. "Characteristics of the western United States snowpack from snowpack telemetry (SNOTEL) data." Water Resources Research 35 (1999): 2145-160.

"Snotel Data & Products." SNOTEL Data Collection Network Fact Sheet. NRCS. 16 Oct. 2008 <http://www.wcc.nrcs.usda.gov/snow/about.html>.

"Southern OR/Northern CA Coasts Coho ESU." National Marine Fisheries Service Northwest Regional Office. NMFS. 24 Apr. 2009 <http://www.nwr.noaa.gov/ESA-Salmon-Listings/Salmon-Populations/Coho/COSNC.cfm>.

Stewart, Iris T., Daniel R. Cayan, and Michael D. Dettinger. "Changes toward earlier streamflow timing across western North America." Journal of Climate 18 (2005): 1136-1155.

Trenberth, K. E. and Hurrell, J. W., "Decadal atmosphere ocean variations in the Pacific." Climate Dyn 9 (1994) 303-319.

U.S.A. USDA Forest Service. Rocky Mountain Research Station. Snowpack-runoff relationships for mid-elevation snowpacks on the workman creek watersheds of central Arizona. By Gerald J. Gottfried, Daniel G. Neary, and Peter F. Ffolliott. USDA Forest Service, 2002.

"USGS Real-Time Water Data Oregon." USGS Real-Time Water Data. United States Geological Society. 16 Oct. 2008 <http://waterdata.usgs.gov/or/nwis/rt>.