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Abstract In the snowmelt dominated hydrology of arid western US landscapes, late summer low streamflow is the most vulnerable period for aquatic ecosystem habitats and trout populations. This study analyzes mean August discharge at 153 streams throughout the Central Rocky Mountains of North America (CRMs) for changes in discharge from 1950–2008. The purpose of this study was to determine if: (1) Mean August stream discharge values have decreased over the last half-century; (2) Low discharge values are occurring more frequently; (3) Climatic variables are influencing August discharge trends. Here we use a strict selection process to characterize gauging stations based on amount of anthropogenic impact in order to identify heavily impacted rivers and understand the relationship between climatic variables and discharge trends. Using historic United States Geologic Survey discharge data, we analyzed data for trends of 40–59 years. Combining of these records along with aerial photos and water rights records we selected gauging stations based on the length and continuity of discharge records and categorized each based on the amount of diversion. Variables that could potentially influence discharge such as change in vegetation and Pacific Decadal Oscillation (PDO) were examined, but we found that that both did not significantly influence August discharge patterns. Our analyses indicate that non-regulated watersheds are experiencing substantial declines in stream discharge and we have found that 89% of all non-regulated stations exhibit a declining slope. Additionally our results here indicate a significant ($\alpha \leq 0.10$) decline in discharge from 1951–2008 for the CRMs. Correlations results at our pristine sites show a negative relationship between air temperatures and discharge and these results coupled with increasing air temperature trends pose serious concern for aquatic ecosystems in CRMs.

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1 Introduction

Water in the interior western United States is a vital resource with seasonally limited supply and an increasing demand; however, there is currently limited knowledge regarding summer discharge trends in the Central Rocky Mountains of North America (CRMs). Over the last decade the CRMs has experienced unprecedented hot summers and dry water years which has escalated concerns over the survival of sensitive aquatic species and the potential impacts to ecosystem services and livelihood for the region.

The CRMs climate varies from semi-arid continental to highland depending on elevation, topography and geographic location (Critchfield 1983). Most areas have cold winters and warm summer months with an average precipitation of 48.3 cm in which ~62% is received as snow (Daly et al. 2008; Serreze et al. 1999). Rivers and watersheds are snowmelt dominated, in that seasonal snowmelt during the spring and summer months are a critical part of each watershed. In snowmelt dominated areas many aquatic plants and animals depend on this seasonal pattern of discharge for reproduction and survival (Ficke et al. 2007). Due to these characteristics, the CRMs are particularly sensitive to changes in air temperature and the estimated trends pose serious concern for the region. Hansen et al. (2006) estimated that annual air temperatures from 1950–1998 have increased between +0.5–1.0°C. Using data from weather stations in western Montana, Pederson et al. (2010) estimated that western Montana has experienced a rise in annual average temperature of +1.33°C from 1900–2000 and even greater increases in minimum and maximum winter temperatures, which is similar to previous observations for the entire western US (Bonfils et al. 2008). Evidence of the sensitivity to increasing air temperatures has been documented in numerous studies across the region including: (1) Decreases in snow water equivalent measurements (Mote 2003; Mote et al. 2005); (2) Increases in the amount of winter precipitation as rain (Knowles et al. 2006); Earlier center of timing of snowmelt (Stewart et al. 2005; Moore et al. 2007); An increase in evaporation (Golubev et al. 2001; Brutsaert 2006). These documented changes in the water balance and the characteristics of CRMs watersheds that make August stream discharge an important target because it provides an integrated view of the cumulative impacts of air temperature increases.

In the CRMs stream water temperatures are typically warmest when air temperatures are highest and stream discharges are lowest. Unfortunately, there is limited availability of historical water temperature data; therefore the following research was performed to evaluate fluctuations in August stream discharge as a proxy for changes in stream temperature. Changes in discharge are correlated with water temperature due to the fact that as the volume of water decreases the capacity of the river to buffer against temperature changes also decreases from reduced heat capacity associated with the decreased volume.

Several previous studies have evaluated historical stream discharge trends throughout the United States, but only a limited effort has been made in the CRMs. One such study examined the annual stream discharge in the CRMs near the United States and Canadian border analyzing 31 rivers over various periods from 1910–2002 (Rood et al. 2005) and found a decreasing trend of 0.1% per year over the historic record for 21 of the 31 rivers analyzed. Additionally, 15 of the 31 rivers investigated had statistically significant declines which provide evidence that a decreasing pattern is not due to random chance. Within the decreasing discharge trends, the majority of decline was observed for rivers in Alberta that flow into the Arctic Ocean (Rood et al. 2005). More recent research in this region has also demonstrated a decline in annual stream flow distributions from 1948–2006 (Luce and Holden 2009). Luce and Holden (2009) found the greatest significant decrease ($\alpha \leq 0.10$) in discharge occurring in the 25th and 50th percentile of annual stream discharge indicating a drying trend overtime. While annual flows

are important measurements to help understand changes occurring within watersheds, they do not indicate when changes are occurring. Annual discharge assessments lump monthly discharge measurements into a 12 month package which masks seasonal changes and does not provide a focused evaluation of the impacts on aquatic ecosystems. Rood et al. (2008) examined summer discharge trends in the CRMs by evaluating monthly flow rates during the 20th century for 14 free flowing rivers in the CRMs. They reported a decrease of summer discharge in all except one river within the study area and a decline in flow of 0.2% per year was in rivers that drain east of the continental divide (Rood et al. 2008).

While the analysis of stream discharge has been documented in select rivers in the CRMs (Hamlet and Lettenmaier 1999; Lins and Slack 1999; Rood et al. 2005, 2008; Luce and Holden 2009), there is a noted lack of knowledge regarding seasonal discharge patterns in this region and the degree of human impact on these discharge trends. Currently, only seven rivers in the CRMs within the U.S. have been analyzed for long-term trends during August (Rood et al. 2008). The work reported here will build upon previous research by analyzing a larger database of streams throughout the CRMs, using a more stringent selection process, and by analyzing more streams and a larger area it allows us to better characterize summer discharge trends on a regional and local level.

Importantly, no studies have attempted to determine the extent to which climatic changes are affecting August stream discharge in the CRMs (Rood et al. 2005, 2008; Luce and Holden 2009; Lins and Slack 1999). It is difficult to make the link between climate change and stream flow due to the magnitude of agricultural and domestic water use which modify natural flow of streams. In order to determine the influence that climatic variables have on stream discharge it is necessary to identify and analyze pristine sites with minimal or no water diversions, water storage and land use change. Our research is also unique in that we identify pristine sites within the region and analyze each for discharge, temperature and precipitation trends and the relationship between climatic variables and discharge. The use of such pristine sites allow us to eliminate the confounding factors of stream water diversion, regulation, and irrigation. By eliminating confounding factors we are able to gain better insight to the possible effects that climate change is having on discharge in the region.

Finally, our work differs from previous discharge studies, because we selected gauging stations based on the proximity of the watershed headwaters to areas protected from human induced land cover change, volume of surface water diversion and irrigation withdrawals by using satellite imagery, and water right records. We used a statistical procedure that enabled us to separate stream discharge trends based on the extent of anthropogenic impact on the watershed and thus provide a unique perspective on discharge patterns across the region. The purpose of the work reported was to determine if: (1) Mean August stream discharge values in the CRMs are declining; (2) Low August stream flow values are occurring more frequently with time; (3) There is a correlation between climatic variables and August discharge at pristine sites

2 Methods: study area

The CRMs study area encompasses Montana, Idaho and Wyoming. Data were available from a total of 2,895 USGS gaging stations, but only those stations that met specific criteria were selected for inclusion in our study (Fig. 1). This strict selection process differs from previous studies because we only accepted stations that had a minimum of 40 years of semi-consecutive (<2 years of consecutive missing data) data were chosen. We chose a minimum of 40 years as long-term assessments have been demonstrated to require at least

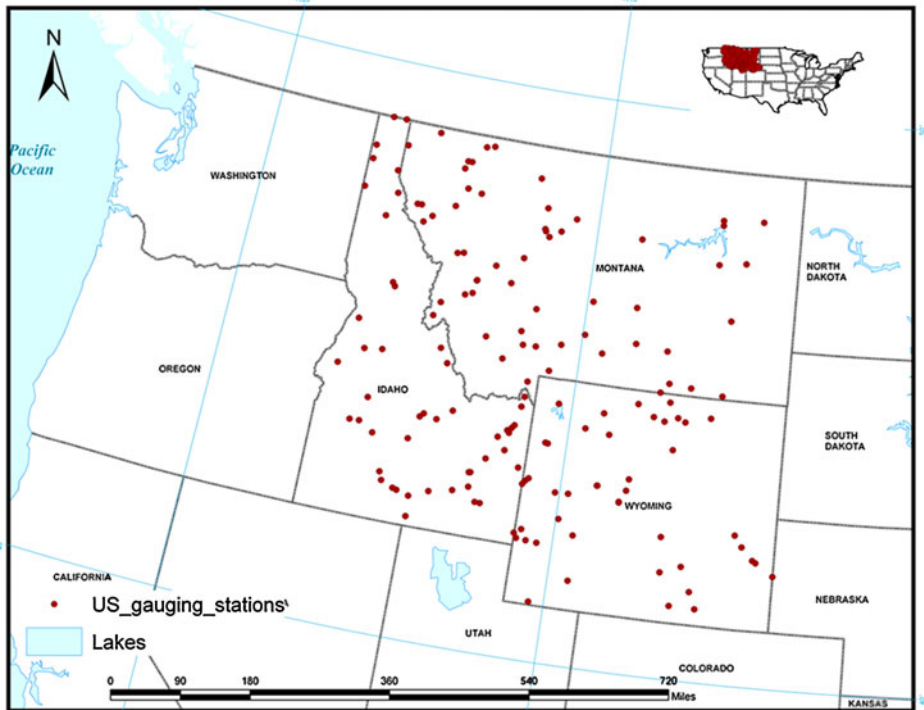


Fig. 1 The Central Rockies August stream discharge study area. The figure shows the location and spatial extent of gauging sites used. The red circles signify a gauging site used in the analysis; 153 individual sites were analyzed

30 years of continuous data (Kundzewicz and Robson 2004). Analyzing records with large amounts of missing data requires interpolation and only provides an estimation of values (Kundzewicz and Robson 2004), we avoided this problem by only selecting data sets with a minimum of missing data and with this selection process reduced the number of possible stations from 2,895 down to 153 (Fig. 1). We chose the past 59 years to analyze in order to capture the impacts of a $\sim 1^\circ\text{C}$ air temperature increase that occurred during this period in the Central Rockies (Hansen et al. 2006; Pederson et al. 2010). Sites were then grouped into three categories based on the amount of anthropogenic impact by analyzing dam records, surface water diversion records, and land use information using satellite imagery (<10 m resolution), water rights records and GIS. Sites were grouped as pristine, unregulated and regulated and the major difference between these sites is the degree of anthropogenic impact. This technique differs from previous research which has not attempted to parse out the effects of human induced climate change, changes in surface water diversion, dam regulation or land use changes (Rood et al. 2008). Analysis of all sites is important, but analysis that does not take into account confounding variables cannot link climatic change to discharge trends due to the large array of other factors that affect discharge. Therefore, sites were classified as pristine if their headwaters were located in areas that human induced land cover change is restricted (National parks and Wilderness areas), had no reservoirs upstream of gauging site and less than five type II (maximum diversion equal to 10–99 acre-feet per year) surface water diversions. Sites were classified as un-regulated if there were no reservoirs upstream of site, but did contain greater than five type II diversions or contained any type III diversions

(maximum diversion greater than or equal to 100 acre-feet per year) surface water diversions. Sites were classified as regulated if there were reservoirs upstream of gauging site. In order to classify sites we examined the amount of surface water diversion, dams and land use of each watershed upstream of all gauging sites using the techniques previously described. We thus ended up with a subset of 15 pristine sites that is unique from the Hydro-Climatic Data Network (HCDN) sites used in previous research (Slack and Landwehr 1992) because by using water diversion records we were able to more accurately select relatively unaltered streams. The HCDN sites were not used because upon inspection many of the HCDN sites contained small dams and diversions upstream of the gauging station as noted in previous research (Moore et al. 2007). An overview of our site characteristics can be seen in Table 1.

2.1 Data collection

Historical discharge records were collected from the United States Geological Survey (USGS) national water information system web interface (<http://waterdata.usgs.gov/usa/nwis/sw>). The web interface allows the user to access historical stream information from 23,777 stations across the United States. The majority of gauging stations record the elevation of water in a river or stream and then converts the water elevation into discharge using an equation that is calculated on site taking into account actual stream discharge and profile measurements. Discharge is usually calculated every 15 min and transmitted every one to four hours to a data base. Monthly estimates are averages from the recorded daily averages. Each site is maintained and all data is screened by the USGS personnel. December–July mean temperature and precipitation model output records for the watersheds upstream of the 15 pristine gauging stations was collected from West Map's Climate Analysis and Mapping Toolbox which uses data computed by the PRISM Model (<http://www.cefa.dri.edu/Westmap/>). August precipitation data was not collected because August is typically an insignificant month for precipitation in the region. Due to the remote locations of many of the sites and limited number of weather stations in the region PRISM model output provides the best available estimate for these parameters (Daly et al. 2008).

2.2 Data analysis

Exploratory data analysis was performed by viewing graphs to visually examine the data for outliers, unique patterns and normality. The Shapiro–Wilk test was then used to formally examine the data for normality (Shapiro and Wilk 1965) and the results from this test provided evidence that the data were not normally distributed forcing us to use a non-parametric approach to data analyses to avoid misleading results (Kundzewicz and Robson 2004). We used the Durbin–Watson test to evaluate the lack of independence between data points (Durbin and Watson 1950)

Table 1 Comparison of gauging site groupings in the Central Rockies. The analysis indicates that the largest decreases in discharge are occurring in the pristine and un-regulated sites over the 1950–2008 period

Site classification	Number of sites	Number of significant trends		Change per record	
		Decreasing	Increasing	Mean	Median
Pristine	16	8	0	−22.87%	−22.15%
Un-regulated	49	13	2	−18.73%	−21.58%
Regulated	88	14	11	−9.44%	−11.84%

and found serial correlation to exist for residuals for the data from at a number of sites. We employed a trend-free pre-whitening (TFPW) procedure (Yue et al. 2002b) to address for serial correlation. This statistical test is a rank based non-parametric test commonly used to assess hydrological and metrological time series data such as discharge, precipitation, temperature data that is typically not normally distributed (Mann 1945; Kendall 1975; Yue et al. 2002a, b). An alpha level of 0.10 was used to assess statistically significant trends with the Mann-Kendall test.

To normalize the discharge data, the slope of each site was divided by the mean discharge of the same gauging station to find a change in discharge rate. Normalized discharge data provides a simple way to compare streams of different sizes. Once a local statistical significance was determined we used a bootstrap resampling technique developed by Douglas et al. (2000) to examine the field significance (Statistical significance of a region) of discharge trends within our site groupings and across the CRMS. In order to examine the effect of cross-correlation, falsely rejecting the null hypothesis, we employed two types of bootstrap resampling methods on TFPW data over two time periods 1957–1996 and 1951–2008 (Douglas et al. 2000; Yue et al. 2002b). We employed the block-bootstrap method, which takes into account spatial correlation, to determine field significance (Douglas et al. 2000). We chose the stated periods to use for our analysis, because our bootstrap methods required the data to be continuous over the time frame. These specific tests were used because it has been proven to work better for non-normally distributed data and because it has been successful in previous statistical analysis of hydrologic systems (Hirsch et al. 1982; Lins and Slack 1999; Douglas et al. 2000; Yue et al. 2002a, b, c; George 2007).

To analyze low discharge frequency the median and the lower and upper limit of the inter-quartile range were calculated for all gauging sites. The median and inter-quartile

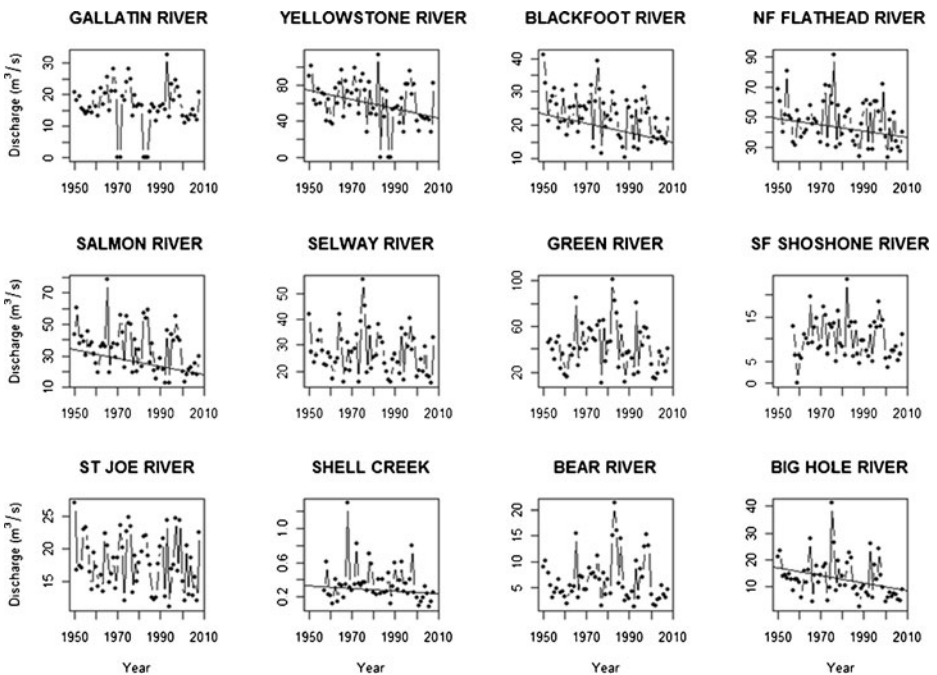


Fig. 2 Discharge records for 12 major rivers in the Central Rockies. All pristine sites had a negative slope as did 89% of all non-regulate sites examined. Site with regression lines signify a statistically significant ($\alpha < 0.10$) trend over time

ranges were used instead of standard deviation because the distribution is not normally distributed. Once the upper and lower limits of the inter-quartile range were found low discharge frequency was focused on to determine the frequency over time that discharge values were less than the 25th percentile. A 5 year moving average was then overlaid over the frequency bar plot to visually detect trends.

To examine the relationship between temperature and precipitation to discharge, at the pristine watersheds, the Spearman and Kendall correlation analyses were performed. These specific tests were chosen because they are commonly used non-parametric methods that have been successful in previous research (Lins and Slack 1999; Douglas et al. 2000; Yue et al. 2002a, b; George 2007; Novotny and Stefan 2007). In order to better determine how climatic variables influence August discharge we developed a linear mixed effect model to model discharge. This model was created in R statistical program using the NLME library (Pinheiro and Bates 2000) and included December–July precipitation and air temperature as well as drainage area as independent variables. We examined simple and complex models and through an Akaike Information Criterion (AIC) analysis determined a best fit model. We also examined the variables in the model for multicollinearity and did not find a significant relationship.

3 Results

3.1 Non-regulated sites

Regional analysis of discharge trends shows a strong decreasing pattern across the CRMs (Fig 2). By examining the distribution of the normalized discharge (slope divided by average discharge) it is possible to determine where the distribution is centered. If the distribution was centered at a value greater than zero discharge trends would be expected to be increasing with time. However, the distribution of all the sites examined ($n=65$) is centered at -21% change and further examination reveals that 89% of all sites had negative slopes (Fig. 3). Our bootstrap analysis revealed that field

Fig. 3 Distribution of normalized change per record for non-regulated sites in the Central Rockies ($n=65$). The distribution is centered at -21% (median value), 89% of all sites had a negative slope or declining discharge trend

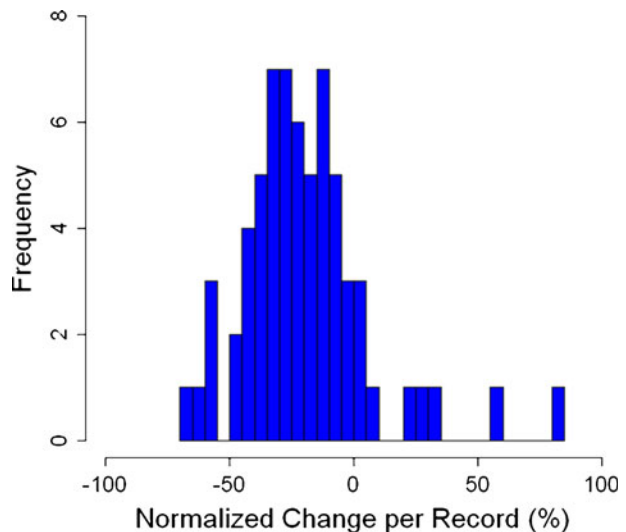


Table 2 Field significance comparison of gauging sites in the Central Rockies using bootstrap methods. The bootstrap methods provide evidence to suggest that decreasing trends are significant across the region over the 1950–2008 period

Region	Years	Period	Stations	Regional mean ¹	Field significance	
					Block_bootstrap ²	Site bootstrap
Pristine	40	1957–1996	13	−5.3	0.4615	0.4139
Pristine	59	1950–2008	9	−257.6	0.0179	0
Un-regulated	40	1957–1996	39	−11.51282	0.4395	0.2044
Un-regulated	58	1951–2008	27	−214.1	0.0313	0
Regulated	40	1957–1996	83	15.74699	0.6237	0.9515
Regulated	58	1951–2008	65	−106.4769	0.0898	0
Northern Rockies	40	1957–1996	134	5.477612	0.5345	0.7665
Northern Rockies	58	1951–2008	93	−148.3656	0.05	0

significance (Statistical significance for a region with more than one gauging site) for each grouping of gauging sites and the entire CRMs had significant decreasing trends over the full time period (1950–2008) (Table 2). Field significance was not observed when more sites were examined over a shorter time period (1957–1996) (Table 2). Widespread decreasing trends and increasing frequency of low flows provide strong evidence that discharge is decreasing throughout the CRMs (Figs. 4 and 5) and provides much needed information for critical August stream flows in this region.

Further examination of changes over different time periods provides supporting evidence of decreasing trends. A similar pattern in the discharge slope was observed for the 58 and 38 year trends of sites suggesting that with time discharge change is uniform with a slight

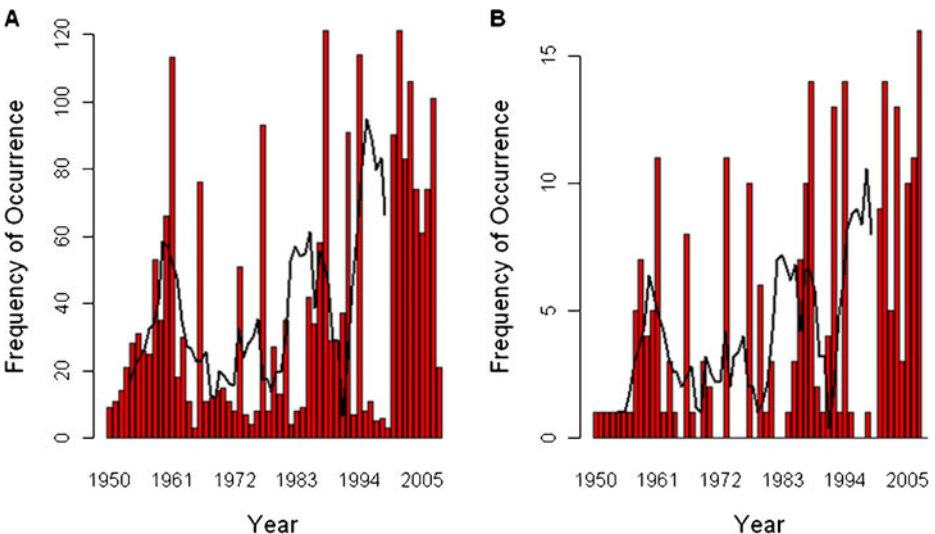


Fig. 4 Frequency of low discharge values (values <25th percentile) for all locations (graph A) and pristine sites (graph B) in the Central Rockies. By examining the 5 year moving average it is evident that a general increase in low discharge frequency with time is occurring and we can see that there has been more low discharge value in the last eight years than in the previous five decades

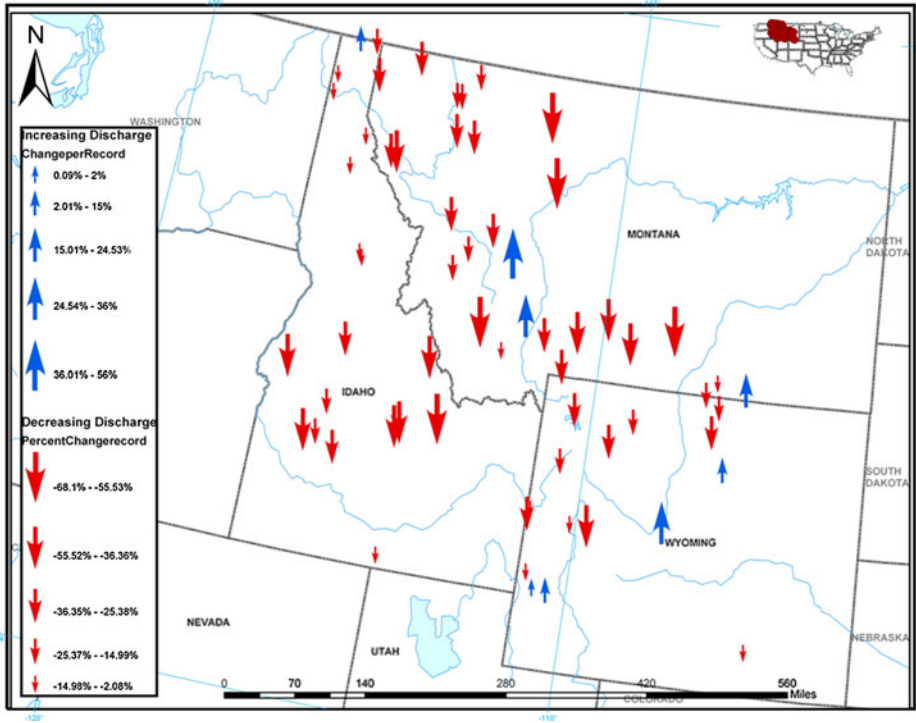


Fig. 5 Amount and type of normalized discharge change per record across the Central Rockies. The downward pointing red arrows signify a decreasing slope and the upward pointing blue arrows signify an increasing slope. The Larger the arrow the larger the discharge change at each gauging station. This figure shows a decreasing trend across the study area with very few positive slopes

decrease toward the end of the 20th century and beginning of the 21st century. This pattern can be seen in the time series graphs of the Yellowstone River, MT (Fig. 6). When other summer months are examined, such as July and September; we found very similar patterns to August trends. An example of these trends for additional months can be seen in Fig. 6 for the Yellowstone and Lochsa Rivers. Both of these patterns suggest that in addition to decreasing August trends there is a general pattern of decreasing summer discharge (July–September) at most sites.

3.2 Pristine sites

From within the non-regulated sites we selected a subset of sites deemed pristine (Gauging stations without reservoirs or surface water diversions upstream). All discharge records analyzed have a decreasing slope and the median change over the record length is -23% (Table 3, Fig. 7). Eight of 15 sites have significant ($\alpha \leq 0.10$) decreasing trends and no sites were observed to have an increasing trend (Table 3). Additionally, bootstrap results reveal that the region is significantly ($\alpha \leq 0.10$) decreasing. December through July temperature records show strong statistical evidence for increasing temperature trends in 14 of the 15 watersheds analyzed (Table 4, Fig. 8). December–July precipitation for most sites is decreasing, but only 8 of 15 sites had a significant decrease in precipitation during the period of record (Table 4). There is a negative correlation between air temperature and

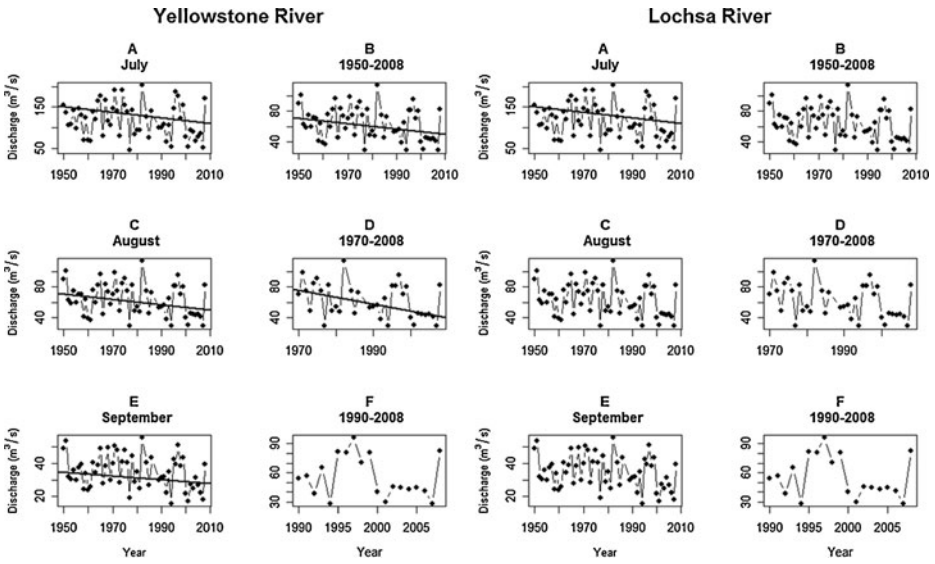


Fig. 6 Seasonal and temporal patterns of the Yellowstone and Lochsa rivers. The two rivers were chosen because they represent examples of strong decreasing trends and no trends for locations in the Central Rockies. At the Yellowstone river changes in discharge are not limited to just August, we seem similar trends from July–September (graphs A, C, E). Additionally, this trend is clearly present for different time periods; graph B (58 years) and graph D (38 years). At the Lochsa site a decreasing slope is present, but it is only statistically significant ($\alpha=0.10$) in July from 1950–2008

Table 3 Statistical significance and change over time for all pristine sites examined. This table shows the slope, significance value and the normalized change over time. Eight of the 16 stations examined had statistically significant negative trends. The majority of sites have large decreasing trends over time

USGS ID	Stream gauge name	TSE slope	P-value	Change per record
05014500	Swift current at many glacier	-0.24	0.0043	-17.3%
12390700	Prospect creek at Thompson falls	-0.56	0.0129	-35.2%
12359800	SF flathead river AB twin creek NR Hungry horse	-5.32	0.0392	-29.4%
13120000	N FK big lost river at wild horse NR chilly	-0.48	0.0585	-40.7%
09196500	Pine creek AB Fremont lake	-1.13	0.0744	-38.3%
12355500	N F flathead river near Columbia falls	-6.39	0.0909	-22.7%
06186500	Yellowstone river at Yellowstone LK outlet	-10.18	0.0930	-25.4%
06278300	Shell creek above shell creek reservoir	-0.06	0.0943	-27.4%
13235000	SF Payette river at Lowman	-1.88	0.1165	-21.6%
13011500	Pacific creek at Moran	-0.27	0.1169	-16.2%
12306500	Moyie river at Eastport	-0.35	0.2121	-15.0%
13313000	Johnson creek at yellow pine	-0.70	0.2273	-32.8%
12414500	St. Joe river at Calder	-0.87	0.3408	-8.1%
12358500	Middle fork of flathead river	-5.14	0.4295	-20.2%
13336500	Selway river nr Lowell	-2.01	0.4365	-12.4%
13337000	Lochsa river nr Lowell	-0.36	0.4525	-3.0%

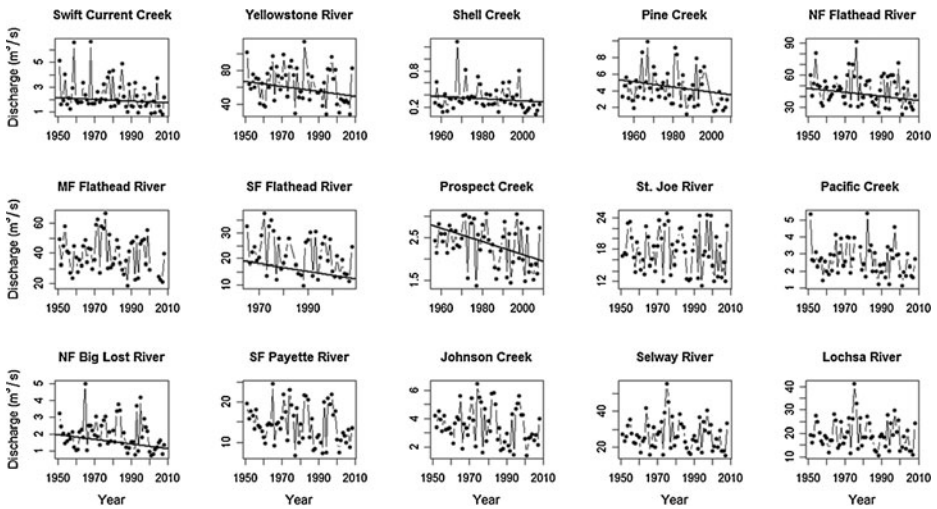


Fig. 7 Discharge records and slope estimation for 15 pristine rivers in the Central Rockies. All pristine sites had a negative slope and sites with regression lines signify a statistically significant ($\alpha \leq 0.10$) trend

discharge, but a positive and negative correlation between precipitation and discharge (Table 5).

The linear mixed effects best model created for the entire CRMs and each pristine gauging station indicates that precipitation, temperature and drainage are statistically

Table 4 Comparison of precipitation, temperature and discharge trends at 15 locations. Precipitation patterns across the sites appear to be generally decreasing with statistically significant trends at eight sites. Temperature trends are significantly increasing across the region and discharge trends are statistically decreasing

Stream gauge	Precipitation trend	Temperature trend	Discharge trend
NF Flathead	— ^a	+ ^a	— ^a
Swift Current	— ^a	+ ^a	— ^a
SF Flathead	— ^a	+ ^a	— ^a
MF Flathead	— ^a	+ ^a	—
Prospect Creek	— ^a	+ ^a	— ^a
St. Joe River	— ^a	+ ^a	—
Lochsa River	—	+ ^a	—
Selway River	—	+ ^a	—
Johnson Creek	—	+ ^a	—
SF Payette River	—	+	—
NF Big Lost River	— ^a	+ ^a	— ^a
Yellowstone River	—	+ ^a	— ^a
Shell Creek	+	+ ^a	— ^a
Pacific Creek	— ^a	+ ^a	—
Pine Creek	+	+ ^a	— ^a

^a Signifies a statistically significant trend ($\alpha = 0.10$)

— Signifies a negative trend

+ Signifies a positive trend

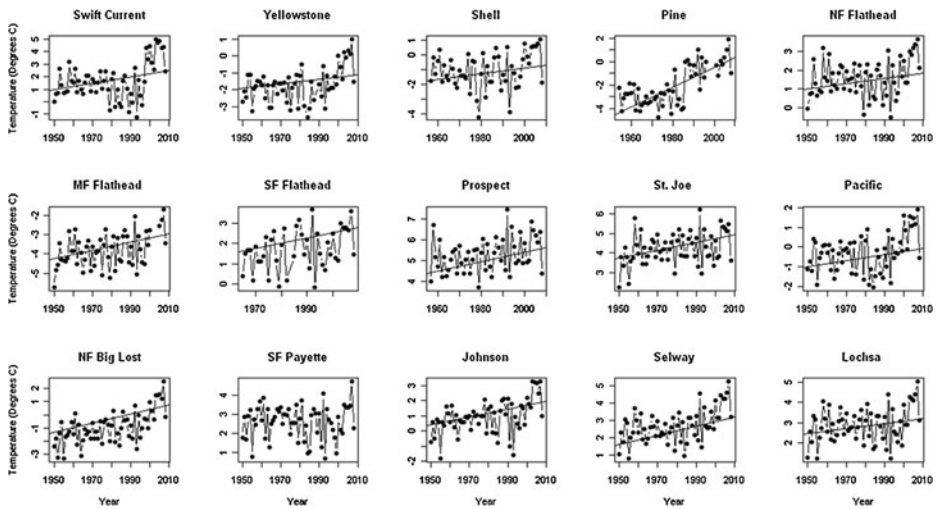


Fig. 8 December–July air temperature records for watershed of 15 pristine sites in the Central Rockies. All except one site has a positive slope and 14 out of 15 locations examined have statistically significant ($\alpha \leq 0.10$) air temperature trends

significant predictors of August discharge (Table 6) and that by incorporating random effects and accounting for heteroscedasticity (differing variances) August discharge was modeled with greater precision than models that use simple linear regression (Table 7) (Fig. 9). We also found that within our model air temperature was the greatest predictor of

Table 5 Spearman and Kendall correlation results for each site. The correlation analysis show that there is a weak to moderate negative correlation between August discharge and temperature but the correlation between August discharge and precipitation has mixed results

Gauging site	Kendall	Discharge /temperature			Kendall	Discharge /precipitation		
		P-value	Spearman	P-value		P-value	Spearman	P-value
SF Flathead	-0.44	0.00	-0.61	0.00	0.04	0.65	-0.02	0.89
NF Flathead	-0.29	0.00	-0.42	0.00	0.32	0.00	0.47	0.00
MF Flathead	-0.39	0.00	-0.53	0.00	-0.25	0.01	-0.49	0.00
Many Glacier	-0.11	0.20	-0.17	0.21	-0.04	0.64	-0.13	0.31
Prospect Creek	-0.37	0.00	-0.55	0.00	0.68	0.00	0.87	0.00
St. Joe River	-0.35	0.00	-0.50	0.00	0.51	0.00	0.70	0.00
Lochsa River	-0.31	0.00	-0.45	0.00	0.05	0.61	0.05	0.70
Selway River	-0.29	0.00	-0.44	0.00	0.10	0.25	0.11	0.43
Johnson Creek	-0.24	0.01	-0.35	0.01	0.17	0.05	0.21	0.10
SF Payette River	-0.21	0.02	-0.30	0.02	0.51	0.00	0.66	0.00
NF Big Lost River	-0.38	0.00	-0.55	0.00	0.62	0.00	0.80	0.00
Yellowstone River	-0.33	0.00	-0.49	0.00	0.16	0.08	0.22	0.09
Shell Creek	-0.39	0.00	-0.54	0.00	0.52	0.00	0.70	0.00
Pacific Creek	-0.26	0.00	-0.39	0.00	-0.04	0.68	-0.07	0.60
Pine Creek	-0.16	0.09	-0.23	0.10	0.45	0.06	0.58	0.06

Table 6 Model comparison results for two models examined. ANOVA results show evidence for increasing model fit with addition of parameters. Model 1 is a simple linear mixed effect model and Model 2 takes into account heteroscedasticity between sites

Model	df	AIC	BIC	logLik	Test	L.Ratio	p-value
1	8	5349.323	5387.161	-2666.66			
2	9	3963.998	4006.566	-1972.99	1 vs 2	1387.325	<.0001

August discharge. In contrast, PDO was found to be a weak and often non-significant predictor of August discharge (data not shown).

4 Discussion: implications for the Central Rockies

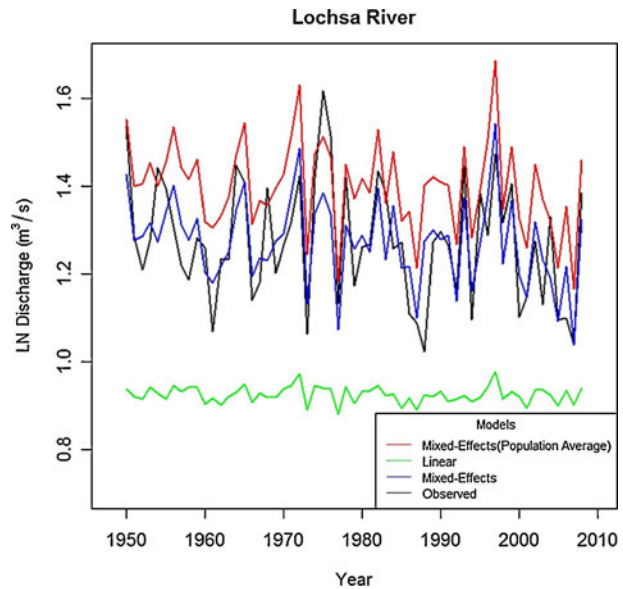
Analyses of long-term stream discharge records across the CRMs indicate that August discharge has generally declined over the last half century, the frequency of low discharge values has been greater in the last 8 years than previous decades (Fig. 4) and changes in air temperature cause or at least influence changes in August discharge. While discharge values are not significantly decreasing in every location our results indicate that there is sufficient evidence to suggest that discharge is declining across the region. Our intent in studying discharge trends was to improve knowledge regarding trends in stream discharge for the CRMs which could be applied to issues in conservation and land management. By separating streams based on the type and amount of anthropogenic control or modification, we feel that we greatly improved our capacity to identify areas in the CRMs where climate change is directly influencing stream discharge. In contrast, those areas that are heavily impacted by human activities can be evaluated for the occurrence of trends, but there is little chance of identifying the cause of these changes. Observation of changing trends in human impacted systems is of great interest; however, teasing out the causality of discharge trends in un-regulated and regulated sites is a complex task that was not within the scope of this study. Detection of trends change depending on the type of analysis, length of data and intensity or type of change (Kundzewicz and Robson 2004; Radziejewski and Kundzewicz 2004). The significance of trends also changes depending on how the analyses are conducted (Daniel 1978; Yue et al. 2002a).

While statistical significance is a common means of differentiating long-term trends from patterns that occur by chance, information from trends that are not statistically significant can also be useful and sometimes statistically significant trends are not useful information (Daniel 1978; Yue et al. 2002a). For example in the analysis of discharge trends in this study, we analyzed the normalized change over time (normalized slope) as well as the significance of the

Table 7 The model results for the August discharge model for the Central Rockies. All parameters are significant

	Value	Std.Error	DF	t-value	p-value
(Intercept)	0.8852	0.4346	820	2.0369	0.042
Precipitation	0.6707	0.2249	820	2.9826	0.0029
Temperature	-0.5435	0.1494	820	-3.6388	0.0003
Drainage Area	0.0241	0.0040	13	5.9663	0

Fig. 9 Model comparison of linear mixed-effect model and a linear regression model. The figure shows a comparison, at the Lochsa site, of the observed, fitted values for the mixed-effect model, fitted values for the population average model and fitted values for a simple linear regression model. For our sites the mixed effect model performed significantly better than simple linear regression



trend and found that a number of stations expressed large decreases in slope, but these trends were not statistically significant (at α level 0.10). It has been stated in previous research (Daniel 1978; Yue et al. 2002a) that this is a common pattern in hydrological analysis and we found several stations that had large changes in discharge, but the relationship was not statistically significant (Table 8). Locations that have large change over time are important information for scientist and managers in the CRMs and these sites should not be disregarded as unimportant. By performing a detailed screening of gauging sites, based on amount of anthropogenic impact, we were able to identify additional impacts from humans that influence stream discharge levels. Data from all pristine sites have decreasing slopes and eight of 15 sites have statistical evidence for a trend ($\alpha \leq 0.10$). The data from these stations show statistically that a decline is occurring from influences beyond local human change in surface water diversions, dam regulation, and land use change.

In addition to confounding anthropogenic effects on discharge several natural periodic events affect the hydrologic cycle in CRMs watersheds. Large disturbances within ecosystems from forest fires and beetle epidemics drastically change the hydrologic cycle within a watershed. These types of disturbance events cause large-scale tree mortality reducing evapotranspiration rates and causing an increase in annual water yield, late

Table 8 Example of significance values and change at gauging sites in the CRMs. The site outlined in black is a site with an insignificant trend ($p < 0.10$), a slope of -5.14 and a normalized change over the record of -20.17% . While this gauging station is not statistically significant, a large change in August discharge is occurring at this site

USGS	Gauge	Slope	p value	Percent Record
6186500	Yellowstone river at Yellowstone LK outlet	-10.18	0.0930	-25.38%
9196500	Pine creek AB Fremont lake	-1.13	0.0744	-38.35%
13011500	Pacific creek at Moran	-0.27	0.1169	-16.23%
6278300	Shell creek above shell creek reservoir, WY	-0.06	0.0943	-27.44%
12358500	Middle fork of flathead river	-5.14	0.4295	-20.17%

summer discharge and monthly high flow (Bethlahmy 1974; Potts 1984). Therefore in the given time frame we would expect the beetle kill and forest fire events to have increased the discharge rates. While it has been documented that climatic oscillations, such as Pacific decadal oscillation (PDO), significantly affect hydrologic processes throughout North America we generally found weak correlations between PDO and August discharge. Previous research has shown that PDO is a major driver of winter precipitation patterns (Mote 2006; Pederson et al. 2004), but from our correspondence analysis it appears that climatic oscillations have less influence on late summer August discharge patterns. Two possible explanations for this weak correlation are that; 1) August discharge is generally less influenced by winter precipitation because snow-melt only contributes to August discharge following winters with unusually heavy precipitation 2) other variables such as air temperature and evapotranspiration rates are more important drivers for August flows. We suspect that many stream flow analyses find a higher correlation with PDO due to the fact that analysis of annual discharge incorporates April–July runoff discharge times which are greatly influenced by PDO patterns and winter precipitation. Additionally, we found a strong negative relationship between air temperature and discharge at our pristine sites suggesting that changes in air temperature are affecting discharge values in the region. A spatial pattern for discharge declines is not evident for non-regulated sites, but it appears that the largest declines are occurring on relatively small (~250–500 km²) watersheds. This may be due to the fact that rivers with large watersheds are more influenced by groundwater or those larger watersheds are more buffered to changes in hydrologic inputs due to the sheer number of sub-drainages.

Trends from our regulated sites are additionally important information on the overall status of streams in the area, but caution should be used in interpreting these results because they are extremely manipulated by energy production at dams, irrigation demand, irrigation recharge and water rights downstream. From our regulated sites ($n=88$), or sites regulated by dams, we found 67% of the regulated sites had a negative slope with a median change over the record of -11.8%. Our bootstrap analysis revealed that field significance for regulated gauging sites and the entire CRMs had significant decreasing trends over the full time period (1950–2008) (Table 2). These results appear to show that August discharge at regulated sites, at certain locations, are declining less across the region. However, these results cannot be interpreted directly because the locations of regulated gauging sites are not distributed randomly across the terrain. Regulated sites tend to be located on rivers with larger drainage areas and may be more controlled by ground water or buffered by the sheer number of sub-watersheds feeding into the basin causing August discharge remain relatively constant.

Our analysis builds upon past research (Hamlet and Lettenmaier 1999; Lins and Slack 1999; Rood et al. 2005, 2008; Luce and Holden 2009) by examining a larger area, more locations and identifying sites that have additional impacts that may influence discharge trends. We specifically focused on August discharge trends, because changes in August discharge have greater potential ecological consequences than other months of the year. For example low discharge levels have the potential, if combined with warm air temperatures, to elevate instream temperature beyond lethal levels for aquatic organisms. In comparison to past research, our results show that decreases in August discharge trends are occurring throughout the CRMs and are not limited to areas east of the continental divide. Additionally, our results of increasing low flow values (<25th percentile) supports work by Luce and Holden (2009) that state dry years are becoming substantially drier in the region. However, due to the fact that we collected monthly data instead of daily data it is not possible to determine if low flow frequency is significantly increasing, but our results add another layer of information to possible long term hydrologic changes within the region. Further research needs to be done to determine if these

trends are significant and if these patterns are caused by changes in air temperature. These results are disconcerting for communities and aquatic ecosystems throughout the CRMs.

4.1 Impacts on fisheries

Discharge in rivers is a critically important water quality parameter that helps maintain cool water temperatures, adequate dissolved oxygen levels and suitable habitat for aquatic biota. When discharge values drop, there is less water in the system making streams more susceptible to elevated air temperatures than at times of high flow. Adequate discharge is most important during summer months when air temperatures are above 32°C posing the risk of heating rivers above the suitable temperature for various aquatic species. Previous research has shown that there is a strong linear relationship between stream temperature and air temperature at moderate air temperatures (0°C–20°C) with a more complex relationship outside of these ranges (Mohseni and Stefan 1999). Current and future estimates in average annual air temperature from historical temperatures are expected to increase in the CRMs making many streams candidates for increases in stream temperatures (Trenberth et al. 2007; Bales et al. 2006; Barnett et al. 2005, 2008). Species most susceptible to elevated water temperatures in the CRMs are native fish from the salmonoid family such as bull trout (*Salvelinus confluentus*), cutthroat trout (*Oncorhynchus clarki*), rainbow trout (*Oncorhynchus mykiss*), arctic grayling (*Thymallus arcticus*) and various salmon species; Chinook (*Oncorhynchus tshawytscha*), coho (*Oncorhynchus kisutch*) and sockeye (*Oncorhynchus nerka*). All salmonoids have a particular stream temperature where growth is greatest with a minimum and maximum range where conditions for growth are adequate, but not optimal. Typically growth curves for salmonoids increase moderately to a optimal water temperature and then decrease rapidly making fish more susceptible to harm from increases in temperature. As native species migrate or decrease in abundance it is predicted that many non-native species, with higher fundamental thermo niches, will move into areas previously or sparsely inhabited by native species (Carveth et al. 2006). Our results provide evidence of decreasing discharge patterns across the region and in combination with expected warmer air temperatures many coldwater species may be negatively impacted from increases in stream temperatures.

5 Conclusions

Our analyses indicate that non-regulated watersheds throughout the CRMs are experiencing significant declines in stream discharge over the last half century and we found that 89% of all stations exhibit a declining slope. Our research confirms that there is a significant decreasing trend in August discharge occurring across the region and low discharge frequency has been greater in the last eight to 10 years than previous decades. Our research also confirms that changes in air temperature influenced changes in August discharge trends for the CRMs over the last half century. These results support previous research (Rood et al. 2005, 2008) which has indicated that decreasing discharge trends are occurring across the region and the driest of years are becoming drier with time (Luce and Holden 2009). However, by examining a greater area and number of stations our research indicates that decreasing August discharge trends are not limited to stations east of the Continental Divide. Through new selection techniques we were also able to analyze stations that had minimal anthropogenic impact on watersheds and by doing this we greatly improved the hope of identifying areas in the CRMs where climate change is causing stream discharge to decrease over time.

The results have serious implications for aquatic ecosystems and communities in the CRMs. Decreasing August discharge in snowmelt dominated watersheds has the potential to severely impact many aquatic flora and fauna in the region. Less water in rivers during summer months will increase competition for water resources in the area and make management of resources difficult. While this research does confirm a declining trends across the region, more research on the causality of trends is needed to explain the extent to which climate change is affecting un-regulated and regulated watersheds in the region. With air temperatures projected to continue increasing into the future, it appears likely that August discharge trends will also decline. An understanding of the relationship between air temperature trends and August discharge trends will be of value to future water resource management and policy decisions.

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References

- Bales RC, Molotch NP, Painter TH, Dettinger MD, Rice R, Dozier J (2006) Mountain hydrology of the western United States. *Water Resour Res* 42:13
- Barnett TP, Adam JC, Lettenmaier DP (2005) Potential impacts of a warming climate on water availability in snow-dominated regions. *Nature* 438:303–309
- Barnett TP, Pierce DW, Hidalgo HG, Bonfils C, Santer BD, Das T, Bala G, Wood AW, Nozawa T, Mirin AA, Cayan DR, Dettinger MD (2008) Human-induced changes in the hydrology of the western United States. *Science* 319:1080–1083
- Bethlahmy N (1974) More streamflow after a bark beetle epidemic. *J Hydrol* 23:185–189
- Bonfils C, Santer BD, Pierce DW, Hidalgo HG, Bala G, Das T, Barnett TP, Cayan DR, Doutriaux C, Wood AW, Mirin A, Nozawa T (2008) Detection and attribution of temperature changes in the mountainous Western United States. *J Clim* 21:6404–6424
- Brutsaert W (2006) Indications of increasing land surface evaporation during the second half of the 20th century. *Geophys Res Lett* 33:4
- Carveth CJ, Widmer AM, Bonar SA (2006) Comparison of upper thermal tolerances of native and nonnative fish species in Arizona. *Trans Am Fish Soc* 135:1433–1440
- Critchfield H (1983) *General climatology*. Prentice-Hall, pp 145–161
- Daly C, Halbleib M, Smith JI, Gibson WP, Doggett MK, Taylor GH, Curtis J, Pasteris PP (2008) Physiographically sensitive mapping of climatological temperature and precipitation across the conterminous United States. *Int J Climatol* 28:2031–2064
- Daniel WW (1978) *Applied nonparametric statistics*, Boston
- Douglas EM, Vogel RM, Kroll CN (2000) Trends in floods and low flows in the United States: impact of spatial correlation. *J Hydrol* 240:90–105
- Durbin J, Watson GS (1950) Testing for serial correlation in least squares regression.1. *Biometrika* 37:409–428
- Ficke AD, Myrick CA, Hansen LJ (2007) Potential impacts of global climate change on freshwater fisheries. *Rev Fish Biol Fish* 17:581–613
- George SS (2007) Streamflow in the Winnipeg River basin, Canada: trends, extremes and climate linkages. *J Hydrol* 332:396–411
- Golubev VS, Lawrimore JH, Groisman PY, Speranskaya NA, Zhuravin SA, Menne MJ, Peterson TC, Malone RW (2001) Evaporation changes over the contiguous United States and the former USSR: a reassessment. *Geophys Res Lett* 28:2665–2668
- Hamlet AF, Lettenmaier DP (1999) Effects of climate change on hydrology and water resources in the Columbia River basin. *J Am Water Resour Assoc* 35:1597–1623
- Hansen J, Sato M, Ruedy R, Lo K, Lea DW, Medina-Elizade M (2006) Global temperature change. *Proc Natl Acad Sci U S A* 103:14288–14293

- Hirsch RM, Slack JR, Smith RA (1982) Techniques of trend analysis for monthly water-quality data. *Water Resour Res* 18:107–121
- Kendall MG (1975) Rank correlation methods. Griffin, London
- Knowles N, Dettinger MD, Cayan DR (2006) Trends in snowfall versus rainfall in the Western United States. *J Clim* 19:4545–4559
- Kundzewicz ZW, Robson AJ (2004) Change detection in hydrological records – a review of the methodology. *Hydrolog Sci J-Journal Des Sciences Hydrologiques* 49:7–19
- Lins HF, Slack JR (1999) Streamflow trends in the United States. *Geophys Res Lett* 26:227–230
- Luce CH, Holden ZA (2009) Declining annual streamflow distributions in the Pacific Northwest United States, 1948–2006. *Geophys Res Lett* 36
- Mann HB (1945) Non-parametric tests against trend. *Econometrica* 13:245–259
- Mohseni O, Stefan HG (1999) Stream temperature air temperature relationship: a physical interpretation. *J Hydrol* 218:128–141
- Moore JN, Harper JT, Greenwood MC (2007) Significance of trends toward earlier snowmelt runoff, Columbia and Missouri Basin headwaters, western United States. *Geophys Res Lett* 34
- Mote PW (2003) Trends in snow water equivalent in the Pacific Northwest and their climatic causes. *Geophys Res Lett* 30:4
- Mote PW (2006) Climate-driven variability and trends in mountain snowpack in western North America. *J Clim* 19:6209–6220
- Mote PW, Hamlet AF, Clark MP, Lettenmaier DP (2005) Declining mountain snowpack in western North America. *Bull Am Meteorol Soc* 86:39–49
- Novotny EV, Stefan HG (2007) Stream flow in Minnesota: indicator of climate change. *J Hydrol* 334:319–333
- Pederson GT, Fagre DB, Gray ST, Graumlich LJ (2004) Decadal-scale climate drivers for glacial dynamics in Glacier National Park, Montana, USA. *Geophys Res Lett* 31
- Pederson GT, Graumlich LJ, Fagre DB, Kipfer T, Muhlfield CC (2010) A century of climate and ecosystem change in Western Montana: what do temperature trends portend? *Clim Chang* 98:133–154
- Pinheiro JC, Bates DM (2000) Mixed-effects models in S and S-PLUS. Springer
- Potts DH (1984) Hydrologic impacts of a large-scale mountain pine beetle (*Dendroctonus ponderosae* Hopkins) epidemic. *Water Resour Bull* 20:373–377
- Radziejewski M, Kundzewicz ZW (2004) Detectability of changes in hydrological records (vol 49, pg 39, 2004). *Hydrolog Sci J-Journal Des Sciences Hydrologiques* 49:351–352
- Rood SB, Samuelson GM, Weber JK, Wywrot KA (2005) Twentieth-century decline in streamflows from the hydrographic apex of North America. *J Hydrol* 306:215–233
- Rood SB, Pan J, Gill KM, Franks CG, Samuelson GM, Shepherd A (2008) Declining summer flows of Rocky Mountain Rivers: changing seasonal hydrology and probable impacts on floodplain forests. *J Hydrol* 349:397–410
- Serreze MC, Clark MP, Armstrong RL, McGinnis DA, Pulwarty RS (1999) Characteristics of the western United States snowpack from snowpack telemetry (SNOTEL) data. *Water Resour Res* 35:2145–2160
- Shapiro SS, Wilk MB (1965) An analysis of variance test for normality (complete samples). *Biometrika* 52:591–611
- Slack JR, Landwehr JM (1992) Hydro-climatic data network: a U.S. Geological Survey streamflow data set for the United States for the study of climate variation. U.S. Geological Survey open file rept 1874–1988
- Stewart IT, Cayan DR, Dettinger MD (2005) Changes toward earlier streamflow timing across western North America. *J Clim* 18:1136–1155
- Trenberth KE, Jones PD, Ambenje P, Bojariu R, Easterling D, Klein Tank A, Parker D, Rahimzadeh F, Renwick JA, Rusticucci M, Soden B, Zhai P (2007) Observations: surface and atmospheric climate change. In: Solomon S, Qin D, Manning M, Chen Z, Marquis M, Averyt KB, Tignor M, Miller HL (eds) *Climate change 2007: the physical science basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge and New York
- Yue S, Pilon P, Cavadias G (2002a) Power of the Mann-Kendall and Spearman's rho tests for detecting monotonic trends in hydrological series. *J Hydrol* 259:254–271
- Yue S, Pilon P, Phinney B, Cavadias G (2002b) The influence of autocorrelation on the ability to detect trend in hydrological series. *Hydrol Process* 16:1807–1829
- Yue S, Pilon P, Phinney B, Cavadias G (2002c) Patterns of Trend in Canadian Streamflow. Proceedings of the 58th Annual Eastern Snow Conference, GCU, May 14–17th, Ottawa, Ontario, Canada (in press)