Climate change effects on stream and river temperatures across the northwest U.S. from 1980–2009 and implications for salmonid fishes

D. J. Isaak · S. Wollrab · D. Horan · G. Chandler

Abstract Thermal regimes in rivers and streams are fundamentally important to aquatic ecosystems and are expected to change in response to climate forcing as the Earth's temperature warms. Description and attribution of stream temperature changes are key to understanding how these ecosystems may be affected by climate change, but difficult given the rarity of long-term monitoring data. We assembled 18 temperature time-series from sites on regulated and unregulated streams in the northwest U.S. to describe historical trends from 1980–2009 and assess thermal consistency between these stream categories. Statistically significant temperature trends were detected across seven sites on unregulated streams during all seasons of the year, with a cooling trend apparent during the spring and warming trends during the summer, fall, and winter. The amount of warming more than compensated for spring cooling to cause a net temperature increase, and rates of warming were highest during the summer (raw trend = 0.17°C/decade; reconstructed trend = 0.22°C/decade). Air temperature was the dominant factor explaining long-term stream temperature trends (82–94% of trends) and inter-annual variability (48–86% of variability), except during the summer when discharge accounted for approximately half (52%) of the inter-annual variation in stream temperatures. Seasonal temperature trends at eleven sites on regulated streams were qualitatively similar to those at unregulated sites if two sites managed to reduce summer and fall temperatures were excluded from the analysis. However, these trends were never statistically significant due to greater variation among sites that resulted from local water management policies and effects of upstream reservoirs. Despite serious deficiencies in the stream temperature monitoring record, our results suggest many streams in the northwest U.S. are exhibiting a regionally coherent response to climate forcing. More extensive monitoring efforts are needed as are techniques for short-term sensitivity analysis and reconstructing historical temperature trends so that spatial and temporal patterns of warming can be better understood. Continuation of warming trends this century will increasingly stress important regional salmon and trout resources and hamper efforts to recover these species, so comprehensive vulnerability assessments are needed to provide strategic frameworks for prioritizing conservation efforts.

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1 Introduction

Thermal regimes in river and stream ecosystems are fundamentally important to fish and other aquatic organisms because most are ectotherms with physiologic processes directly controlled by temperatures of the ambient environment (Neuheimer and Taggart 2007; Buisson et al. 2008; Pörtner and Farrell 2008; Durance and Ormerod 2009). As a result, temperature strongly dictates the distribution and abundance of individual species across many spatial and temporal scales (Brannon et al. 2004; Rieman et al. 2007; Wenger et al. 2011a). As anthropogenic climate change progresses and the Earth's temperatures warm this century, aquatic communities in rivers and streams will have to shift to track thermally suitable habitat, but could encounter difficulties in linear stream networks that are often heavily fragmented by water resource development (Daufresne and Boet 2007; Heino et al. 2009). Moreover, populations of many recreationally and economically important cold-water fishes like trout and salmon are already constrained by unsuitably warm temperatures and additional warming may simply result in net losses of habitat (Mohseni et al. 2003; Rieman et al. 2007; Isaak et al. 2010a; Wenger et al. 2011b). A critical step to understanding potential climate change impacts on aquatic resources, therefore, is describing the rates at which streams may be warming and the factors that contribute to warming so that potential biological responses may be better understood and predicted.

Thermal regimes in streams reflect the balance of numerous physical processes that cause heating or cooling with short- (e.g., hourly, daily) or long-term (e.g., annual, decadal) temperature trends due simply to changes in the relative importance of these processes through time. Short-wave solar radiation is the dominant warming factor in stream heat budgets (Webb and Zhang 1997; Johnson 2003) but warming also occurs from long-wave atmospheric radiation, sensible heat transfer between air and water, direct conduction from the stream bed, friction created by water flow over the bed, and advective heat gains from precipitation and groundwater inputs (Brown 1969; Webb and Zhang 1997; Caissie 2006; Webb et al. 2008). Stream heat budgets are frequently altered by human activities that increase solar gains through removal of riparian vegetation (Moore et al. 2005), diversion of water out of streams (Meier et al. 2003), thermal effluents from powerplants, warm runoff from paved surfaces in urban environments, (Nelson and Palmer 2007), and storage of water in reservoirs (Olden and Naiman 2009; Poff et al. 2010). These factors, however, alter stream thermal regimes at relatively restricted spatial and temporal scales in comparison to the pervasive effects of climate change across the broad extents of regional river networks that often encompass 100,000's stream kilometers. Air temperatures affect stream temperatures everywhere throughout these networks via several mechanisms that include direct sensible heat transfer, long-wave atmospheric radiation (Brown 1969; Webb and Zhang 1997; Webb et al. 2008), and heating of groundwater that warms streams through advection (Taylor and Heinz 2009; Gunawardhana and Kazama 2011). Moreover, additional indirect effects may occur as air temperatures warm in association with anthropogenic climate change and cause stream discharge regimes to change in ways that could alter stream sensitivity to warming (Hockey et al. 1982; Meier et al. 2003). Across much of the western U. S., for example, warming air temperatures have been linked to increasing precipitation rainfall fractions (Knowles et al. 2006), decreasing snow accumulations (Mote et al. 2005, Knowles et al. 2006), and earlier snowmelt (Hamlet et al. 2005; Mote et al. 2005). As a result, the timing of spring stream freshets driven by snowmelt has advanced 2–3 weeks in the last 50 years (Regonda et al. 2005; Stewart et al. 2005). Because streams discharge more water earlier in the year, less remains in the summer when flows have been trending lower for many decades (Stewart et al. 2005; Rood et al. 2008; Luce and Holden 2009; Leppi et al. 2011).

In contrast to the extensive long-term meteorological and flow gaging records that have been valuable for documenting many trends in climate-related parameters (e.g., Mote et al. 2005; Stewart et al. 2005; Leppi et al. 2011), few long-term stream temperature records exist. The best long-term records in the U.S. are typically associated with municipal water supplies, U.S. Geological Survey stream gages, or hydroelectric facilities on larger rivers that are often subject to varying degrees of local thermal alterations (Olden and Naiman 2009; Kaushal et al. 2010). Not surprisingly, therefore, studies based on observational records of sufficient length to address potential climate effects are rare, often include only a single site (Langan et al. 2001, Petersen and Kitchell 2001; Patterson et al. 2007), or have been done to assess shorter-term climate cycles like the Pacific Decadal Oscillation (PDO) or El Niño Southern Oscillation (ENSO; Kiffney et al. 2002; Mote et al. 2003). Only two studies (Hari et al. 2006; Kaushal et al. 2010) have looked at multiple streams contemporaneously across multiple decades to discern long-term warming trends. In each instance, such trends were commonly detected, but a variety of factors related to urbanization, climate cycles, and reservoir management also affected the results. No observational study, to our knowledge, has attempted to describe background rates of stream temperature warming associated with climate change or to examine seasonal patterns that could be driven by concurrent trends in climate forcing variables like air temperature and stream discharge.

Here, we examine 18 temperature time-series from sites on unregulated and regulated northwest U.S. streams that span the period from 1980–2009 to assess historical trends. Our objectives were to: 1) determine whether regionally coherent stream temperature trends were apparent, 2) determine whether trends differed between sites on free-flowing streams and those downstream of reservoirs, 3) describe seasonal variation in temperature trends, and 4) assess the relative influence of variation in air temperature and discharge on stream temperature trends. Lastly, we discuss the implications of our findings for conservation of salmon and trout in the northwest U.S.

2 Climate in the northwest U.S.

The climate in the northwest U.S. has been well studied, initially because of the dominance of climate cycles like the PDO and ENSO in regional weather patterns. These phenomena reflect periodicity in ocean conditions at different temporal scales (PDO~20–30 years, ENSO~2–5 years) that result in phases of conditions in the Pacific Northwest that are generally wetter and cooler or warmer and drier conditions than average (Mantua and Hare 2002). These phases may have strong, sometimes dominant effects on temporal variation in stream flows and temperatures (Kiffney et al. 2002; Mote et al. 2003).

More recently, the region's climate has been extensively studied in association with anthropogenic climate change (Mote 2003, Mote et al. 2005, Hamlet et al. 2007). Important motivations for this work include above average rates of past warming (Mote 2003, Saunders et al. 2008), projected future warming (Mote et al. 2008), and the region's heavy reliance on water supplies associated with seasonal snowpacks that are showing sensitivity to a warming climate (Mote et al. 2005; Knowles et al. 2006; Hamlet et al. 2007; Barnett et al. 2008). Warming rates have varied during the 20th century, but a consistent warming trend believed to be associated with climate change emerged in the late 1970's/early1980's and persists to the present (Mote 2003, Hamlet et al. 2007).

3 Methods

3.1 Stream temperature data

Data for this assessment were queried out of the U.S. Geological Survey National Water Information System (NWIS; http://waterdata.usgs.gov/nwis), which hosts historical and real-time records for a variety of stream discharge, temperature, and other water quality attributes measured at gage sites across the United States. Our query included only sites in the states of Oregon, Montana, Idaho, and Washington that had multiple years of stream temperature measurements and only those years of site data were retained that had at least 300 daily observations. This excluded years that could have omitted entire seasons (temperature sensor malfunctions often occur over consecutive days) and potentially biased annual temperature summaries. The time-series of remaining years with data were then examined and only those sites having at least 20 of the 30 years in the period from 1980–2009 were retained (average number of years was 26). These criteria represented a compromise that provided a contemporaneous view of the largest number of stream sites over the longest period and yielded 18 sites for the analysis (Fig. 1; Table 1). Extending the record prior to 1980 was impossible for many sites because most time-series were initiated in the late 1970's.

The 18 sites used in this assessment encompassed a wide range of stream sizes, elevations, and climatic conditions, but most drained mountainous watersheds and forested landscapes with various landuse histories and limited impacts from urbanization (Table 1). Many of the sites were located in the Oregon coast range and were subject to a moderate maritime climate with annual precipitation of 100–300 cm falling mostly as rain (some snow at higher elevations) during fall, winter, and spring months. Peak flows in these streams typically occurs during the winter and early spring. Sites further inland in Idaho and Montana were generally higher elevation and drier (30–150 cm), with most precipitation
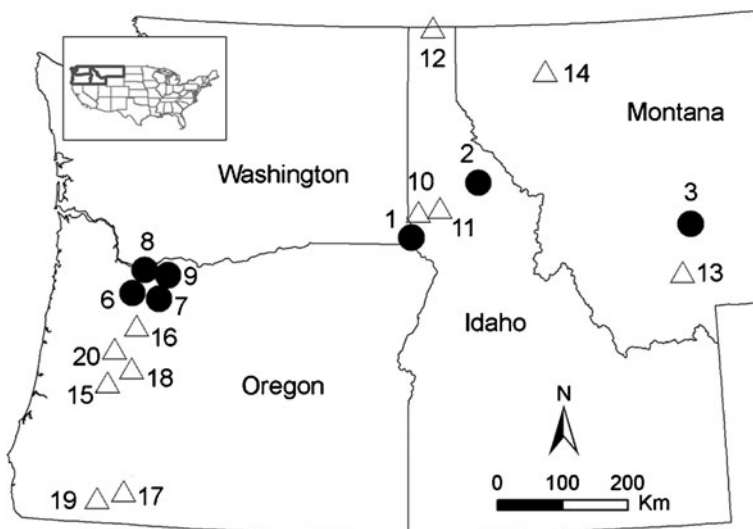

Fig. 1 Locations of 18 river and stream monitoring sites used to assess temperature trends in the northwest U.S. from 1980–2009. Circles denote sites in the unregulated thermal category; whereas triangles denote sites in the regulated category

Table 1 U.S. Geological Survey gage sites for rivers and streams in the northwest U.S. with long-term temperature records that were used to assess trends from 1980–2009. Values in parentheses are the temperature standard deviations and number of years used in the analysis after screening for missing data

Site	Gage number	Gage elevation (m)	Watershed area (km²)	Landcover	Thermal category	Upstream reservoir distance (km)	Average stream temperature (°C)			
							Spring	Summer	Fall	Winter
1. Snake River Near Anatone, WA	13334300	256	240765	Grassland, desert	Unregulated	160	9.4 (0.67, 27)	19.5 (0.89, 28)	14.2 (0.54, 27)	3.9 (0.55, 27)
2. North Fork Clearwater River, ID	13340600	506	3356	Forest	Unregulated	–	5.7 (0.71, 24)	15.5 (1.42, 26)	8.2 (0.62, 23)	1.1 (0.59, 25)
3. Missouri River, MT	6054500	1191	37992	Grassland, forest	Unregulated	–	8.9 (0.91, 30)	18.8 (1.17, 30)	8.7 (0.83, 28)	0.5 (0.32, 28)
6. South Fork Bull Run River, OR	14139800	302	39	Forest	Unregulated	–	6.3 (0.85, 29)	12.2 (0.86, 29)	8.6 (0.51, 30)	4.1 (0.56, 30)
7. Fir Creek, OR	14138870	439	14	Forest	Unregulated	–	5.5 (0.77, 27)	10.7 (0.82, 30)	8.1 (0.48, 29)	4.0 (0.47, 28)
8. North Fork Bull Run River, OR	14138900	323	21	Forest	Unregulated	–	5.9 (0.84, 29)	10.3 (0.36, 27)	7.8 (0.47, 30)	3.7 (0.53, 29)
9. Bull Run River, OR	14138850	329	124	Forest	Unregulated	–	5.8 (0.79, 28)	12.0 (0.82, 28)	8.4 (0.50, 26)	3.6 (0.53, 27)
10. Clearwater River at Spaulding, ID	13342500	235	24042	Forest	Regulated	30	7.8 (0.90, 27)	14.7 (2.06, 28)	10.2 (0.91, 27)	3.5 (0.44, 23)
11. Clearwater River Near Peck, ID	13341050	283	20657	Forest	Regulated	5	6.7 (0.60, 29)	13.4 (1.56, 29)	9.6 (0.55, 26)	3.2 (0.46, 26)
12. Kootenai River, ID	12322000	518	35482	Forest	Regulated	25	7.3 (0.88, 24)	15.4 (1.27, 25)	11.0 (0.63, 26)	3.8 (0.80, 21)
13. Madison River, MT	6041000	1429	5661	Grassland, forest	Regulated	1	7.3 (1.16, 27)	18.1 (0.98, 28)	8.5 (0.86, 26)	1.4 (0.33, 26)
14. Flathead River, MT	12363000	908	11561	Forest	Regulated	15	5.1 (0.52, 29)	12.2 (1.30, 28)	7.1 (1.25, 29)	2.6 (0.44, 30)
15. Fall Creek, OR	14151000	194	481	Forest	Regulated	1	8.7 (0.76, 23)	12.8 (1.47, 24)	11.9 (0.79, 24)	6.2 (0.79, 22)
16. North Santiam River, OR	14181500	333	1173	Forest	Regulated	1	5.8 (0.40, 26)	9.1 (0.97, 26)	11.5 (0.64, 26)	5.1 (0.60, 27)
17. Rogue River Near McLeod, OR	14337600	454	2429	Forest	Regulated	2	7.6 (0.56, 28)	11.8 (0.59, 29)	8.5 (0.59, 28)	5.5 (0.45, 28)
18. Blue River, OR	14162200	322	227	Forest	Regulated	1	6.4 (0.46, 23)	9.1 (1.30, 26)	12.6 (1.31, 25)	5.2 (0.59, 26)
19. Rogue River at Dodge Bridge, OR	14339000	388	3146	Forest	Regulated	16	8.5 (0.74, 27)	13.2 (0.76, 27)	9.0 (0.44, 28)	5.4 (0.48, 27)
20. South Santiam River, OR	14187200	162	1442	Forest	Regulated	1	8.4 (0.73, 22)	12.1 (0.55, 22)	11.0 (0.64, 22)	6.5 (0.59, 25)

falling as snow during the winter and spring periods. Peak runoff at these sites occurs in late spring and early summer as air temperatures warm enough to melt accumulated snowpacks.

3.2 Stream temperature metrics

Mean daily stream temperatures were obtained (or calculated as the average of the daily maxima and minima) for each year in a temperature time-series that met the 300 day criterion described above. The calendar year average of these values was used as the estimate of annual stream temperature. Similar summaries were constructed for each year's seasonal periods; Spring (March, April, May), Summer (June, July, August), Fall (September, October, November), and Winter (December, January, February). As a minimum threshold, we required temperature measurements from 75 of the days in a seasonal period for that season to be included in the analysis. Because of a general concern that climatic extremes will change faster than mean conditions (Jentsch et al. 2007; IPCC 2007), we also summarized each year's Minimum Weekly Average Temperature (MinWAT) and the Maximum Weekly Average Temperature (MaxWAT) from the seven-day rolling averages of daily means.

3.3 Air temperature and discharge data

To assess linkages between stream temperature and air temperature and discharge, we summarized the latter variables from climate stations associated with each of the 18 monitoring sites. Air temperature data were not available at the 18 stream temperature sites so were obtained from the nearest three weather stations in the U.S. Historical Climatology Network (Menne et al. 2009; http://cdiac.ornl.gov/epubs/ndp/ushcn/background.html) that had the most complete daily records from 1980–2009. The air monitoring stations were located 26–168 km away from the stream temperature sites, but strong regional and landscape level correlations among air temperatures (Beever et al. 2010; Holden et al. 2011) suggest these remote locations provided sufficiently precise information for our purposes. Moreover, Mohseni et al. (1998) demonstrated that separation distances up to 244 km had no discernable effect on the accuracy of stream temperature models developed using air temperature data from remote stations. To minimize the possibility that anomalous readings from one air temperature station could adversely affect our results, we averaged daily measurements from the three weather stations associated with each stream temperature site to make a composite air temperature record (Pearson correlations among the air temperature time-series averaged 0.96).

Daily discharge measurements were available from the stream gage at the same site as the stream temperature measurements and were downloaded from the U.S. Geological Survey National Water Information System (NWIS; http://waterdata.usgs.gov/nwis). Given the periodicity in discharge data associated with PDO cycles (Hamlet and Lettenmaier 1999; Mote et al. 2003), a longer period of record than 1980–2009 was necessary to accurately represent trends associated with long-term climate change. A standard period often considered in many hydrologic assessments of climate change in the western U.S. is 50–60 years because it encompasses two recent opposing PDO phases (Luce and Holden 2009; Stewart et al. 2005; Hamlet et al. 2007). Time-series for the discharge data, therefore, were obtained back to 1954 to examine a 56 year period because that was also a consistent start date for most of the stream gages. Daily mean discharge and air temperature values were summarized for each year and the same seasonal and annual periods as those described above for stream temperatures. Table 2 summarizes the trends observed in these data during recent decades.

Table 2 Decadal trends by season in air temperatures and stream flows associated with 18 temperature monitoring sites on rivers and streams in the northwest U.S. (SD in parentheses). Discharge data were obtained from the USGS gage co-located with the water temperature sensor and air temperature data were averages from the nearest three NOAA Cooperative observer weather stations

Climate variable	Thermal category	Spring	Summer	Fall	Winter	Annual
30 year air temperature trend (°C/decade)	Unregulated	−0.13 (0.08)	0.36 (0.10)	0.17 (0.10)	0.12 (0.12)	0.13 (0.018)
	Regulated	−0.12 (0.14)	0.35 (0.082)	0.16 (0.086)	0.13 (0.11)	0.12 (0.036)
56 year discharge trend (% change/decade)	Unregulated	−1.1% (2.4%)	−3.5% (1.2%)	−0.8% (3.4%)	−3.5% (2.2%)	−2.1% (1.1%)
	Regulated	−5.5% (6.2%)	−1.7% (6.7%)	−0.22% (5.1%)	−3.82% (6.7%)	−2.8% (1.0%)

[a] Percentages calculated relative to the average discharge at individual gages from 1980–2009.

3.4 Data analysis

Data associated with the 18 sites were stratified into two categories for subsequent analyses; sites with stream temperature data measured downstream of reservoirs that could alter thermal trends (hereafter "regulated sites") and those with measurements taken on free-flowing rivers and streams (hereafter "unregulated sites"). One exception was the Snake River site, which was included in the unregulated category because the nearest reservoir was 160 km upstream. The spatial lags over which stream temperatures are correlated are generally much less than this (Isaak et al. 2010a), so it was assumed that river temperatures would equilibrate to local climatic conditions before reaching the temperature site. Moreover, two large unregulated tributaries, the Salmon River and the Grande Ronde River enter the Snake River and double its size upstream of the Anatone temperature site to further dilute any remaining reservoir effects.

Patterns of regional coherence in stream temperatures were described by calculating Pearson correlations among all pairwise combinations of sites for each of the seasonal periods. We tested whether the correlations among sites within the two stream classes differed statistically using two-sample t-tests ($\alpha=0.05$). Trends from raw data at individual sites were estimated from simple linear regressions of each temperature metric versus year over the 1980–2009 period (Fig. 2). The slope parameter for year was multiplied by 10 to convert annual rates to decadal rates. The average rate was then calculated across all the streams in a thermal category (annually or within
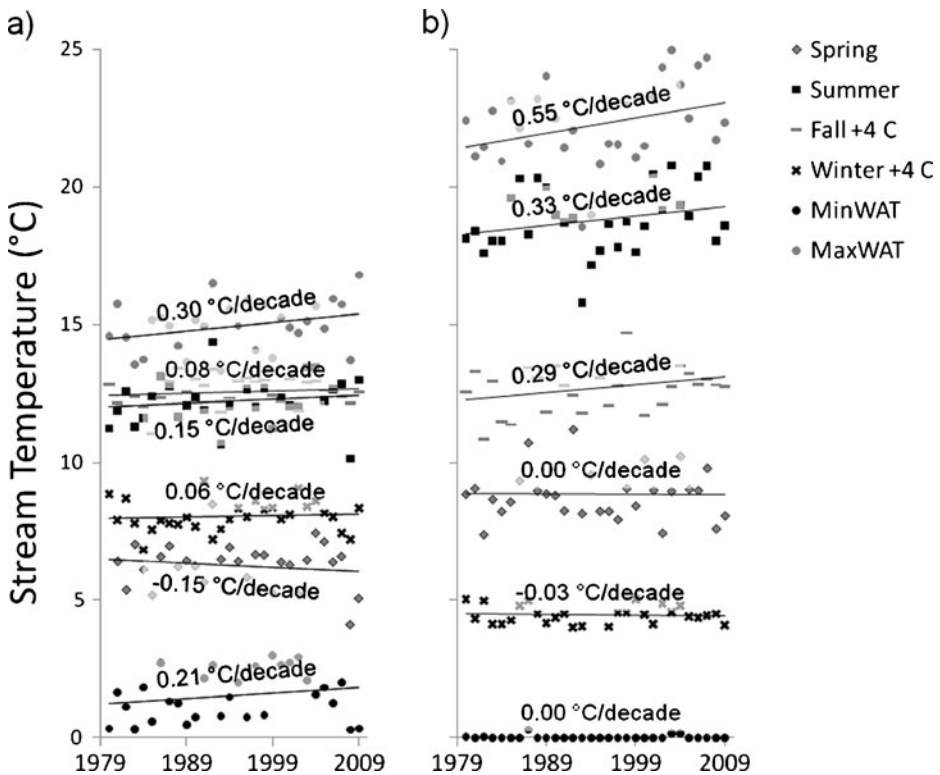

Fig. 2 Examples of raw seasonal temperature trends at two unregulated sites; the South Fork Bull Run River, OR (**a**) and the Missouri River near Toston, MT (**b**) from 1980–2009. Trend lines represent simple linear regressions of the raw time series and trend estimates are the slope parameters converted to decadal rates. Fall and winter temperatures were offset for better visibility by adding 4°C to all values

a seasonal period) and tested for statistical difference from zero using a one sample *t*-test. We tested the group as a whole rather than the significance of trends at individual sites because of our interest in ascertaining broad, regional patterns that were anticipated with climate change.

Trend estimates from raw data suffer two potential deficiencies, however. These include bias that may result from missing years of observations and could be important given the relatively short length of available time-series (Table 1). This short length also means that trend estimates could be unduly influenced by regional climate cycles because the PDO, in particular, has a periodicity approximating the length of stream temperature time series in the northwest U.S. (Mantua and Hare 2002). We therefore derived a complimentary set of reconstructed trend estimates using multiple regression models to overcome these deficiencies. This linear modeling approach was chosen over the nonlinear approaches often employed in similar reconstructions (e.g., Mohseni et al. 1998; Webb et al. 2003; Van Vliet et al. 2010) because temperatures in the streams we studied were rarely warm enough for the nonlinear behavior of atmospheric heat exchange processes to be relevant (Mohseni and Stefan 1999). Multiple regressions have also worked well in previous stream temperature reconstructions (Moatar and Gailhard 2006; Isaak et al. 2010a) and pilot analyses we conducted yielded more accurate results than the nonlinear approaches.

Reconstructed trend estimates were obtained by first developing a multiple regression that predicted stream temperature from the air temperature and discharge values associated with a monitoring site. Once this link was established and parameter estimate existed for air temperature and discharge, the trends in the predictors at a site were used to describe the total amount of stream temperature change from 1980–2009. This approach was not affected by missing data because monitoring records for air temperatures and discharge data were nearly continuous or were made so through adjustments based on inter-station correlations in climate station data (Menne et al. 2009). Parameters in the regression models also provided flexibility in terms of the climate scenarios considered. Rather than having to rely exclusively on changes that occurred during the last 30 years, for example, it was possible to consider trends that occurred over longer time periods, so we used 56 year discharge trends to offset the effects of opposing PDO phases in the reconstructed trend estimates. We retained the air temperature trend rates for the 30-year period from 1980–2009 in the reconstructions because of the globally coherent warming signal that emerged approximately 30 years ago and because air temperature increases have been accelerating (IPCC 2007; Meehl et al. 2009).

The final advantage to the multiple regression approach for reconstructing trends was that the parameter estimates for discharge and air temperature provided insights regarding how stream temperatures were responding to regional climate forcing. To determine whether discharge and air temperature effects were additive or multiplicative, we tested for significant interactions between these predictors. Standardized regression coefficients were also calculated to determine the relative importance of the predictors in causing inter-annual variation in the raw stream temperature time-series. Finally, the reconstructed stream temperature trends from 1980–2009 were decomposed and associated with each predictor to assess the relative influence of each on long-term stream temperature trends.

4 Results

Pairwise correlations among stream temperatures at the 18 sites varied by season and thermal class (Table 3), with correlations among unregulated sites being significantly stronger than those among regulated sites (annual period: $r_{unregulated} = 0.74$ versus $r_{regulated}$ 0.41; Table 3). The one seasonal exception was the winter period when streams were coldest and least thermally

Table 3 Pairwise correlations between summer stream temperatures from 1980–2009 for 18 rivers and streams in the northwest U.S. Values in bold are for streams in the unregulated thermal category; numbers correspond to the same streams in Table 1. Table inset shows average pairwise correlations among all sites by season; asterisks indicate seasons when the correlations differed statistically between thermal categories ($\alpha \leq 0.05$)

	1	2	3	6	7	8	9	10	11	12	13	14	15	16	17	18	19
2	**0.80**																
3	**0.67**	**0.52**															
6	**0.61**	**0.61**	**0.50**														
7	**0.58**	**0.64**	**0.47**	**0.96**													
8	**0.45**	**0.56**	**0.26**	**0.73**	**0.71**												
9	**0.69**	**0.77**	**0.50**	**0.89**	**0.92**	**0.77**											
10	0.17	0.31	−0.04	0.14	0.09	0.17	0.19										
11	0.10	0.30	−0.13	0.03	0.01	0.11	0.15	0.95									
12	0.29	0.43	0.19	0.15	0.25	0.34	0.25	0.43	0.47								
13	0.73	0.54	0.88	0.48	0.44	0.21	0.40	−0.25	−0.30	0.12							
14	0.41	0.39	0.28	0.17	0.25	0.24	0.28	−0.65	−0.63	0.00	0.46						
15	0.15	−0.25	0.06	−0.04	−0.09	−0.06	−0.08	−0.26	−0.34	−0.09	0.18	0.08					
16	0.20	0.15	0.27	0.01	0.03	0.26	0.01	−0.37	−0.36	0.13	0.29	0.49	0.11				
17	0.75	0.60	0.38	0.42	0.42	0.35	0.47	−0.08	−0.21	0.15	0.58	0.34	0.05	0.39			
18	0.32	0.45	0.02	0.41	0.41	0.35	0.46	0.63	0.52	0.45	−0.05	−0.34	−0.39	0.02	0.38		
19	0.68	0.54	0.44	0.56	0.51	0.43	0.55	−0.15	−0.29	0.02	0.62	0.31	0.13	0.33	0.88	0.42	
20	−0.18	0.03	−0.34	−0.12	−0.12	0.29	0.02	0.73	0.64	0.05	−0.54	−0.36	−0.48	−0.23	−0.23	0.44	−0.32

Table inset:

Thermal category	Spring*	Summer*	Fall*	Winter*	Annual*
Unregulated	0.81	0.65	0.59	0.61	0.74
Regulated	0.58	0.20	0.28	0.49	0.41

variable. The discrepancy between stream classes was also apparent in efforts to develop multiple regression models for the trend reconstructions. These regressions performed well at unregulated sites ($R^2 \sim 0.70$; RMSE~ 0.33°C) but poorly at regulated sites ($R^2 \sim 0.34$; RMSE~ 0.68°C), where the parameter estimates were also inconsistent. This suggested thermal patterns at regulated sites were effectively decoupled from the local climates by the reservoir effects and local water management policies. As a result, temperature trend estimates at regulated sites were based only on the raw trend estimates.

Temperature trends across the seven unregulated sites were significantly different from zero during many seasons of the year (Figs. 3 and 4; Appendix A). A cooling trend was apparent during the spring and warming trends during other seasons, with warming rates highest during the summer (raw trend = 0.17°C/decade; reconstructed trend = 0.22°C/decade). Estimates based on the raw data were usually smaller and less precise than reconstructed estimates, suggesting that missing data and short-term discharge trends were influencing the estimates. Comparison of trends in annual temperature extremes (MinWAT raw trend = 0.21°C/decade, $p < 0.01$; MaxWAT raw trend = 0.28°C/decade, $p < 0.01$) to the summer and winter periods in which they occurred (Fig. 3) suggested more rapid warming of the year's highest and lowest weekly temperatures.

In contrast to the unregulated sites, statistically significant trends across the 11 regulated sites were never detected. This remained true even after estimates were excluded from two sites on the Clearwater River where cold-water releases from an upstream reservoir had caused dramatic cooling trends (Fig. 3; Appendix A). Seasonal averages at the remaining 9
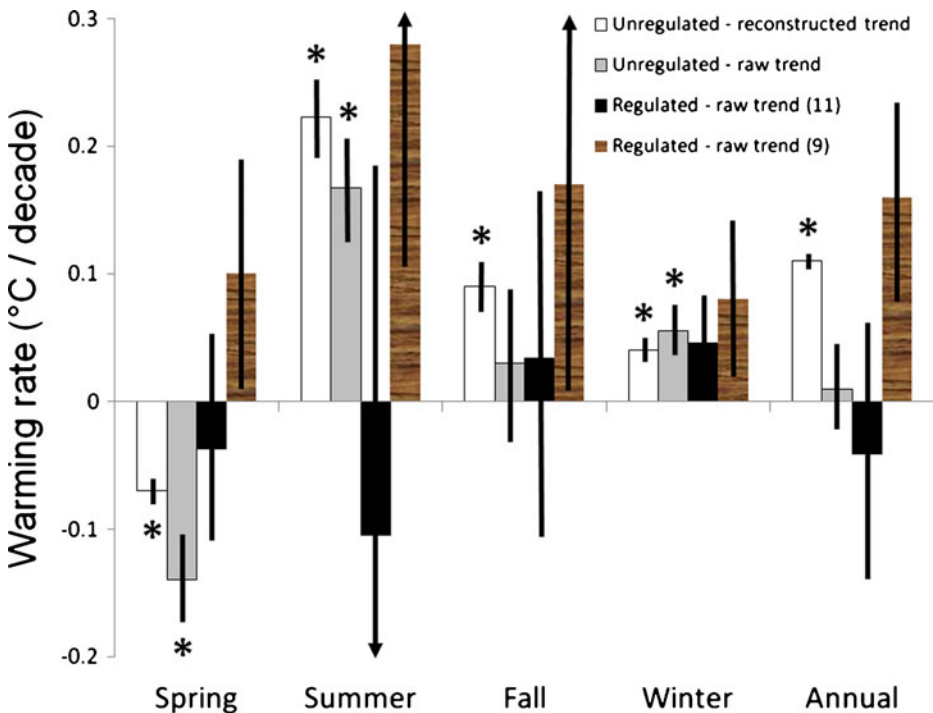

Fig. 3 Seasonal temperature trend estimates across 18 stream sites in the northwest U.S. Error bars denote ± 1 SE; asterisks denote trends that are significantly different from zero at $\alpha \leq 0.05$. Arrows indicate SE values that extend beyond the Y-axis scale
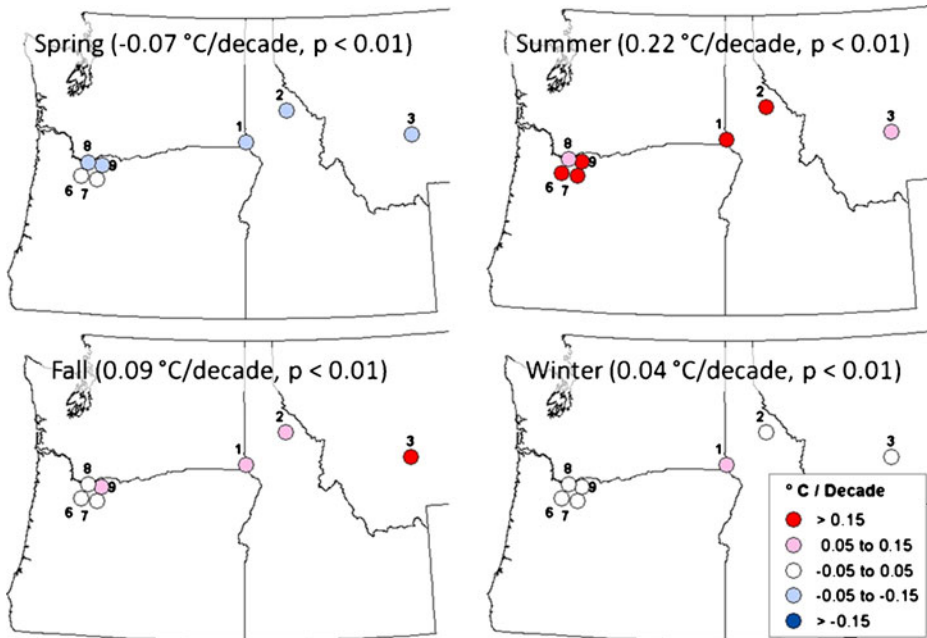
Fig. 4 Spatial variation in seasonal temperature trends from 1980–2009 based on reconstructed historical trends for seven unregulated river and stream sites across the northwest U.S.

sites were indicative of warming, but considerable variation among sites precluded ascribing statistical significance.

Multiple regressions at the seven unregulated sites indicated a consistent relationship between air temperature and stream temperature, with the air temperature parameter being statistically significant and positively related to stream temperature in all 35 of the seasonal and annual regressions calculated (Appendix B). The discharge relationship was less consistent, with this parameter negatively related to stream temperature in 28 of 35 regressions but statistically significant only in half (17 of 35). Significant interactions between air temperature and discharge occurred in only 2 of the 35 regressions, suggesting that these effects were additive and could be considered separately. Comparison of the standardized regression coefficients for air temperature and discharge indicated air temperature was the dominant factor accounting for inter-annual variation in stream temperatures (48–86% of variation), except during the summer when discharge accounted for half the inter-annual variation (Fig. 5; Appendix C). Trend decomposition suggested air temperature trends consistently accounted for the majority of stream temperature trends (82–94%) observed from 1980–2009 (Fig. 5; Appendix C).

5 Discussion

A sample of 18 stream sites with long-term temperature monitoring records is a small one from which to generalize, especially when the majority of these sites was affected by upstream reservoirs and did not provide useful trend data for assessing responses to climate forcing. Moreover, none of the unregulated sites was likely to have "pristine" thermal conditions, given more than a century of anthropogenic land uses, forest management, water abstractions, and degradation of riparian ecosystems in this region (McIntosh et al. 2000; Hessburg and Agee

Fig. 5 Relative contributions of air temperature and discharge to inter-annual variation in raw stream temperature time-series (**a**) and long-term temperature trends based on decomposition of reconstructed historical trends (**b**) at seven unregulated river and stream sites in the northwest U.S. Temperature values under bars are the total stream temperature changes that occurred from 1980–2009 based on the reconstructed trends
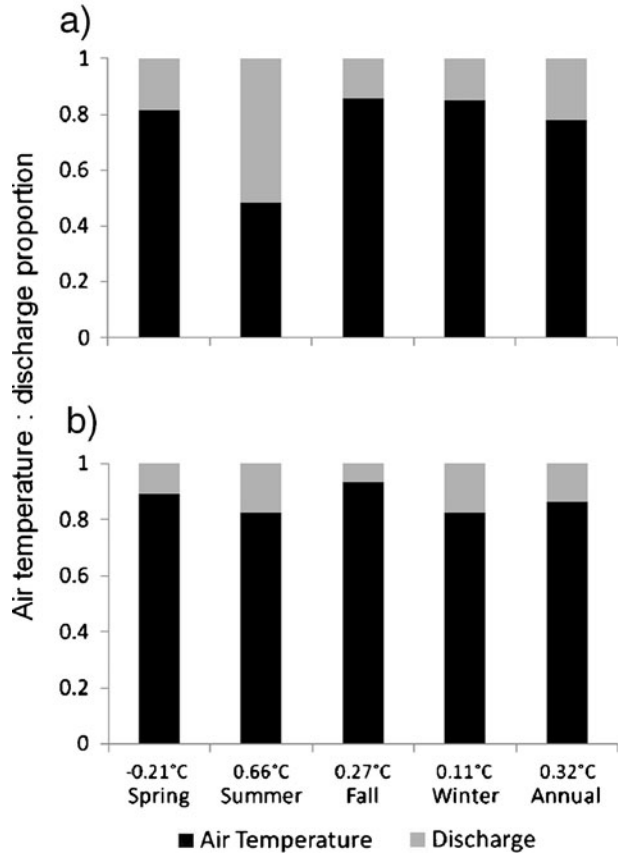
2003). The temperature data at these seven sites, however, are some of the few long-term monitoring records that have not been significantly altered by the proximity of upstream reservoirs or urbanization and it is unlikely that factors other than climate would have occurred systematically across these sites to cause the patterns we observed. The consistency of the temperature responses at these sites, which included important diversity (i.e., coastal and inland sites, large and small streams, high and low elevation sites), suggests that many streams in this region are responding similarly to regional climate forcing. Significant warming during many seasons of the year has more than offset a spring cooling trend in recent decades to cause a net temperature increase that generally tracks regional air temperature increases (Mote et al. 2003; Mote et al. 2005, Hamlet et al. 2007). As a result, this study adds to the growing list that documents warming of the Earth's rivers and streams (Petersen and Kitchell 2001; Morrison et al. 2002; Bartholow 2005; Hari et al. 2006; Webb and Nobilis 2007; Moatar and Gailhard 2006; Durance and Ormerod 2009; Kaushal et al. 2010), and makes a useful contribution by providing trend estimates that are not potentially confounded by short-term climate cycles, urbanization, or reservoir development.

Current projections for air temperature increases across the northwest U.S. (IPCC 2007; Mote et al. 2008) suggest stream temperatures will continue to warm this century. Moreover, these projections suggest air temperature increases during the next several decades will occur at rates 50–100% faster than in recent decades (Mote et al. 2008; Mantua et al. 2010). Air temperature increases of this magnitude during the summer would imply stream temperature warming rates of 0.3°C/decade–0.45°C/decade. Total thermal gains of 1.2°C–1.8°C could be

expected by midcentury (assuming the ~60% ratio for stream:air warming rates we observed), which supports recent estimates Mantua et al. (2010) made for rivers across the state of Washington. Air temperature increases during non-summer seasons are projected to occur more slowly (Mote et al. 2008), and periods of cooling as we observed in the spring may even persist for decades at a time (Easterling and Wehner 2009), but it appears that fish and other aquatic organisms will ultimately have to adjust to warmer stream temperatures.

5.1 Seasonal trends and attribution

Air temperature was a much stronger predictor of stream temperatures than discharge in our models as others have found when these factors are considered simultaneously (Hockey et al. 1982; Webb et al. 2003; Moatar & Gailhard 2006; Isaak et al. 2010a; Van Vliet et al. 2010). Moreover, seasonal stream temperature trends (both warming and cooling) tracked air temperature trends during the same season and sometimes ran counter to the consistent warming effect otherwise expected from the general decline in discharge observed during all seasons at the monitoring sites (Table 2). Statistical interactions between air temperature and discharge were rare in the regression models, however, suggesting that stream temperature sensitivity to air temperature forcing was not contingent on discharge level. Rather, the two effects appear to be additive and the seasonal variation in stream warming rates is drawn from how the two predictors operate in concert or opposition over a period of time. So, for example, the largest warming trend during the summer resulted from the effects of the largest air temperature increases added to the largest discharge decreases, rather than smaller discharges being more easily warmed by air temperature increases.

Mechanistic explanations regarding how air temperatures affect stream temperatures have been treated in detail on numerous occasions (Mohseni and Stefan 1999; Caissie 2006; Webb et al. 2008), so are not addressed at length here. It suffices to say that air temperature affects more than one physical process in stream heat budgets and warms streams directly through sensible heat transfer, indirectly by increasing groundwater temperatures and advective heat gains (Taylor and Heinz 2009; Gunawardhana and Kazama 2011), and by radiating more long-wave radiation into streams (Webb and Zhang 1997; Webb et al. 2008). Less understood are mechanistic relationships between discharge and stream temperatures because it has often been assumed that this effect operated indirectly by increasing the sensitivity of streams to air temperature increases (e.g., Smith and Lavis 1975). The lack of a significant interaction in our regression models, however, suggests a different explanation. Discharge may in reality be a surrogate for water velocity such that higher discharges are indicative of decreased travel time through a reach and less opportunity for streams to equilibrate to local microclimatic conditions (Meier et al. 2003). This could explain why stream slope is often negatively related to stream temperature in river-network scale models (Sloat et al. 2005; Wehrly et al. 2009; Isaak et al. 2010a). An alternative mechanism may be that discharge equates to the relative influence of the snowpack and the amount of cold groundwater inputs along stream courses since many of the streams we studied are snowmelt dominated systems. In years with smaller snow accumulations, these groundwater inputs may be diminished and initial temperatures in headwater source areas warmer. Regardless, studies clarifying the mechanistic role of discharge in regulating stream temperatures would be useful.

5.2 Temperature monitoring needs

One of the strongest conclusions from this study is that long-term and representative monitoring of river and stream temperatures has been inadequate. Most monitoring records exist at sites that

are near reservoirs or in urban environments (Kaushal et al. 2010), which largely compromises their utility for understanding a phenomenon such as climate change. Moreover, there are hundreds of thousands of unregulated stream kilometers that support fish and other aquatic organisms in the northwest U.S., yet perhaps only seven sites with more than a few decades of full year data to provide some indication of long-term temperature trends. In recent years, natural resource agencies have begun to deploy thousands of temperature sensors in streams across the region (Isaak et al. 2010b; Isaak and Horan 2011) but these efforts are poorly coordinated, often redundant, and typically limited to summer data collections due to concerns about instrument losses during annual floods. Implementation of an extensive monitoring network that generated full-year data would be invaluable and could be accomplished at a fraction of current costs if properly coordinated. Spatial databases, reliable and inexpensive sensor technology, and improved methods for establishing permanent sites in streams should make this easier in the future (Dunham et al. 2005; Isaak et al. 2010b; Isaak and Horan 2011).

Better monitoring efforts are important, but actions in the near-term to mitigate the threats posed by climate change will require information soon regarding how temperatures are changing across a broad array of streams. Historical reconstructions like those employed here or in previous studies (Moatar and Gailhard 2006; Isaak et al. 2010a; Van Vliet et al. 2010) could provide a powerful means of leveraging useful information from existing databases without waiting decades for monitoring data to accumulate. Another useful technique may be sensitivity analyses (Mohseni et al. 1999; Trumbo et al. 2010) wherein inter-annual changes in stream temperatures are examined across many monitoring sites spread along important environmental gradients (Post et al. 2009 provide a biological example). In the span of a few years, a monitoring network could generate the data necessary to disentangle the relative roles of spatial variation in local climate forcing (i.e., changes in air temperature and stream flow; Daly et al. 2009; Holden et al. 2011) and stream responsiveness due to geomorphic or other considerations (i.e., glaciation, elevation, ground water buffering; Hari et al. 2006; Brown and Hannah 2008; Tague et al. 2008) in effecting stream temperature change. To the extent that non-climate factors matter, they might then be used to develop geographic classification schemes for mapping the relative vulnerabilities of streams to climate change (e.g., Wolock et al. 2004; Santhi et al. 2008). These data would also contribute to a more general understanding of how temporal variation in stream thermal regimes is spatially structured and facilitate attribution of this variability to appropriate mechanisms at regional, landscape, and stream scales.

5.3 Implications for salmonid fishes

As streams and rivers across the northwest U.S. warm this century, it will have significant biological implications for both the quality and quantity of habitats available to species of regional importance like salmon and trout. Several anadromous salmon species that return to spawn each year in this region do so during the summer period when average temperatures and seasonal extremes (i.e., MaxWATs) are warming most rapidly. In some instances, these migrations are now periodically disrupted during especially warm periods as the fish pause to congregate near cold-water sources (Goneia et al. 2006; Sutton et al. 2007; Keefer et al. 2009) and fish that migrate during the year's warmest temperatures often return less successfully to their spawning areas (Cooke et al. 2004; Keefer et al. 2008). Thermal "events" wherein hundreds or thousands of adult salmon die simultaneously because thermal tolerances are exceeded have been documented in recent years (Lynch and Risley 2003, Doremus and Tarlock 2008; Keefer et al. 2010) and important recreational fisheries are now sometimes suspended during warm periods to minimize additional fish stress (Brick et al. 2008). The frequency of these thermal impacts to populations during warm summer periods appears likely to increase in the future

(Jentsch et al. 2007; Mantua et al. 2010), so understanding where thermal tolerances are close to being exceeded for key fisheries resources is an important priority.

Warming temperatures are also expected to have less dramatic, but wide-ranging population effects. Zones of species sympatry and thermal boundaries at the edges of species distributions are expected to gradually shift upstream (Parmesan and Yohe 2003; Root et al. 2003; Rieman and Isaak 2010) as the outcomes of competitive interactions are increasingly skewed towards species with warmer temperature tolerances (DeStaso and Rahel 1994; McMahon et al. 2007) and physiologic limits are exceeded (Pörtner and Farrell 2008). Such shifts will reduce habitats available to native trouts like cutthroat trout and bull trout that often persist in the colder waters upstream of encroaching non-native fishes (Peterson and Fausch 2003; Rieman et al. 2006; Fausch et al. 2006). Warmer cold season temperatures and annual minima also mean that biological processes will proceed at slightly faster rates during the winter period. Although this is a relatively quiescent time for the adults of many species in temperate streams, many salmon and trout species spawn in the fall and eggs incubate in stream substrates before hatching late in the winter or early spring. Egg development and hatching dates are strongly regulated by rates of degree-day accumulation (Crisp 1988; Beacham and Murray 1990), suggesting that warming trends will reduce the time between spawning and juvenile hatching. Accelerated egg development could benefit populations in high elevation streams that are currently too cold and unproductive to support populations (Bystrom et al. 2006; Coleman and Fausch 2007) but in other streams could desynchronize juvenile hatching and emergence dates from optimal periods dictated by annual floods and food availability (Brannon et al. 2004). In a few instances, migration dates of salmon past hydroelectric dams in northwest U.S. rivers appear already to be shifting in response to warming temperatures (Keefer et al. 2008; Crozier et al. 2008) but data to describe long-term biological responses during other life-stages or across spatial distributions are rare.

5.4 Management implications

Ongoing temperature increases will profoundly influence the ecology of salmonids as described above, but the summer period, in particular, may become a key bottleneck for many species. Not only are temperatures warming most rapidly during this period, but the volume of available habitat is shrinking as summer stream discharges across the region continue multi-decadal declines that have also been partially linked to climate change (Stewart et al. 2005; Luce and Holden 2009; Leppi et al. 2011). Many things can be done to ameliorate stresses on salmonids during this period (Rieman and Isaak 2010). On large rivers where cold-water storage is available behind reservoirs, water releases could be timed to decrease temperatures during critical biological periods as has been the case on the Clearwater River for migrating salmon in northern Idaho the last two decades. On smaller streams, maintaining or restoring instream flows and improving riparian communities to increase stream shading could offset significant amounts of future warming where degradation is severe (Meier et al. 2003; Moore et al. 2005; Cristea and Burges 2009). Removal of barriers to fish movement could decrease fragmentation and provide populations the flexibility to shift their distributions and track thermal habitat as needed (Fausch et al. 2006; Daufresne and Boet 2007; Isaak et al. 2010a). Basic fish distribution monitoring programs are also needed (Rieman et al. 2006; Isaak et al. 2009) so that anticipated shifts in species distributions can be accurately described in future decades to provide a clearer understanding of how salmonids integrate and respond to changes in thermal conditions (McCullough et al. 2009).

Tactical responses are key, but needed conservation projects are likely to greatly exceed available resources, so strategic prioritization schemes are essential. Improving regional monitoring

networks and new models capable of accurately downscaling climate change effects on stream thermal regimes and other attributes across broad areas can provide the information necessary to implement such schemes (e.g., Rieman et al. 2007; Isaak et al. 2010a; Wenger et al. 2010; Wenger et al. 2011b). This information, however, needs to be integrated into detailed aquatic vulnerability assessments so that it provides "actionable intelligence" regarding priorities for specific projects at both regional and local scales. If these vulnerability assessments were used by consortiums of collaborating agencies with sets of common goals, available conservation resources could be leveraged across agencies and redundancies minimized (Rieman et al. 2010).

6 Conclusion

A growing number of studies predict substantial disruptions to aquatic ecosystems from climate change within the northwest U.S. (Battin et al. 2007; Rieman et al. 2007; Crozier et al. 2008; Schindler et al. 2008; Isaak et al. 2010a; Mantua et al. 2010; Wenger et al. 2011a) and more broadly (Eaton and Schaller 1996; Keleher and Rahel 1996; Mohseni et al. 2003; Hari et al. 2006; Heino et al. 2009). The trends in river and stream temperatures we document, in combination with increasing evidence of thermal constraints on some populations (Cooke et al. 2004; Goneia et al. 2006; Sutton et al. 2007; Keefer et al. 2007; Doremus and Tarlock 2008; Keefer et al. 2009), suggest these predictions are being realized. Although most species have persisted through greater climatic perturbations in past millennia, modern climate change is happening especially rapidly, at the end of an already warm period, and is being imposed on populations that are often already depressed and fragmented from a century of intense human development (McIntosh et al. 2000; Hessburg and Agee 2003). To minimize the losses of biodiversity that could occur in the next half century, much needs to be learned in a relatively short period of time about changing stream and river thermal regimes and aquatic ecological responses (McCullough et al. 2009).

The task is substantial, but the resources to create the necessary infrastructure for improved stream temperature monitoring, modeling, and strategic assessments would represent a tiny portion of those typically available for aquatic conservation purposes. In the northwest U.S., almost $4 billion U.S. dollars have been spent in recent decades to monitor and restore salmon and trout habitats (McDonald et al. 2007). These efforts have met with some success, but mainly have helped minimize declines in many species and stream habitats (McDonald et al. 2007; Al-Chokhachy et al. 2010). In a warmer, less predictable future, past investments and future project successes could be vulnerable to rising stream temperatures that gradually or catastrophically shift habitat suitability away from target species (Lawler et al. 2009). The apparent shift in recent years to cooler PDO conditions across the northwest U.S. may provide a brief respite before a warming trend is resumed that will become increasingly stressful for many salmonid fishes in the northwest U.S. This opportunity should be used to gain important information about stream temperature regimes and develop better tools, knowledge, and prioritization schemes for what may lie ahead.

Appendix A

Table 4 Seasonal temperature trends at individual sites on 18 rivers and streams in two thermal classes across the northwest U.S. from 1980–2009. Trend rates from raw data were estimated as the slope parameter of simple linear regressions (multiplied by 10 to convert to decadal rate) of stream temperature versus year. Subscripts denote the r^2 of the simple linear regressions. Values in parentheses are decadal rates based on trends reconstructed using multiple regressions with air temperature and discharge as predictors

Site	Thermal category	Spring period (°C/decade)	Summer period (°C/decade)	Fall period (°C/decade)	Winter period (°C/decade)	Annual period (°C/decade)
1. Snake River Near Anatone, WA	Unregulated	$-0.18_{6\%}$ (−0.11)	$0.27_{7\%}$ (0.20)	$-0.15_{6\%}$ (0.12)	$0.09_{2\%}$ (0.08)	$-0.08_{2\%}$ (0.13)
2. North Fork Clearwater River, ID	Unregulated	$-0.31_{15\%}$ (−0.12)	$0.05_{0\%}$ (0.33)	$-0.10_{2\%}$ (0.13)	$0.01_{0\%}$ (0.05)	$-0.10_{2\%}$ (0.11)
3. Missouri River, MT	Unregulated	$-0.01_{0\%}$ (−0.05)	$0.33_{6\%}$ (0.14)	$0.29_{10\%}$ (0.18)	$-0.03_{1\%}$ (0.01)	$0.16_{6\%}$ (0.08)
6. South Fork Bull Run River, OR	Unregulated	$-0.15_{2\%}$ (−0.05)	$0.15_{2\%}$ (0.29)	$0.08_{2\%}$ (0.05)	$0.06_{1\%}$ (0.02)	$0.04_{0\%}$ (0.11)
7. Fir Creek, OR	Unregulated	$-0.08_{1\%}$ (−0.05)	$0.21_{5\%}$ (0.27)	$0.01_{0\%}$ (0.05)	$0.09_{3\%}$ (0.03)	$0.07_{1\%}$ (0.11)
8. North Fork Bull Run River, OR	Unregulated	$-0.15_{2\%}$ (−0.05)	$0.07_{3\%}$ (0.10)	$0.13_{6\%}$ (0.04)	$0.05_{1\%}$ (0.04)	$0.02_{0\%}$ (0.09)
9. Bull Run River, OR	Unregulated	$-0.10_{1\%}$ (−0.06)	$0.09_{1\%}$ (0.23)	$-0.08_{2\%}$ (0.05)	$0.10_{3\%}$ (0.03)	$-0.01_{0\%}$ (0.12)
Average =		-0.14^{a} (-0.07^{a})	0.17^{a} (0.22^{a})	0.03 (0.09^{a})	0.05^{a} (0.04^{a})	0.01 (0.11^{a})
10. Clearwater River at Spaulding, ID	Regulated	$-0.22_{5\%}$	$-1.84_{63\%}$	$-0.33_{11\%}$	$-0.01_{0\%}$	$-0.71_{55\%}$
11. Clearwater River Near Peck, ID	Regulated	$0.06_{1\%}$	$-1.47_{68\%}$	$-0.34_{32\%}$	$0.17_{10\%}$	$-0.40_{37\%}$
12. Kootenai River, ID	Regulated	$-0.44_{18\%}$	$-0.25_{3\%}$	$-0.02_{0\%}$	$-0.19_{4\%}$	$-0.09_{2\%}$
13. Madison River, MT	Regulated	$0.20_{2\%}$	$0.45_{16\%}$	$0.22_{5\%}$	$0.03_{1\%}$	$0.17_{6\%}$
14. Flathead River, MT	Regulated	$-0.06_{1\%}$	$1.05_{53\%}$	$1.00_{51\%}$	$-0.16_{10\%}$	$0.44_{45\%}$
15. Fall Creek, OR	Regulated	$-0.25_{10\%}$	$0.59_{14\%}$	$0.07_{1\%}$	$0.16_{4\%}$	$0.05_{1\%}$
16. North Santiam River, OR	Regulated	$0.05_{1\%}$	$0.52_{21\%}$	$-0.11_{3\%}$	$0.19_{8\%}$	$0.16_{13\%}$
17. Rogue River Near McLeod, OR	Regulated	$0.41_{40\%}$	$0.27_{15\%}$	$0.17_{7\%}$	$0.01_{0\%}$	$0.25_{25\%}$
18. Blue River, OR	Regulated	$-0.19_{14\%}$	$-0.48_{11\%}$	$-0.77_{28\%}$	$0.05_{0\%}$	$-0.38_{27\%}$
19. Rogue River at Dodge Bridge, OR	Regulated	$0.30_{13\%}$	$0.33_{14\%}$	$0.24_{21\%}$	$0.19_{11\%}$	$0.17_{10\%}$
20. South Santiam River, OR	Regulated	$-0.31_{15\%}$	$-0.33_{32\%}$	$0.24_{13\%}$	$0.06_{1\%}$	$-0.11_{4\%}$
Average =		-0.04	-0.11	0.03	0.05	-0.04

[a] Statistically significant at $\alpha \leq 0.05$

Appendix B

Table 5 Multiple regression relationships predicting stream temperatures from air temperature and discharge from 1980–2009 for seven unregulated river and stream sites in the northwest U.S. Discharge data were obtained from the USGS gage co-located with the water temperature sensor and air temperature data were averages from the nearest three NOAA Cooperative Observer weather stations

Site	Regression equations[a]	R^2	RMSE(°C)	Significant air temperature–discharge interaction?	COOP stations
Spring period					
1. Snake River Near Anatone, WA	$y=3.43+0.588^a(\text{air °C}) - 0.00013(\text{m}^3/\text{s})$	0.68	0.37	No	102845, 457059, 355593
2. North Fork Clearwater River, ID	$y=1.48+0.548^a(\text{air °C}) - 0.00373(\text{m}^3/\text{s})$	0.79	0.32	No	102845, 457938, 245745
3. Missouri River, MT	$y=7.05+0.583^a(\text{air °C}) - 0.00499^a(\text{m}^3/\text{s})$	0.85	0.35	Yes	248597, 241318, 249023
6. South Fork Bull Run River, OR	$y=1.01+0.716^a(\text{air °C}) - 0.183^a(\text{m}^3/\text{s})$	0.85	0.32	No	353402, 354003, 357500
7. Fir Creek, OR	$y=0.0139+0.701^a(\text{air °C}) - 0.313(\text{m}^3/\text{s})$	0.89	0.26	No	353402, 354003, 357500
8. North Fork Bull Run River, OR	$y=0.768+0.710^a(\text{air °C}) - 0.307^a(\text{m}^3/\text{s})$	0.84	0.33	No	353402, 354003, 357500
9. Bull Run River, OR	$y=-0.276+0.810^a(\text{air °C}) - 0.0392(\text{m}^3/\text{s})$	0.83	0.32	No	353402, 354003, 357500
Average =		0.82	0.32		
Summer period					
1. Snake River Near Anatone, WA	$y=9.02+0.559^a(\text{air °C}) - 0.00116^a(\text{m}^3/\text{s})$	0.81	0.39	No	Same as above
2. North Fork Clearwater River, ID	$y=5.44+0.650^a(\text{air °C}) - 0.0256^a(\text{m}^3/\text{s})$	0.96	0.28	No	
3. Missouri River, MT	$y=9.00+0.670^a(\text{air °C}) - 0.00521^a(\text{m}^3/\text{s})$	0.62	0.71	No	
6. South Fork Bull Run River, OR	$y=3.17+0.595^a(\text{air °C}) - 0.803^a(\text{m}^3/\text{s})$	0.85	0.33	No	
7. Fir Creek, OR	$y=2.78+0.527^a(\text{air °C}) - 2.73^a(\text{m}^3/\text{s})$	0.85	0.31	Yes	
8. North Fork Bull Run River, OR	$y=6.89+0.217^a(\text{air °C}) - 0.319^a(\text{m}^3/\text{s})$	0.45	0.26	No	
9. Bull Run River, OR	$y=5.69+0.445^a(\text{air °C}) - 0.272^a(\text{m}^3/\text{s})$	0.79	0.37	No	
Average =		0.76	0.38		
Fall period					
1. Snake River Near Anatone, WA	$y=9.42+0.438^a(\text{air °C}) - 0.00011(\text{m}^3/\text{s})$	0.51	0.37	No	
2. North Fork Clearwater River, ID	$y=2.47+0.607^a(\text{air °C})+0.00349(\text{m}^3/\text{s})$	0.41	0.47	No	
3. Missouri River, MT	$y=6.64+0.453^a(\text{air °C}) - 0.00387(\text{m}^3/\text{s})$	0.67	0.46	No	

Table 5 (continued)

Site	Regression equations[a]	R^2	RMSE(°C)	Significant air temperature-discharge interaction?	COOP stations
6. South Fork Bull Run River, OR	$y=4.04+0.417^a(\text{air }°C)+0.161^a(\text{m}^3/\text{s})$	0.60	0.32	No	
7. Fir Creek, OR	$y=3.27+0.482^a(\text{air }°C)+0.0864(\text{m}^3/\text{s})$	0.59	0.30	No	
8. North Fork Bull Run River, OR	$y=3.72+0.378^a(\text{air }°C)+0.215^a(\text{m}^3/\text{s})$	0.57	0.30	No	
9. Bull Run River, OR	$y=3.19+0.518^a(\text{air }°C)+0.00844(\text{m}^3/\text{s})$	0.56	0.33	No	
Average =		0.56	0.36		
Winter period					
1. Snake River Near Anatone, WA	$y=3.48+0.309^a(\text{air }°C) - 0.0000015(\text{m}^3/\text{s})$	0.59	0.35	No	
2. North Fork Clearwater River, ID	$y=0.806+0.211^a(\text{air }°C)+0.0087^a(\text{m}^3/\text{s})$	0.53	0.40	No	
3. Missouri River, MT	$y=1.10+0.113^a(\text{air }°C) - 0.00061(\text{m}^3/\text{s})$	0.34	0.26	No	
6. South Fork Bull Run River, OR	$y=2.78+0.490^a(\text{air }°C)+0.0232(\text{m}^3/\text{s})$	0.72	0.29	No	
7. Fir Creek, OR	$y=3.25+0.407^a(\text{air }°C) - 0.118(\text{m}^3/\text{s})$	0.73	0.24	No	
8. North Fork Bull Run River, OR	$y=3.09+0.489^a(\text{air }°C) - 0.160^a(\text{m}^3/\text{s})$	0.78	0.24	No	
9. Bull Run River, OR	$y=2.57+0.448^a(\text{air }°C) - 0.00431(\text{m}^3/\text{s})$	0.70	0.28	No	
Average =		0.63	0.29		
Annual period					
1. Snake River Near Anatone, WA	$y=3.94+0.731^a(\text{air }°C) - 0.000141(\text{m}^3/\text{s})$	0.66	0.32	No	
2. North Fork Clearwater River, ID	$y=1.31+0.743^a(\text{air }°C) - 0.00439(\text{m}^3/\text{s})$	0.47	0.50	No	
3. Missouri River, MT	$y=7.86+0.423^a(\text{air }°C) - 0.00677^a(\text{m}^3/\text{s})$	0.64	0.38	No	
6. South Fork Bull Run River, OR	$y=0.316+0.839^a(\text{air }°C) - 0.116(\text{m}^3/\text{s})$	0.76	0.27	No	
7. Fir Creek, OR	$y=1.15+0.713^a(\text{air }°C) - 0.720^a(\text{m}^3/\text{s})$	0.74	0.26	No	
8. North Fork Bull Run River, OR	$y=1.77+0.603^a(\text{air }°C) - 0.241(\text{m}^3/\text{s})$	0.71	0.23	No	
9. Bull Run River, OR	$y=0.827+0.811^a(\text{air }°C) - 0.0812^a(\text{m}^3/\text{s})$	0.75	0.28	No	
Average =		0.68	0.32		

[a] Statistically significant at $\alpha \leq 0.05$

Appendix C

Table 6 Relative contributions of air temperature and discharge to reconstructed seasonal stream temperature trends and inter-annual variation in raw time series (standardized regression coefficients) from 1980–2009 at seven unregulated river and stream sites in the northwest U.S

Site	Reconstructed trends		
	Total stream temperature change (°C)	Air temperature, discharge contributions (°C)[a]	Standardized b_x's (air temperature, discharge)[b]
Spring Period			
1. Snake River Near Anatone, WA	−0.325	−0.307, −0.018	0.78, −0.12
2. North Fork Clearwater River, ID	−0.346	−0.453, 0.107	0.80, −0.20
3. Missouri River, MT	−0.155	−0.198, 0.043	0.81, −0.25
6. South Fork Bull Run River, OR	−0.143	−0.168, 0.024	0.81, −0.20
7. Fir Creek, OR	−0.147	−0.164, 0.017	0.88, −0.14
8. North Fork Bull Run River, OR	−0.150	−0.166, 0.017	0.80, −0.22
9. Bull Run River, OR	−0.181	−0.189, 0.009	0.85, −0.17
Average =	−0.207		
Summer Period			
1. Snake River Near Anatone, WA	0.600	0.564, 0.036	0.55, −0.57
2. North Fork Clearwater River, ID	0.978	0.604, 0.374	0.41, −0.83
3. Missouri River, MT	0.409	0.316, 0.093	0.57, −0.39
6. South Fork Bull Run River, OR	0.868	0.759, 0.108	0.56, −0.50
7. Fir Creek, OR	0.795	0.672, 0.123	0.51, −0.57
8. North Fork Bull Run River, OR	0.308	0.277, 0.032	0.47, −0.35
9. Bull Run River, OR	0.684	0.567, 0.118	0.40, −0.64
Average =	0.663		
Fall Period			
1. Snake River Near Anatone, WA	0.358	0.348, 0.010	0.70, −0.03
2. North Fork Clearwater River, ID	0.388	0.390, −0.002	0.62, 0.08
3. Missouri River, MT	0.528	0.452, 0.076	0.77, −0.15
6. South Fork Bull Run River, OR	0.148	0.128, 0.021	0.77, 0.30
7. Fir Creek, OR	0.150	0.148, 0.003	0.76, 0.06
8. North Fork Bull Run River, OR	0.129	0.116, 0.014	0.76, 0.26
9. Bull Run River, OR	0.161	0.158, 0.003	0.74, 0.06
Average =	0.266		
Winter Period			
1. Snake River Near Anatone, WA	0.251	0.248, 0.003	0.77, −0.01
2. North Fork Clearwater River, ID	0.140	0.192, −0.052	0.47, 0.51
3. Missouri River, MT	0.015	0.011, 0.004	0.58, −0.03
6. South Fork Bull Run River, OR	0.072	0.076, −0.004	0.84, 0.06
7. Fir Creek, OR	0.077	0.064, 0.013	0.86, −0.12
8. North Fork Bull Run River, OR	0.127	0.076, 0.051	0.91, −0.28
9. Bull Run River, OR	0.077	0.070, 0.008	0.85, −0.04
Average =	0.109		

Table 6 (continued)

Site	Reconstructed trends		
	Total stream temperature change (°C)	Air temperature, discharge contributions (°C)[a]	Standardized b_x's (air temperature, discharge)[b]
Annual Period			
1. Snake River Near Anatone, WA	0.384	0.381, 0.003	0.78, −0.08
2. North Fork Clearwater River, ID	0.342	0.296, 0.046	0.60, −0.15
3. Missouri River, MT	0.247	0.157, 0.090	0.52, −0.45
6. South Fork Bull Run River, OR	0.334	0.322, 0.011	0.84, −0.11
7. Fir Creek, OR	0.323	0.274, 0.050	0.77, −0.25
8. North Fork Bull Run River, OR	0.260	0.232, 0.028	0.77, −0.18
9. Bull Run River, OR	0.365	0.311, 0.054	0.78, −0.26
Average =	0.322		

[a] Stream temperature change at a site from 1980–2009 associated with 30 year trend in air temperature and 56 year trend in discharge.

[b] Standardized coefficients were derived from multiple regressions in Appendix A.

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