Title

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Abstract

The Navarro River, which flows through southern Mendocino County, is home to two species of salmonids (steelhead and coho salmon), both of which have experienced a significant decline in recent years and are listed as Threatened and Endangered under the Federal Endangered Species Act (respectively). Maintaining surface water flows in the Navarro Watershed is critical to the continued survival of these species. Our study tests for a statistically significant decline in stream flow in the Navarro River between 1951 and 2010. In addition, we compared our observed stream flow trends with precipitation data to understand if stream flow declines can be explained by similar declines in precipitation or if anthropogenic causes may have had an impact. To visualize stream flow trends, we ran regression analyses with year as the independent variable and three flow metrics as the dependent variables: annual 7-day low flow, mean annual flow for January and mean annual flow for September. We compared trends in January and September flows to look for a more significant decline in September, when water demand for agriculture is higher. Our results indicate a statistically significant decline in 7-day low flows over the last 60 years, a pattern that was not explained by changes in precipitation over the same time period. Our results also indicated a more significant decline in September, when water demand for agriculture would be high, compared to January, when water demand would be low. Although other possible causes for this decline are possible, our results suggest that human water use is having a significant impact on stream flow in the Navarro River Watershed.

Introduction

The hydrologic regime of the Navarro River, like most rain-dominated systems in coastal Northern California, is driven by the Mediterranean climate. Long-term precipitation patterns from the nearby Ukiah Valley indicate the typical pattern of wet winters and dry summers

(Figure 1). When rain falls on a watershed, a portion of it is intercepted by vegetation, some infiltrates into the soil and much of it flows overland and into increasingly larger channels (Gordon et al. 1992, Dunne and Leopold 1978). The amount of run-off is determined by the interactions between rainfall intensity, vegetation, topography and geology (Kennard et al. 2009). Within days of the cessation of precipitation, surface runoff subsides. The stream flow that continues is derived almost exclusively from groundwater sources; this is termed base-flow (Mount 1995).

Groundwater is a general term used to describe rainwater that has infiltrated into soil and/or fractured geologic material. The groundwater table refers to the upper extent of sub-surface water that occurs when these porous, semi-permeable substrates become fully saturated with water. Where stream channels dissect the landscape, they often intersect the groundwater table, which leads to discharge of groundwater into the stream via direct seepage or from nearby springs (Mount 1995). The slow metering of these flow sources is responsible for sustained flows during dry periods and, most importantly, during the summer. Subsequent rainfall (and infiltration) replenishes these sub-surface reserves in a process known as groundwater recharge.

The quantity and timing of riverine surface flows are critical to the ecological integrity of river systems (Poff et al. 1997, Kiernan et al. in press). Anthropogenic alteration of stream flow has been linked to degradation of aquatic ecosystem function, and the degree of effect is often proportional to the magnitude of flow alteration (Poff and Zimmerman 2010). More specifically, research in the nearby Russian River indicates that direct water withdrawals from small streams can substantially reduce flows during the dry season. This same research showed a strong positive relationship between stream flows and juvenile salmon over-summer survival that was in turn correlated with the amount of upstream vineyard development (Grantham et al. in press).

Richter et al. (1996) proposed a method for quantitatively evaluating human-induced hydrologic changes to river systems. The 32 parameters they defined are designed to target ecologically significant features of surface and groundwater regimes influencing aquatic ecosystems. The whole suite of metrics characterizes the intra-annual variation in water conditions. However, for our study, we are concerned primarily with the metrics that characterize summer base flows. Measures of extreme minimum flows used by the authors include the 1-day, 3-day, 7-day, 30-day and 90-day average flows for their lowest respective periods. Sanderson et al. (2011) apparently modified these summer flow metrics by standardizing each with the division of mean annual flow. Whatever the case, there appears to be a variety of methods and metrics that can be applied for this purpose and no single parameter has emerged as the universal measure of ecologically relevant low summer flow.

Study Site

The Navarro River flows through the Pacific Coast Mountain Range in southern Mendocino County in Northern California and drains into the Pacific Ocean near the town of Albion, about 15 miles south of the town of Mendocino. The river drains a total area of approximately 315 square miles, which includes the Anderson Valley (Navarro Watershed Working Group n.d.).

The Navarro River Watershed is home to approximately 4,500 people, mostly clustered around the towns of Boonville and Philo (Navarro Watershed Working Group n.d.). The watershed area consists of approximately 70% forested land, 25% rangeland, and 5% agriculture land (North Coast Regional Water Quality Control Board 2005). In the past, land use in the Navarro River Watershed consisted mostly of timber production, livestock grazing and various types of agriculture including prune plums, apples and hops. While livestock grazing and orchards are still present, recent land use has focused primarily on commercial timber production and viticulture (Navarro Watershed Working Group n.d.). Vineyards are most prevalent in the Anderson Valley portion of the watershed (North Coast Regional Water Quality Control Board 2005). In addition, about 15% of the watershed is currently managed for timber production (National Marine Fisheries Service 2010).

Salmonids in the Navarro River Watershed

The Navarro River Watershed supports two species of anadromous fish: Steelhead trout (*Onchorynkis mykiss)* and Coho salmon (*Onchoynkis kitsuch)*. Coho salmon are listed as Endangered under the Federal Endangered Species Act (ESA) and steelhead are listed as Threatened. Over the last 50 years, the populations of both species have declined in the Navarro River (MacElwee n.d.). Coho salmon have experienced a more significant decline in population size than steelhead trout and recently, have been found in only one sub-basin of the Navarro Watershed (MacElwee n.d.). Despite their decline, steelhead are still found in all sub-basins in the Navarro Watershed (MacElwee n.d., Entrix, Inc. 1998).

Many factors have contributed to the decline of these two species in the Navarro River, including habitat loss. This includes a lack of available pool habitats, lack of large wood in the stream, increases in water temperatures and increases in fine sediment (MacElwee n.d., Entrix, Inc. 1998). Stream flow alteration is an addition factor that has likely contributed to this decline.

Goals and Objectives

The specific goals of our study are to test the hypothesis that the volume of river flows in the Navarro River has diminished over the last 60 years. We also evaluate rainfall records for similar temporal trends. The purpose in this is to determine if changes in stream flow can be explained by changes in the amount, variation or timing of rainfall over the last 60 years. We will also compare flows in different seasons over time as a means of testing for hydromodification in the summer months. In addition, we will discuss the implications of decreased stream flows for salmonids present in the Navarro River Watershed.

Methods

Stream flow data was obtained from the USGS Surface-Water Data for the Nation. The specific gage used was USGS gage number 11468000, located about 5 miles upstream of the mouth of the Navarro River. The gage accounts for a total drainage area of 303 square miles, approximately 96% of the total watershed area. Daily stream flow data from this gage is available beginning in October 1950 (water year 1951) to water year 2010. However, all data from the 2006 water year is absent from USGS records online and was therefore not included in our analyses.

We summarized mean daily flow data into three separate metrics to facilitate our analysis: the annual 7-day low flow; mean annual flow for January, and; mean annual flow for September. The 7-day low flow was the lowest average flow measured over 7 consecutive days for any given year. Monthly flows for January and September were calculated by averaging the daily average over the month.

Trends in stream flow data were analyzed by plotting multiple regressions using year as the independent variable and stream flow parameters as the dependent variables. We did this for all three data summaries: 7-day low flow, average September flow and average January flow.

These simple linear regressions allowed us to visualize temporal trends in the data, but the highly variable results made it difficult to determine whether the observed trends were significant. We therefore conducted additional analyses to test our hypothesis that summer flows were diminishing over time. We first used a Welch t-test to compare the observed regression slope of the 7-day low flow with the null hypothesis that these flows had a zero slope (i.e. that there was no decline in slope over time).

Next, we wanted to see if trends in summer flows could be explained by precipitation patterns, so we plotted total annual precipitation for the same time period (1951-2010). Precipitation data used in this analysis was obtained online from the Desert Research Institute's Western Climate Center database. Data located closer to the stream gage would have been ideal, but no local record of rainfall with the same period of record was available. The nearest suitable location was located in the town of Ukiah, approximately 25 miles inland from the stream gage. Rainfall data from this gage dates back to 1898.

We plotted both the total annual rainfall in inches and total spring precipitation (March, April and May) for each year. Spring precipitation was analyzed separately based on the idea that spring precipitation may have the most significant impact on summer base-flows. We looked for a downward trend in total annual precipitation and spring precipitation by plotting a regression with year as the independent variable and rainfall as the dependent variable.

Finally, to see if patterns in summer flows were independent of hydrologic patterns in other times of year, we performed a hydromodification test where we compared stream flow trends between January (when the stream was likely less impacted by water withdrawals) to September (when diversion demand was likely greatest). We tested the resulting regression slope for each metric using the same Welch t-test to detect a significant difference between the observed slope of the regression and the null hypothesis of zero slope.

T-tests assume sample data is normally distributed, so we tested all metrics described above for normality using quantile/quantile plots and the Shapiro-Wilk normality test. We used an F-test to compare variances in the data but, since the Welch t-test corrects for unequal variance, we tested only January flows, which had unequal variance, and assumed similar results for the rest of the data.

Results

Our analysis of the 7-day low flow data from the Navarro River showed a clear declining trend over time, with more consistent declines in recent years (Figure 2). While the linear regression was weak (r^2=0.34) because of the high degree of annual variation, it had a negative slope (-0.013) which, when compared to a zero slope, was highly significant (p-value=2.2×10^{-16}).

We plotted similar time series of precipitation data (Figures 3 and 4) and again found weak values for the regression constants due to high variability. However, the slopes of both the annual and spring precipitation were nearly flat, indicating no temporal pattern of declining precipitation that might explain the flow observations.

The results of our hydromodification test also showed significant results. We predicted that January would have no declining trend based on the assumed lack of impairment at that time of year. However, the very weak regression (r^2 =0.016) showed a slight negative slope, which was nearly significant (p-value=0.053) (Figure 5). The September flows showed a pronounced decline as expected and the change in slope from zero was highly significant ($r^{2=}$0.22, p-value=2.2×10^{-16}) (Figure 6).

Annual precipitation was the only metric to pass the Shapiro-Wilk normality test (p-value=0.14). However, the residuals of September flow regressed against water year approximated normality. The other metrics were skewed right.

Discussion

Our analysis provides statistically significant evidence for reductions in summer base-flows in the Navarro River from 1951 to 2010. Several previous investigators have conducted similar analyses of flow data in the Navarro River based on concerns that degradation of summer flows may be a factor in the decline of salmonids in the watershed (KRISweb 2011). In 1991, the Mendocino County Water Agency plotted annual runoff against the minimum daily flow from 1951 to 1988 using the same USGS gage data (Jackson 1991). No statistical analysis was conducted, but a decreased ratio looks possible from the graph (Figure 7). Jackson also noted that similar trends were not evident in nearby watersheds.

In 2009, the Berkeley Water Center compared the recession rates of summer period flows at the Navarro River gage for three time periods: 1951-1955, 1975-1979 and 2004-2008 (Figure 8). Hunt (2009) used a recession constant, a recession rate function normalized by flow magnitude. No statistical comparison of groups was conducted, but he concluded that the recession constant increased over time, suggesting an increase in water extraction (Hunt 2009).

Tom Holley, Hydrologist for the National Marine Fisheries Service (NMFS) also examined flow records at the Navarro gage in 2010. He plotted quantile regressions of mean annual flows. He found a downward trend in the lower 25% quantile (Figure 9). However, the p-value for the slope was not significant at a critical value of 0.01 (p-value of 0.13). Similar analyses of mean and 75% quantiles showed no downward trend (Holley 2010).

Zac Robinson, owner of Husch Vineyards and representative of the Mendocino Winegrape and Wine Commission, conducted the most thorough analysis of Navarro River flow at the USGS gage to date (Robinson 2011). He compared weekly median flows from 1951-1979 with those from 1980-2009 (Figure 10). He noted the apparent decline in flow and went on to estimate consumptive water use in the basin and plot it against median flows (Figure 11). He concluded the decline in flows was not likely due to water withdrawals because most vineyard water use was withdrawn from storage ponds (Robinson 2011).

While it is clear that summer base flows are diminishing, the factors contributing to this decline are less well understood. We explored the possibility that rainfall patterns might explain the declines in stream flow. However, our findings show no significant decline in precipitation between 1951 and 2010. We assumed that antecedent rainfall was the principal driver of summer base-flows, so we also examined spring precipitation, which also showed no pattern of change. We conclude from this cursory assessment that changes in annual rainfall are not a likely explanation for changes in flow. However, additional analyses of precipitation could be conducted. For example, Robinson (2011) suggests that a shift to later fall rains may have some explanatory power.

Our hypothesis is that human use of water in the summer months is driving the decline in summer flow. However, we do not have access to consumptive water use data. We responded to this dilemma in part by looking for evidence that summer flows were out of synchrony with the rest of the hydrologic cycle. The assumption being that an observed de-coupling of flow patterns between seasons would suggest an anthropogenic effect. When we compared average stream flows in January (when water diversions would likely be minimal) to those in September (when diversion demand would be high), we found a highly significant downward trend in September only. We view this as evidence of an anthropogenically derived alteration of summer base flows. Assuming no change in precipitation patterns, the run-off relationship between January and September should remain constant as long as the landscape features influencing hydrology, such as infiltration rate, remain constant. Unfortunately for our analysis, a multitude of landscape changes have likely occurred along with changes in consumptive water uses since 1951. The subsequent changes to landscape hydrology confound our ability to isolate the effects of water withdrawals.

Landscape changes in the Navarro River include the age and species composition of forests, conversion of rangeland to agriculture and increases in roads and rural development. The long history of ranching and timber harvest in the basin has increased sediment loads, leading to aggraded stream channels. Roads, which are appurtenant to these other activities, are responsible for an estimated 80% of the anthropogenic sediment yield in the basin (USEPA 2000). Robinson (2011) suggests regrowth of forests within the watershed may be changing hydrology, leading to increased soil water demand and increased interception of precipitation.

Without historical information on the volume, rate, location, source and timing of water diversions in the basin, it is difficult to establish any relationship between water use and cumulative degradation of flows. Aside from limiting analytical inferences, this represents an impediment to accurately tracking and protecting public trust resources when explicit diversion data is unavailable.

Declining summer base-flows decrease available habitat for salmonids and reduce water quality. This can manifest as complete desiccation of tributary channels, as observed in portions of the Navarro River Watershed (KRISweb 2011). Or, available habitat may become disconnected due to lowered flows. Habitats may also become uninhabitable due to increases in water temperatures or dissolved oxygen (KRISweb 2011, Bisson 2008). In addition, increases in water temperatures can impact species lower on the food chain and change the food sources available to salmonids (Bisson 2008).

These hydraulic habitat attributes are fundamental to aquatic species' existence and are directly related to flow (Annear et al. 2004). This axiom is as true for salmonids as it is for any other aquatic organism. Sanderson et al. (2011) categorized flow alterations based on their effect on trout. Their least suitable category, which was judged to be inadequate to support trout, was defined as summer low flows less than 10% of the mean annual flow (mean September flow was one of the flow metrics tested in that study). The Navarro River data consistently exceeded this 10% ratio from 1951 through 1961, yet only exceeded it in 2 of 10 years from 2000 through 2010. In addition, Grantham et al. (in press) showed a strong positive relationship between stream flows and juvenile salmon over-summer survival in tributaries of the Russian River (California).

This study evaluates flow conditions at a single point near the outlet of the watershed, which has provided an excellent opportunity to assess the cumulative effects of all activities in the basin on summer flows. While these data are a good indicator for flow conditions, they cannot discern spatial variation within the watershed. For example, we have no way of knowing whether flow changes are occurring in the tributaries, where most of the spawning and rearing of salmonids takes place, or if it is limited to the mainstem. Agriculture is focused mainly within the southern portion of the basin, potentially affecting the mainstem, Indian, Anderson and Ranceria creeks as well as other small tributaries throughout the basin. Comparing flow conditions in these areas with flows in tributaries with different land uses may help identify causative factors.

Though we have not directly examined those attributes here, the fact remains that salmonid populations in the Navarro River have suffered significant declines and that watershed conditions have likely been a significant factor in that decline. Furthermore, the Environmental Protection Agency (USEPA 2000) concluded that water diversions supporting viticulture in the Navarro River has reduced summer base-flows, disconnected aquatic habitat and increased water temperatures. Given the available information, water use appears to have played a role in the degradation of flows and those reductions are likely affecting the aquatic ecosystem in negative ways.

Conclusions and Recommendations

Water defines fish habitat more than any other factor (Chamberlin et al. 1991), and the growing water demand across the world is increasing the stress on river ecosystems, causing concern for both biodiversity and people (Sanderson et al. 2011). Given the importance of both consumptive water uses and the mandate to protect and recover threatened and endangered salmonids, we suggest action, informed by more specific research, be taken to restore flows in the basin. Concurrent with preliminary actions, the role of water diversions on the decrease in summer flows should be investigated more thoroughly to identify causative factors with greater spatial and seasonal specificity.

We recommend that historical information on agricultural development and consumptive water use data be obtained and compared with trends in the entire hydrologic cycle at the sub-basin scale. Existing and future water use, whether from direct diversion, storage or from groundwater should be inventoried and monitored to provide an accurate accounting of effects, if any, on public trust resources.

Acknowledgements

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Figures

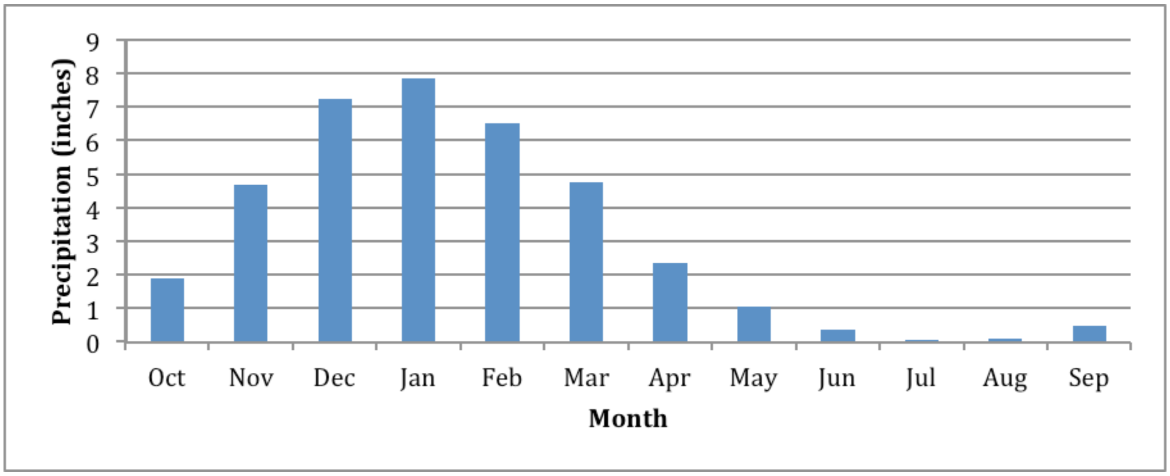

Figure 1. Monthly average rainfall in Ukiah, California from 1898- 2010 indicating the typical Mediterranean rainfall pattern of wet winters and dry summers (DRI Western Region Climate Center 2010).

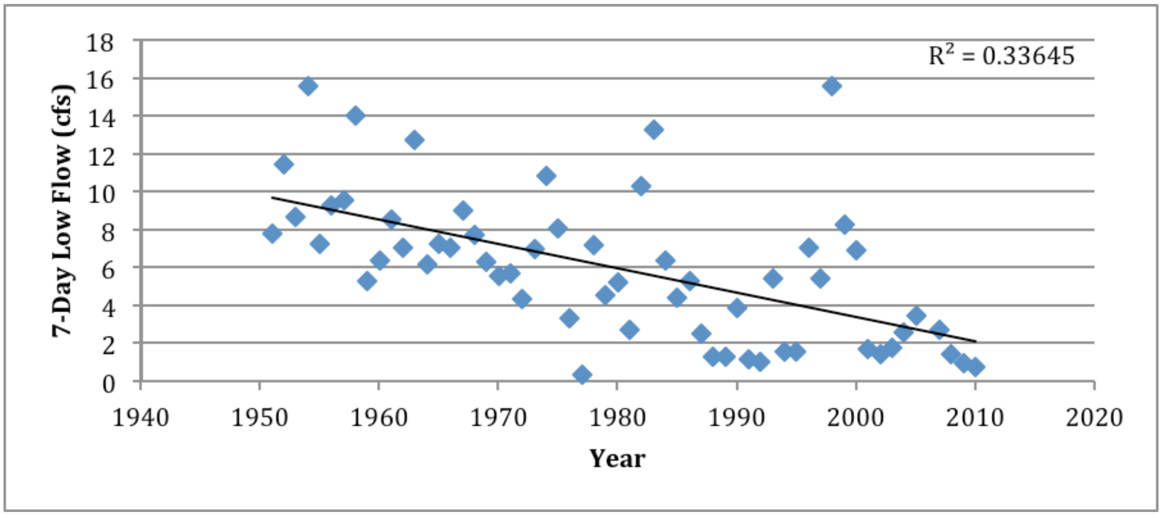

Figure 2. The lowest seven day flow period for each year at the Navarro River USGS gage (#11468000) from 1951 through 2010. These data indicate a decline in summer base flows over time.

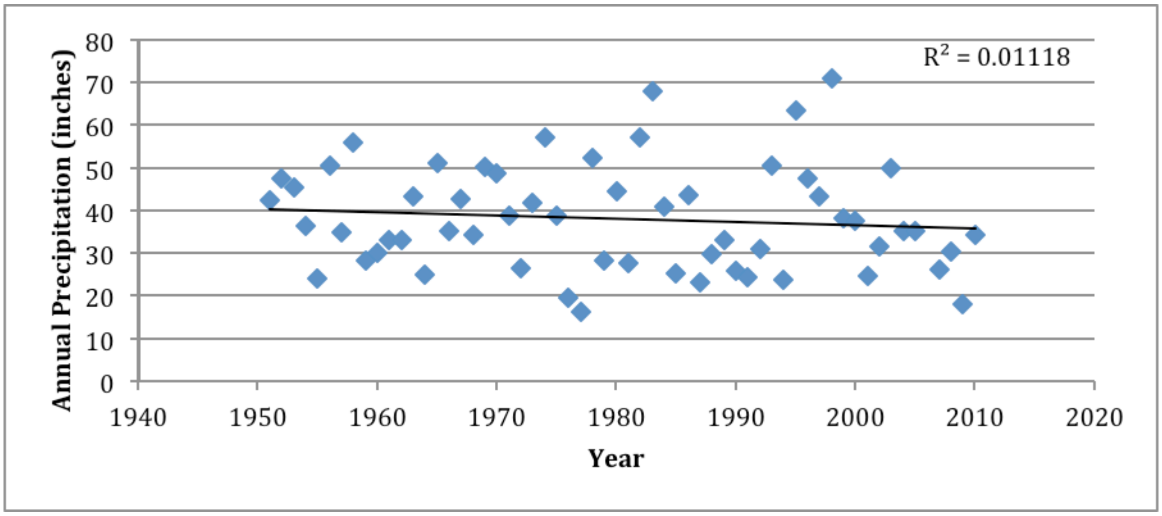

Figure 3. Annual precipitation (in inches) for the Ukiah Valley, approximately 25 miles east of the Navarro River gage site, from 1951 through 2010. These data indicate no change in precipitation patterns to explain the decline in summer base flows.

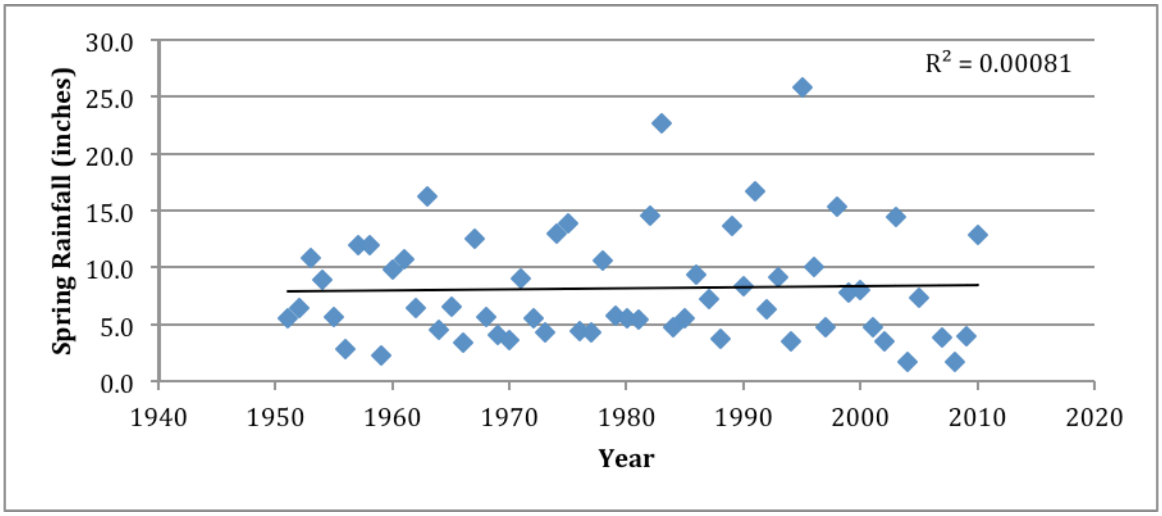

Figure 4. Variable but consistent rainfall patterns are also apparent for spring rainfall patterns (March, April and May totals for Ukiah Valley). These may be more influential on summer baseflow conditions than total annual precipitation.

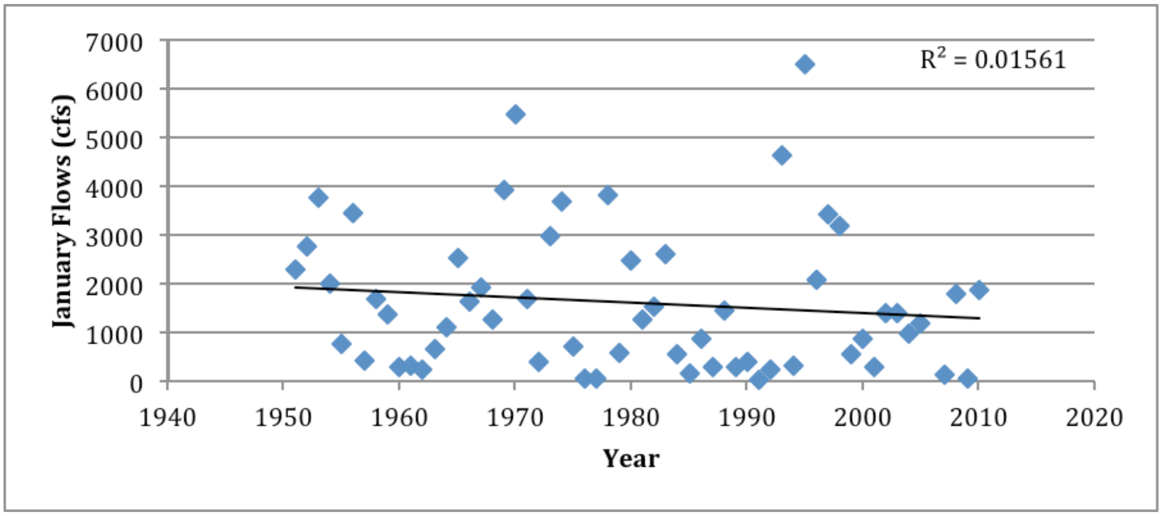

Figure 5. Total flows for the month of January in each year showing a minor (insignificant) downward trend over time. Our assumption is that water diversion is less likely to occur during this time of year, so the trend in January would be different than that of September when flows are low and water demand is high.

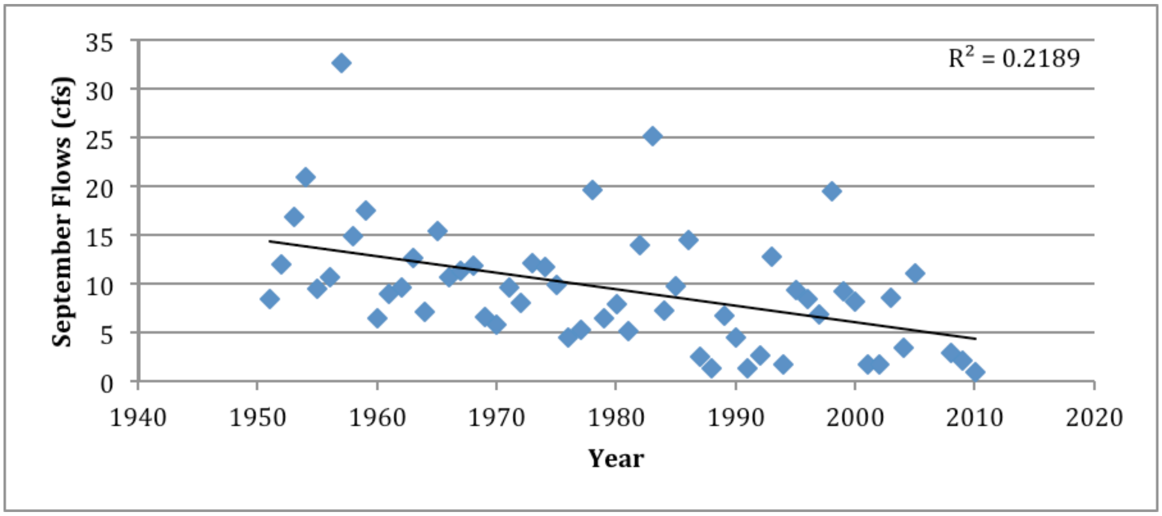

Figure 6. September flows showing a highly significant decline in discharge over time (p-value = $2.2\text{x}10^{-16}$). Note difference in y-axis scale compared to Figure 5.

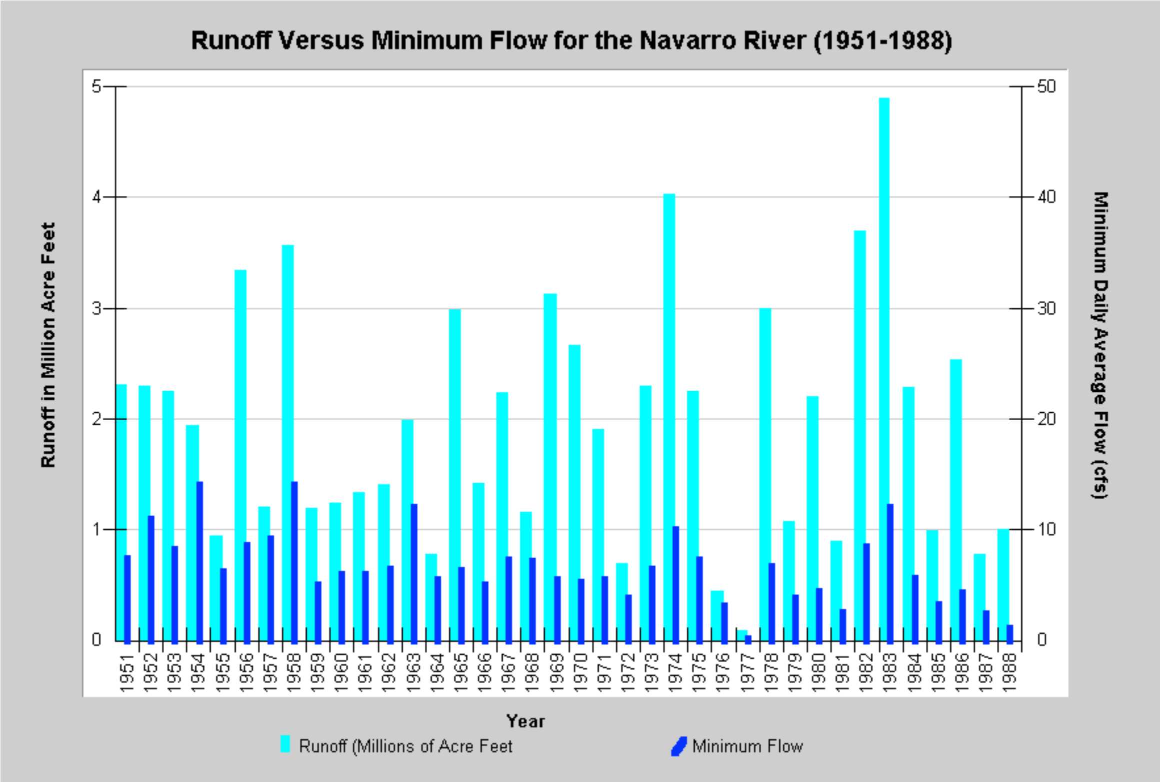

Figure 7. Relationship between minimum daily average flow and annual runoff from the USGS gage on the Navarro River (Jackson 1991 in KRIS Navarro).

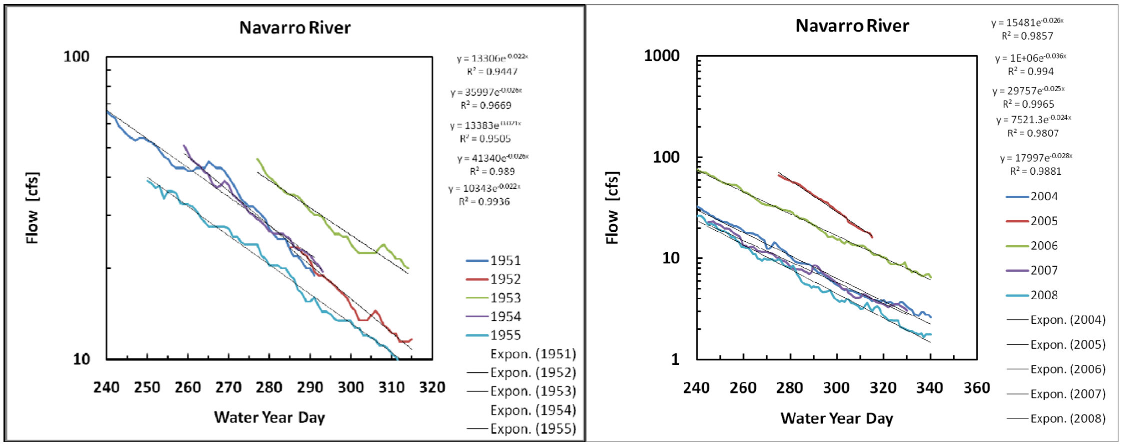

Figure 8. Plots of stream flow versus day of the water year for 1951-1955 (A) and 2004-2008 (B) suggesting an increase in the slope of regressions between the two periods (Hunt 2009).

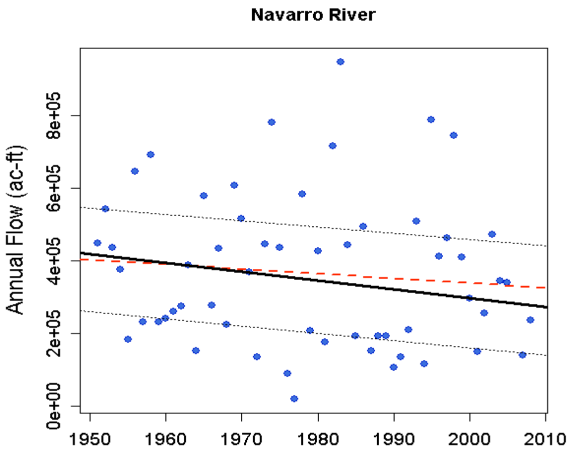

Figure 9. Lower 25% quartile regression of mean annual flows from the USGS gage on the Navarro River showing a declining trend. A test for a regression slope less than zero used to determine if drier years are getting drier failed to yield a significant value (p-value=0.13) (Holley 2010).

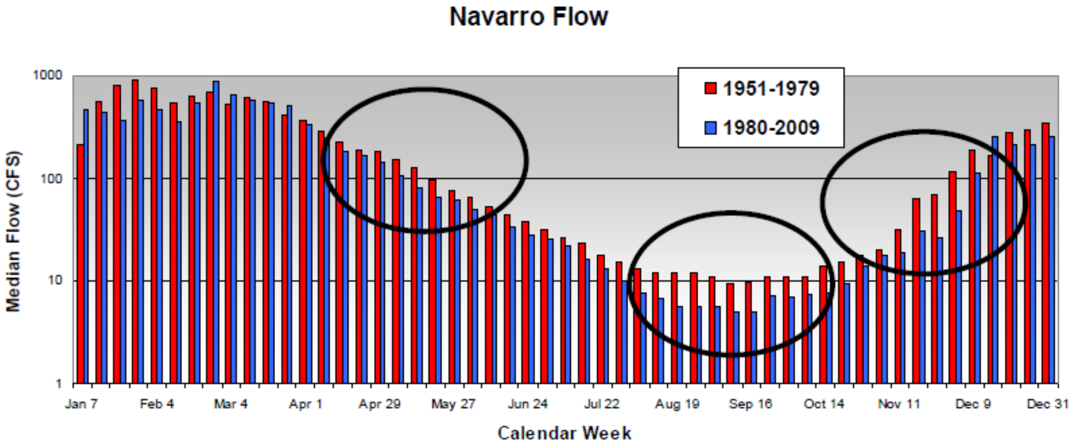

Figure 10. Weekly median flows from 1951-1979 and from 1980-2008 indicating reduced summer flows for the more recent period (Robinson 2011).

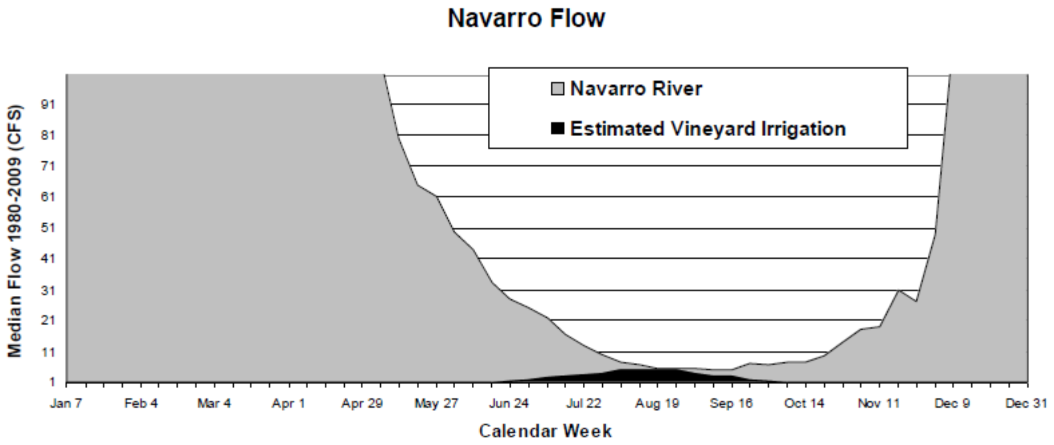

Figure 11. Weekly median flows from 1980 to 2009 from the Navarro River compared to the estimated water demand for vineyard irrigation (Robinson 2011).