The following supplement accompanies the article

Assessing freshwater life stage vulnerability of an endangered Chinook salmon population to climate change influences on stream habitat

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1. Description of climate, hydrology, and population modelling

We extracted monthly surface air temperature and precipitation for the period 2070–2099 under the A1B greenhouse gas emissions scenario from 4 GCMs used by the IPCC's 4th Assessment Report (IPCC 2007). These GCMs were the Parallel Climate Model (PCM1), the Community Climate Systems Model (CCSM3), the European Center-Hamburg Model (ECHAM5), and the Canadian Global Climate Model (CGCM3.1). We selected these 4 GCMs because they were among the 10 GCMs producing the least bias in retrospective modeling of historical climate in the Pacific Northwest (Hamlet et al. 2010) and because, among the 10 GCMs, they spanned the range of future (2070–2099) air temperature and precipitation. PCM1 projected less warming for central Washington State, ECHAM5 more warming, while the projections from the other 2 GCMs were intermediate. The 3 warmer GCMs projected an increase in precipitation of approximately 9%, while PCM1 projected a 44% increase. All GCMs projected that the greatest increases would occur in spring. These models were downscaled for the Pacific Northwest region using the hybrid delta method, from approximately a 200 km, monthly resolution to a 150 m, 3 h scale required for the hydrology models we used (Hamlet et al. 2010).

To model the response of stream temperature and discharge to changes in air temperature and precipitation, we used the downscaled meteorological estimates from the GCMs as inputs to the Distributed Hydrology Soil Vegetation Model (DHSVM) (Wigmosta et al. 1994, 2002, Casola et al. 2009, Elsner et al. 2010). The DHSVM represents surface and subsurface hydrologic processes based on land cover, soil type and depth, topology, and solar radiation to provide estimates of surface water temperatures and discharge at 3 h intervals for each 200 m segment of stream. Seven DHSVMs were calibrated for the Wenatchee River Basin, covering most of the subbasins and all of the major salmon habitat, using the available record of hydrologic data collected by the US Forest Service and the US Geological Survey (Table 1). We summarized the output produced from the meteorological estimates for the period 2070–2099 for each sixth-field hydrologic unit code (HUC6 hereafter; Seaber et al. 1987) spatial unit in each subbasin as mean daily water temperature during the in-gravel egg incubation and rearing stage (August-May), mean daily water temperature during the summer rearing stage (August–September), mean of daily maximum water temperature during the spawning stage (August–September), and lowest discharge during August (Honea et al. 2009; Jorgensen et al. 2009).

We modeled salmon response to changes in habitat conditions using Shiraz, a spatially explicit simulation model of salmon population dynamics. Shiraz was developed to assess the relative importance of habitat variables that have well-characterized links to survival rather than to precisely predict future population numbers (Scheuerell et al. 2006). It does so by estimating the number of fish surviving discrete life history stage time steps depending on the number of fish entering a stage, maximum habitat capacity (set at values less than infinity to model density dependence), and empirically derived functions relating stage-specific survival to environmental parameters such as stream flow and water temperature, resulting in variable survival through each life stage, depending on the location of the fish (Moussalli & Hilborn 1986). The model has been used to evaluate the potential effectiveness of habitat restoration actions (Scheuerell et al. 2006, Honea et al. 2009) and to assess potential climate change impacts on another population of Chinook salmon (Battin et al. 2007). Shiraz was calibrated for the Wenatchee River population of spring-run Chinook salmon by Honea et al. (2009). For this population, density dependence was modelled to occur at the summer rearing and spawning life stages using habitat capacity values for each HUC6 subwatershed area. For each habitat scenario described in the manuscript, the model was run through 100 yr to ensure that the modeled fish population was in equilibrium with the habitat conditions modeled. The mean number of spawners, 2991, produced by the model for current habitat conditions is, as should be expected, larger than the observed mean of 1793 for the period 1960 to 2011 (NWFSC 2015) likely due to the influence of other variables, such as predation and variations in marine-derived nutrients, with weaker empirical links to survival than the variables included in the model. We included in our population model only those habitat variables that have been specifically linked to the survival of spring Chinook by detailed field or laboratory studies and for which habitat data have been collected from the Wenatchee River basin. Additional details of the population model, calibration for spring Chinook salmon in the Wenatchee River Basin, and influence of harvest and hatcheries are described by Honea et al. (2009).

2. Results of the climate and hydrology modeling

The overall pattern of water temperature change by the end of the century (2070–2099) was similar under each climate model we used; however, the magnitude of predicted water temperature change varied somewhat across GCMs. The climate projections from the 2 GCMs predicting an intermediate amount of warming (CGCM3.1 and CCSM3) and the more extreme GCM (ECHAM5) all resulted in an average increase in water temperature of ~2°C for the in-gravel incubation and rearing stage, an increase of 2.5 to 3.0°C for the summer rearing stage, and an increase of 2.5 to 2.8°C for the spawning stage (Figs. 1, 2 and 3, respectively). The GCM projecting less warming (PCM1) resulted in a smaller increase in water temperature for the incubation, summer rearing, and spawning stages (0.4 to 0.7°C).

Our modeling indicates that stream discharge changes also are likely in response to the air temperature and precipitation estimated for the end of the century (Fig. 4). Late summer discharge in the northern tributaries that support approximately 95% of the population (i.e. Chiwawa, White, and Little Wenatchee rivers, as well as Nason Creek) decreased by 30 to 40% in the 3 GCMs producing larger estimates of water temperature increase; however, in response to PCM1 inputs, late summer discharge increased by approximately 70% because it was the only GCM that projected a substantial increase in precipitation during the summer months (~26% greater than current climate conditions). During the in-gravel egg incubation and rearing period from August to May, the magnitude of mean annual peak discharge increased by 27 to 34% (depending on GCM) for the Chiwawa River where most wild spawning occurs in the Wenatchee River Basin, while the estimated current 10 yr and 100 yr peak discharge events returned with frequencies of 4 to 5 yr and 9 to 15 yr, respectively, at end-of-century climate (Fig. 5).

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Tables

Table 1. Water temperature and discharge data sources for calibration of the hydrology models. HUC6: the last 3 digits of the sixth-field hydrologic unit code as shown in Fig. 2, USGS: USA Geological Survey, USFS: US Department of Agriculture Forest Service, *Q*: discharge, and *T*: temperature

Station ID	Begin	End	Agency	Lat.	Long.	Type	HUC6
12454000	1-Jan-54	31-Dec-83	USGS	47.8740	120.8704	Q	102
12456500	15-May-91	30-Sep-04	USGS	47.8373	120.6623	Q	203
12457000	1-Jan-60	30-Sep-04	USGS	47.7629	120.6662	Q	304
12458500	1-Jan-63	31-Dec-01	USGS	47.5582	120.6679	Q	403
12459000	1-Jan-60	30-Sep-04	USGS	47.5832	120.6195	Q	405
12462000	1-Jan-55	31-Dec-57	USGS	47.5165	120.4762	Q	504
12462500	1-Oct-62	30-Sep-04	USGS	47.4993	120.4245	Q	505
W_CHWA_03	13-Jun-97	16-Sep-02	USFS	47.7985	120.6337	T	203
W_CHWA_09	11-Jul-98	16-Sep-02	USFS	47.8379	120.6506	T	203
W_CHWA_31	10-Aug-99	22-Sep-02	USFS	47.8976	120.6963	T	203
W_ICIC_09	13-Jun-97	15-Sep-02	USFS	47.5534	120.7699	T	403
W_INGA_01	5-Jun-98	15-Sep-02	USFS	47.4630	120.6599	T	502
W_LTWE_10	13-Jun-97	16-Sep-02	USFS	47.8341	120.8775	T	104
W_MISS_12	19-Jun-96	15-Sep-02	USFS	47.4181	120.5083	T	503
W_MISS_20	19-Jun-96	15-Sep-02	USFS	47.5234	120.4734	T	504
W_NASO_00	18-Jun-96	15-Sep-02	USFS	47.8095	120.7148	T	302
W_PESH_14	20-Jun-96	15-Sep-02	USFS	47.4778	120.6562	T	502
w_SAND_01	21-May-01	15-Sep-02	USFS	47.4300	120.5061	T	504
W_WENA_46	25-Jun-97	15-Sep-02	USFS	47.6147	120.7199	T	304
W_WHIT_03	11-Jul-98	15-Sep-02	USFS	47.8472	120.8306	T	102
W_WHIT_11	13-Jun-97	17-Sep-02	USFS	47.8772	120.8718	T	102

Fig. captions

Fig. 1. Change in water temperature (mean of daily mean) during the in-gravel incubation and rearing stage in the 2080s relative to current conditions as estimated by: (a) Warm (PCM1); (b) Warmer1 (CCSM3); (c)Warmer2 (CGCM3.1); and (d) Warmest (ECHAM5). White indicates areas not covered by the hydrology model
Fig. 2. Change in water temperature (mean of daily mean) during the summer rearing stage in the 2080s relative to current conditions as estimated by (a) Warm (PCM1); (b) Warmer1 (CCSM3); (c)Warmer2 (CGCM3.1); and (d) Warmest (ECHAM5). White indicates areas not covered by the hydrology model

Fig. 3. Change in water temperature (mean of daily maximum) during the spawning stage in the 2080s relative to current conditions as estimated by (a) Warm (PCM1); (b) Warmer1 (CCSM3); (c)Warmer2 (CGCM3.1); and (d) Warmest (ECHAM5). White indicates areas not covered by the hydrology model

Fig. 4. Mean monthly discharge for the lower Chiwawa River (area 203 in Fig. 2 of main article) where Warm is PCM1, Warmer1 is CCSM3, Warmer2 is CGCM3.1, and Warmest is ECHAM5

Fig. 5. Recurrence interval of maximum discharge during the in-gravel incubation and rearing period (August-May) in the lower Chiwawa River (HUC6 203 in Fig. 2 of main article) where Warm is PCM1, Warmer1 is CCSM3, Warmer2 is CGCM3.1, and Warmest is ECHAM5

Fig. 1:

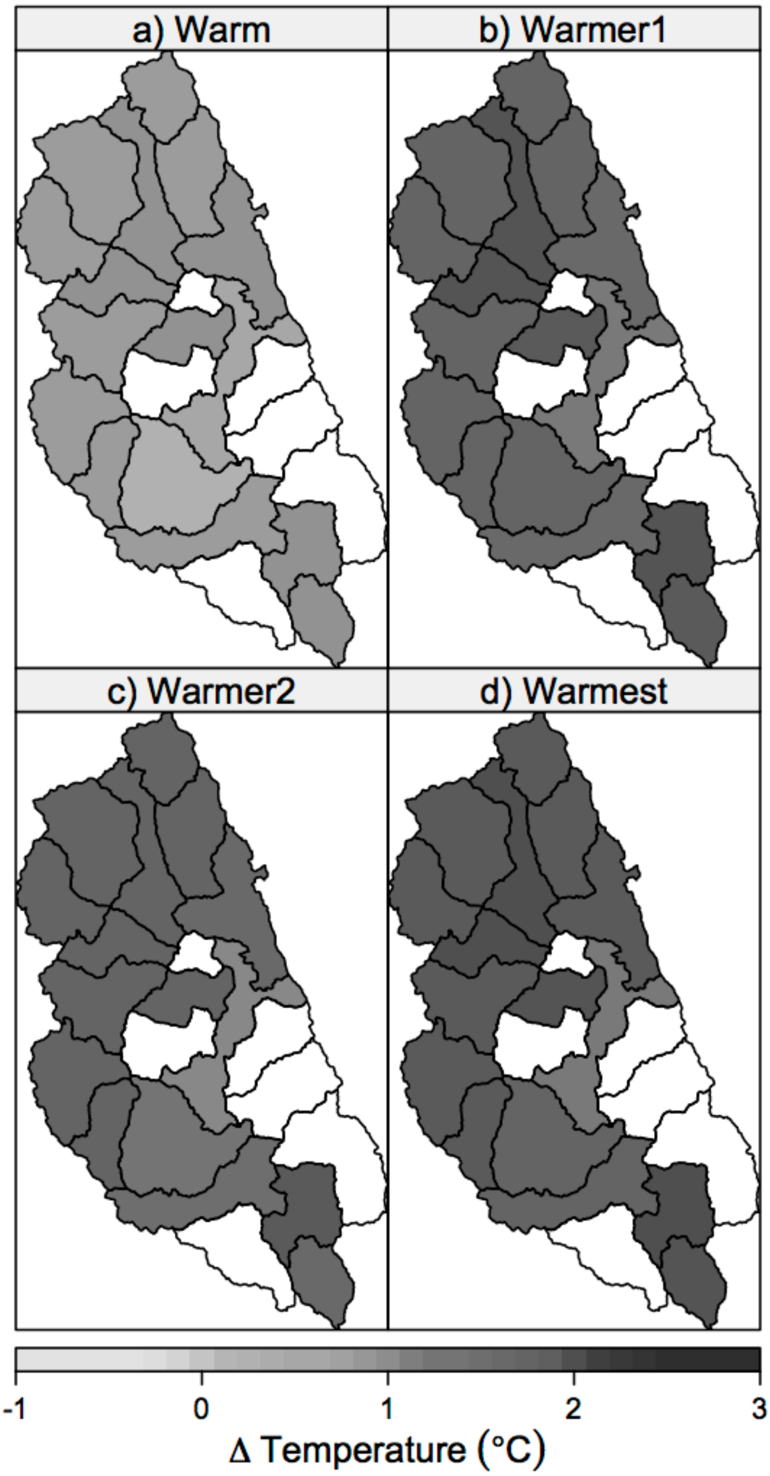


Fig. 2:

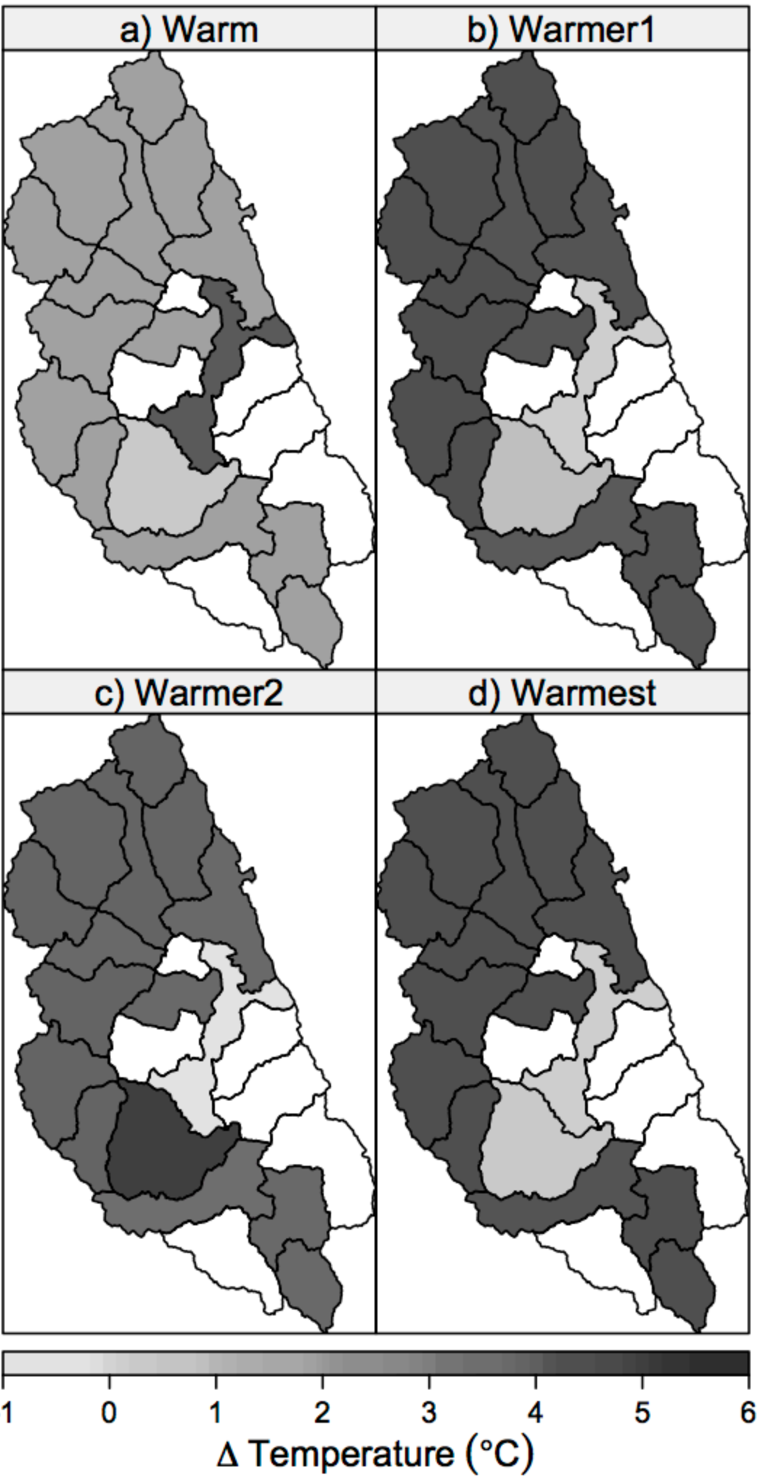

a) Warm
b) Warmer1
c) Warmer2
d) Warmest
-1
0
1
2
3
4
5
6
Δ Temperature (°C)

Fig. 3:

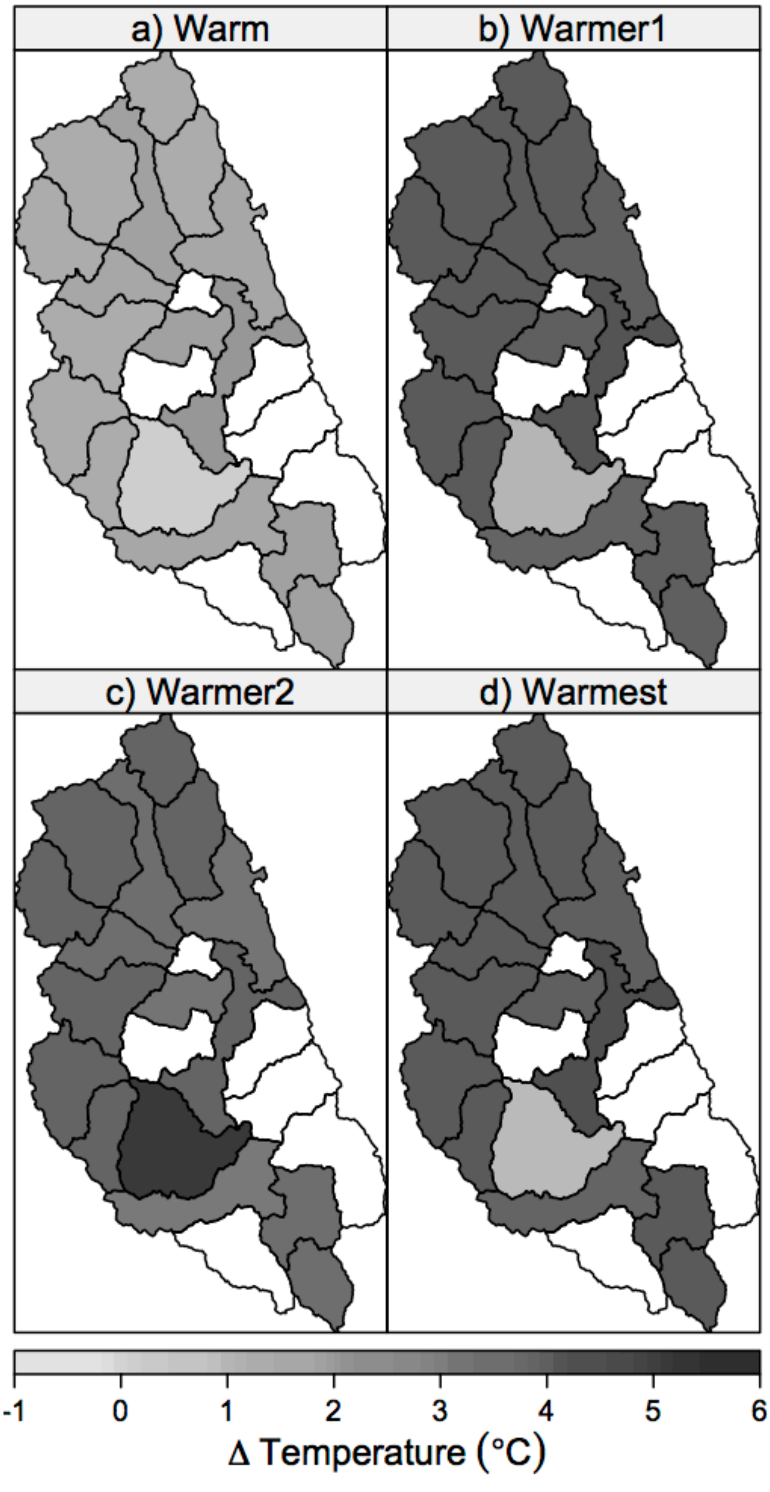

a) Warm
b) Warmer1
c) Warmer2
d) Warmest
-1
0
1
2
3
4
5
6
Δ Temperature (°C)

Fig. 4:

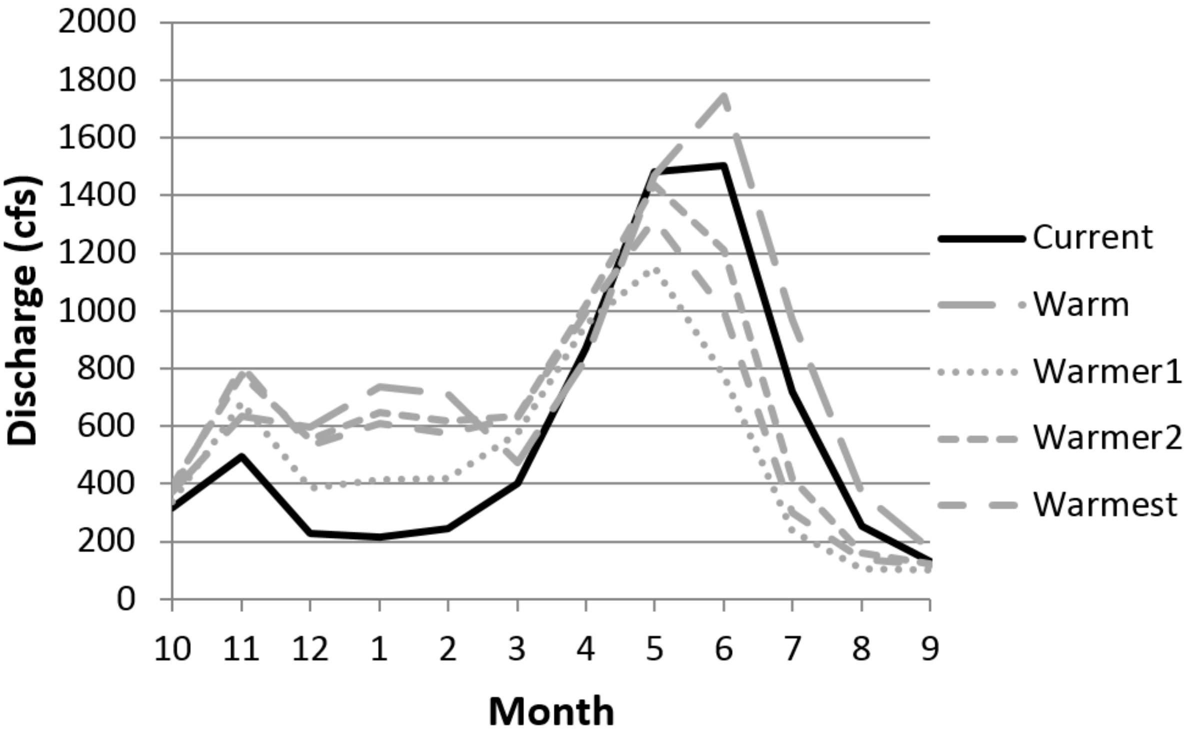
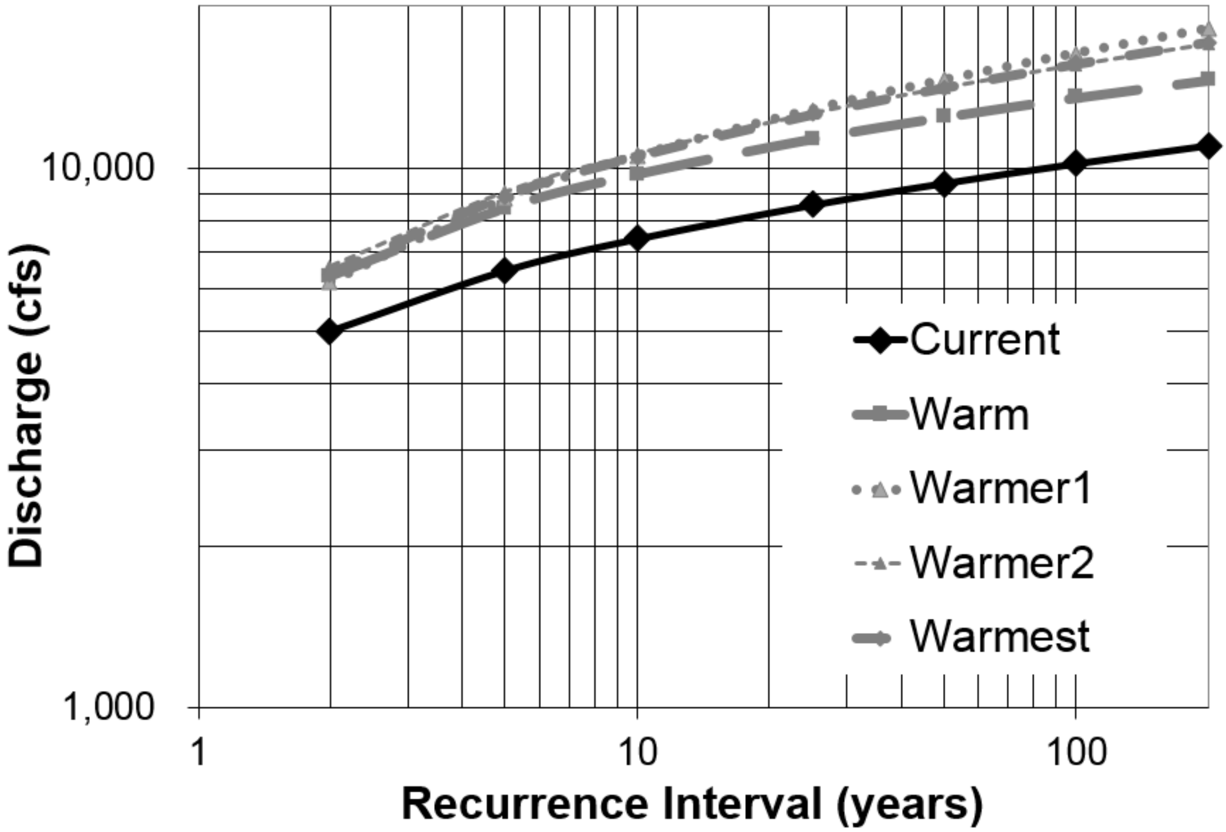

2000
1800
1600
1400
1200
1000
800
600
400
200
0
Discharge (cfs)
10
11
12
1
2
3
4
5
6
7
8
9
Month
Current
Warm
Warmer1
Warmer2
Warmest

Fig 5:


10,000
1,000
Discharge (cfs)
1
10
100
Recurrence Interval (years)
Current
Warm
Warmer1
Warmer2
Warmest