Analysis of Trends in Climate, Streamflow, and Stream Temperature in North Coastal California

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Abstract

As part of a broader project analyzing trends in climate, streamflow, vegetation, salmon, and ocean conditions in northern California national park units, we compiled average monthly air temperature and precipitation data from 73 climate stations, streamflow data from 21 river gaging stations, and limited stream temperature data from salmon-bearing rivers in north coastal California. Many climate stations show a statistically significant increase in both average maximum and average minimum air temperature in early fall and midwinter during the last century. Concurrently, average September precipitation has decreased. In many coastal rivers, summer low flow has decreased and summer stream temperatures have increased, which affects summer rearing habitat for salmonids. Nevertheless, because vegetative cover has also changed during this time period, we cannot ascribe streamflow changes to climate change without first assessing water budgets. Although shifts in the timing of the centroid of runoff have been documented in snowmelt-dominated watersheds in the western United States, this was not the case in lower elevation coastal rivers analyzed in this study.

Keywords: streamflow, climate, temperature, precipitation, northern California

Introduction

In north coastal California, daily, seasonal, and decadal variations in abiotic drivers (e.g., precipitation, fog, streamflow, and temperatures of air, ocean, and streams) regulate many ecological processes, including the distribution of vegetation and wildlife and frequency of disturbances from fires, floods, landslides, and biotic pests. However, the exact nature of the linkages between abiotic drivers and the direct and indirect effect of these drivers on species of concern and their habitat are not well understood.

In addition to needing greater understanding of the basic linkages between abiotic and biotic ecosystem elements, the question of climate change is of increasing concern to land managers. They need to understand how climate change has already affected natural resources and whether other changes may be looming. Without this understanding it is increasingly difficult to judge the effects of management efforts (e.g., stream restoration), evaluate the resilience of existing habitats, or plan future management actions.

Complicating a manager's ability to respond to climate change effects is the common assumption of stationarity—the idea that natural systems fluctuate within an unchanging envelope of variability (Milly et al. 2008). The stationarity assumption is being compromised by major shifts in background environmental conditions. These major shifts may be changing the timing, magnitude, and intensity of critical abiotic elements in this region. In addition, the common assumption that restoration planning can use historical reference conditions as a goal may not be valid if extrinsic drivers display nonstationarity. Consequently, the understanding of trends, variability, and interactions among abiotic drivers is needed to inform restoration strategies, prioritize restoration sites, and implement scenario planning to foster strategic thinking about future conditions and management alternatives.

The National Park Service (NPS), through its Inventory and Monitoring Program, has monitored many abiotic drivers and has conducted several biological surveys. A major concern is the decline of salmon populations in coastal California park streams. In central and northern California, several salmon and steelhead populations have been in decline for years and many are federally listed as threatened or endangered. In 1997, coho salmon *(Oncorhynchus kisutch)* were federally listed as

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Table 1. Gaging stations used in analysis.

Station name	Agency	County	Period of record (water years)	Drainage area (km^2)
Bull Creek near Weott	USGS	Humboldt	1961–2010	72.8
Eel River at Scotia[1]	USGS	Humboldt	1911–2010	8,062.7
Elder Creek near Branscomb	USGS	Mendocino	1968–2009	16.8
Lacks Creek	USGS/NPS	Humboldt	1981–2010	43.8
Little Lost Man Creek near Orick	USGS/NPS	Humboldt	1975–2010	9.0
Little River near Trinidad	USGS	Humboldt	1956–2010	104.9
Mad River near Arcata[2]	USGS	Humboldt	1951–2010	1,256.2
Mattole River near Petrolia	USGS	Humboldt	1951–2010	634.6
North Fork Caspar Creek	USFS[3]	Humboldt	1964–2003	4.7
Olema Creek	NPS	Marin	1998–2010	40.0
Panther Creek near Orick	USGS/NPS	Humboldt	1980–2010	15.7
Prairie Creek above Brown Creek	NPS	Humboldt	1990–2008	10.6
Prairie Creek above May Creek	NPS	Humboldt	1991–2008	32.6
Redwood Creek at O'Kane	USGS	Humboldt	1973–2010	175.3
Redwood Creek at Orick	USGS	Humboldt	1954–2010	720.0
Redwood Creek at GOGA	NPS	Marin	1998–2010	18.1
San Geronimo Creek	MMWD[4]	Marin	1980–2009	24.3
Smith River at Crescent City	USGS	Del Norte	1932–2010	1,590.3
South Fork Caspar Creek	USFS	Humboldt	1964–2003	4.2
South Fork Eel River at Leggett	USGS	Mendocino	1966-2009	642.3
Van Duzen River at Bridgeville	USGS	Humboldt	1951–2008	575.0

[1]Flow regulated by Lake Pillsbury and diversion through Potter Valley power plant at drainage area of 883 km^2
[2]Flow regulated by Ruth Reservoir at drainage area of 313 km^2
[3]U.S. Forest Service Pacific Southwest Research Station
[4]Marin Municipal Water District

threatened in the Southern Oregon/Northern California Evolutionary Significant Unit, including Redwood National Park, and as endangered in the Central California Coast.

Factors affecting coho populations include elevated stream temperatures (Welsh et al. 2001), water withdrawals, dams, loss of spawning and rearing habitat, and extreme hydrologic events (Carlisle et al. 2009). Millions of dollars are being spent in coastal parks on watershed and stream restoration projects. As the NPS plans salmon restoration activities in coastal watersheds, it is critical to understand the abiotic factors and interactions that affect salmonid populations (MacCall and Wainwright 2003, Battin et al. 2007).

The objectives of this study are to identify trends in climate drivers and hydrologic regimes that may be having local and regional effects on salmon populations in north coastal California streams, with an emphasis on four national park units, Redwood National Park (REDW), Golden Gate National Recreation Area (GOGA), Point Reyes National Seashore (PORE), and Muir Woods National Monument (MUWO).

Study Area

The climate and streamflow monitoring stations used in this study are located along the north coast of California from the San Francisco Bay area (37°N) to the Oregon border (42°N). The region has a Mediterranean climate with mild, rainy winters and generally cool, dry summers. Coastal fog is a common occurrence in the summer months. Mean daily minimum temperatures in January range from 0.4 to 7°C and mean daily maxima in July range from 14 to 30°C. Mean annual precipitation is moderate to high, generally more than 100 cm, but as low as 70 cm in the southern part of the region and more than 200 cm in the northern mountains. The region is dominated by the Coast Range, which separates the coastal area from the hotter Central Valley farther inland.

Table 2. P-values for trends in air temperature and precipitation at four national park units.

	REDW[1]	GOGA	PORE	MUWO
Average annual precipitation	0.512	0.906	0.772	0.451
Average annual temperature				
Maximum	0.269	**<0.001**[2]	**<0.001**	**<0.001**
Mean	0.810	**<0.001**	**<0.001**	**<0.001**
Minimum	0.414	**<0.001**	**<0.001**	**<0.001**
Average monthly temperature (maximum)				
January	**0.095**	**<0.001**	**0.002**	**<0.001**
February	0.700	**0.007**	**0.019**	**0.002**
March	0.692	**0.010**	**0.034**	**0.004**
April	**0.027**	0.152	0.123	**0.079**
May	0.960	**0.002**	**0.002**	**0.002**
June	0.257	0.923	0.626	0.993
July	0.854	0.538	0.406	0.287
August	0.214	**<0.001**	**<0.001**	**0.080**
September	0.578	**0.005**	**0.006**	**0.032**
October	0.243	**0.001**	**0.003**	**0.003**
November	**0.022**	0.443	0.762	0.414
December	0.843	**0.042**	0.187	**0.016**

[1]REDW, Redwood National Park; GOGA, Golden Gate National Recreation Area; PORE, Point Reyes National Seashore; MUWO, Muir Woods National Monument
[2]Values in bold show statistically significant increasing trends at the 90% level.

Methods

The PRISM (Parameter-elevation Regressions on Independent Slopes Model) Climate group at Oregon State University provided air temperature and precipitation data. The PRISM group incorporated climate data from specific points (climate stations) and extrapolated those data to describe air temperature and rainfall in selected national park units (http://prismmap.nacse.org/klamath). Long-term trends in maximum, mean, and minimum temperatures and precipitation were examined through linear regression. Streamflow records were obtained for gaging stations operated by the U.S. Geological Survey (USGS), REDW, GOGA, and PORE. Most datasets consisted of mean daily streamflow and peak flows. Streamflow records from 67 gaging stations located along north coastal California were examined. Many of the rivers have altered hydrologic regimes because of impoundments or diversions, and others had short (<10 years) periods of record or large data gaps. Nineteen stations with adequate records and unimpaired flow regimes were retained for more in-depth analysis, as well as two rivers with dams in their headwaters (Table 1). Drainage areas ranged from 4.2 to 8,063 km^2. Some stations also included stream temperature records from in situ temperature data loggers with sampling intervals that ranged from 15 to 60 minutes. Daily maximum, mean, and minimum water temperatures were calculated from these datasets. Following the approach of Gu et al. (1999), we used air temperature and streamflow as independent variables with stream temperature as the dependent variable in a multiple regression analysis. Because salmon migration, spawning, and rearing success are dependent on magnitude and timing of flow, we analyzed the 7-day low flow and the dates of percentiles of cumulative runoff volumes. Cumulative runoff curves were constructed by accumulating mean daily discharge for each water year (WY; October 1–September 30). Various percentiles of runoff could then be calculated. For example, the timing of the center of mass of flow (the date by which 50 percent of the runoff has occurred, or CT) was calculated for each station.

Results

The PRISM results cover the period of 1895 to 2007. Figure 1 shows an example of PRISM output for GOGA. Park units in the San Francisco Bay area (GOGA, MUWO, and PORE) showed a statistically significant increase in annual maximum, mean, and

minimum air temperatures of about 1°C during the last 100 years (Table 2). On a monthly basis, significant increases were detected in January, February, March, May, August, September, and October. Farther north, in REDW, air temperature did not increase significantly. No trend in annual precipitation was detected, but all park units showed statistically significant decrease (at the 90-percent level) in September rainfall during the last century, a decrease of 10 mm in the south and 30 mm in the north.

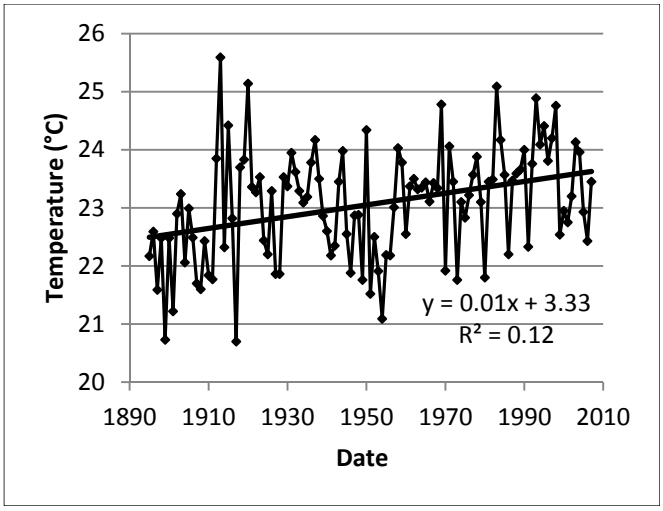

Figure 1. Average daily maximum air temperature for August calculated for GOGA by PRISM.

Timing of runoff was assessed at 21 gaging stations. CT ranged from December to April but commonly occurred in early February (Figure 2). CT was fairly synchronous among watersheds from the San Francisco Bay area north to the Oregon border (Figure 2). Since the late 1940s, CT has shifted towards earlier in the water year in many mountainous rivers of western North America (Stewart et al. 2004). In contrast to trends documented in those mountainous watersheds with large snowmelt components, none of the lower elevation coastal streams in this study showed a significant trend at the 0.10 level of earlier or later runoff based on CT values.

Another streamflow characteristic of concern for fish is summer low flow. The 7-day low flow decreased at 10 of the stations over the period of record. Redwood Creek at Orick is an example of this decrease (Figure 3). Other stations that exhibited a statistically significant decrease at the 90-percent level were Mattole, Van Duzen, and South Fork Eel rivers and Lacks, Olema, North Fork Caspar, Elder, Redwood at O'Kane, and San Geronimo creeks. Statistical significance does not automatically imply a biological significance. Nevertheless, lower flows are associated with less pool volume for summer rearing of salmon or dry river reaches. In addition, solar radiation can heat a smaller mass of water faster than greater water volumes, leading to elevated stream temperatures.

Coho salmon are very sensitive to elevated stream temperatures, and stream temperature tends to peak in late July or early August. The maximum weekly average temperature (MWAT) in the southern streams (Olema Creek in PORE and Redwood Creek in GOGA) ranged from 14.2°C in WY2010 to 19.1°C in WY2006, based on measurements from WY2003 to 2010. MWATs in Prairie Creek above May Creek in REDW were somewhat cooler, ranging from 13.1°C to 15.8°C from WY1997 to 2010. In contrast, MWATs in Redwood Creek at O'Kane were consistently above 16.8°C, the temperature restriction for coho assessed by Welsh et al. (2001). At this station MWATs ranged from 19.8°C to 23.9°C, based on measurements from WY1997 to 2010.

The relationship between air temperature (as a surrogate for solar radiation, which directly affects water temperature) and stream temperature was assessed for Redwood Creek near the O'Kane gaging station, where several years of air and stream temperature data were available (Sparkman, California Department of Fish and Game, personal commun.). For the months of June, July, and August, daily maximum stream temperature was strongly correlated with both daily maximum air temperature and mean daily streamflow at the gaging station ($n = 400$, $r^2 = 81$ percent, p-value <0.0001).

Discussion

Gaging station records have different periods of record, so a full statistical comparison among the stations could not be done. Consequently, the trends noted in this paper should be considered a starting point for more in-depth analyses in specific watersheds. For example, a decrease in summer low flows can be problematic for salmonid habitat, but it cannot simply be ascribed to climate change without assessing other possible influences. Minor diversions for domestic or agricultural use are not quantified, and some illegal water diversions may also influence summer low flows. Sedimentation in river beds may cause surface runoff to go subsurface, decreasing the amount of available surface flow in the summer. Regrowth of trees in formerly logged watersheds can increase the evapotranspiration demand and decrease summer low flow (Reid and Lewis, in press). A decrease in summer

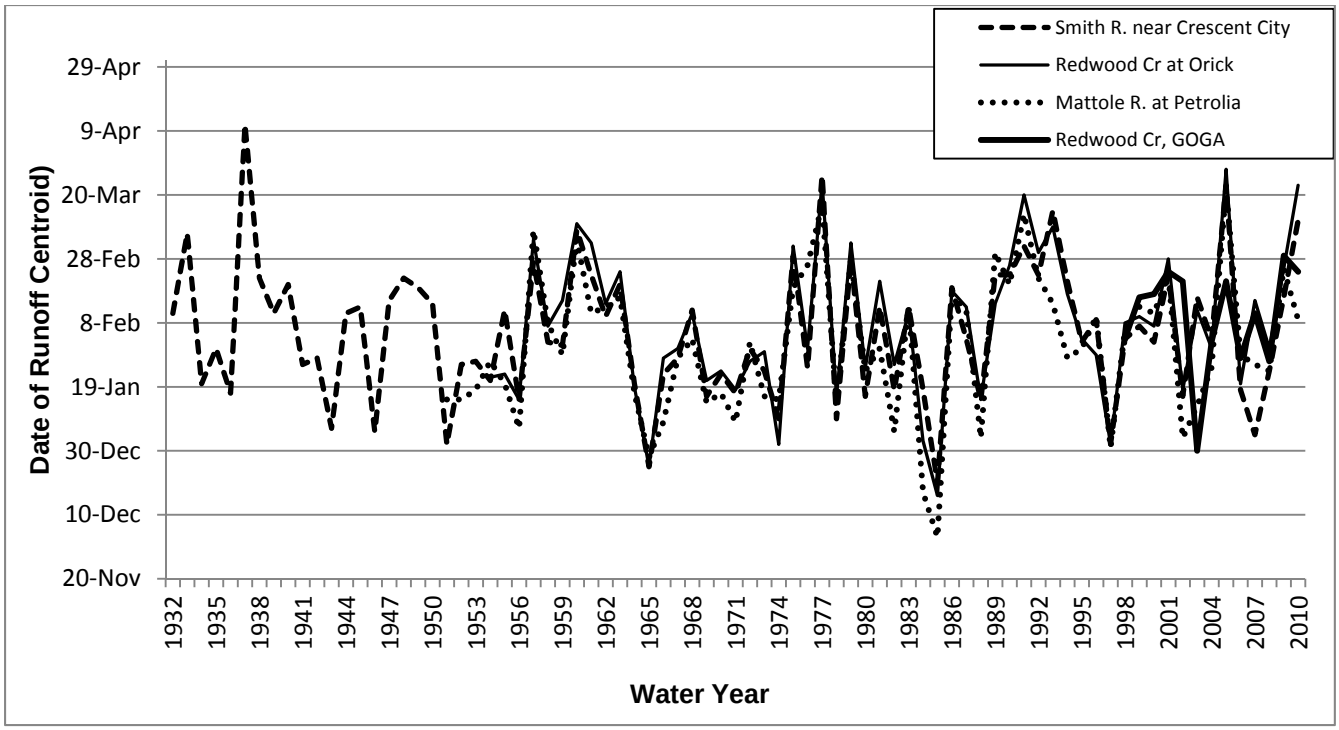

Figure 2. Timing of runoff centroid for four rivers, spanning the coastal region from the Oregon border (Smith River near Crescent City) to the San Francisco Bay area (Redwood Creek at GOGA).

fog can also increase the evapotranspiration demand. Preliminary analysis of fog frequency at two sites within the study area suggests a decrease in fog in recent years (Johnstone and Dawson 2010). Nevertheless, the full spatial and temporal distribution of fog is not known, and further analysis based on remote sensing data of coastal fog is in progress. Future research will also assess changes in vegetative cover during the period of streamflow records.

Interannual variations in climate are linked to the El Niño/Southern Oscillation phenomenon (ENSO). Annual flood peaks in coastal rivers at the north end of our study area are significantly smaller during El Niño conditions; south of 35°N (south of San Francisco) they are significantly larger during an El Niño phase (Andrews and others 2004). Future research will examine trends in other aspects of runoff (in CT, low flows, etc.) with respect to ENSO events.
Elevated stream temperatures in Redwood Creek at O'Kane in 2006 and 2009 led to fish kills (Sparkman, California Department of Fish and Game, personal commun.), and stream temperatures at many locations along Redwood Creek in REDW are above the temperatures preferred by coho (Welsh et al. 2001, Madej et al. 2006). Increases in stream temperature can be exacerbated by the diversion of streamflow for agriculture or other uses, or if reduced rainfall decreases summer baseflow. Consequently, if air temperature increases or summer flow decreases, we can expect warmer summer stream temperatures, adding to stressful conditions for summer-rearing salmonids and for unique runs of adult summer steelhead holding in pools throughout the summer.

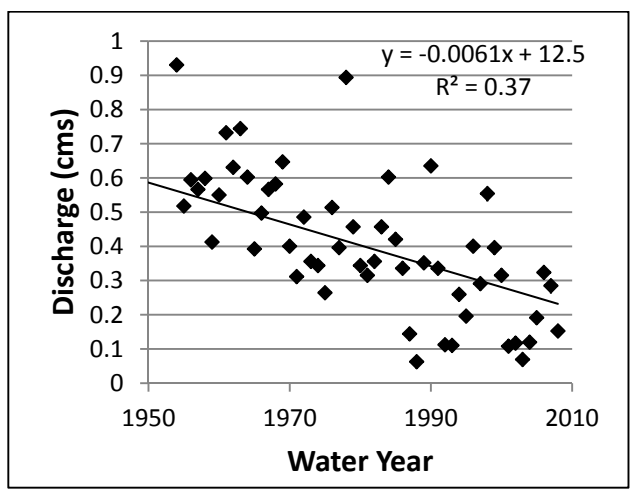

Figure 3. Seven-day minimum flow at Redwood Creek at Orick, USGS Station #11482500.

Conclusions

The PRISM climate data for four national park units in north coastal California show increases in annual maximum, mean, and minimum air temperatures of

about 1°C during the last century for the three sites near San Francisco Bay, but not at Redwood National Park farther north. September rainfall has decreased at all four units over this same time period. Summer low flow has decreased in several streams in this region, although the causes for the decrease are not fully understood. Daily maximum stream temperature is correlated with daily maximum air temperature and mean daily streamflow. Maximum weekly average stream temperatures in some of the streams exceeded the value preferred by coho salmon (<16.8°C).

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