HYDROLOGIC CHANGE IN A COAST REDWOOD FOREST, CASPAR CREEK EXPERIMENTAL WATERSHEDS: IMPLICATIONS FOR SALMONID SURVIVAL

Elizabeth Keppeler[1]

Abstract—The 52-year record of streamflow from the Caspar Creek Experimental Watersheds shows a trend toward decreasing rainfall and streamflow during the fall season when coho salmon *(Oncorhynchus kisutch)* migrate upstream to spawn. Rainfall records show a slight declining trend in fall totals and a slight increasing trend in spring totals since 1962, but only November shows a significant decrease in rainfall with year. Mean daily flows between late-October and mid-December declined by about one third. "Fish-passage" flows became less frequent in November. These flows were correlated with adult coho abundance estimates. The first-of-season peak flow, needed to breach the seasonally-formed sandbar at the Caspar Creek estuary and open access to upstream spawning habitat, occurred later. Results were similar on the South Fork (logged 1967-1973) and North Fork (logged 1985-92).

INTRODUCTION

During the fall and winter of 2013-14, coho salmon (*Oncorhynchus kisutch*) were thwarted from making their annual migration from the ocean to their native streams along much of California's coast because of persistent drought and lack of streamflow. These anadromous fish are acutely dependent on fall freshets, which ordinarily breach seasonally-formed sandbars at river mouths and open access to the spawning habitat of north and central coast streams. Although numerous factors affect salmonid survival and productivity, climatic variation (including severe storms, drought, El Niño-Southern Oscillation (ENSO), and hydrologic regime shifts) can alter both marine and freshwater habitat conditions and impact salmonid abundance. The marked decline of California's coho populations triggered federal listing in 1996 and 1997 under the Endangered Species Act, as well as state listing in 2005. Maintaining and increasing the number of spawning adults is a key goal for coho recovery (CDFG 2004, NMFS 2012). Adequate flows for fall spawning, spring out-migration, and summer rearing conditions are essential to species survival along the California coast south of Punta Gorda.

Climatic change is affecting background environmental conditions and may result in altered timing, magnitudes, and frequencies of hydrologic processes. Shifts in runoff have been documented in mountainous, snowmelt-dominated watersheds of the western U.S. (Safeeq and others 2014, Peterson and others 2008, Stewart and others 2004). Null and others (2010) reported changes in centroid timing (CT) of runoff in high elevation west-slope Sierra Nevada watersheds, but found little change in runoff timing in low elevation watersheds that did not reach the Sierra Nevada Crest. In north coastal California, Madej (2011) examined long-term climate data and runoff records from 19 gauged watersheds and found no trends in annual rainfall other than a decrease in September. No change in the CT was detected in these lower elevation coastal streams. Summer low-flow (defined as 7-day minimum) decreased at 10 of the sites, including North Fork Caspar Creek. Burt and others (2014) examined the impacts of extreme climatic variability on post-logging streamflow response at the H.J. Andrews Experimental Forest, Oregon. Because interannual variability is high relative to long-term climate trends (Abatzoglou and others 2014), data sets spanning multiple decades are essential for analyzing the hydrologic response to climatic variation and forest management.

For this analysis, 52-year rainfall and streamflow records from the Caspar Creek Experimental Watersheds were used to explore trends in the seasonal distribution of precipitation and runoff with particular emphasis on the critical fall period when coho migrate to the headwaters of Caspar Creek. Understanding these trends is essential if strategies are to be developed for effectively managing water resources and mitigating potential harm to endangered salmonid populations resulting from altered hydrologic regimes.

[1]Hydrologist, USDA Forest Service, Pacific Southwest Research Station, Fort Bragg, CA 95437

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STUDY AREA

Caspar Creek is a perennial fifth order coastal stream draining 21.7 km^2 of largely forested topography in the Coast Range of northern California. At its headwaters, 10 km from the Mendocino coast, elevations attain 322 m and hillslopes can be as steep as 60° (Fig. 1). The forest, composed primarily of coast redwood (*Sequoia sempervirens*) and Douglas-fir (*Pseudotsuga menziesii*), was first logged from the 1860's to 1904 and continues to be managed for research and timber production in the modern era.

Two experimental watersheds, the 473-ha North Fork (NF) and the 424-ha South Fork (SF), occupy the Caspar Creek headwaters in the Jackson Demonstration State Forest. Within the experimental watersheds, rainfall, streamflow, and sediment yields have been measured continuously since 1962 as part of a long-term partnership between the California Department of Forestry and Fire Protection and the U.S. Forest Service. Road construction and harvests of second-growth timber were carried out in 1967, 1971-1973 (SF) and in 1985-1986, 1989-1992 (NF). Beginning in 1962, NF and SF streamflow has been

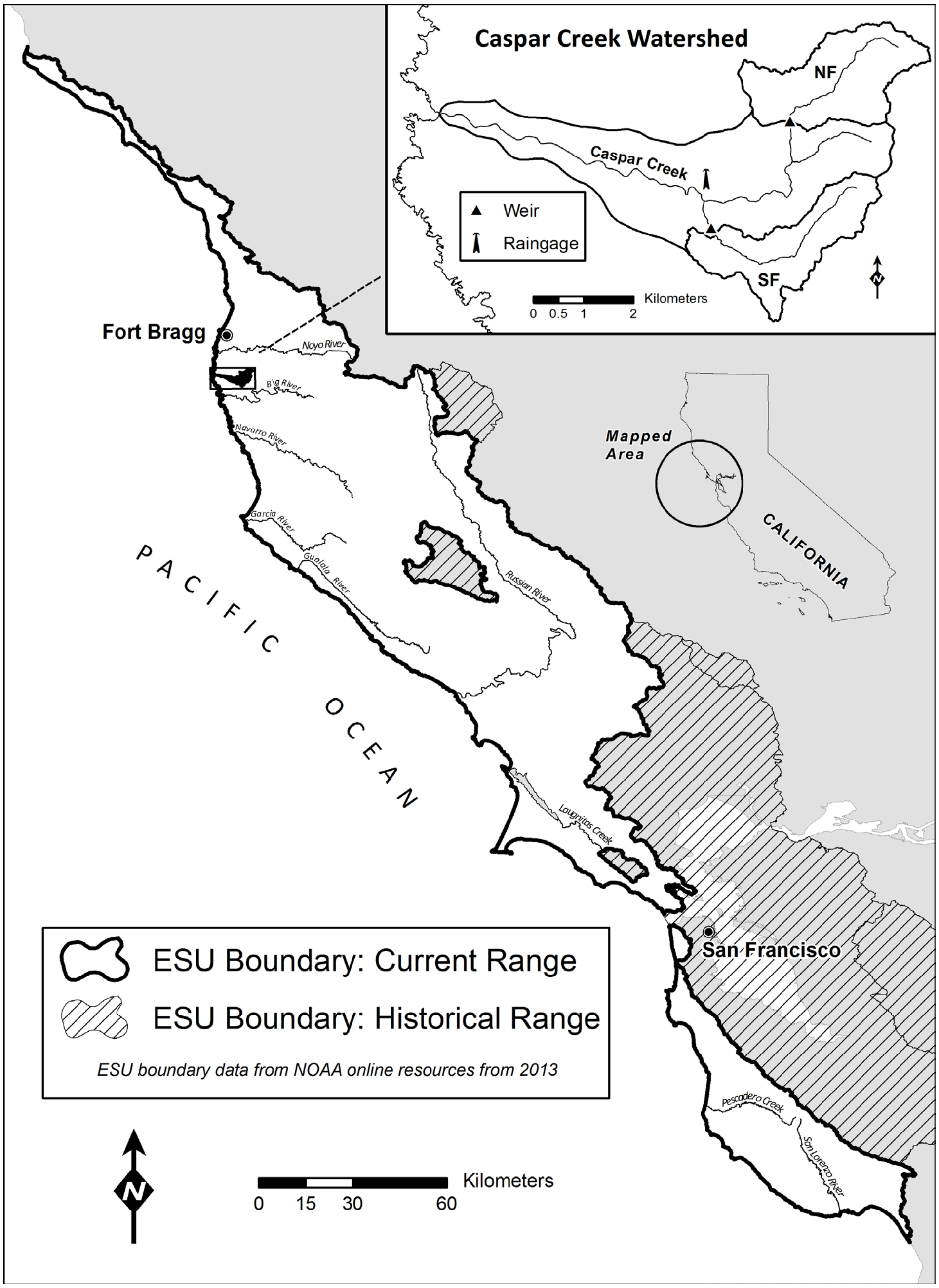

Figure 1—Central California Coast Coho Salmon Evolutionarily Significant Unit and Caspar Creek Watersheds.

measured at sharp-crested compound weirs, and recording rain gauges have been in operation at multiple elevations (Henry 1998).

Annual precipitation averaged nearly 1150 mm and varied from 305 mm to 2202 mm over the 52 year record at the S620 rain gauge (Fig. 1). Snowfall is rare and hydrologically insignificant. Roughly 95 percent of annual rainfall occurs between October and April, with the centroid of annual precipitation occurring in mid-January. Night and morning fog occurs frequently during summer months. Temperatures are mild, with mean monthly temperatures ranging between 7°C and 15°C. Stream temperatures measured above the NF weir are considered to be within the desirable range for native fish, with weekly averages peaking during August-September at 13 to 15.5°C and dropping to winter minimums of 5 to 7°C.

Caspar Creek lies within the Central California Coast Coho Salmon Evolutionarily Significant Unit (CCC-ESU) and supports anadromous coho salmon (*Oncorhynchus kisutch*) and steelhead (*Oncorhynchus mykiss*) along 14 km of channel. Coho travel upstream in mid-November through early January to spawn. Eggs hatch after five to seven weeks, and fry emerge from stream gravels during March through May or later. As the summer progresses, juveniles move to deeper pools to feed and grow. Coho typically emigrate to the ocean as yearlings from April through June, and then return to their native streams to spawn after two years in the ocean (CDFG 2004). Both spawning and out-migration are triggered by short-term increases in discharge and changes in stream temperature. Estimates of "escapement," the number of adult salmon surviving the marine environment to return to spawn, are used to monitor current abundances and predict future populations. These data demonstrate high interannual variability and declining regional abundance (Gallagher and others 2014) despite the implementation of fishing restrictions, increasingly stringent habitat protection measures, and major restoration efforts in recent decades.

METHODS

Daily precipitation totals measured near the confluence of the SF with mainstem Caspar were used in this analysis. Trends in monthly and seasonal precipitation were examined using linear regression with water year (here considered to begin on August 1st) as the independent variable. In addition, because fall rainfall accumulations must increase discharges enough to erode the sandbar that forms at the mouth of Caspar Creek before coho can return to spawn, exceedance dates for seasonal thresholds of 300 mm and 500 mm were calculated for each year. Field experience suggests that 300 mm of cumulative precipitation is necessary to diminish the soil moisture deficit sufficiently to generate a storm flow, and 500 mm is needed to wet up the soil profile to groundwater depth.

NF and SF ten-minute discharges, mean daily flow (MDF), and instantaneous peak flows were examined. Flow data for hydrologic year (HY) 1977 and early HY63 were unavailable. Several approaches were used to evaluate changes in seasonal flow over the 52-year record. Analysis was first performed graphically to visually compare streamflow patterns by decade. The mean and median MDF by date were calculated for each decade, and 30-day averages were computed to smooth the resulting flow index. This visual analysis revealed a fairly distinct divergence in the later two decades relative to the first three, and the data were consolidated accordingly into two groups: HY63-92 and HY93-12. The difference in average MDF between the two groups was then assessed to provide a measure of change in the seasonal runoff patterns. Additionally, the data were divided into two groups of equal years for T-test comparisons of mean MDF in the earlier versus later streamflow record.

Next, flow durations for fall "fish-passage flows" were tallied from 10-minute discharge records. Passage flows for adult anadromous salmonids encompass a range of 85 to 1331 L s^{-1} according to NOAA Fisheries and California Department of Fish and Wildlife design guidelines for the Caspar Creek fish ladders (Winzler & Kelly and others 2006). For each water year, instantaneous discharges within this range were tallied by month for the November to January spawning season, omitting HY63 and HY77 where the records were incomplete. These flow durations, expressed as cumulative days, were regressed against water year to evaluate trends. Caspar escapement estimates were regressed against seasonal passage flow durations to determine if coho returns were correlated to these flows. Escapement estimates were only available for 2000-2014 (Gallagher and others 2014).

Lastly, the seasonal distribution of storm peaks was explored. NF instantaneous peak flows greater than 680 L s^{-1} were tallied by date. Although the threshold is arbitrary biologically, this magnitude of peak flow (0.15-year recurrence interval at the NF weir) is used to define storms for many of the flow and sediment yield analyses performed on the Caspar Creek data set. Caspar Creek flows of this magnitude are sufficiently powerful to erode the sandbar at the mouth and typically result in elevated discharges of sufficient duration for coho migration to occur. The date of the first fall peak, the last spring peak, and the length of the storm season (expressed as the number of days between the two) were calculated for each water year. Regression analysis was used to evaluate trends.

RESULTS

Most indices of fall rainfall and streamflow showed declining trends with time, but few were statistically significant. In contrast, spring trends were weakly positive, but none were statistically significant ($p=0.10$).

Rainfall

Caspar Creek rainfall records suggest a slight declining trend in fall totals and a slight increase in spring totals since 1962, but only November shows a significant decrease (*p=0.05*) in rainfall with year. Regression results indicate that the date on which cumulative precipitation exceeded 300 mm has shifted to occur later in the season (*p=0.093*), resulting in a predicted delay of 22 days in attaining this seasonal threshold (Dec04 in 1963 versus Dec26 in 2014). A similar trend observed in the 500 mm exceedance date was also significant (*p=0.092*) (Fig. 2).

Streamflow

Streamflow response reflects not only rainfall inputs, but is also influenced by soils, topography, vegetation, and antecedent moisture conditions. The comparison of 30-day average MDF for 1963-1992 with that since 1992 shows reduced fall flows in recent decades relative to the earlier data (Fig. 3). On the NF, MDF between October 24th and December 14th averaged 86 L s^{-1} for the first three decades of record versus 59 L s^{-1} for the most recent two decades – a decline of 31 percent. The largest differences were observed in late November. When these data were divided into two sets of 24 years (HY64-88 and HY89-12), the mean of the more recent data was significantly lower (*p=0.021*) than that of the earlier time period. For the remainder of the year, average MDF was slightly higher in the two most recent decades. SF results were similar to NF, showing a decline of one third (89 versus 59 L s^{-1}) for October 24th and December 14th and slightly elevated flows during late-spring. These similarities suggest that logging was not an influential factor in this result.

Of greater biological significance is the timing and duration of fish-passage flows (85 to 1331 L s^{-1}). About 18 percent of Caspar Creek weir flows fall within this range. No significant trends in annual frequencies of these flows were detected. Passage flows for November-December showed decreasing, but statistically insignificant, trends with year. Only November passage flows exhibited a significant decreasing trend over the length of record (*p=0.013* NF, *p=0.017* SF). Mean frequency of these flows during the November-January spawning season is 27 days. Although November accounts for only 15 percent of these flows, November streamflow exceeded the minimum fish-passage flow during 20 (NF) and 18 (SF) of the 25 years between 1964 and 1989, while November flows allowed fish passage during only 12 (NF) and 10 (SF) of the last 25 years (Fig. 4).

Further evidence of a possible hydrologic regime shift was observed in the seasonal distribution of NF storm peaks greater than 680 L s^{-1}. Fall storms (October-December) have not occurred during 18 of 52 water years, with 13 stormless falls occurring since 1989. Although the declining trend was not statistically significant, stormless falls were twice as frequent during the second half of the 52-year record. Mean fall storm count for 1989-2014 was significantly lower than for 1963-1988 (*p=0.081*). The apparent increasing trend in spring storm counts was not significant. Similarly, examination of the date of the first and last storm of the season showed a significant delay in the arrival of the first storm (*p=0.013*), while the delay

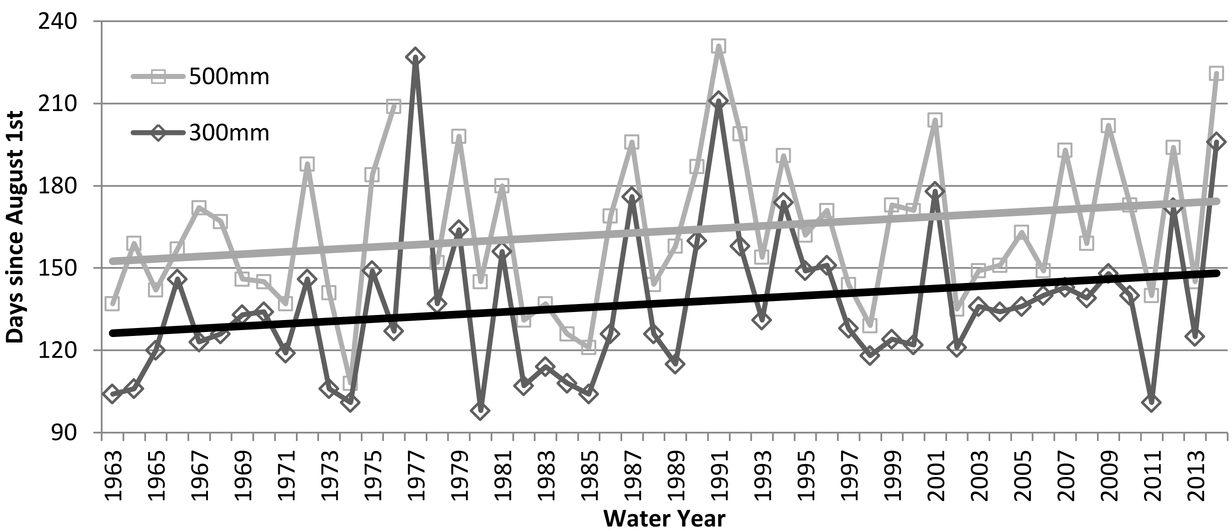

Figure 2—Seasonal rainfall threshold exceedance dates. Both 300 mm and 500 mm trends significant (p=0.093, 0.092). Median date for 300 mm is December 11th (day 133) and for 500 mm is January 5th (day 170). (Less than 500 mm precipitation recorded during HY77).

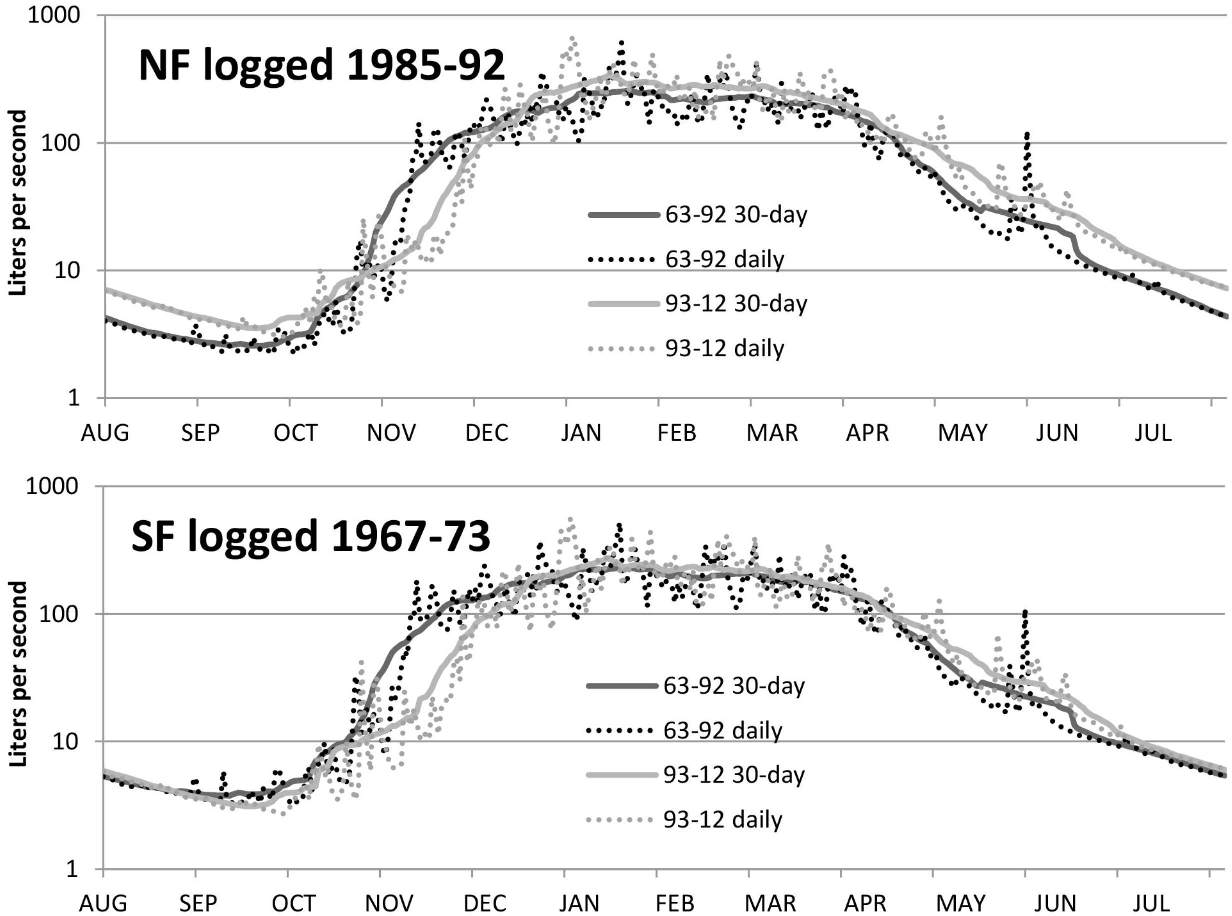

Figure 3—Mean daily flow 1963-1992 and 1993-2012, mean daily average and 30-day running average.

in arrival of the final storm of the extended winter season was not significant. This pattern might appear to indicate a shortened high flow season; however that trend was also not significant (Fig. 5).

DISCUSSION

While interannual variability is large relative to trends observed here, evidence of a possible hydrologic regime shift is present for both NF and SF, suggesting that timber harvest history was not a strong influence on the overall trend. Fall season rainfall, fish-passage flows, and first-of-season storm peaks all show signs of delayed occurrence across the span of the 52-year Caspar Creek data set. The consequence of this delay is less evident. Botkin and others (1994) reported that minimum flows in November, were strongly correlated with the abundance of spring Chinook salmon adults returning to spawn on Oregon's Rogue River three years later. Others have correlated fall flows with coho abundance in the nearby Noyo River, noting a weak positive relationship between juvenile abundance and mean monthly flows for the time period between the preceding November 15th and January 15th (Stillwater Sciences, 2008). When Caspar coho escapement estimates for 2000-2014 were regressed against fish-passage flows for November through January, the relationship was significant (*p= 0.028*) only when an exceptionally high 2005 abundance estimate was omitted. This anomaly may be explained by the exceptional 2002 return and subsequent favorable ocean conditions during the two-year marine life stage of this three-year cohort. Gallagher and others (2012) found that marine survival was more important to total survival than freshwater survival. Brood cycle population dynamics, ocean conditions, and freshwater (particularly winter) habitat qualities all influence coho abundance. Nonetheless, the prospect of delayed onset of fall rains and reduced fall flows into the future suggests that coho spawning migrations may be increasingly impeded.

Recent reports detail the formation and persistence of a stagnant weather pattern along the west coast during the past three winters, including 2014-15. A persistent region of atmospheric high pressure nicknamed the "ridiculously resistant ridge" has been blamed for the recent California drought, leading to forecasts of continued abnormally dry weather. Temperatures are warming faster in the Arctic than anywhere else in the world. This arctic amplification

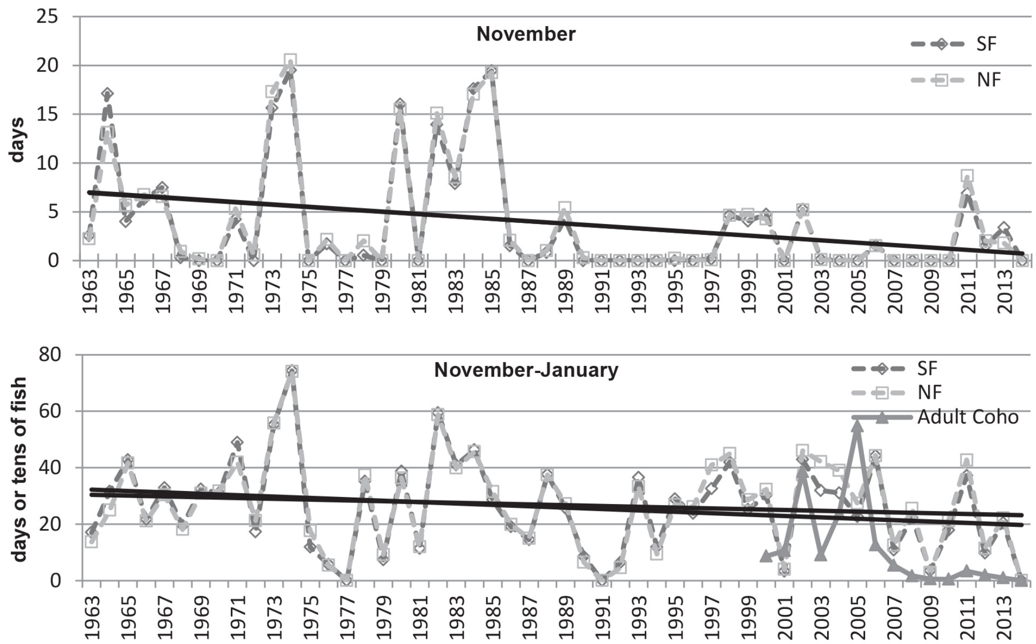

Figure 4—Duration of fish-passage flows (85 to 1331 L s^{-1}) expressed as days within flow range for North Fork and South Fork and adult coho abundance estimate expressed as tens of fish. Only November trends significant (p=0.017 SF, 0.013 NF).

has spurred climate scientists to investigate the pathways by which arctic changes can influence mid-latitude weather and extreme events (Cohen and others 2014). Possible linkages include changes in storm paths and altered jet stream characteristics, both of which are key drivers of mid-latitude weather along the west coast. Temporal concentration (intensification) of precipitation brought about by altered atmospheric circulation is cause for concern not only because extreme events trigger high winter flows that negatively impact over-winter salmonid survival (Gallagher and others 2012), but also because the lack of sufficient fall rainfall may leave adult coho unable to enter their natal streams to spawn. Greater understanding of these linkages and their effects on coastal streams and anadromous fisheries is needed.

FUTURE DIRECTIONS

Caspar Creek is one of several long-term research sites providing data for the understanding forest ecosystems and management impacts. Because of the length of record, consistency of measurements, and use of established controls, data from research watersheds are invaluable for addressing complex issues of climate and hydrology. Reid and Lewis (2011) developed an antecedent precipitation model to calculate expected flows from the NF in the absence of logging to model the effects of altered rainfall and harvest in the Caspar Creek watersheds. This approach may prove useful to further explore the consequences of hydrologic regime shift in this watershed. In addition, it may be useful to examine potential water quality and stream temperature effects brought about by reduced or delayed fall flows using an interdisciplinary approach. Fisheries biologists can provide additional insights into the effects of a compressed or delayed migration season on coho recovery and restoration planning. Other kinds of climatic change (for example, temperature increases and altered fog frequency) will also influence streamflow and freshwater habitat conditions.

The observational study discussed herein does not demonstrate a causal link between global climatic trends and patterns observed at Caspar Creek. Cause and effect may be established only through further monitoring and climate modelling advances. Meanwhile, it remains critically important to pursue applied and process-based research that enhances our understanding of ecosystem function and resilience. Forest management and timber harvest activities will continue across the forested landscapes of the western U.S. Maintaining natural processes while utilizing forest products, managing to reduce wildfire severity, and ensuring adequate water supplies will require strategic thinking, interdisciplinary research, and adaptive management.

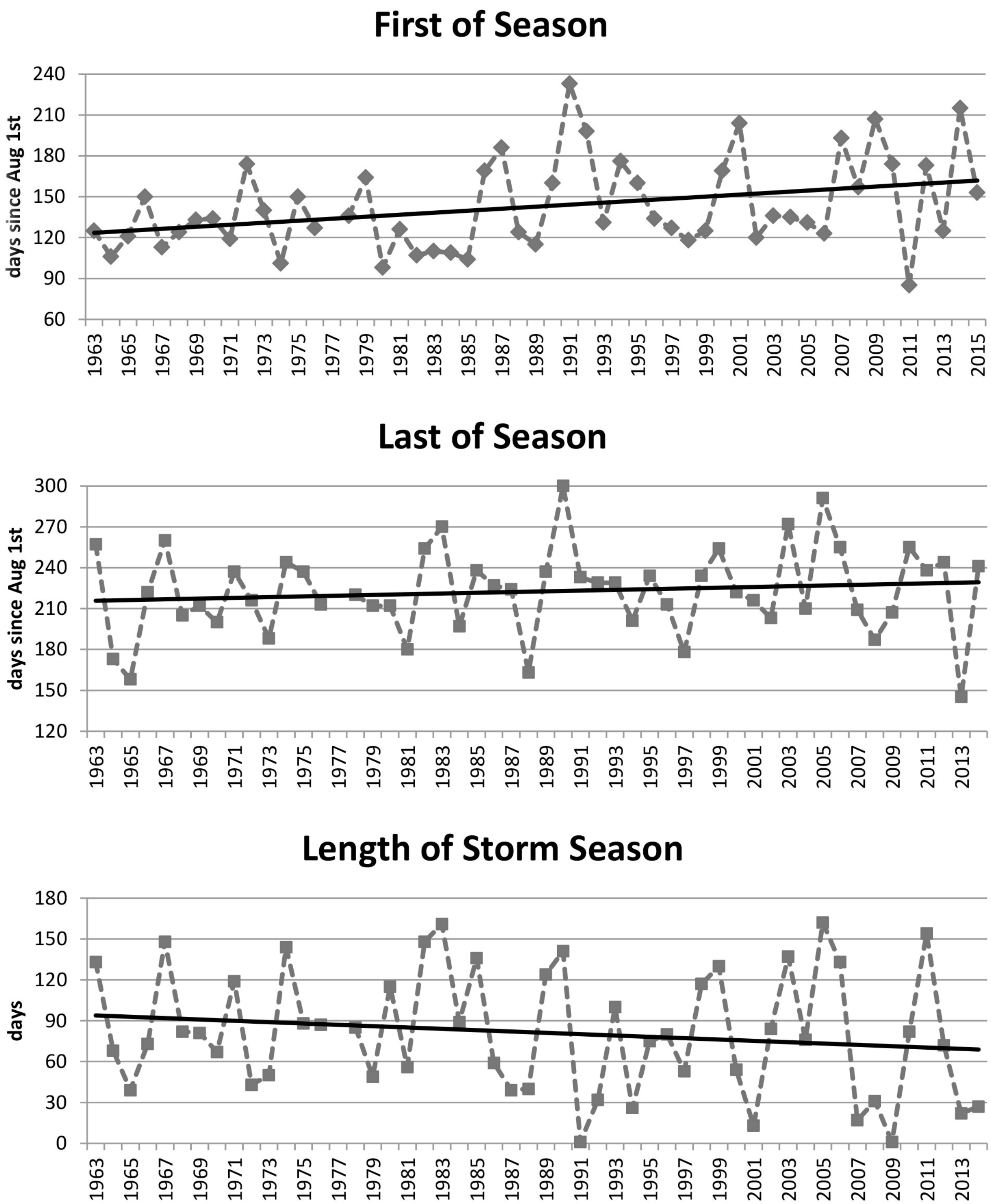

Figure 5—First fall peak flow, last spring peak flow, and length of storm season by hydrologic year. Only first-of-season trend significant *(p=0.013)*.

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