Final Report for the project

Agreement No.: 4600009009

Study of the Water, Sediment and Mercury Inflows to Cache Creek Settling Basin based on Cache Creek Watershed Hydrology and Future Climate Conditions

By

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1. Introduction

1.1. Purpose of the Project

Cache Creek Settling Basin (CCSB), located two miles east of Woodland, California, was constructed to preserve the floodway capacity of Yolo Bypass by entrapping sediment. Cache Creek is the main source of mercury entering San Francisco Bay-Delta. Entrapping sediment also entraps mercury, so the settling basin also helps preserve aquatic life of San Francisco Bay-Delta. The major objectives of this study are as follows:

i. To perform flow, suspended sediment, and mercury data compilation and gap analysis for Cache Creek watershed. An initial study showed that mercury data in the watershed is scarce and a grab sampling program is needed. The UC Davis group will coordinate with DWR and USGS to establish additional grab sampling programs in the watershed.

ii. To develop detailed flow, sediment and mercury conditions for Cache Creek and its tributaries for historical and future conditions by coupling the Watershed Environmental Hydrology Modeling and Climate Change Modeling approaches. The purpose is to provide concurrent flow, sediment and mercury information in the Cache Creek watershed in order to provide better sediment and mercury loading estimates. Reconstruction of realistic and comprehensive historical and future climate and flow conditions will eliminate the need to install and maintain new flow stations and rain gages within the basin.

iii. To use the simulated flow, sediment and mercury conditions in the Cache Creek watershed to investigate opportunities for trapping part of the mercury at upstream locations of the Cache Creek watershed, thereby reducing the mass loading rate of sediment into the Basin.

iv. To extend and support the ongoing Cache Creek Settling Basin / Yolo Bypass Project with Contract No. 4600008165. In addition to modeling flow, sediment transport and sediment trap efficiency in CCSB, mercury transport and mercury trap efficiency are planned to be modeled. Once calibrated and validated, Cache Creek Watershed Environmental Hydrology Modeling will lead to better prediction of sediment and mercury inlet boundary conditions for CCSB. Sediment and mercury trap efficiency under different climate change projections is planned to be investigated. Climate change projections may be more severe than the current conditions leading to more adverse loading conditions for CCSB. With growing public concern and with the passage of Global Warming Solutions Act of 2006 (Assembly Bill 32), there is increasing pressure to address global warming within the context of National Environmental Policy Act (NEPA) and California Environmental Quality Act (CEQA).

1.2. Scope of Work

The major objectives of the proposed project, stated above, are to be realized by means of the following project milestones:

Milestone 1: Perform the flow, suspended sediment, and mercury data compilation and data gap analyses for Cache Creek Watershed. An initial study showed that mercury data in the watershed is scarce and a grab sampling program is needed. UC Davis group will collaborate with DWR and USGS to finalize details of an additional grab sampling program in the watershed.

Milestone 2: Downscale dynamically an ensemble of GCM (Global Climate Model) simulations of the historical and future climatic conditions that are at coarse resolution over California (grid resolution ~200-300km) to a grid resolution of 3 km over Cache Creek Watershed by means of the atmospheric model component of a Regional Hydro-climate model (RegHCM) (Chen et al. 1996; Kavvas et al. 2000, 2007; Yoshitani et al. 2001) in order to simulate the historical and projected atmospheric and hydrologic conditions under the historical observed emission conditions and under future greenhouse gas emissions scenarios SRES A1B, SRES A1FI, SRES A2, and SRES B1 from the Special Report on Emissions Scenarios (SRES) (Nakicenovic et al. 2000) from the worst-case scenario SRES A1FI to the best-case scenario SRES B1.

Milestone 3 : Initiate the coupling of the regional-scale atmospheric model component with Watershed Environmental Hydrology Model (WEHY) (Kavvas et al. 2004). Required parameter maps for the WEHY model will be prepared using GIS with the existing soil, land cover and elevation databases. Boundary conditions of WEHY model will be prepared based on the simulation results of the regional-scale atmospheric model component.

Milestone 4 : Apply the WEHY model's hydrologic module to Cache Creek Watershed for the historical period in order to calibrate and validate the hydrologic module by the historical flow data.

Milestone 5 : Run the WEHY model using boundary conditions developed from future climate conditions.

Milestone 6: Estimate the flood frequencies for Cache Creek Watershed based on 13 different future hydro-climate simulation conditions, obtained by RegHCM for the Cache Creek watershed under 13 future climate projections from GCMs with various GHG Emissions Scenarios.

Milestone 7: After obtaining the field sampling data on concurrent flow, sediment and mercury, calibrate and validate the environmental module of WEHY model to implement the model to Cache Creek watershed.

Milestone 8: After its calibration and validation by concurrent flow, sediment and mercury field sampling data over Cache Creek watershed, run the WEHY-Environmental module to reconstruct the historical and project the future concurrent flow, sediment and mercury conditions over the watershed. The calibrated and validated WEHY model for Cache Creek watershed will be run under projected future climate conditions (based on 13 different future hydro-climate projections, obtained from downscaling 13 future climate projections of GCMs under the previously-mentioned 4 different SRES scenarios by means of the regional hydro-climate model of Cache Creek watershed) to provide the concurrent flow, sediment and mercury

inflow conditions to the Cache Creek Settling Basin (CCSB). By means of the estimated flow, sediment and mercury inflow conditions for CCSB, both for the historical period as well as the future period during 21st century, the already calibrated and validated hydrodynamic model of the CCSB can then be run to predict reliably the trap efficiencies at CCSB.

Milestone 9: Use the results of historical and future concurrent flow, sediment and mercury conditions at Cache Creek watershed, estimated by WEHY model, to investigate opportunities for trapping part of the mercury at upstream locations within Cache Creek watershed. From the WEHY model-estimated historical and future concurrent flow, sediment and mercury conditions at the Cache Creek watershed, the data gaps in sediment rating curve will be completed.

2. Background

2.1. Cache Creek Watershed

The Cache Creek watershed drains approximately 3,000-km^2 to the CCSB, which discharges to the Yolo Bypass before flowing into the Sacramento River. Containing abandoned mines and natural sources such as geothermal springs and mercury-enriched soils, the Cache Creek watershed is a significant contributor of mercury to the Sacramento-San Joaquin Delta. This mercury pollution causes adverse health effects for both humans and wildlife in the Cache Creek watershed, and downstream in the Sacramento River, Sacramento-San Joaquin Delta, and the San Francisco Bay. Therefore, understanding sources and distribution of mercury in Cache Creek and developing control strategies to reduce exports is necessary.

Cache Creek Watershed is composed of upper (approximately 2,500 km^2) and lower (approximately 500 km^2) Cache Creek basins (see Figure 1). Upper Cache Creek has two major tributaries: the North Fork of Cache Creek and Bear Creek. Reservoirs at Indian Valley and Clear Lake control and regulate water flowing into lower Cache Creek. The lower Cache Creek basin flows into the CCSB. A weir is located at the outlet of the settling basin to help entrap sediment.

A number of inactive mines lie in the watershed, draining into Cache Creek. Runoff from historic mercury mines in the Rathburn-Petray group discharge primarily to Bear Creek. Harley Gulch drains a 14 km^2 subwatershed in the upper Cache Creek basin. The inactive Turkey Run and Abbott mercury mines drain to Harley Gulch. Davis Creek drains also into the upper Cache Creek basin. Davis Creek subwatershed includes the Reed, Harrison and Manhattan mercury mines. Sulphur Creek flows from its headwaters to Bear Creek. Inactive mines along the creek include the Elgin, Clyde, Empire, Manzanita, West End, Central, Cherry Hill, and Wide Awake mines. Sources of mercury in Cache Creek watershed include discharge from numerous inactive mines, erosion of stream beds and banks containing mercury, natural and anthropogenic erosion of soils with naturally occurring mercury, natural and altered geothermal springs, and atmospheric deposition (Central Valley Regional Water Quality Control Board, 2005 and 2008).

Occurrence of methyl-mercury in Cache Creek largely parallels the sources of total mercury. Upper Cache Creek watershed is the major source of methyl-mercury. Clean sediment entering the streambed in the lower Cache Creek watershed dilutes sediment mercury concentrations. Mercury loads from the major and mine-related tributaries (North Fork Cache Creek, Clear Lake outflow, Bear Creek, Harley Gulch, and Davis Creek) contribute 12-15 percent of the mercury loads measured in Cache Creek at Rumsey. The majority of the inorganic mercury loads are from unknown source areas, which include smaller, unmeasured tributaries and mercury in the creek bed and banks (Central Valley Regional Water Quality Control Board, 2004 and 2005).

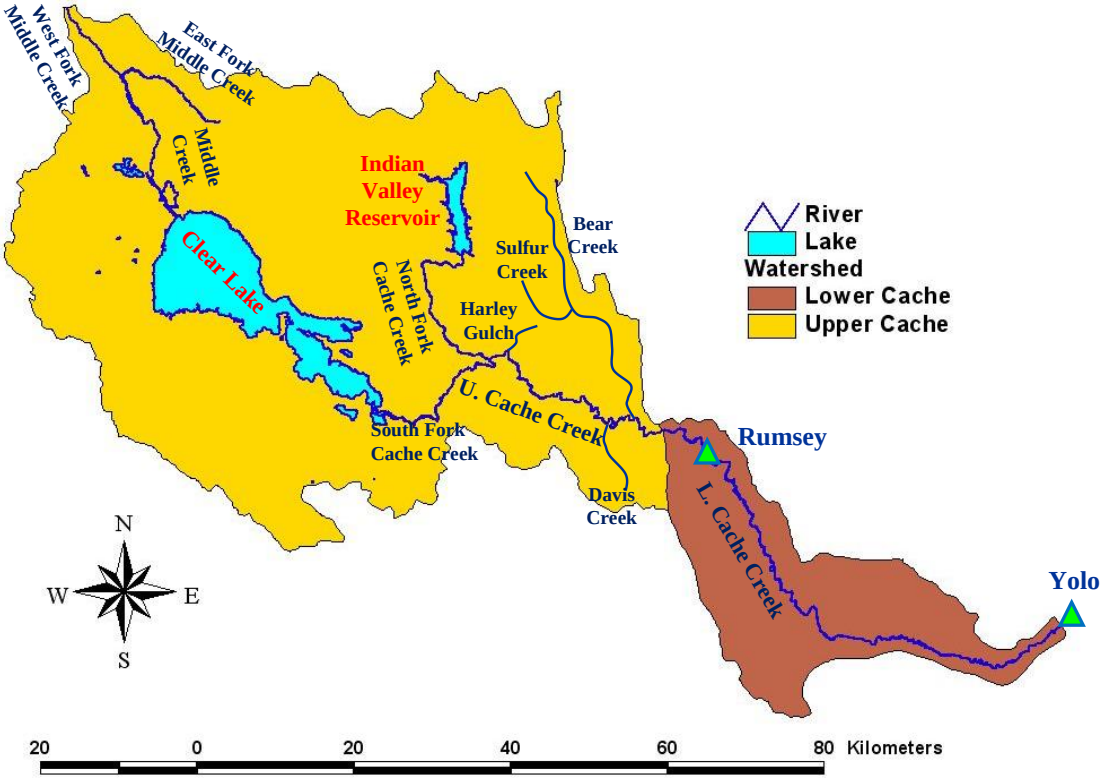

Figure 1- Cache Creek Watershed

3. Methodology

Climate change and Watershed Environmental Hydrology Modeling approaches facilitate realistic and comprehensive computation of water, sediment and mercury balances in the Cache Creek Watershed for historical and future climate conditions. The models are to be calibrated and validated by means of comparisons of the model-simulated historical flows, sediment and mercury conditions in the watershed against corresponding historical observations. By means of an ensemble of 13 possible realizations of the future hydro-climate conditions over Cache Creek Watershed, simulated by the models, an ensemble prediction of trap efficiency of CCSB can then be performed by hydraulic and sediment / mercury transport modeling using boundary conditions that can be built from the model-simulated water, sediment and mercury outflows from the Cache Creek Watershed into the CCSB. Schematics of modeling approaches for historical and future climate conditions are depicted in Figures 2 and 3, respectively.

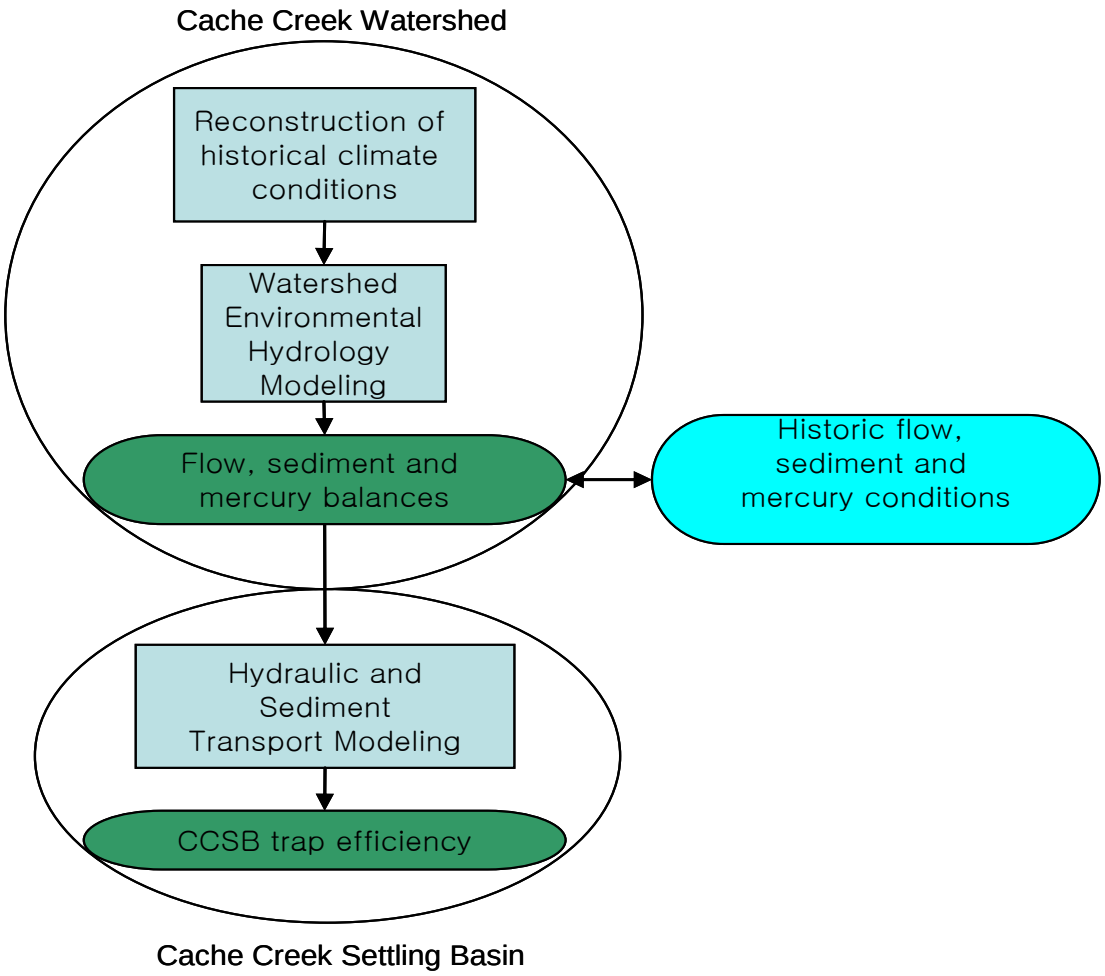

Figure 2- A schematic description of the modeling approach for the historical conditions

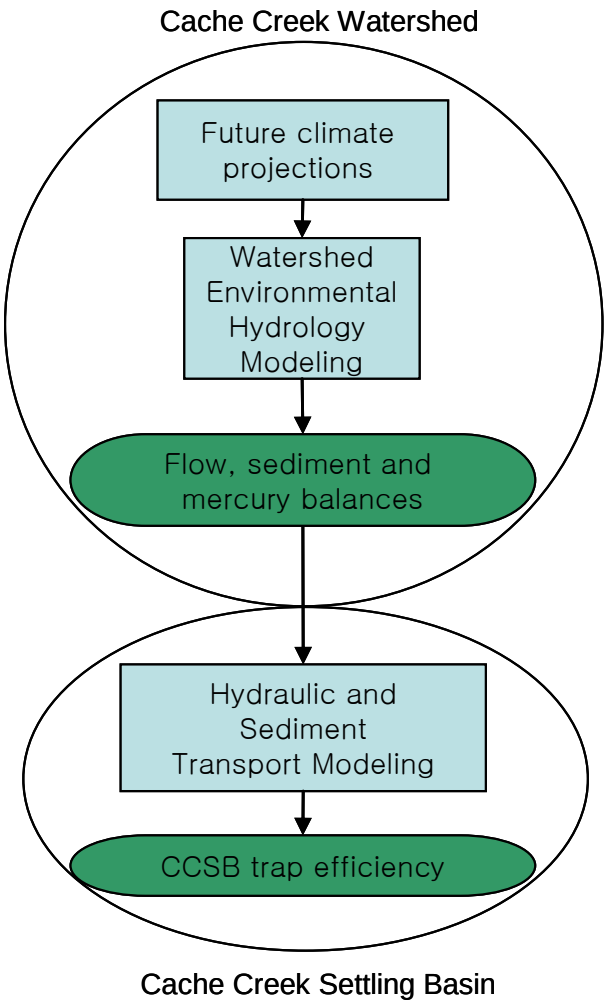

Figure 3- A schematic description of the modeling approach for future conditions

3.1. Regional Hydro-Climate Modeling

The dynamical downscaling of the GCM climate simulations may be performed by means of a Regional Hydro-climate model (RegHCM) to a grid resolution of 3km over the Cache Creek Watershed. The RegHCM consists of two major model components: a mesoscale (regional scale) atmospheric model component, and a regional land surface hydrology model component (Chen et. al. 1996; Kavvas et. al. 1998; Kavvas et al. 2000, 2007). The atmospheric model component of the RegHCM is MM5 (the Fifth Generation Mesoscale Model) from NCAR (US National Center for Atmospheric Research). The regional land surface hydrology model is based on upscaled hydrologic conservation equations (Chen et. al. 1993; Chen et. al., 1994a,b; Kavvas et

al. 1998). It has been applied to hydro-meteorological phenomena over a wide range of scales at various locations around the world, ranging from continental-scale cyclone development to local valley flows (Chen et. al. 2008; Ohara et. al. 2008; Shaaban et. al. 2008).

The Penn State/NCAR Mesoscale Model (PSU/NCAR) originated from The Pennsylvania State University in the early 70's. The Fifth-Generation NCAR / Penn State Mesoscale Model (MM5) (Grell et al. 1995) is the latest in a series of models developed from a mesoscale (regional scale) model originally documented by Anthes and Warner (1978). The PSU/NCAR mesoscale model is a limited-area, hydrostatic or nonhydrostatic, terrain-following sigma-coordinate model designed to simulate or predict regional-scale atmospheric circulation over any limited area on Earth. It is continuously being improved by contributions from users at several universities and government laboratories. The most recent version of The Penn State/NCAR Mesoscale Model is the Fifth-Generation Penn State/NCAR Mesoscale Model (MM5).

3.2. Hydrology and Environmental Modeling

The Watershed Environmental Hydrology model (WEHY) is an award-winning watershed hydrology model (ASCE 2006 Best paper award) recently developed (Kavvas et al, 2004, Chen et al, 2004a,b; Kavvas et al. 2006) after about a decade of research effort. WEHY is a physically based watershed hydrology and sediment/nutrient/heavy metal transport model based upon areally-averaged hydrologic conservation equations and transport equations in order to account for the effect of spatial heterogeneity in land surface and subsurface conditions on the hydrologic flow and environmental processes.

By developing a detailed geographical information system (GIS) for the vegetation, land use/land cover conditions, soils, topography and geology of the watershed being modeled, model parameters are objectively estimated by computer algorithms relating parameter values to land surface and subsurface conditions, rather than simply fitting the model. As such, it is applicable to the modeling of hydrologic processes at any geographical location, even in ungauged or data-poor basins.

In its land surface hydrology component, WEHY model describes interception, bare soil evaporation, direct evaporation from ponded water over the plant leaves, soil water flow, and plant transpiration. The boundary layer component of MM5 provides information on the velocity, temperature, and relative humidity profiles in the atmosphere above the land surface. Evapotranspiration from land surfaces to the atmosphere is computed by means of the boundary layer velocity and relative humidity information on one hand, and from the soil water flow process and plant physiology that dictate the soil moisture availability, on the other. Soil water flow is computed as a component of the WEHY model. The model can describe both the Hortonian (infiltration excess) runoff mechanism as well as the variable-source-area runoff mechanism (Dunne, 1978). As such, it is applicable both to vegetated watersheds as well as to arid/semiarid watersheds.

WEHY subdivides a watershed first into model computational units (MCU) that are delineated from the digital elevation map of the watershed by means of a geographic information system (GIS) analysis (Chen et al. 2004a). These MCUs are either individual hillslopes or first-order-subwatersheds within a watershed. Their identification and delineation are described in Chen et. al.(2004a). WEHY computes the surface and subsurface hillslope hydrologic processes that take place at these MCUs, in parallel and simultaneously.

In its environmental module (Kavvas et al. 2006), the WEHY model simulates sediment, nutrient and heavy metal transport through a watershed by means of physically-based transport equations. In the WEHY model erosion, deposition and transport processes of sediment take place in various domains, starting from hillslope interrill areas, moving to rills, and then to streams

4. Sediment and Mercury Data Compilation and Data Gap Analysis

4.1. Soil Erosion in Cache Creek Watershed

Erosion is the detachment of soil particles caused by water or glacial ice. Eroded sediment is both a physical and chemical pollutant. Chemically, eroded sediment degrades water quality and transports nutrients such as phosphorus, nitrogen, and heavy metals such as mercury.

The potential source areas of sediment and mercury in Cache Creek Watershed can be approximately identified through the Universal Soil Loss Equation (USLE). Identifying source areas will help in the development of boundary conditions of sediment and mercury transportation in Cache Creek Watershed. A schematic description of the Universal Soil Loss Equation calculation methodology is depicted in Figure 4. Using USLE, the average annual soil loss can be calculated by

$$A = R \cdot K \cdot LS \cdot C \cdot P$$

where A is average annual soil loss (ton/acre/year), R is rainfall factor (ft-ton-in. / acre-h-year), K is erodibility factor (ton/acre/R), LS is length slope factor, C is soil cover factor, and P is conservation practice factor.

Figure 5 shows the estimated parameters of USLE. The soil erosion map of Cache Creek Watershed is plotted using USLE in Figure 6. Mercury point sources are located at high erosion areas in the upper Cache Creek Watershed. In lower Cache Creek Watershed, there is a high erosion area but no mercury point source. Therefore, sediment entering from lower Cache Creek watershed acts to dilute the sediment mercury concentrations. The soil erosion map will help the development of boundary conditions for sediment and mercury transport in Cache Creek Watershed.

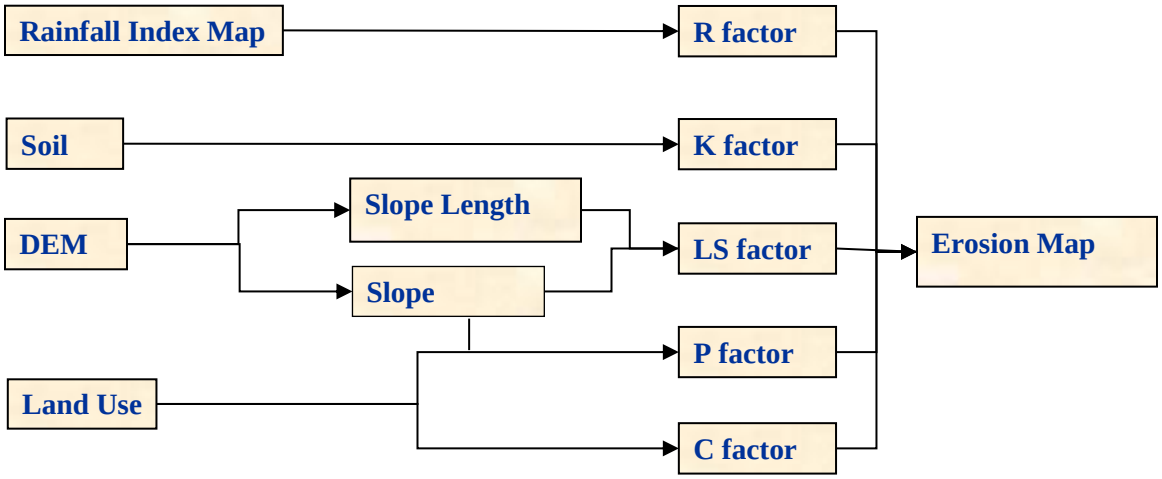

Figure 4- A schematic description of the Universal Soil Loss Equation calculation

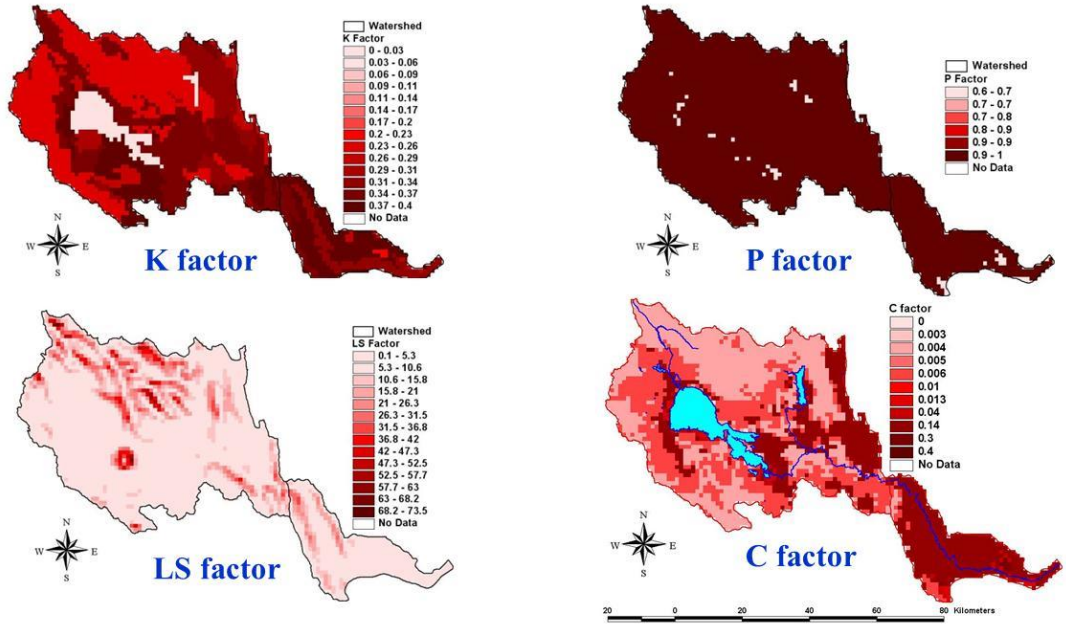

Figure 5- Estimated parameters for USLE over the Cache Creek watershed

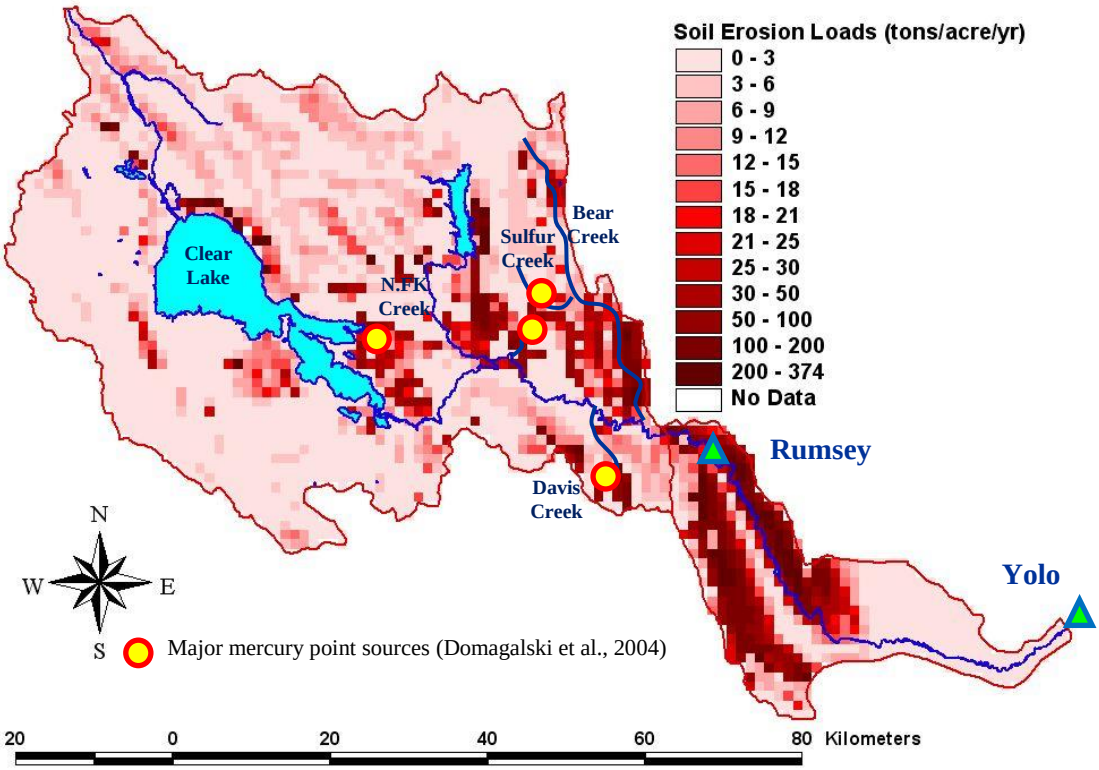

Figure 6- The soil erosion map of Cache Creek Watershed using USLE

4.2. Sensitivity Analysis for trap efficiency at CCSB

Recently, a CCSB Mercury Study assessed potential modifications of CCSB to increase sediment and mercury deposition while improving the quality of Cache Creek outflows (CDM, 2004a, 2004b, 2007).

Conclusions about sediment and mercury trap efficiency of CCSB in CDM (2007) study were based on HEC-6 model (CDM, 2004b) that was developed by US Army Corps of Engineers in 1997. The Corps model only covers the training channel portion of CCSB. CDM (2004b) extended the Corps model from the outlet of the training channel to greater CCSB area based on a 2D hydraulic model that was developed by the Corps (documented in 1987 General Design Memorandum). Model input was based on the 1983 survey data. Using HEC-6 model described in CDM (2004b).

We present the influence of the sediment rating curve and inlet flow conditions on CCSB sediment trap efficiency. Our analyses showed that trap efficiency is very much dependent on the sediment rating curve and inlet flow conditions. Therefore, a rigorous approach should be used to determine the sediment rating curve and inlet flow conditions.

a) Inflow Boundary Conditions

The Corps constructed a computational hydrograph for simulating the entire 50-year project life using USGS daily flows at the Yolo stream gage from 1980-1989. This 10-year period was repeated five times to generate the 50-year simulation period (CDM, 2004b). Daily Average Discharge (cfs) at Cache Creek at Yolo during water years 1904-2008 and 1980-1989 are depicted in Figures 7 and 8, respectively. Repeating the relatively short 10-year historical flow record for analysis purposes may not be representative of the real life conditions. The 30,000 cfs discharge, which is the design capacity of upstream Cache Creek levee system, has approximately a 10-year return period. Hence, this 30,000 cfs discharge is added every 10-years in our sensitivity analysis.

b) Sediment Rating Curve

"The Corps developed the inflowing sediment load estimate as described in the 1997 HEC-6 analysis (Corps 1997). The sediment inflow is input into the model as a relationship between streamflow discharge rate versus total sediment load (in tons/day), which includes both bedload and suspended load. This relationship was based primarily on a sediment-discharge curve documented in the General Design Memorandum (Corps 1987), which was ultimately derived from long-term instantaneous samples collected by the USGS between 1943 and 1971." (CDM, 2004b).

Instantaneous suspended sediment load data are available from 10/14/1957 to 09/30/1986 for Cache Creek at Yolo. (source: http://nwis.waterdata.usgs.gov, USGS 11452500). This dataset is depicted in Figure 9. Bed load was measured to be 7.3% of suspended sediment load at Cache Creek at Yolo for the water years 1960-1963 in Lustig and Busch (1967). Total sediment load at Cache Creek at Yolo was measured and a regression line was given in Lustig and Busch (1967). However, the regression equation does not represent flows larger than 13000 cfs. In our sensitivity analysis, three rating curves are used and they are tabulated in Table 1 below. The actions to fill the data gaps in the sediment rating curve can be completed by generating simultaneously the sediment loads and the corresponding flows larger than 13000 cfs. Such concurrent sediment and flow data can be obtained by gauge observations or simulations of WEHY-Hydrologic and Environmental module. The observation method cannot be accomplished easily since the flows larger than 13000 rarely happen. In the meantime, simulation method using WEHY model is able to generate numerous concurrent sediment and flows larger than 13000 cfs. However, WEHY model can only provide those concurrent data by simulations after calibration and validation processes by means of observations. In this project, the calibration and validation processes for WEHY-Environmental module could not be accomplished due to insufficient concurrent flow, sediment and mercury data. Without calibration and validation, the environmental module cannot generate reliable sediment and mercury data that can then be used to produce the sediment rating curve. Therefore, collection of field sediment and mercury data is crucial for accomplishing the objectives of this project.

4.2.1 Results and Discussion

The sediment balance and trap efficiency in CCSB and in the training channel, obtained from a 50 year simulation, are tabulated in Tables 2 and 3, respectively. Using the assumptions described in CDM (2004b), the average trap efficiency in CCSB is 51%, 30%, 60% and 60% during the periods 2008-2043, 2008-2018, 2018-2028, and 2028-2043, respectively. Using the new assumptions for flow and sediment rating curves ("new estimate"), the average trap efficiency in CCSB is obtained as 43%, 11%, 60% and 57% during the periods 2008-2043, 2008-2018, 2018-2028, and 2028-2043, respectively. More conservative results were obtained using the sediment rating curve given in Lustig and Busch (1967). According to Table 3, the trap efficiency of the training channel is considerably lower when compared to that of the settling basin. The sediment trap efficiency in CCSB, obtained by means of a 100 year simulation, is tabulated in Table 4. This table shows that the life span of CCSB is very much dependent on the inflow conditions and the sediment rating curve used.

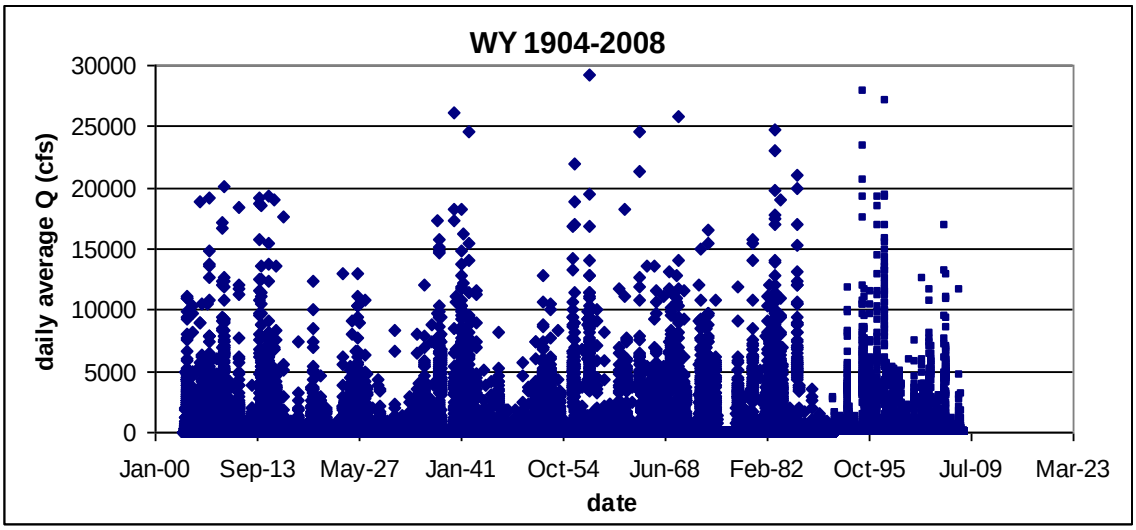

Figure 7- Daily Average Discharge (cfs) at Cache Creek at Yolo between 1904-2008 water years

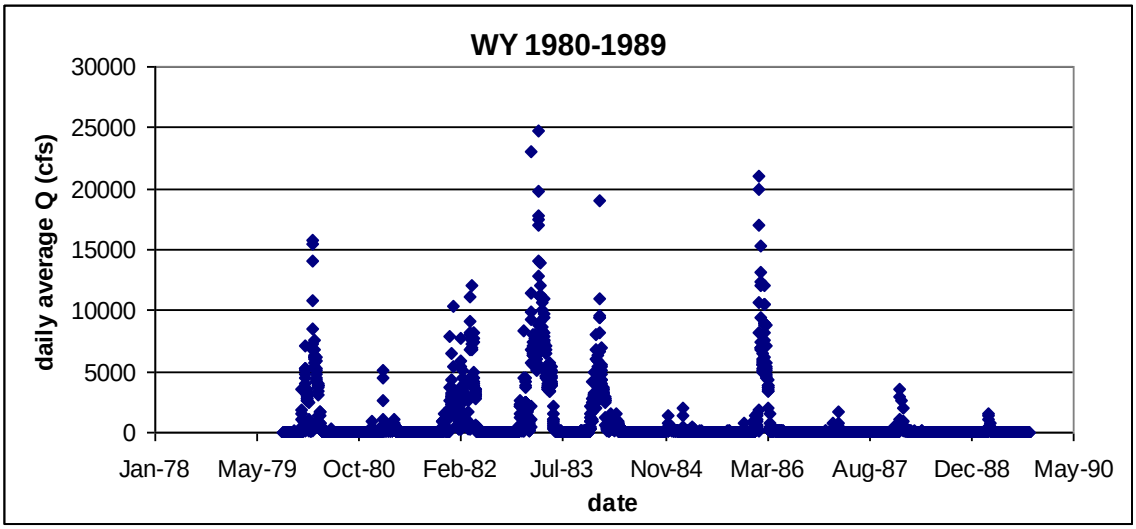

Figure 8- Daily Average Discharge (cfs) at Cache Creek at Yolo during 1980-1989 water years

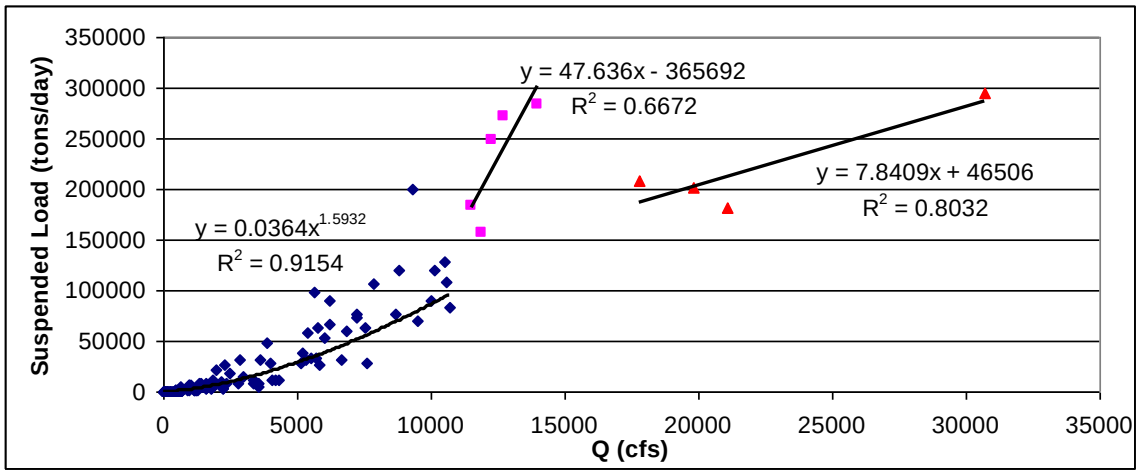

Figure 9- The sediment rating curve at Cache Creek at Yolo that is used in this study

Table 1- Discharge (cfs) versus total sediment load (tons per day) at Cache Creek at Yolo

Q (cfs)	CDM (2004b)[1]	New estimation[2]	Lustig and Busch (1967)[3]
50	15	20	4
100	41	60	17
500	400	780	420
1,000	1,188	2,352	1,658
5,000	15,350	30,555	40,190
10,000	47,340	92,189	158,660
20,000	146,700	218,256	626,329
30,000	285,300	302,423	1,398,424

[1] Corps developed the inflowing sediment load estimate as described in Corps 1997. CDM (2004b) used the same rating curve.

[2] Developed for sensitivity analysis using instantaneous suspended sediment load data from 10/14/1957 to 09/30/1986. Bed load is assumed to be 7.3% of suspended sediment load (Lustig and Busch, 1967).

[3] $Q_s=0.00189Q_w^{1.981}$ where Q_s is total sediment discharge in tons per day and Q_w is water discharge in cfs.

Table 2- Sensitivity analyses for sediment balance and trap efficiency in CCSB using a 50-year simulation

	CDM (2004b)[1]		New Estimate[2]		Lustig and Busch (1967) [3]	
	1993-2043[4]	**1983-2043[5]**	**1993-2043[4]**	**1983-2043[5]**	**1993-2043[4]**	**1983-2043[5]**
Years 2008-2043						
Sediment outflow (ac-ft)	11074	12040	23976	24322	43801	46343
Sediment inflow (ac-ft)	22390	22537	42341	42515	70216	71078
Trapped (ac-ft)	11316	10497	18365	18193	26416	24735
Ave. Trap eff.	0.51	0.47	0.43	0.43	0.38	0.35
Ave. trapped per year (ac-ft)	323	300	525	520	755	707
Years 2008-2018[6]						
Sediment outflow (ac-ft)	4943	5895	11841	12120	20052	20219
Sediment inflow (ac-ft)	7097	7135	13306	13377	21706	22111
Trapped (ac-ft)	2154	1240	1465	1257	1654	1892
Ave. Trap eff.	0.3	0.17	0.11	0.09	0.08	0.09
Ave. trapped per year (ac-ft)	215	124	147	126	165	189
Years 2018-2028						
Sediment outflow (ac-ft)	2735	2743	5276	5239	8729	8907
Sediment inflow (ac-ft)	6823	6878	13161	13223	21905	22174
Trapped (ac-ft)	4088	4135	7885	7984	13176	13267
Ave. Trap eff.	0.6	0.6	0.6	0.6	0.6	0.6
Ave. trapped per year (ac-ft)	409	414	788	798	1318	1327
Years 2028-2043						
Sediment outflow (ac-ft)	3395	3402	6859	6962	15020	17216
Sediment inflow (ac-ft)	8469	8524	15873	15915	26605	26792
Trapped (ac-ft)	5074	5122	9014	8953	11585	9576
Ave. Trap eff.	0.6	0.6	0.57	0.56	0.44	0.36
Ave. trapped per year (ac-ft)	338	341	601	597	772	638

[1] HEC-6 simulation in 2004 TM

[2] Same assumptions as HEC-6 model described in CDM (2004b) except 30000 cfs flow is added every 10 years and new sediment rating curve is used (see Table 1).

[3] Same assumptions as HEC-6 model described in CDM (2004b) except 30000 cfs flow is added every 10 years and the sediment rating curve of Lustig and Busch (1967) is used (see Table 1).

[4] 1993-2043 is the HEC-6 simulation period in 2004 TM

[5] Instead of 1993, HEC-6 model started at 1983 since the cross-section of the settling basin was constructed using 1983 survey data.

[6] In the year 2018 the weir at the outlet of the settling basin is assumed to be raised 6 ft.

Table 3- Sensitivity analyses for sediment balance and trap efficiency in the training channel using a 50-year simulation.

	CDM (2004b)[1]		New Estimate[2]		Lustig and Busch (1967) [3]	
	1993-2043[4]	**1983-2043[5]**	**1993-2043[4]**	**1983-2043[5]**	**1993-2043[4]**	**1983-2043[5]**
Years 2008-2043						
Sediment outflow (ac-ft)	22390	22537	42341	42515	70216	71078
Sediment inflow (ac-ft)	23713	23713	44434	44434	74830	74830
Trapped (ac-ft)	1324	1176	2093	1919	4613	3752
Ave. Trap eff.	0.06	0.05	0.05	0.04	0.06	0.05
Ave. trapped per year (ac-ft)	38	34	60	55	132	107
Years 2008-2018[6]						
Sediment outflow (ac-ft)	7097	7135	13306	13377	21706	22111
Sediment inflow (ac-ft)	7403	7403	13921	13921	23273	23273
Trapped (ac-ft)	305	268	615	544	1567	1162
Ave. Trap eff.	0.04	0.04	0.04	0.04	0.07	0.05
Ave. trapped per year (ac-ft)	31	27	61	54	157	116
Years 2018-2028						
Sediment outflow (ac-ft)	6823	6878	13161	13223	21905	22174
Sediment inflow (ac-ft)	7398	7398	13911	13911	23266	23266
Trapped (ac-ft)	575	520	750	689	1361	1092
Ave. Trap eff.	0.08	0.07	0.05	0.05	0.06	0.05
Ave. trapped per year (ac-ft)	57	52	75	69	136	109
Years 2028-2043						
Sediment outflow (ac-ft)	8469	8524	15873	15915	26605	26792
Sediment inflow (ac-ft)	8912	8912	16602	16602	28291	28291
Trapped (ac-ft)	443	389	728	687	1686	1499
Ave. Trap eff.	0.05	0.04	0.04	0.04	0.06	0.05
Ave. trapped per year (ac-ft)	30	26	49	46	112	100

[1] HEC-6 simulation in 2004 TM

[2] Same assumptions as HEC-6 model described in CDM (2004b) except 30000 cfs flow is added every 10 years and a new sediment rating curve is used (see Table 1).

[3] Same assumptions as HEC-6 model described in CDM (2004b) except 30000 cfs flow is added every 10 years and the sediment rating curve of Lustig and Busch (1967) is used (see Table 1).

[4] 1993-2043 is the HEC-6 simulation period in 2004 TM

[5] Instead of 1993, HEC-6 model started at 1983 since the cross-section of the settling basin was constructed using the 1983 survey data.

[6] In the year 2018 the weir at the outlet of the settling basin is assumed to be raised 6 ft.

Table 4- Sensitivity analyses for sediment balance and trap efficiency in CCSB using 100-year simulation.

	CDM (2004b)[1]	New Estimate[2]	
	1993-2093[3]	1993-2093[3]	1983-2093[4]
Years 2008 - 2043			
Ave. Trap eff.	0.51	0.43	0.43
Ave. trapped per year (ac-ft)	323.3	522.5	519.9
Sediment inflow (ac-ft)	22390	42221	42514
Years 2008 and 2093			
Ave. Trap eff.	0.51	0.31	0.29
Ave. trapped per year (ac-ft)	351.3	395.1	376.9
Sediment inflow (ac-ft)	57990	109461	109609
Years 2008 - 2018[5]			
Ave. Trap eff.	0.30	0.11	0.09
Ave. trapped per year (ac-ft)	215.4	146.5	125.5
Sediment inflow (ac-ft)	7097	13306	13361
Years 2018 - 2028			
Ave. Trap eff.	0.60	0.60	0.60
Ave. trapped per year (ac-ft)	408.8	788.5	798.0
Sediment inflow (ac-ft)	6823	13161	13236
Years 2028 - 2038			
Ave. Trap eff.	0.60	0.57	0.57
Ave. trapped per year (ac-ft)	420.0	760.2	756.3
Sediment inflow (ac-ft)	7010	13283	13320
Years 2038 - 2048			
Ave. Trap eff.	0.59	0.51	0.48
Ave. trapped per year (ac-ft)	422.7	676.6	648.1
Sediment inflow (ac-ft)	7171	13347	13379
Years 2048 - 2058			
Ave. Trap eff.	0.57	0.35	0.30
Ave. trapped per year (ac-ft)	405.3	474.3	407.2
Sediment inflow (ac-ft)	7097	13395	13364
Years 2058 - 2068			
Ave. Trap eff.	0.55	0.16	0.13
Ave. trapped per year (ac-ft)	389.5	211.0	173.5
Sediment inflow (ac-ft)	7105	13422	13441

[1] HEC-6 model described in CDM (2004b)

[2] Same assumptions as HEC-6 model described in CDM (2004b) except 30000 cfs flow is added every 10 year and new sediment rating curve is used (see Table 1).

[3] 50 year simulation (1993-2043) period used in CDM (2004b) is extended to 100 year by using the same flow data twice.

[4] Instead of 1993, HEC-6 model started at 1983 since cross-section of the settling basin was constructed using 1983 survey data.

[5] In year 2018, weir at the outlet of the settling basin is assumed to be raised 6 ft.

4.3. Data Availability and Recommendations for Data Collection

4.3.1 Data Availability

Observation data are crucial for model calibration and validation for both watershed hydrology and environmental modeling. The information on available data for this study has been surveyed through various data sources such as CDEC, USGS web-based inventories and reports related to the Cache Creek watershed.

a) Streamflow Data

Figure 10 shows the available streamflow gauges from USGS, CDEC, and Yolo Flood Control and Water Conservation District. The purple-color tables indicate the flow gauges with real-time flow data and the yellow-color tables indicate the flow gauges with daily flow data. As shown in Figure 10, most real-time (or hourly) data are available only since late 1990s and are not sufficient for model calibration and validation.

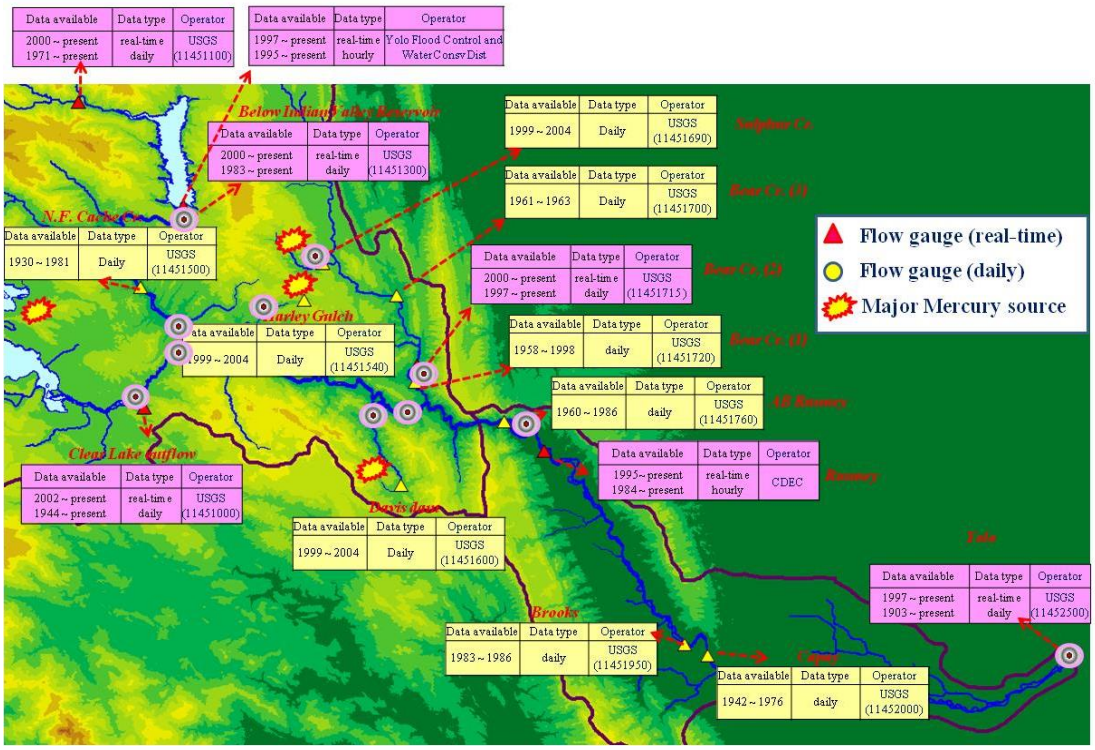

Figure 10- Available streamflow gauges for this study

b) In-water Mercury/Sediment Data

Figure 11 shows the availability of historical field/lab sampling data from USGS web-based inventory. The data from USGS were sampled instantaneously for both (mercury or/and sediment) solute and flow. However, most total suspended sediment and mercury data have been obtained from occasional samples.

Figure 12 shows the available data from Cooke et al. (2004) who collected the data through several projects. Although the collected data include the solutes (TSS, THg, MeHg, and flow), it is not clear whether the flow and solutes were sampled simultaneously. It should be noted that the simultaneous solute/flow data are crucial to estimate the water quality loads such as sediment and mercury. The data availability of mercury and sediment in water from USGS and Cooke et al. (2004) studies is shown in Figure 13. Instantaneous grab sampling data concurrent with flow data are required for model calibration and validation.

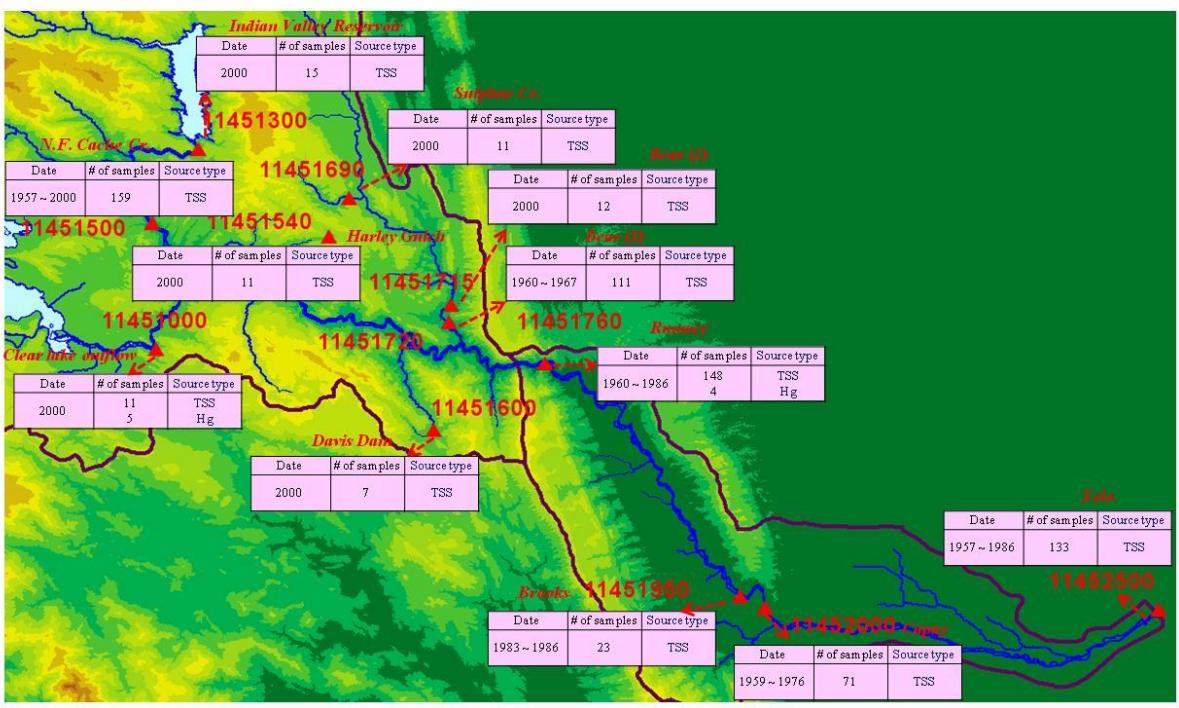

Figure 11- Historical field/lab sampling data from USGS

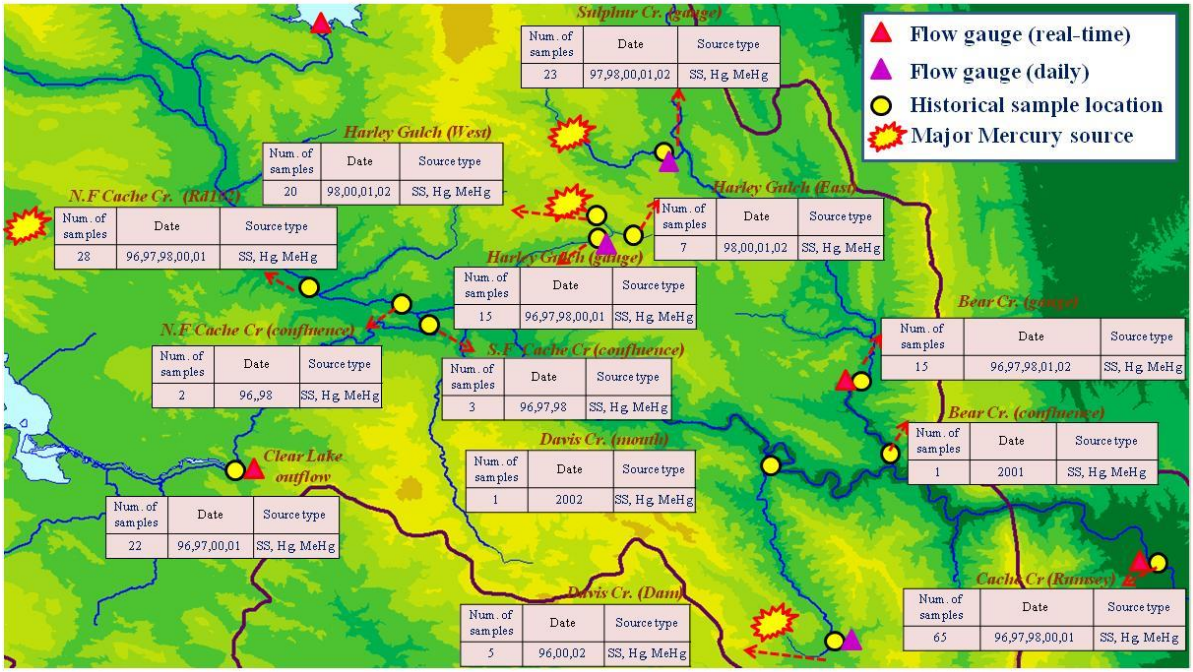

Figure 12- Historical field/lab suspended sediment and mercury data from Cooke et al. (2004)

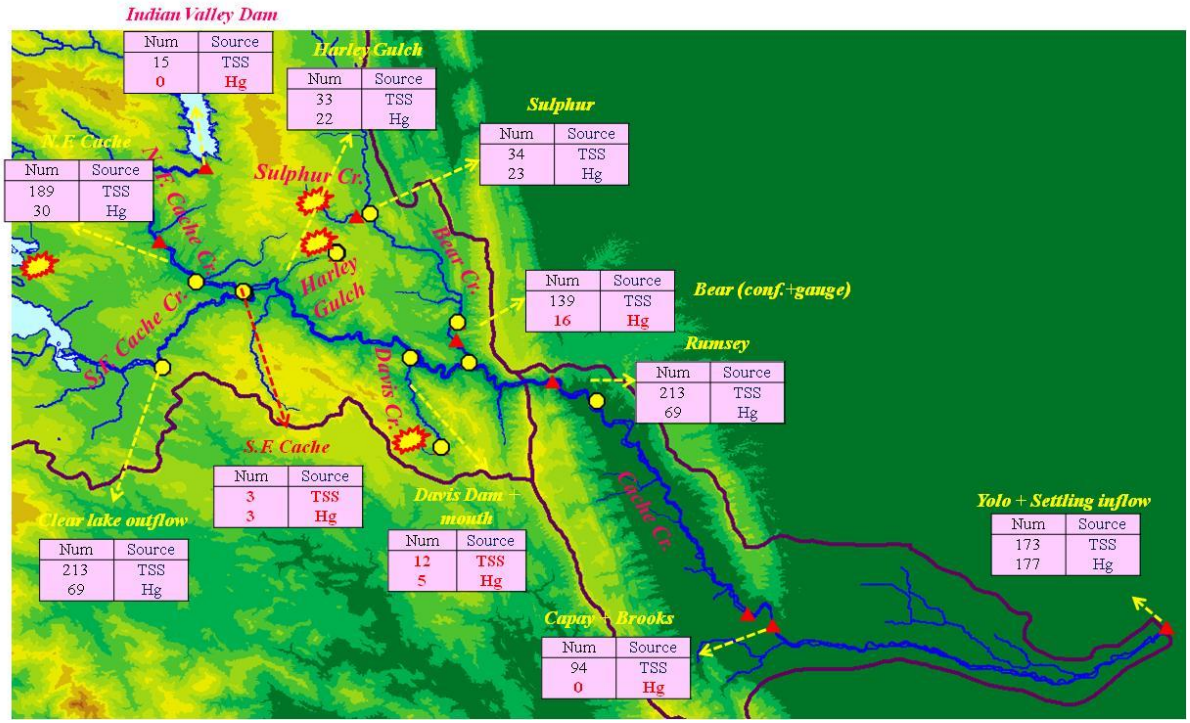

Figure 13- Available historical field/lab sediment and mercury data from Cooke et al. (2004) and USGS

c) Mercury/ Sediment Data in Soils

The mercury in the stream may be in suspension or may be deposited, and this phenomenon can be accounted for in model simulations. Some valuable mercury and sediment data in soils has been reported (Foe and Bosworth, 2008; Bosworth and Morris, 2009). The mercury in sediment samples was collected in the depositional areas, streambeds, and banks (Bosworth and Morris, 2009 for Bear Creek and its tributaries; Foe and Bosworth, 2008 for Cache Creek Canyon) as showed in Figures 14 through 19. The sampling locations cover the major mercury source areas from the Clear lake outflow to upstream of Rumsey. However, there is no data between Rumsey and Yolo. In fact, the mercury concentration decreases from Rumsey toward Yolo. Capay dam is located between Rumsey and Yolo, and it may play an important role in mercury and suspended sediment trapping and transport. Hence, additional mercury data within the stream are required for realistic model simulations. One necessary sampling location would be between Rumsey and Capay dam, and another location would be between Capay dam and Yolo.

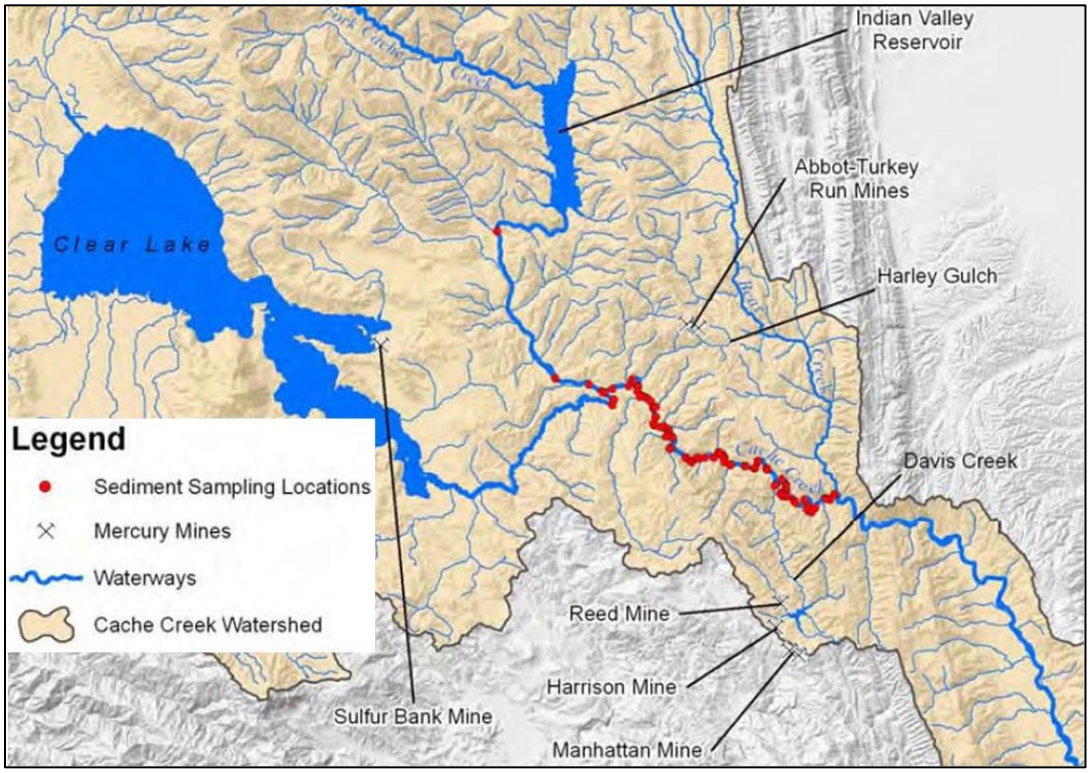

Figure 14- Overview of sampling locations for Cache Creek Canyon (Foe and Bosworth, 2008)

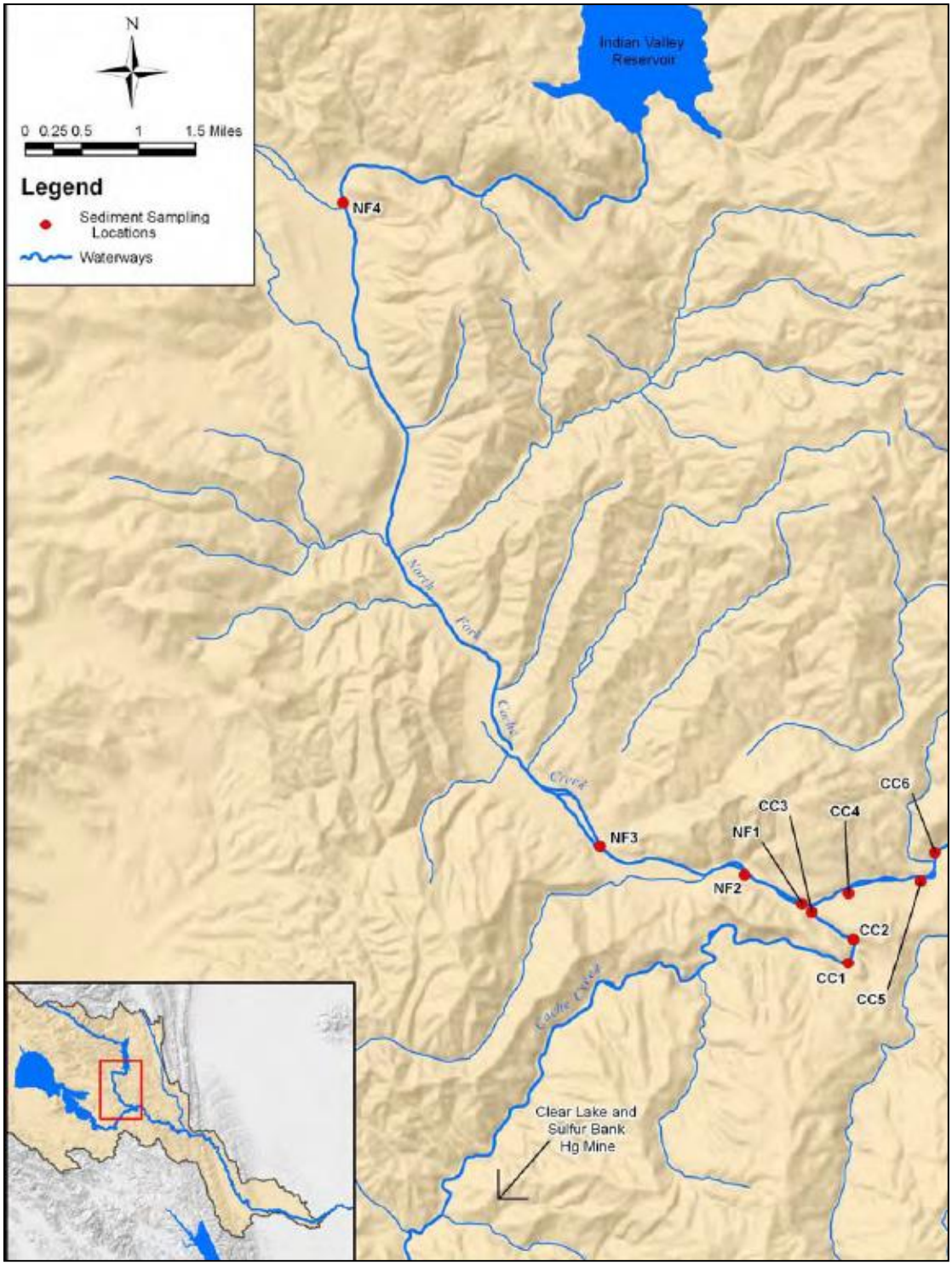

Figure 15- Sampling locations from Cache Creek, North Fork downstream toward Bear Creek (Foe and Bosworth, 2008)

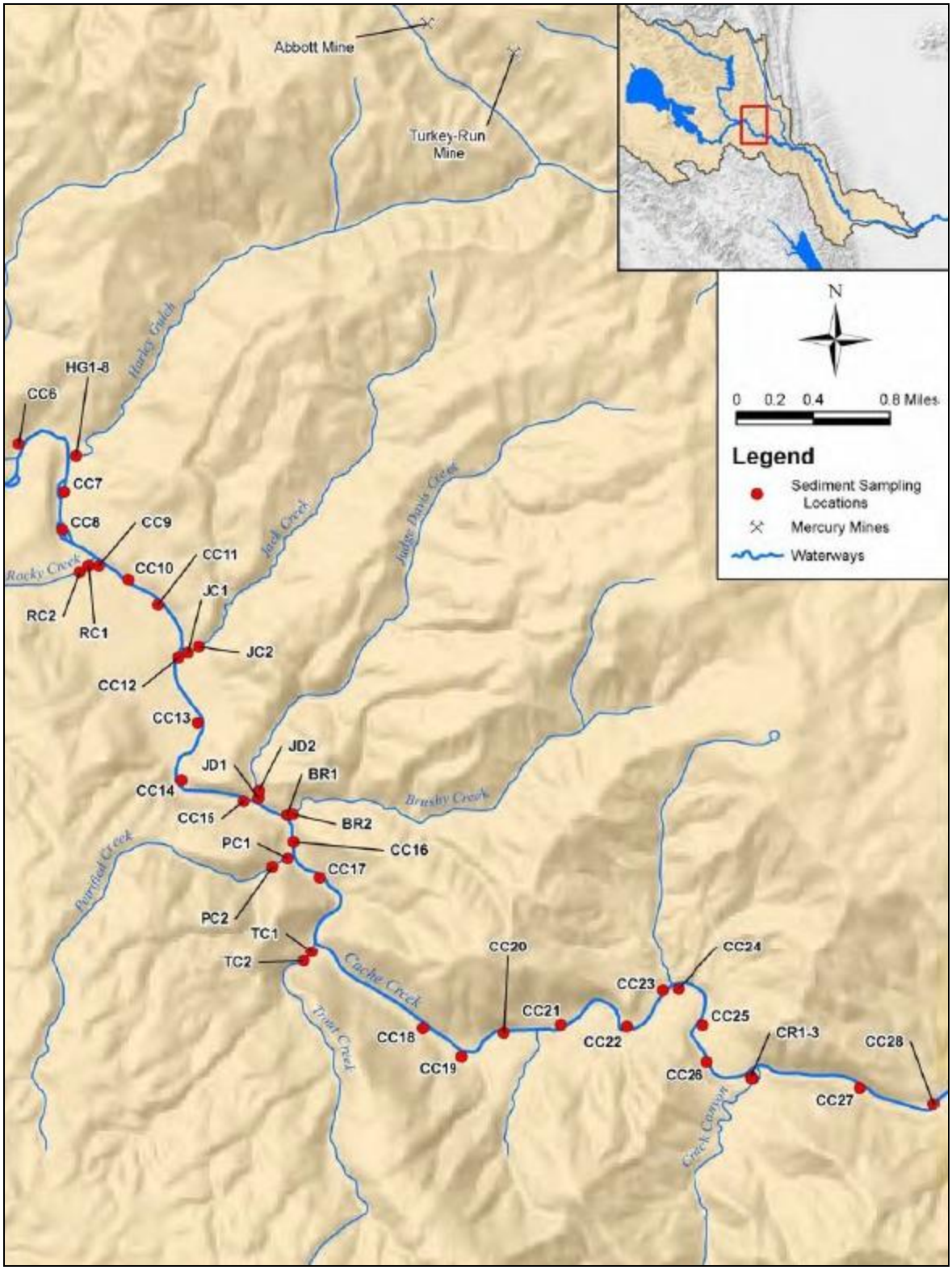

Figure 16- Sampling locations from Cache Creek, North Fork downstream toward Bear Creek, continued (Foe and Bosworth, 2008)

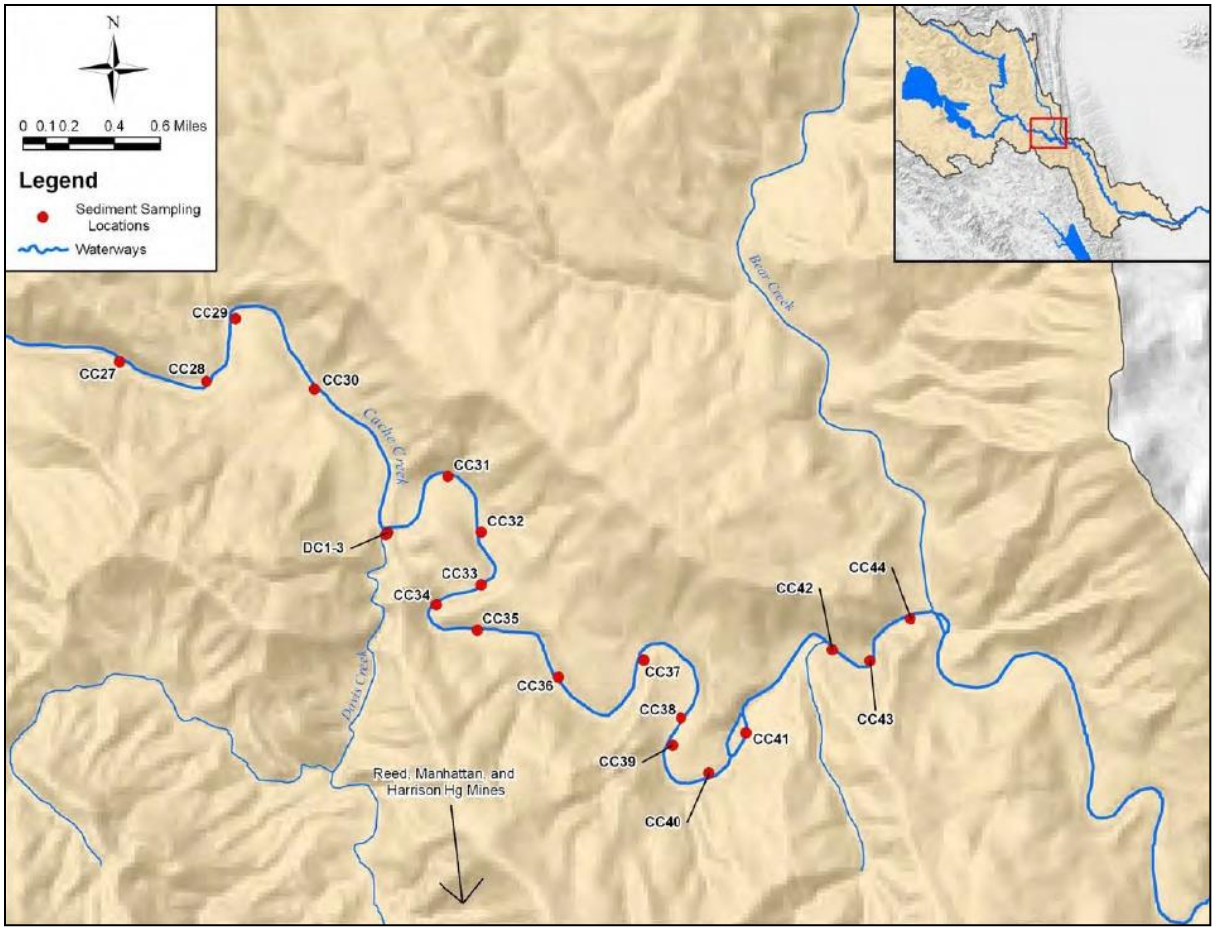

Figure 17- Sampling locations from Cache Creek, North Fork downstream toward Bear Creek, continued (Foe and Bosworth, 2008)

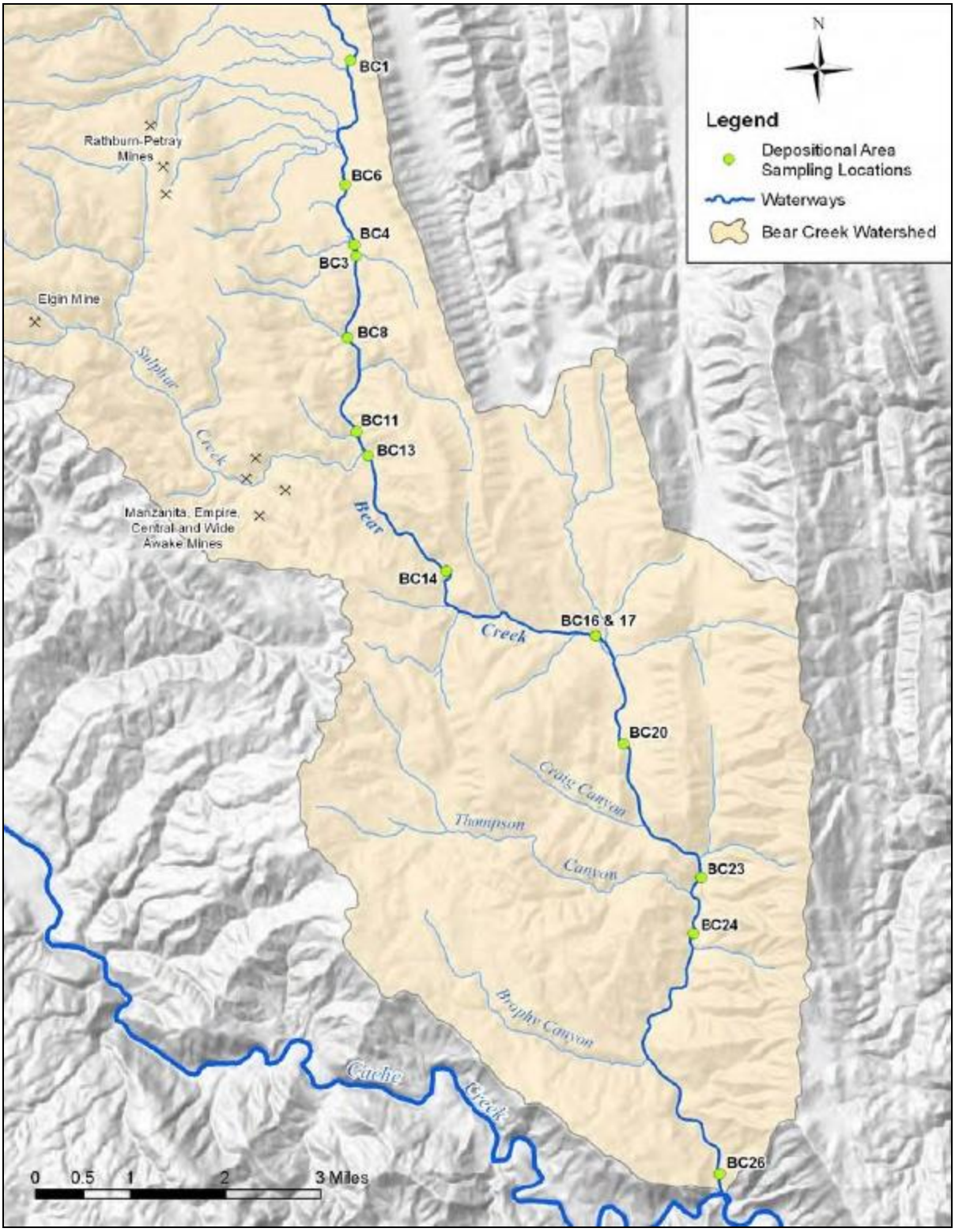

Figure 18- Sampling locations at Bear Creek (Bosworth and Morris, 2009)

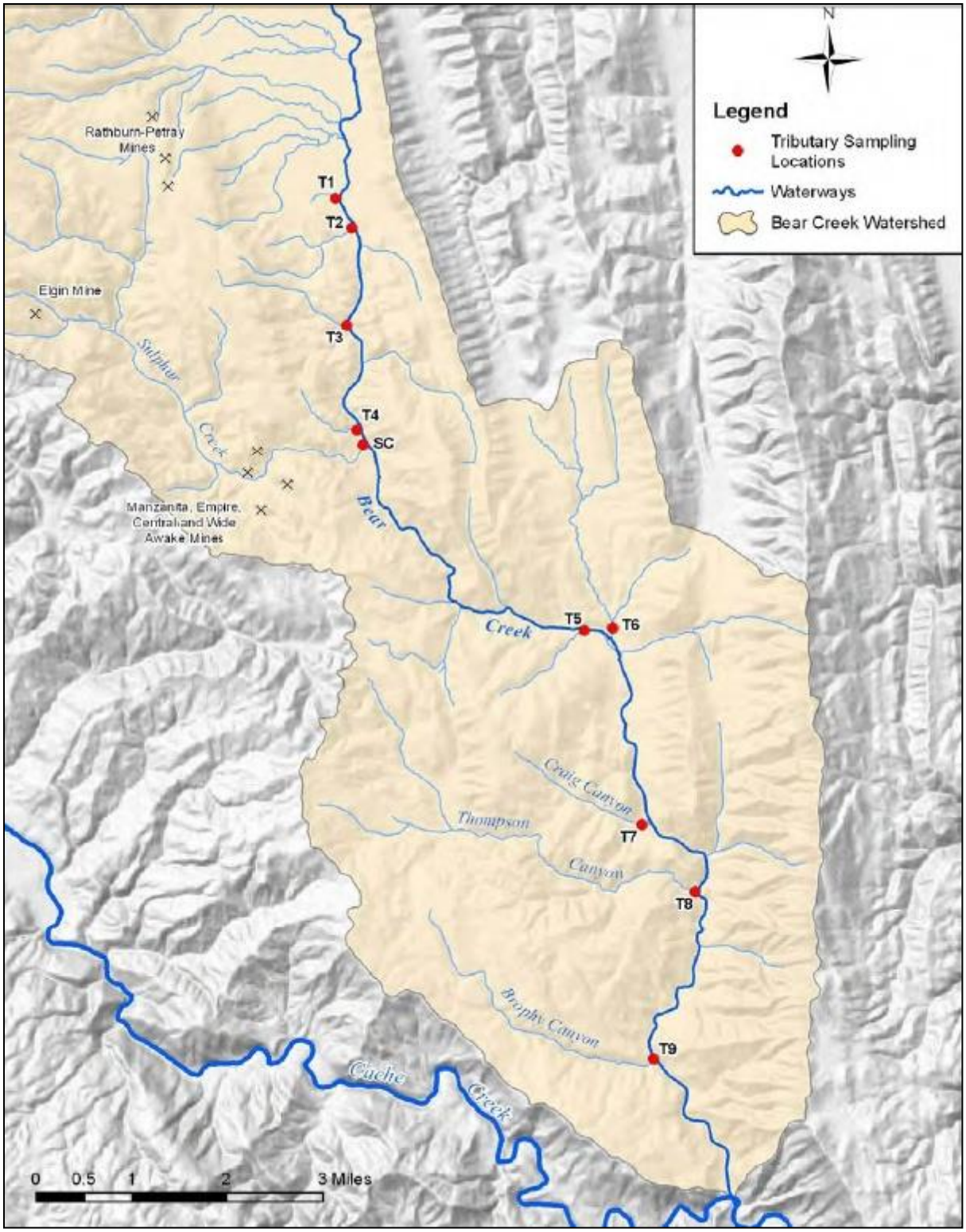

Figure 19- Sampling locations at the tributaries of Bear Creek (Bosworth and Morris, 2009)

4.3.2 Recommendations for Data Collection

As stated above, the data collected in various previous projects at Cache Creek watershed are insufficient for utilization in the calibration and validation of WEHY environmental hydrology model fundamentally due to lack of concurrent flow-sediment-mercury observations. There is an urgent need for a field-monitoring program at several locations, distributed over the watershed.

The desired sampling locations are shown in Figure 20 below. However, the substantial cost of realizing the desired sampling program is recognized. As such, if it is not possible to perform the monitoring at the 11 desired locations due to cost constraints, it is still absolutely essential to carry out a sampling program for sediment and mercury, simultaneously with the flow observations, at least at the Rumsey station. Accordingly, the following sampling data which should be collected simultaneously with streamflow data, are recommended as essential for the calibration and validation of an environmental hydrology model, such the WEHY model, in order to produce reliable and scientifically defensible simulations of flow, sediment and mercury at the Yolo station in order to be able to reconstruct the portion of the sediment rating curve corresponding to flows above 13000 cfs:

- **Instantaneous grab sampling data (suspended sediment, and mercury)**
  - At Rumsey station
- **Data on Mercury within the streambed (soil) at**
  - At Rumsey station

which should be collected **concurrently with flow measurements**.

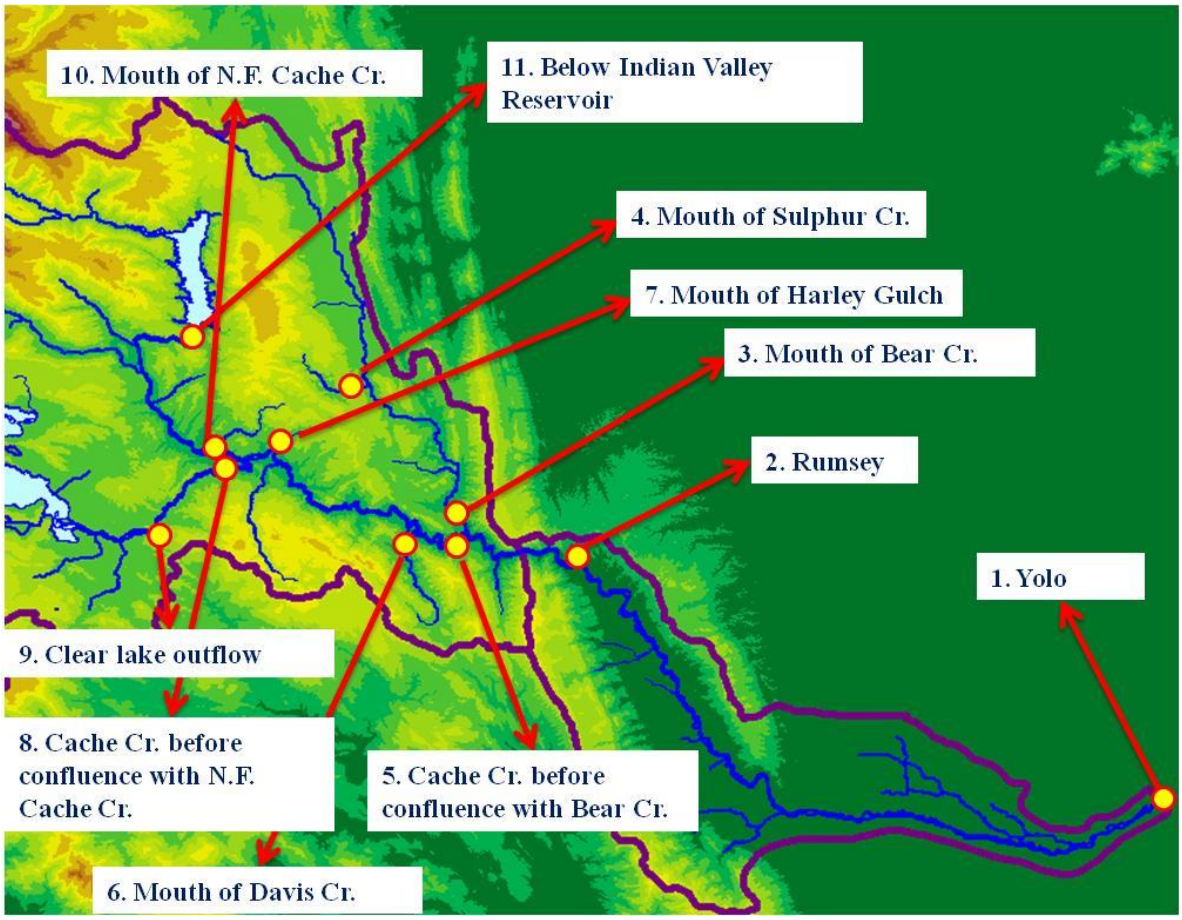

Figure 20- Overview of desired sampling locations (11 locations)

5. Reconstruction of Historical and Projection of Future Climate Conditions

Since the hydrologic module of the WEHY model was successfully calibrated and validated for the Cache Creek watershed, it was possible to reconstruct the historical flows and to project the outflows from the watershed during the 21st century under various emission scenarios, two global climate models and various initial conditions. In the following the details of this work are given.

5.1. Setting up the MM5 modeling domains over Cache Creek watershed

Spatially distributed atmospheric data at fine time intervals are required to simulate streamflow using the WEHY model. However, atmospheric data at hourly time intervals for sufficiently long periods are scarce within the Cache Creek watershed. Hence, the historical atmospheric data were reconstructed during the simulation periods at hourly intervals and at 3km grid resolution over the whole Cache Creek watershed.

The methodology for generating a reconstructed atmospheric variable at the scale of the Cache Creek watershed begins with obtaining the NCAR/NCEP global reanalysis data from NCAR via anonymous file transfer protocol (ftp). The NCAR/NCEP reanalysis data comprise a global set of atmospheric data on a regular grid with a horizontal spatial scale of approximately 210×210 km for latitudes near the Cache Creek watershed. Reanalysis data are derived from the analysis of various data sources including land surface, ship, rawinsonde, pibal, aircraft, and satellite. These data are assimilated into a global circulation model to create an atmospheric database that is uniform in space and time and is consistent with the observed values (Kalnay et al. 1996). The reanalysis data products used for this project are atmospheric data (pressure, winds, relative and specific humidity, temperature, and potential temperature) at 6-h intervals over the Cache Creek watershed and surrounding land and ocean.

These data are used as initial and boundary conditions for the mesoscale (regional-scale) climate model MM5. The fifth-generation NCAR/Penn State University mesoscale model (MM5) is the latest in a series of regional-scale atmospheric models developed from a mesoscale model documented in Grell et al. (1994). The PSU/NCAR mesoscale model is a limited-area, hydrostatic or nonhydrostatic, terrain-following sigma-coordinate model designed to simulate or predict mesoscale and regional-scale atmospheric circulation over any limited area on earth. Hydrostatic simulations assume the hydrostatic approximation for vertical motion in the atmosphere that is suitable for large-scale (greater than 20 km grid scale) simulations. In its nonhydrostatic mode, the MM5 model simulates the full vertical momentum equation and, as such, can describe satisfactorily the air motions over steep mountainous terrain at small grid scales (such as a few kilometers) suitable for atmospheric inputs into a watershed model. MM5

contains a wide range of physical process routines to model advection, diffusion, radiation, boundary layer processes, surface layer processes, moisture dynamics, and cumulus convection. The MM5 has flexible grid sizes and multiple nesting capabilities. These nesting capabilities can be run in both two-way and one-way nesting modes and allow MM5 to be coupled with either atmospheric data (such as NCAR/NCEP historical reanalysis data) or other models (such as General Circulation Model simulation data) that are at larger grid resolution. Therefore, MM5 is capable of atmospheric process simulations on any grid scale, limited only by the data resolution, data quality, and computational resources available.

When coupled with large-resolution historical atmospheric data, such as NCEP/NCAR reanalysis data, MM5 can reconstruct these atmospheric data (precipitation, temperature, radiation, relative humidity, wind, etc.) at significantly finer spatial resolutions. This higher resolution data are more suitable for watershed hydrologic modeling studies. In this project, four one-way nested grids were set up within the model to create a downscaling process from the 210×210 km scale reanalysis data to the 3×3 km scale over the Cache Creek watershed.

Figure 21 shows the spatial extent of the four grid domains. Each nested grid has a spatial resolution of 1/3 of the parent grid and focuses more on the project area of the Cache Creek watershed. The 1/3 ratio is recommended in the user documentation for MM5 (Grell et al. 1994). The first domain has a spatial grid resolution of 81 km, the second 27 km, the third 9 km, and the fourth 3 km. This series of nested domains allows the large-scale archived atmospheric data to be economically downscaled to the region of interest at the desired resolution. Data for seven variables were extracted: precipitation, atmospheric temperature, relative humidity, wind speed, incoming solar radiation, downward longwave radiation, and latent heat flux. In addition to these variables, dew point temperature was computed from the simulation results and stored.

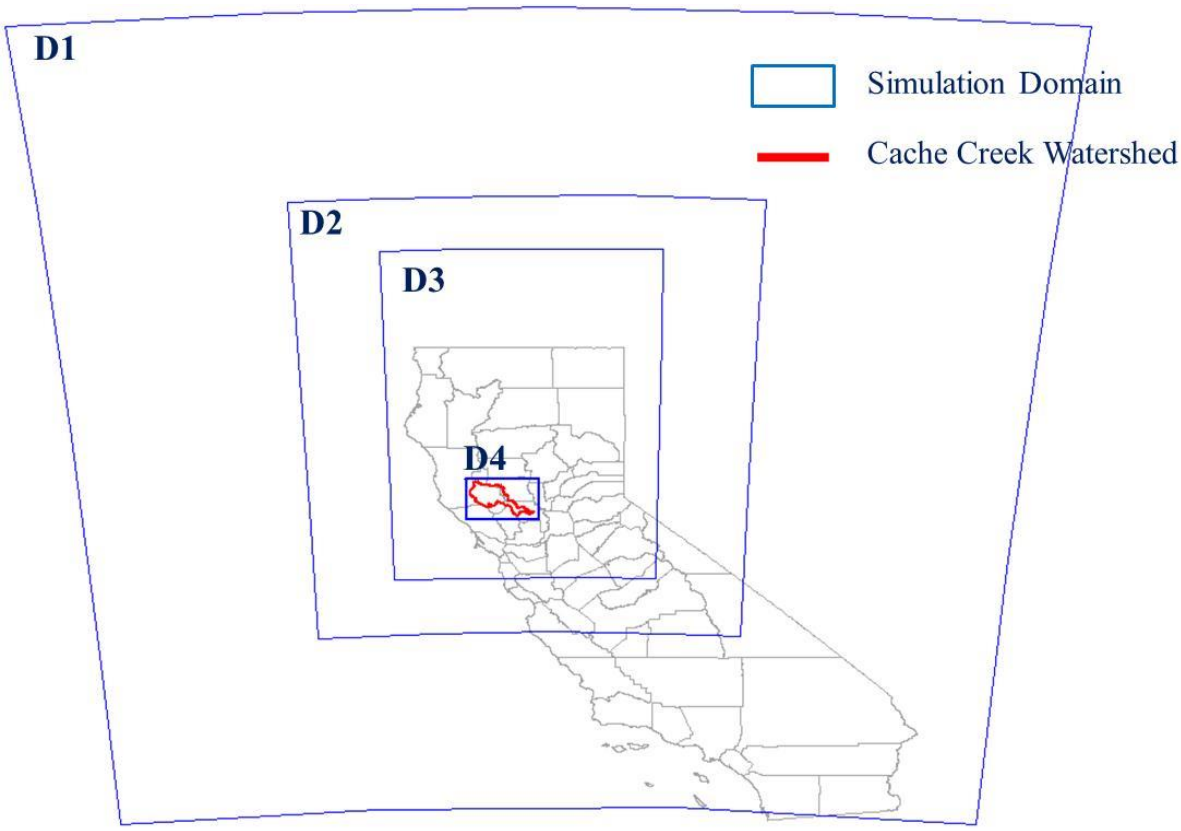

Figure 21- Depiction of four nested domains used for the MM5 simulation for the Cache Creek watershed

5.2. Regional Climate Model validation based on NCAR/NCEP reanalysis data-based climate variables

Figure 22 shows the sample comparisons between MM5-simulated historical precipitation fields and PRISM data for the mean monthly precipitation of December, January, and February from 1950 to 2007 over Cache Creek watershed. NCAR/NCEP global reanalysis data that were used for the initial and boundary conditions of the regional climate model MM5 for the above-mentioned period, have coarse grid resolution of approximately 210km by 210 km. These coarse resolution data were then downscaled by MM5 regional atmospheric model to 3 km by 3 km grids over Cache Creek watershed.

In general, the spatial distributions of mean monthly precipitation for December, January, and February, reconstructed by MM5 by downscaling the NCAR/NCEP reanalysis data, match reasonably well with the PRISM monthly data. Figure 23 shows the graphical comparison of

mean monthly precipitation from 1950 to 2007. The MM5 simulation results match the PRISM monthly data almost perfectly.

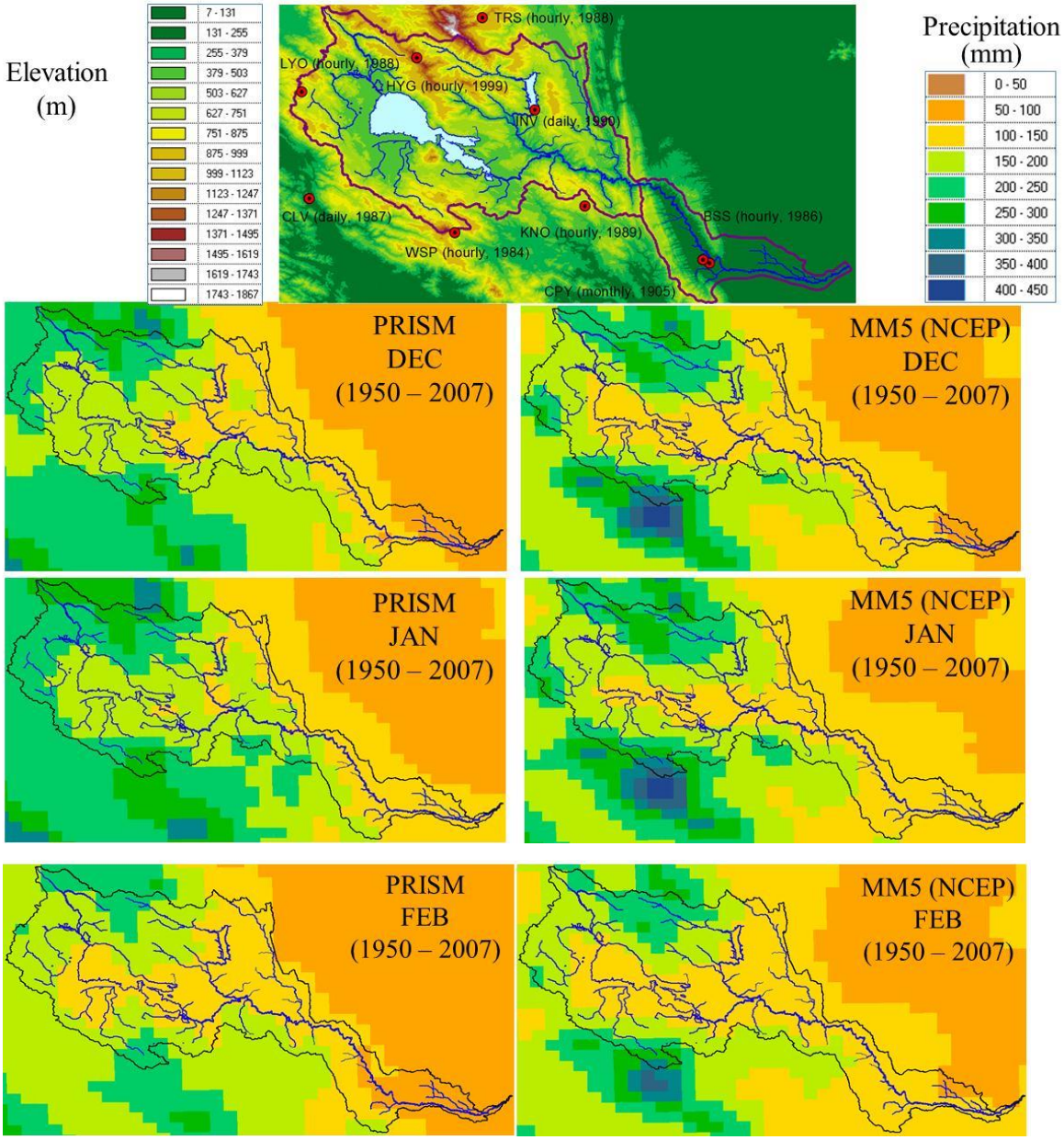

Figure 22- Example comparison of mean monthly precipitation for December, January and February between PRISM data and MM5 simulation results during 1950 to 2007

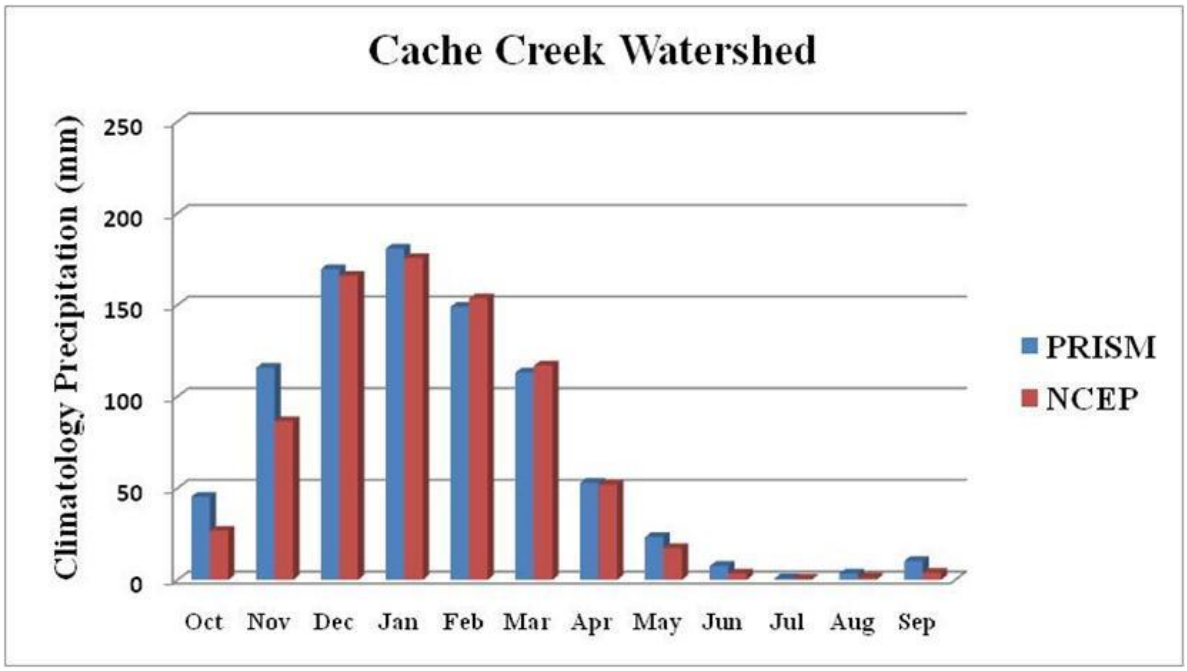

Figure 23- Graphical comparison of mean monthly precipitation between PRISM data and MM5 simulation results over Cache Creek watershed during 1950 to 2007

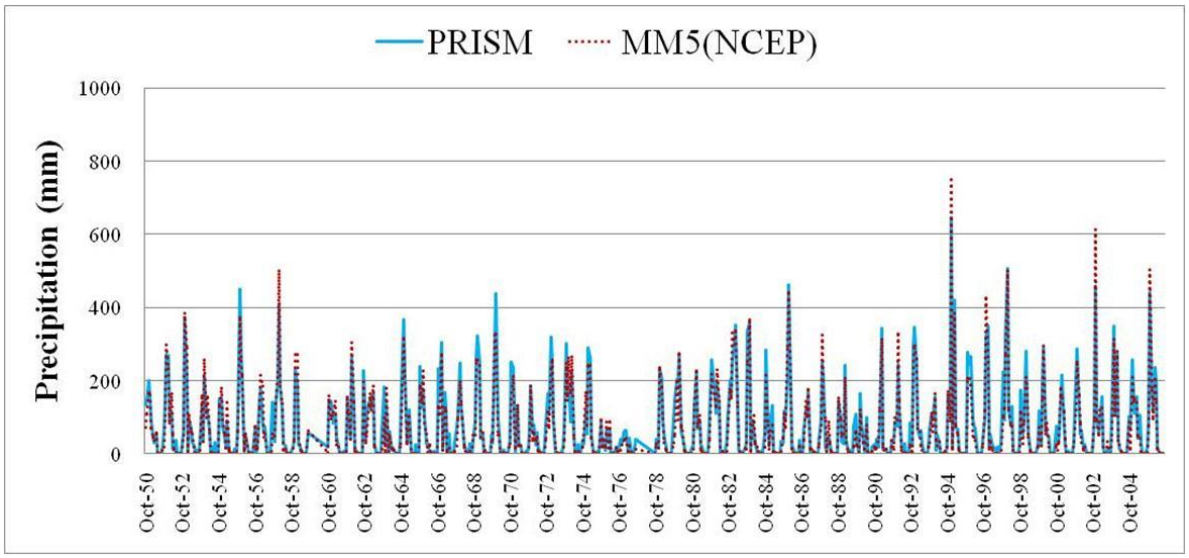

Figure 24- Graphical comparison of monthly precipitation between PRISM data and MM5 simulations during 1950 to 2007

Table 5- Statistical test results for the comparison of MM5-simulated (NCEP) versus PRISM precipitation during 1950 – 1999 for the Cache Creek watershed

Statistical value	PRISM	MM5(NCEP)
Mean (mm)	72.71	66.98
STDEV (mm)	97.82	98.10
RMSE (mm)		28.84
Nash-Sutcliffe efficiency (E_{NS})		0.91
Correlation coefficient (R)		0.96
Chi-square critical (α=0.05)		18.31
Chi-square calculated		7.29

Figure 24 compares graphically the monthly basin-averaged precipitation from 1950 to 2007 from the MM5 simulation results (by downscaling the NCAR/NCEP reanalysis data) and the PRISM data. MM5 simulation results match the PRISM data quite well, as can be seen in Fig 24. In order to test the performance of MM5-simulation more comprehensively, the MM5-simulated versus corresponding PRISM values were evaluated by mean, standard deviation (*STDEV*), correlation coefficient (R), root mean square error, Nash-Sutcliffe efficiency (E_{NS}), and Chi-square goodness-of-fit test from 1950 to 2007 (see Table 5). The mean and standard deviation (*STDEV*) are similar to PRISM values. The correlation coefficient (R) is 0.96 and Nash-Sutcliffe efficiency (E_{NS}) value is 0.91. Furthermore, the MM5 simulation results passed the Chi-square goodness-of-fit test. It should be noted that no bias-correction was necessary for MM5-simulated precipitation values.

Only one station, KNO of CDEC, had observations of air temperature and solar radiation to use for validation of MM5 simulations. Figure 25 and Figure 26 show the comparisons of the MM5-simulated (based on NCEP/NCAR reanalysis data) and ground-observed monthly mean values for air temperature (Figure 25) and solar radiation (Figure 26) during 2000 – 2011 at KNO CDEC station. As shown in these figures, the MM5-simulated monthly mean air temperature and solar radiation values matched the ground-observed KNO CDEC station values perfectly. As such, the comparison results and statistical tests indicate the reliability and capability of MM5

historical climate simulations by downscaling the coarse-resolution atmospheric observations from NCEP/NCAR reanalysis data.

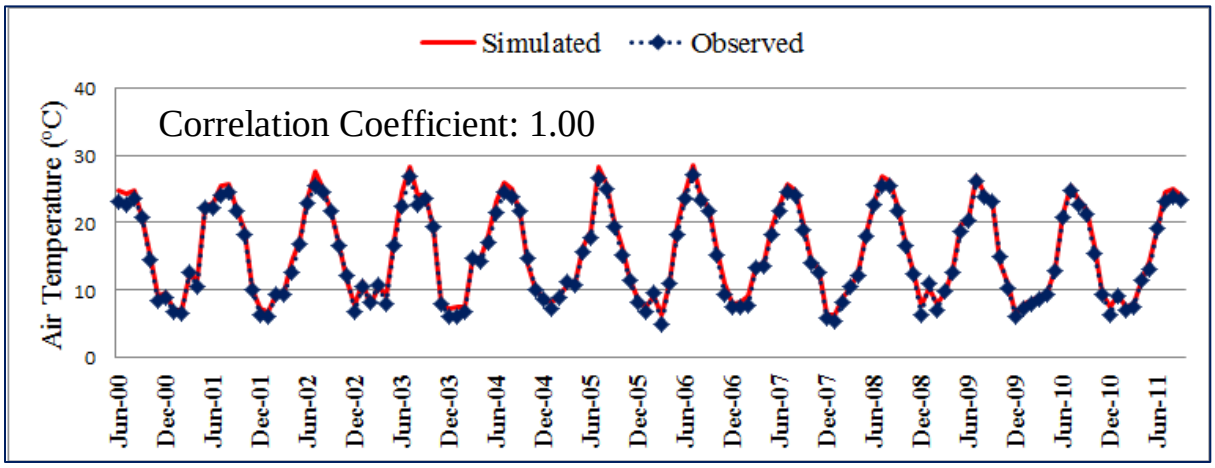

Figure 25- Comparisons of simulated (MM5-NCEP) and observed (CDEC) monthly mean temperature from 2000 through 2011 at KNO station. No bias-correction was applied.

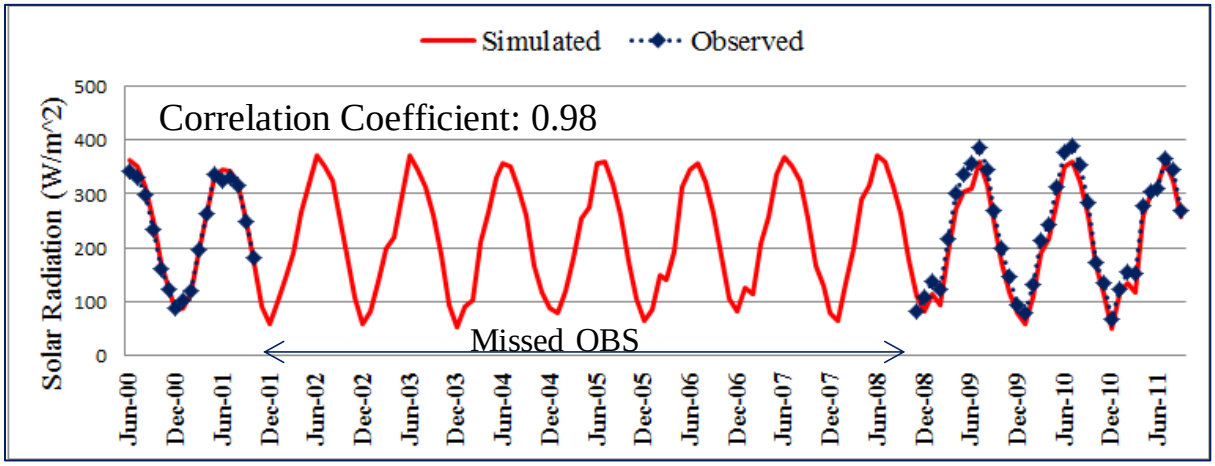

Figure 26- Comparisons of simulated (MM5-NCEP) and observed (CDEC) monthly mean solar radiation from 2000 through 2011 at KNO station. No bias-correction was applied.

5.3. Model validation of GCM-based climate variables

In order to be able to perform comparisons between the historical climate conditions and the 21st century future climate conditions that are projected based on downscaling two global climate model (ECHAM5-GCM and the CCSM3-GCM) projections, it is necessary also to simulate the historical climate conditions based on the historical climate simulations of the two GCMs in order to achieve consistency among the comparisons.

As such, GCM-based MM5 historical climate simulations for the late twentieth century (ECHAM5: 1950-1999, CCSM3: 1900-1999) were also performed over Cache Creek watershed. It is noted that the ECHAM5-GCM and the CCSM3-GCM based precipitation simulations by MM5 include biases and require correcting. For this project, the bias correction was conducted based on the monthly climatology of precipitation from the PRISM data. The determined bias was then incorporated into ECHAM5-GCM-based and CCSM3-GCM-based future precipitation projections by MM5 over Cache Creek watershed.

Figure 27 compares graphically the MM5-simulated precipitation (by downscaling CCSM3 and ECHAM5 GCM outputs) and PRISM precipitation with respect to monthly basin-averaged precipitation from 1900 to 1999 for CCSM3 and from 1950 to 1999 for ECHAM5 over Cache Creek watershed. In this Figure 27, the MM5 simulation results match the PRISM monthly data reasonably well.

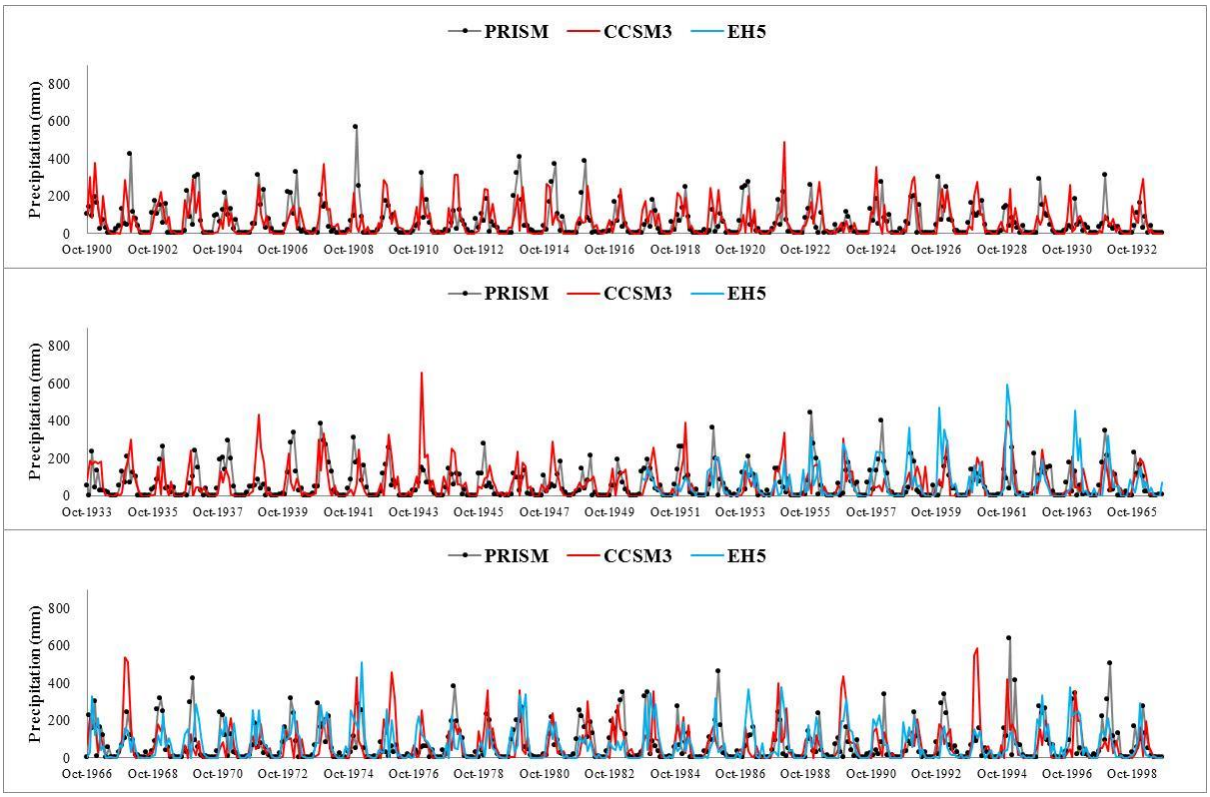

Figure 27- Comparisons of MM5-simulated monthly precipitation versus PRISM monthly precipitation from water year 1901 to water year 1999 for Cache Creek watershed

Unlike NCAR/NCEP reanalysis data based MM5 simulations, GCM-based MM5 simulation results may not be suitable for comparison to the time-series of observed precipitation because the GCM simulations focus on the climatology of the specified period rather than the prediction of actual precipitation during the period. Thus, it is more important whether the distribution of the GCM-based MM5 simulation results is comparable to the corresponding distribution of observations. The quartile-quartile plot is a good method to see whether the distribution of simulated values deviate from the distribution of observed values. Figure 28 shows the comparison of quartile-quartile plot for the Cache Creek watershed average monthly precipitation between MM5-simulated (based on GCM historical simulations) and PRISM precipitation during water year 1951 to water year 1999. As shown in Figure 28, MM5-simulated precipitation values from both CCSM3 and ECHAM5 GCMs are distributed very well against PRISM precipitation values.

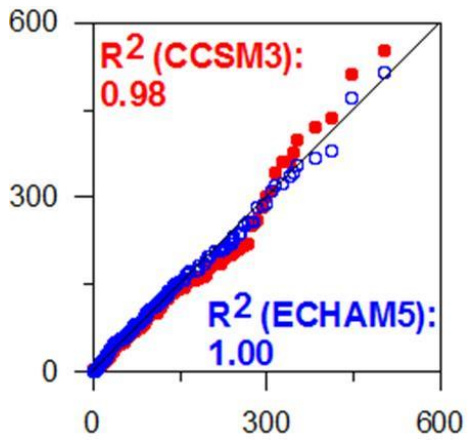

Figure 28- Quartile-quartile plot of Cache Creek watershed average monthly precipitation between MM5-simulated (based on GCM historical simulations) and PRISM precipitation during water year 1951 to water year 1999. Red color indicates the comparisons for CCSM3-based precipitation and blue color indicates the comparisons for ECHAM5-based precipitation.

Long-term precipitation trends were also investigated based on the 10-year moving average of annual precipitation between GCMs-based MM5 simulations and PRISM values during water year 1901 to water year 1999 (see Figure 29). In general, the MM5-simulated precipitation trends are similar to the corresponding precipitation trends from PRISM.

The Chi-square goodness-of-fit test comparing the GCMs-based MM5 simulations versus the corresponding PRISM values during water years 1951 to 1999, was also passed (see Figure 30). As such, these comparison results and statistical tests indicate the reliability and capability of MM5 reconstruction of the historical climate conditions by downscaling historical climate simulations from a GCM's historical control run.

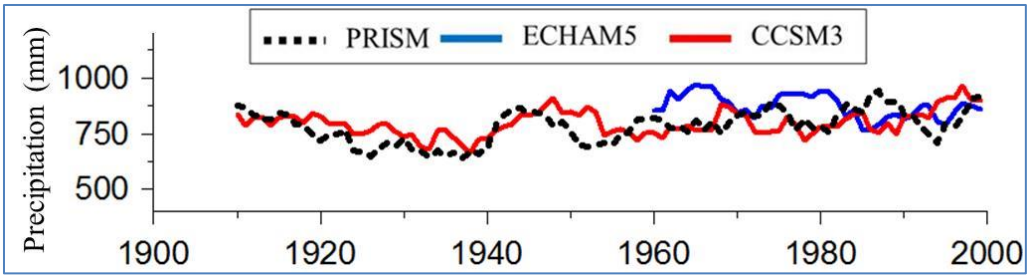

Figure 29- Comparisons of 10-year moving Cache Creek watershed average annual precipitation between PRISM observations and MM5-simulated precipitation during water year 1901 to water year 1999

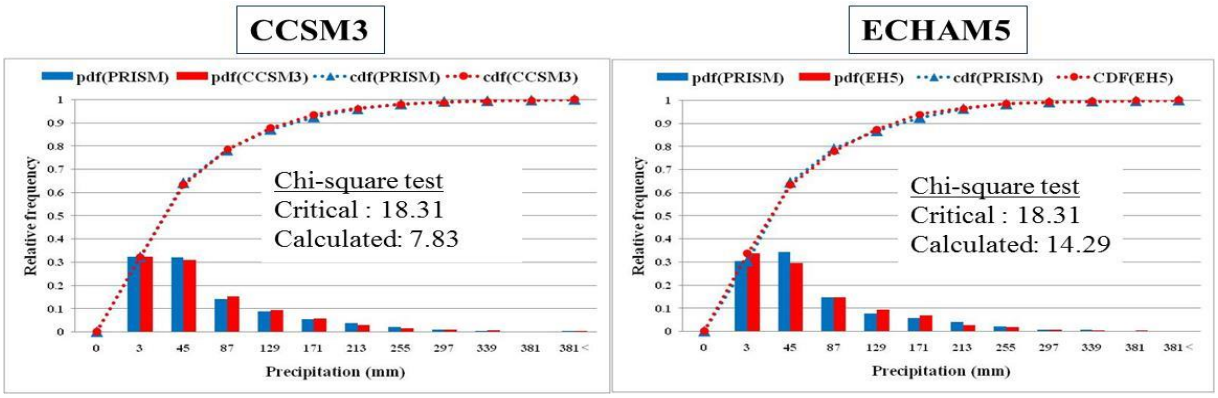

Figure 30- Chi-square goodness-of-fit test results of Cache Creek watershed average monthly precipitation between PRISM and MM5-simulated precipitation during water year 1951 to water year 1999

5.4. Reconstruction of historical climate data

It is possible to develop a full historical flow record at Cache Creek watershed outlet (taken as Yolo station) by reconstructing the missing historical flow data by the calibrated and validated WEHY watershed model, provided that the corresponding historical climate data are also reconstructed by a regional climate model, such as MM5, over the watershed. Based on such a full flow record at the Yolo station, it is then possible to simulate the historical sediment inflow conditions to Cache Creek Settling Basin once a comprehensive sediment rating curve is developed. In the following, the details on the reconstruction of the historical climate conditions during 1951-2011 water years period over Cache Creek watershed will be given. In a later section, the reconstruction of the corresponding historical flow conditions will be discussed.

Reconstruction of historical climate data based on the NCAR/NCEP reanalysis data from water year 1951 through water year 2011 and on the two GCM outputs (CCSM3 and ECHAM5) from water year 1951 through water year 1999 was completed to build the necessary atmospheric boundary conditions for WEHY model's flow simulations over the watershed.

Figure 31 through Figure 33 show sample spatial plots of NCAR/NCEP reanalysis data-based MM5 simulation results for 61-year average monthly precipitation, monthly mean air temperature and monthly mean shortwave solar radiation fields during 1950 – 2011 over Cache Creek watershed. It can be seen clearly from Figure 31 that MM5-simulated precipitation fields show banded precipitation structures around the mountain ridges due to the orographic effects over Cache Creek watershed. Meanwhile the spatial fields of MM5-simulated air temperature show dependence on elevation since the high elevations around mountain ridges have relatively low temperatures while the low elevations have relatively high temperatures (see Figure 32). Atmospheric data such as precipitation, short and long wave radiation, wind speed, relative humidity and air temperature are crucial information for the WEHY watershed model. However, it is difficult to obtain such spatially distributed hydro-atmospheric data in sparsely-gauged watersheds like Cache Creek at fine resolutions in time and space. By means of MM5-downscaled climate data for a historical period of 61 years and for the 21st century future period it was possible to construct the necessary atmospheric data for the WEHY watershed model's flow simulations.

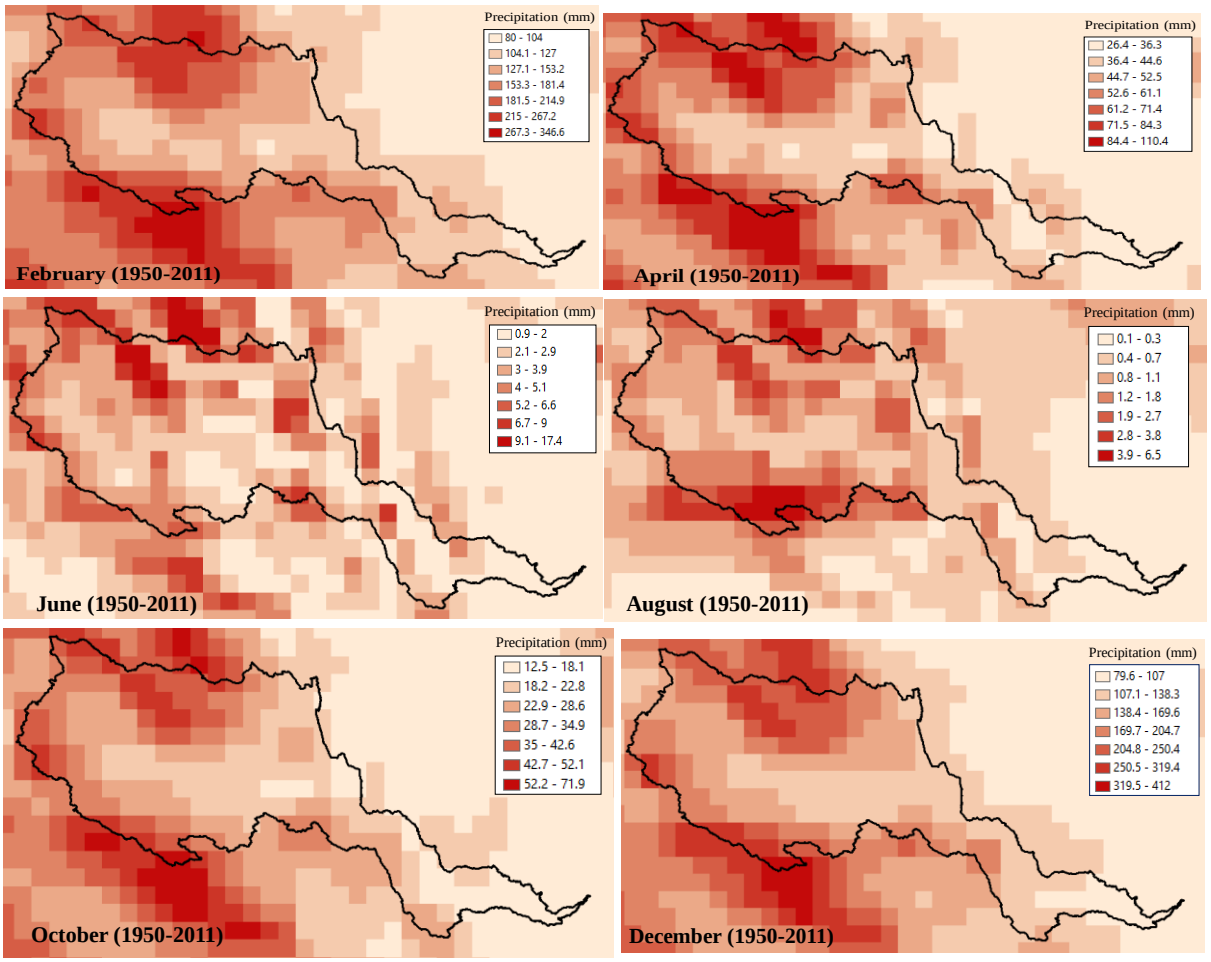

Figure 31- Sample spatial plots of NCAR/NCEP reanalysis data-based MM5 simulation results for the mean monthly precipitation (February, April, June, August, October and December) during 1950 – 2011 over Cache Creek watershed.

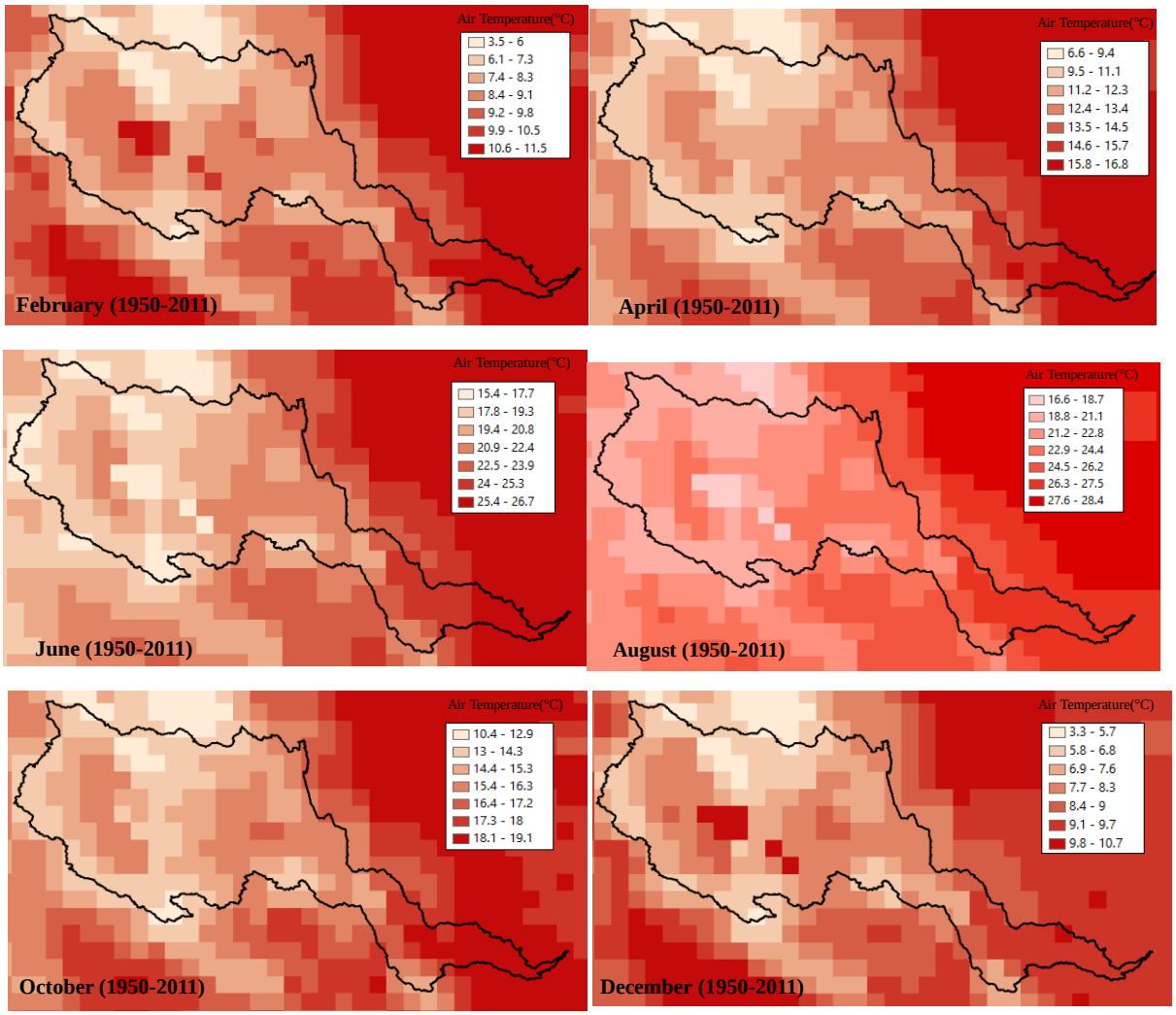

Figure 32- Sample spatial plots of NCAR/NCEP reanalysis data-based MM5 simulation results for 61-year average monthly mean air temperature (February, April, June, August, October and December) during 1950 – 2011 over Cache Creek watershed.

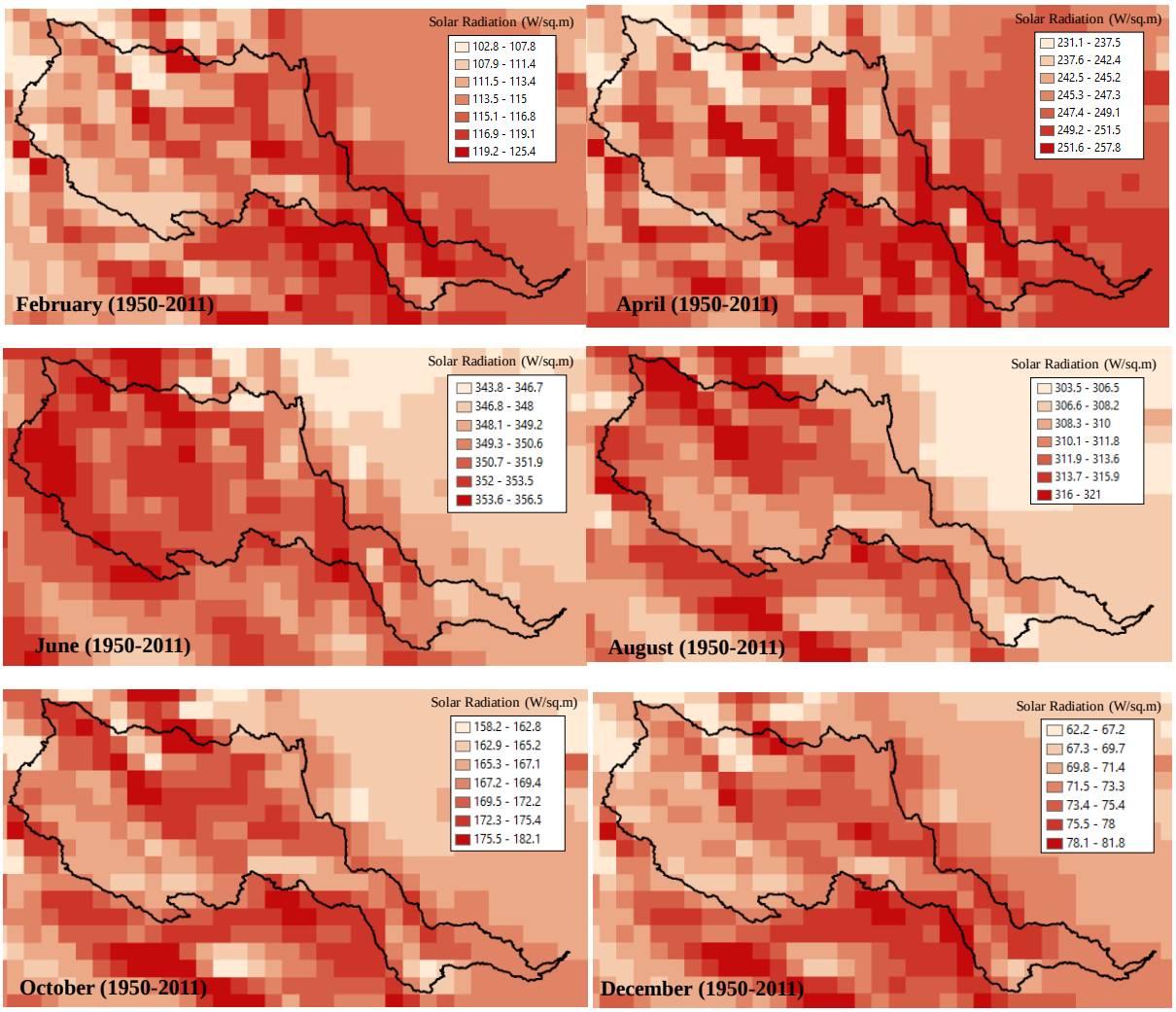

Figure 33- Sample spatial plots of NCAR/NCEP reanalysis data-based MM5 simulation results for 61-year average monthly mean shortwave solar radiation (February, April, June, August, October and December) during 1950 – 2011 over Cache Creek watershed.

Figure 34 and Figure 35 show the sample plots of basin-average monthly precipitation, monthly mean air temperature, wind speed, shortwave solar radiation and longwave solar radiation over the Cache Creek watershed that were reconstructed by MM5 simulations using NCAR/NCEP reanalysis historical data and from the GCM (CCSM3 and ECHAM5)-based historical climate simulation data. The historical climate data were then used as input data for the WEHY model flow simulations.

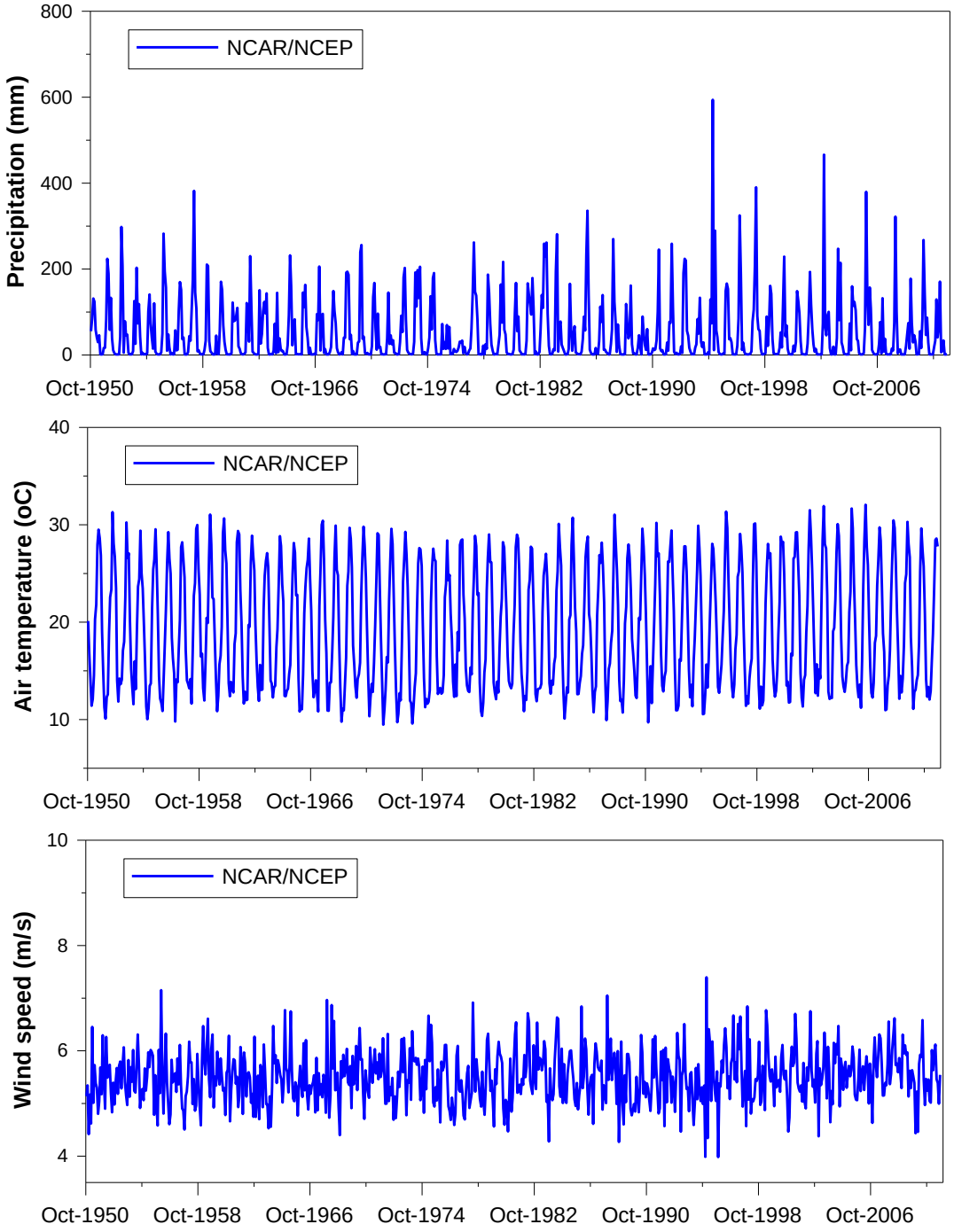

Figure 34- Sample plots of historical basin-average monthly precipitation, monthly mean air temperature, wind speed, shortwave solar radiation and longwave solar radiation that were reconstructed by MM5 regional climate model during 1950 – 2011 over Cache Creek watershed by downscaling the NCAR/NCEP reanalysis data (continued in the next page)

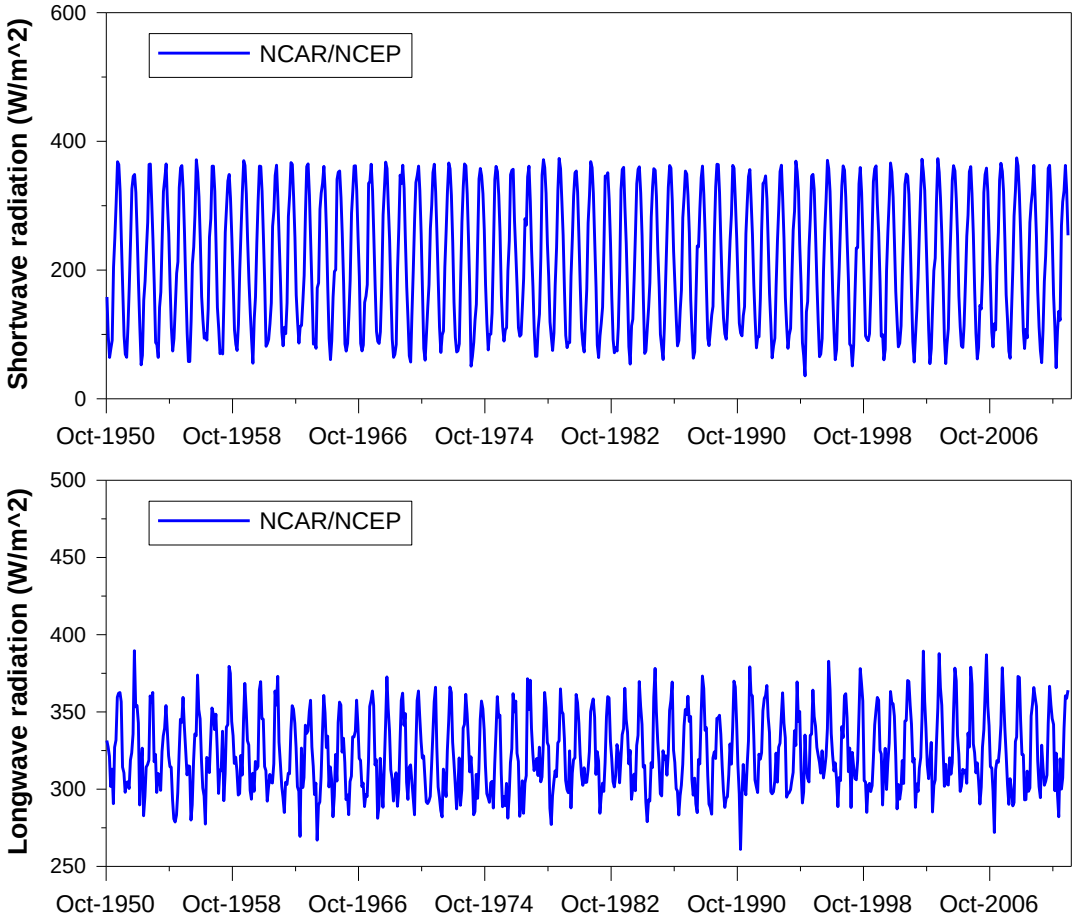

Figure 34- Sample plots of historical basin-average monthly precipitation, monthly mean air temperature, wind speed, shortwave solar radiation and longwave solar radiation that were reconstructed by MM5 regional climate model during 1950 – 2011 over Cache Creek watershed by downscaling the NCAR/NCEP reanalysis data

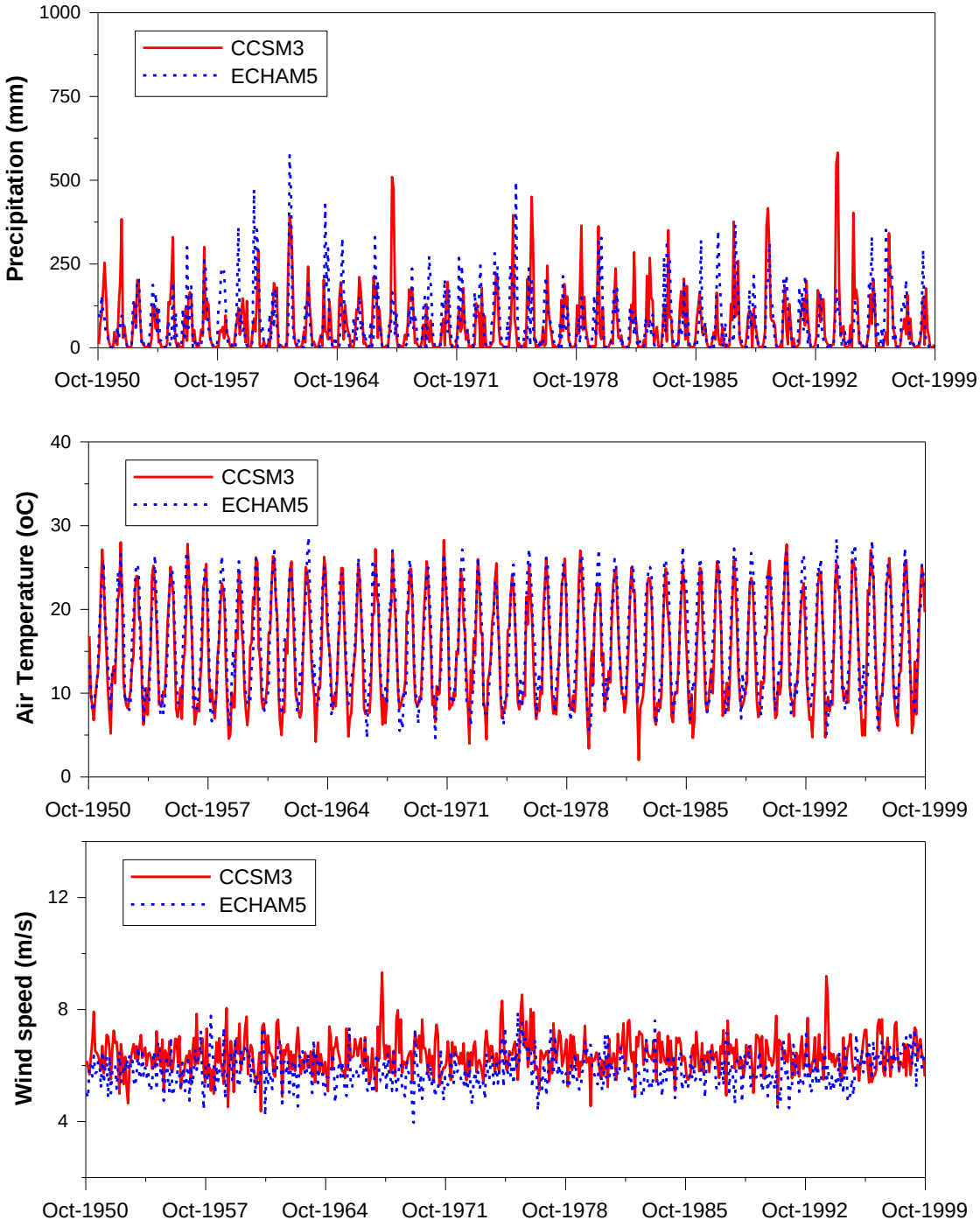

Figure 35- Sample plots of historical basin-average monthly precipitation, monthly mean air temperature, wind speed, shortwave solar radiation and longwave solar radiation that were reconstructed by MM5 regional climate model during 1950 – 2000 over Cache Creek watershed by downscaling the GCM (CCSM3 and ECHAM5) historical control simulations (continued next page)

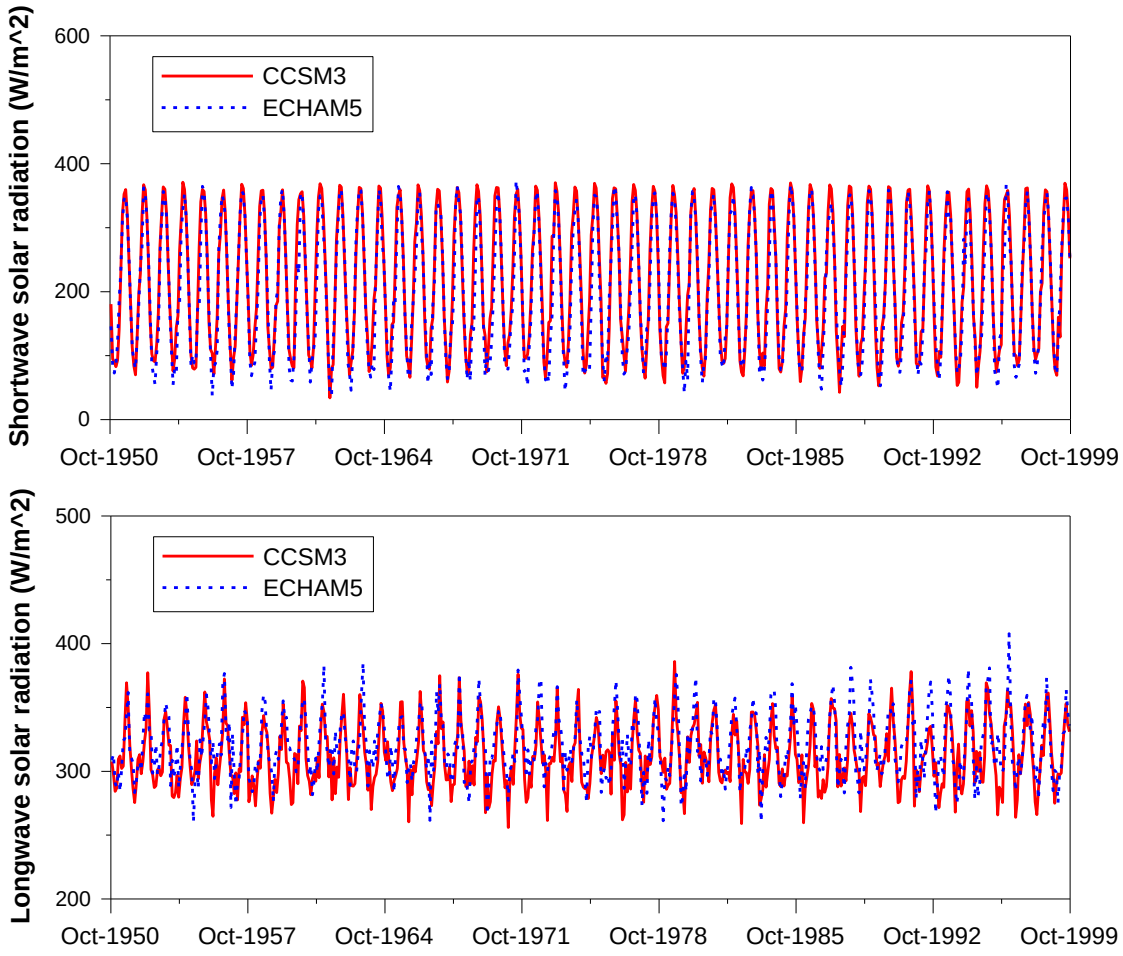

Figure 35- Sample plots of historical basin-average monthly precipitation, monthly mean air temperature, wind speed, shortwave solar radiation and longwave solar radiation that were reconstructed by MM5 regional climate model during 1950 – 2000 over Cache Creek watershed by downscaling the GCM (CCSM3 and ECHAM5) historical control simulations

5.5. Projection of Future Climate Conditions

In order to quantify the flow conditions at Cache Creek watershed under the future hydro-climate conditions by means of WEHY model simulations, it is necessary to first project the future climate conditions by the regional climate model MM5. Then these future climate conditions provide the necessary climate input data for the WEHY model's simulations of the future hydrologic conditions over the Cache Creek watershed that provide the inlet boundary conditions for the CCSB hydraulic model.

MM5 regional climate model's projections of the 21st century future climate conditions over Cache Creek watershed were based on 9 climate projections from ECHAM5 GCM (A1B1, A1B2, A1B3, A2-1, A2-2, A2-3, B1-1, B1-2, and B1-3 scenarios) and 4 climate projections from CCSM3 GCM (A1B, B1, A2, and A1FI scenarios). In this report, three climate variables (precipitation, air temperature and solar radiation) are presented as sample future climate variables constructed by MM5 regional climate model over Cache Creek watershed.

5.5.1 Projection of precipitation under future climate change conditions

It is difficult to select a specific GCM and a specific emissions scenario for the projection of the future climate because the future climate conditions are unknown and evolving in time and space. One plausible approach for future climate projections is to consider an ensemble of projections and then use the ensemble average of all individual projection realizations (13 realizations in this project) with a confidence band.

In this study, the future projection of precipitation under a changing climate is based on the ensemble of projections by the regional atmospheric model MM5, based on 9-projection realizations from ECAHM5 GCM (under A1B1, A1B2, A1B3, A2-1, A2-2, A2-3, B1-1, B1-2, and B1-3 scenarios), and on 4-projection realizations from CCSM3 GCM (under A1B, B1, A2, and A1FI scenarios). Figure 36 compares the GCM control run-based MM5 historical precipitation simulation against the GCM projections-based future MM5-projected ensemble average annual Cache Creek watershed-average precipitation with 95 % confidence interval. As

shown in Figure 36, a trend in annual precipitation over Cache Creek watershed cannot be claimed, based on Mann-Kendall test (at 95% confidence level).

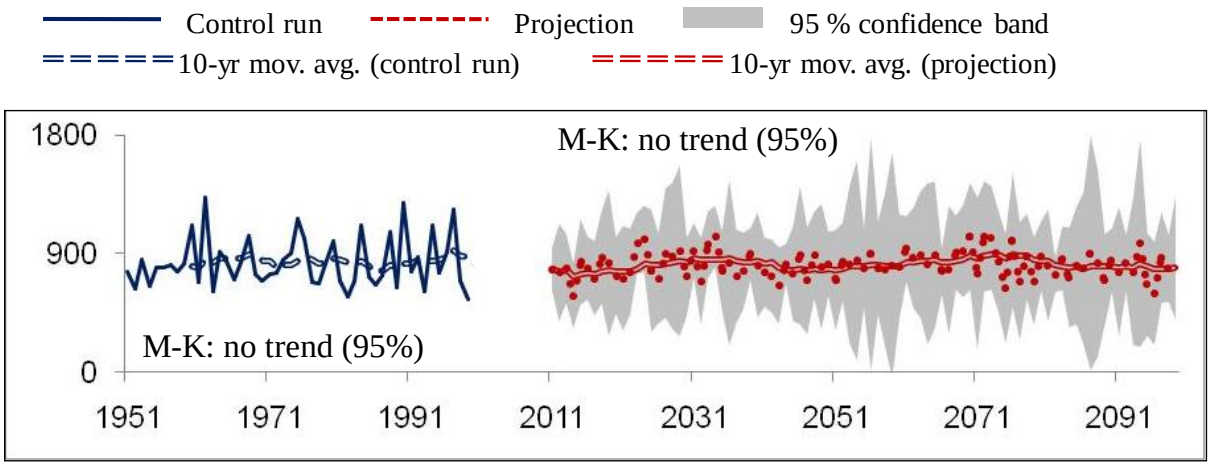

Figure 36- Comparison of historical GCM control run-based MM5 simulation versus the future GCM (ECHAM5 and CCSM3)-based MM5 projection of ensemble average annual precipitation (ensemble average of 13-projection realizations) for Cache Creek watershed

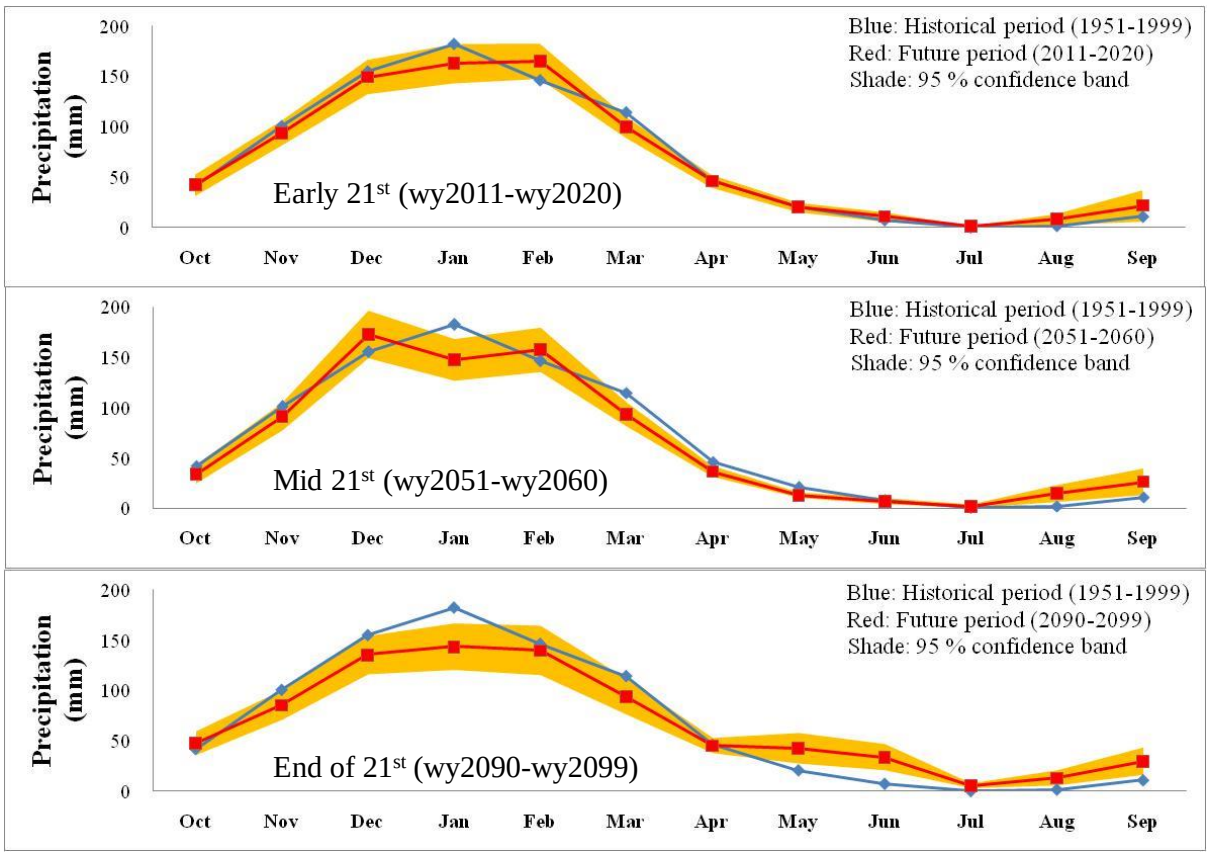

Figure 37- Comparison of the future mean monthly precipitation (ensemble average of 13-projection realizations) at early 21st century, at mid-21st century and at the end of the 21st century against the historical mean monthly precipitation during wy1990-wy1999 over Cache Creek watershed

Figure 37 shows the GCM-based future projections by MM5 simulations for mean monthly precipitation during each 10-year period at the early-, mid- and end of the 21st century together with their respective confidence bands (95 %), compared against the historical mean monthly precipitation for Cache Creek watershed. If the historical mean monthly precipitation at each month is within the confidence band of the GCM-based future projections by MM5, the projected future mean monthly precipitation is not significantly different than the historical mean monthly precipitation. Meanwhile, if the historical mean monthly precipitation at any month is outside the confidence band of the corresponding GCM emission scenario-based future projection for that month, the future mean monthly precipitation for that month is significantly different than the historical mean monthly precipitation for the specified month. From Figure 37 it may be inferred that the projected mean monthly precipitation is significantly less during

January at the mid-21st century (wy2051-wy2060) and at the end of the 21st century (wy2090-wy2099) when compared against the corresponding historical mean monthly precipitation (wy1990-wy1999) over Cache Creek watershed. Meanwhile the projected mean monthly precipitation is significantly increased during the dry season (May, June, August and September) at the end of the 21st century (wy2090-wy2099) when compared against the corresponding historical mean monthly precipitation (wy1990-wy1999) over Cache Creek watershed.

Additionally, the Cache Creek watershed -average annual 72-hour maximum precipitation values are compared between the historical period (wy1901 – wy1999) and the projection period (wy2001 – wy2099) in Figure 38. The projected annual 72-hour maximum precipitation values, based on the MM5 downscaled CCSM3 GCM's projections for A1B, A2, B1 and A1FI scenarios, have in general heavier tails than the historical annual 72-hour maximum precipitation values. Furthermore, CCSM3 GCM's A1FI scenario-based MM5 projection of annual 72-hour maximum precipitation values also have a heavier relative frequency histogram tail than the historical annual 72-hour maximum precipitation values.

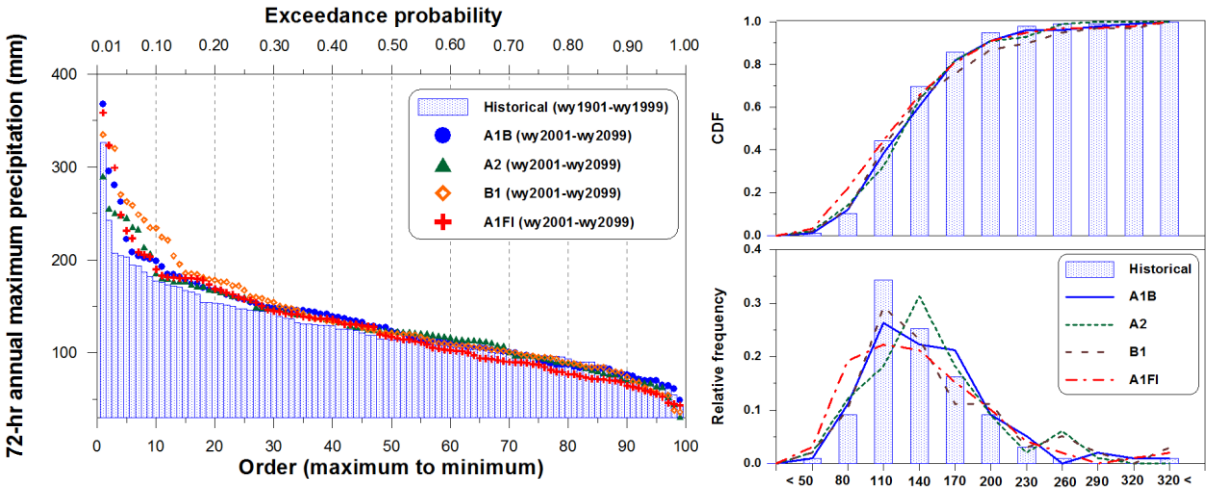

Figure 38- Comparison of Cache Creek watershed-average annual 72-hour maximum precipitation between the historical period (wy1901 – wy1999) and the projection period (wy2001 – wy2099)

5.5.2 Projection of air temperature and solar radiation under future climate conditions

Air temperature and solar radiation for the future 21st century climate was also projected based on the downscaling of ECHAM5 GCM projections (for A1B1, A1B2, A1B3, A2-1, A2-2, A2-3, B1-1, B1-2, and B1-3 emission scenarios) and on the downscaling of CCSM3 GCM projections (for A1B, B1, A2, and A1FI emission scenarios) of the 21st century climate.

Unlike precipitation, the annual mean air temperature, which is shown in Figure 39, has a clear warming trend toward the end of the 21st century when compared against the historical period. The change in annual mean air temperature is about 3.0 ℃ at the end of the 21st century over Cache Creek watershed. Meanwhile, no significant trend was found in the annual mean solar radiation toward the end of the 21st century, as shown in Figure 40.

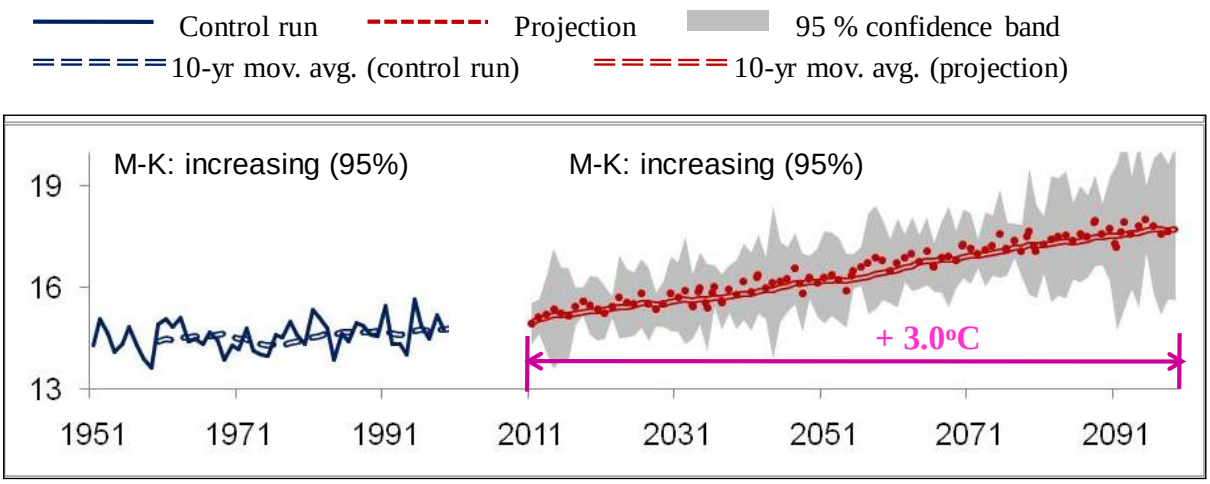

Figure 39- Comparison of historical and MM5-downscaled GCM (ECHAM5 and CCSM3) projections of annual mean air temperature (ensemble average of 13-projection realizations) for Cache Creek Watershed

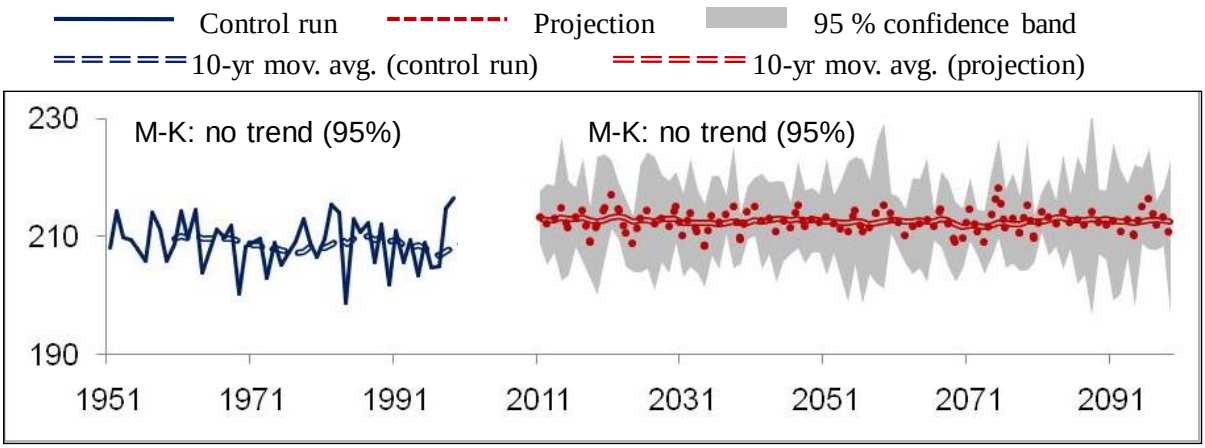

Figure 40- Comparison of historical and MM5-downscaled GCM (ECHAM5 and CCSM3) projections of annual mean solar radiation (ensemble average of 13-projection realizations) for Cache Creek watershed

6. Reconstruction of Historical and Projection of Future Hydrologic Conditions

6.1. Implementation of WEHY Model

6.1.1 Delineation of stream reaches and model computational units

The Watershed Environment Hydrology (WEHY) model (Chen et al, 2004a,b; Kavvas et al, 2004; Kavvas et al, 2006), utilizes the upscaled hydrologic conservation equations to account for the effect of heterogeneity within natural watersheds such as the Cache Creek watershed. First, the watershed is subdivided into model computational units (MCUs). These MCUs are either individual hillslopes or first-order-subwatersheds, and account for the surface and subsurface hillslope hydrologic processes.

The Cache Creek watershed was delineated into 43 stream reaches (see Figure 41) and 86 hillslopes (MCUs) (see Figure 42) by means of geographic information system (GIS) analysis of 30-m resolution U.S. Geological Survey Digital Elevation Model. In Figure 42, besides the 86 hillslopes (MCUs), 43 subbasins are shown, within each of which two hillslopes (MCUs) are separated by a channel reach. The overland flow and subsurface stormflow from two neighboring hillslopes carry flows uniformly into a channel reach. These flows are computed for each hillslope MCU. The 43 stream reaches form the channel network. Once the hillslope flow is generated for MCUs, hourly hillslope flows are fed to the channel network as lateral input, and routed further to the basin outlet.

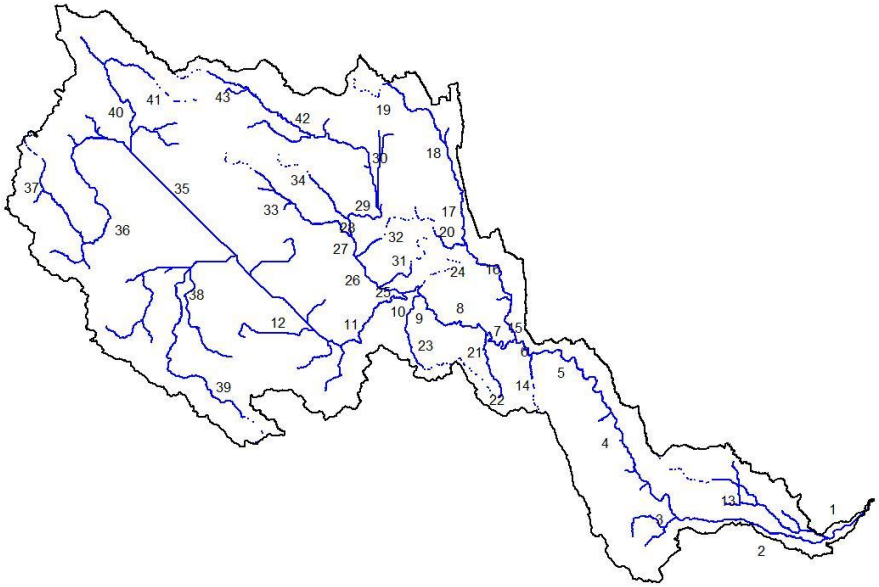

Figure 41- Delineated 43 stream reaches in the WEHY model for the Cache Creek watershed

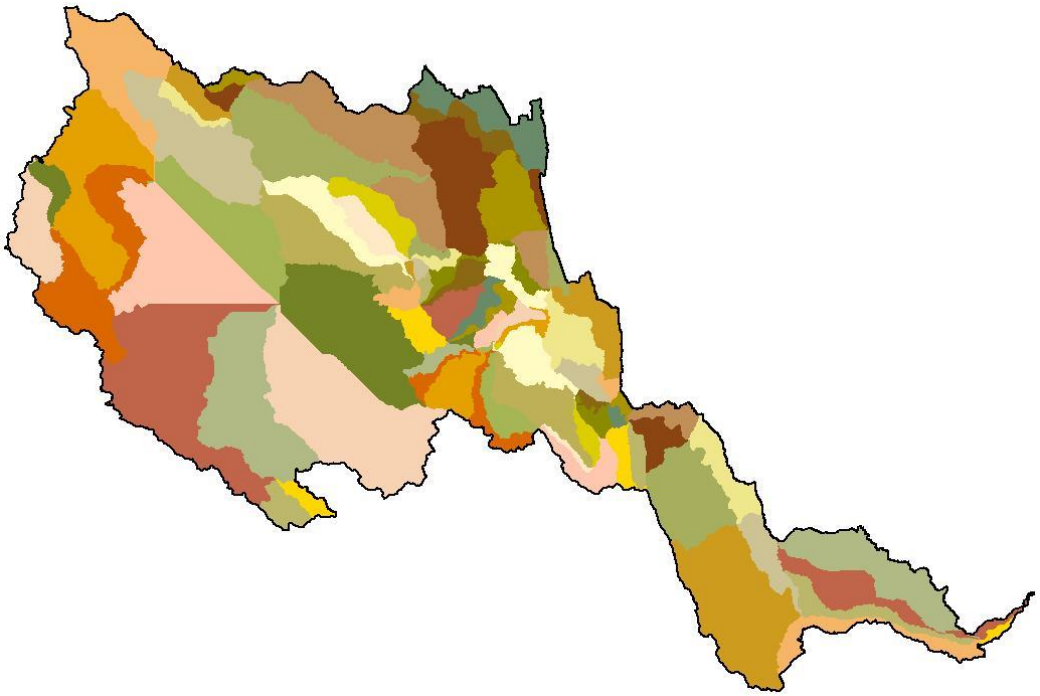

Figure 42- Delineated 86 model computational units (MCUs) in the WEHY model for the Cache Creek watershed

6.1.2 Estimation of WEHY model parameters

WEHY model is a physically based hydrologic model requiring physical parameters including geomorphologic parameters, soil hydraulic parameters, and land surface parameters. Geomorphologic parameters for the delineated stream reaches and MCUs in the WEHY model for the Cache Creek watershed were estimated from the prepared GIS database. These geomorphologic parameters such as surface slope, aspect, flow direction, and elevation, define the flow domains and the configurations of rills and interrill areas for MCUs of the WEHY model for the Cache Creek watershed.

The WEHY model also requires the land surface parameters (leaf area index, roughness height, albedo, emissivity and vegetation root depth) and soil hydraulic parameters (saturated hydraulic conductivity, soil depth, soil porosity and bubbling pressure) with a time and spatial variability in order to account for the heterogeneity within the watershed.

Land surface parameters were estimated using the multi-source land cover data from California Wildlife Habitat Relationships (CWHR) and reference information from Asner et al. (2003), Scurlock et al. (2001) and Canadell et al. (1996). Monthly mean Leaf Area Index values were obtained from MODIS satellite driven data (1 km spatial resolution). Soil parameters were estimated using the Soil Survey Geographic (SSURGO) Database (Natural Resources Conservation Service, NRCS) and reference information from Gale and Grigal (1987), Canadell et al. (1996), McCuen et al. (1981) and Yoshitani et al. (2002).

These parameters were acquired and stored in the Cache Creek watershed GIS database. In Figure 43 the estimated leaf area index, as function of the month of the year is shown. Figure 44 shows the land surface parameters, while Figure 45 shows the soil hydraulic parameters obtained from this database.

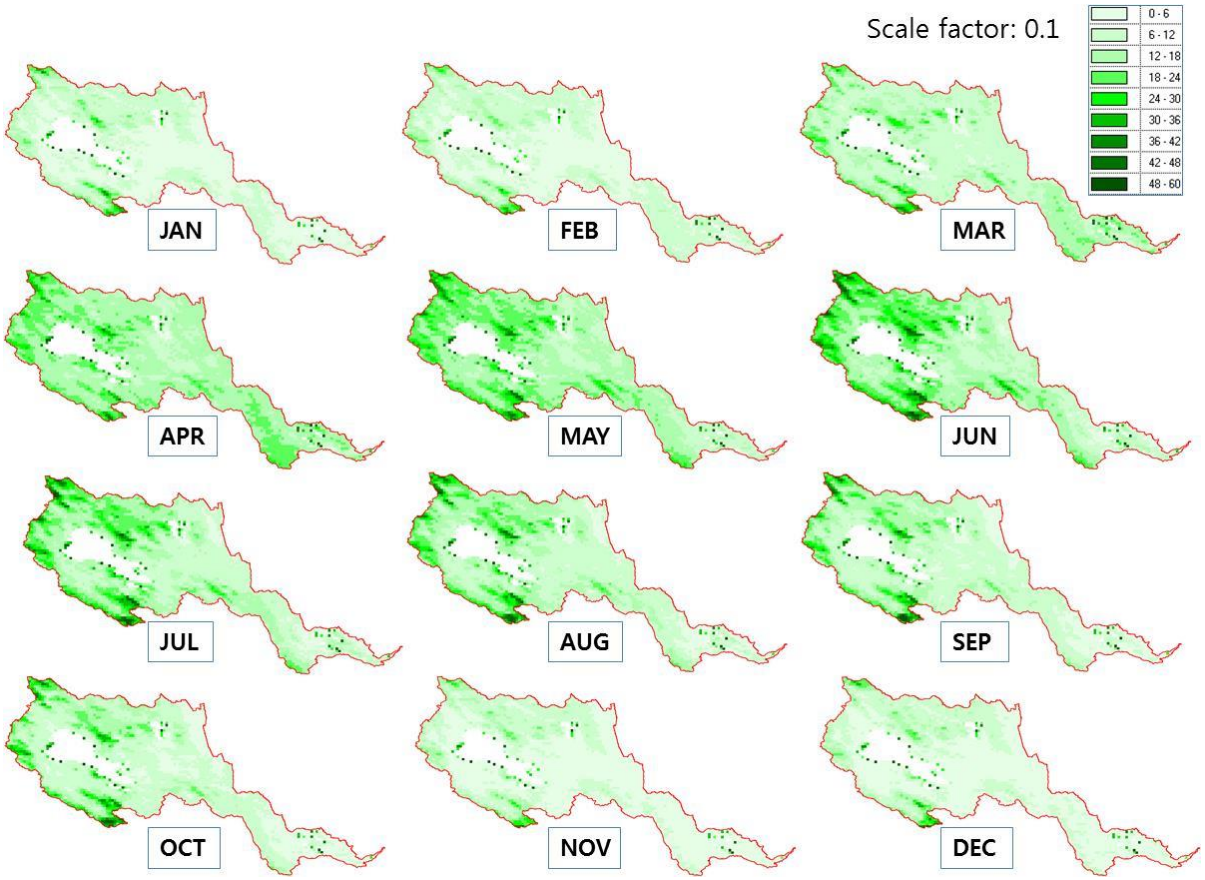

Figure 43- Leaf Area Index (LAI) obtained from MODIS satellite data for the Cache Creek watershed

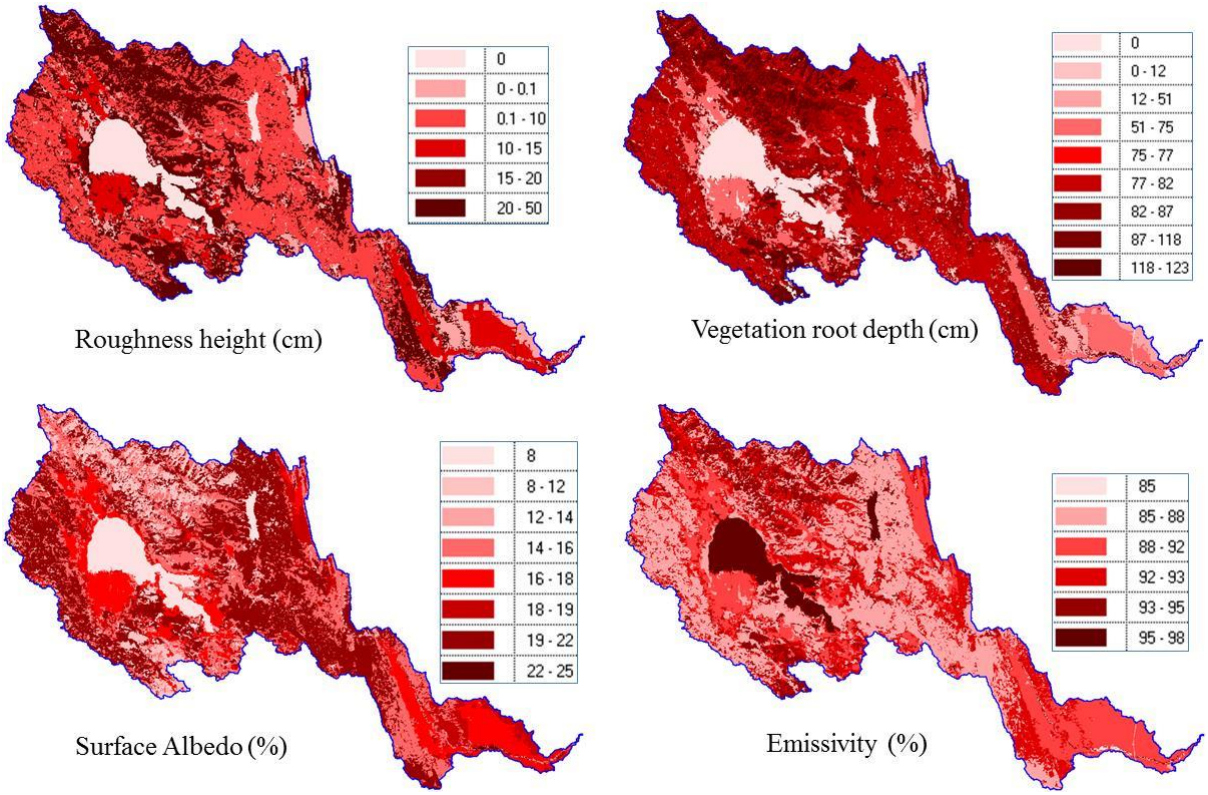

Figure 44- Sample of distributed land surface parameters based on the CalSIL data and reference information for the Cache Creek watershed

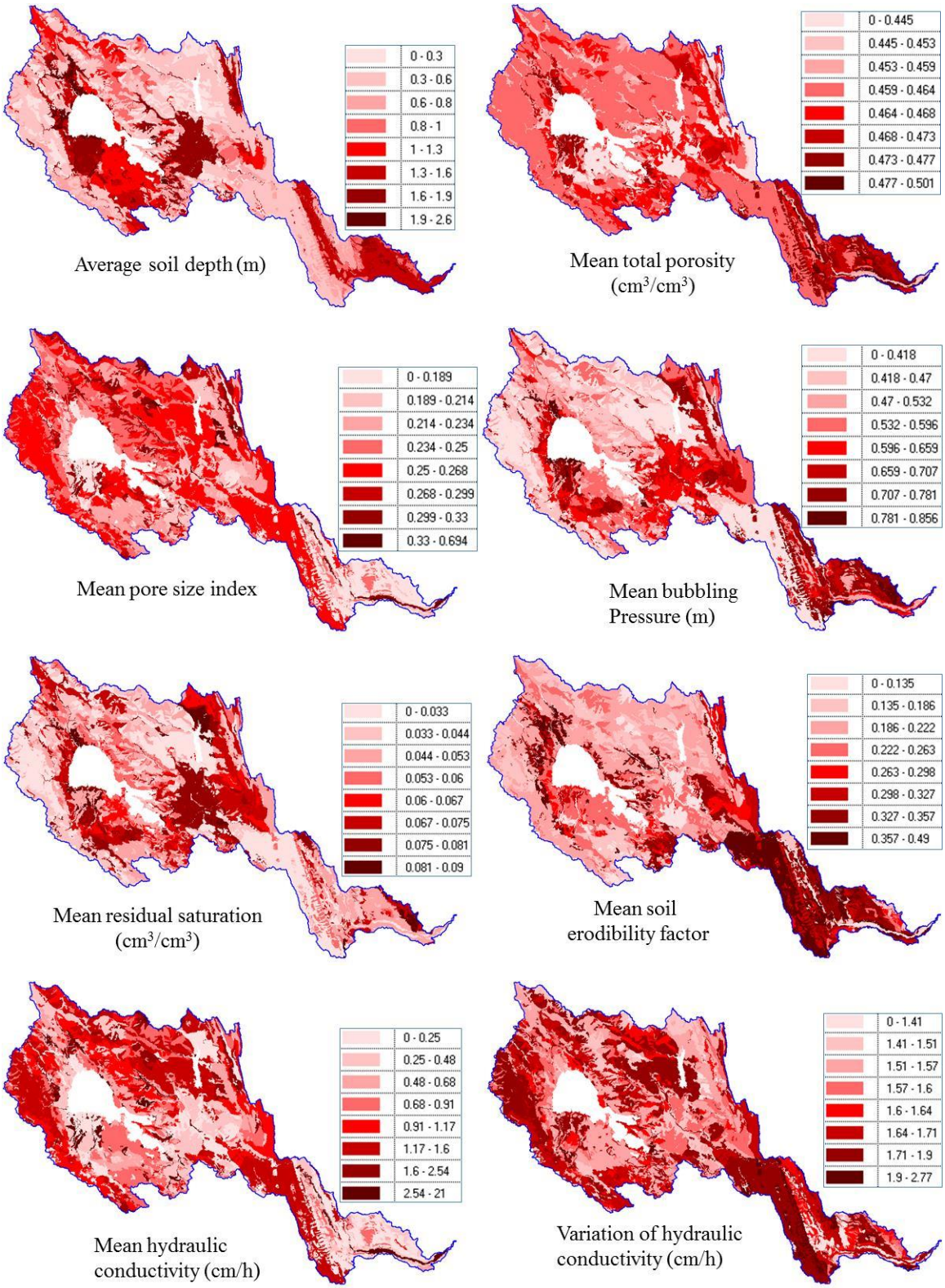

Figure 45- Sample of distributed soil hydraulic parameters based on the SSURGO data and reference information for the Cache Creek watershed

6.1.3 Estimation of historical climate conditions for each model computational unit (MCU) in WEHY model

The reconstructed historical climate conditions at each MM5 simulation grid point cannot be connected directly to WEHY model because an MCU's geometry does not coincide with the shape of the rectangular MM5's grids. In order to account for the effect of topography on the hydrologic processes, it is necessary to quantify the atmospheric inputs such as precipitation, air temperature, solar radiation and wind speed at each of the MCUs within the modeled watershed.

Figure 46 shows sample plots of 61-year average monthly precipitation, monthly mean air temperature, wind speed and shortwave solar radiation from the NCAR/NCEP reanalysis data for each MCU for January and July during 1950 – 2011. Figure 47 and Figure 48 show the sample plots of GCMs (CCSM3 and ECHAM5)-based averaged monthly precipitation, monthly mean air temperature, wind speed and shortwave solar radiation at each model computational unit (MCU) for January and July during 1950 – 2000 over Cache Creek watershed. The reconstructed historical climate conditions at each model computational unit are used directly as input atmospheric data set for the WEHY model.

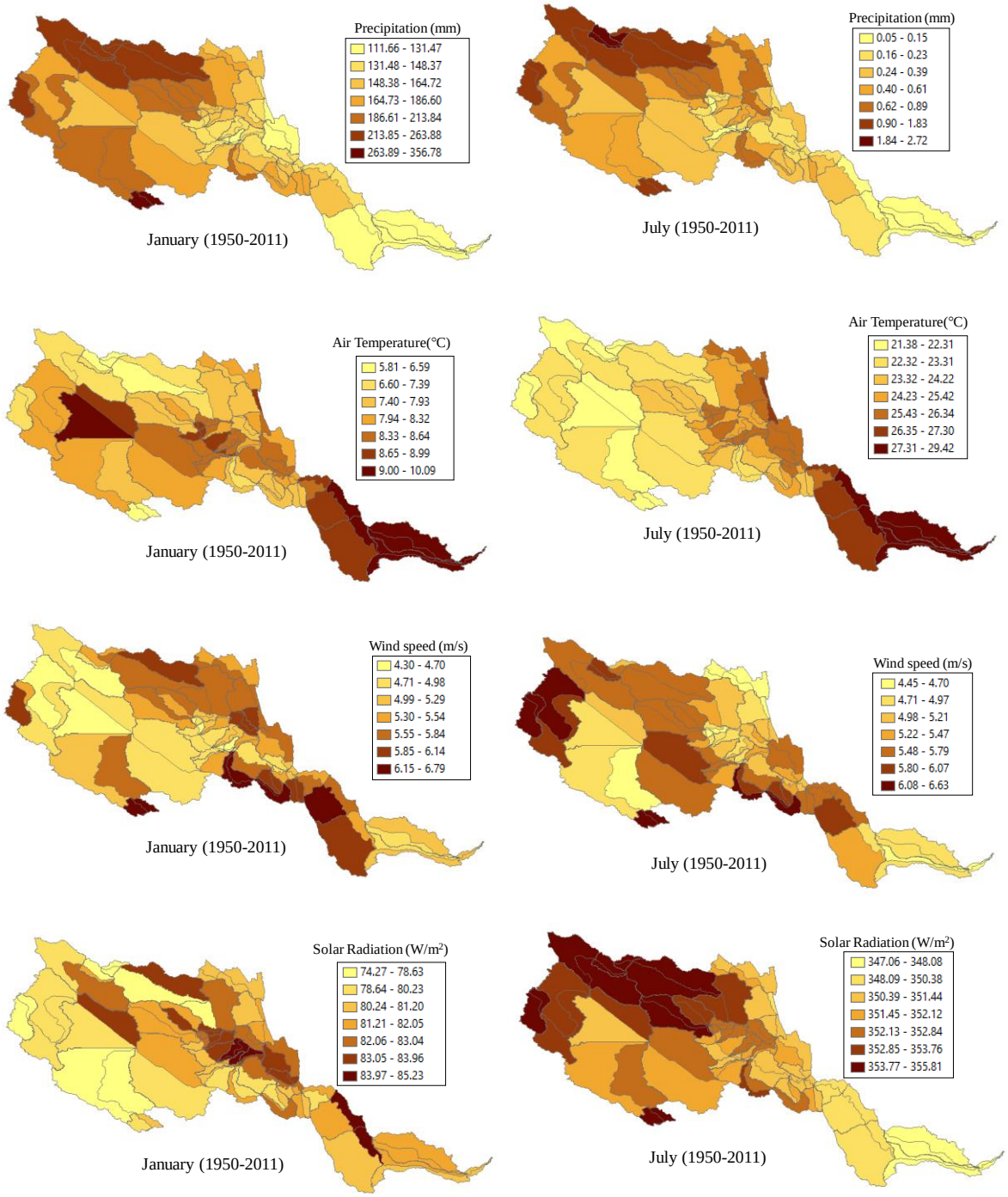

Figure 46- Sample plots of NCAR/NCEP reanalysis data-based 61-year average monthly precipitation, monthly mean air temperature, wind speed and shortwave solar radiation at each model computational unit (MCU) for January and July during 1950 – 2011 over Cache Creek watershed.

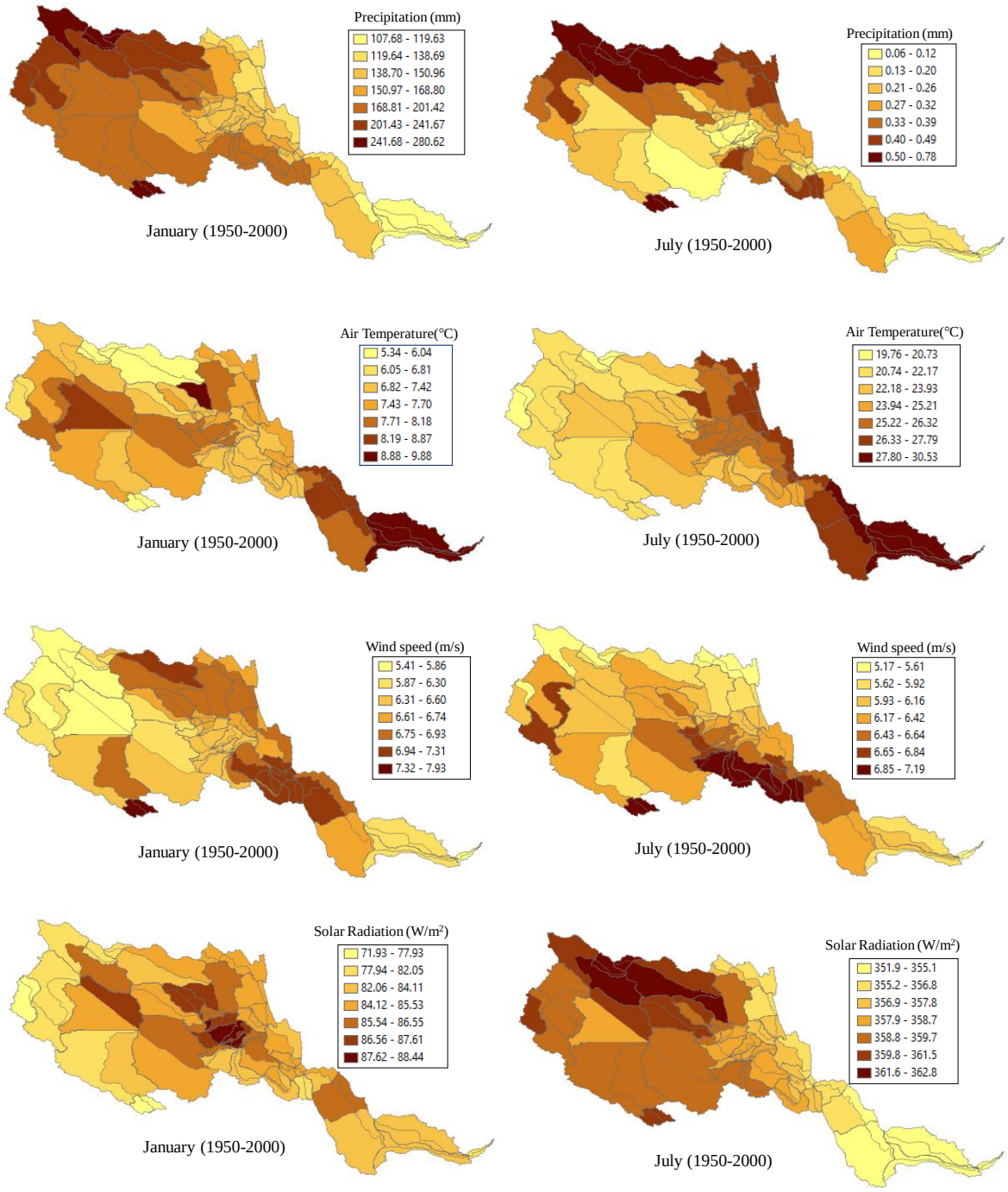

Figure 47- Sample plots of CCSM3 GCM-based 61-year average monthly precipitation, monthly mean air temperature, wind speed and shortwave solar radiation at each model computational unit (MCU) for January and July during 1950 – 2000 over Cache Creek watershed.

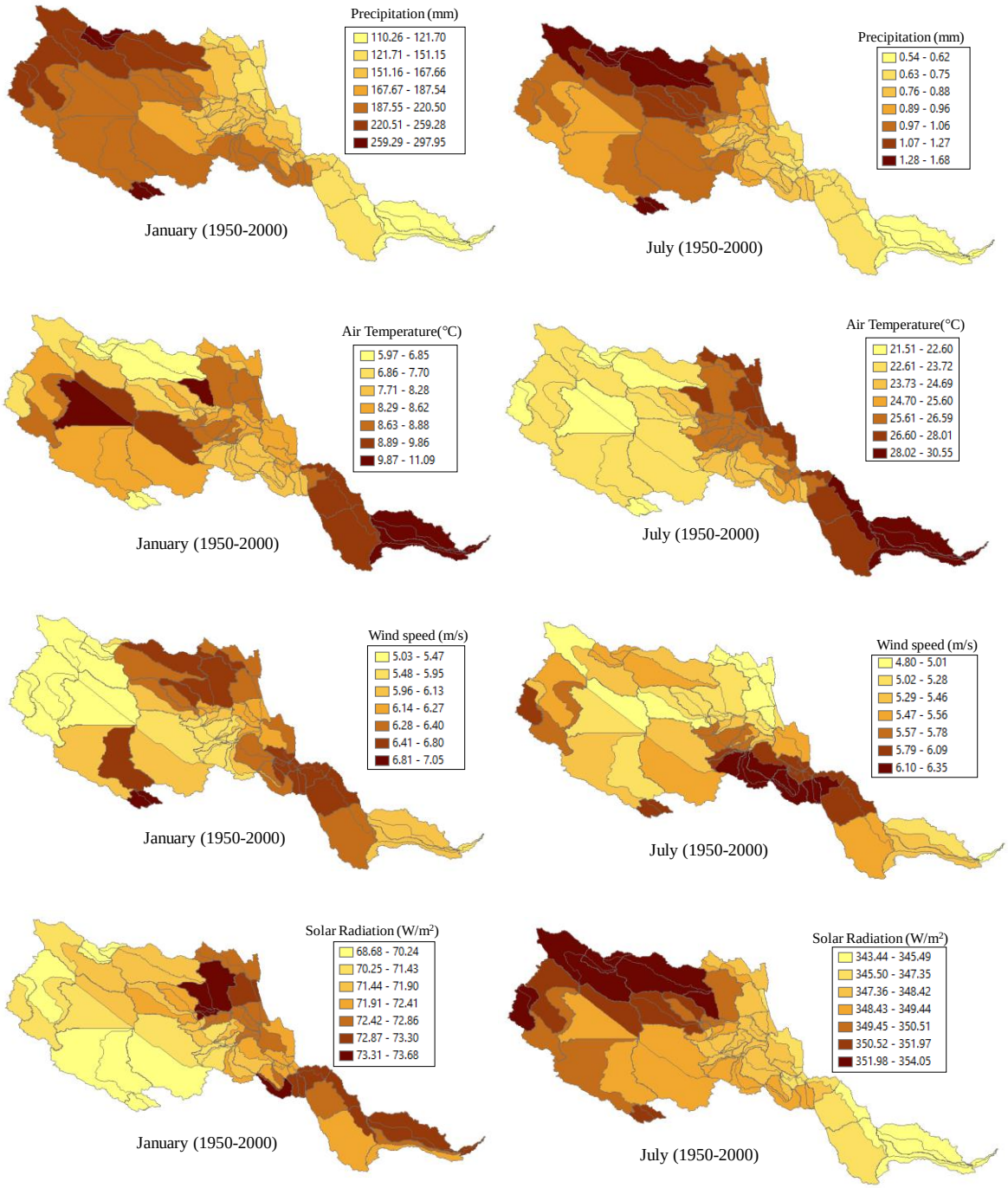

Figure 48- Sample plots of ECHAM5 GCM-based 61-year average monthly precipitation, monthly mean air temperature, wind speed and shortwave solar radiation at each model computational unit (MCU) for January and July during 1950 – 2000 over Cache Creek watershed.

6.2. Calibration and Validation of WEHY Model for Streamflow Simulations

Using the estimated WEHY model parameters and the implemented climate conditions for each model computational unit, the hydrology component of the Watershed Environmental Hydrology (WEHY) model performed hydrologic simulations for the Cache Creek watershed. Two flow observation stations (Yolo USGS and Rumsey CDEC stations in Figure 49) were used for model calibration (2 years: wy1998 – wy1999) and validation (18 years: wy1993 – wy2010). For model calibration purposes, the NCAR/NCEP reanalysis data-based MM5 historical climate simulation results were used as the input atmospheric data for WEHY model. As can be seen in Figure 49, the two reservoirs (Clear Lake and Indian Valley reservoir) located upstream of Cache Creek watershed, play an important role for both flood control and water conservation. The Capay diversion dam, located downstream of Cache Creek, is also important, diverting irrigation water through two canals (West Adams canal and Winters canal). The operation rules for these hydraulic structures are crucial to simulate the historical flow conditions by WEHY model. The operation rules for Clear Lake were obtained from the documentation of the Solano and Gopcevic Decrees (Superior Court of the State of California, 1978) and from public documents of Lake County, and were incorporated into WEHY model. However, the information on the operation rules for Capay diversion dam and Indian Valley reservoir is very limited. As such, the operation rules for Capay diversion dam and for Indian Valley reservoir were developed for the WEHY model based on the comparison of model simulations with historical observations and on the limited available information.

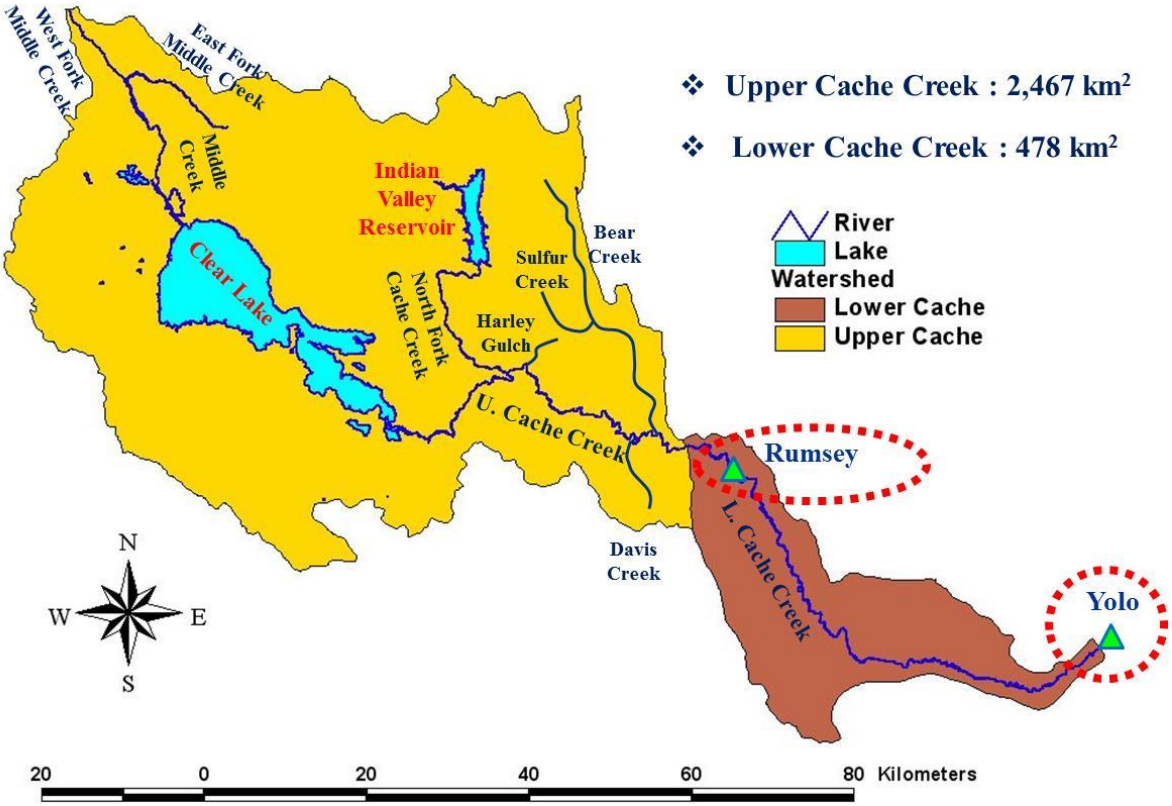

Figure 49- Location of observation stations for model calibration and validation

Using the estimated model parameters and the implemented climate conditions for each model computational unit, the WEHY model simulated the hydrologic conditions in the Cache Creek watershed. As stated earlier, the information on the operation rules for Clear Lake, Indian Valley Reservoir and Capay diversion dam is very limited. Hence, the observed outflow from two dams (Clear Lake and Indian Valley Reservoir) were first used in order to test the WEHY model performance instead of using the simulated outflow from the two dams.

Figure 50 shows the model calibration results (October 1997 -September 1999: 2 years) at Yolo USGS station and Rumsey CDEC station. This figure compares graphically the observed and simulated hourly discharge values at the two flow gauging stations. As can be seen in Figure 50, the model-simulated hydrographs match the corresponding observations at both Rumsey CDEC station and Yolo USGS station. The rising and the recession segments of the simulated hydrographs are very similar to the corresponding observations. The timing and magnitude of peak discharges are also very similar in comparisons both at Rumsey and Yolo stations.

Using the same parameter sets, determined through the calibration process, a validation run was performed for years between 1993 and 2010 for the Cache Creek watershed. Figures 51 and 52 show the validation results of monthly (1993 – 2010: 18 years) flow discharge at Rumsey CDEC station and Yolo USGS station. The NCAR/NCEP reanalysis - MM5 simulation-based WEHY streamflow simulations match almost perfectly the corresponding observations. However, it is important to note that in these model simulations the observed outflows from Clear Lake and Indian Valley Reservoir were used.

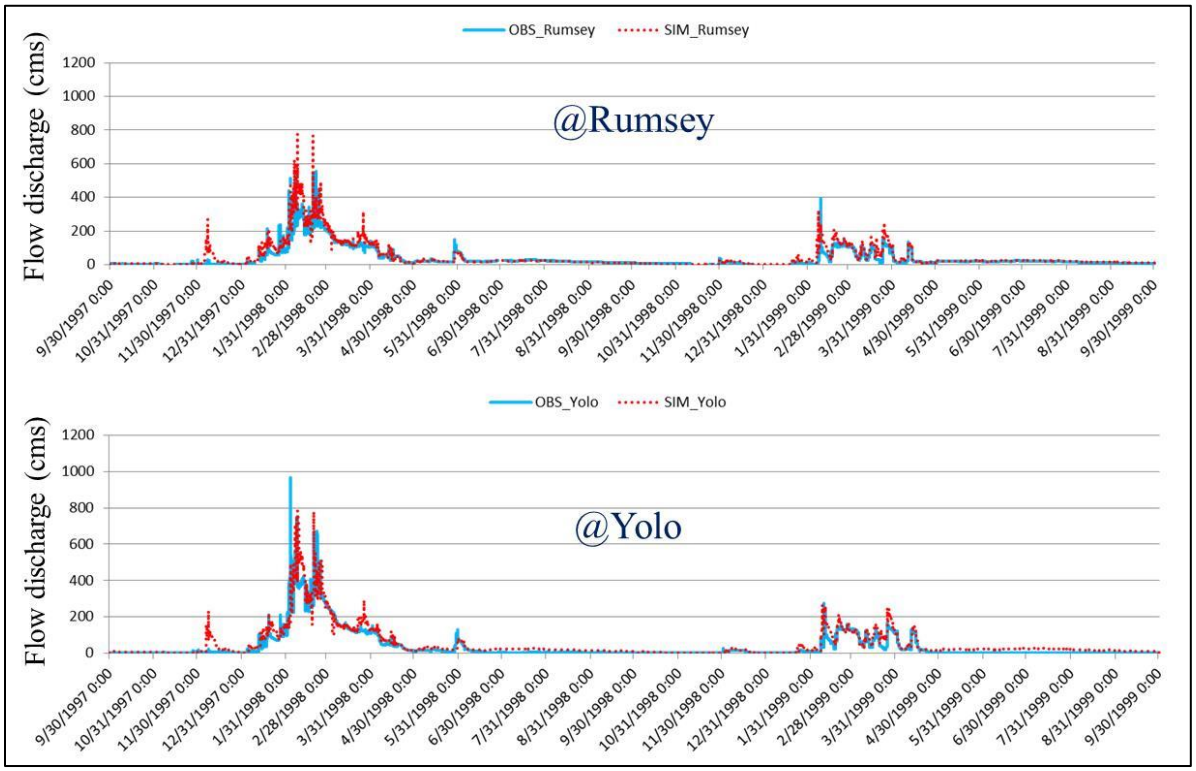

Figure 50- Calibration results for hourly flow discharge at Rumsey CDEC station and Yolo USGS station during 10/1997-9/1999

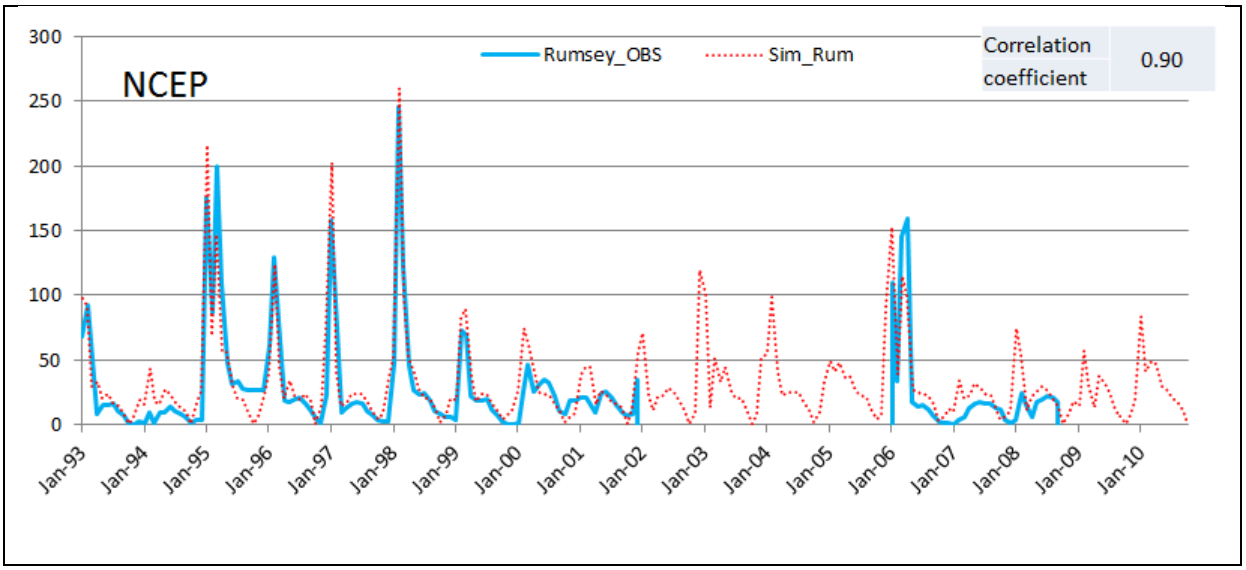

Figure 51- Validation results for monthly flow discharge at Rumsey CDEC station during 1993 – 2010 (cms)

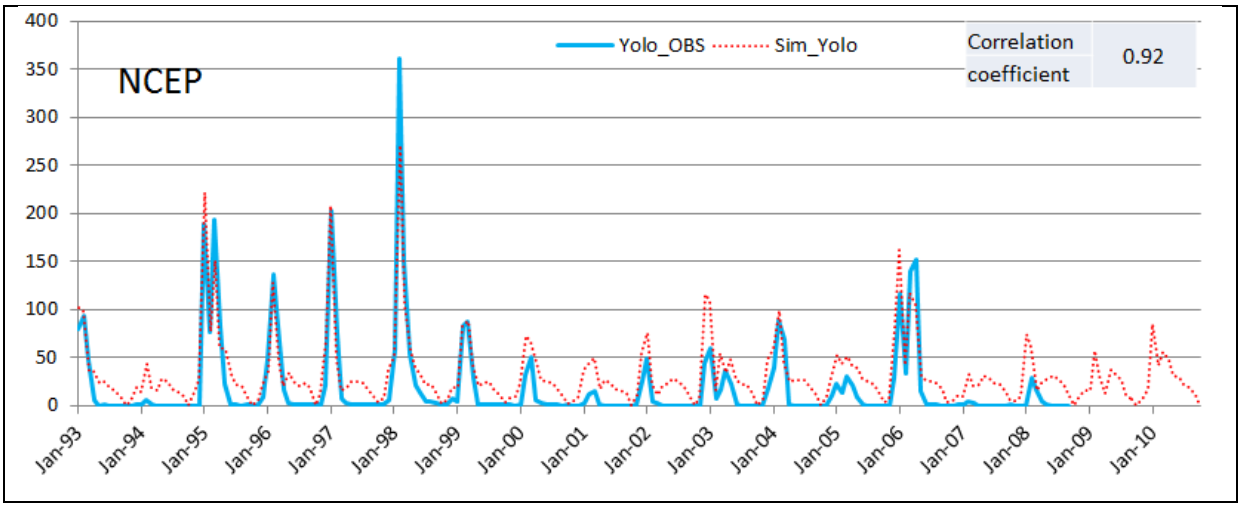

Figure 52- Validation results for monthly flow discharge at Yolo USGS station during 1993 – 2010 (cms)

Although the flow simulation results by WEHY model were calibrated and validated satisfactorily, the operation rules for the existing reservoirs should be incorporated into the model in order to reconstruct the historical flows and to project the future flows for the Cache Creek watershed reliably. The operation rules for Clear Lake and Indian Valley Reservoir were incorporated to WEHY model based on the given information and historical records and on some

preliminary model simulations. Additionally, the operation rule for Capay diversion dam was derived based on the historical records.

Figures 53 and 54 show the comparison results at Rumsey flow station and at Yolo flow station between observed flows and the corresponding model-simulated flows after applying the operation rules for Clear Lake, Indian Valley Reservoir and Capay diversion dam into the model simulations. As shown in these figures, simulated flow after application of operation rules is similar to the WEHY simulation results with observed outflows from Clear Lake and from Indian Valley Reservoir. In other words, inclusion of operation rules into the WEHY model enabled the model to reproduce the historical flow behavior quite well at Rumsey and Yolo flow gauging stations. Consequently, the same operation rules for these reservoirs were used in WEHY model's simulations of the future flows within the Cache Creek watershed.

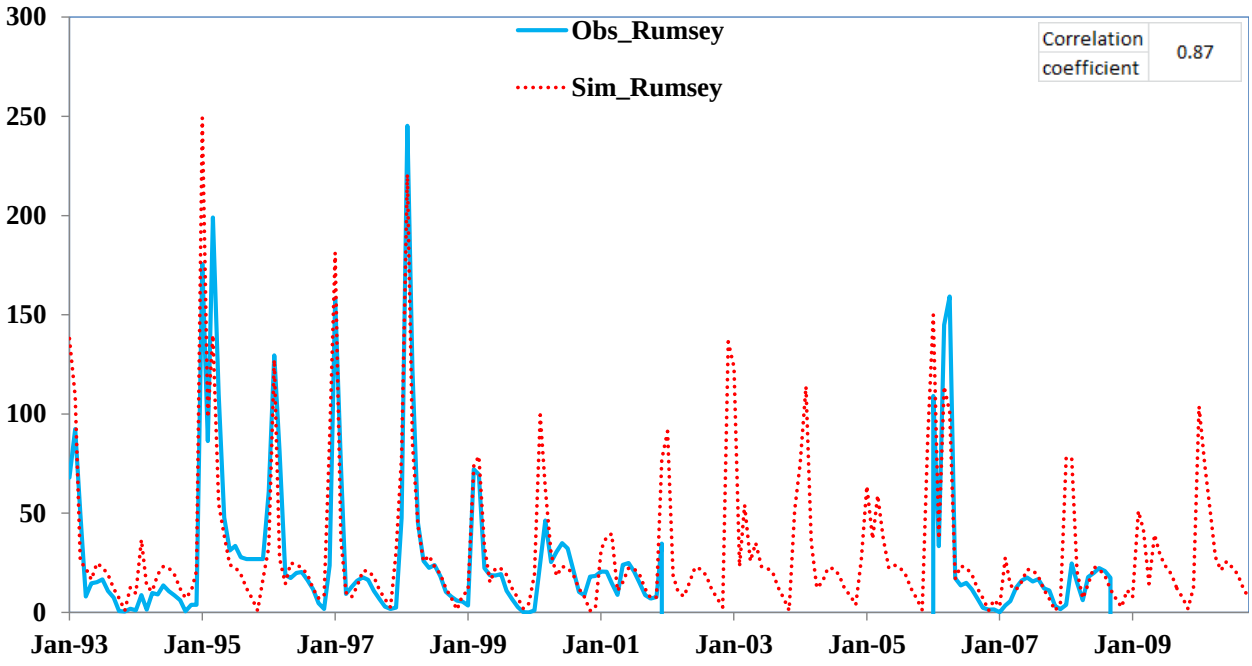

Figure 53- Validation results of monthly flow discharge at Rumsey CDEC station during 1993 – 1999 using the operation rules for Clear Lake and Indian Valley reservoirs (cms)

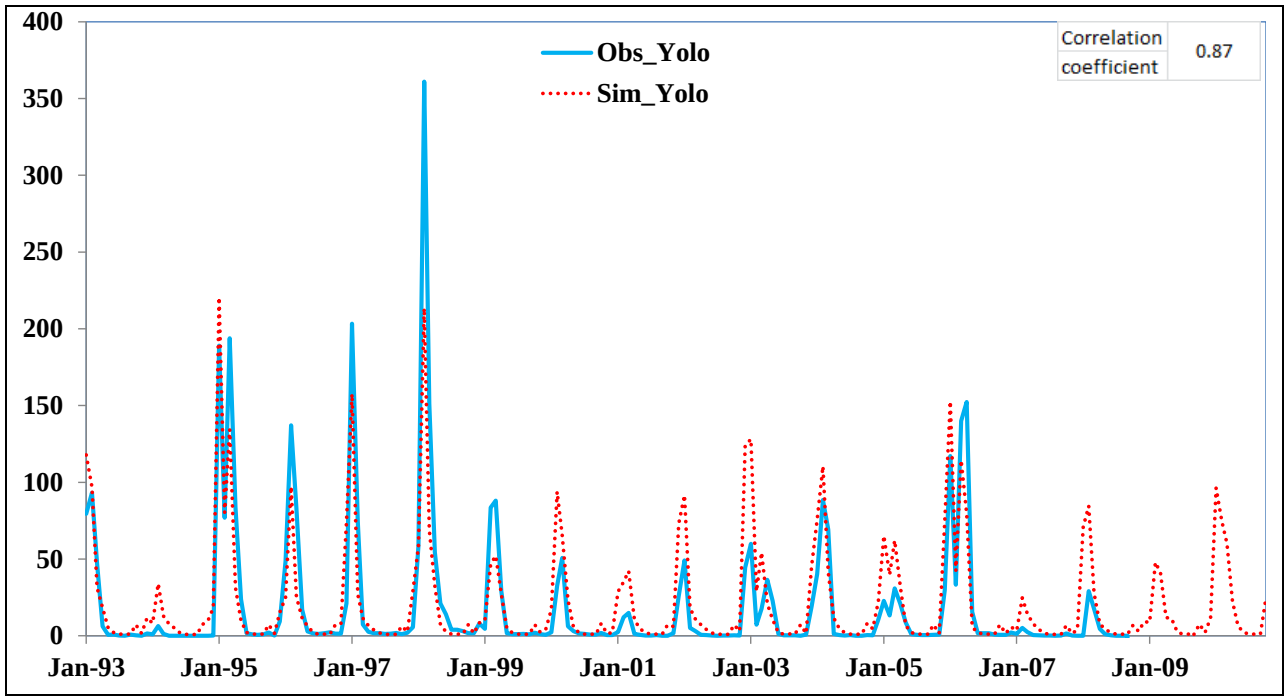

Figure 54- Validation results of monthly flow discharge at Yolo CDEC station during 1993 – 1999 using the operation rules for Clear Lake and Indian Valley reservoirs (cms)

6.3. Reconstruction of historical flow conditions

The historical flow conditions from October, 1950 to September, 2010 were reconstructed based on the NCAR/NCEP reanalysis data and the calibrated and validated WEHY model. The operation rules for Clear Lake, Indian Valley Reservoir and Capay diversion dam were incorporated in this reconstruction. Figures 55 and 56 show the reconstructed monthly mean flow discharge at Rumsey CDEC station and Yolo USGS station, respectively, from October 1950 to September 2010.

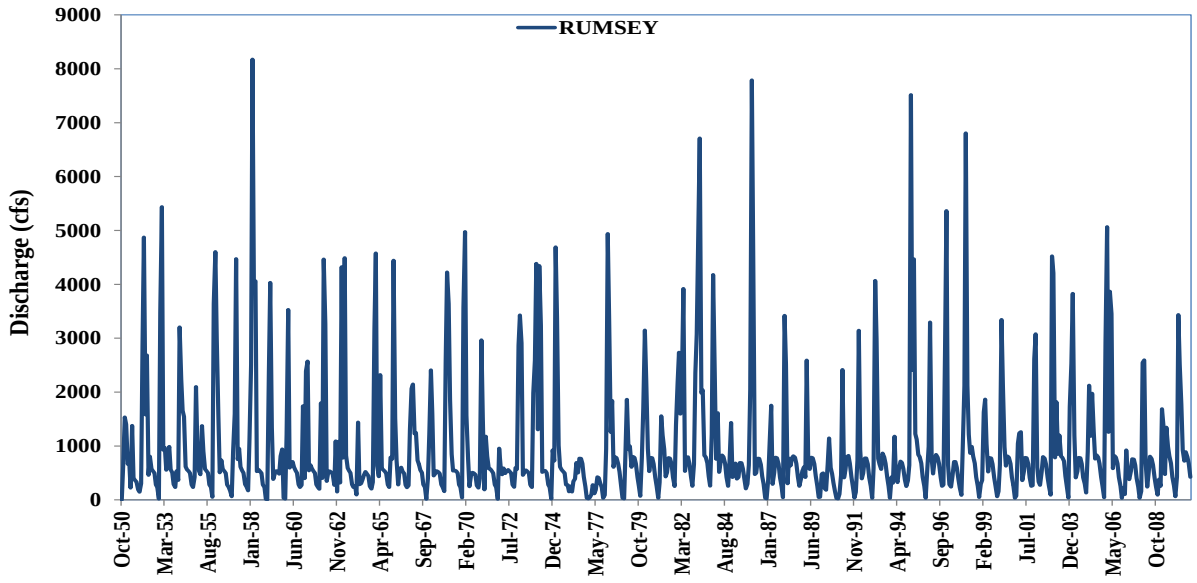

Figure 55- Reconstructed monthly mean discharge based on the NCAR/NCEP reanalysis data from October, 1950 to September, 2010 at Rumsey CDEC station

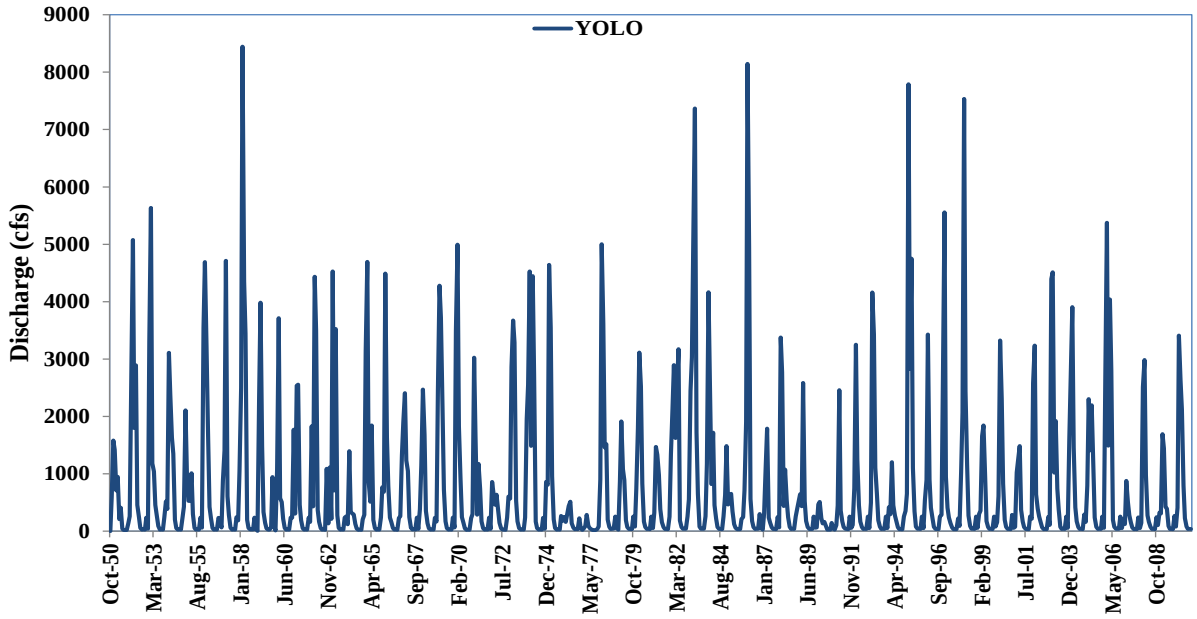

Figure 56- Reconstructed monthly mean discharge based on the NCAR/NCEP reanalysis data from October, 1950 to September, 2010 at Yolo USGS station

6.4. Future Flow Simulation and Flood Frequency Analysis

The calibrated and validated WEHY model hydrologic module projected the future flows throughout the 21st century by using as its input the projected future climate conditions that were previously described.

WEHY simulations produced thirteen individual hourly flow time series for water years 2010 through 2099, which are shown in Figure 57. These hydrographs were computed at the Yolo USGS station before Cache Creek enters the Yolo settling basin. Streamflows are presented in cubic meters per second (m^3/s) and will be referred to as cms. These results form an ensemble of possible future flows under a broad range of climate change scenarios.

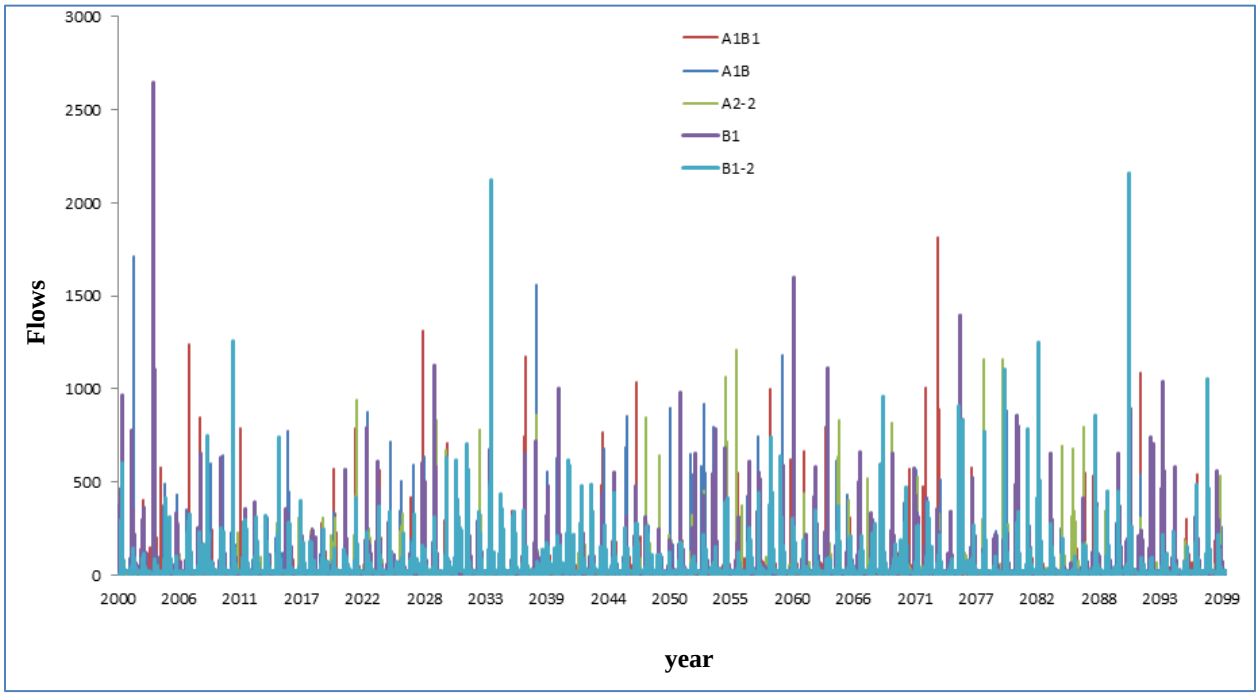

Figure 57- Projected Hourly Flow Hydrographs at Yolo gauging station based on SRES Scenarios

System trends throughout time may not be discernable from the time series data. Transforming data into the frequency domain may elucidate behaviors of interest. Given the inescapable uncertainty in studying future events, system behaviors are more meaningful to examine than specific events. Probability of future events of interest has traditionally been estimated through frequency analysis- the fitting of a probability distribution to a series of observations. Such

analysis allows for predictions beyond the range of observed data and provides summary statistics. While useful and routinely employed, this method is not without its limitations. The fitted distribution is reflective of historical observations, and the short streamflow records that are available may be insufficient to describe the system. Fitting a distribution also assumes that the underlying distribution is not changing in time, and that the system is stationary with past events representing future events. Climate change challenges this assumption of stationarity.

Performing frequency analysis of future simulated streamflows using the modeling chain described above addresses the above limitations of data scarcity and the assumption of stationarity. Comparing analyses of the first-half and second-half of the 21st century, enables the study of how the flood regime may be changing in time. Frequency analysis is performed on annual maximum flow. This dataset is shown in Figure 58. Summary statistics for the projected annual maximum flows during the 21st century at Yolo gauging station are given in Table 6 below. These series of annual maxima (for all realizations) were then divided into two time windows of 45 years: 2010-2054, and 2055-2099. These annual maxima are assumed to be independent but with different identical distributions within 2010-2054 and 2055-2099 time windows of the 21st century. Under this assumption of local stationary within each of these 45-year time windows, from the simulated annual maximum flows of Figure 58, one distinct frequency histogram for each of the two time windows within 21st century were estimated. The computed histograms which show the number of annual maximum flow occurrences as function of flow discharge, are shown in Figure 59 for the two time windows during 21st century. Histograms are useful for visualizing the distribution of flow magnitudes, predicted number of occurrences and relative occurrence likelihood. Meanwhile, the probabilistic behavior of the projected annual maximum flows during the 21st century at Yolo gauging station is shown in Figure 60 by means of their relative frequency histograms as they evolve by climate change during the two consecutive time windows of the 21st century. Since the annual maximum flood return period is a fundamental decision variable in the planning and management of hydraulic structures, the annual maximum flows as function of return period were also computed from the projected flows during the 21st century at Yolo gauging station. As shown in Figure 61, the annual maximum flow as a function of return period varies not only with the return period but

also as a function of the time window within 21st century, reflecting the effect of changing climate on the extreme flows at Cache Creek watershed.

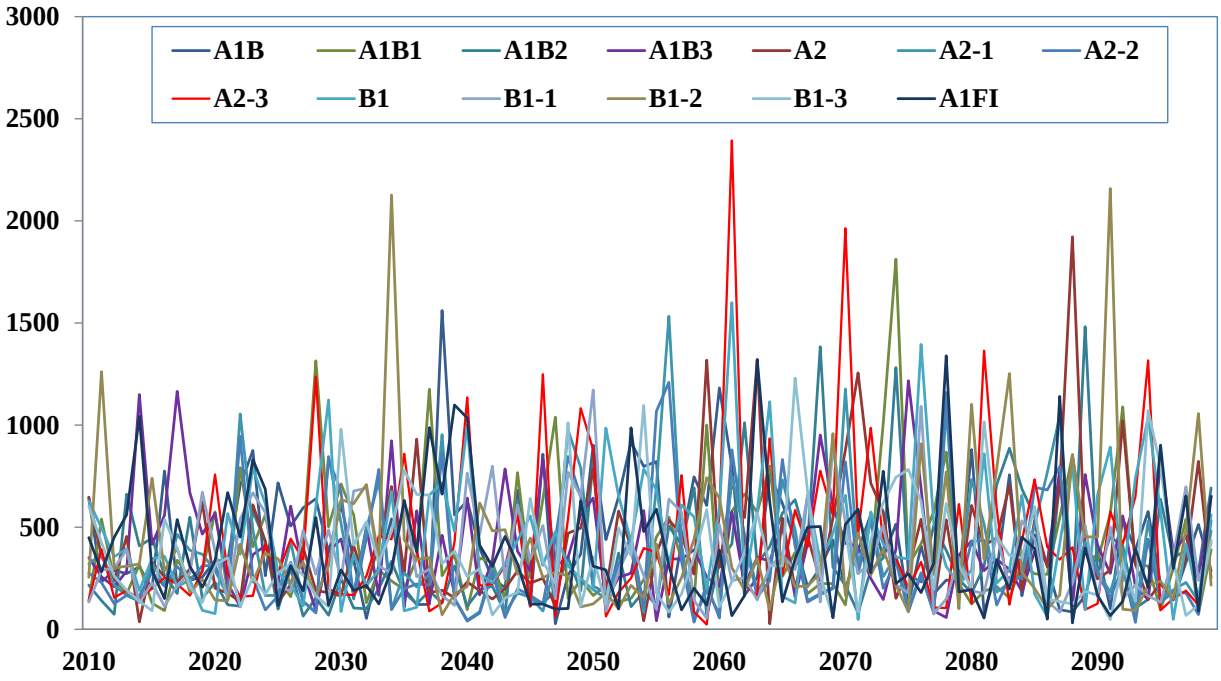

Figure 58-Annual maximum model-simulated streamflows during 21st century at Yolo gauging station

Table 6. Summary statistics for model-projected annual maximum flows during the two time periods of the 21st century at Yolo gauging station

Time Period	Mean (cms)	Maximum (cms)	Variance	Skewness
2010-2054	377.51	2126.3	79766.11	1.87
2055-2099	435.16	2394	113908.5	1.80

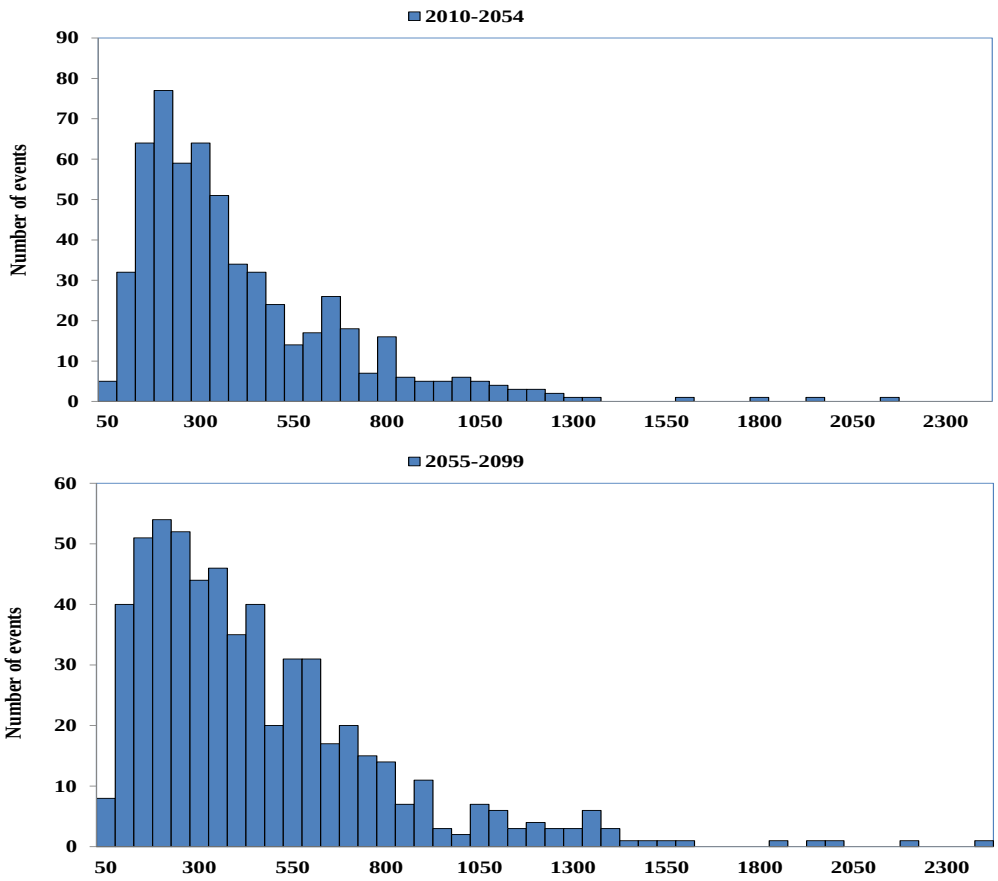

Figure 59- Histograms of annual maximum flows separated into 45-year increments (2010-2054, and 2055-2099) for all flow projections during 21st century at Yolo station

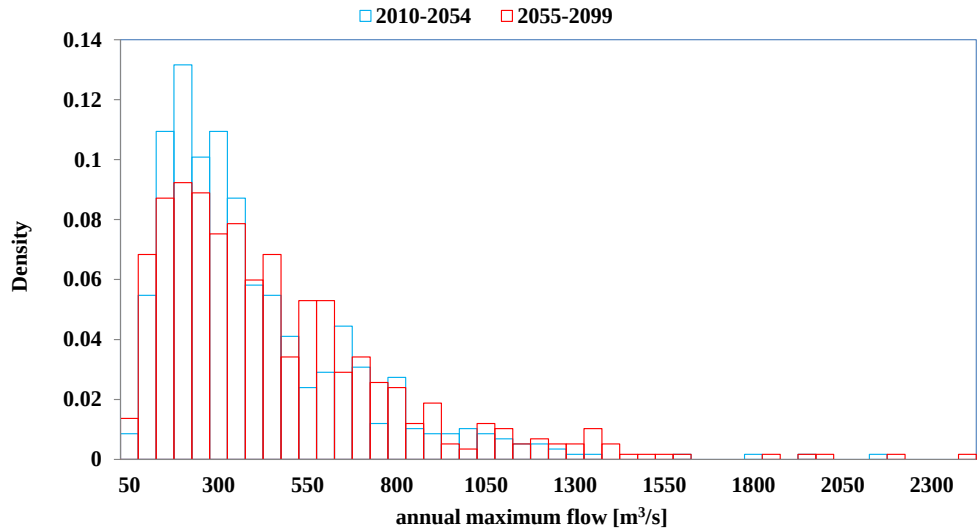

Figure 60- Relative frequency histogram of annual maximum flows separated into 45-year increments (2010-2054, and 2055-2099) for all flow projections during 21st century at Yolo gauging station

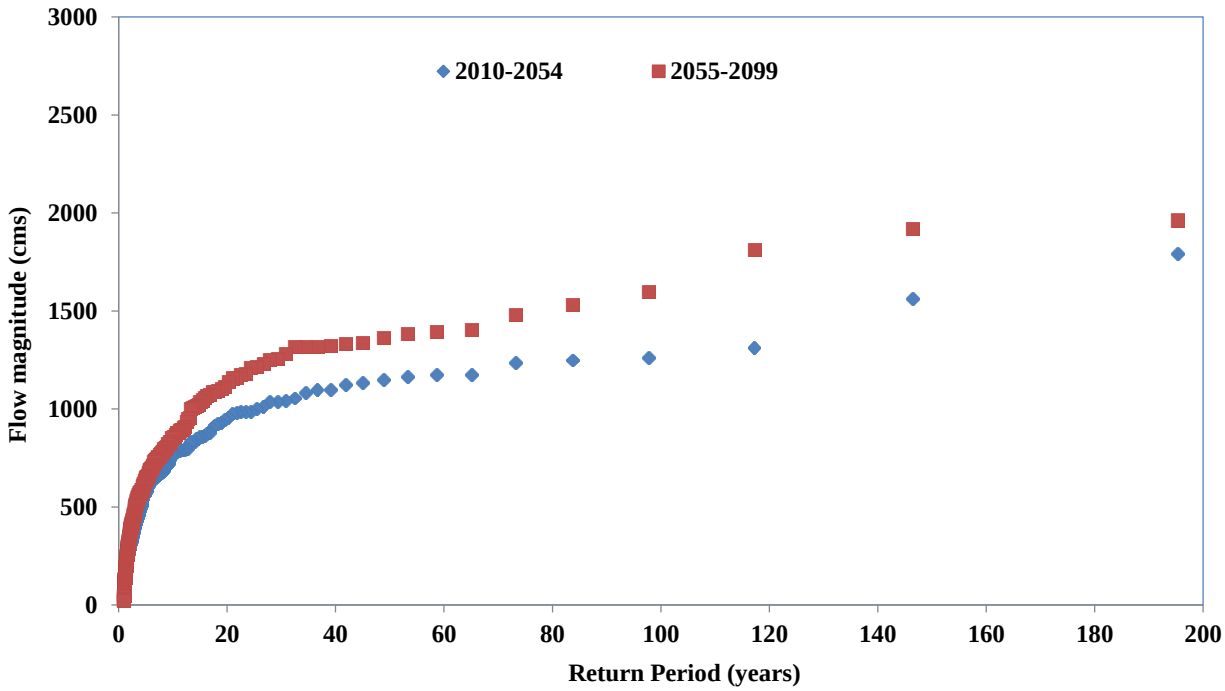

Figure 61-Evolution of the annual maximum flow as function of return period throughout the 21st century for all flow projections at Yolo gauging station

Figures 60 and 61 show the evolution of the flood regime as the magnitudes of simulated extreme events grow throughout the 21st century. This evolution is noticeable for flood events exceeding the channel capacity of 850 cms (~30,000 cfs). The most extreme event during 2010 through 2054 is 2,126.3 cms (75,089cfs), increasing to 2,394 cfs (84,543 cfs) during 2055 through 2099.

Table 7. Annual maximum flow discharge (cms) as function of return period during the two selected time periods in 21st century

Return Period	2010-2054	2055-2099
200 years	1797.5 cms	1973.3 cms
100 years	1267.5 cms	1625.1 cms

Return period flows were linearly interpolated from calculated exceedance probabilities. No extrapolation of relative frequencies (a fundamental step of standard frequency analysis) was necessary in this study, given the extensive dataset of model-simulated flows. Return periods were calculated using the Weibull plotting position. Referring to Table 7, comparing 2010-2054 and 2055-2099, the 100-year flood discharge magnitude grows 28% and the 200-year flood discharge magnitude grows 9.7 %.

While the methodology used in this study is computationally intensive, this new physically-based framework for computing the flood frequencies does not rely on the assumption of stationarity. These results support the discussion on the intensification of the water cycle under climate change and the hypothesis of floods growing in magnitude (Huntington 2006, Hirabayashi et al. 2008, Milly et al. 2008). Evolution of the return period flood flows and other descriptive statistics suggests that traditional flood frequency analysis and the assumption of stationarity may no longer be the best way to study and describe the future extreme flow events.

The simulated annual maximum flows underscores the importance of concurrent flow and sediment observations to augment the sediment-rating curve as the calculated 100-year floods for the two selected time periods during the 21st century all exceed 13,000 cfs when the curve becomes sparsely populated. These simulated flows and flood frequency analysis provide input data for the simulations of hydraulics in the Cache Creek Settling basin and would be useful in future water quality studies of the Cache Creek Watershed.

7. Discussion, Conclusions and Recommendations

Due to lack of concurrent flow, sediment and mercury data within the Cache Creek watershed, the sediment and mercury conditions within the Cache Creek watershed are quite uncertain. As a consequence of such lack of concurrent flow and sediment data, the sediment rating curve that is necessary for the estimation of sediment inflows into the Cache Creek Settling Basin (CCSB) has substantial uncertainty for flows above 13,000 cfs. One way to fill the gap in the sediment rating curve and to gain a better understanding of sediment and mercury conditions within the Cache Creek watershed is to develop a comprehensive field sampling program for collecting concurrent flow, sediment and mercury data at various locations within the watershed, as proposed in Figure 20 of this report. However, such a field sampling program is cost prohibitive. A financially feasible field program can focus on one or two key flow gauging station locations, such as Rumsey station and/or Yolo station, within the watershed in order to collect the necessary concurrent flow, sediment and mercury data. However, one may have to wait for a long time for the occurrences of flows that exceed 13,000cfs in order to develop a sufficiently large sample of concurrent flow and sediment discharges in order to be able to fill the gap in the sediment rating curve for flows above 13,000cfs. An alternative approach to filling the gap in the sediment rating curve is to combine computer modeling of flow-sediment-mercury with a field sampling program where the field collected concurrent flow-sediment-mercury data, at least at one gauging station, such as Rumsey, can then be utilized for the calibration and validation of a watershed environmental hydrology model, such as the WEHY model. Once calibrated and validated by the field data, the WEHY model can then be utilized to reconstruct the historical concurrent flow and sediment conditions at the Cache Creek watershed that can then be used to fill the gap in the sediment rating curve for inflows to the CCSB for flows exceeding 13,000cfs. Hence, the main objective of this project was to develop detailed flow, sediment and mercury conditions for Cache Creek and its tributaries for historical and future conditions by coupling the Watershed Environmental Hydrology (WEHY) model with a regional climate model (MM5 in this project) in order to simulate concurrent flow, sediment and mercury information in the Cache Creek watershed both for the historical period as well as for the 21st century. Then such information could be used to fill the gap in the sediment rating curve, and to provide better estimates of sediment and mercury loads to CCSB. Reconstruction of realistic and comprehensive historical and future climate, flow, sediment and mercury conditions would

eliminate the need to install and maintain many flow-sediment-mercury stations and rain gages within the Cache Creek watershed. The simulated flow, sediment and mercury conditions in the Cache Creek watershed could then be used also to investigate opportunities for trapping part of the mercury at upstream locations of the Cache Creek watershed, thereby reducing the mass loading rate of sediment into the Basin.

Once the sediment rating curve is constructed for the full range of flow conditions by means of the WEHY model-estimated concurrent flow-sediment-mercury outflows from the Cache Creek watershed, it could then be utilized to predict the concurrent flow and sediment inflows reliably into CCSB as the upper boundary condition of the CCSB hydrodynamic model. By means of such a reliable inflow boundary condition, the hydrodynamic model of CCSB could then estimate reliably the trap efficiencies for the CCSB during the 21st century under various engineering action scenarios.

Within the above framework, DWR and USGS have initiated a field sampling program, focusing on collecting concurrent flow-sediment-mercury data at the Rumsey station. However, the performance period of this project coincided with a severe drought period in California, and no significant flows were recorded at the Rumsey station during the project period. Under these circumstances the UC Davis JAHL, the contractor for this project, was still able to implement a regional climate model, MM5, over Cache Creek watershed at 3km spatial grid resolution, and was able to reconstruct the historical climate conditions during 1950-2010 at hourly intervals over the whole watershed. This exercise was accomplished by means of dynamically downscaling the coarse-grid-resolution NCAR/NCEP reanalysis historical climate data at about 280km grid resolution to 3km grid resolution over the Cache Creek watershed by means of the MM5 regional climate model. This modeling approach was validated by comparison of historical precipitation, reconstructed by NCAR/NCEP reanalysis data-based MM5 simulations, against PRISM data over the watershed, and by comparing the MM5-simulated historical air temperature and solar radiation against observations at a field station by means of various statistical measures.

Once the historical climate conditions were reconstructed for the 1950-2010 period by the NCAR/NCEP reanalysis data-based MM5 simulations, these climate information were input into the hydrologic module of WEHY model in order to calibrate and validate it with historical flow data in Cache Creek watershed. Since the hydrologic module of WEHY model is fully-physically-based, almost all of its parameters are estimated objectively from the existing land databases. However, few parameters of WEHY model, such as stream widths and roughness coefficients, still need to be estimated by calibration based on available flow data. Also, the operation rules of the main reservoirs in the watershed (Clear Lake, Indian Valley Reservoir and Capay Dam) had to be derived from existing documents and from model simulations. Accordingly, two years of flow data at Rumsey and Yolo stations were used for model calibration. Once the WEHY model hydrologic module was calibrated, it was then run with the reconstructed climate inputs for a separate 8-year period over Cache Creek watershed in order to simulate the flows in space at various locations along the main Cache Creek and along its tributaries at hourly intervals during this period. Then these simulated flows were compared against their observed counterparts at Rumsey and Yolo stations for their validation. These comparisons yielded very satisfactory model performance results with the correlation coefficient of 0.87 even when the unknown operation policies of the existing reservoirs within the watershed had to be determined by the project team. Once the WEHY model's hydrologic module was validated in this way, the calibrated model was then run for the October 1950- September 2010 period with the reconstructed climate data over the watershed as its input, to reconstruct the flows at hourly increments along the Cache Creek main river branch and along its tributaries to obtain the comprehensive information on the flow conditions within the watershed during October 1950- September 2010.

In order to reconstruct the historical sediment and mercury conditions at Cache Creek watershed during October 1950-September 2010 at hourly increments, it was then necessary to calibrate and validate the environmental module of WEHY model (Kavvas et al. 2006) by the concurrent flow-sediment-mercury field sampling data. However, during the project performance period, due to extremely dry conditions at the watershed no such data could be collected. As such, it was not possible to calibrate and validate the environmental module of WEHY model, and, hence, it was not possible to simulate neither the historical nor the future sediment and mercury loads

within Cache Creek watershed or from the watershed to the CCSB. Consequently, due to lack of field data on concurrent flow-sediment-mercury during the project performance period it was not possible to fill the gap in the sediment rating curve for flows above 13,000cfs although there are quite a few WEHY model-simulated flows at Yolo station during 21st century that exceed 13,000cfs, as may be seen from Figure 57. Consequently, the Milestones 7 and 9 of the project could not be accomplished while only the flow part of Milestone 8 could be accomplished.

Under these circumstances, as explained in Section 4.1., the project team resorted to utilizing the Universal Soil Loss Equation (USLE) in order to approximately identify the potential source areas of sediment and mercury in Cache Creek watershed. A map that identifies these potential source areas, in terms of annual soil erosion loads, was developed and is given in Figure 6.

With the calibrated and validated WEHY model hydrologic module for Cache Creek watershed it was also possible to project the future flow conditions over the watershed, based on the dynamically-downscaled ensemble of 13 climate projections from two GCMs (German ECHAM5 and NCAR's CCSM3) by the regional climate model MM5 under a wide spectrum of future greenhouse gas emission scenarios (A1B, A2, B1 and A1FI). However, before embarking onto this exercise, this projection approach was validated by first dynamically-downscaling the historical control run climate simulations of ECHAM5 and CCSM3 GCMs at 3km grid resolution over the Cache Creek watershed, and comparing these simulations against corresponding PRISM data. From these comparisons the model bias due to uncertainty in the GCM control simulations was identified and corrected. Afterwards, the bias-corrected historical precipitation simulations of the model were compared against the corresponding PRISM data with favorable statistical test results, thus validating this modeling approach. Then the validated modeling approach was applied to the downscaling of the ensemble of 13 future climate projections from ECHAM5 and CCSM3 GCMs for the 21st century at 3km grid resolution and hourly time intervals over the Cache Creek watershed. The identified model bias during historical comparisons was then incorporated to the downscaled future climate projections in order to account for this model bias. Then these bias-corrected future climate conditions during the 21st century were input to WEHY model's hydrologic module in order to simulate the detailed flow conditions over Cache Creek watershed at hourly intervals along the main Cache

Creek branch and its tributaries throughout the 21st century. Then based on the 1170 years of flow data from the ensemble of 13 projections during 2010 through 2099, shown in Figure 57, it was then possible to perform a comprehensive flood frequency analysis of the outflows from Cache Creek watershed at Yolo gauging station, and estimate the 100-year and 200-year return period annual maximum flood peak discharges at the Yolo station without resorting to any extrapolation of the frequency curve (such extrapolation is a standard step in the classical frequency analysis). The results of this frequency analysis are summarized in Table 7 and Figures 59, 60 and 61. As may be seen from these figures and Table 7, which are in cubic meters per second (cms) flow discharge units, the flood frequencies evolve during two periods of the 21st century with changing climate. Referring to Table 7, while the 100-year flood peak discharge during the 2010-2054 period is 49 % higher than the channel capacity of 30,000cfs (44,800 cfs), the estimated 100-year flood peak discharge in the later period of the century is 91.2 % higher.

With the reconstructed historical flow conditions and the projected future flow conditions during 21st century along the main branch and tributaries of the Cache Creek by the calibrated and validated WEHY model hydrologic module, a comprehensive picture of the flow conditions in the Cache Creek watershed have been obtained in this project. Accordingly, the Milestones 1, 2, 3, 4, 5 and 6 of the project were accomplished successfully. Once concurrent flow-sediment-mercury field data that cover a range of flow conditions, are obtained at Rumsey station, then such data can be utilized to calibrate and validate the environmental module of WEHY model for Cache Creek watershed. Once the environmental module of WEHY model is calibrated and validated by field data, then it will be possible to achieve the remaining Milestones 7, 8 and 9 of the project to complete the sediment rating curve and to provide the comprehensive historical and future flow-sediment-mercury inflow data to CCSB.

7.1. Recommendations for future actions.

Before simulating sediment load and mercury transport with the simulated flow discharge, it is necessary to calibrate and validate the WEHY-Environmental module over the Cache Creek watershed by means of concurrent flow-sediment-mercury data. However, as mentioned in

Section 4.3., the field data collected in various previous projects and in the current project at Cache Creek watershed are insufficient for utilization in the calibration and validation of WEHY environmental hydrology model, fundamentally due to lack of concurrent flow-sediment-mercury observations. There is an urgent need for a field-monitoring program at several locations, distributed over the watershed.

The desired sampling locations are shown in Figure 20. However, the substantial cost of realizing the desired sampling program is recognized. As such, if it is not possible to perform the monitoring at the 11 desired locations due to cost constraints, it is still absolutely essential to carry out a sampling program for sediment and mercury, simultaneously with the flow observations, at least at the Rumsey station. Accordingly, the following sampling data which should be collected simultaneously with streamflow data, are recommended as essential for the calibration and validation of the environmental hydrology module of WEHY model in order to produce reliable and scientifically defensible simulations of flow, sediment and mercury at the Yolo station in order to be able to reconstruct the portion of the sediment rating curve corresponding to flows above 13000 cfs, and in order to develop reliable flow-sediment-mercury inflow data for CCSB:

- **Instantaneous grab sampling data (suspended sediment, and mercury) concurrently with the flow discharge measurements**
  - At Rumsey station
- **Data on Mercury within the streambed (soil)**
  - At Rumsey station

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