TECHNICAL MEMORANDUM NO. 6

EFFECTS OF CLIMATE CHANGE ON ASHLAND CREEK, OREGON

City of Ashland
Water Conservation and Reuse Study and Comprehensive Water Master Plan

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Final Report

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EXECUTIVE SUMMARY

Ashland's water supply is provided primarily by surface water inflows to Reeder Reservoir from the east and west forks of Ashland Creek. The Ashland Creek watershed accumulates significant snowpack in winter, and historical streamflows typically peak in May/June for the East fork and April/May for the West fork in response to melting snow. Global climate model simulations from the Intergovernmental Panel on Climate Change Fourth Assessment Report (IPCC AR4) project warmer temperatures and changes in the seasonality of precipitation for the Pacific Northwest region of North America. Because snowpack is sensitive to these kinds of changes, losses of snowpack and resultant streamflow timing shifts (more flow in winter, less in summer) are common impacts to water supply that have been shown in many previous studies throughout the region.

In this study we apply a fine-scale hydrologic model implemented over Ashland Creek to simulate the effects of projected changes in temperature and precipitation from the IPCC AR4 on snowpack and streamflow. Ten realizations of 2040s climate (each associated with a Global Climate Model) for the A1b emissions scenario are used as input to the hydrologic model and are compared to a historical baseline simulation from 1920-2000.

Summary of Results

Figure ES.1 shows projected annual average temperature and precipitation for the ten climate change scenarios used in the study and historical conditions. Temperatures are about 2° C +/- 0.5° C (3.6° F +/- 0.9° F) warmer than historical conditions on average. Annual precipitation shows a small systematic change of a few percent with a range from about 650mm (90% of historical) to 880mm (122% of historical). Scenarios are generally wetter in winter and drier in summer, however.

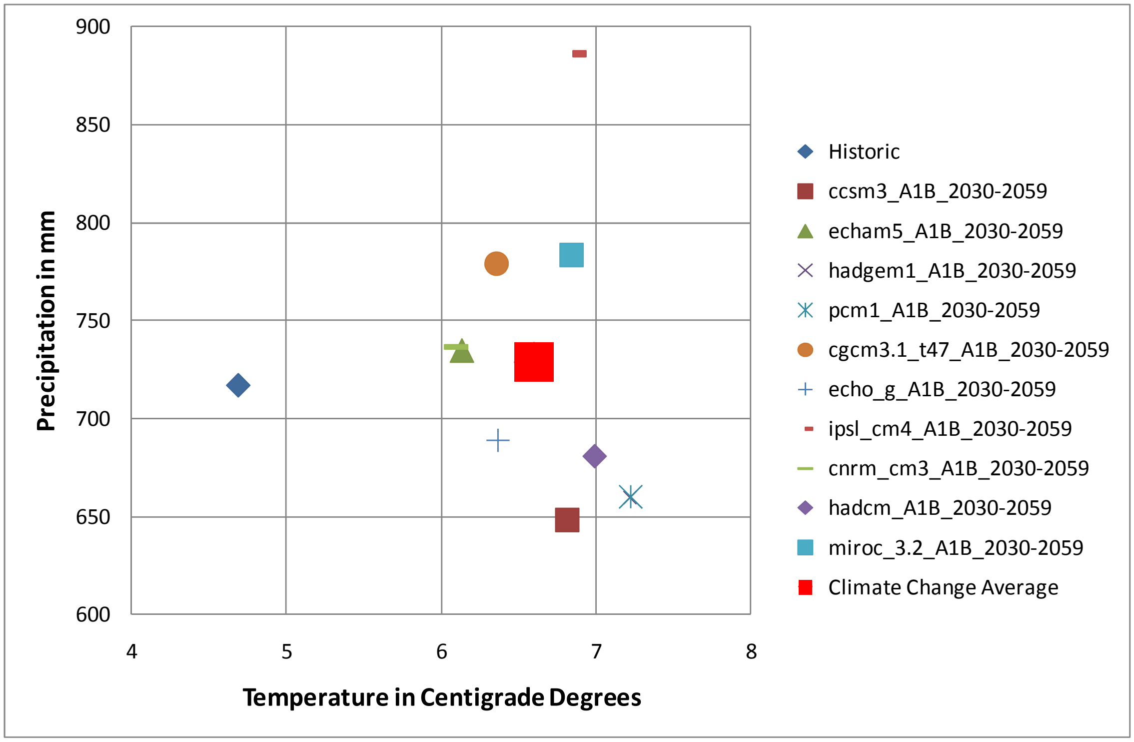

Figure ES .1 Downscaled Annual Precipitation and Temperature Projections for Ten Different Climate Change Scenarios for the 2040s Compared to Historical Data

These changes in temperature and precipitation result in substantial changes in snowpack and streamflow in the East Fork hydrologic simulations (Figures ES.2 and ES.3), including earlier and reduced peak snow water equivalent, increases in Oct-March streamflow and decreases in April-September streamflow. Extreme low flows also become markedly more severe due to lower soil moisture in late summer and corresponding reductions in base flow in the simulations (Figure ES.4). Changes in the West Fork (not shown) are similar.

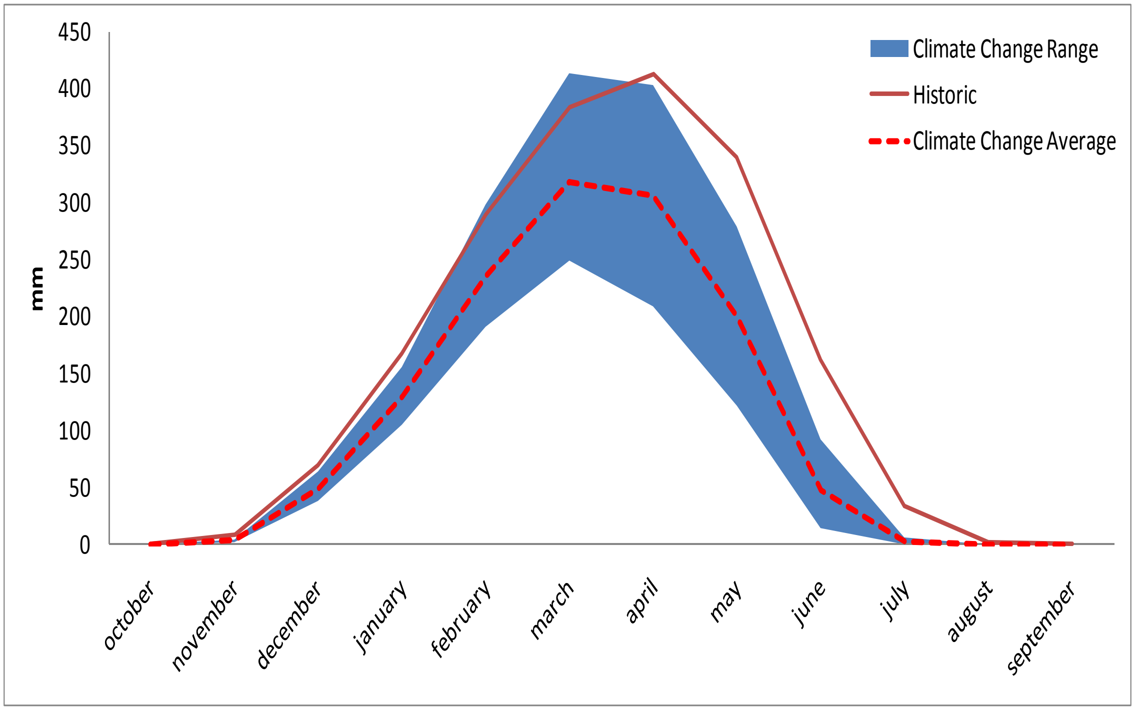

Figure ES.2 East Fork mean Snow Water Equivalent for the historical period (1920 to 2000) and A1b climate change scenarios for the 2040s

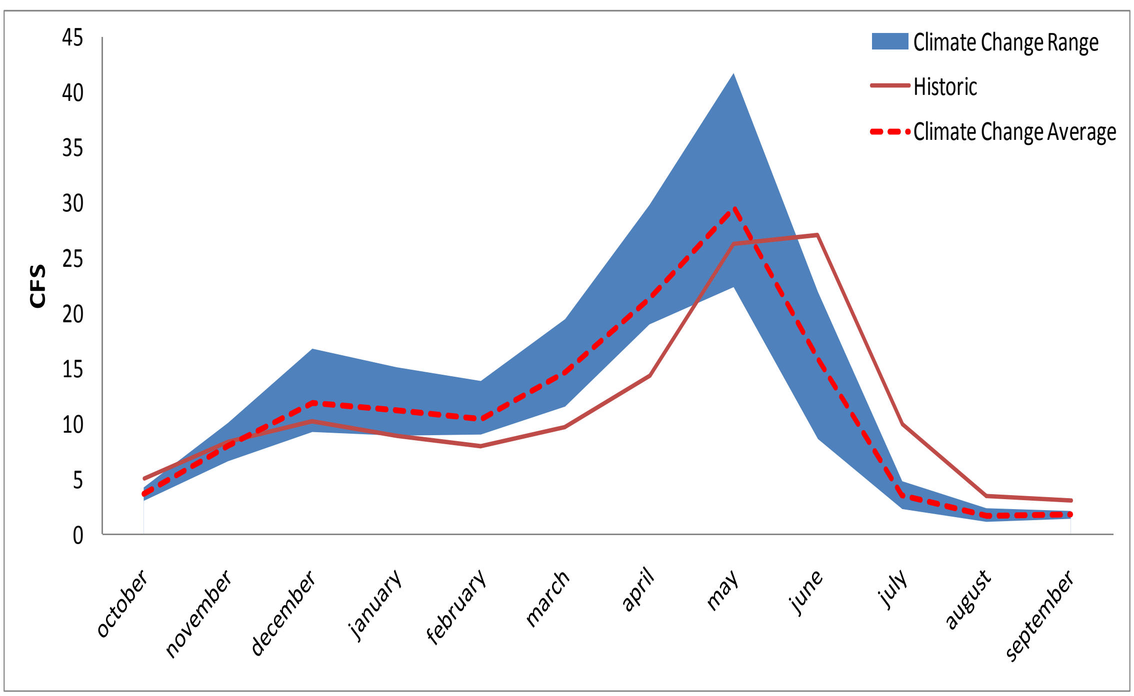

Figure ES.3 East Fork Average Monthly Streamflow for the historical period (1920 to 2000) and A1b climate change scenarios for the 2040s.

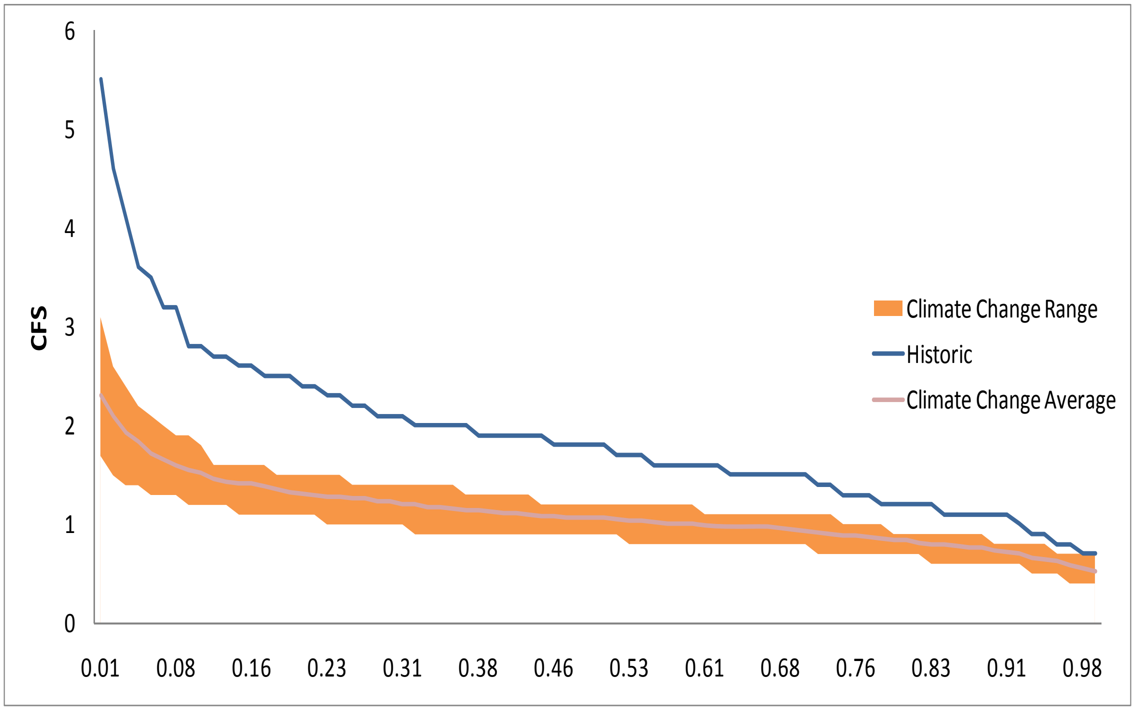

Figure ES.4 Quantiles for extreme low streamflow for the historical period (1920 to 2000) and A1b climate change scenarios for the 2040s

Changes in streamflow for the combined east and west forks for historical and 2040s climate change conditions are shown in Figure ES.5. Average annual changes in streamflow are negligible in the simulations (less than 1 percent), but cool season flows are increased and warm season flows reduced. On average April-September flow is reduced by about 13 percent for the projected 2040s conditions in comparison with historical conditions. May-September flow is reduced by about 26 percent in comparison with historical conditions.

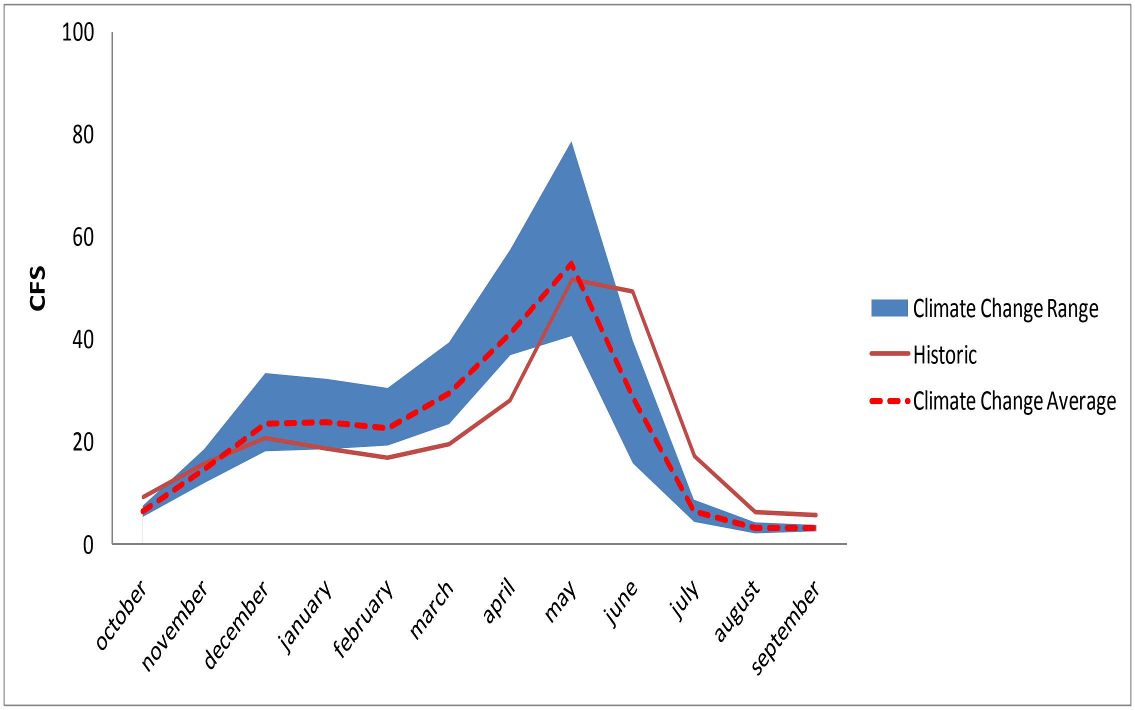

Figure ES.5 Combined Monthly Streamflow of the West and East Forks for the historical period (1920 to 2000) and A1b climate change scenarios for the 2040s

Conclusions

The hydrologic simulations show that projected temperature and precipitation changes in the Pacific Northwest for the 2040s associated with the A1b scenario will result in substantial reductions in spring snowpack, May-September streamflow, and extreme low flows in Ashland Creek.

Although there is considerable uncertainty in these projections because of differences in the global climate model simulations, all scenarios show reductions in average April 1 snow water equivalent in both east and west forks, and nine out of ten scenarios of combined flow show reductions in May through September streamflow. Likewise, extreme low flows in every future simulation year are lower than their historical counterparts. Thus there is little question of the general nature of these fundamental changes in watershed processes, uncertainty in the absolute value of the changes notwithstanding.

It is important to note that changes in the future will also vary from decade to decade due to natural variability of precipitation and temperature. In relatively cool and wet decades water supply impacts may be reduced from the averages shown above, whereas in relatively warm and dry decades water supply impacts may be larger than shown.

TECHNICAL REPORT

INTRODUCTION

Ashland Creek is located in Jackson County, Oregon, United States, near Interstate 5 and the California border, and located in the south end of the Rogue Valley. The West Fork basin has an area of 10.5 mi^2 and the East Fork has an area of 8.14 mi^2. Both branches of the Ashland creek drain to the Reeder Reservoir. In this study we implemented the Distributed Hydrological Vegetation Model over the East and West branches of the river with the objective of simulating the effects of climate change on streamflow in these basins.

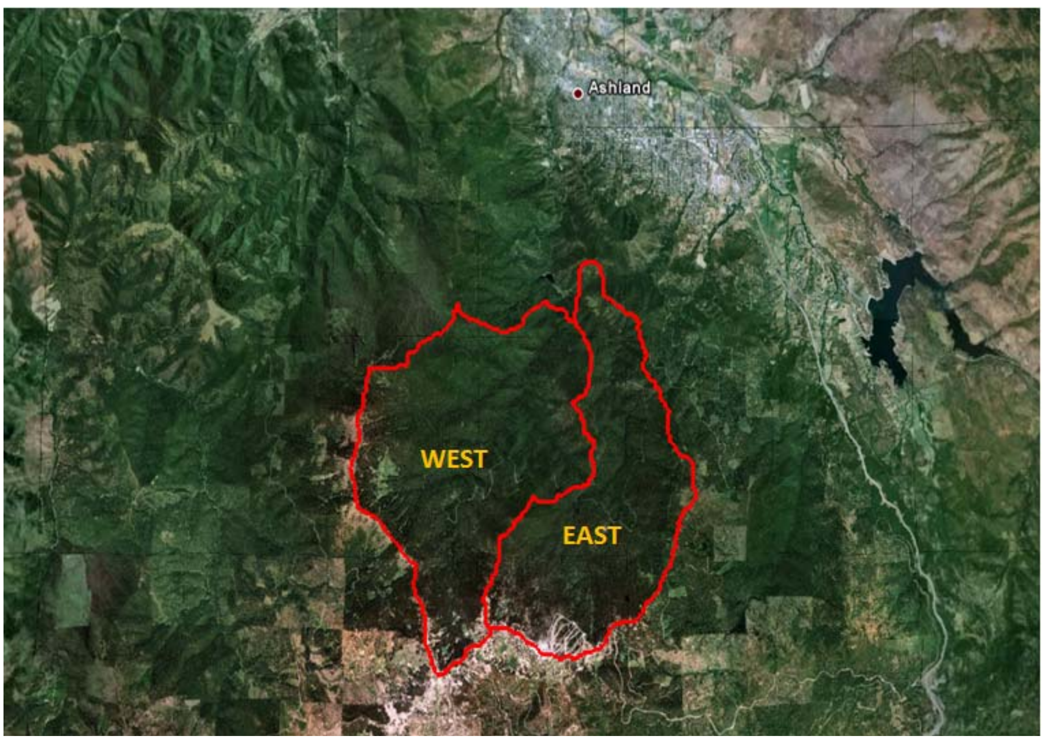

Figure 1 East and West Fork of Ashland Creek, near Ashland, OR. Flow is to the North (top of Map) into Reeder Reservoir.

Hydrologic Model

The Distributed Hydrologic Surface Vegetation Model (DHSVM) (Wigmosta et al. 1994) which explicitly represents the effects of topography and vegetation on water fluxes through the landscape has been implemented over the Ashland Creek watershed near Ashland, Oregon (Figure 1). DHSVM is typically applied at high spatial resolutions on the order of 50 meters for watersheds up to 100,000 km^2 and at sub-daily timescales for multi-year simulations. This distributed hydrologic model has been applied predominantly to mountainous watersheds in the Pacific Northwest in the United States.

DHSVM, as with any distributed hydrologic model, requires extensive information about the simulated basin. The first type of information is static data and can be divided in three main categories: elevation, vegetation cover and soils. The second type is dynamic, or time series, information which includes meteorological data that can be obtained from weather stations or derived from others models. In the basins modeled, observing stations do not have sufficiently long records or do not exist in a spatially relevant location. Therefore, gridded products provide the spatial coverage that observing stations may lack

DHSVM consists of computational grid cells centered on Digital Elevation Model (DEM) elevation nodes, which explicitly represent the effects of topography in the basin. DEM data are used to define absorbed shortwave radiation, precipitation, air temperature, and down-slope water movement. In DHSVM each cell may exchange surface and subsurface water with its neighbors resulting in a three-dimensional redistribution across the basin. This water is routed across the basin using the defined stream channel network.

In this study, we implemented DHSVM v2.4. Some modifications to the code in comparison with previous versions include the addition of a deep groundwater layer, expansion of surface and subsurface flow paths from 4 to 8 directions, allowance of the re-infiltration of water from the stream channel network back into the soil layer, the division of surface flows resulting from runoff from impervious surfaces by the fraction of impervious area, and the calculation of water temperature within the channel network.

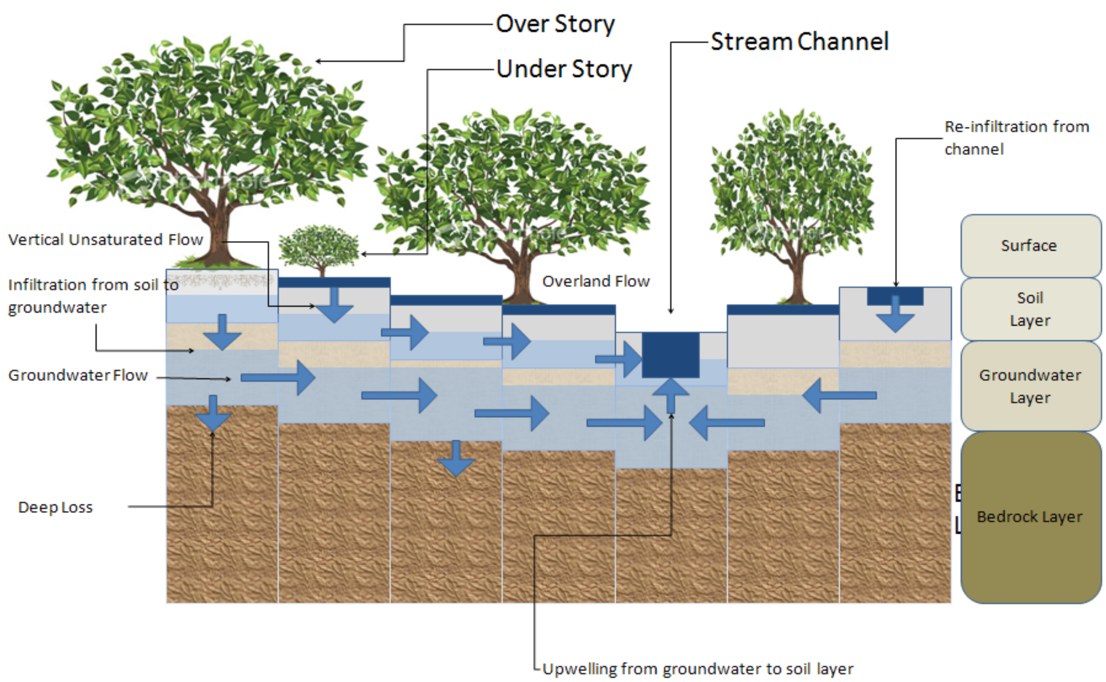

Figure 2 Schematic diagram of the Distributed Hydrology Vegetation Model (DHSVM)

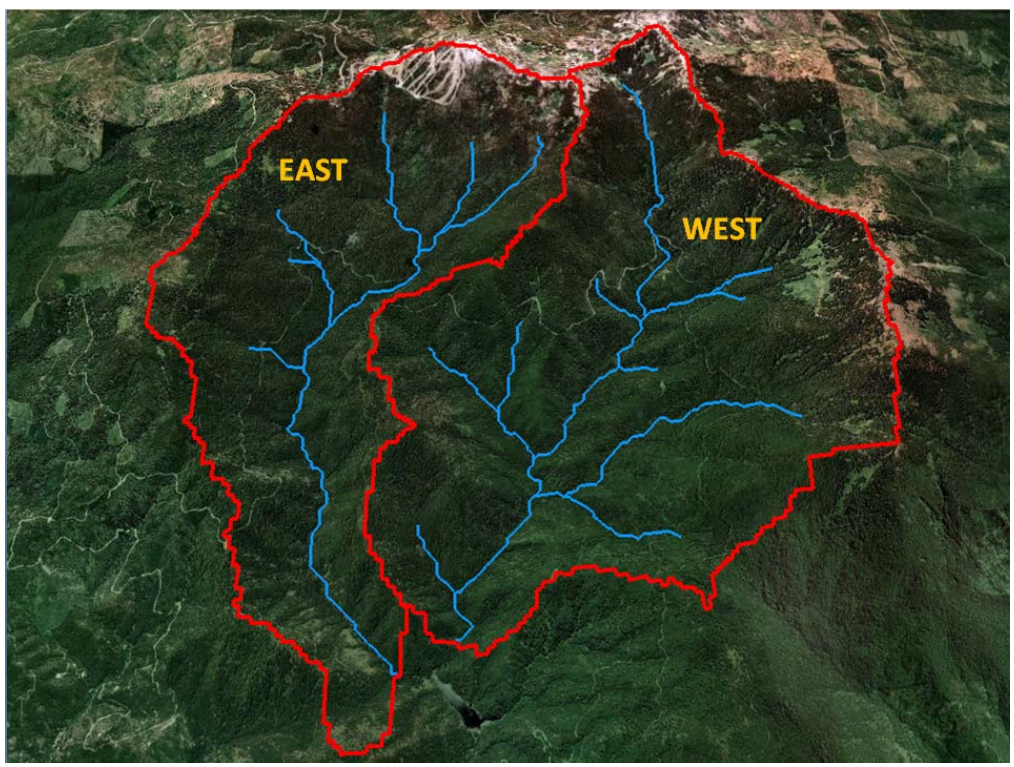

Figure 3 Digitized stream networks used in the hydrological model implementation. Flow is roughly from South to North (top to bottom in the figure). (Note Reeder Reservoir in the lower center portion of the figure.)

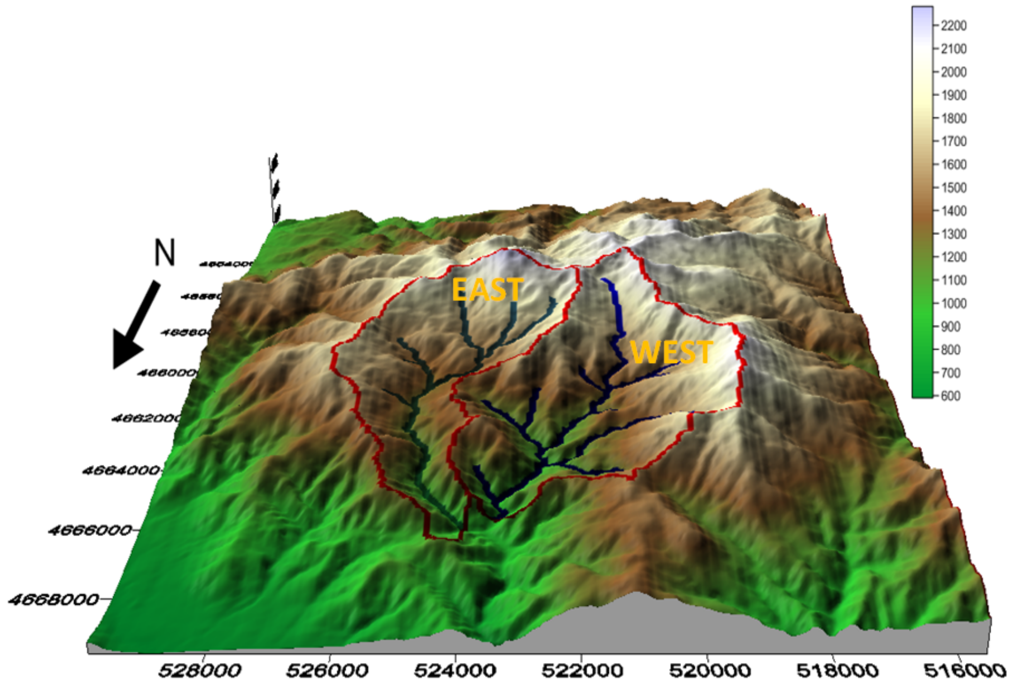

Figure 4 Digital elevation model used in the hydrologic model implementation

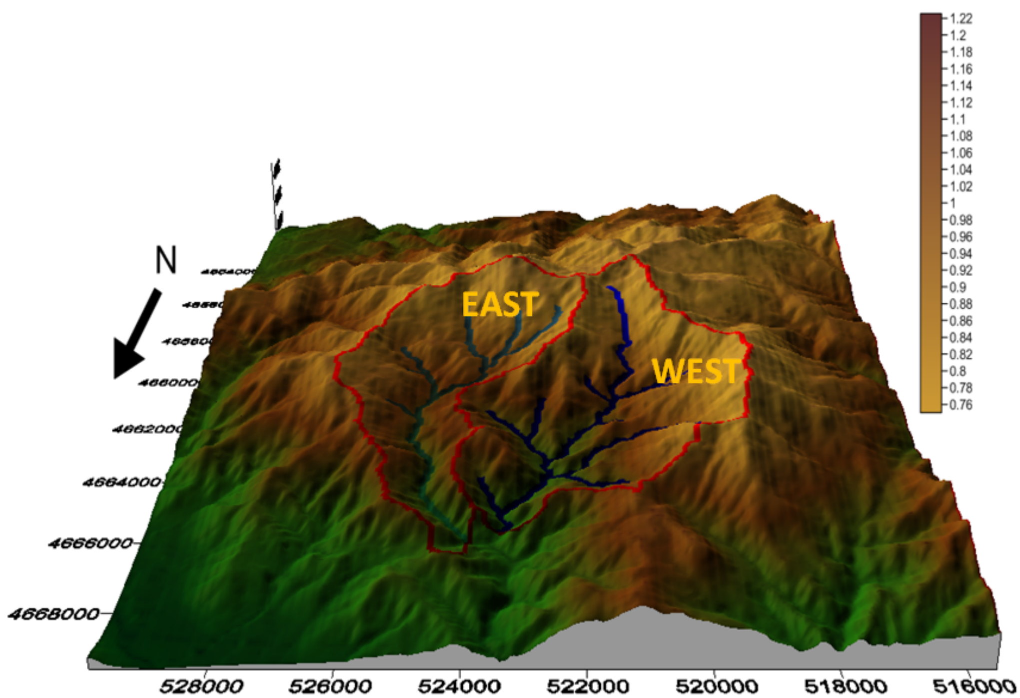

Figure 5 Soil depth model used in the hydrologic model implementation

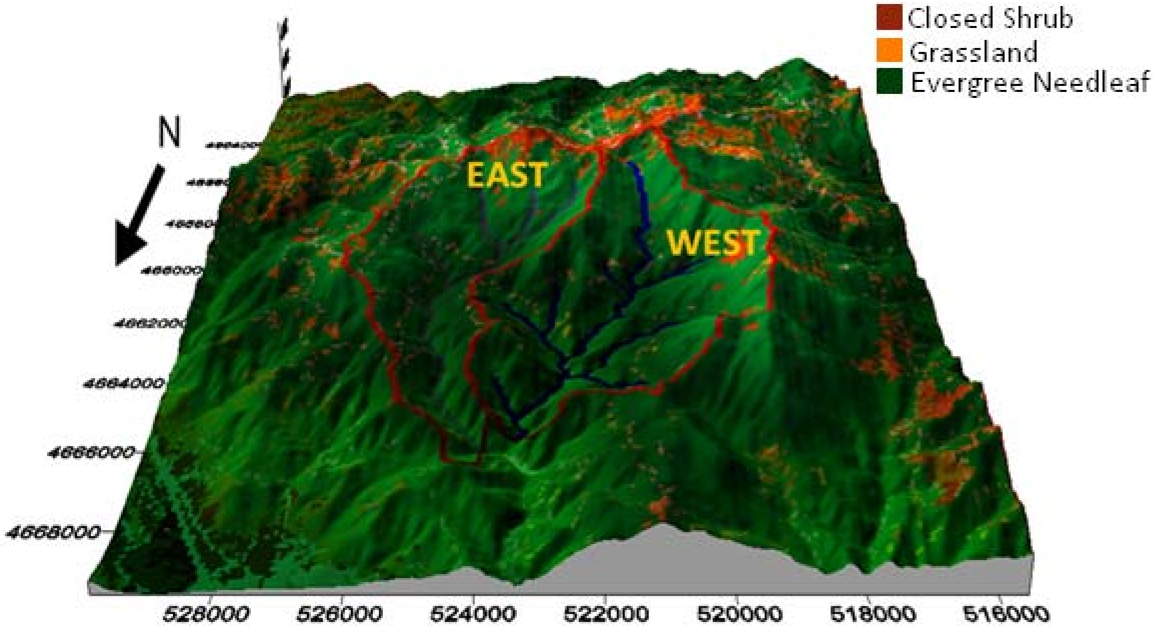

Figure 6 Land cover classes used in the hydrologic model implementation.

Climate Change Scenarios

The climate change scenarios evaluated using DHSVM were downscaled from Global Climate Models (GCM) models to 1/16 degree resolution following methods described by Hamlet et al. (2010). The downscaled data were monthly averages for maximum temperature, minimum temperature and total monthly precipitation. The GCM data is bias corrected using the historical gridded meteorological data series using quantile mapping techniques described by Wood et al. (2002). In this process the historical dataset is aggregated to monthly time step and the coarser GCM spatial resolution and the GCM data is bias corrected to produce a new dataset that closely matches the statistics of observations. These data are then spatially downscaled and temporally disaggregated using the Hybrid Delta downscaling method described by Hamlet et al. (2010) (Figure 7). The end product combines the realistic time series and spatial variability of storms from the historical dataset with the bias-adjusted future climate change signals for temperature and precipitation from the GCM scenarios. The resulting daily downscaled temperature and precipitation scenarios were downloaded from the Columbia Basin Climate Change Scenarios Project website [http://www.hydro.washington.edu/2860/] for the ten GCMs included in the study for the A1b emissions scenario (Table 1) (see also Mote and Salathé 2010), and were post-processed to produce 3-hourly forcings for DHSVM using methods described by Carrasco and Hamlet (2010).

Table 1 List of Global Climate Models (GCMs) used in the study

Global Climate Models**	Period Of Analysis
UKMO-HadCM3	2030-2059
CNRM-CM3	2030-2059
ECHAM5/MPI-OM	2030-2059
ECHO-G	2030-2059
PCM	2030-2059
CGCM3.1(T47)	2030-2059
CCSM3	2030-2059
IPSL-CM4	2030-2059
MIROC3.2(medres)	2030-2059
UKMO-HadGEM1	2030-2059

**Global Climate Model scenarios are described by Mote and Salathé (2010)

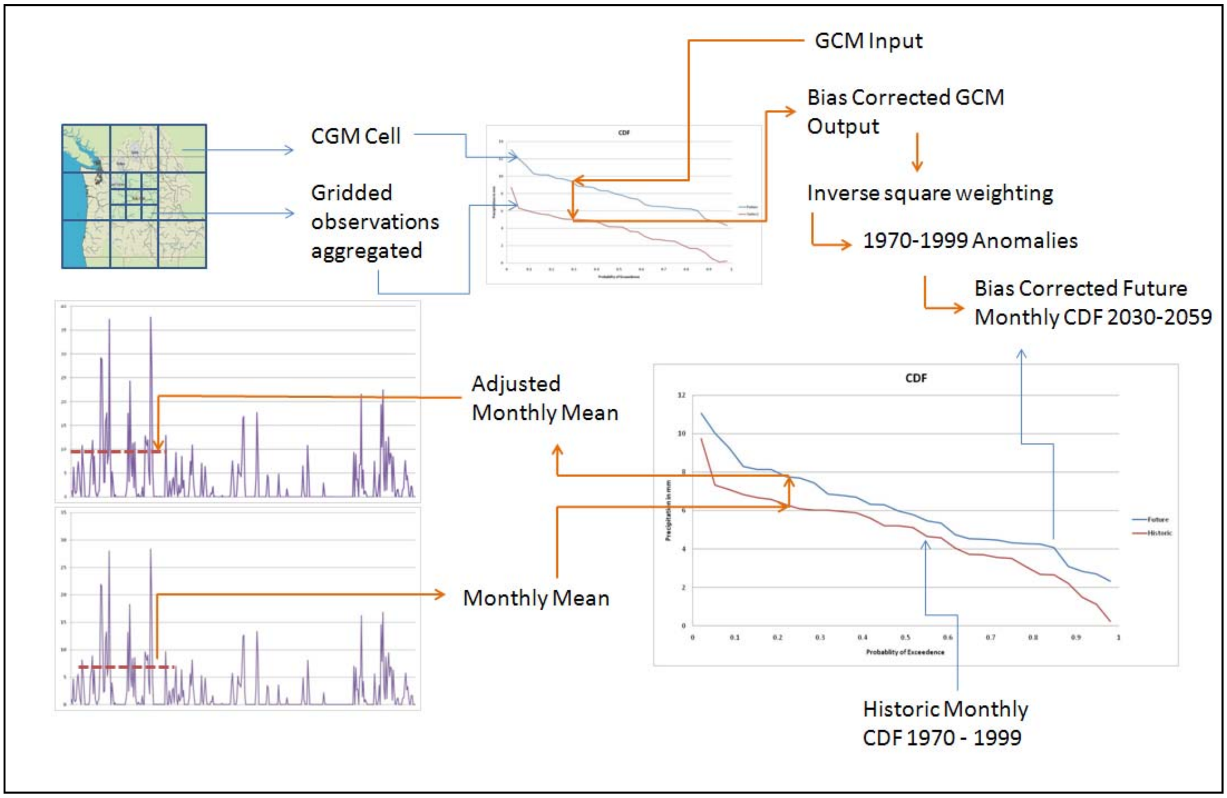

Figure 7 Overview of the downscaling process

Table 1 Average Monthly Temperature in Celsius Degrees for Historic data and GCM simulations

	Historic	ccsm3 GCM	cgcm3 GCM	Cnrm GCM	echo 5 GCM	echo g GCM	Hadcm GCM	Hadgm GCM	ipsl cm4 GCM	miroc 3.2 GCM	pcm 1 GCM
October	6.2	8.0	7.8	7.9	8.2	8.4	8.7	8.3	8.4	8.3	7.9
November	0.8	2.5	1.7	2.2	2.8	2.0	2.5	2.2	2.5	2.7	2.4
December	-1.2	-0.3	0.0	-0.2	0.2	-0.2	0.2	0.3	0.8	0.8	0.3
January	-2.7	-1.4	-0.9	-2.0	-2.4	-1.4	-2.2	-0.2	-0.8	-0.6	-0.9
February	-1.6	0.4	0.3	-1.1	-1.0	0.0	-0.9	0.3	0.3	0.4	-0.8
March	-0.6	1.2	1.5	0.0	-0.4	0.9	0.6	1.6	1.0	1.4	0.3
April	1.6	2.7	2.0	2.4	2.8	3.1	3.0	2.9	3.5	3.0	3.2
May	5.6	7.9	6.4	6.5	7.0	6.6	7.4	8.0	7.4	7.8	6.9
June	9.0	12.0	10.6	11.2	11.3	10.8	12.3	12.7	11.7	11.4	10.7
July	14.1	17.9	16.8	16.6	16.0	16.4	19.7	18.0	16.7	16.6	16.0
August	13.8	17.6	16.9	16.4	15.8	16.3	17.6	17.4	16.9	16.5	15.8
September	11.2	13.4	13.3	13.2	13.5	13.7	14.8	15.2	13.9	14.0	13.6

Table 2 Monthly precipitation in mm for historical data and ten 2040 GCM scenarios

	Historic	ccsm3 GCM	cgcm3 GCM	Cnrm GCM	echo 5 GCM	echo g GCM	Hadcm GCM	Hadgm GCM	ipsl cm4 GCM	miroc 3.2 GCM	pcm 1 GCM
October	46.2	44.2	46.8	40.0	49.2	44.6	41.7	45.9	48.4	57.6	52.5
November	95.5	97.7	102.5	116.8	94.7	101.5	102.0	92.2	108.2	136.5	88.9
December	123.2	126.0	126.1	129.2	135.4	92.6	118.7	112.9	181.7	157.0	112.7
January	114.2	74.9	141.9	122.8	127.9	113.7	116.1	106.1	157.8	117.0	102.0
February	89.8	72.5	99.9	97.6	76.2	95.3	90.2	73.4	126.7	80.8	91.8
March	81.5	86.6	90.6	78.9	95.6	95.3	77.6	78.3	107.9	85.0	90.4
April	53.6	64.9	70.1	62.5	51.5	49.6	53.2	54.5	59.1	48.5	56.0
May	45.0	35.2	40.4	40.5	41.6	48.0	34.0	37.4	41.8	33.4	43.7
June	26.4	18.8	21.3	17.5	15.8	21.4	15.1	15.0	17.6	34.7	23.5
July	8.3	2.1	5.5	4.4	4.8	4.6	5.8	10.9	6.0	7.7	6.1
August	11.8	3.2	15.5	8.4	22.1	6.7	7.0	14.3	9.5	12.0	7.5
September	21.5	22.6	18.4	17.9	19.7	16.1	19.2	19.0	21.7	13.4	17.3

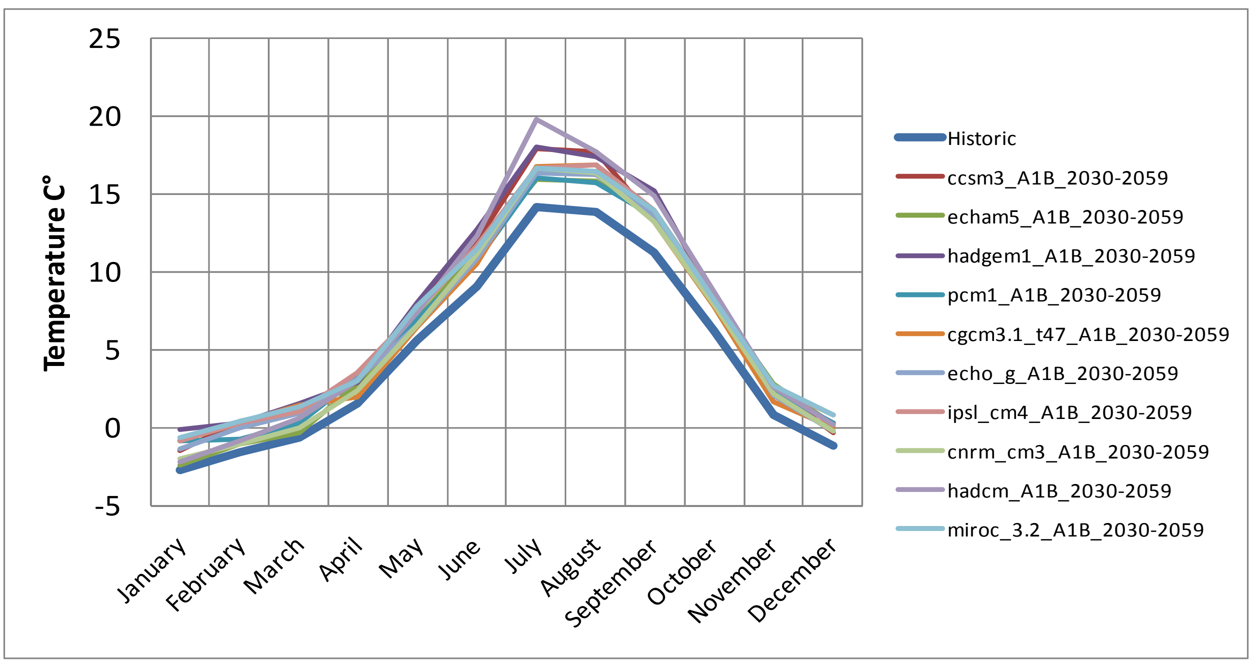

Figure 8 Average monthly temperature for historical data and ten 2040 GCM scenarios

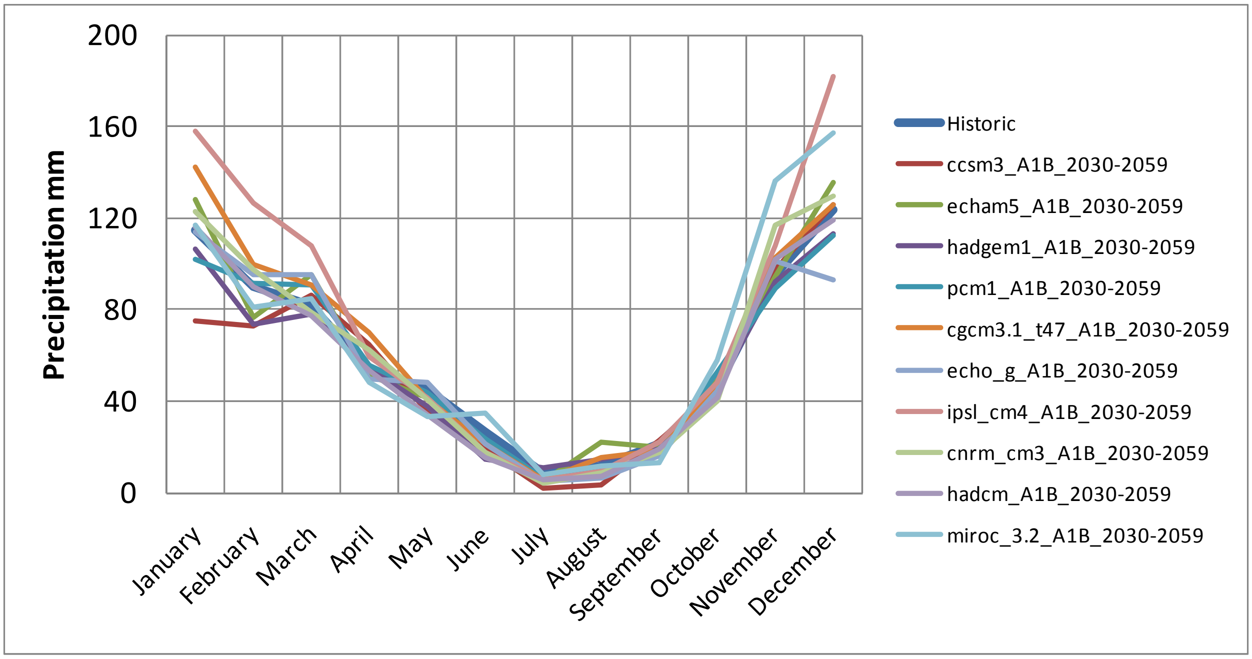

Figure 9 Average precipitation for historical data and ten 2040 GCM scenarios

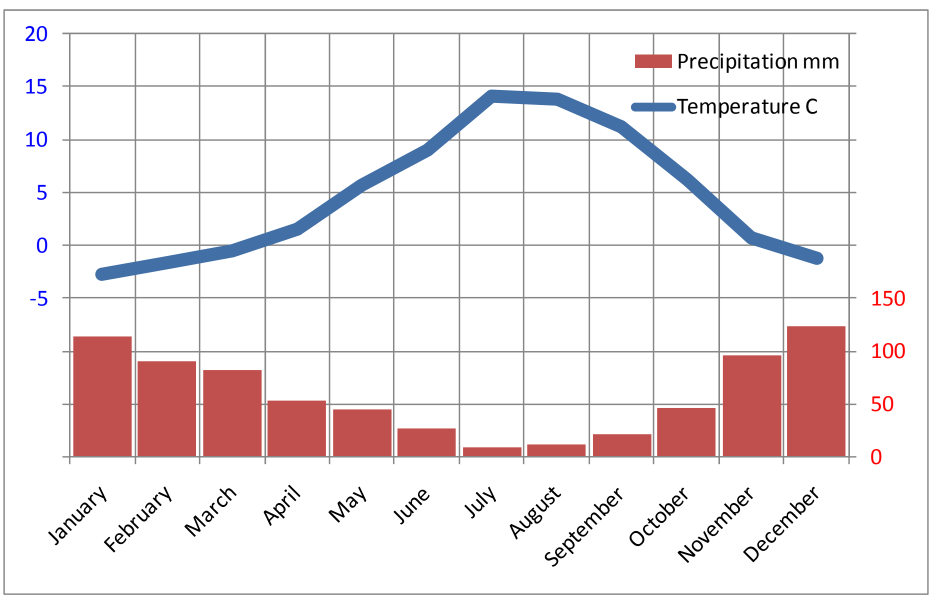

Figure 10 Average monthly meteorological data from 1916 to 2006

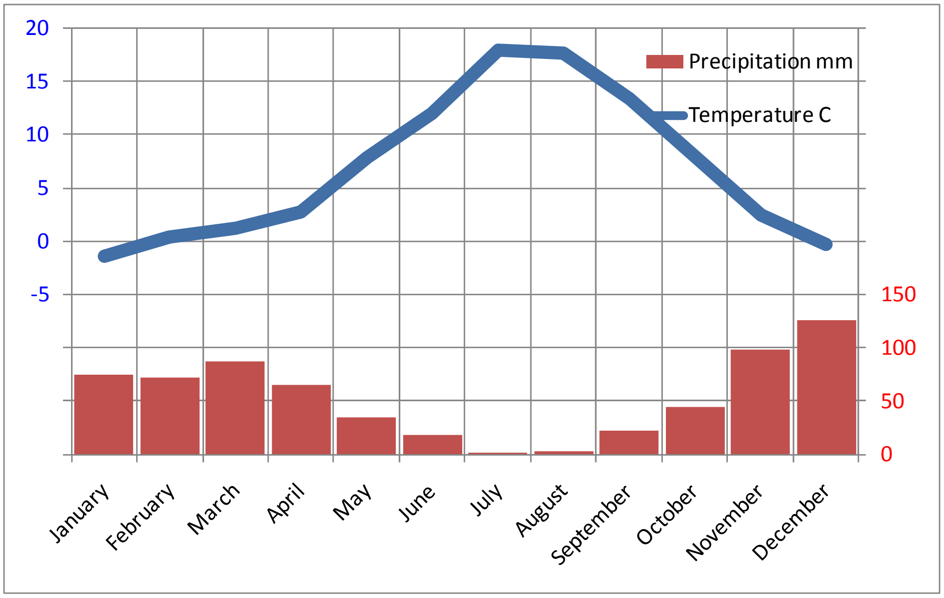

Figure 11 Average Meteorological data from 2030 to 2059 for GCM ccsm3_A1B

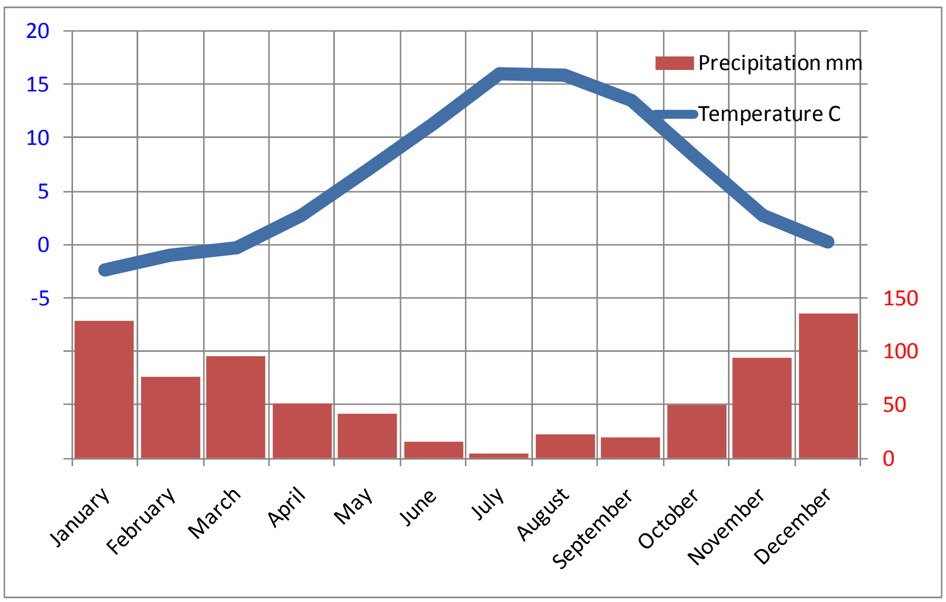

Figure 12 Average Meteorological data from 2030 to 2059 for GCM echam5_A1B

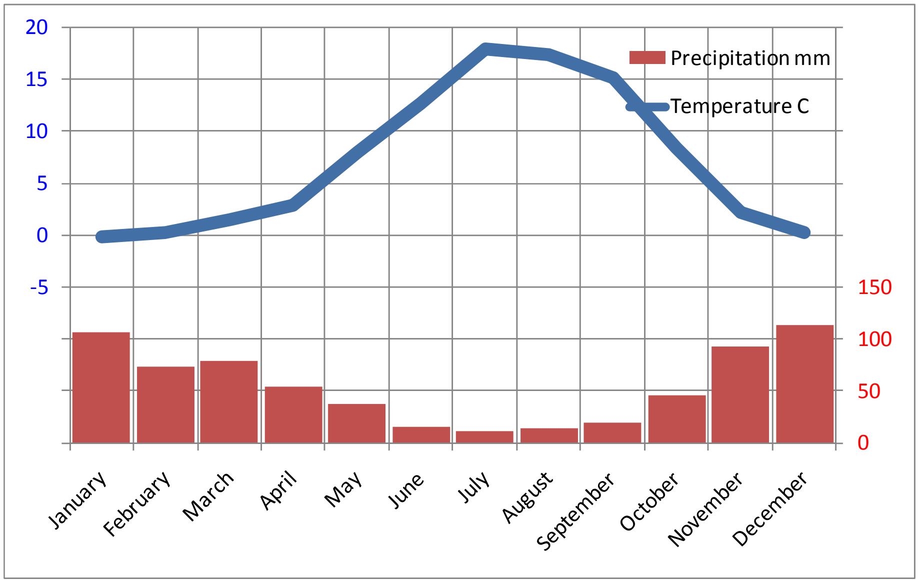

Figure 13 Average Meteorological data from 2030 to 2059 for GCM hadgem1_A1B

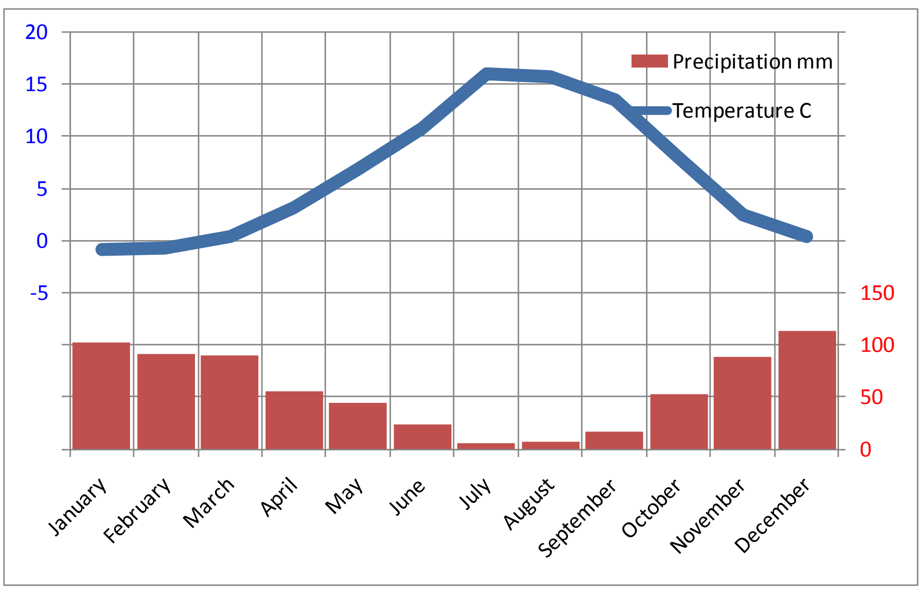

Figure 14 Average Meteorological data from 2030 to 2059 for GCM pcm1_A1B

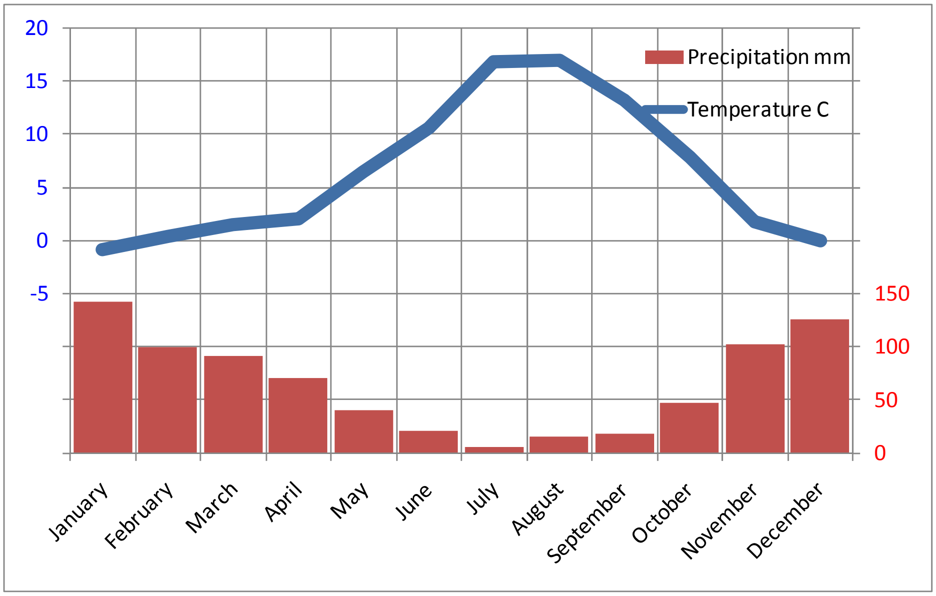

Figure 15 Average Meteorological data from 2030 to 2059 for GCM cgcm3.1_t47_A1B

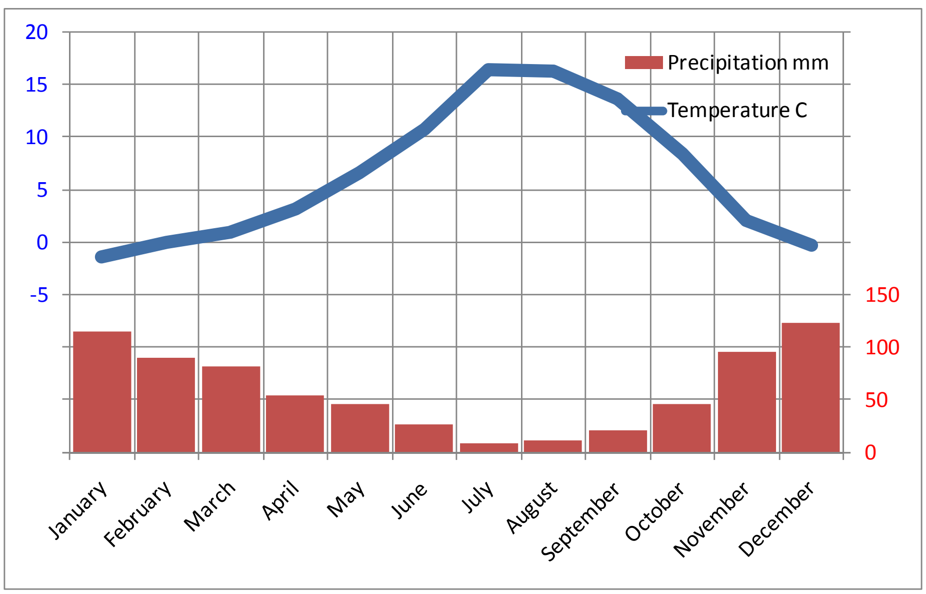

Figure 16 Average Meteorological data from 2030 to 2059 for GCM echo_g_A1B

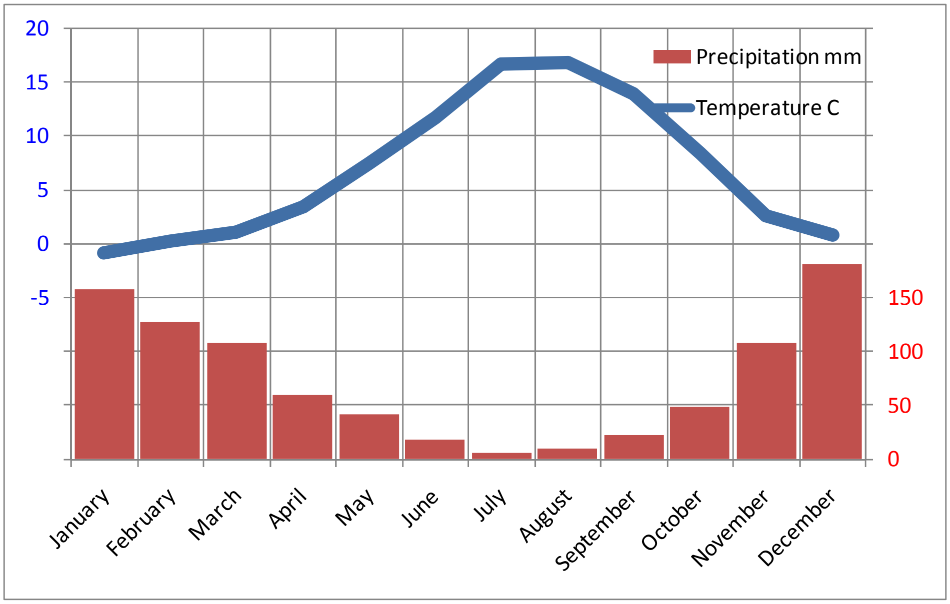

Figure 17 Average Meteorological data from 2030 to 2059 for GCM ipsl_cm4_A1B

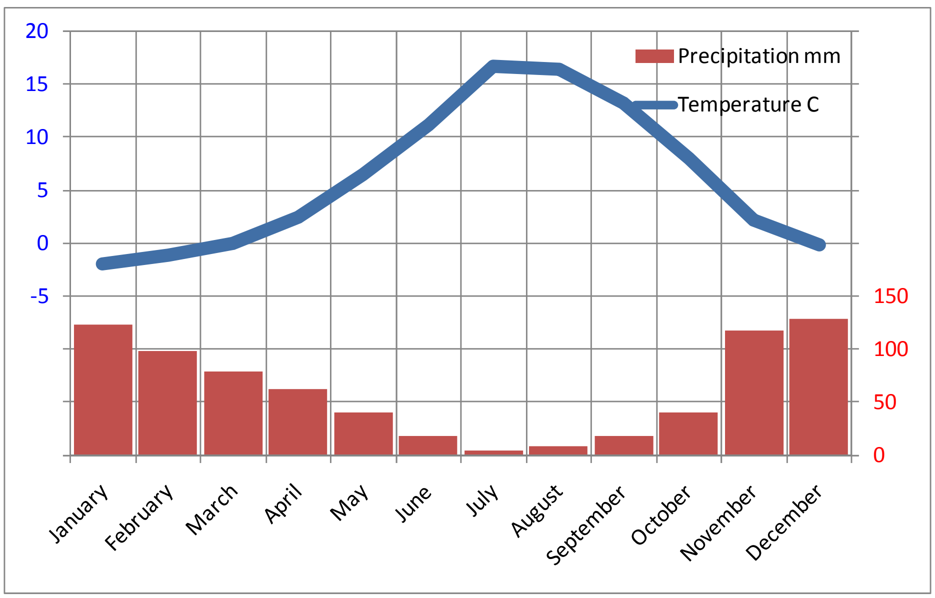

Figure 18 Average Meteorological data from 2030 to 2059 for GCM cnrm_cm3

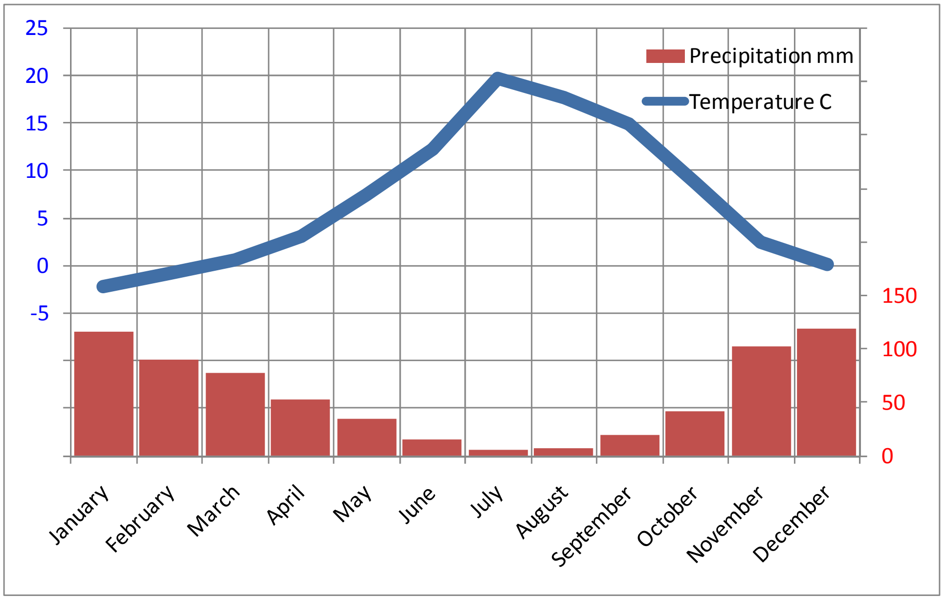

Figure 19 Average Meteorological data from 2030 to 2059 for GCM hadcm_A1B

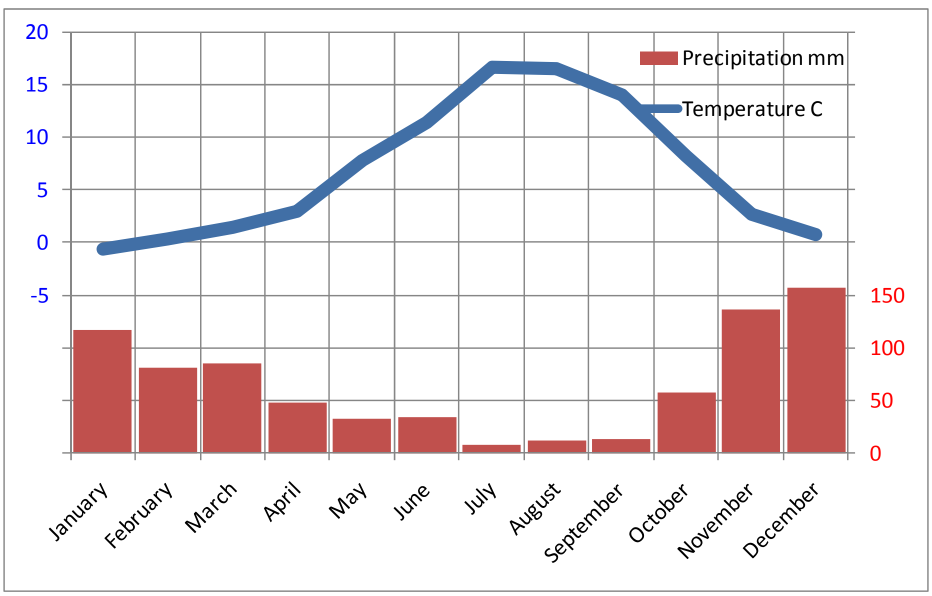

Figure 20 Average Meteorological data from 2030 to 2059 for GCM miroc_3.2_A1B

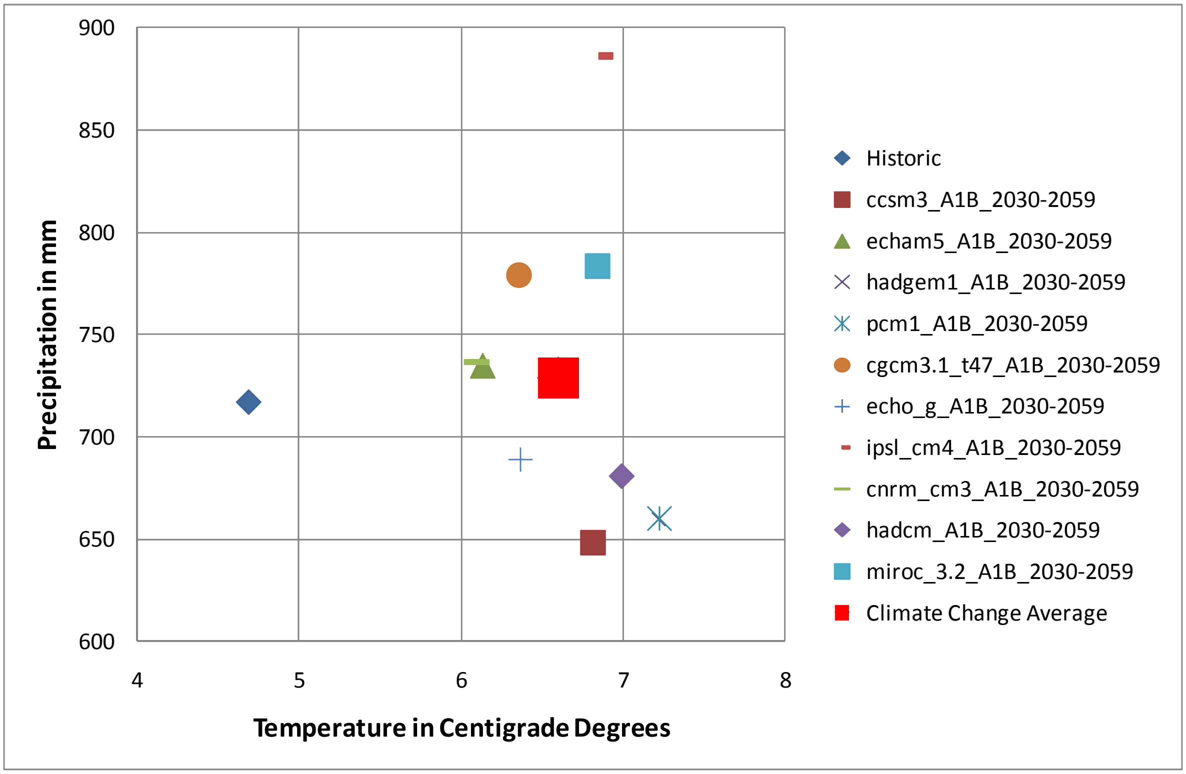

Figure 21 Downscaled annual precipitation and temperature projections for ten different climate change scenarios for the 2040s compared to historical data.

USGS STREAMFLOW DATA STATIONS

West Fork Ashland Creek near Ashland, OR

Location. Lat 42° 08'55", long 122° 42'55" near line between NW 1/4 SW 1/4 sec.28, T.39 S., R.1 E., Jackson County, Hydrologic Unit 17100308, in Rogue River National Forest, on left bank 0.3 mi upstream from city diversion, 2.5 mi south of Ashland, and at mile 0.4.

Drainage Area. 10.5 mi^2, at diversion dam 0.3 mi downstream.

Period of Record. September 1924 to January 1933, water years 1954-60, 1963, annual maximum; December 1974 to September 1982, Oct. 2002 to current year. Monthly discharge only for some periods published in WSP 1318.

Gage. Water-stage recorder and crest-stage gage. Datum of gage is 2,961.75 ft above NGVD of 1929. Sept. 10, 1924, to Jan. 31, 1933, water-stage recorder at site about 0.2 mi upstream at different datum. Oct. 14, 1953 to Sept. 30, 1963, crest-stage gage at diversion dam 0.3 mi downstream at different datum. Oct. 1, 2002 to Aug. 29, 2005, water-stage recorder at same site at datum 1.00 ft higher.

Remarks. No regulation or diversion above station.

Extremes for Period of Record. Maximum discharge, 330 ft^3/s Dec. 2, 1962, gage height,15.51 ft, site and datum then in use, from rating curve defined by computation of peak flow over dam; minimum, 0.8 ft^3/s Sept. 7, 2005

Calculated stats for period: 1975, 1 to 1978 ,12

	Obs	Sim	Sim/Obs
Avg Flow	8.8	8.7	0.98
Std Dev	6.6	7.2	1.08

Correlation Coefficient	=0.831
RMSE	= 4.047
RMSE/Obs Mean	= 0.459
MSE/Obs Var	= 0.372
Nash-Sutcliff Eff.	= 0.680

Monthly Stats:

Mon	ObsAvg	SimAvg	Bias	RMSE	ObsStDev	SimStDev
1	9.69	8.45	-1.24	2.21	5.75	4.32
2	8.14	7.83	-0.31	3.25	3.94	2.91
3	10.66	8.70	-1.96	5.63	6.08	4.02
4	11.25	8.90	-2.34	4.82	4.91	4.03
5	16.45	18.84	2.39	7.93	11.28	11.98
6	16.42	19.79	3.37	7.44	13.27	17.09
7	6.86	6.47	-0.39	1.13	3.90	4.35
8	4.81	3.72	-1.09	1.61	4.39	5.45
9	4.60	3.59	-1.01	1.09	4.56	5.45
10	3.55	3.85	0.30	0.64	5.43	4.91
11	5.41	5.82	0.41	0.77	3.59	3.07
12	8.06	8.01	-0.05	1.41	4.17	2.84

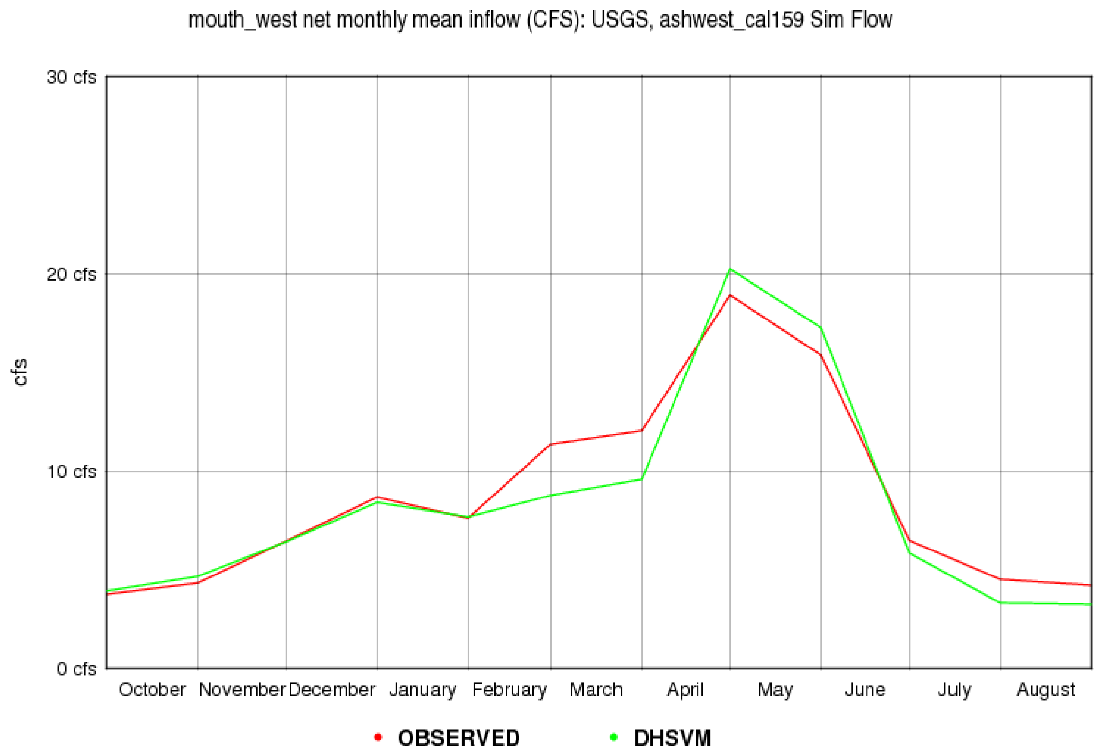

Figure 22 Hydrograph for the Calibration Period January 1974 to December 1978, Validation Period January 1979 to December 1982

Calculated statistic for validation period for period: 1979, 1 to 1980, 12

	Obs	Sim	Sim/Obs
Avg Flow	9.3	8.3	0.90
Std Dev	7.2	6.2	0.86

Correlation Coefficient	= 0.899
RMSE	= 3.330
RMSE/Obs Mean	= 0.360
MSE/Obs Var	= 0.211
Nash-Sutcliff Eff.	= 0.715

Monthly Stats:

Mon	ObsAvg	SimAvg	Bias	RMSE	ObsStDev	SimStDev
1	4.66	8.29	3.62	3.62	4.59	0.01
2	5.56	7.09	1.54	1.54	3.69	1.20
3	14.17	9.04	5.12	5.12	4.92	0.75
4	15.29	12.36	-2.93	2.93	6.04	4.07
5	28.81	25.92	-2.88	2.88	19.56	17.63
6	13.79	7.18	-6.61	6.61	4.54	1.11
7	4.97	3.37	-1.61	1.61	4.27	4.92
8	3.38	1.70	-1.68	1.68	5.87	6.59
9	2.65	1.85	-0.79	0.79	6.60	6.44
10	4.64	4.31	0.33	0.33	4.61	3.98
11	6.60	6.97	0.37	0.37	2.65	1.32
12	6.47	11.42	4.95	4.95	2.78	3.13

East Fork Ashland Creek Near Ashland, OR

Location. Lat 42° 09'10", long 122° 42'30", in NW 1/4, NW 1/4 sec.28, T.39 S., R.1 E., Jackson County, Hydrologic Unit 17100308, in Rogue River National Forest, on left bank 0.1 mi upstream from city diversion dam, 2.5 mi south of Ashland, and at mile 0.2.

Drainage Area. 8.14 mi^2, at diversion dam 0.1 mi downstream.

Period Of Record. September 1924 to January 1933, water years 1954-60, 1963, annual maximum; December 1974 to September 1982, Oct. 2002 to current year.

Gage. Water-stage recorder and crest-stage gage. Datum of gage is 2,903.70 ft above NGVD of 1929. Sept. 10, 1924 to Jan. 31, 1933, water-stage recorder at site about 200 ft downstream at different datum. Oct. 19, 1953 to Sept. 30, 1963, crest-stage gage at diversion dam 0.1 mi downstream at different datum.

Extremes For Period Of Record. Maximum discharge, 335 ft^3/s Dec. 2, 1962, gage height, 5.42 ft, site and datum then in use, from rating curve defined by computation of peak flow over dam; minimum discharge, 0.47 $ft^{3/}s$ Mar. 14, 1977, result of freeze up.

Extremes Outside Period Of Record. Flood of Jan. 15, 1974, is the highest since at least 1925. Discharge, 5,630 ft^3/s by slope-area measurement of peak flow, gage height, 10.2 ft from flood marks. Peak believed to be affected by release from debris dams breaking upstream.

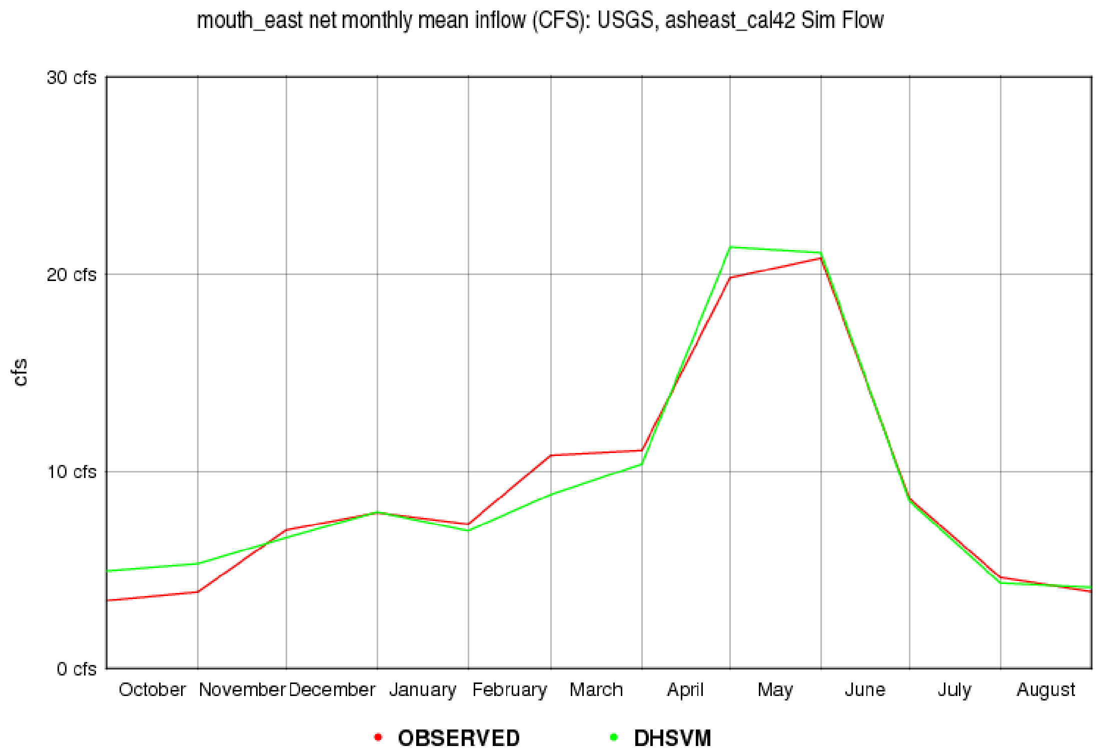

Figure 23 Hydrograph for the Calibration Period January 1974 to December 1978, Validation Period January 1979 to December 1982

Calculated stats for period: 1975, 1 to 1978 ,12

	Obs	Sim	Sim/Obs
Avg Flow	9.2	9.6	1.04
Std Dev	8.7	7.9	0.91

Correlation Coefficient	= 0.854
RMSE	= 4.574
RMSE/Obs Mean	= 0.498
MSE/Obs Var	= 0.277
Nash-Sutcliff Eff.	= 0.667

Monthly Stats:

Mon	ObsAvg	SimAvg	Bias	RMSE	ObsStDev	SimStDev
1	8.27	7.83	-0.44	1.66	4.75	3.82
2	7.56	7.08	-0.48	2.60	4.27	3.08
3	10.09	8.65	-1.45	4.23	6.18	4.05
4	9.92	9.54	-0.38	3.66	5.19	3.78
5	17.57	18.85	1.28	8.80	12.79	10.80
6	21.92	24.21	2.29	10.56	21.88	20.95
7	9.16	9.66	0.50	1.37	4.94	6.13
8	4.88	4.91	0.04	2.45	4.65	5.63
9	4.08	4.56	0.48	1.10	5.35	5.52
10	3.19	4.79	1.59	1.67	6.05	4.89
11	4.86	6.64	1.79	1.84	4.49	3.10
12	8.78	8.29	-0.49	2.49	5.31	3.14

Calculated statistic for validation period for period: 1979, 1 to 1980, 12

	Obs	Sim	Sim/Obs
Avg Flow	10.5	10.3	0.97
Std Dev	6.9	7.1	1.03

Correlation Coefficient	= 0.887
RMSE	= 3.352
RMSE/Obs Mean	= 0.318
MSE/Obs Var	= 0.237
Nash-Sutcliff Eff.	= 0.778

Monthly Stats:

Mon	ObsAvg	SimAvg	Bias	RMSE	ObsStDev	SimStDev
1	13.40	10.93	-2.47	4.99	7.57	2.75
2	10.86	9.38	-1.48	2.26	4.52	2.93
3	12.97	9.84	-3.13	3.29	2.51	0.56
4	14.06	14.75	0.69	2.75	3.83	4.63
5	24.44	27.80	3.36	3.45	14.55	17.89
6	18.25	14.80	-3.46	5.69	7.92	7.78
7	9.07	6.82	-2.24	2.29	3.03	4.63
8	4.54	2.37	-2.18	2.27	6.07	7.90
9	3.37	2.45	-0.92	0.92	7.18	7.81
10	3.68	4.70	1.02	1.02	6.91	5.63
11	4.27	7.30	3.03	3.12	6.43	3.04
12	7.60	12.03	4.42	4.49	2.95	2.03

RESULTS

East Fork

Snow Water Equivalent – East Fork

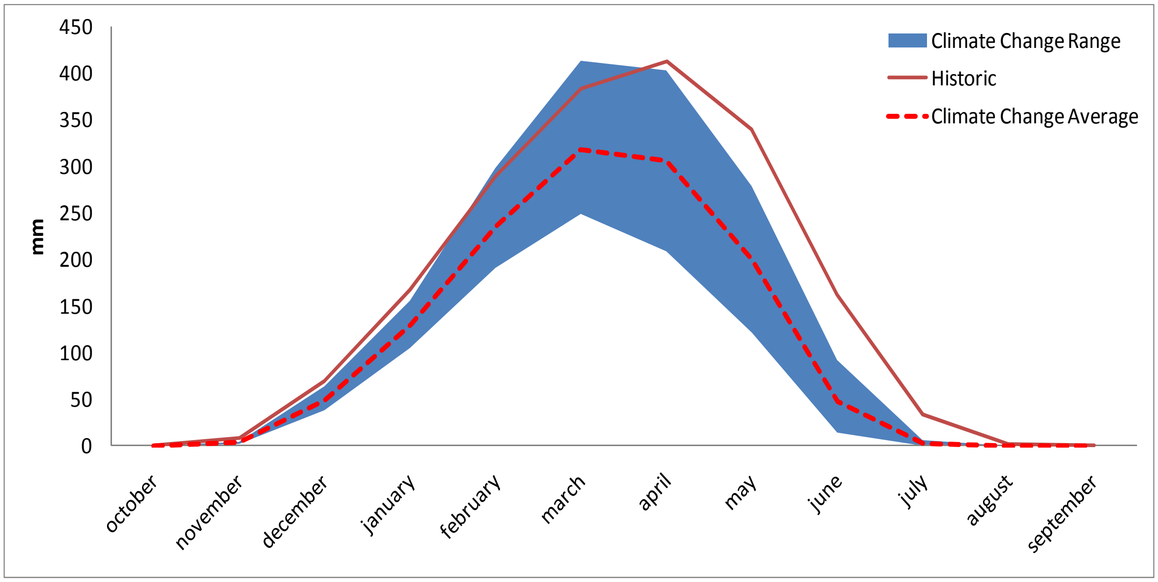

Figure 24 East Fork Mean Snow Water Equivalent for the historical period 1920 to 2000 and climate change scenarios for the 2040s

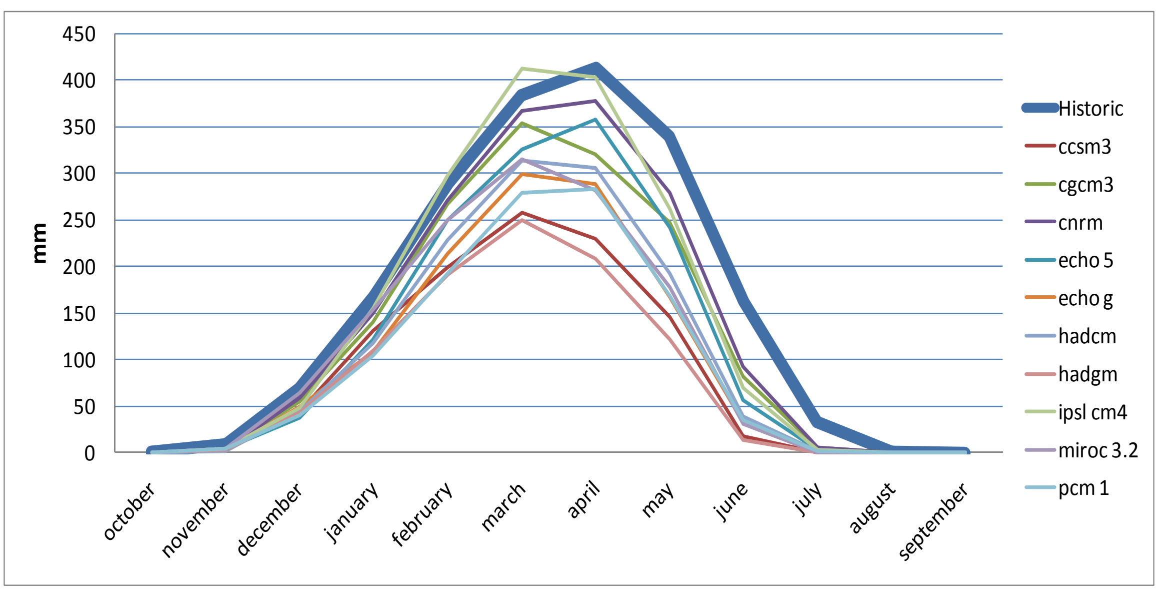

Figure 25 East Fork mean Snow Water Equivalent for the historical period 1920 to 2000 and climate change scenarios for the 2040s

Table 3 Mean Monthly Snow Water Equivalent for the period historic period 1920 to 2000 and climate change scenarios from 2030 to 2059

	Historic	ccsm3 GCM	cgcm3 GCM	Cnrm GCM	echo 5 GCM	echo g GCM	Hadcm GCM	Hadgm GCM	ipsl cm4 GCM	miroc 3.2 GCM	pcm 1 GCM
October	0.6	0.1	0.1	0.1	0.2	0.1	0.1	0.1	0.1	0.1	0.1
November	8.6	3.3	4.2	2.8	4.0	2.7	2.0	2.5	3.8	3.9	4.3
December	69.1	44.3	55.6	58.8	38.2	49.1	44.1	42.7	48.7	63.9	40.2
January	167.4	131.2	139.8	149.0	121.2	108.8	117.5	109.7	155.5	153.0	105.0
February	289.1	198.4	267.4	270.7	249.9	213.8	228.3	190.8	297.6	249.3	192.2
March	383.0	256.9	353.8	367.3	325.0	298.9	313.4	249.0	412.5	314.3	278.4
April	412.2	230.0	320.5	377.9	356.9	288.1	306.0	208.8	402.2	281.9	283.5
May	339.1	145.6	247.0	278.4	241.3	166.8	192.9	121.7	261.9	177.2	167.8
June	162.1	18.0	81.3	92.1	57.0	32.7	39.4	14.3	69.5	31.3	35.5
July	33.5	0.1	6.3	5.1	2.7	1.1	1.2	0.1	3.7	1.1	1.2
August	1.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
September	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Table 4 Snow Statistics for the period historic period 1920 to 2000 and climate change scenarios from 2030 to 2059, Julian Day of 10% accumulation (JD 10% SWE) , Julian Day of maximum accumulation (JD MAX SWE), Julian Day of 90% melting of the accumulated snow (JD 90% MELT SWE), Maximum Snow Water Equivalent (MAX SWE) , Days Between 10% of accumulation to 90
% of melting (DAYS 10% - 90%)

	Historic	ccsm3 GCM	cgcm3 GCM	Cnrm GCM	echo 5 GCM	echo g GCM	Hadcm GCM	Hadgm GCM	ipsl cm4 GCM	miroc 3.2 GCM	pcm 1 GCM
JD 10% SWE	57.0	57.4	57.6	58.8	64.1	56.7	61.1	59.3	62.9	54.3	62.5
JD MAX SWE	180.4	165.3	166.6	176.5	177.2	168.4	169.5	159.2	169.7	162.4	171.0
JD 90% MELT SWE	258.6	228.9	246.5	246.9	241.6	237.4	234.9	226.3	242.8	234.6	235.7
MAX SWE	443.8	284.9	379.8	411.6	378.1	329.6	343.6	271.4	447.2	337.7	316.7
DAYS 10% - 90%	201.6	171.5	189.0	188.1	177.4	180.7	173.7	167.0	180.0	180.3	173.2

Evapotranspiration – East Fork

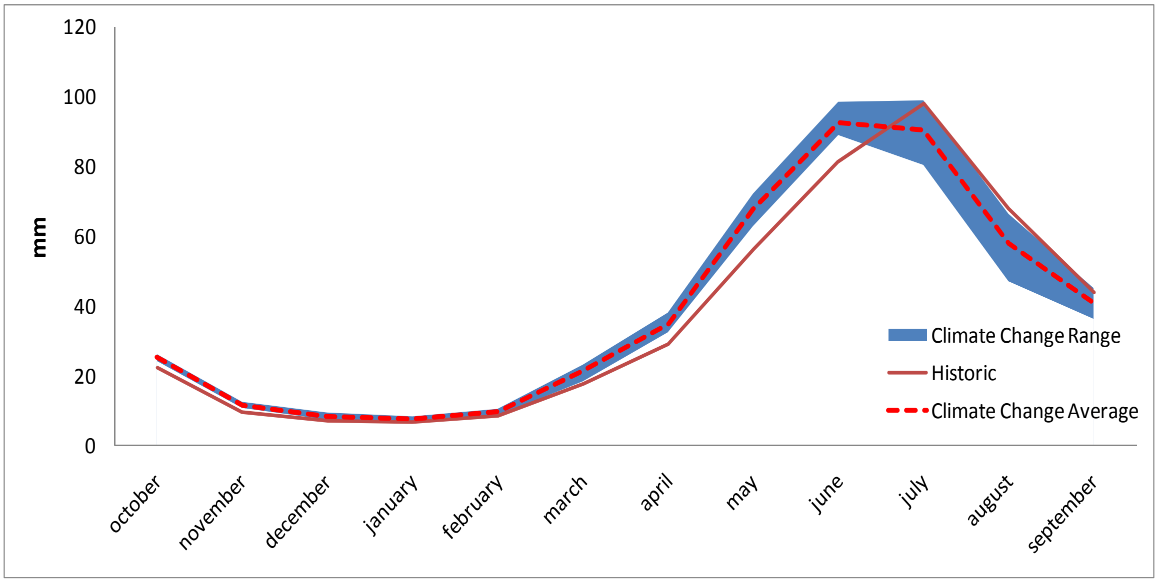

Figure 26 East Fork monthly evapotranspiration for the historical period 1920 to 2000 and climate change scenarios for the 2040s

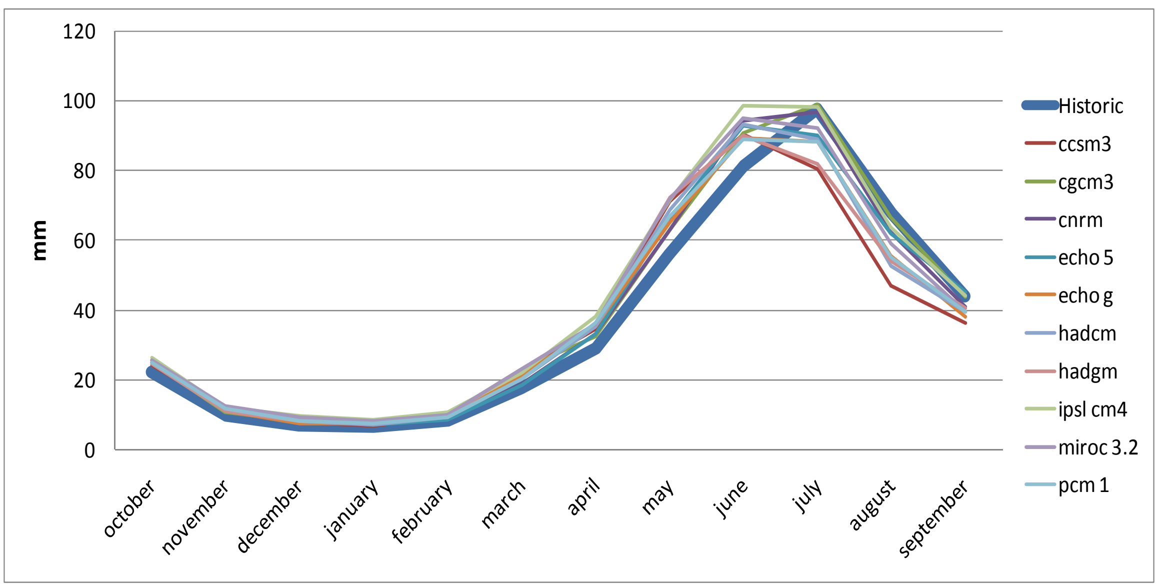

Figure 27 East Fork monthly evapotranspiration for the historical period 1920 to 2000 and climate change scenarios for the 2040s

Table 5 Accumulated Monthly Evapotranspiration for the period historic period 1920 to 2000 and climate change scenarios from 2030 to 2059

	Historic	ccsm3 GCM	cgcm3 GCM	Cnrm GCM	echo 5 GCM	echo g GCM	Hadcm GCM	Hadgm GCM	ipsl cm4 GCM	miroc 3.2 GCM	pcm 1 GCM
October	22.4	24.3	25.0	24.9	25.8	25.6	25.3	24.6	26.3	25.6	24.9
November	9.8	11.7	10.9	11.6	12.3	11.3	11.7	11.3	12.0	12.7	11.7
December	7.2	7.9	8.2	8.1	8.5	7.6	8.3	8.3	9.5	9.2	8.4
January	6.8	6.8	8.2	7.3	7.1	7.5	7.1	8.4	8.5	8.2	7.7
February	8.5	9.7	10.2	9.1	8.8	10.0	9.3	9.7	10.6	10.2	9.3
March	17.6	22.4	23.1	19.0	18.5	21.6	20.3	23.3	22.2	23.1	20.2
April	29.1	34.7	32.6	33.0	33.3	35.3	35.4	35.9	38.1	36.0	36.5
May	56.2	71.1	63.0	62.9	66.2	65.1	68.6	72.2	71.5	71.8	66.9
June	81.3	90.4	90.8	94.3	92.9	89.2	93.4	89.9	98.5	94.9	89.0
July	97.8	80.4	98.9	96.9	89.9	88.2	88.8	81.7	98.2	92.1	88.1
August	67.9	47.1	66.4	62.1	61.9	55.4	52.6	54.1	63.7	59.2	55.3
September	44.0	36.4	43.7	41.0	45.2	38.1	39.7	40.7	44.2	39.5	39.4

Streamflow – East Fork

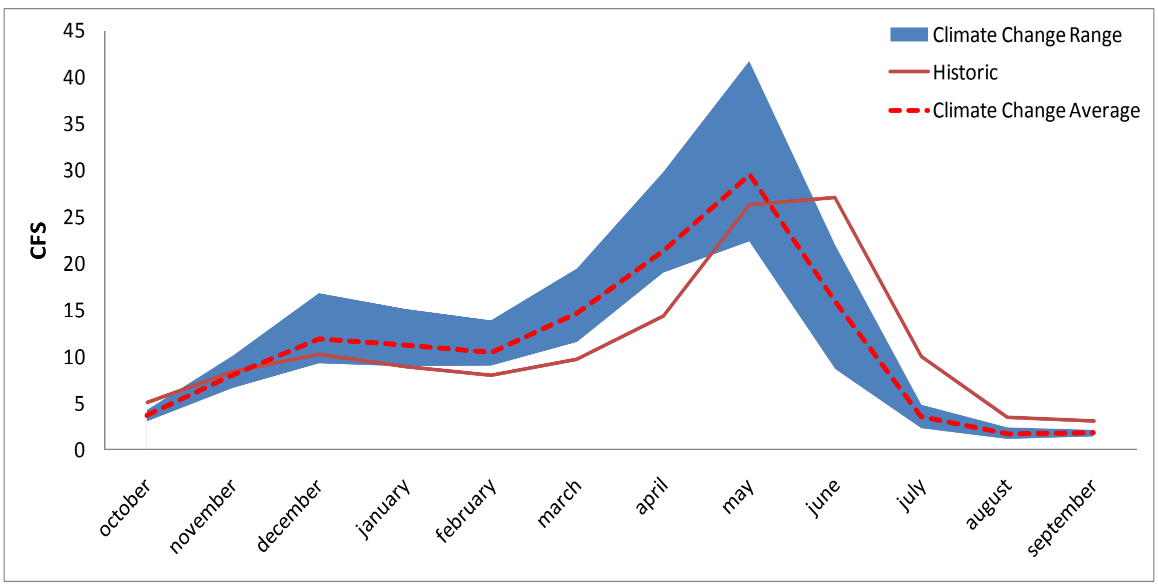

Figure 28 East Fork average monthly streamflow for the historical period 1920 to 2000 and climate change scenarios for the 2040s

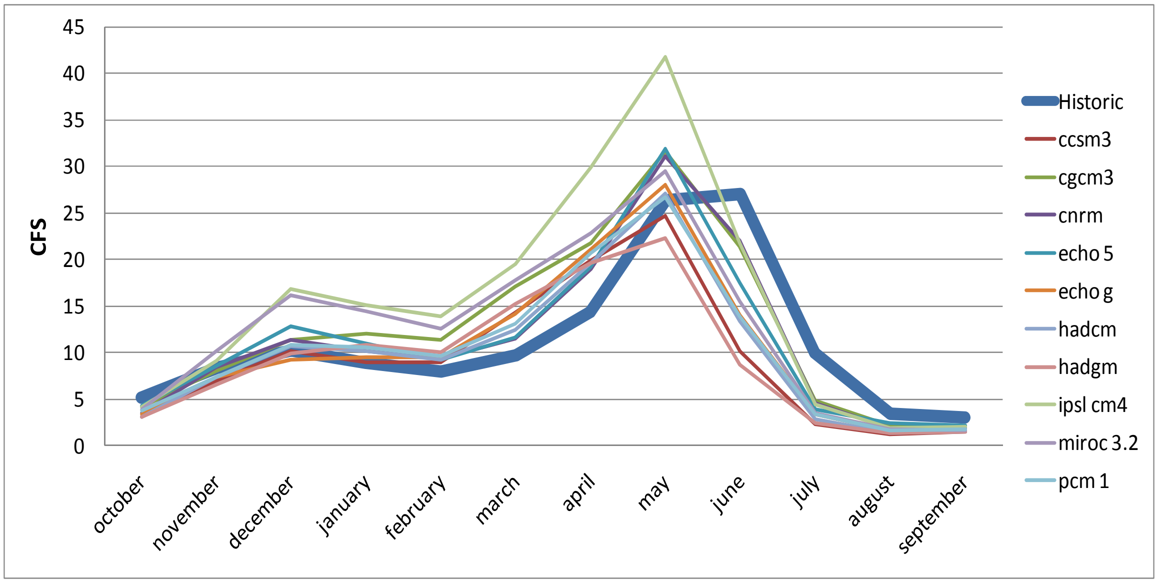

Figure 29 East Fork average monthly streamflow for the historical period 1920 to 2000 and climate change scenarios for the 2040s

Table 6 Average monthly streamflow (units cfs) for the historical period 1920 to 2000 and climate change scenarios for the 2040s

	Historic	ccsm3 GCM	cgcm3 GCM	Cnrm GCM	echo 5 GCM	echo g GCM	Hadcm GCM	Hadgm GCM	ipsl cm4 GCM	miroc 3.2 GCM	pcm 1 GCM
October	5.13	3.11	4.15	3.56	4.29	3.38	3.06	3.08	4.22	3.97	3.79
November	8.33	7.03	8.04	8.37	8.61	7.33	7.33	6.63	9.07	10.12	7.42
December	10.27	10.14	11.38	11.35	12.8	9.27	10.73	9.93	16.83	16.19	10.89
January	8.93	8.93	11.97	10.22	10.91	9.47	10.12	10.86	15.15	14.4	10.62
February	7.95	9.03	11.35	9.41	9.29	9.48	9.23	9.99	13.91	12.5	9.64
March	9.71	14.29	17.1	11.56	11.67	14.16	12.37	15.23	19.5	17.75	13.08
April	14.36	19.86	21.75	18.96	19.22	21.15	19.59	19.66	29.82	22.79	20.66
May	26.32	24.67	31.68	31.11	31.93	27.98	27.07	22.31	41.75	29.42	26.66
June	27.07	10.11	21.34	21.96	17.48	14.02	13.38	8.64	21.77	15.46	13.91
July	9.95	2.33	4.85	4.57	3.86	3.34	2.81	2.39	4.41	3.47	3.39
August	3.47	1.18	2.17	1.91	2.41	1.63	1.43	1.41	1.94	1.83	1.69
September	3.07	1.5	2.04	1.92	2.16	1.67	1.52	1.45	2	1.7	1.71

Extreme Values – East Fork

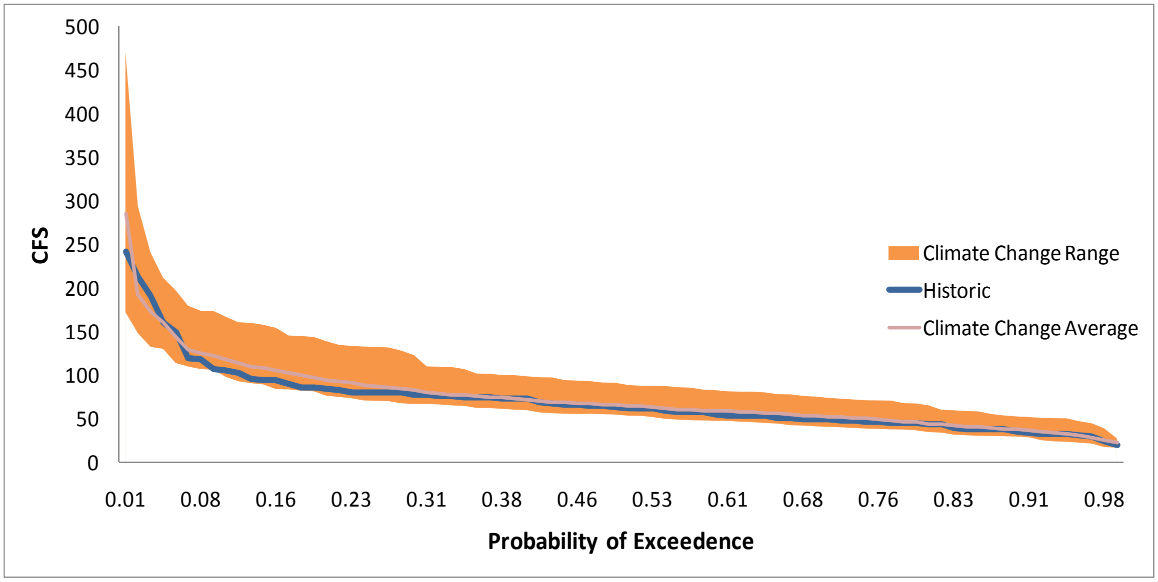

Figure 30 East Fork quantiles for extreme flood for the historical period 1920 to 2000 and climate change scenarios for the 2040s

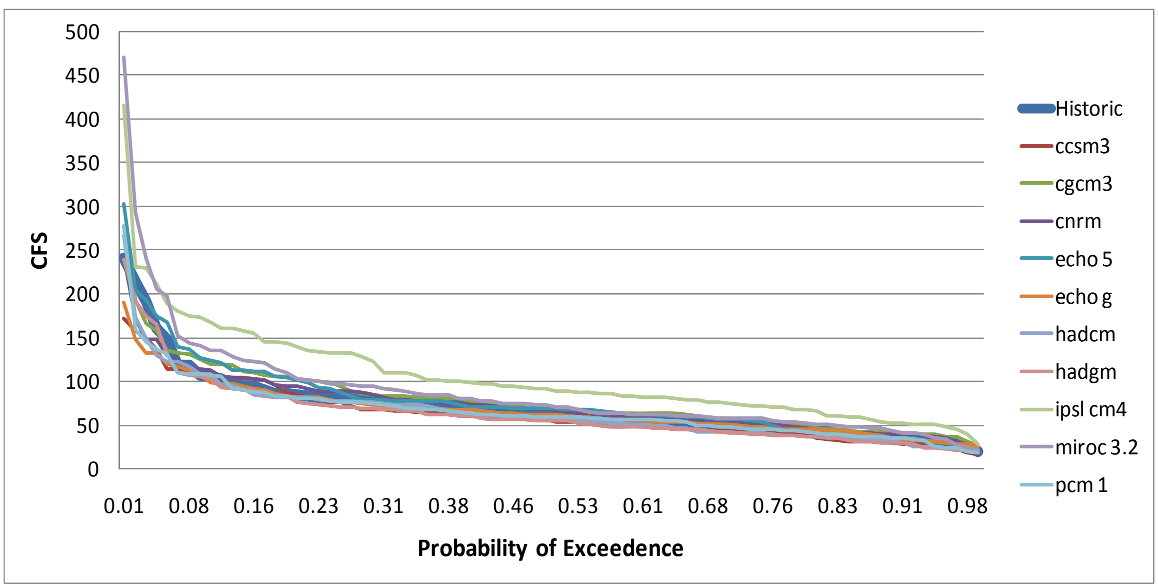

Figure 31 East Fork quantiles for extreme flood for the historical period 1920 to 2000 and climate change scenarios for the 2040s

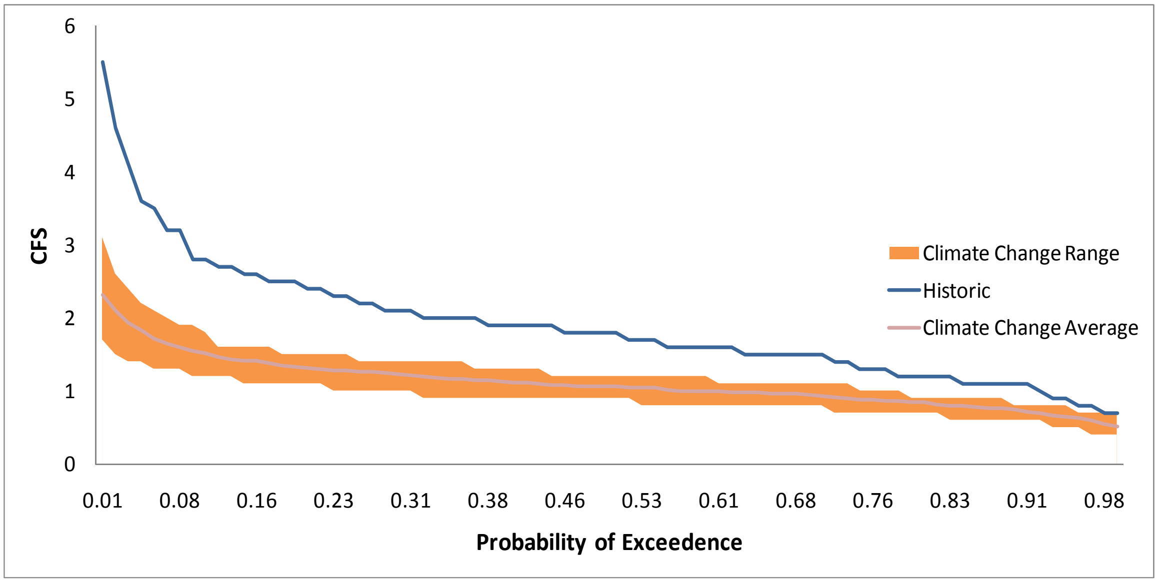

Figure 32 East Fork quantiles for extreme 7-day low streamflow for the historical period 1920 to 2000 and climate change scenarios for the 2040s

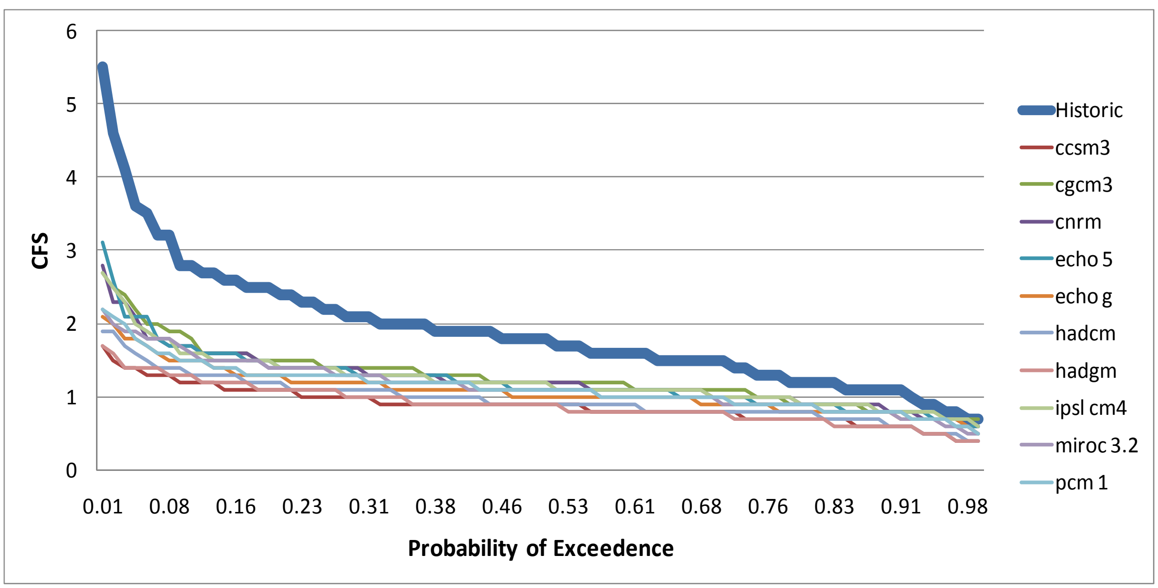

Figure 33 East Fork quantiles for extreme 7-day low streamflow for the historical period 1920 to 2000 and climate change scenarios for the 2040s

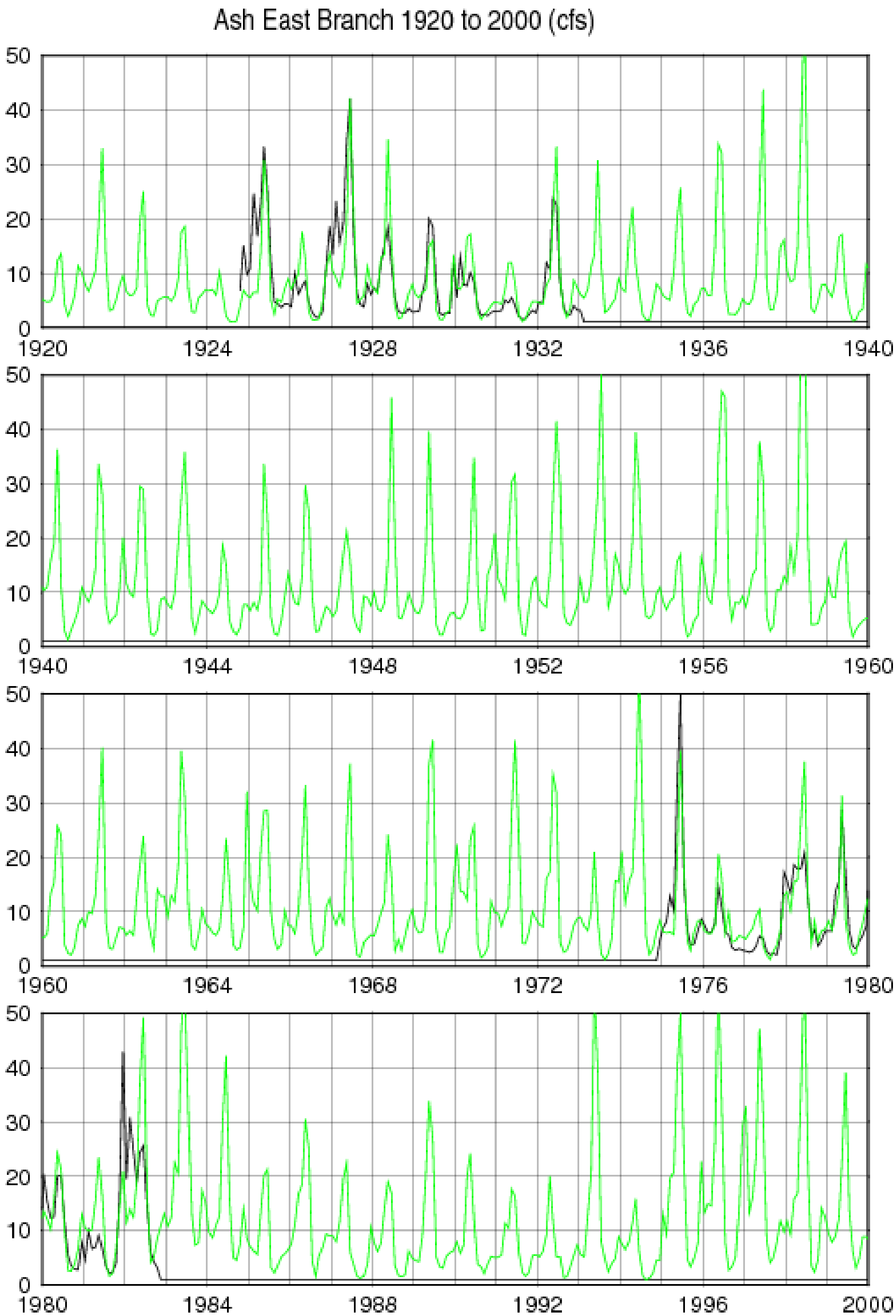

Figure 34 East Fork simulated monthly average streamflow (units cfs). (Black line represents observed values).

WEST FORK

Snow Water Equivalent – West Fork

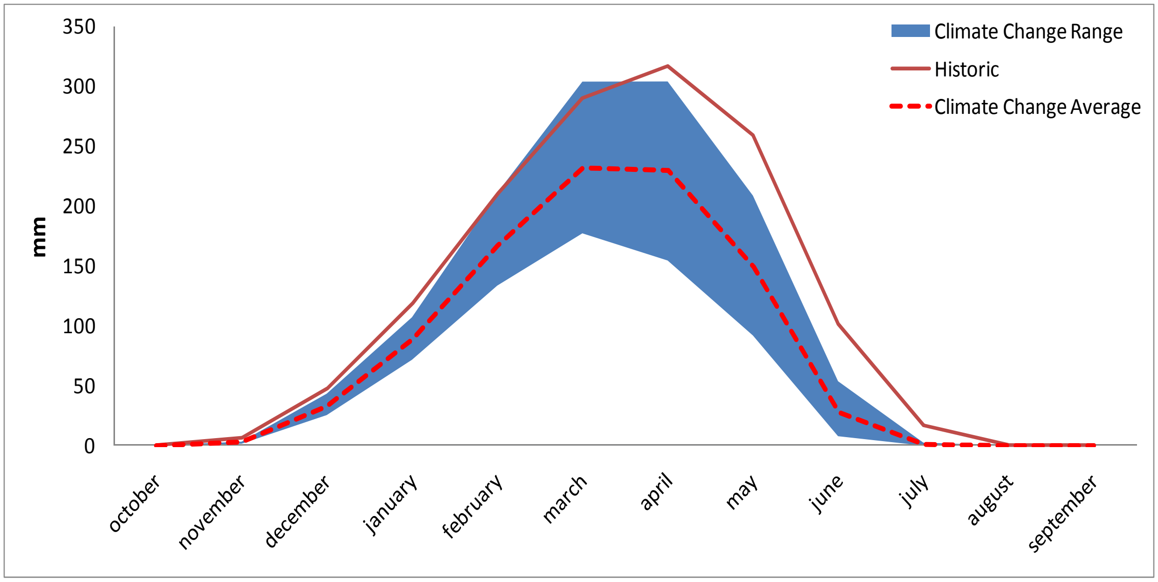

Figure 35 West Fork mean Snow Water Equivalent for the historical period 1920 to 2000 and climate change scenarios for the 2040s

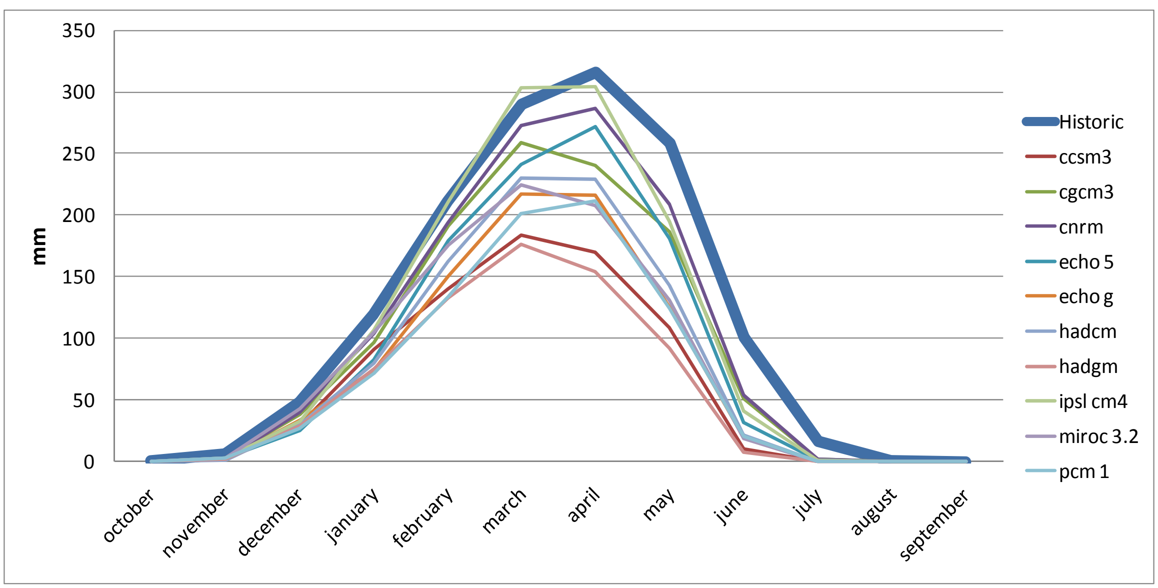

Figure 36 West Fork mean Snow Water Equivalent for the historical period 1920 to 2000 and climate change scenarios for the 2040s

Table 7 West Fork mean Monthly Snow Water Equivalent for the historical period 1920 to 2000 and climate change scenarios for the 2040s

	Historic	ccsm3 GCM	cgcm3 GCM	Cnrm GCM	echo 5 GCM	echo g GCM	Hadcm GCM	Hadgm GCM	ipsl cm4 GCM	miroc 3.2 GCM	pcm 1 GCM
October	0.4	0.10	0.08	0.07	0.10	0.05	0.04	0.04	0.08	0.06	0.07
November	6.1	2.49	3.30	2.39	2.86	2.25	1.65	1.92	2.83	3.07	3.09
December	47.8	29.62	38.11	40.26	25.42	33.76	29.86	29.09	32.57	43.31	27.20
January	119.2	91.35	96.82	103.99	82.99	74.51	80.23	75.24	107.05	105.14	71.48
February	210.8	139.96	190.78	194.37	179.55	150.79	162.23	133.15	210.94	175.01	133.92
March	289.8	183.39	258.67	273.15	241.58	217.54	230.17	176.67	303.72	224.65	201.63
April	316.1	170.08	239.97	286.33	271.70	216.08	229.57	154.03	303.85	207.71	211.18
May	258.5	108.93	186.65	208.60	180.59	125.53	142.91	91.64	194.70	130.99	124.51
June	101.0	10.24	51.09	53.81	31.77	19.78	21.88	7.92	41.35	18.49	20.82
July	16.3	0.03	2.54	1.83	1.03	0.42	0.42	0.05	1.47	0.35	0.39
August	0.4	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
September	0.0	0.01	0.01	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.01

Table 8 West Fork Snow Statistics for the historical period 1920 to 2000 and climate change scenarios for the 2040s, Julian Day of 10% accumulation (JD 10% SWE) , Julian Day of maximum accumulation (JD MAX SWE), Julian Day of 90% melting of the accumulated snow (JD 90% MELT SWE), Maximum Snow Water Equivalent (MAX SWE) , Days Between 10% of accumulation and 90% of melting (DAYS 10% - 90%).

	Historic	ccsm3 GCM	cgcm3 GCM	Cnrm GCM	echo 5 GCM	echo g GCM	Hadcm GCM	Hadgm GCM	ipsl cm4 GCM	miroc 3.2 GCM	pcm 1 GCM
JD 10% SWE	58.2	58.3	58.8	60.3	65.7	58.2	62.8	59.3	63.9	54.9	63.4
JD MAX SWE	181.7	165.9	167.4	178.2	178.4	170.1	172.2	159.4	171.4	163.4	173.9
JD 90% MELT SWE	254.6	229.5	245.6	244.7	239.9	237.3	234.4	227.4	241.7	234.6	235.2
MAX SWE	343.2	209.3	282.3	312.0	287.4	244.5	256.1	196.4	335.8	245.3	234.3
DAYS 10% - 90%	196.4	171.2	186.8	184.4	174.2	179.1	171.7	168.1	177.8	179.7	171.8

Evapotranspiration – West Fork

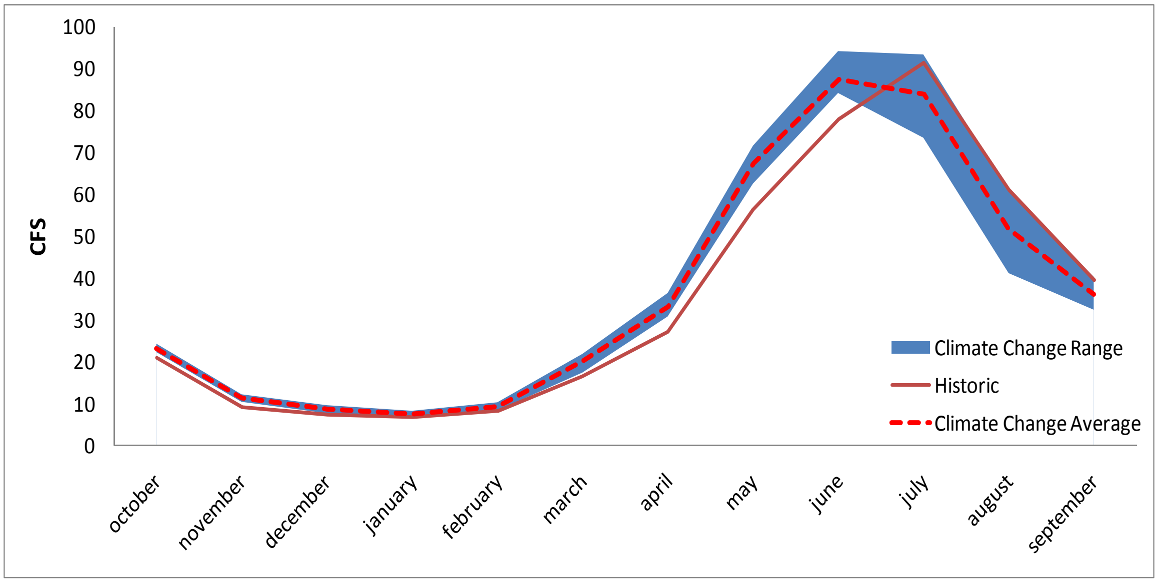

Figure 37 West Fork Monthly Evapotranspiration for the historical period 1920 to 2000 and climate change scenarios for the 2040s

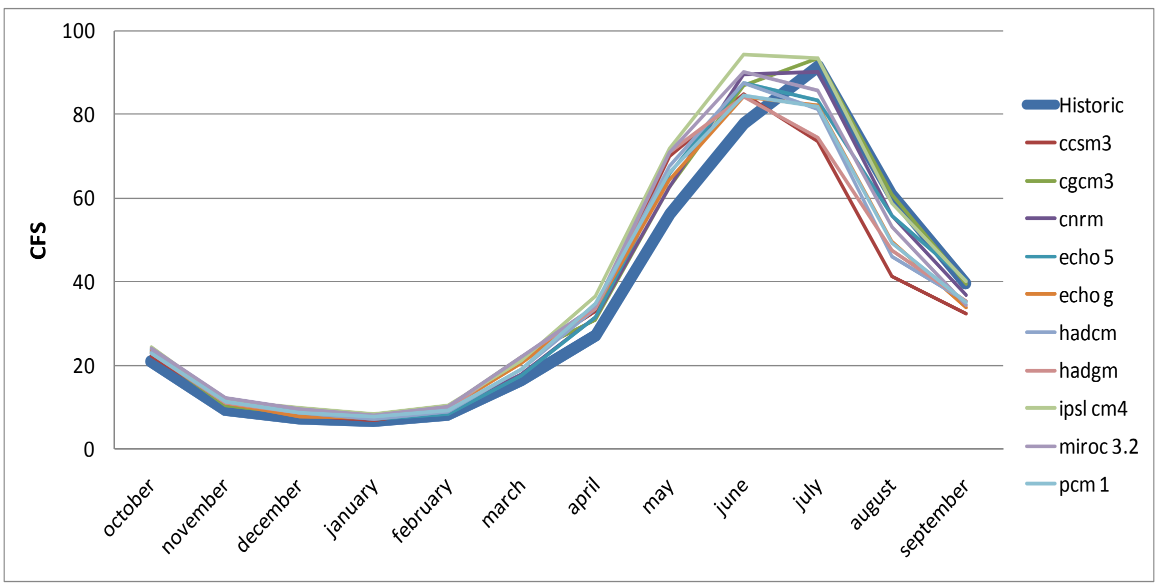

Figure 38 West Fork Monthly Evapotranspiration for the historical period 1920 to 2000 and climate change scenarios for the 2040s

Table 9 West Fork Accumulated Monthly Evapotranspiration for the historical period 1920 to 2000 and climate change scenarios for the 2040s

	Historic	ccsm3 GCM	cgcm3 GCM	Cnrm GCM	echo 5 GCM	echo g GCM	Hadcm GCM	Hadgm GCM	ipsl cm4 GCM	miroc 3.2 GCM	pcm 1 GCM
October	21.1	22.4	23.3	23.0	23.9	23.5	23.2	22.8	24.5	24.0	22.9
November	9.3	11.3	10.6	11.2	11.9	11.0	11.4	10.9	11.6	12.3	11.3
December	7.4	8.2	8.5	8.3	8.8	7.8	8.5	8.5	9.8	9.5	8.7
January	6.7	6.8	8.2	7.3	7.1	7.5	7.1	8.4	8.4	8.1	7.7
February	8.3	9.6	10.0	8.8	8.5	9.8	9.1	9.5	10.5	10.0	9.2
March	16.6	21.3	22.0	17.9	17.5	20.5	19.1	22.0	21.0	22.0	19.1
April	27.3	32.9	30.9	31.3	31.5	33.6	33.5	33.7	36.5	34.2	34.8
May	56.3	69.9	62.6	62.6	65.9	64.3	67.7	70.9	71.7	71.0	66.1
June	77.7	84.9	86.9	89.6	87.5	84.2	87.5	84.2	94.3	90.0	84.4
July	91.5	73.5	93.3	90.2	83.3	82.1	81.3	74.4	93.4	85.8	81.9
August	60.9	41.3	60.9	55.9	55.7	49.4	46.1	47.4	58.8	53.0	49.4
September	39.5	32.5	39.3	36.7	40.4	33.8	35.2	35.2	40.1	34.5	35.0

Stream Flow

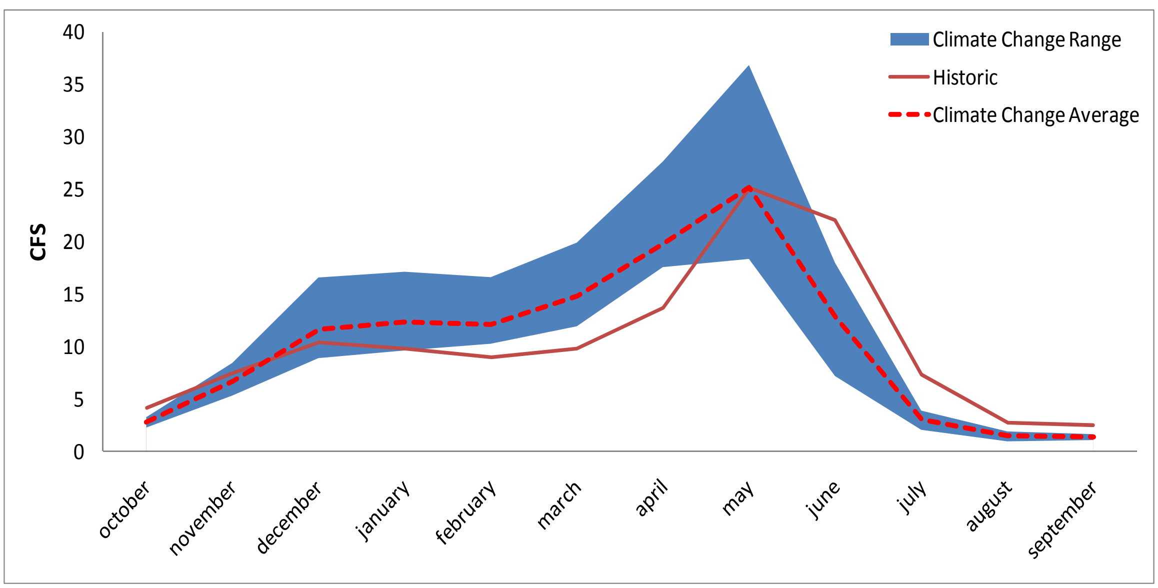

Figure 39 West Fork Average Monthly Streamflow for the historical period 1920 to 2000 and climate change scenarios for the 2040s

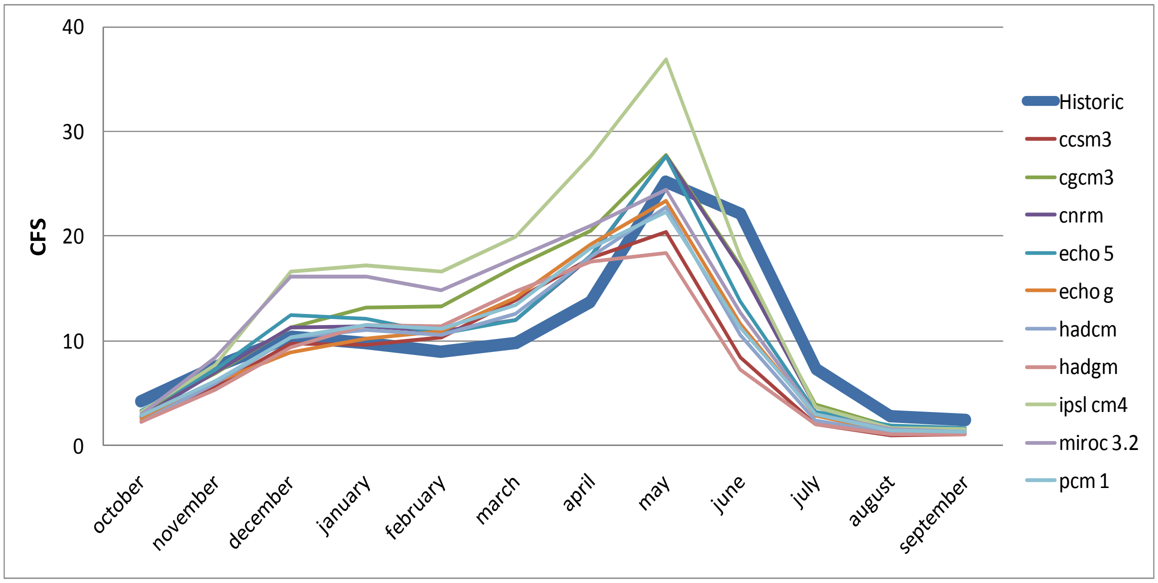

Figure 40 West Fork Average Monthly for the historical period 1920 to 2000 and climate change scenarios for the 2040s

Table 10 West Fork Average Monthly Streamflow for the historical period 1920 to 2000 and climate change scenarios for the 2040s

	Historic	ccsm3 GCM	cgcm3 GCM	Cnrm GCM	echo 5 GCM	echo g GCM	Hadcm GCM	Hadgm GCM	ipsl cm4 GCM	miroc 3.2 GCM	pcm 1 GCM
October	4.2	2.34	3.23	2.77	3.31	2.58	2.32	2.3	3.28	2.99	2.89
November	7.5	5.69	6.89	7.06	7.23	6.06	5.97	5.35	7.74	8.48	6.15
December	10.43	9.74	11.23	11.31	12.44	8.92	10.32	9.37	16.62	16.12	10.38
January	9.83	9.66	13.24	11.39	12.1	10.22	11.02	11.51	17.17	16.19	11.47
February	8.96	10.29	13.35	10.93	10.74	10.91	10.63	11.37	16.65	14.8	11.15
March	9.81	13.89	17.13	11.95	12.05	14.17	12.56	14.75	19.94	17.88	13.38
April	13.73	17.93	20.58	17.99	18.19	19.25	18.09	17.6	27.67	20.98	18.83
May	25.16	20.44	27.75	27.65	27.66	23.34	22.82	18.37	36.87	24.4	22.25
June	22.11	8.46	17.19	16.94	13.81	11.63	10.58	7.22	18.03	12.76	11.32
July	7.33	2.09	3.94	3.69	3.27	2.93	2.41	2.09	3.76	3.02	2.94
August	2.78	1	1.81	1.61	1.95	1.38	1.19	1.15	1.67	1.53	1.43
September	2.49	1.16	1.62	1.53	1.7	1.33	1.19	1.12	1.6	1.35	1.36

Extreme Values – West Fork

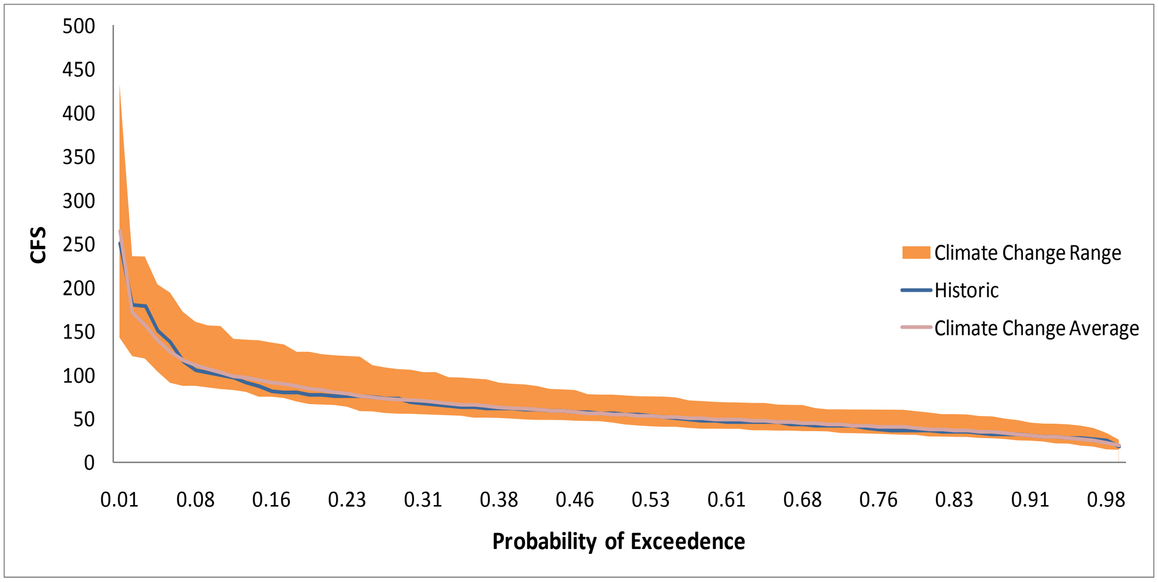

Figure 41 West Fork quantiles for extreme daily flood for the historical period 1920 to 2000 and climate change scenarios for the 2040s

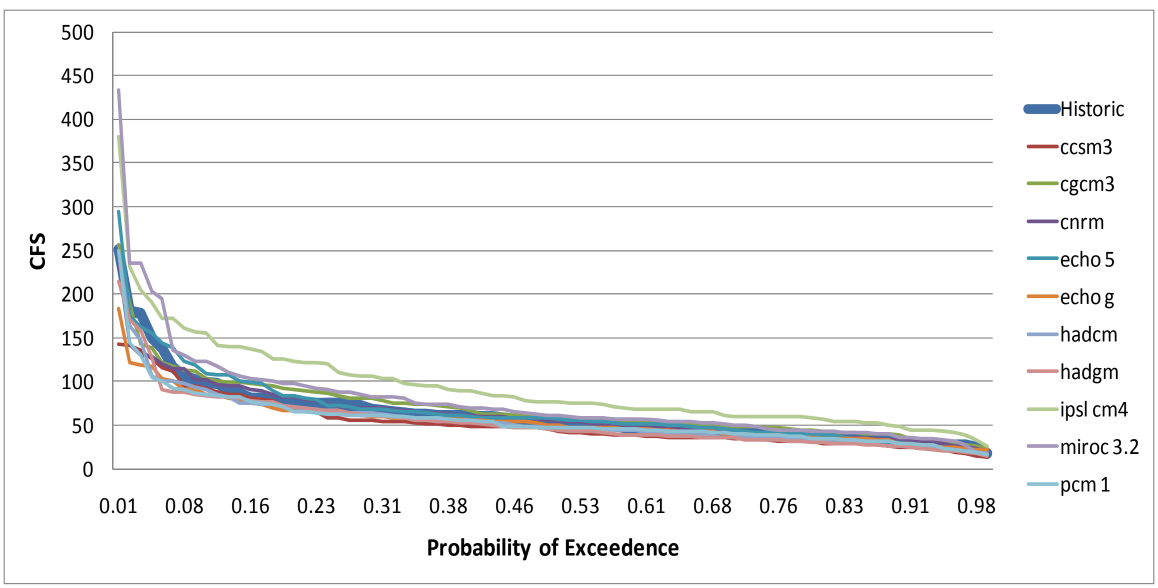

Figure 42 West Fork quantiles for extreme daily flood for the historical period 1920 to 2000 and climate change scenarios for the 2040s

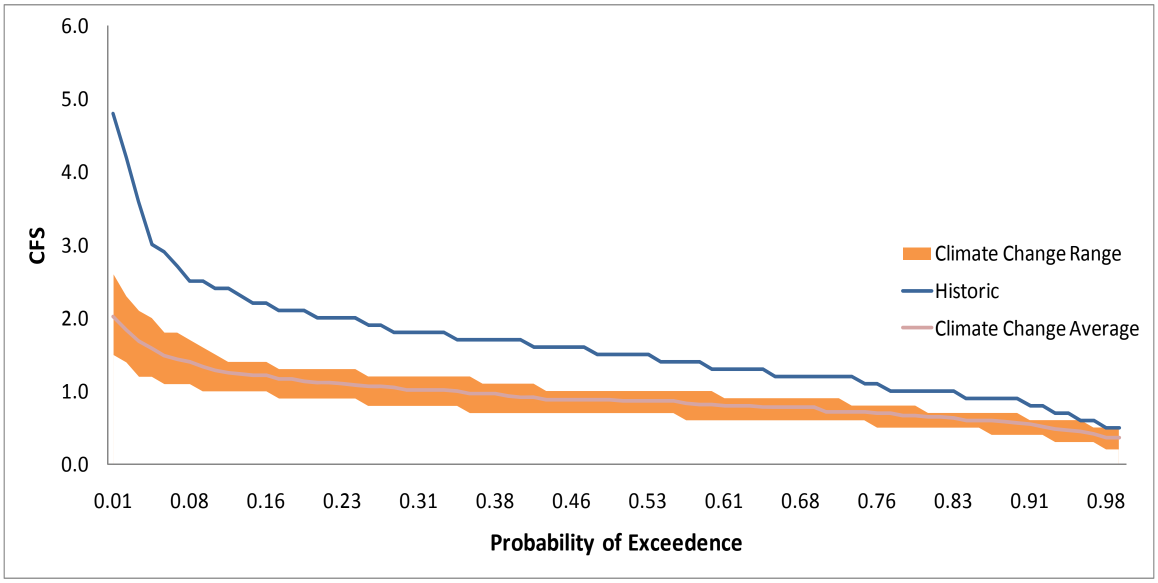

Figure 43 West Fork quantiles for extreme 7-day low streamflow for the historical period 1920 to 2000 and climate change scenarios for the 2040s

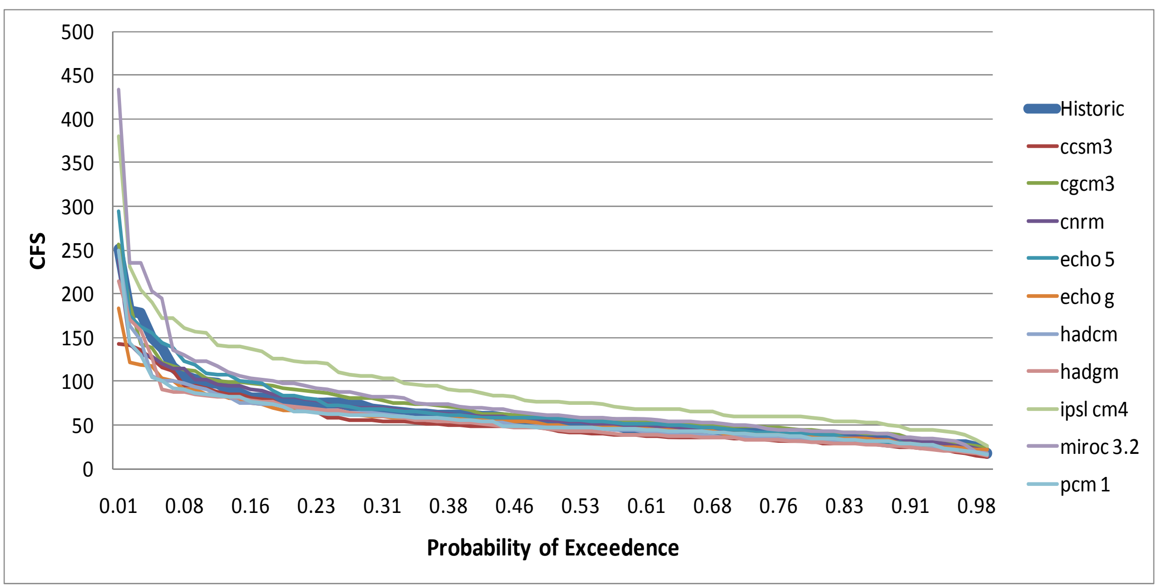

Figure 44 West Fork quantiles for extreme 7-day low streamflow for the historical period 1920 to 2000 and climate change scenarios for the 2040s

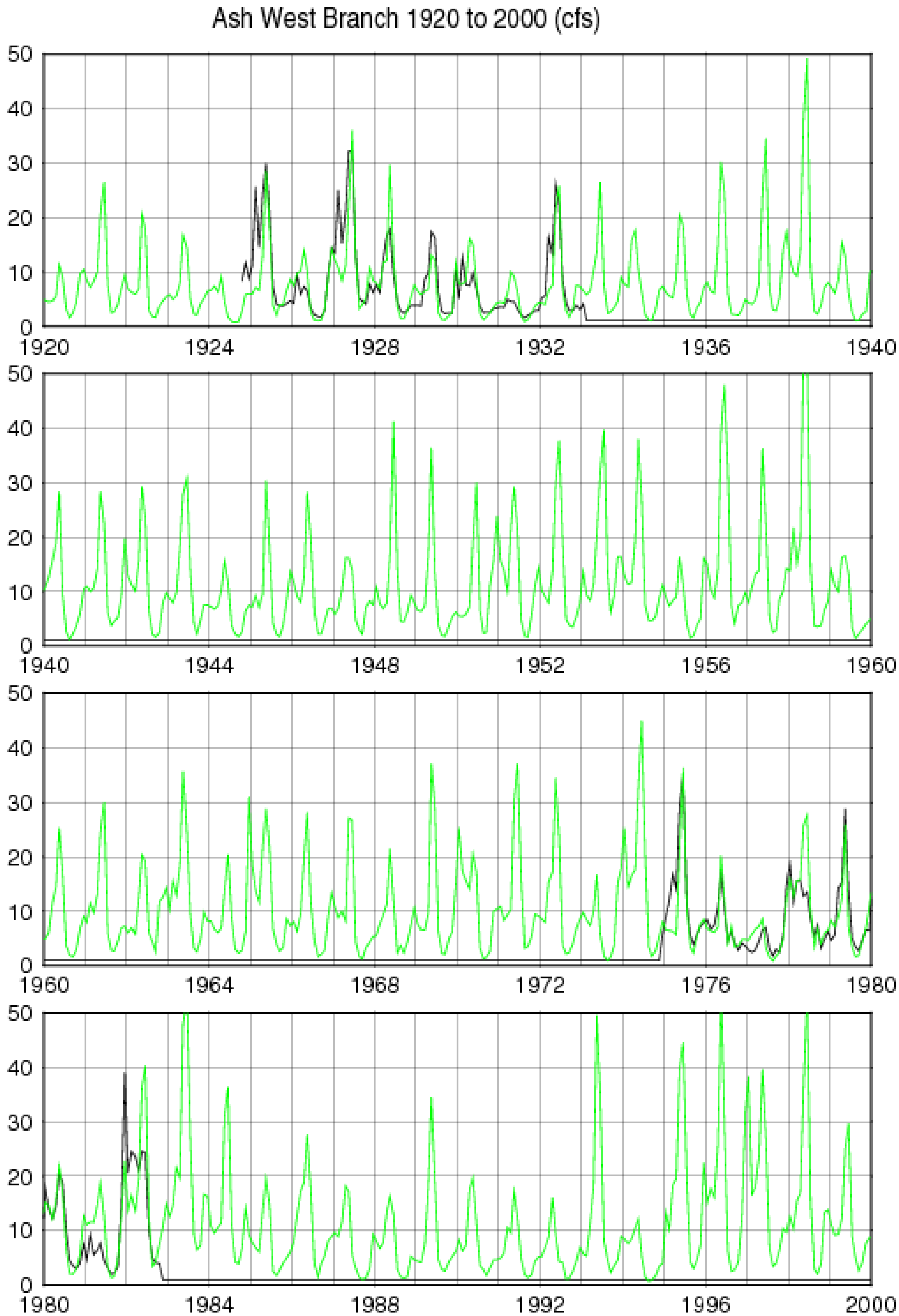

Figure 45 West Fork simulated monthly average streamflow (units cfs). (Black line represents observed values.)

East and West Forks – Combined Streamflows

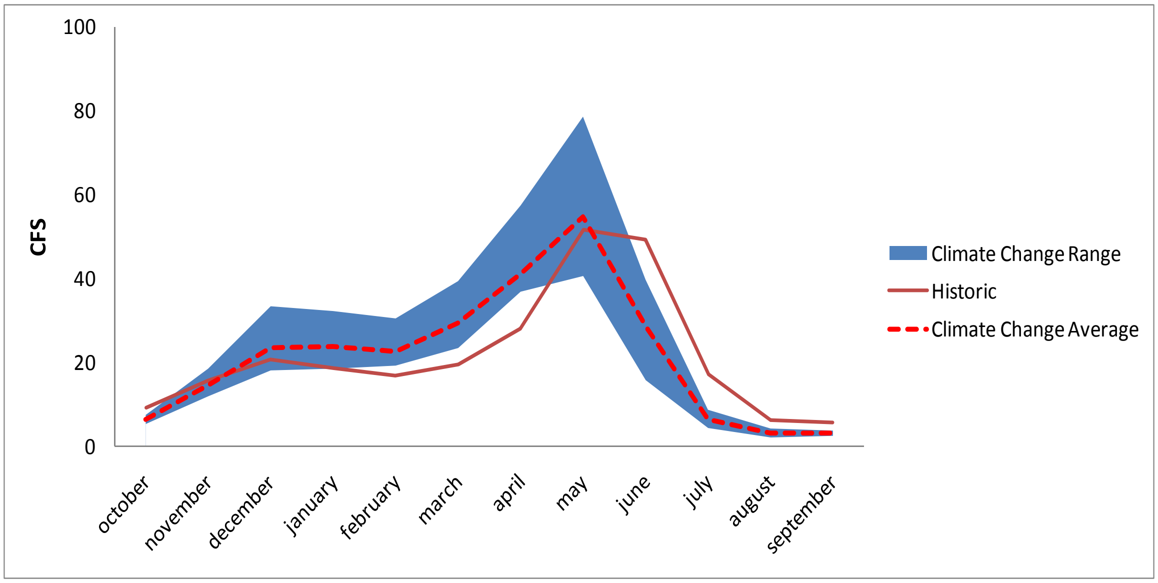

Figure 46 Combined monthly streamflow of the West and East Branches for the historical period 1920 to 2000 and climate change scenarios for the 2040s

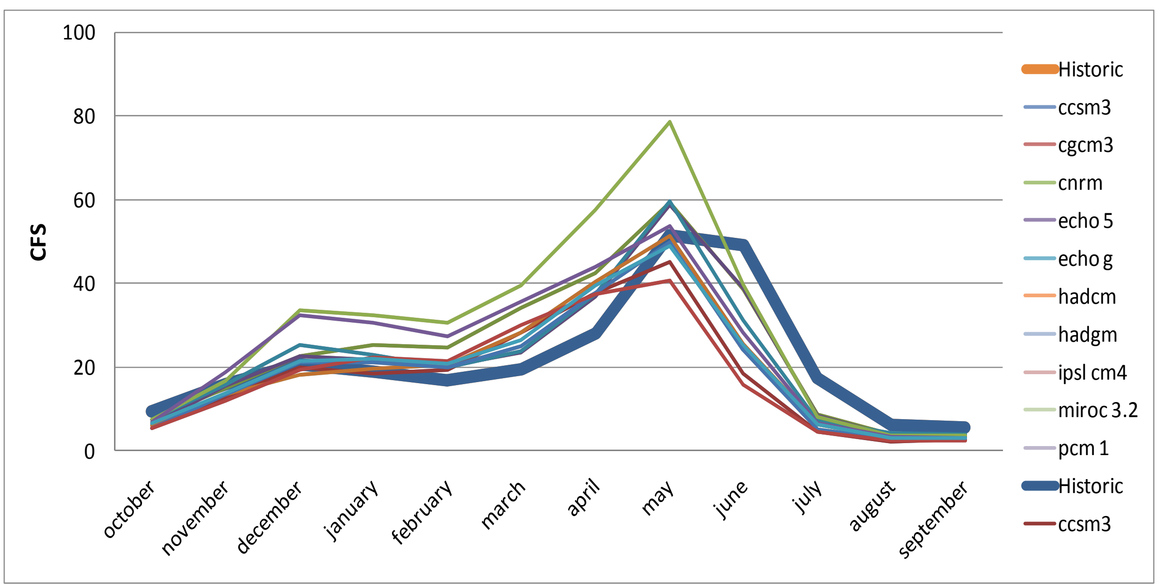

Figure 47 Combined monthly streamflow of the West and East Branches for the historical period 1920 to 2000 and climate change scenarios for the 2040s

Table 11 Combined Monthly Streamflow in cfs of the West and East Branches for the historical period 1920 to 2000 and climate change scenarios for the 2040s

	Historic	ccsm3 GCM	cgcm3 GCM	Cnrm GCM	echo 5 GCM	echo g GCM	Hadcm GCM	Hadgm GCM	ipsl cm4 GCM	miroc 3.2 GCM	pcm 1 GCM
October	9.3	5.5	7.4	6.3	7.6	6.0	5.4	5.4	7.5	7.0	6.7
November	15.8	12.7	14.9	15.4	15.8	13.4	13.3	12.0	16.8	18.6	13.6
December	20.7	19.9	22.6	22.7	25.2	18.2	21.1	19.3	33.5	32.3	21.3
January	18.8	18.6	25.2	21.6	23.0	19.7	21.1	22.4	32.3	30.6	22.1
February	16.9	19.3	24.7	20.3	20.0	20.4	19.9	21.4	30.6	27.3	20.8
March	19.5	28.2	34.2	23.5	23.7	28.3	24.9	30.0	39.4	35.6	26.5
April	28.1	37.8	42.3	37.0	37.4	40.4	37.7	37.3	57.5	43.8	39.5
May	51.5	45.1	59.4	58.8	59.6	51.3	49.9	40.7	78.6	53.8	48.9
June	49.2	18.6	38.5	38.9	31.3	25.7	24.0	15.9	39.8	28.2	25.2
July	17.3	4.4	8.8	8.3	7.1	6.3	5.2	4.5	8.2	6.5	6.3
August	6.3	2.2	4.0	3.5	4.4	3.0	2.6	2.6	3.6	3.4	3.1
September	5.6	2.7	3.7	3.5	3.9	3.0	2.7	2.6	3.6	3.1	3.1

REFERENCES

Carrasco, P., A.F. Hamlet, 2010: Fine Scale Hydrologic Model Implementation and Fine-Scale/Macro-Scale Model Inter-comparison Study [http://www.hydro.washington.edu/2860/products/sites/r7climate/study_report/CBCCSP_chap6_dhsvm_draft_20100721.pdf]

Hamlet, A.F., E.S. Salathe, Jr., P. Carrasco, 2010: Statistical Downscaling Techniques for Global Climate Model Simulations of Temperature and Precipitation with Application to Water Resources Planning Studies [http://www.hydro.washington.edu/2860/products/sites/r7climate/study_report/CBCCSP_chap4_gcm_final.pdf]

Mote, P.W., E.P. Salathe, 2010: Future climate in the Pacific Northwest, *Climatic Change,* DOI: 10.1007/s10584-010-9848-z

Wigmosta, M.S., L.W. Vail, and D.P. Lettenmaier, 1994: Distributed hydrology vegetation model for complex terrain. Water. Resources. Res. 30(6): 1665 – 1679

Wood AW, Maurer EP, Kumar A, Lettenmaier DP, 2002: Long range experimental hydrologic forecasting for the eastern U.S. J. Geophys. Res., 107 (D20): 4429