FINAL REPORT
ON
THE WATERSHED MODELING AND EDUCATION PROJECT
FOR
THE LOWER TUSCAN AQUIFER

by

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1. Introduction and Objectives

Percolation of infiltrated water from the watersheds into the groundwater aquifer systems of Northern Sacramento Valley is very important for the water resources in the area. In this project a physically based model was used to estimate the run-off from the Big Chico Creek, Little Chico Creek, Butte Creek and Deer Creek watersheds into the groundwater aquifer system of Butte County, which is proposed for increased pumping in order to substitute for surface water supplied to the Sacramento Valley Water Management Agreement (SVWMA). Components of the aquifer system underlie four counties in the northern Sacramento Valley, at the surface in Butte and Tehama Counties and dipping to a depth of over 1000 feet below Glenn and Colusa Counties. SVWMA parties have agreed to provide some of their surface water to improve Delta water standards. The Lower Tuscan groundwater aquifer is envisioned as one groundwater source for that program, as it is believed to be confined as it dips below the ground surface and is believed to hold large quantities of groundwater. The Integrated Water Flow Model (IWFM) is used for the Butte Basin Groundwater Model (BCDWRC, 2008). IWFM is a quasi-3 dimensional finite-element model and a water resources management and planning model that simulates groundwater, surface water, surface-groundwater interaction as well as other components of the hydrologic cycle, as shown in **Figure 1**.

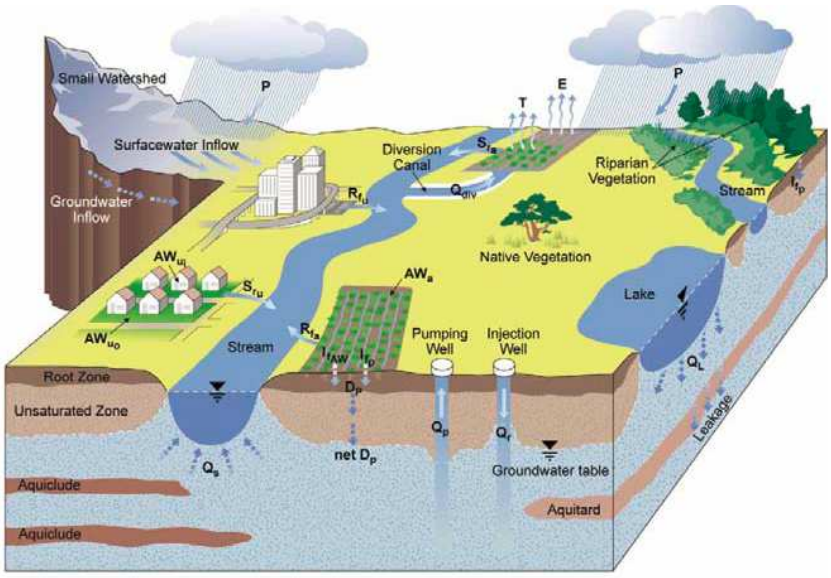

Figure 1- IWFM Hydrologic Components (BCDWRC, 2008)

IWFM was formerly known as IGSM2 (Integrated Groundwater and Surface water Model 2nd generation) with a name change taking place in September 2005. IWFM was developed by the staff in the Modeling Support Branch of California DWR's Bay-Delta Office. IWFM is an important water resource management tool for Butte County to complete local integrated water resource planning.

One of the critical points in the application of the IWFM is how to determine the inflow data from foothills watersheds into the IWFM model boundary. It is very important for the simulation results of the groundwater model to set up the boundary inflow condition to the model domain appropriately and accurately. The main objective of this project is to estimate the run-off from the foothills watersheds into the IWFM ground water model boundary. The recharge estimate provided by this project will determine the input into the IWFM and contribute to better management of the aquifer in order to maintain local water supply reliability as the aquifer contributes to statewide water supply reliability needs. It will assist water managers in protecting water users and ecosystems that are dependent on groundwater levels.

One of the problems in the estimation of the run-off in the project is that there is no existing precipitation data at some mountainous watersheds. Success in Prediction in Ungauged Basins (PUB) is a challenging problem in Hydrology. Today in most parts of the world, a significant amount of spatial information like remote sensing images, is available. However the hydrological information derived from such sources cannot be a complete answer to the PUB problem. For example, the physically based distributed hydrology models require a lot of spatially distributed hydro-atmospheric data as the input data to the models. Atmospheric data such as precipitation, short and long wave radiation, wind speed, relative humidity, air temperature, etc., are crucial information in the application of a land surface parameterization or snow accumulation and melting process modeling. However, it is very difficult to obtain the spatially distributed hydro-atmospheric data in mountainous watersheds at fine resolution in time and space. In order to overcome this problem, a dynamic downscaling of global reanalysis data can be used as a powerful tool to reconstruct the hydro-atmospheric data at ungauged or sparsely gauged basins as it enables us to apply the physically based distributed models to the basins with the spatially distributed input data at the fine resolution.

In this project, reconstruction of historical hydro-climate data based on a regional hydro-climate model (RegHCM) with the physically based, spatially distributed watershed environmental hydrology (WEHY) model is applied to the foothills region in order to estimate the run-off from the studied watersheds. Furthermore, some parts of the watersheds, especially

Deer Creek and Butte Creek watershed, are located at high elevation (> 2000m) and are covered by snow during the winter seasons when snowmelt is an important contributor to the river stream discharge during dry seasons (especially April, May, and June). Therefore, snow accumulation and melting processes are taken into account during the watershed modeling for the precise estimation of the runoff from these watersheds in the project.

The project, called "The Watershed Modeling and Education Project for the Lower Tuscan Aquifer", consisted of:

- Collection of hydrologic data over the foothills region
- Critical dry and wet periods analysis using historical hydrologic data
- Development of a geographical information system (GIS) over the foothills region
- Reconstruction of historical hydro-climate data over the foothills region
- Snow accumulation and melting process modeling
- WEHY Model implementation, calibration and validation for the foothills watersheds
- Estimation of inflow data from the watersheds to the recharge zone land surface boundary of the IWFM groundwater model

2. Overview of the Foothills Watersheds

The foothills watersheds, Big Chico Creek, Little Chico Creek, Butte Creek and Deer Creek watersheds, in Northern California were selected in the project as shown in **Figure 2**. The watersheds are located at the foothills and are covered by various vegetation types through elevations from 86 m to 1,798m (Big Chico Creek watershed), from 87m to 1065m (Little Chico Creek watershed), from 69m to 2187m (Butte Creek watershed) and from 150m to 2390m (Deer Creek watershed), so that the land use/cover of this area is geophysically and biologically heterogeneous. **Figure 3** shows the land cover and vegetation map obtained from Multi-source Land Cover Data in the foothills region, published by California Spatial Information Library (CaSIL), with a USGS land use classification. The watersheds are mainly covered by vegetation such as the ever green needle leaves, deciduous broad leaves, and so on. **Figure 4** and **5** show example pictures of the watersheds. It can be seen from **Figure 4** that some open spaces can be

found in the lower sectors of the watersheds. The run-off from these watersheds is simulated using the WEHY model in the project, and is used as input into the IWFM groundwater model, as discussed later. **Figure 6** shows the model domains of the IWFM and WEHY model.

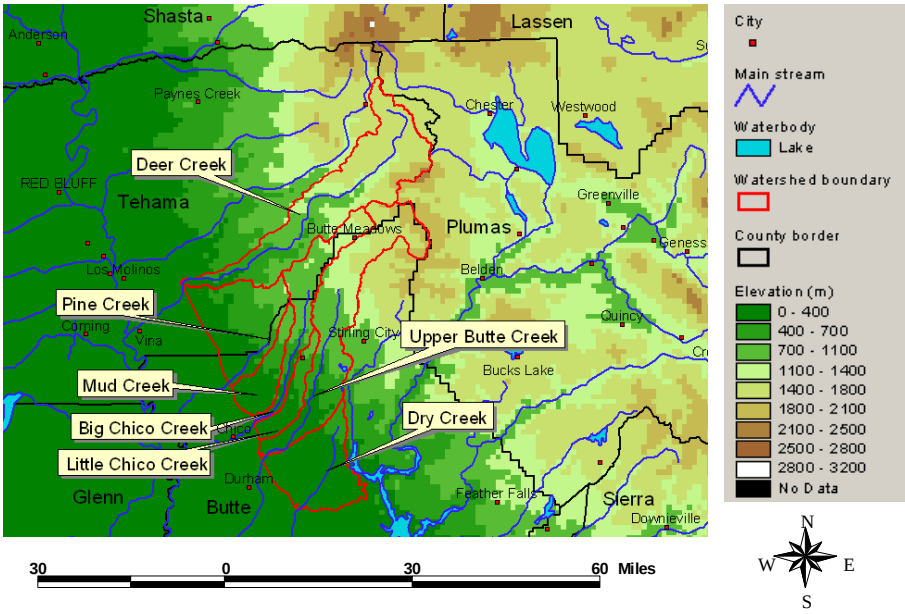

Figure 2- Map of the foothills watersheds that contribute to the Butte Basin Groundwater Model

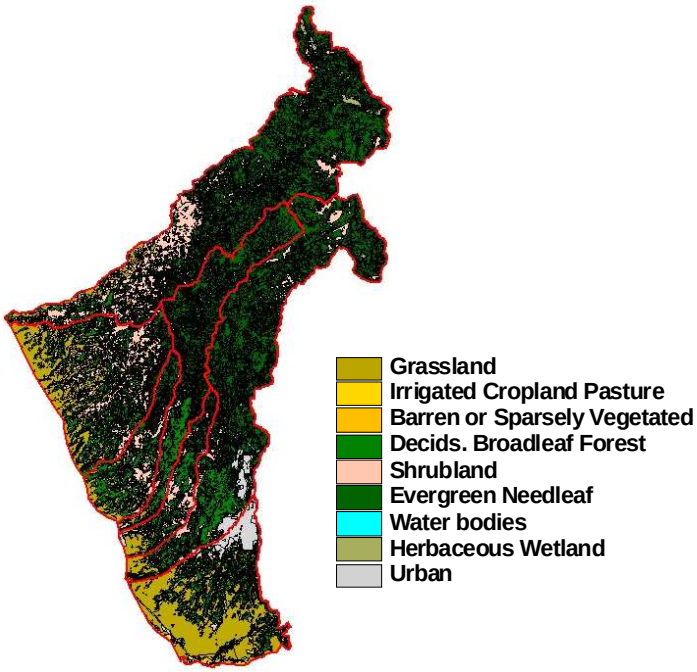

Figure 3- Vegetation and land use/cover map over the foothills watersheds

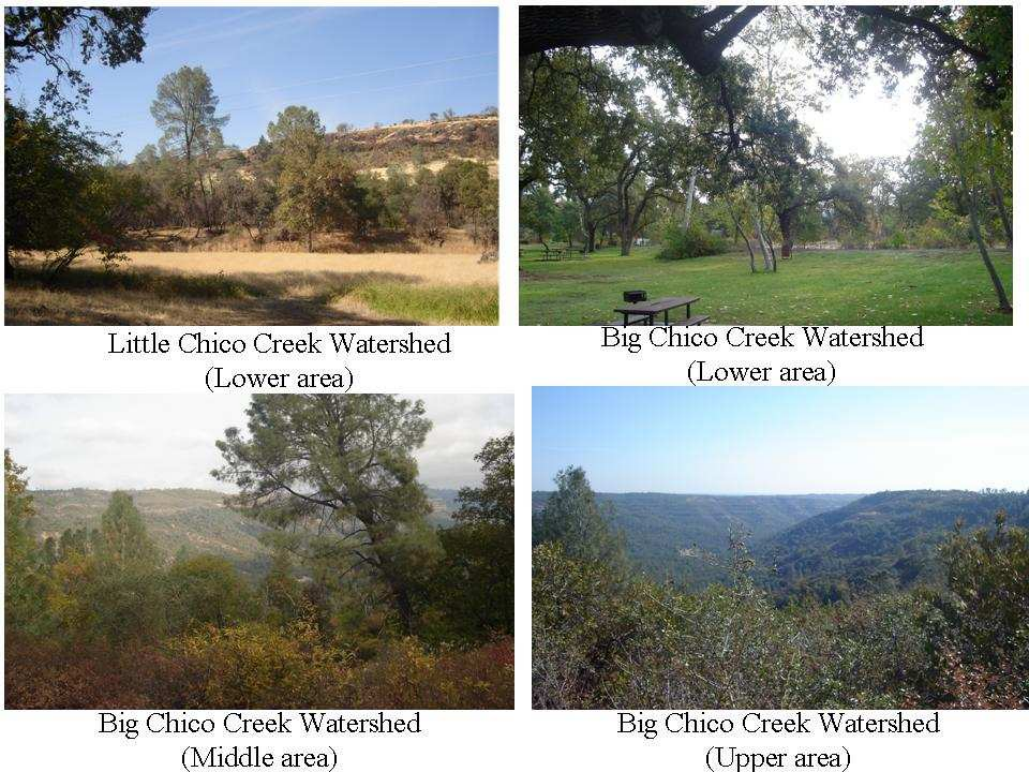

Figure 4- Example pictures of the foothills watersheds

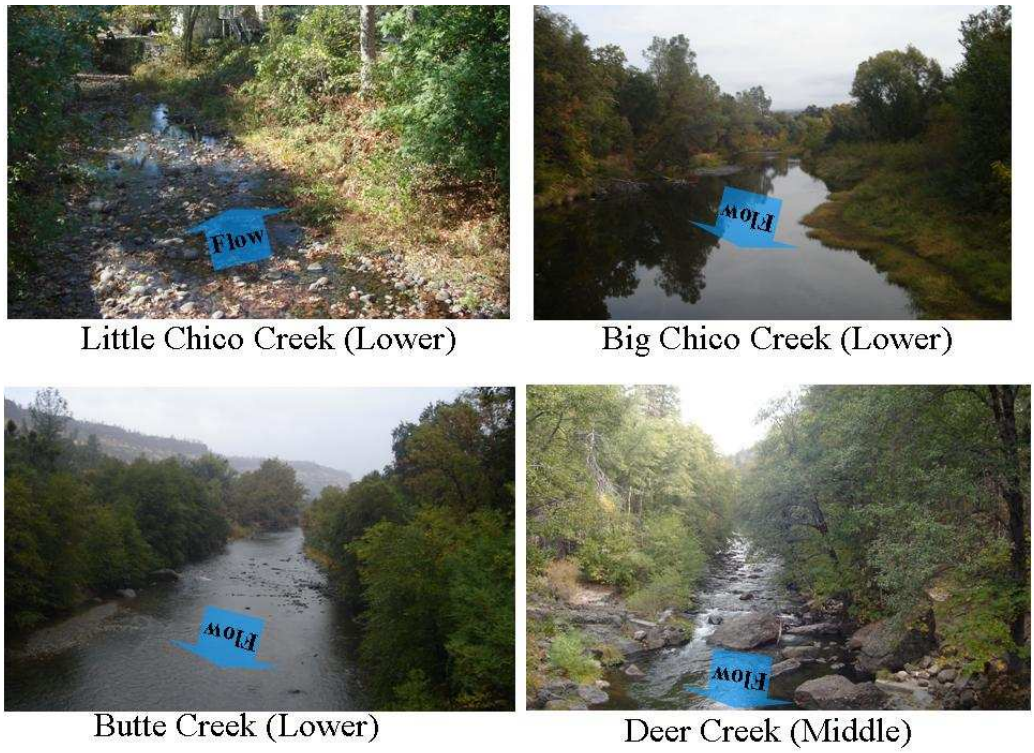

Figure 5- Example pictures of the creeks in the foothills watersheds

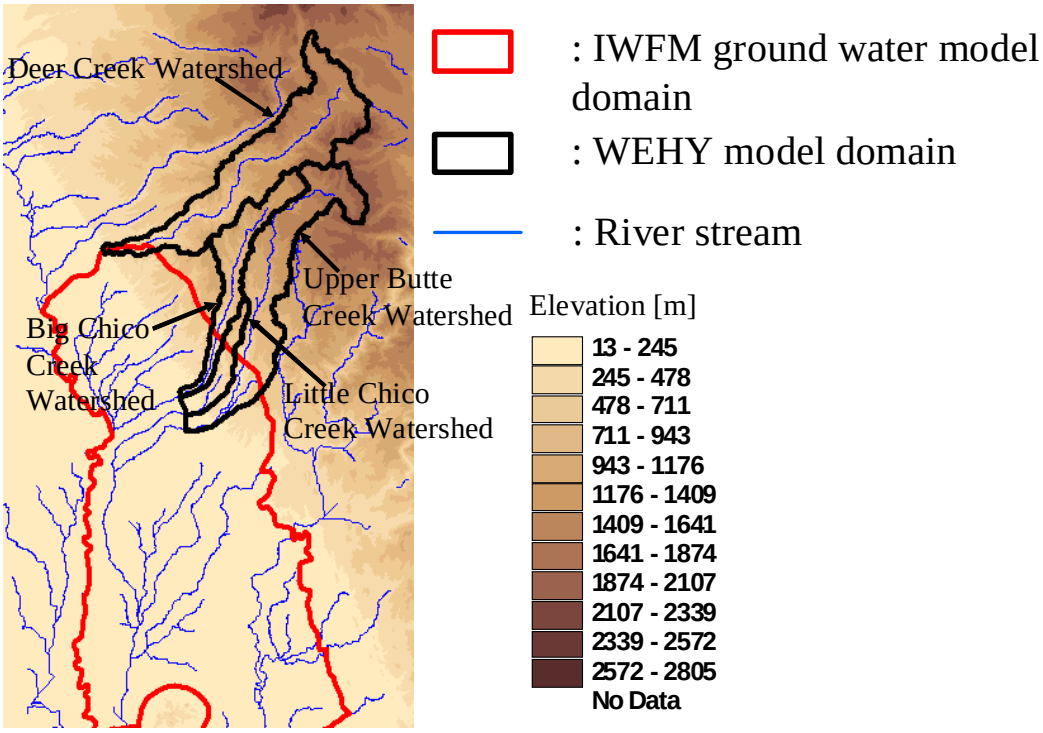

Figure 6- Model domains of the WEHY model and IWFM groundwater model.

Historical records of hydrologic ground observation data are indispensable for the model calibration and validation processes. Various data sources were searched in order to collect the publicly available information on historical atmospheric data. 13 stations from California Data Exchange Center (CDEC) of CDWR and 1 station at the Little Chico Creek from CDWR Northern District for the precipitation, stream discharge, and snow data were found in the project area (**Table 1**). **Figure 7** shows the digital elevation map with the ground observation station points over the watersheds. Some observation stations can be found in the area, but there is no precipitation station in the Deer Creek and Big Chico Creek watersheds. Furthermore, there are only two stations (DES and CAR) which provide hourly precipitation over the watersheds. In general, there are a few meteorological observation stations at the mountainous watersheds compared to the valley or urban areas. It should be emphasized that the importance of the spatial variability of precipitation on the runoff hydrograph has been long recognized and the orographic precipitation is a well-known and common phenomenon in Sierra Nevada. The effects of spatial distribution of the precipitation due to the orographic characteristics should be considered for the input precipitation data to the watershed models applied to the high elevation area. The ground

observation stations are usually installed in the valleys of the watershed for easy access, maintenance and installation, so that a basin average precipitation based on the ground observation data tends to miss the high intensity precipitation observed at the hilltops of the watershed. For the physically based, spatially distributed land surface parameterization and snow accumulation and melting process modeling, a lot of spatially distributed hydro-meteorologic data such as precipitation, air temperature, relative humidity, wind speed, short and long wave radiation etc., are required. However, it is difficult to find spatially distributed hydro-meteorologic data at the mountainous watersheds at fine resolution in time and space. In order to reconstruct the historical hydro-climate data over the foothills region at the fine spatial resolution, a dynamic downscaling is utilized in this project. Because regional climate models, employed for the dynamic downscaling, simulate the physical atmospheric processes locally, the regional climate features such as orographic precipitation and extreme climate events can be simulated by these models. Furthermore, this downscaling approach makes it possible to apply the physically based, distributed hydrologic models to the ungauged and heterogeneous basins.

Table 1- Location information and data source of the ground observation stations in the foothills region

Station ID	Station Name	X	Y	Z (m)	Data Source	Data
DCV	DEER CREEK NR VINA	-121.947	40.014	146	CDEC	Discharge
BIG	BIG MEADOW (KERN CO)	-121.777	39.768	2359	CDEC	Discharge
BCK	BUTTE CREEK NR CHICO	-121.709	39.726	91	CDEC	Discharge
A40280	A40280	-121.770	39.750	129	DWRND	Discharge
BTM	BUTTE MEADOWS	-121.500	40.100	1487	CDEC	Precipitation
CAR	CARPENTER RIDGE	-121.582	40.069	1467	CDEC	Precipitation
DES	DE SABLA (DWR)	-121.610	39.872	826	CDEC	Precipitation
DSB	DE SABLA (PG&E)	-121.617	39.867	826	CDEC	Precipitation
PRD	PARADISE FIRE STATION	-121.617	39.750	533	CDEC	Precipitation
CST	COHASSET	-121.771	39.875	488	CDEC	Precipitation
CHI	CHICO	-121.783	39.712	70	CDEC	Precipitation
CES	CHICO UNIV FARM	-121.817	39.700	56	CDEC	Precipitation
HMB	HUMBUG	-121.368	40.115	1981	CDEC	Snow
FEM	FEATHER RIVER MEADOW	-121.422	40.355	1646	CDEC	Snow

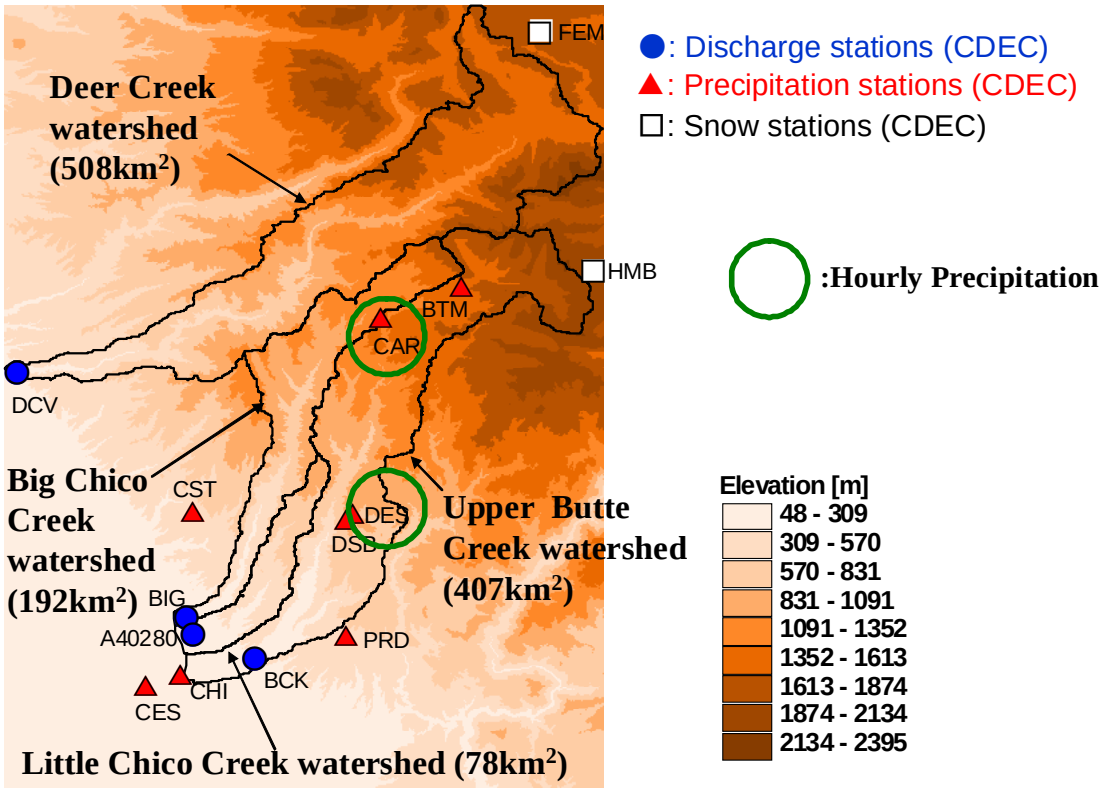

Figure 7- Available observation stations over the foothills watersheds

3. Methodology

In order to estimate the run-off from the foothills watersheds to the recharge zone land surface boundary of the IWFM ground water model for the Lower Tuscan Aquifer system, all the hydrologic processes in the watersheds must be modeled properly. The physically-based (or process-based) modeling approach for the hydrological processes is required in order to simulate the river stream discharge at the ungauged or sparsely gauged basins. For this project, several model layers, shown in **Figure 8**, were organized and implemented: a regional hydroclimate model, a snow accumulation and melting model, a hillslope process model, and a river channel routing model. The modeled hydrologic quantities are calibrated and validated by the field-monitored data at every modeling step.

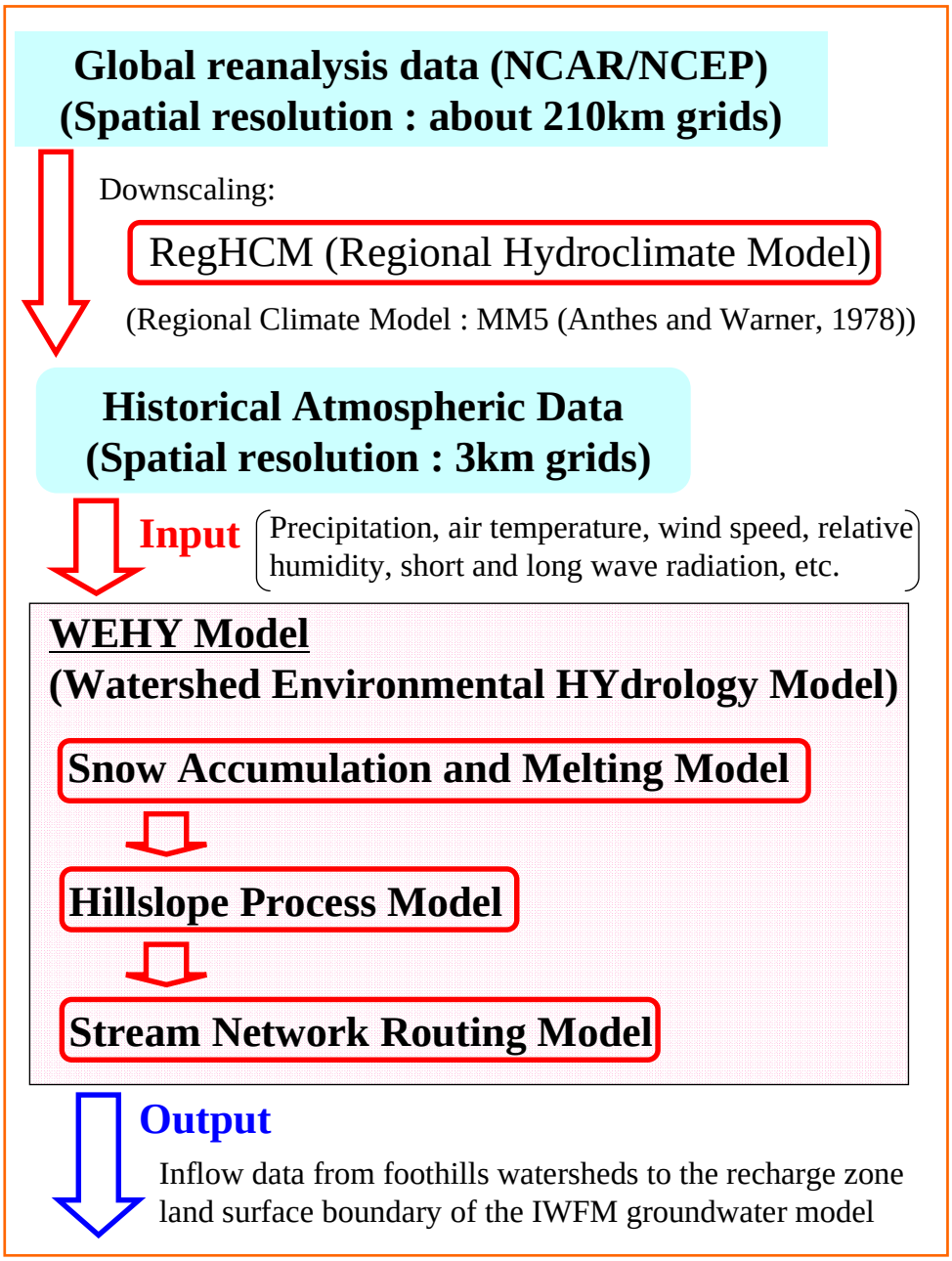

Figure 8- Watershed hydrology modeling methodology

4. Critical Dry and Wet Period Analysis

For the watershed modeling, the calibration process for model parameters and the validation process of the model simulation results are important to obtain better simulation results and to

evaluate the model performance and reliability. In general, some model parameters need to be adjusted by trial and error to improve model simulation results. Then the calibrated model for the intended area should be checked for its reliability and performance based on the observed data during the validation period. It is important that the model should be able to simulate not only the usual average condition of the watersheds but also the critical wet and dry periods, which include the extreme flood and drought events, with the calibrated and averaged parameters of the model. These critical dry and wet years are very important for the watersheds' management, flood prediction, water supply, and so on.

In order to identify the dry and wet years of the foothills watersheds, critical dry and wet period analysis was performed using the historical stream flow and precipitation data at Butte Creek and Deer Creek watersheds. **Figure 9** and **Figure 10** show the time series of the observed annual mean river stream discharge and annual precipitation data at the Butte Creek and Deer Creek.

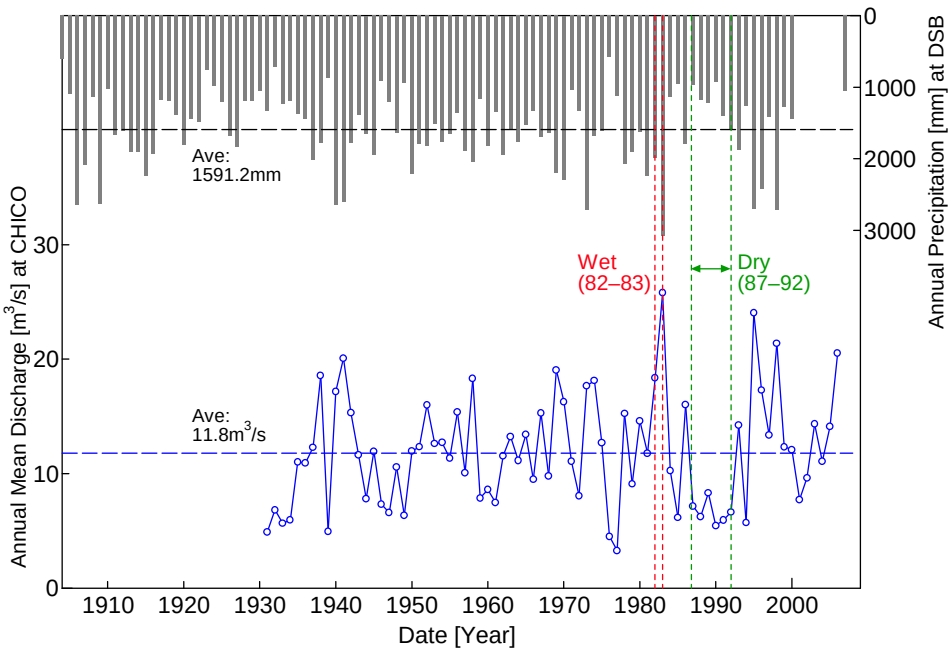

Figure 9- Time series of the observed annual precipitation and annual mean discharge at Butte Creek

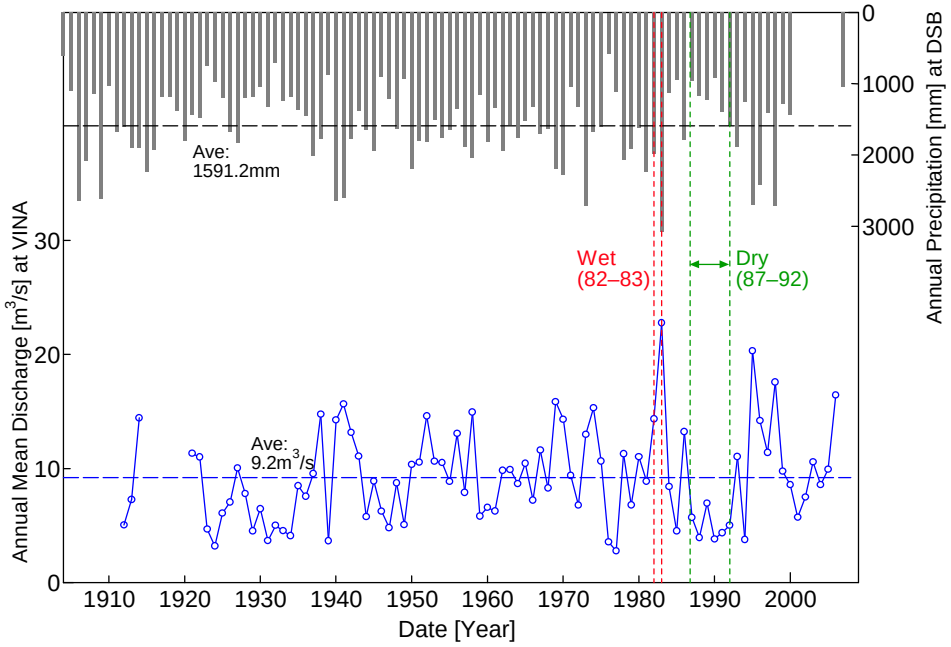

Figure 10- Time series of the observed annual precipitation and annual mean discharge at Deer Creek

It is seen from **Figure 9** and **Figure 10** that the largest discharge value is found in 1983. It is also found that the consecutive dry years are observed from 1987 through 1992. It should be noted that there is the smallest annual mean discharge value in 1977. However, from the point of view of the water resource management, consecutive dry years are more difficult to manage the water supply for the irrigation and drinking water uses. Therefore, continuous dry years from 1987 through 1992 were selected as the critical dry period for the model validation.

Figure 11 and **Figure 12** show the time series of the accumulative river discharge at Butte Creek and Deer Creek from 1965 through 2007. In these figures steep gradients mean wet years and mild gradients mean dry years.

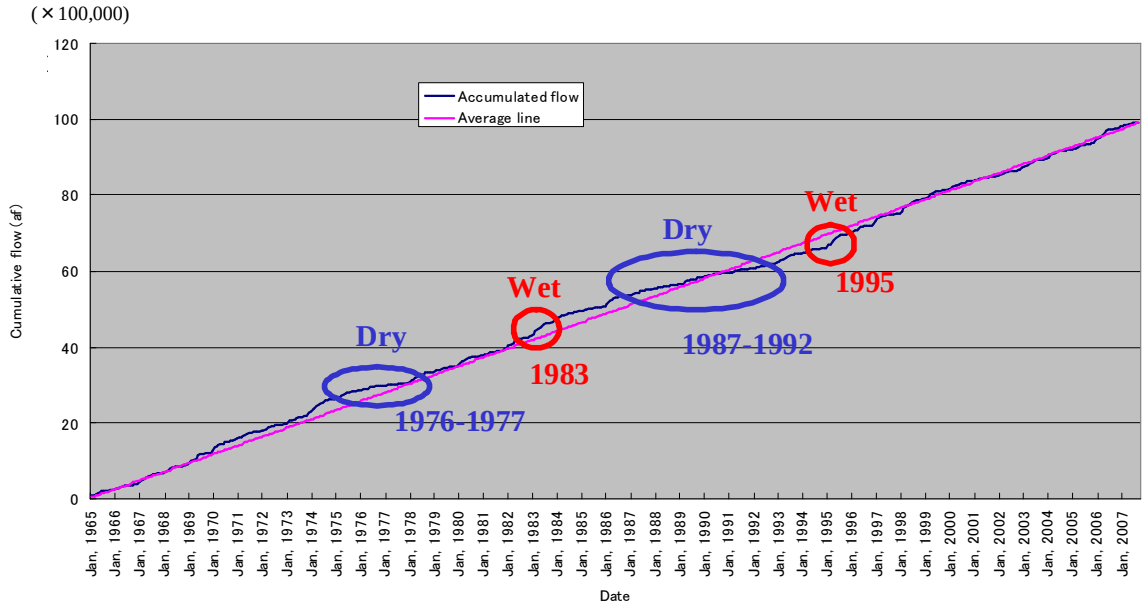

Figure 11- Time series of the cumulative inflow at Butte Creek from 1965 through 2007

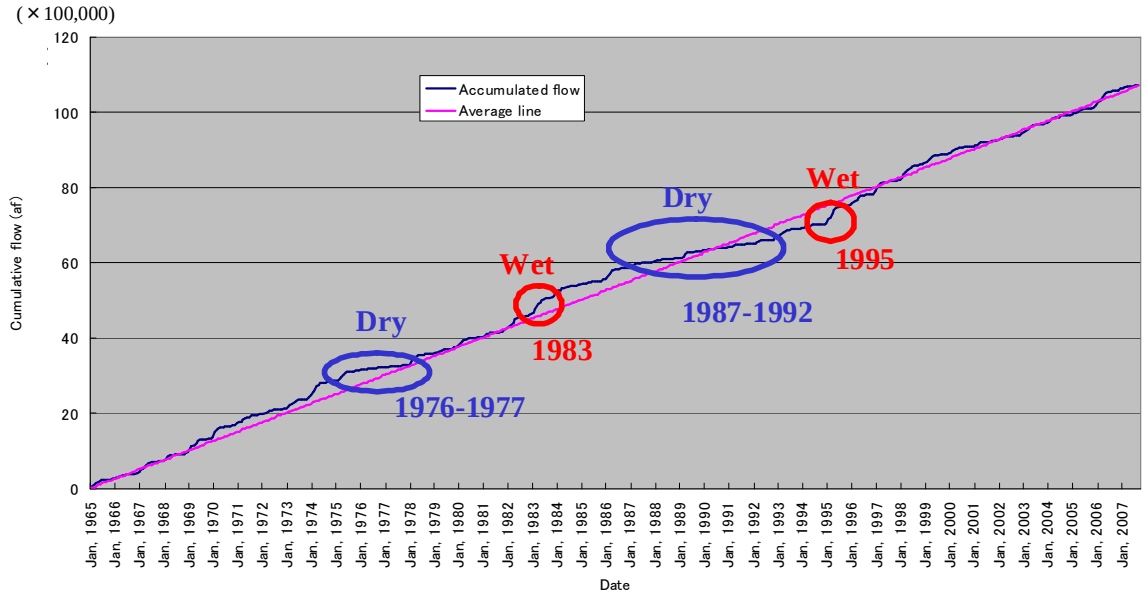

Figure 12- Time series of the cumulative inflow at Deer Creek from 1965 through 2007

Figures 13 and **14** show the time series of the surplus value of the river discharge from averaged flow at Butte Creek and Deer Creek from 1965 through 2007. If the accumulated discharge line is above the horizontal axis (average line), it means the cumulative water resource has surplus and the period can be identified as wet year. From the **Figures 13** and **14**, it can be clearly seen that the dry years from 1987 through 1992 define a critically dry period as the cumulative discharge line is far below the average line. Thus, we determined that 1982-1983 was

the critical wet period, and 1987-1992 was the critical dry period, the modeling effort was focused on for model validation. Furthermore, the period from 2004 through 2005 was selected for the calibration period of the model since abundant data, especially hourly time increment data, are available during the period.

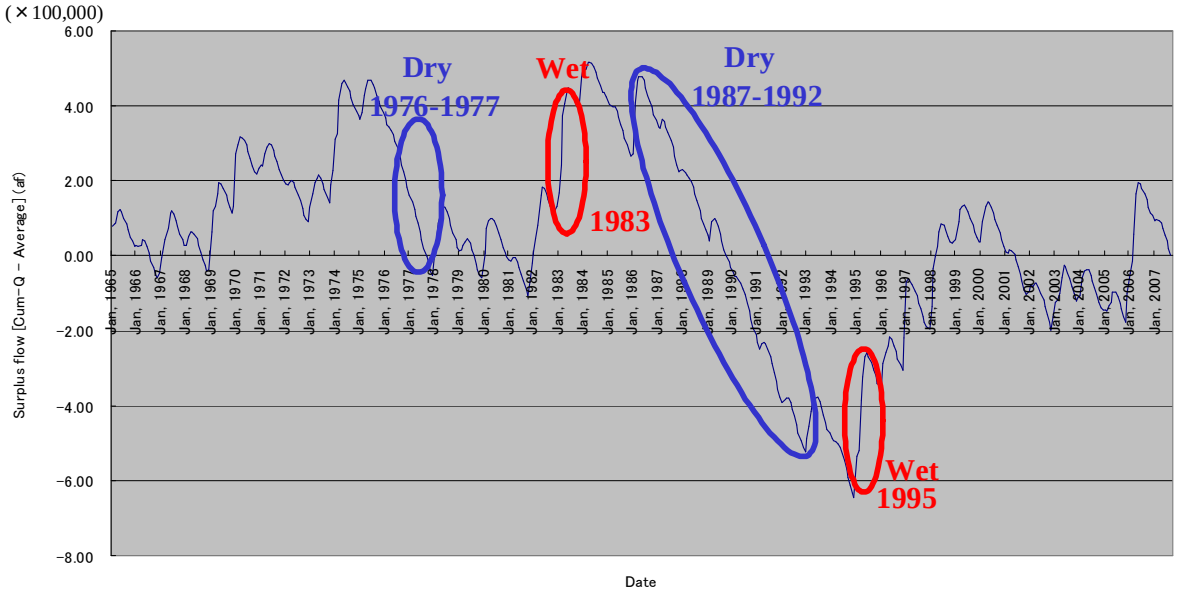

Figure 13- Time series of the surplus inflow at Butte Creek from 1965 through 2007

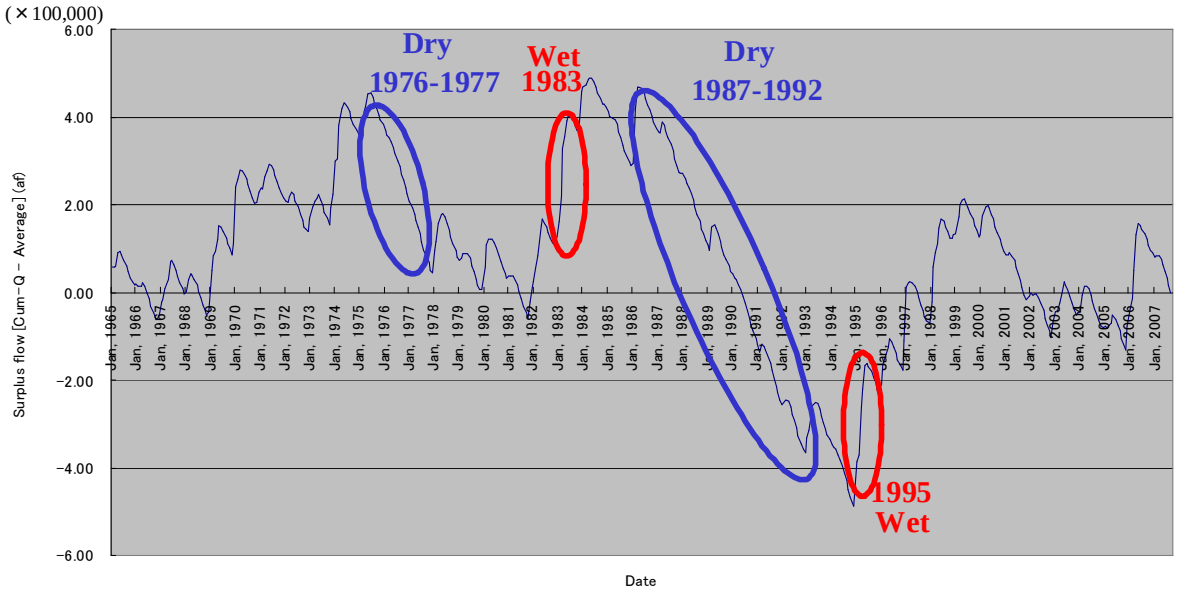

Figure 14- Time series of the surplus inflow at Deer Creek from 1965 through 2007

5. Development of a Geographic Information System (GIS) for the Foothills Watersheds

In order to support watershed modeling, a geographic information system (GIS) was established for the project. The geo-referenced data, including spatially distributed data and point data from various sources were downloaded and processed. The Universal Transverse Mercator (UTM) coordinate system was selected as the standard GIS coordinate system for the Project. The Universal Transverse Mercator Coordinate system divides the World into 60 zones, each being 6 degrees longitude wide, and extending from 80 degrees south latitude to 84 degrees north latitude. The UTM "ZONE 10" projection is used for the project. If the original dataset is not in the selected coordinate system, it is re-projected into the UTM "ZONE 10" coordinates. All the geo-referenced datasets in this project have been defined in this coordinate system. An example GIS map in **Figure 2** shows geophysical elevation, the locations of cities, stream channels, county boundaries, and the watershed boundary for the foothills watersheds.

It should be emphasized that the vegetation parameters are crucial for the land surface parameterizations and snow models, and seasonal and spatial variabilities of these parameters should be considered for the modeling. Recent advances in remote sensing techniques and advanced GIS database and tools enable us to obtain the spatial and temporal properties of land surface parameters.

1) Digital Elevation Model (DEM) Data

The digital elevation model (DEM) data at 1 arc second resolution that corresponds to about 30 meter resolution, was downloaded from the Seamless Data Center of USGS and processed for the foothill watersheds and its adjacent regions. It was re-projected into UTM ZONE10 coordinates by utilizing a projection extension of ArcView software. The final processed DEM was also clipped in order to cover only the project area.

2) Watershed Delineation and River Stream Network Data

Based upon the DEM at about 30 m resolution by USGS, delineation of the watersheds was carried out for the foothills watersheds using the Arc View tools. The derived channel network and watershed delineations, based on the reconditioned DEM, are shown in **Figure 15**.

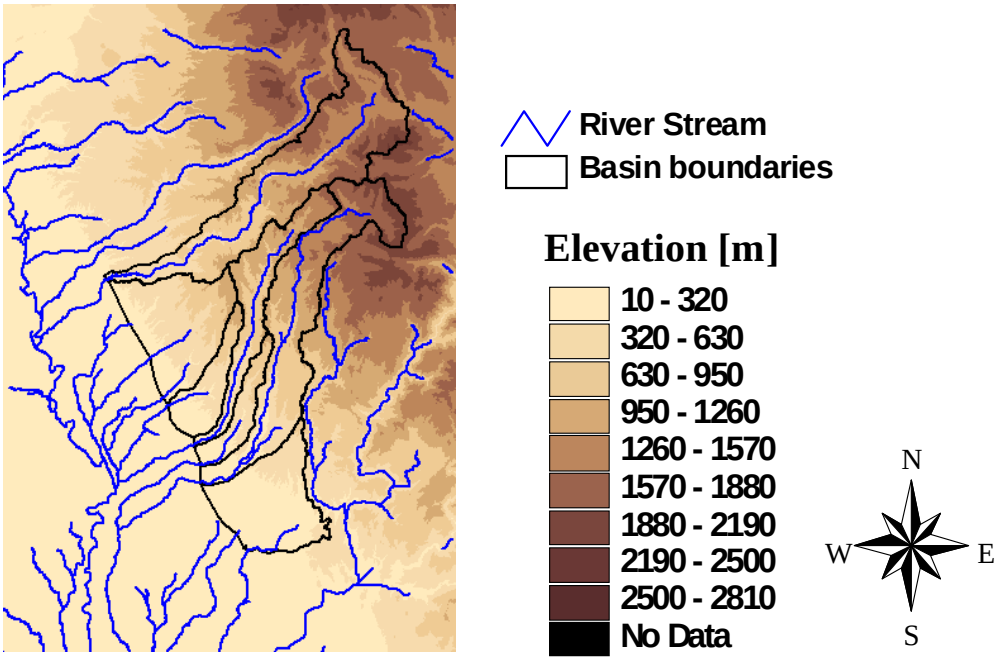

Figure 15- Derived channel network and watershed delineations

3) Vegetation and Land Cover/use Data

From vegetation and land cover/use data the parameters such as the roughness height, surface albedo, emissivity and vegetation root depth for the land surface parameterization and snow model are determined. These vegetation parameters are important to calculate the evapotranspiration and snow accumulation and melting in the land surface processes. For the vegetation data Multi-source Land Cover Data based upon the local survey, published by CaSIL, which has 100 m spatial resolution, was employed and implemented into the foothill watersheds GIS system, as shown in **Figure 16**. Furthermore, the effective rooting depth of the vegetations was estimated from the vegetation types and land cover/use by means of Gale and Grigal (1987).

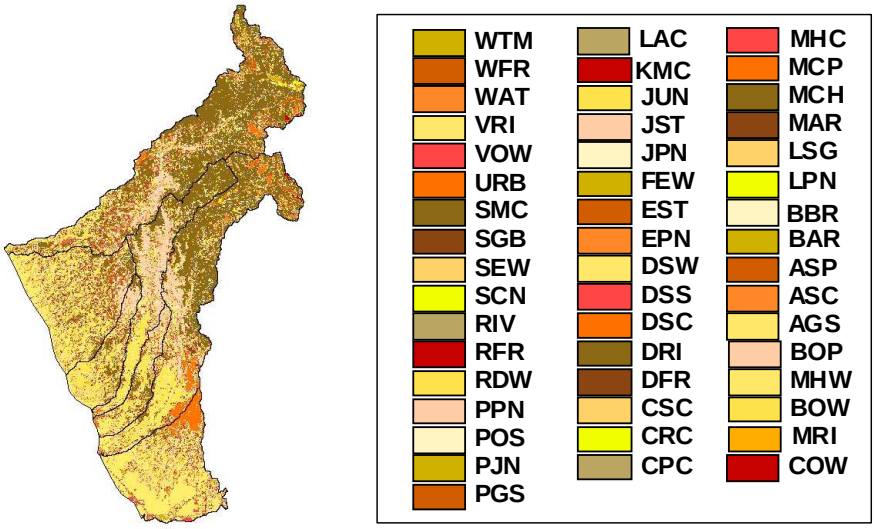

Figure 16- Local vegetation and land cover/use survey map over the foothills region published by CaSIL

Leaf Area Index (LAI) is defined as the amount of leaf area (m^2) in a canopy per unit ground area (m^2) and is very important for the evapotranspiration and snow accumulation and melting processes. The monthly LAI derived by MODIS (MODerate resolution Imaging Spectroradiometer; Wolfe et al. 1998 and so on) satellite images were obtained at a spatial grid resolution of 1 km x 1km. **Figure 17** shows example LAI maps over the foothills watersheds in 2004.

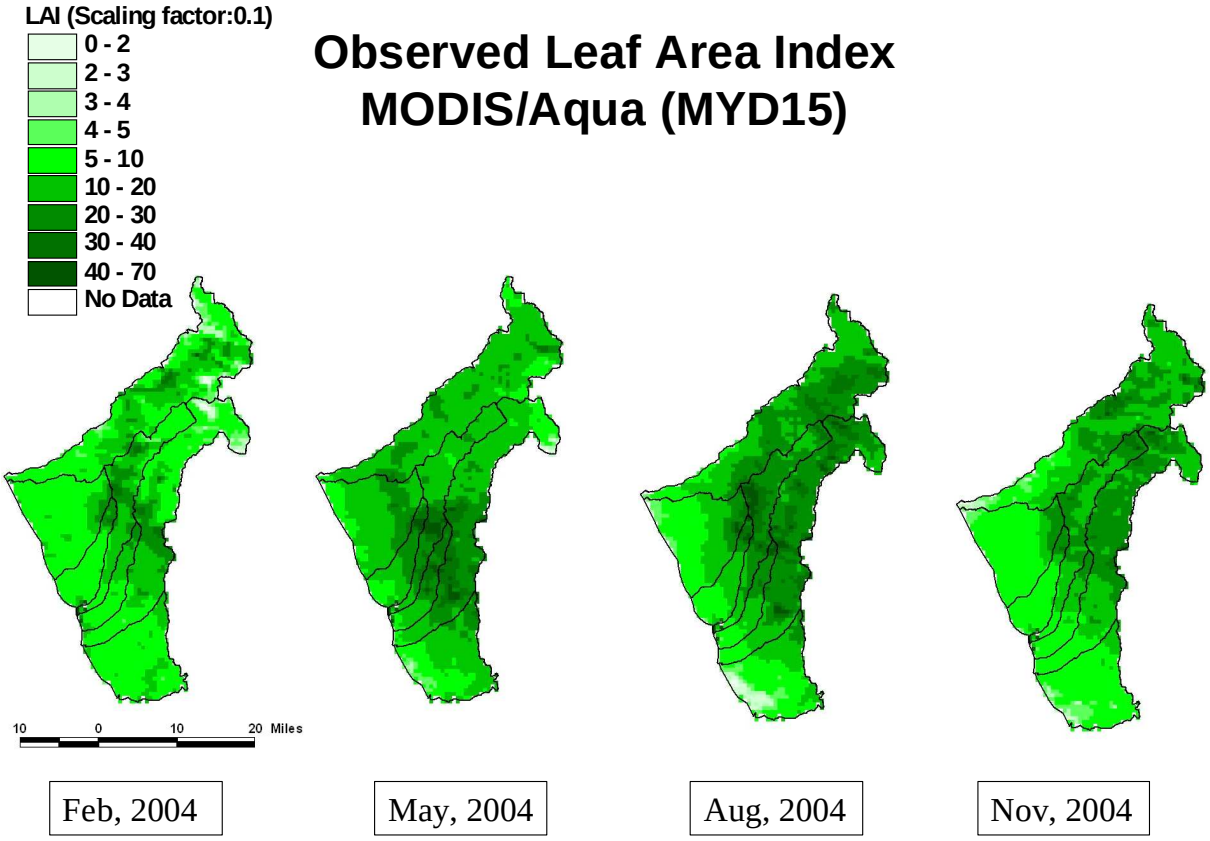

Figure 17- Example LAI maps over the foothills watersheds in 2004

4) Soil Survey Data

Water flow in soils is modeled mathematically by a combination of the mass conservation equation, Darcy's law, the soil water retention relationship, and water saturation versus hydraulic conductivity relationship in WEHY model (Chen et al. 1994 a,b, Kavvas et al. 2004, Chen et al. 2004 a,b). There are a total of 6 soil hydraulic parameters that need to be estimated for WEHY model: 1) mean of volumetric water content at saturation, 2) mean of residual volumetric water content, 3) mean of bubbling pressure head, 4) mean of pore size distribution index, 5) mean of saturated hydraulic conductivity, and 6) variance of saturated hydraulic conductivity.

These soil parameters were estimated by means of the USDA Soil Survey Geographic database called "SSURGO" (Soil Conservation Service, 1991) which has the finest available spatial resolution over the project area, shown in **Figure 18**, and by the relationships between

soil texture and soil hydraulic parameters (Rawls et al., 1982 and McCuen et al., 1981), shown in **Table 2**. Different colors represent the different soil types in **Figure 18**. From the SSURGO data set and soil texture table soil parameters such as the soil depth, saturated hydraulic conductivity, total porosity, pore size distribution index, bubbling pressure, and residual saturation in terms of their depth averages can be obtained.

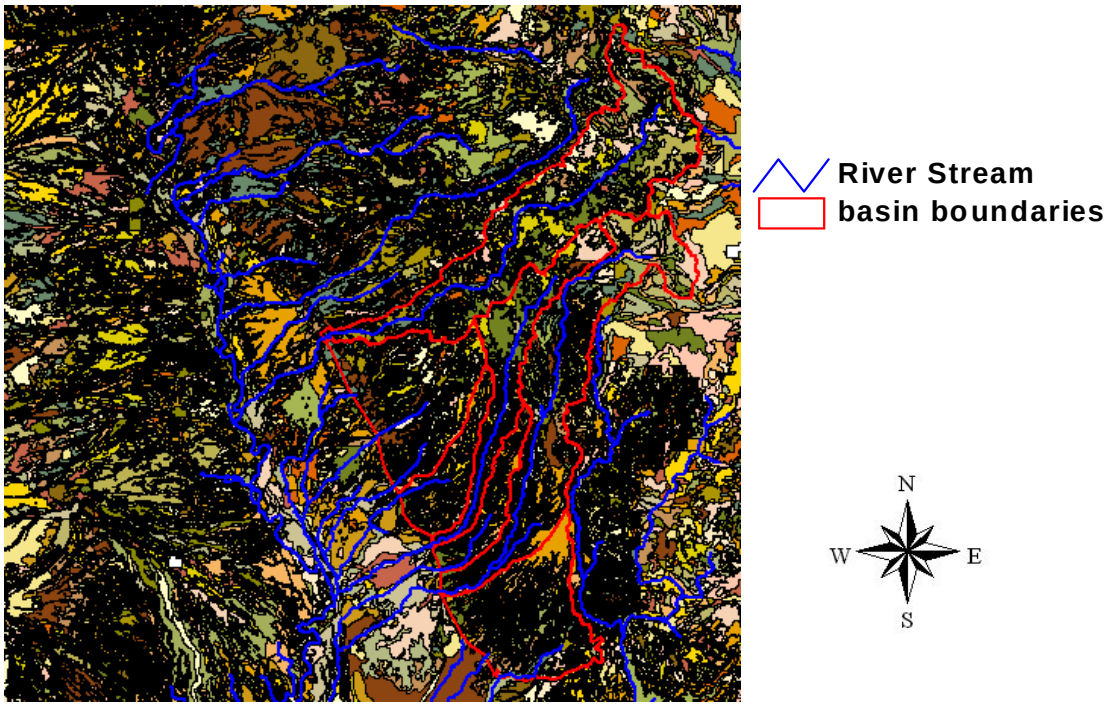

Figure 18- Soil map derived from SSURGO dataset

Table 2- Soil texture classes and their properties (Rawls et al., 1982 and McCuen et al., 1981)

Soil texture class		Mean Sat. hydraulic conduct.	SD of Sat. hydraulic conduct.	Mean Total Porosity	Mean Residual Saturation	Mean Bubbling Pressure	Mean Pore Size Dist. Index
		(cm/h)	(cm/h)			(cm)	
1	Sand	21.00	1.66	0.437	0.020	15.98	0.694
2	Loamy sand	6.11	1.24	0.437	0.035	20.58	0.553
3	Sandy loam	2.59	1.17	0.453	0.041	30.20	0.378
4	Loam	1.32	1.33	0.463	0.027	40.12	0.252
5	Silt loam	0.68	1.15	0.501	0.015	50.87	0.234
6	Sandy clay oam	0.43	1.20	0.398	0.068	59.41	0.319
7	Clay loam	0.23	1.20	0.464	0.075	56.43	0.242
8	Silty clay loam	0.15	1.16	0.471	0.040	70.33	0.177
9	Sandy clay	0.12	1.51	0.430	0.109	79.48	0.223
10	Silty clay	0.09	1.48	0.479	0.056	76.54	0.150
11	Clay	0.06	1.26	0.475	0.090	85.60	0.165
12	Organic	1.32	1.33	0.463	0.027	40.12	0.252

6. Reconstruction of Historical Hydro-climate Data over the Foothills Region

In order to apply the physically based, spatially distributed watershed models for the ungauged or sparsely gauged basins, historical atmospheric data over the investigated area should be reconstructed. However, for example, the U.S. National Center for Atmospheric Research/National Center for Environmental Prediction (NCAR/NCEP) global reanalysis atmospheric data resolution is approximately 210km in the horizontal directions, and in 6-hour time intervals. These data are too coarse for watershed hydrologic modeling. Hence, it is necessary to downscale and process these data in order to reconstruct historical precipitation data over the foothills region at the scale of few kilometers (~3km) for the watershed modeling. A regional hydrologic-atmospheric model (RegHCM) can be used for the dynamic downscaling of the historical global reanalysis atmospheric data to foothills region at fine spatial resolution for utilization in the watershed modeling. The model has already been used at various watersheds in the world, and has been tested and validated over those watersheds by the UC Davis group (Kavvas et al. 1998, Yoshitani et al. 2002, Anderson et al. 2007, Ohara et al. 2007, Yoshitani et

al. 2009, Jang et al. 2010). An atmospheric component of the RegHCM is MM5 (Fifth Generation Mesoscale Model; Anthes and Warner 1978). MM5 is a nonhydrostatic model which can be downscaled even to 1km spatial resolution. Hence, it is able to capture the impact of steep topography and land surface/land use conditions of watersheds on the local atmospheric conditions.

The global reanalysis data products used for this project are atmospheric data (pressure, wind, relative and specific humidity, temperature, and potential temperature) at 6-h intervals over the foothills watersheds and surrounding land and ocean provided by NCEP/NCAR. These data are used as initial and boundary conditions for the RegHCM. In this project, four one-way nested grids were set up within the model to create a downscaling from about the 210×210 km scale reanalysis data to the 3×3 km scale over the foothills watersheds. **Figure 19** shows the spatial extent of the four nested domains for the RegHCM simulation of the foothills region, and **Table 3** lists domain size and grid resolution data. Each nested domain has a spatial resolution of 1/3 of the parent grid and focuses more on the project area of the foothill watersheds. 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 grids allows the large-scale archived atmospheric data to be economically downscaled to the region of interest at the desired resolution.

Table 3- Nested grid data for the foothills region

Domain	Grid resolution (km)	Number of grids	Domain area (km^2)
1	81	26×26	4,435,236
2	27	26×26	492,804
3	9	26×26	54,756
4	3	26×26	6,084

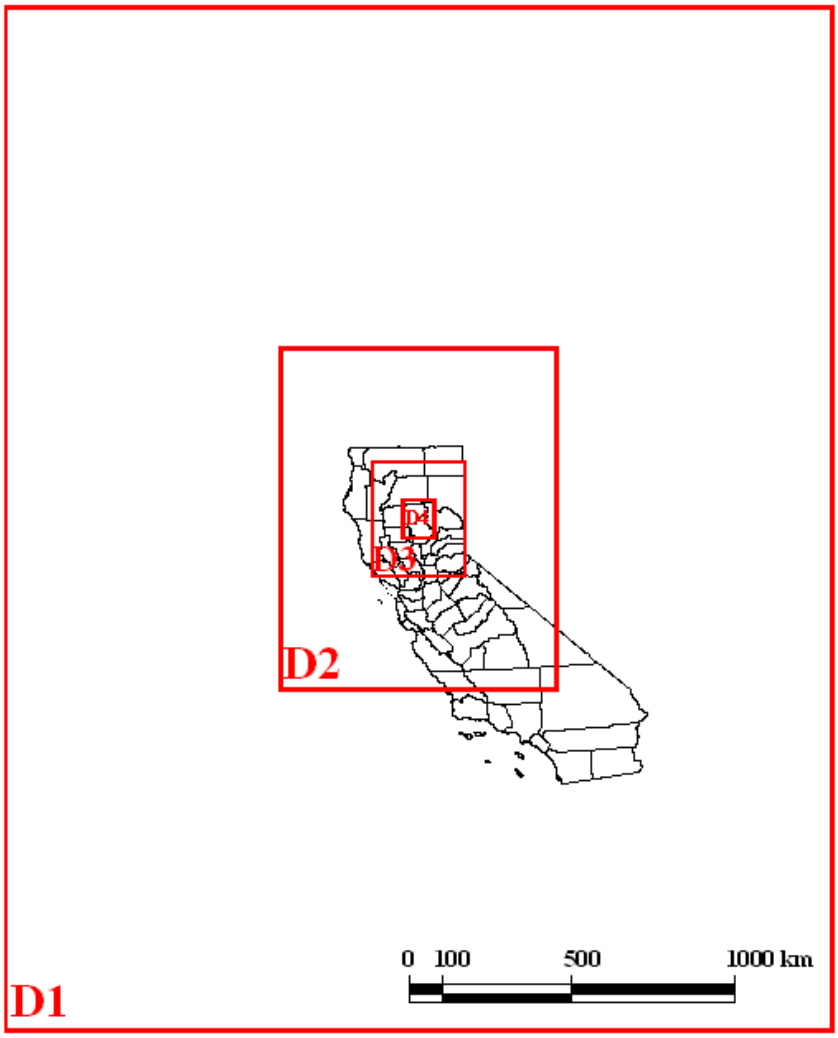

Figure 19- Depiction of four nested grids used for the MM5 simulation of the foothills watersheds.

Figure 20 shows the comparisons of the observed and model simulated monthly precipitation at each observation station during the January 1982 – December 1992 period. **Figure 21** shows the comparisons of the observed and model simulated monthly mean air temperature at each observation station during the January 1984 – December 1992 period. It is seen from these figures that the observed and simulated precipitation and mean air temperature matched very well at monthly time scale.

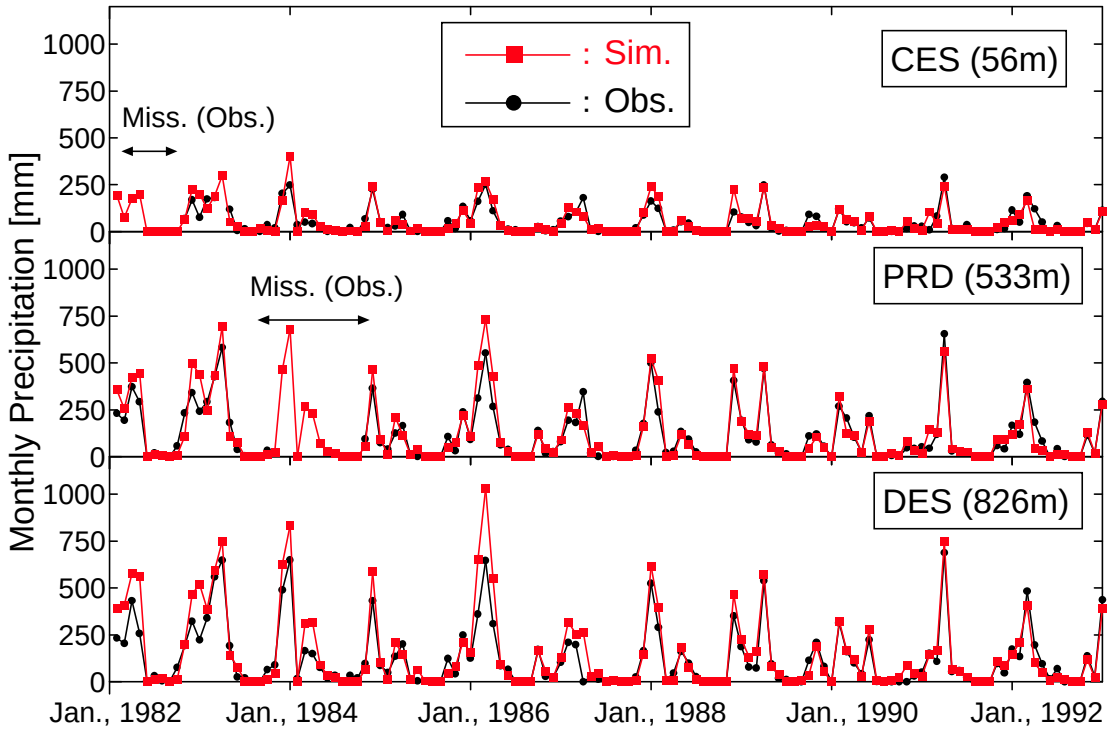

Figure 20- Comparisons of the observed and model simulated monthly precipitation at each observation station from January 1982 through December1992

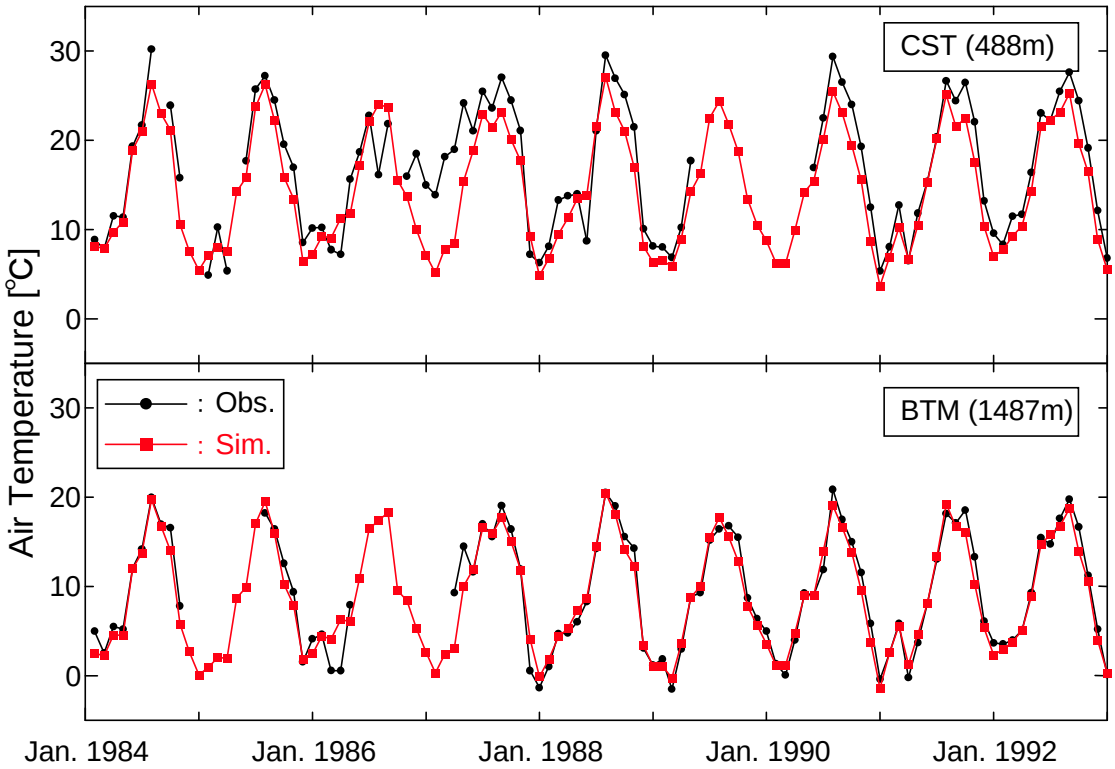

Figure 21- Comparisons of the observed and model simulated monthly mean air temperature at each observation station from January 1984 through December1992

Figure 22 shows a comparison between the model simulated precipitation field and PRISM (Parameter-elevation Regressions on Independent Slopes Model) data over the foothills region for December 1987. PRISM data sets, developed by Oregon State University, provide interpolated ground precipitation observation data that have 4km spatial resolution and monthly time intervals over USA from 1895 to present.

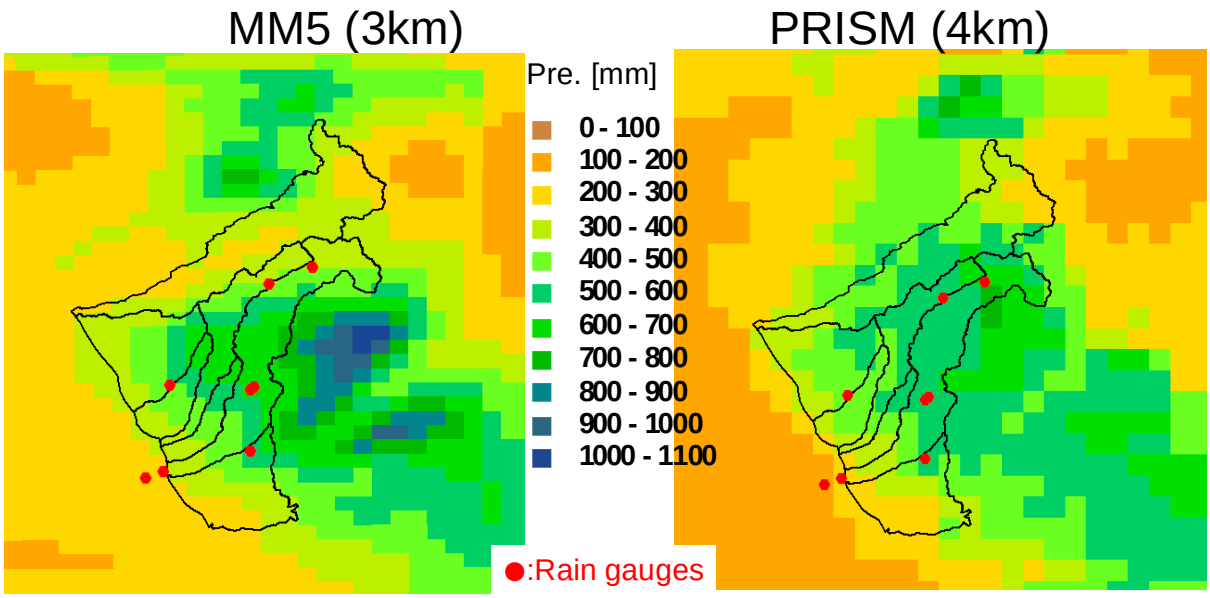

Figure 22- Comparison of model simulated precipitation field and PRISM data over the foothills region for December 1987

MM5 simulation and PRISM precipitation fields are similar both with respect to magnitude and spatial distribution. However, reconstructed precipitation fields show high intensity precipitation structures around the high elevation area due to the orographic effects while PRISM data do not show these structures. The reason is that the precipitation fields of PRISM data are based on the data interpolation of the ground observation stations which usually are installed in the valleys of the watershed for easy access, maintenance and installation, so that PRISM data tends to miss the high intensity precipitation observed at the hilltops of the watershed. This comparison supports the advantage of the dynamic downscaling based on the RegHCM employed in this project. These results related to the dynamic downscaling of NCAR/NCEP reanalysis data are quite encouraging for the watershed modeling in the foothills region.

7. Hydrologic Modeling for the Foothills Watersheds

The WEHY model that utilizes upscaled hydrologic conservation equations to account for the effect of heterogeneity within natural watersheds was applied to Deer Creek, Butte Creek, Big Chico Creek and Little Chico Creek watersheds. WEHY model is a physically based spatially distributed watershed hydrology model that is based upon upscaled conservation equations for interception, snow accumulation/snowmelt, evapotranspiration, infiltration, unsaturated flow, subsurface stormflow, overland flow, channel network flow, and regional groundwater flow. A schematic description of the WEHY model is shown in **Figure 23**. A structural description of the WEHY model is shown in **Figure 24**.

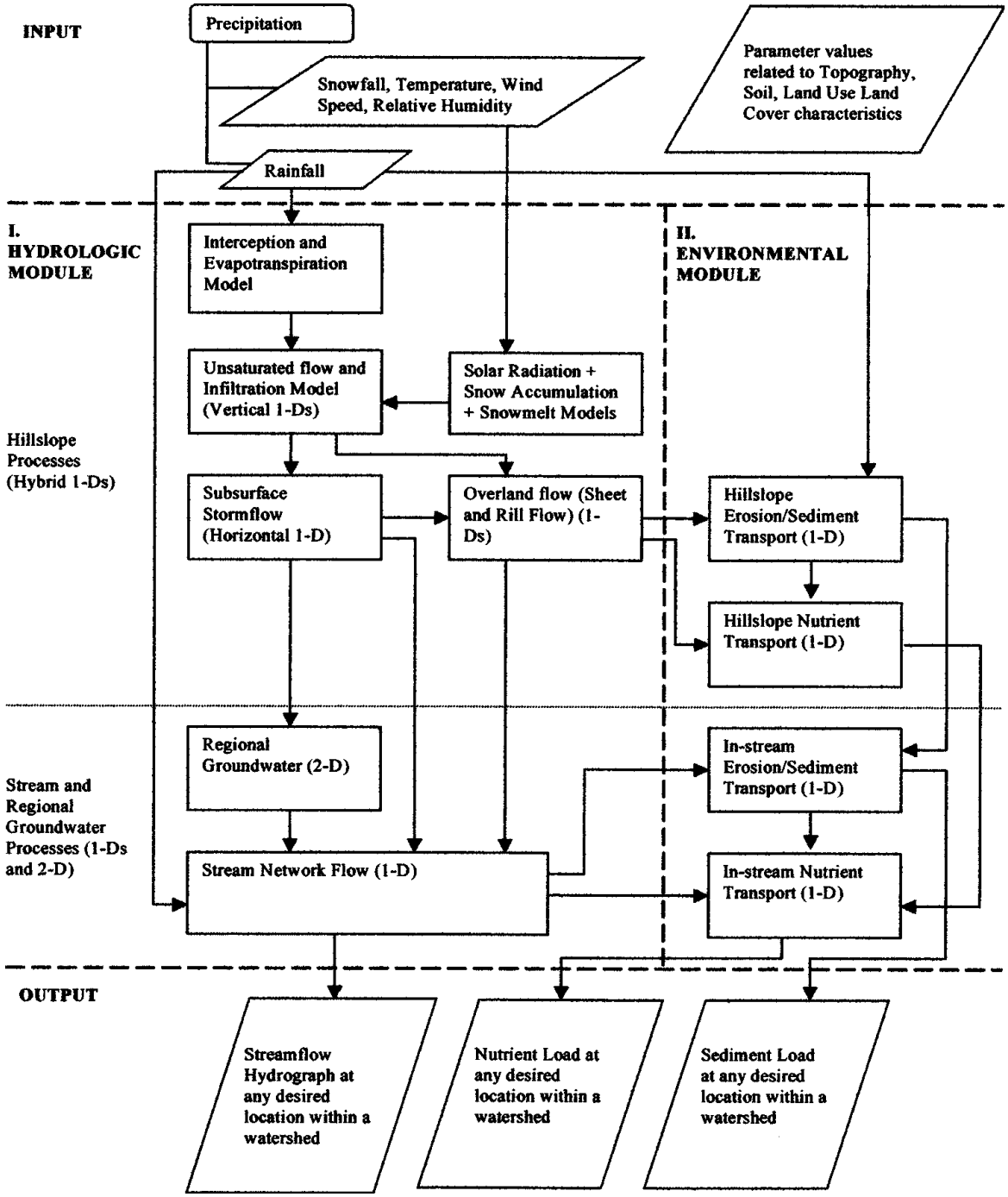

Figure 23- Schematic description of WEHY model (Kavvas et al. 2004)

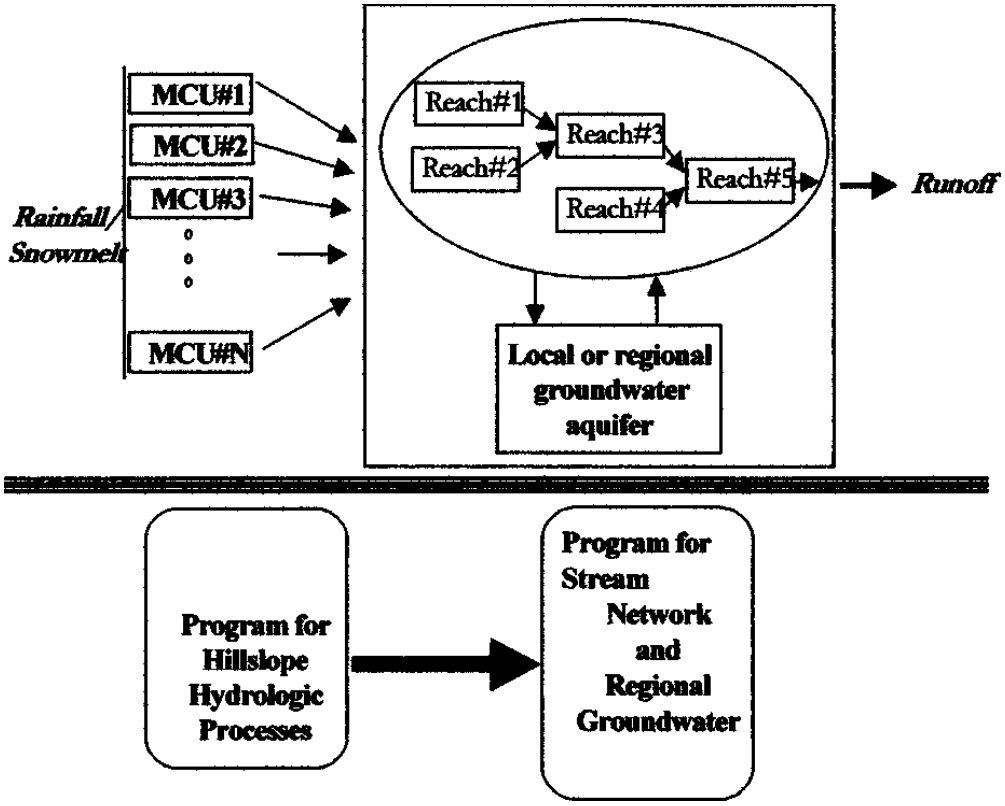

Figure 24- Structural description of WEHY model (Kavvas et al. 2004)

The emerging parameters in the WEHY model are areal averages and areal variance/covariances of the original point-scale parameter values. It is possible to implement and use WEHY model at any ungauged or sparsely gauged watershed since its parameters are estimated directly from the land features of the watershed. WEHY model can be used either for event-based runoff prediction, or for long-term continuous-time runoff prediction. Detailed descriptions of the WEHY model have been given previously elsewhere (Kavvas et al. 2004, Chen et al. 2004a, b, Kavvas et al. 2006).

In order to validate the model applicability and reliability, calibration and validation periods were selected for the application of the model based on the critical dry and wet periods analysis, described in the earlier chapter. The calibration period is the hydrologic year from October 2004 to September 2005 and the validation period is the hydrologic years from October 1982 through September 1992. The validation period includes critically dry and wet years in Northern California.

1) Configuration and Parameter Estimation for WEHY Model

As may be seen from **Figure 24**, the WEHY model subdivides a watershed first into model computational units (MCUs) that are delineated from the DEM of the watershed by means of a geographic information system analysis (see Chen et al. 2004a). Delineated MCUs map and river stream network at each watershed are shown in **Figure 25**, and the total number of MCUs at each watershed are listed in **Table 4**.

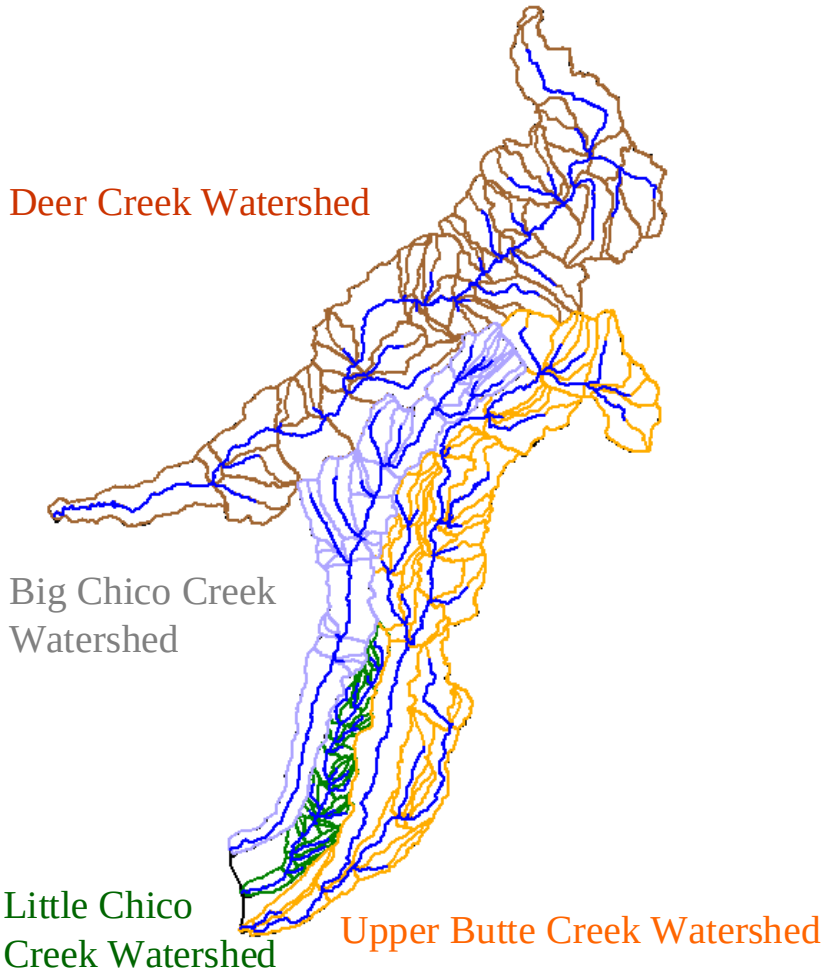

Figure 25- Delineated MCUs map and river stream network at each watershed

Table 4- Total number of MCUs at each watershed

Watersheds	Catchment Area (km2)	Total Number of MCU	Mean MCU Size (km2)
Big Chico Creek Watershed	192	54	3.6
Little Chico Creek Watershed	78	77	1.0
Deer Creek Watershed	508	94	5.4
Butte Creek Watershed	407	92	4.4

These MCUs are either individual hillslopes or first-order watersheds. The WEHY model computes the surface and subsurface hillslope hydrologic processes that take place at these MCUs, in parallel and simultaneously. These computations yield the flow discharges to the stream network and the underlying unconfined groundwater aquifer of the watershed that are in dynamic interaction both with the surface and subsurface hillslope processes at MCUs as well as with each other (as may be seen in **Figures 23 and 24**). These discharged flows are then routed by means of the stream network and the unconfined groundwater aquifer routing.

Parameters of each stream reach and of each MCU are estimated directly from the GIS database of the watersheds, which contains information about the physical characteristics of the watersheds. Estimation of the geomorphologic, soil hydraulic and vegetation parameters for MCUs of the WEHY model, as was described by Chen et al. (2004a) in detail, was performed by first overlaying the boundaries of the MCUs on the DEM map, the soil class map, and the vegetation class map. These maps were already implemented as the GIS dataset into the watersheds, described in the earlier chapter. Then all of the parameters of an MCU were retrieved from the GIS data that are associated with the grid cells inside the boundary of that MCU. As explained in the paper br Chen et al. (2004a), stationary heterogeneity of parameters within a hillslope was assumed. Consequently, the same mean and variance values of the parameters at the hillslope scale were used for all transects within that hillslope.

Geomorphologic parameters for the delineated stream reaches and MCUs in the WEHY model for the foothills watershed were obtained using the general procedures described in Chen et al. (2004a) and the foothills watersheds GIS database. The geomorphologic parameters define the flow domains and the configurations of rills and interrill areas for MCUs of the WEHY model for the foothills watershed. **Figure 26** shows the delineated rill distributions at each watershed.

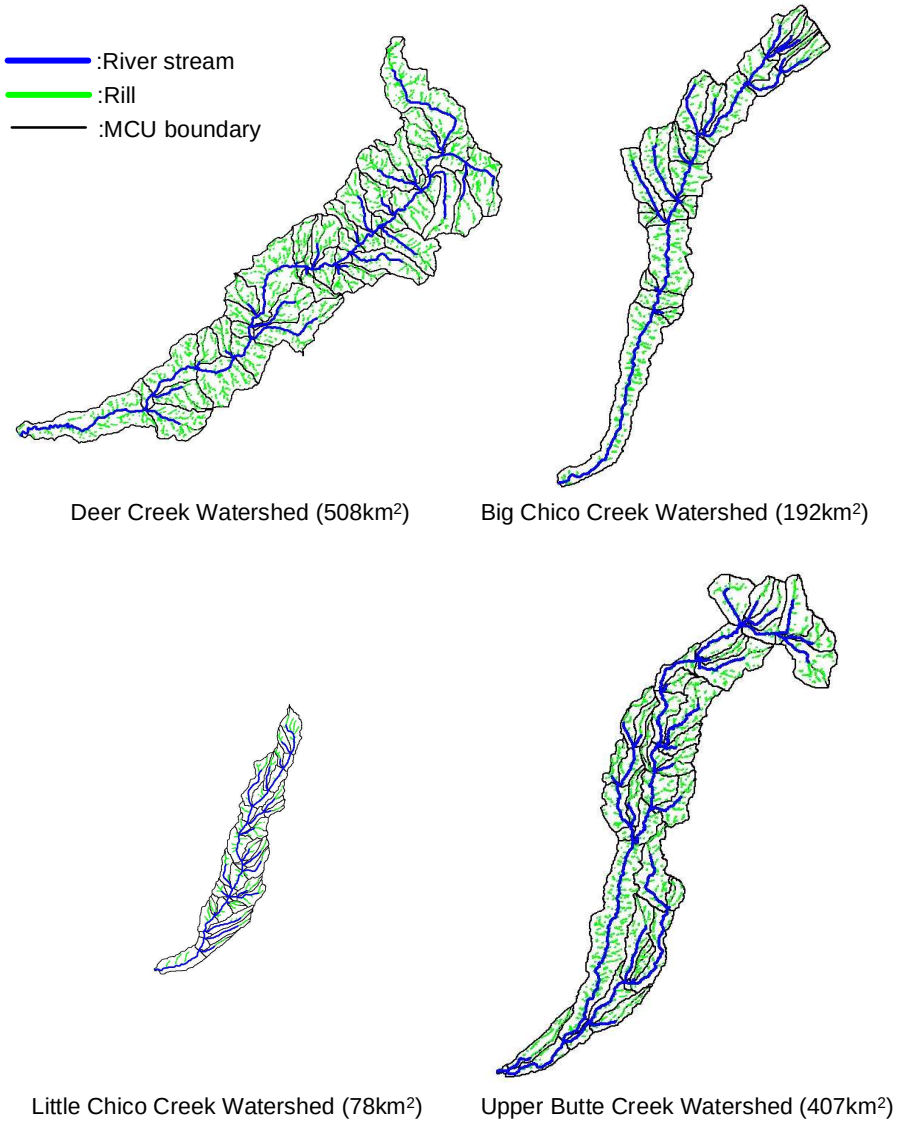

Figure 26- Delineated rill distribution maps at each watershed

Figures 27-30 show the soil parameters of the WEHY model at each MCU. **Figures 31** and **32** show the vegetation parameters of the WEHY model at each MCU. Furthermore, seasonal LAI maps over the foothills region were developed from the satellite remote sensed data (MODIS). **Figure 33** shows the monthly mean LAI values at each watershed at every month. Besides the geomorphologic parameters, the soil hydraulic parameters and vegetation parameters shown in **Figures 26-33**, other model parameters, such as Chézy coefficients for stream reaches and MCUs, also need to be evaluated in order to run the model. The Chézy coefficients were first taken to be 2 ($ft^{1/2}/s$) for overland flow, 5 for rill flow, and 10–25 ($ft^{1/2}/s$) for the main stream channel flow and these values were calibrated based on the observed river discharge data.

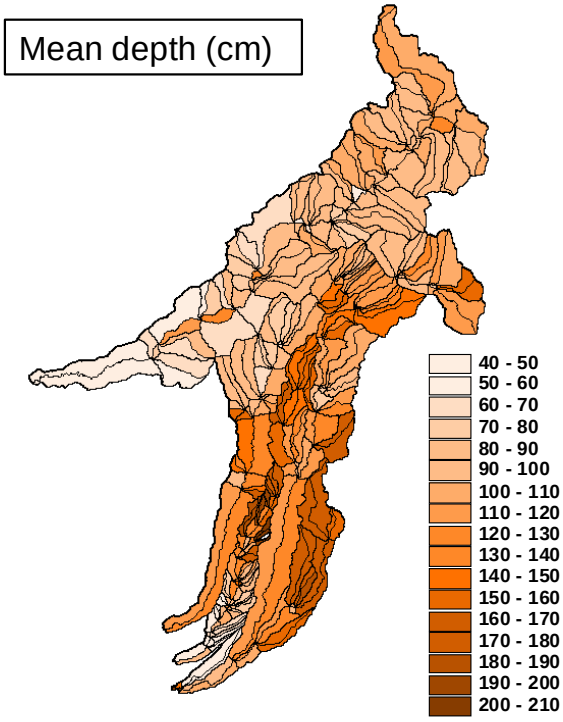

Figure 27- Mean soil depth map in the foothills watersheds

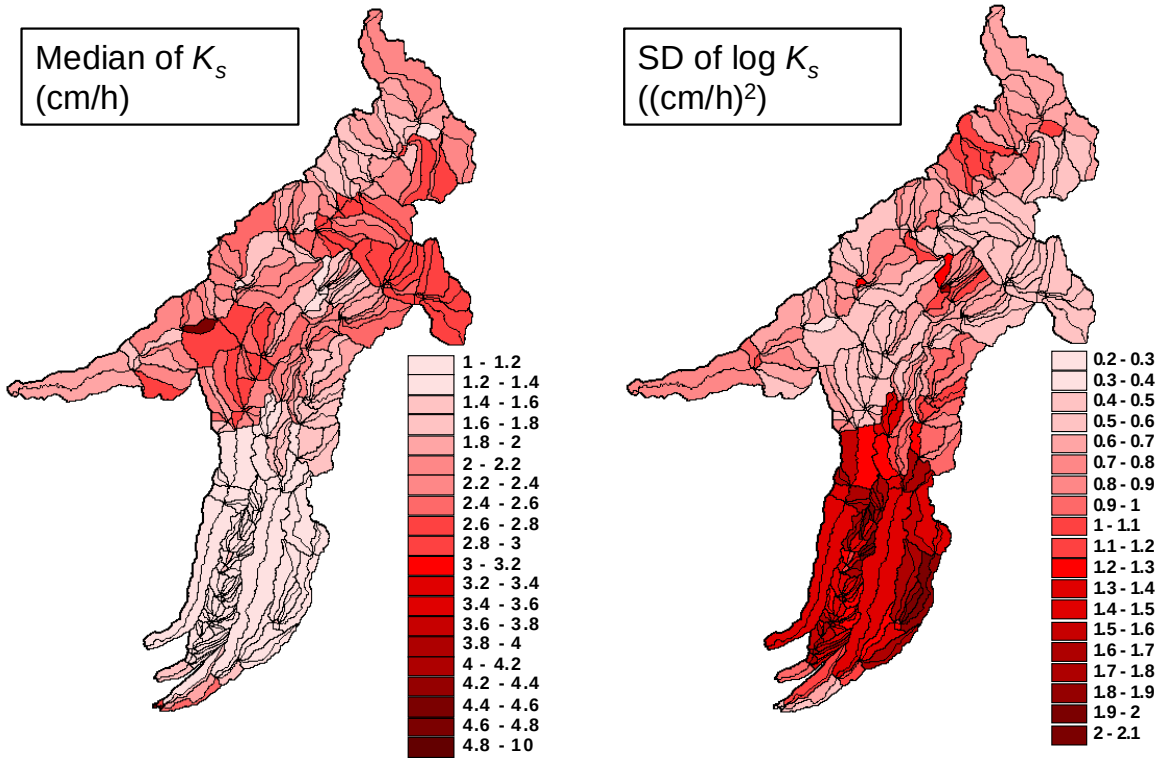

Figure 28- Median of saturated hydraulic conductivity and standard deviation of log saturated hydraulic conductivity map in the foothills watersheds

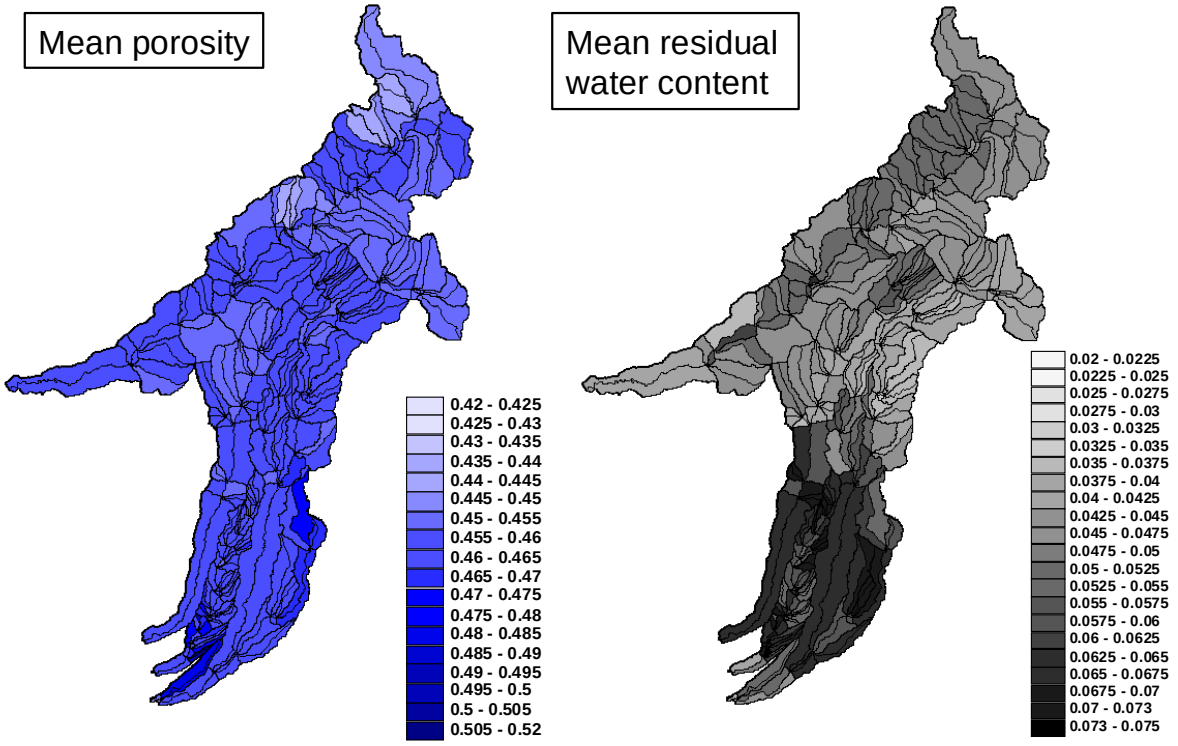

Figure 29- Mean porosity and mean residual water content map in the foothills watersheds

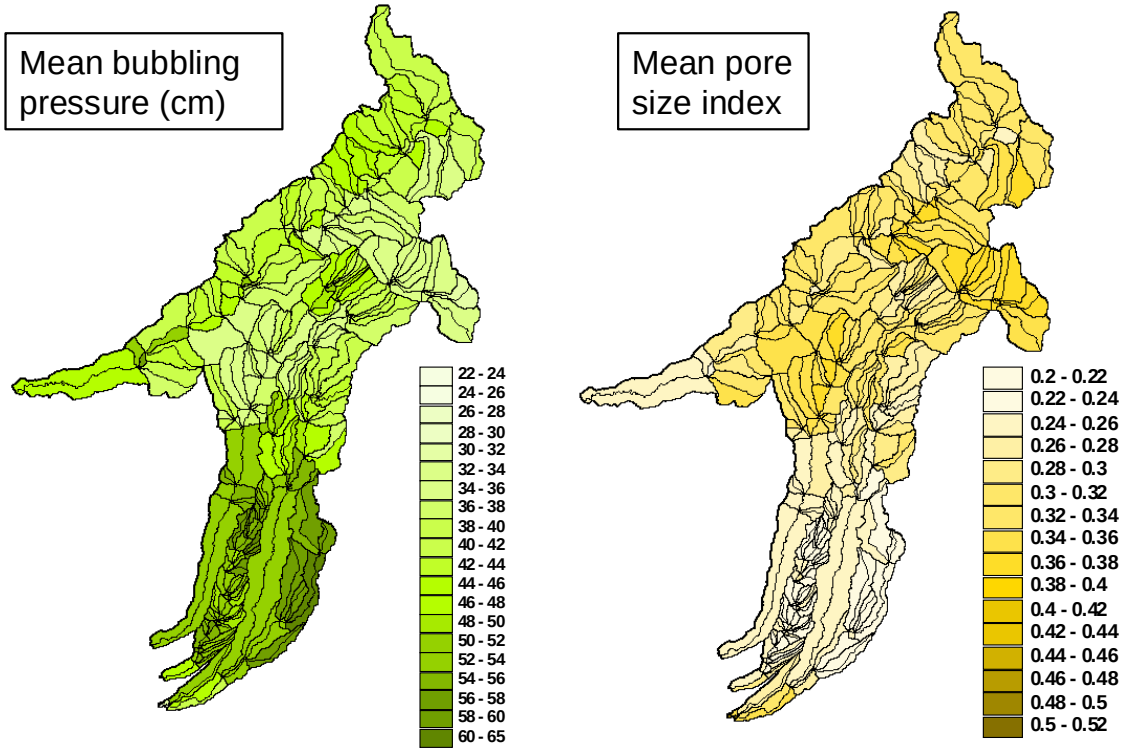

Figure 30- Mean bubbling pressure and mean pore size index map in the foothills watersheds

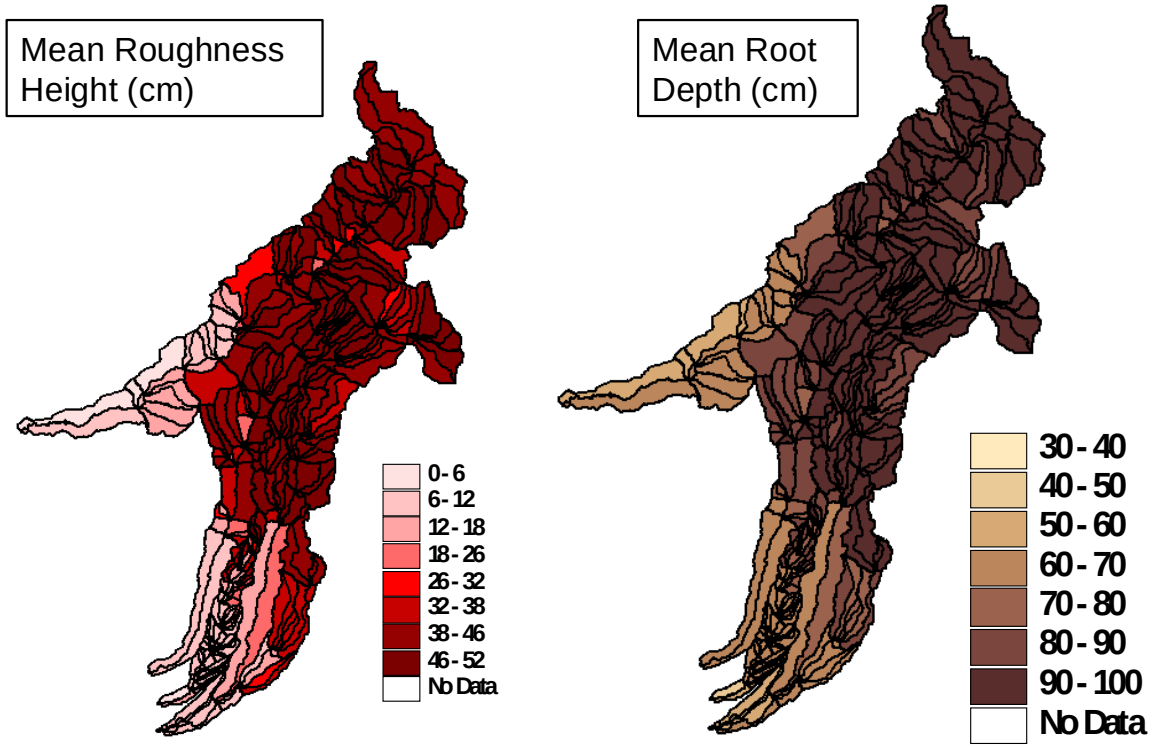

Figure 31- Mean roughness height and mean root depth map in the foothills watersheds

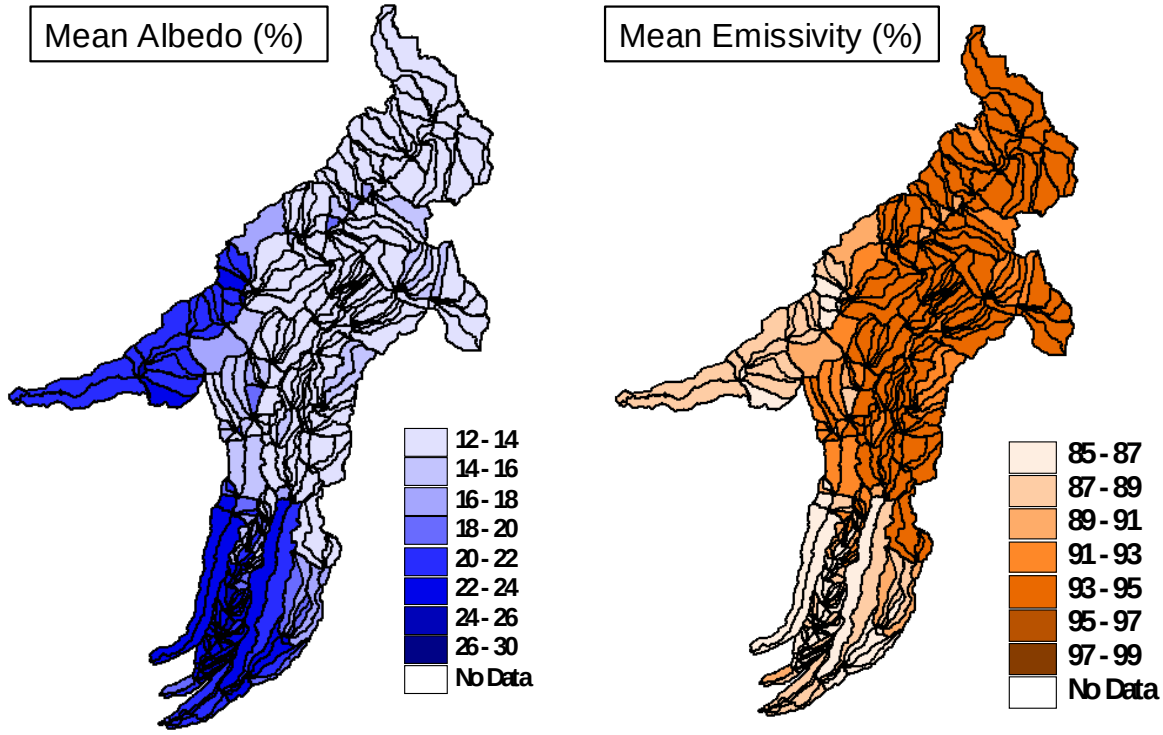

Figure 32- Mean albedo and mean emissivity map in the foothills watersheds

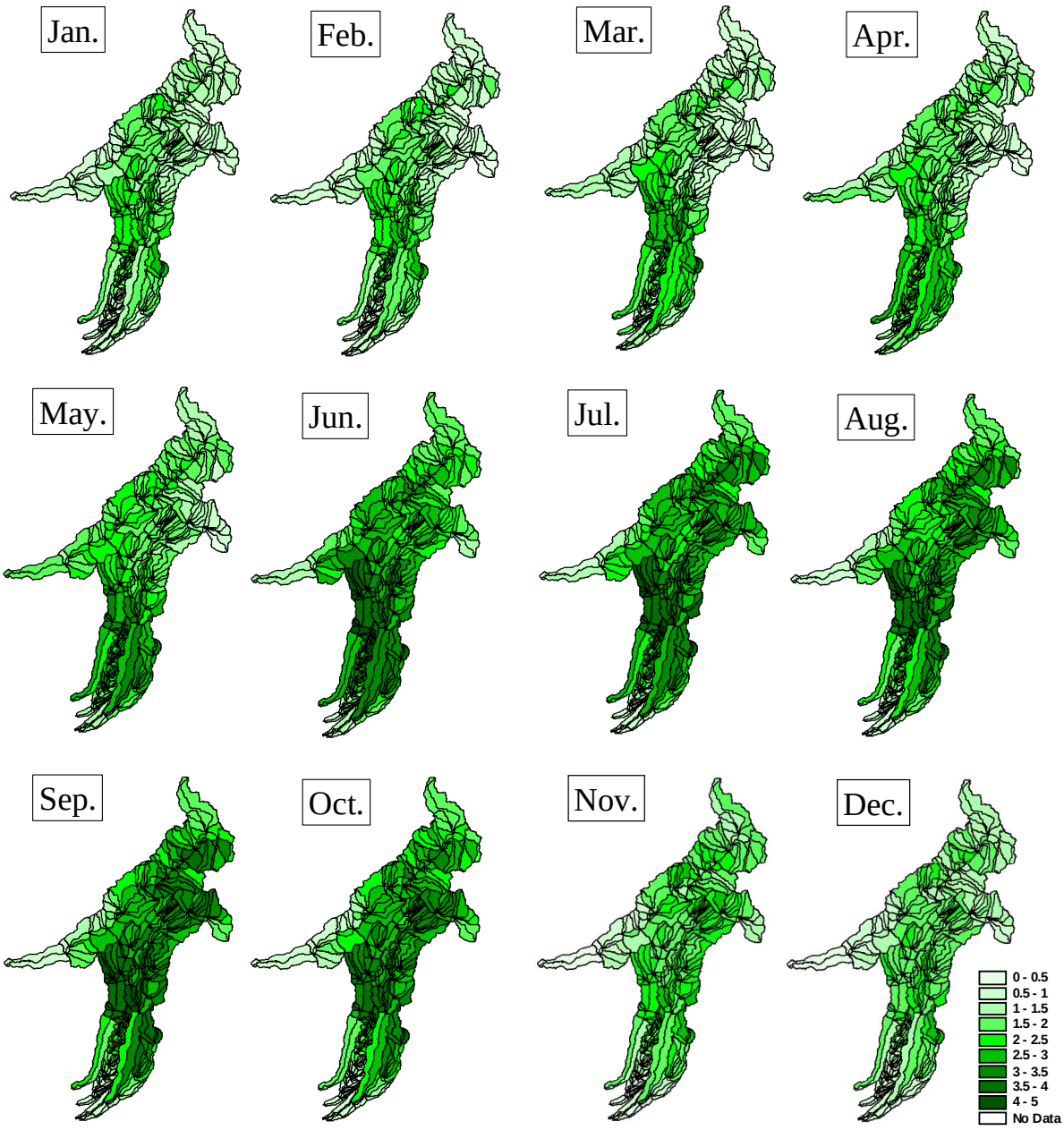

Figure 33- Seasonal mean LAI maps in the foothills watersheds

2) Snow Accumulation and Melting Process Modeling

The snow component of the WEHY model is based upon the depth-averaged energy balance equations that were developed by Horne and Kavvas (1997), and extended by Ohara et al. (2006) in order to incorporate the effect of topography-modified solar radiation on the spatial

distribution of snow melt, snow temperature, and snow depth, explicitly. Air temperature, wind speed, precipitation, and relative humidity are the required inputs to the snow algorithm of the model. **Figures 34** and **35** show the schematic description of the snow module of the WEHY model. In the model, a snow pack is divided into three layers in the vertical direction: a skin layer, a top active layer and a lower inactive layer, as shown in **Figure 35**.

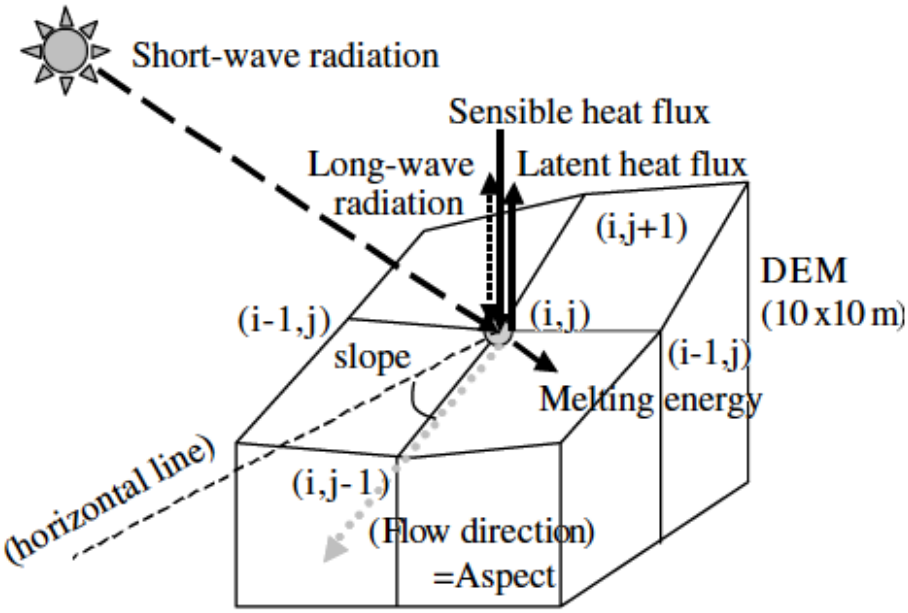

Figure 34- Sketch of spatially distributed snow model (Ohara et al. 2006)

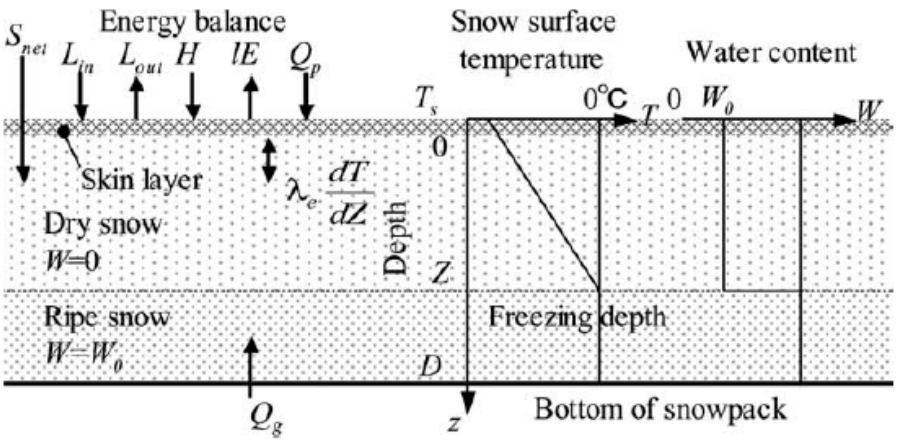

Figure 35- Illustration of the approximation of snow temperature vertical profile (Ohara et al. 2006)

For the input atmospheric data to the WEHY model, the reconstructed hydro-climate data at 3km spatial resolution based on the dynamic downscaling of NCAR/NCEP global reanalysis data

were employed. Parameters related to snow module such as the snow surface albedo were determined from the literature (Ohara et al., 2006).

Figure 36 shows the time series of the observed and model simulated snow water equivalent at the field observation sites in the foothills region during the calibration period. **Figure 37** shows the time series of the observed and model simulated snow depth at the field observation site in the foothills region during the calibration period. **Figure 38** shows the simulated snow cover extent and the maximum snow extent derived with MODIS/Terra snow cover at each first day of the month during the calibration period.

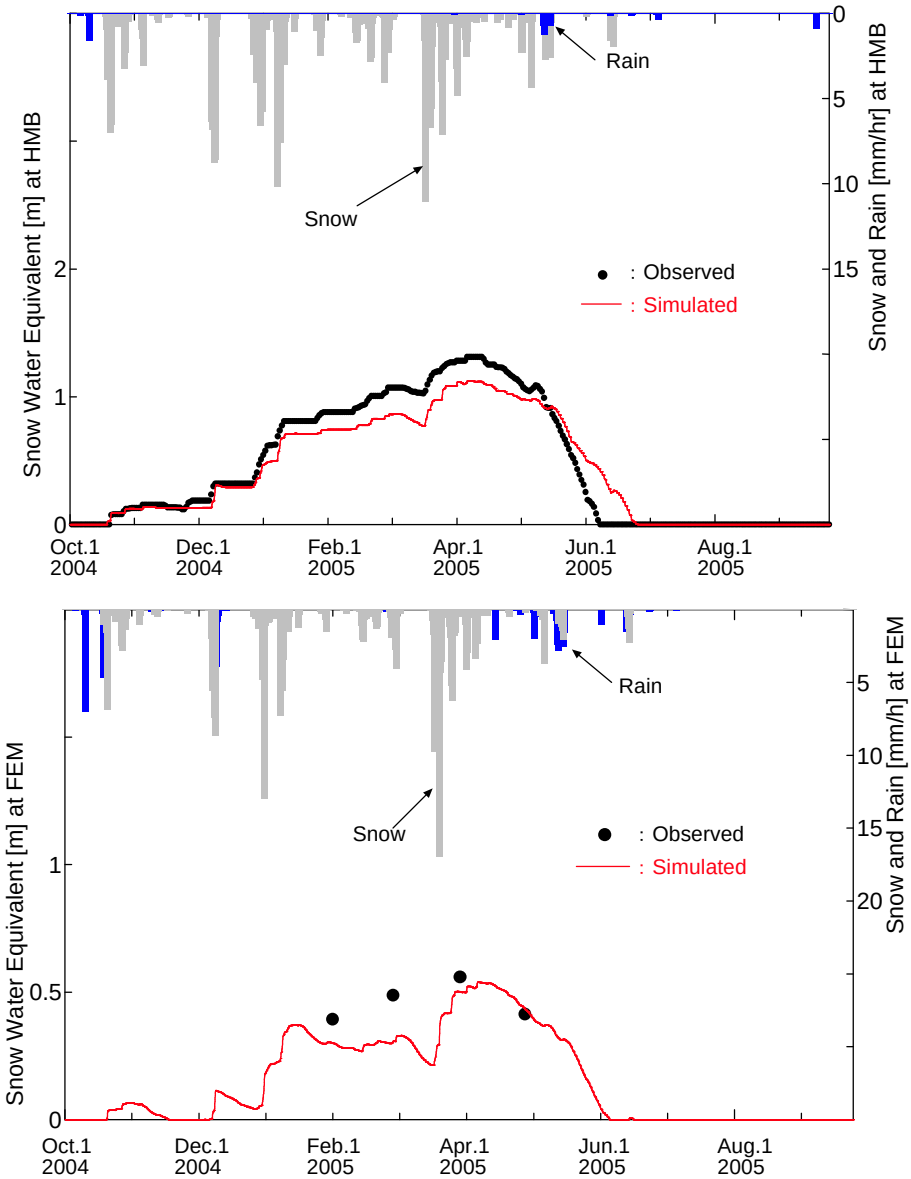

Figure 36- Time series of the observed and model simulated snow water equivalent at the field observation sites in the foothills region from October 2004 through September 2005

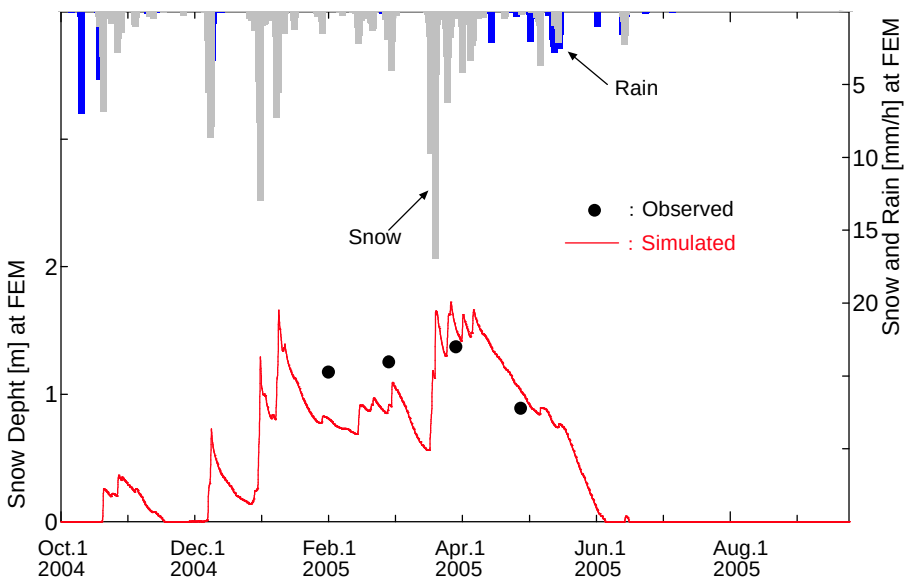

Figure 37- Time series of the observed and model simulated snow depth at the field observation site in the foothills region from October 2004 through September 2005

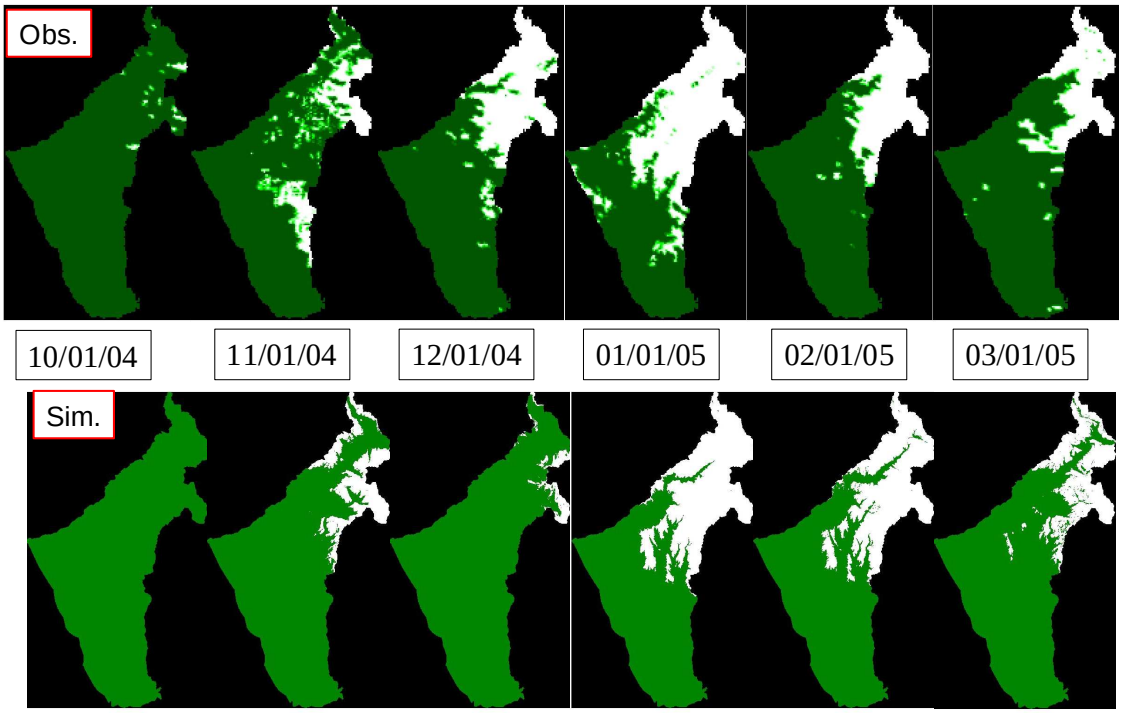

Figure 38- Model simulated snow cover extent and the maximum snow extent derived with MODIS/Terra snow cover at each first day of the month over the foothills region from October 2004 through March 2005

These figures indicate that the spatial and temporal distributions of snow cover are modeled reasonably well and these results are quite encouraging for the application of the hydrologic module of the WEHY model.

3) Hillslope Process Modeling and Stream Network Routing

First, the model was applied to the calibration period using the observed precipitation data as the input and calibration factors such as the initial soil moisture condition and Chezy roughness coefficient of surface hillslope were determined. Then calibrated model was applied to the validation period using the dynamically downscaled atmospheric data as the input. **Figures 39-42** show the time series of the observed and model simulated stream discharge at the field observation sites of each watershed in the foothills region during the calibration period. It should be emphasized that the soil and vegetation parameters are not calibration factors in the model, and parameters that were automatically determined from the GIS datasets were used in the model without any calibration. It is noted that there is no available data for stream discharge at Little Chico Creek during the calibration period. Therefore, the period from October 1991 through September 1992 was selected and daily mean discharge data were used for the calibration at Little Chico Creek. It can be seen from **Figures 39-42** that the simulated discharge data matched reasonably well with the observed ones except for the simulation result at Deer Creek (**Figure 42**). This is because there is no available hourly precipitation data in Deer Creek watershed, and hence we had to use the precipitation data of the CAR station that is located outside of the Deer Creek watershed, and, hence, is not appropriate to represent the precipitation field as the input data to Deer Creek watershed. This is the exactly the PUB problem, as we already mentioned in the former chapter.

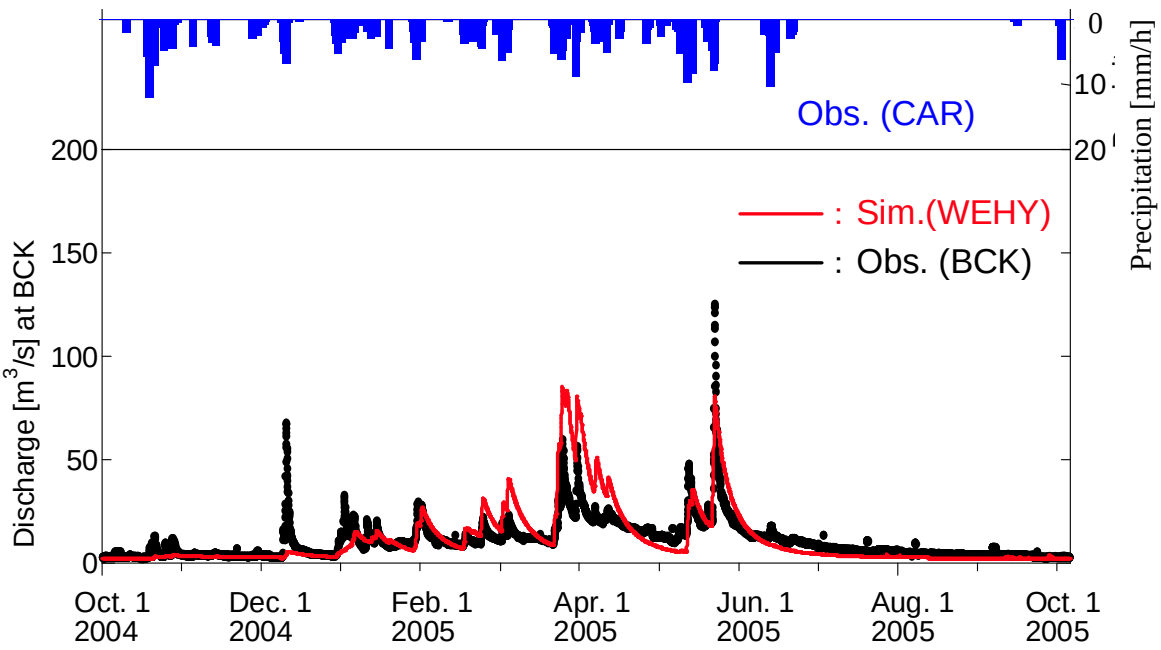

Figure 39- Time series of the observed and model simulated hourly stream discharge at the field observation site of the Butte Creek from October 2004 through September 2005

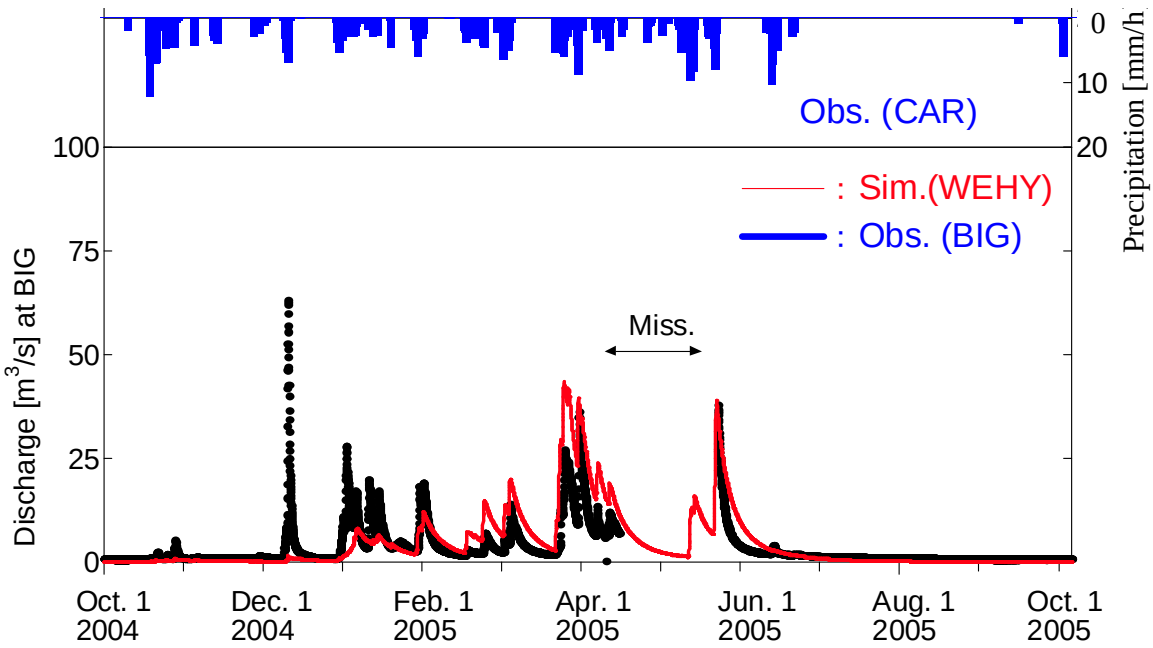

Figure 40- Time series of the observed and model simulated hourly stream discharge at the field observation site of the Big Chico Creek from October 2004 through September 2005

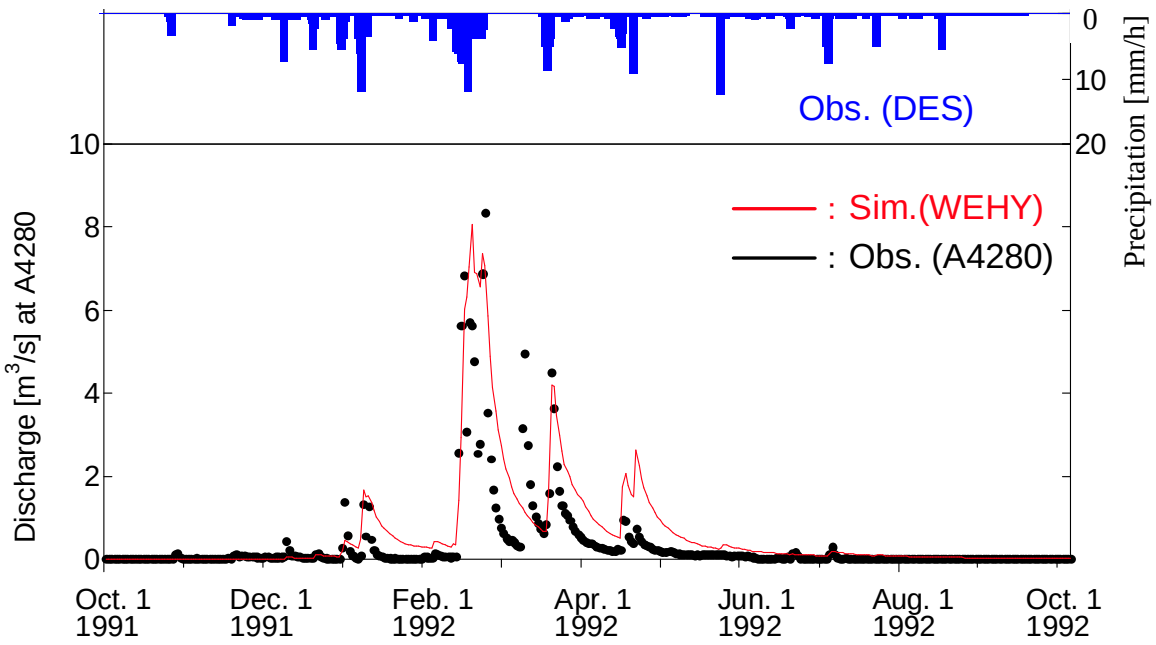

Figure 41- Time series of the observed and model simulated daily mean stream discharge at the field observation site of the Little Chico Creek from October 1991 through September 1992

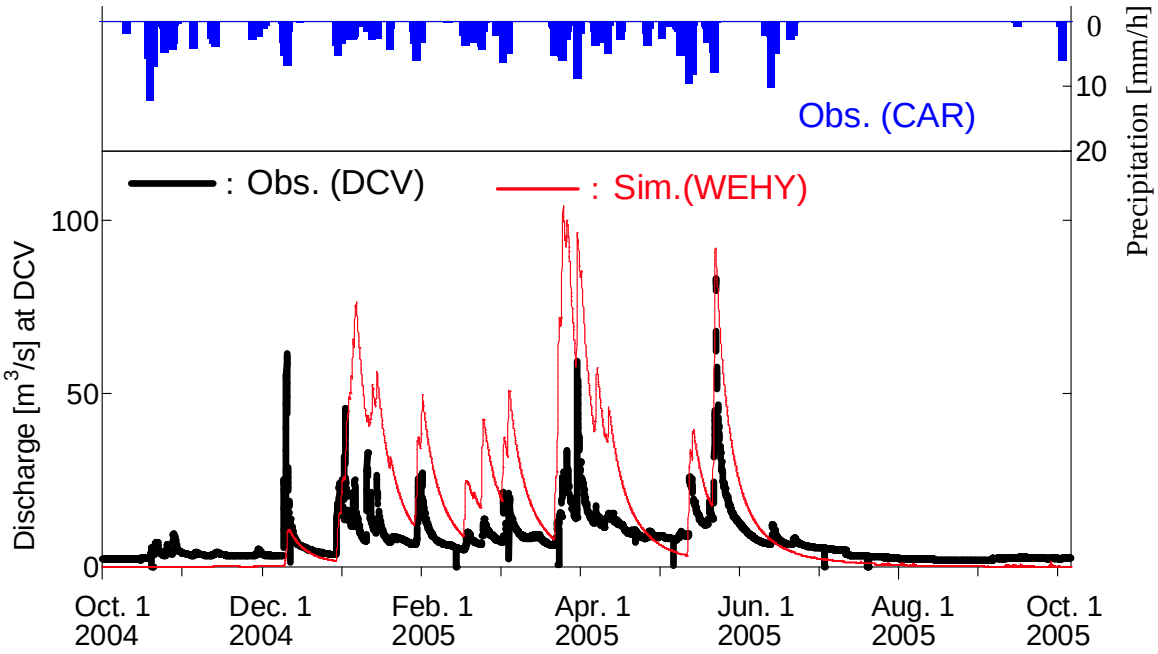

Figure 42- Time series of the observed and model simulated hourly stream discharge at the field observation site of the Deer Creek from October 2004 through September 2005

In order to validate the model simulation results, calibrated models at each watershed were applied to the validation period. It should be emphasized that in the validation simulation the dynamically downscaled atmospheric data were employed as the input data to the models. **Figures 43-46** show the time series of the observed and model simulated daily mean stream discharge at each observation station during the validation period. It can be seen from **Figures 41-44** that the observed and simulated daily discharge data matched well at the peak timings and values during both dry and wet years. Especially in Deer Creek watershed (**Figure 46**), the simulation result using the downscaled atmospheric input data for the validation period is apparently better than that using the observed precipitation input data for the calibration period. From these results, we concluded that the presented dynamic downscaling with the physically based distributed hydrology model employed in the project works quite well, and it can be a very useful tool for the flow prediction and watershed modeling in ungauged or sparsely gauged basins.

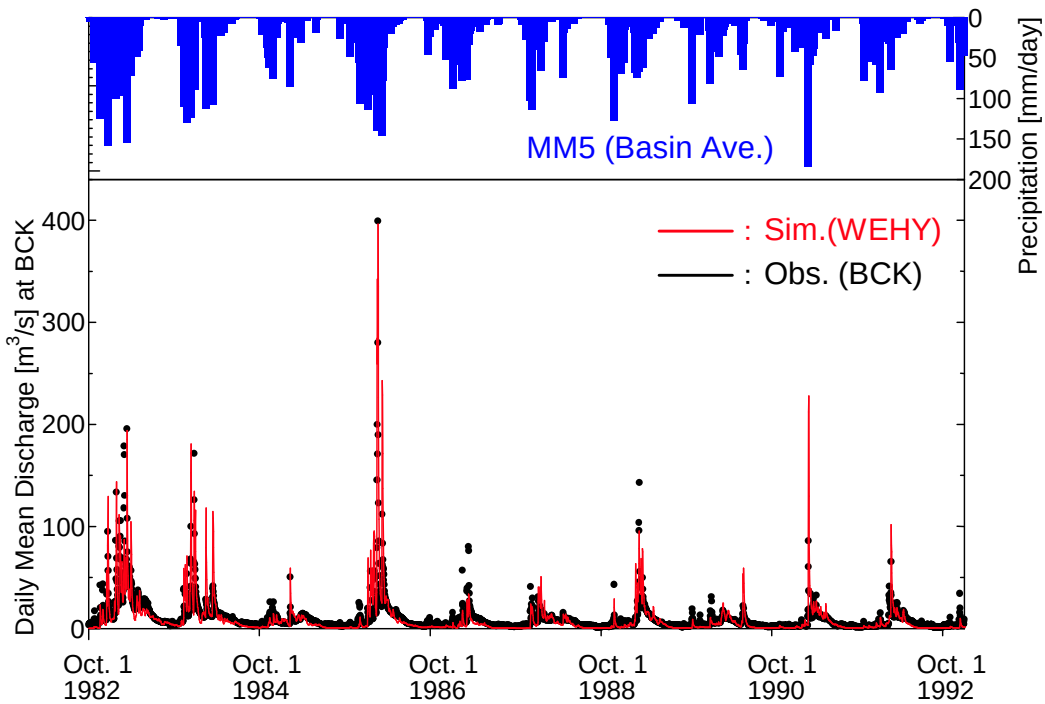

Figure 43- Comparisons of the daily mean discharge between WEHY model simulation and observations at Butte Creek watershed from October 1982 through September 1992

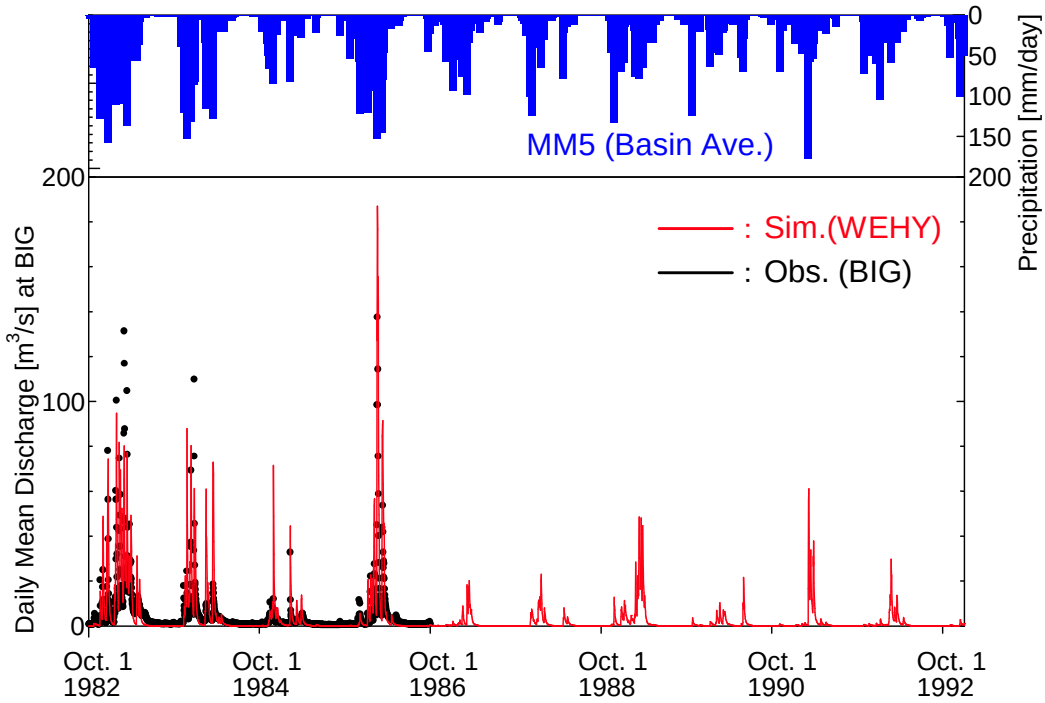

Figure 44- Comparisons of the daily mean discharge between WEHY model simulation and observations at Big Chico Creek watershed from October 1982 through September 1992

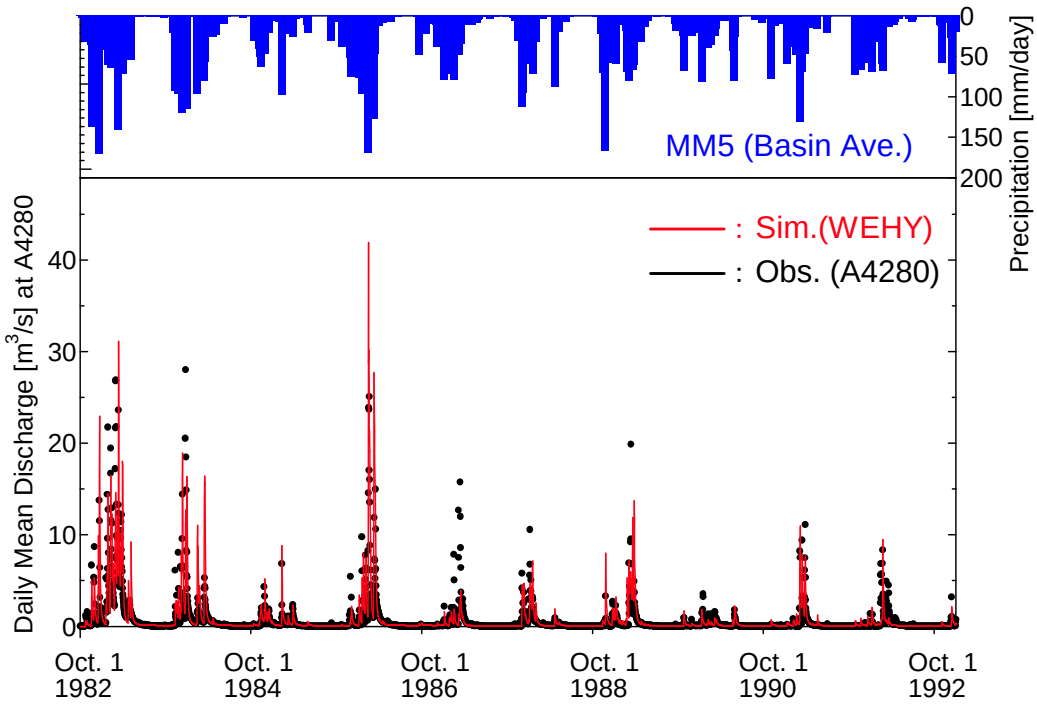

Figure 45- Comparisons of the daily mean discharge between WEHY model simulation and observations at Little Chico Creek watershed from October 1982 through September 1992

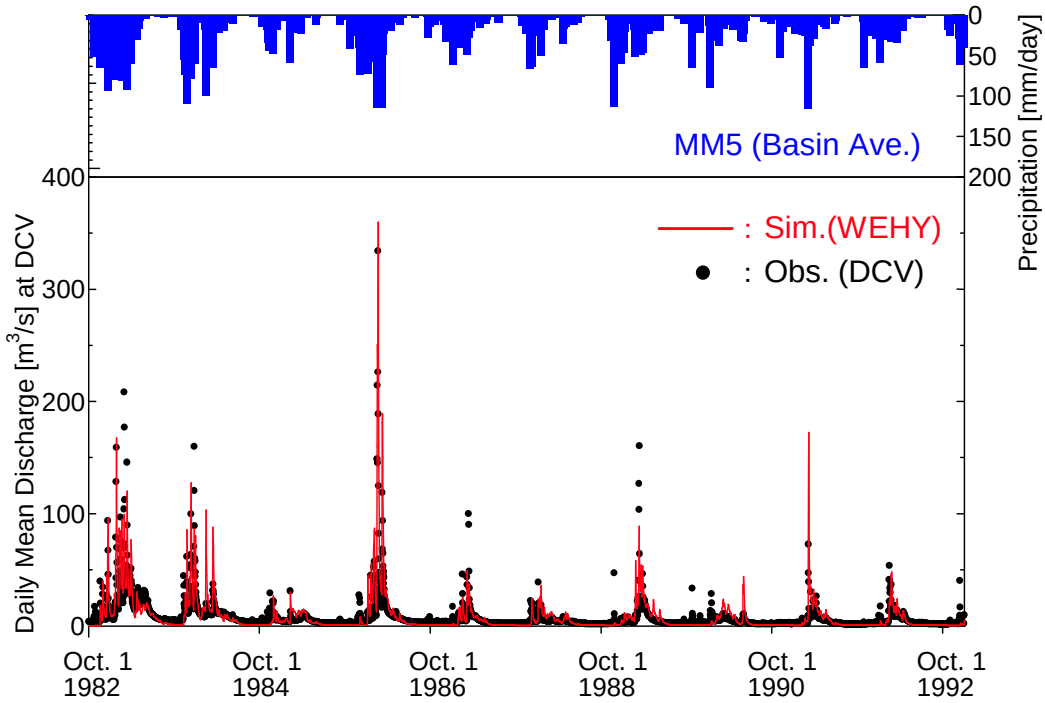

Figure 46- Comparisons of the daily mean discharge between WEHY model simulation and observations at Deer Creek watershed from October 1982 through September 1992

4) Model Evaluation at the Monthly Time Scale

For the groundwater flow models, water inflow volume from boundary watersheds at the monthly time scale is important because the time scale of the groundwater flow movement is much slower than that of the surface water flow. In this section the WEHY simulation results were compared to the observed values at the monthly time scale, and were evaluated based on some statistical goodness-of-fit criteria such as the root mean square error (RMSE) and Nash-Sutcliffe efficiency (Nash and Sutcliffe 1970). In the Nash-Sutcliffe efficiency, an efficiency of 1 corresponds to a perfect match of modeled discharge to the observed data. The closer the model efficiency is to 1, the more accurate the model is.

Figures 47 and **48** show the comparison of the observed and model simulated monthly river stream discharge data at each observation station during the validation period.

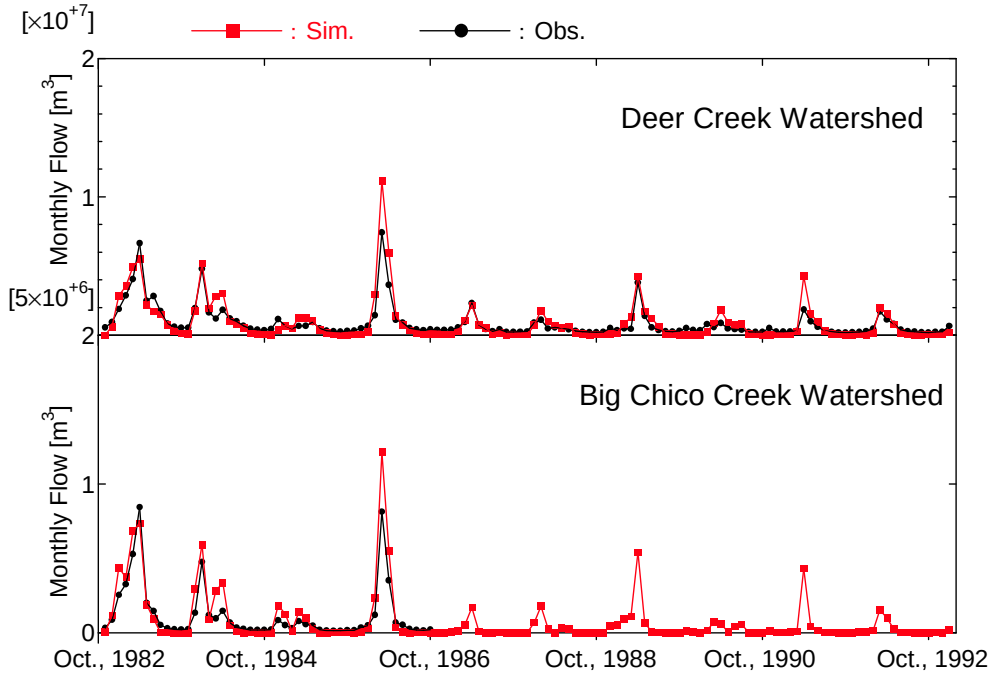

Figure 47- Comparisons of the monthly flow volume between WEHY model simulation and observations at Deer Creek watershed (Upper) and Big Chico Creek watershed (Lower) from October 1982 through September 1992

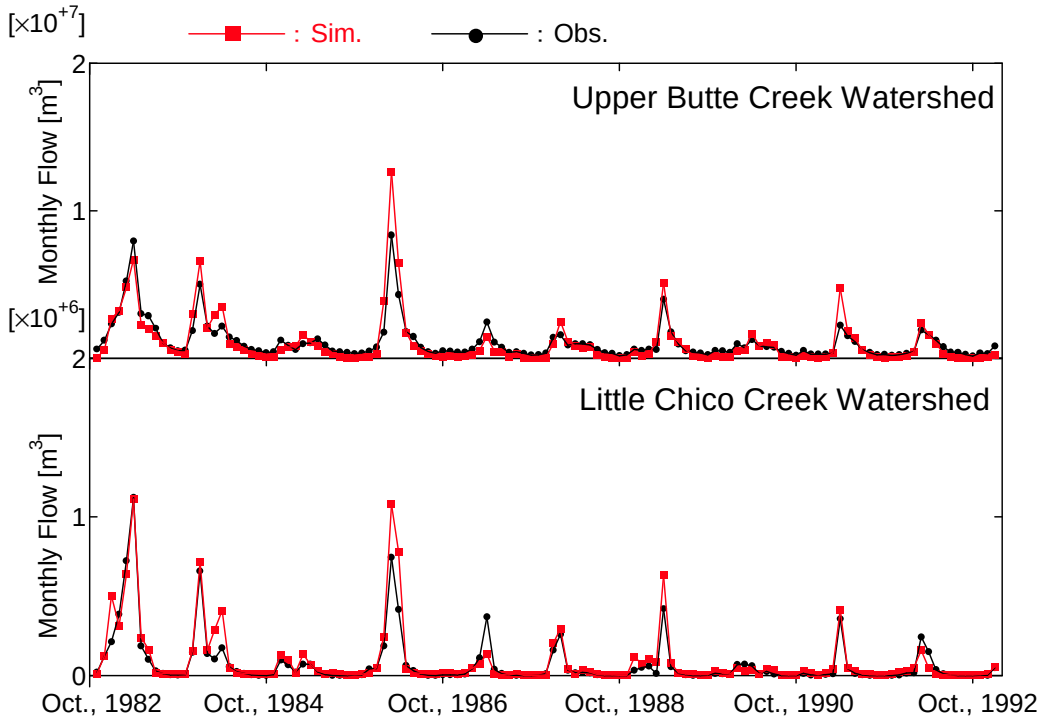

Figure 48- Comparisons of the monthly flow volume between WEHY model simulation and observations at Butte Creek watershed (Upper) and Little Chico Creek watershed (Lower) from October 1982 through September 1992

It can be seen from **Figures 47** and **48** that the simulation results and observed data matched very well at the monthly time scale. **Table 5** shows the RMSE, relative RMSE and Nash-Sutcliffe efficiency values for the simulations at each watershed. These statistical goodness-of-fit criteria strongly support the reliability of the simulation results of the model employed in the project. From these goodness-of-fit results, it may be inferred that the model simulation results are quite reliable for providing inflow data from the watersheds to the recharge zone land surface boundary of the IWFM ground water model for the Lower Tuscan Aquifer system and to improve the model performance of the IWFM.

Table 5- RMSE, Relative RMSE, and Nash-Sutcliffe Efficiency values for the simulation results at each studied watershed

Watershed	RMSE (mm)	Relative RMSE	Nash-Sutcliffe Efficiency
Big Chico Creek	2.49	1.20	0.90
Deer Creek	1.23	0.67	0.76
Little Chico Creek	0.90	0.75	0.80
Butte Creek	1.68	0.65	0.83

8. Inflow Data from the Foothills Watersheds to the Recharge Zone Land Surface Boundary of the IWFM Groundwater Model

In order to obtain reliable results from groundwater model simulations, and to be able to manage the groundwater levels appropriately, inflow data from the foothills watersheds to the recharge zone land surface boundary of the groundwater model should be provided reliably. In the project the calibrated and validated WEHY model was implemented in the foothills watersheds. WEHY model is a fully physically based and distributed model, so that we can obtain the discharge data from any point of the river stream network depending upon the spatial increment of the routing simulation. **Figure 49** shows the map of the boundaries of the watersheds and IWFM ground water model domain. In the figure the Green color circles represent the cross points of the WEHY model river stream network and IWFM ground water model domain. Simulated inflow data will be used as the input data to the IWFM model at these

cross points. **Figure 50** shows the time series of the daily mean inflow data at each cross point from October 1982 through September 1992. These inflow data were derived from the WEHY model which was implemented in the foothills watersheds, based on a rigorous calibration and validation study. The inflow data provided by this project will be improving the simulation results of the IWFM ground water model for the Lower Tuscan Aquifer system.

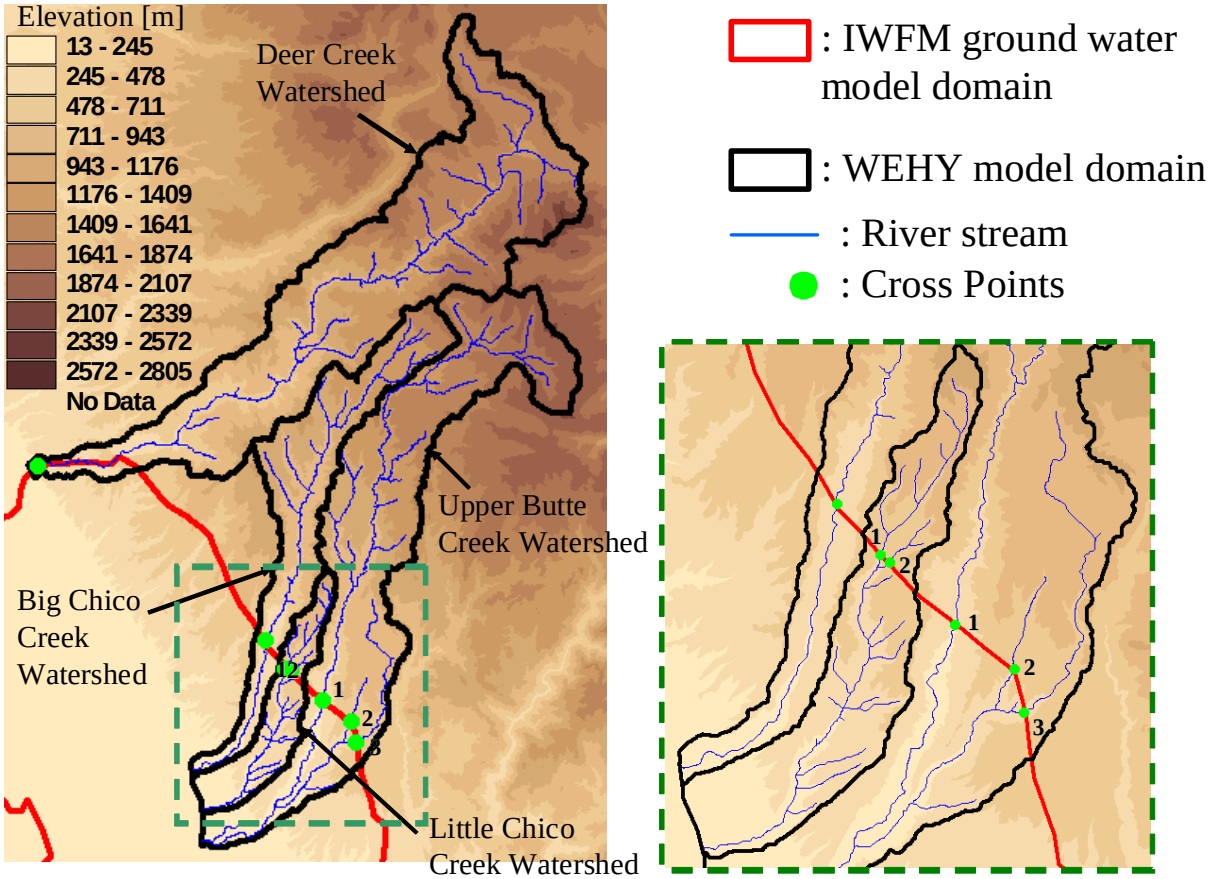

Figure 49- Cross points of the river stream network of the WEHY model and the model domain of the IWFM groundwater model

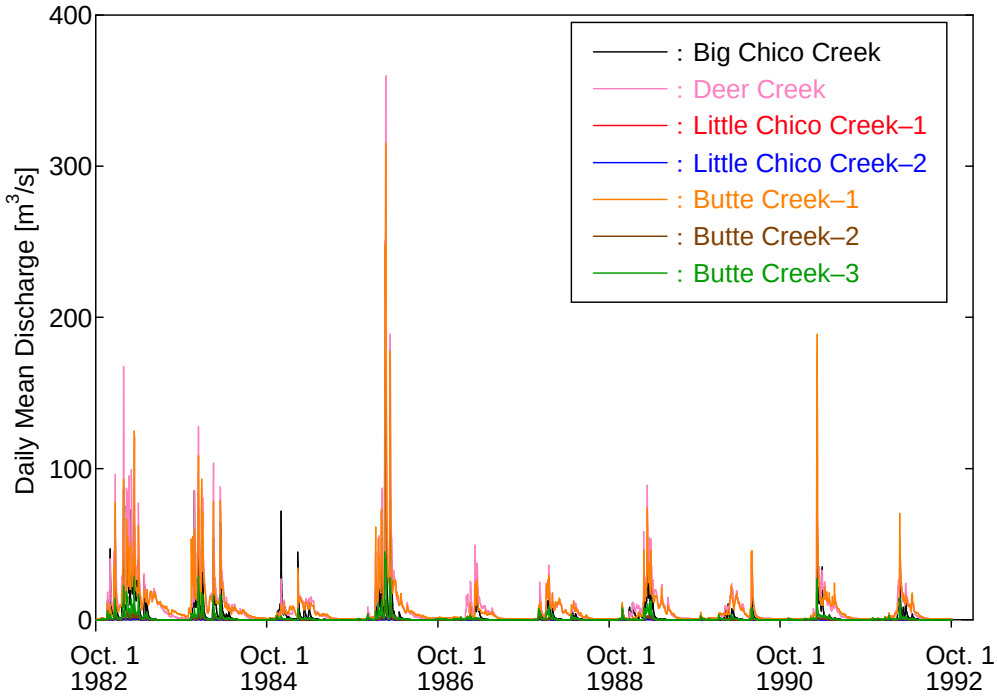

Figure 50- Inflow data from the foothills watersheds to the recharge zone land surface boundary of the IWFM groundwater model from October 1982 through October 1992

9. Summary and Conclusions

In this project, reconstruction of historical hydro-climate data based on a regional hydro-climate model (RegHCM) with the physically based, spatially distributed watershed environmental hydrology (WEHY) model was applied to the Deer Creek, Big Chico Creek, Little Chico Creek, and Butte Creek foothills watersheds in Northern California in order to estimate the run-off from these watersheds to the IWFM ground water model surface boundary. The recharge estimate provided by this project will provide the input into the Butte Basin Groundwater Model, and contribute to better management of the aquifer to protect local water supply reliability as the aquifer contributes to statewide water needs. It will assist water managers in protecting water users and ecosystems that are dependent on groundwater levels.

Success in flow prediction in an ungauged basin (PUB) is a challenging problem in Hydrology. It is possible to implement and use WEHY model at any ungauged or sparsely gauged watershed since its parameters are estimated directly from the land features of the watershed. Furthermore, historical atmospheric data are dynamically downscaled from NCAR/NCEP global reanalysis

data that cover the whole world. As such, this dataset enables modelers to obtain spatially distributed atmospheric variables at fine spatial resolution at hourly time increments. The application results of the dynamic downscaling and WEHY model were quite encouraging toward the solution of the PUB problem, because the results presented in the project were obtained from no calibration for the soil and vegetation parameters in the WEHY model. From these results, it is concluded that the presented dynamic downscaling with the physically based distributed hydrology model can be a useful tool for flow prediction and watershed modeling in ungauged or sparsely gauged basins like the foothills watersheds that are the focus of this project.

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