Journal of Hydrologic Engineering. Submitted December 22, 2011; accepted August 7, 2012;
posted ahead of print August 18, 2012. doi:10.1061/(ASCE)HE.1943-5584.0000701

WEHY-HCM for Modeling Interactive Atmospheric-Hydrologic Processes at Watershed Scale: II. Model Application to Ungauged and Sparsely-gauged Watersheds

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Abstract

The objective of this study is to evaluate the potential of the Watershed Environmental Hydrology Hydro-Climate Model (WEHY-HCM) for modeling runoff at ungauged or sparsely-gauged watersheds. The WEHY-HCM employs an atmospheric module (Fifth Generation Mesoscale Model, MM5) that is coupled with its process-based Watershed Environmental Hydrology (WEHY) module. In this study the atmospheric component of the WEHY-HCM was utilized for the dynamical downscaling of the coarse NCAR/NCEP historical global reanalysis atmospheric data over a foothills region in Northern California in order to reconstruct the historical hydro-climate data over four watersheds in the foothills region at 3

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km grid scale at hourly intervals. The WEHY-HCM's atmospheric module performance was evaluated by the comparison of model-reconstructed precipitation and air temperature against ground observations in time and space with satisfactory results. These results lead to the conclusion that WEHY-HCM may be useful at sparsely-gauged or ungauged watersheds for producing nonexistent atmospheric data as input to the modeling of surface and subsurface hydrologic processes at such watersheds. By means of the reconstructed atmospheric data as its input, the WEHY module of WEHY-HCM was then applied to the Sierra foothills region, encompassing Big Chico Creek (192 km^2), Little Chico Creek (78 km^2), Upper Butte Creek (407 km^2) and Deer Creek (508 km^2) watersheds in Northern California, USA. The model simulations of daily and monthly runoff at these watersheds, when compared against historical observations by means of visual inspections and statistical tests during a validation period yielded satisfactory results. Therefore, it is concluded that the WEHY-HCM may be useful in producing both atmospheric data and runoff simulations over ungauged and sparsely gauged watersheds.

CE Database subject headings: Hydrologic prediction in ungauged basins; Dynamic downscaling; Watershed Hydro-Climate model; Process-based modeling

Introduction

Physically based distributed models play significant roles in watershed hydrology and environmental modeling. They assist the development and implementation of management strategies for improving watershed function and environmental quality, and the assessment of the land use/cover and climate change impacts on the water resources and flood disasters in watersheds. This is because the distributed models can incorporate topographic features and geologic and land cover variability and provide the spatial variability and pathways of water and substances through a watershed. The distributed models

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strongly rely on precipitation or other atmospheric data input to drive the simulation of runoff or environmental processes. For example, 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 difficult to obtain such spatially distributed hydro-atmospheric data in ungauged or sparsely-gauged watersheds at fine resolutions in time and space. Accordingly, it is difficult to apply the physically based distributed models to the watersheds where data are limited or unavailable. As such, success in making predictions in ungauged basins (PUB) is a challenging problem in hydrology (Sivapalan et al., 2003; Cavadias et al., 2001; Sedaghi and Singh, 2010).

Recent advances in remote sensing technology makes it possible to obtain hydrologic information in ungauged basins (Coe and Birkett, 2004; Bjerklie et al., 2005; Sun et al., 2009; Sayama et al., 2011; Kure et al., 2012). For example, Sun et al. (2009) proposed a methodology for estimating discharge in large ungauged basins that utilized a rainfall runoff model and hydraulic information obtained from remote sensing. Sayama et al. (2011) used the satellite driven precipitation data, named GSMaP (Global Satellite Mapping of Precipitation) developed and provided by JAXA (Japan Aerospace Exploration Agency), for the rainfall runoff inundation analysis in Pakistan. GSMaP provides nearly real time hourly precipitation data that covers the whole globe at a 0.1 degree resolution in space. Kure et al. (2012) employed the GSMaP data for the statistical downscaling of the global climate model projections for the climate change study in the Republic of Tajikistan. As such, in most parts of the world, a significant amount of spatial information through remote sensing imagery is currently available. However, the hydrological information derived from such sources provides only the historical data. Also, the remote sensing data provide usually the land surface information that may contain some uncertainty.

One of the solutions to the PUB problem may be a Regional Climate Model (RCM) coupled with a

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physically based watershed hydrology model. Regional or global data sets obtained from reanalysis of observations using a General Circulation Model (GCM) can be a useful data set for the PUB problem because this kind of data set covers the whole globe. However, spatial resolutions of the GCM outputs are usually too coarse for the watershed hydrology modeling, so that some kind of spatial downscaling technique, such as dynamical downscaling using an RCM, is required (Kavvas et al., 1998; Westrick et al., 2002; Anderson et al., 2007; Yoshitani et al., 2009, Chen et al., 2011, Ohara et al., 2011). One of the advantages in the physically based or process based watershed hydrology models (e.g. Kavvas et al., 2004; Kampf and Burges, 2007; Sayama and McDonnell, 2009) is that these models can be implemented at any ungauged or sparsely-gauged watershed without any model parameter calibration based on the observed river discharge data since their parameters are estimated directly from the land features of the watershed. However, as is already discussed, physically based models require atmospheric input data which are not available at ungauged watersheds. From this perspective, the Watershed Environmental Hydrology Hydro-Climate Model (WEHY-HCM, Kavvas et al., 2012) that employs atmospheric components coupled with the physically based, spatially distributed Watershed Environmental Hydrology (WEHY) Model can be used as a tool to reconstruct the hydro-atmospheric data at ungauged or sparsely-gauged basins.

The objective of this study is to estimate the runoff from ungauged or sparsely-gauged basins using the WEHY-HCM in order to explore its utility. WEHY-HCM is applied to the Sierra foothills region, encompassing Big Chico Creek, Little Chico Creek, Upper Butte Creek and Deer Creek watersheds in northern California, USA. Some of the watersheds, especially Deer Creek and Butte Creek watersheds, are located at high elevation (> 2,000 m) 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 - June). Therefore, the module on snow accumulation and melting processes in the WEHY model is

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necessary for the precise estimation of the runoff from these watersheds.

Study Region and Study Period

Big Chico Creek (192 km^2), Little Chico Creek (78 km^2), Upper Butte Creek (407 km^2) and Deer Creek (508 km^2) watersheds in Northern California were selected as the target watersheds in this study, as shown in **Figure 1**. These watersheds are located at the foothills and are covered by various vegetation types through elevations 86 - 1,798 m (Big Chico Creek watershed), 87 - 1,065 m (Little Chico Creek watershed), 69 - 2,187 m (Butte Creek watershed) and 150 - 2,390 m (Deer Creek watershed). Hence, the land use/cover of this area is heterogeneous. **Figure 2** 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, http://www.atlas.ca.gov/download.html), with a USGS land use classification. Vegetation primarily consists of evergreen needle and deciduous trees.

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. The calibration period was the hydrologic year from October 2004 to September 2005 and the validation period was the hydrologic years from October 1982 through September 1992. The validation period included critically dry (1987 - 1992) and wet (1982 and 1983) years in Northern California.

Historical records of ground data are needed for the model calibration and validation processes. Fourteen stations from California Data Exchange Center (CDEC, http://cdec.water.ca.gov/) of California Department of Water Resources were located in the study area, measuring precipitation, stream flow discharge, and snow data (**Figure 3)**. There are no precipitation stations in the Deer Creek and Little Chico Creek watersheds. Furthermore, there are only two stations (DES and CAR) which provide hourly precipitation over the other two watersheds.

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Reconstruction of Historical Atmospheric Data at Fine Resolution at the Target Watersheds

In order to apply watershed models to the ungauged or sparsely-gauged watersheds, such as the target watersheds of this study, historical atmospheric data over the investigated area should be reconstructed. However, the existing U.S. National Center for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) global reanalysis atmospheric data resolutions are approximately 210 km in the horizontal directions, and at 6-hour time intervals over Northern California. These data are too coarse for watershed hydrologic modeling. Hence, it is necessary to downscale these data over the study region at fine space-time resolution for hydrologic modeling applications. In order to reconstruct historical atmospheric data at the target watersheds, the NCEP/NCAR coarse-resolution global atmospheric reanalysis data were dynamically downscaled to 3 km grid resolution at hourly intervals over the target watersheds by means of the MM5 atmospheric module (Anthes and Warner ,1978; Grell et al., 1995) of the WEHY-HCM, described in Kavvas et al. (2012). NCEP/NCAR global reanalysis data were used as initial and boundary conditions for MM5. Four one-way nested grids (**Figure 4)** were set up within the model to create a downscaling process from the approximately 210 km $\times$210 km scale reanalysis data to the 3 km$\times$3 km scale over the four studied foothills watersheds in Northern California (**Table 1**). Each nested domain had a spatial resolution of 1/3 of the parent grid and focused more on the study area of the foothill watersheds. The 1/3 ratio was recommended in the user's documentation for MM5 (Grell et al,. 1995).

Figure 5 shows the comparisons of the observed and model simulated monthly precipitation at each observation station during the January 1982 - December 1992 period. **Figure 6** 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 well at monthly time scale. Simulation results were evaluated based on the coefficient of determination (R^2), root mean square error (RMSE), Nash-Sutcliffe efficiency (Nash and Sutcliffe, 1970), and Chi-square goodness-of-fit criteria, as shown in **Table 3**. In the Nash-Sutcliffe efficiency, an efficiency of 1 corresponds to a perfect match of the modeled discharge to the observed data. The closer the model efficiency is to 1, the more accurate the model is. It is seen from these figures and table that the observed and simulated precipitation and mean air temperature matched very well at monthly time scale. The goodness-of-fit statistics, shown in **Table 3,** support the reliability of the simulation results of the model.

Figure 7 shows a comparison between the model simulated precipitation field and PRISM (Parameter-elevation Regressions on Independent Slopes Model) data over the studied foothills region in Northern California for December 1987. PRISM data sets, developed by Oregon State University (Daly et al., 2008), provide interpolated ground precipitation observation data that have 4 km spatial resolution and monthly time intervals over USA from 1895 to present. WEHY-HCM simulated and PRISM estimated precipitation fields are similar both with respect to magnitude and spatial distribution. However, model simulated precipitation fields show high intensity precipitation structures around the high elevation areas 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. Hence, 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 WEHY-HCM employed in this study. These results, related to the dynamical downscaling of NCEP/NCAR reanalysis data, are encouraging for the watershed modeling in the specified foothills region of Northern California.

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Modeling the Hydrologic Processes by the WEHY-HCM at the Target Watersheds

The WEHY watershed hydrology module of WEHY-HCM (Kavvas et al., 2012) was applied to Deer Creek, Butte Creek, Big Chico Creek and Little Chico Creek watersheds by means of the atmospheric data that were reconstructed by the MM5 component of WEHY-HCM in order to simulate the hydrologic processes at these watersheds. Detailed descriptions of the WEHY model are given elsewhere (Kavvas et al., 2004; Chen et al., 2004a, b; Kavvas et al., 2006; Kavvas et al., 2012). Briefly, the WEHY model computes the surface and subsurface hillslope hydrologic processes 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 as well as with each other. These discharged flows are then routed by means of the stream network and the unconfined groundwater aquifer routing. The snow processes are modeled by an energy balance, three-layer snowpack module.

One of the advantages of the physically based models is that the model parameters are based on geophysical and vegetation properties, and can be estimated directly from the Geographical Information System (GIS), developed based on the land databases. Hence, in order to implement the WEHY model over the target watersheds it was necessary to develop a GIS for these watersheds. The digital elevation model (DEM) data at 1 arc second resolution (~ 30 m) were downloaded from the Seamless Data Center (http://seamless.usgs.gov/) USGS (Gesch et al., 2009) and processed for the target watersheds and their adjacent regions. Vegetation parameters such as roughness height, albedo, emissivity and vegetation root depth for the land surface, were determined from NCAR Reference Table with Multi-source Land Cover Data (Bonan et al., 2002), published by CaSIL, which has 100 m spatial resolution. In order to consider the seasonal change of vegetation, monthly mean Leaf Area Index (LAI) values were determined from

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MODIS (MODerate resolution Imaging Spectroradiometer; Wolfe et al., 1998) satellite driven data at 1 km spatial resolution. For the estimation of soil parameters such as saturated hydraulic conductivity, soil depth, soil porosity and bubbling pressure, the USDA Soil Survey Geographic database SSURGO (Soil Conservation Service, 1991) which has the finest available spatial resolution over the study area, was used along with the relationships between soil texture and soil hydraulic parameters (McCuen et al., 1981).

The target watersheds were subdivided into model computational units (MCUs) (**Figure 8** and **Table 2**) that were delineated from the DEMs of the watersheds by means of a GIS analysis (Chen et al., 2004a) which also produced the corresponding stream networks. These MCUs are either individual hillslopes or first-order watersheds.

Parameters of each stream reach and of each MCU were estimated directly from the GIS database of the watersheds, which contained information about the physical characteristics of the watersheds. Estimation of the geomorphologic, soil hydraulic and vegetation parameters for MCUs of the WEHY model by the procedure of Chen et al. (2004a) was performed by first overlaying the boundaries of the MCUs on the DEM map, the soil class map, and the vegetation class map. Then all of the parameters of an MCU were retrieved from the GIS data that were associated with the grid cells inside the boundary of that MCU. As explained in 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.

As examples of model parameter estimation, **Figure 9** shows the mean soil depth and median of saturated hydraulic conductivity values at each MCU of the studied foothills watersheds. **Figure 10** shows the monthly mean LAI values at each watershed at every month. Besides the geomorphologic parameters, the soil hydraulic parameters and vegetation parameters, 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 calibrated based on the observed river discharge data. However, if there are no historical river flow data, the Chezy roughness coefficients can still be estimated from the readily observable physical characteristics of the streams at the studied watersheds, using tables in Chow (1959), Henderson (1966) or ASCE Task Force on Friction Factors in Open Channels (1963).

Snow processes at the target watersheds were modeled by the snow component of WEHY model that is described in Ohara and Kavvas (2006). Air temperature, wind speed, precipitation, and relative humidity are the required inputs to the snow component of the model. The reconstructed atmospheric data by the atmospheric component of WEHY-HCM provided these inputs. Snow module parameters such as the snow surface albedo were determined from the literature (Ohara and Kavvas, 2006). Snow water equivalent, snow depth and snow cover modeling results over the study region are shown respectively in **Figures 11 – 13**.

In order to model the hillslope hydrologic processes and routing the flows through the stream network of a target watershed, the WEHY-HCM was applied to the calibration period using the observed precipitation data as the input and the watershed runoff observations as the output. Through calibration the initial soil moisture condition and Chezy roughness coefficient at each MCU (hillslope), and Manning's roughness coefficient at each segment of the stream network were determined. Then the calibrated model was applied to the validation period using the atmospheric data that was dynamically downscaled by the atmospheric module of the WEHY-HCM, as the input. It is noted that the soil and vegetation parameters are not calibration factors in the model, and were determined directly from the GIS dataset. It is also noted that there were no available data for stream discharge at Little Chico Creek during the calibration period (October 2004 – September 2005 period). Therefore, October 1991 - September 1992 was selected and daily mean discharge data were used for the calibration at Little Chico

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Creek. **Figures 14** and **15** show the time series of the observed and model simulated stream discharge at the field observation sites of each watershed in the studied foothills region during the calibration period.

In order to validate the model performance and reliability, the calibrated models at each watershed were then applied to the validation period. In the validation simulations the atmospheric data that were dynamically downscaled by the atmospheric module of the WEHY-HCM, provided the input to the watershed hydrology module of WEHY-HCM. **Figures 16 - 19** show the time series of the observed and model simulated daily and monthly mean stream discharge at each observation station during the validation period.

Discussion of WEHY-HCM Application Results

The application of WEHY-HCM to the aforementioned four target watersheds during the calibration and validation periods were evaluated both by visual inspections as well as by statistical methods.

The performance of the snow module was investigated by comparison of model simulations against limited observations. **Figure 11** shows the time series of the observed and model simulated snow water equivalent at two field observation sites in the study region during the calibration period. **Figure 12** shows the time series of the observed and model simulated snow depth at one of the field observation sites in the study region during the calibration period. **Figure 13** shows the simulated snow cover extent and the maximum snow extent that were derived from MODIS/Terra snow cover at 500 m resolution (Hall et al., 2000) each first day of the month during the calibration period. The visual inspections of these figures indicate that the snow water equivalent and snow depth were modeled well at the observation sites while the spatial and temporal distributions of snow cover were modeled well over the target watersheds.

From the calibration results in **Figures 14** and **15** it is seen that the WEHY-HCM-simulated

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discharge matched the corresponding observations well except at Deer Creek (right hand side of **Figure 14**). This is because there are no available hourly precipitation data at Deer Creek watershed. Hence the precipitation data of the CAR station that is located outside of the Deer Creek watershed, had to be used for calibration. While the CAR station is the closest to the Deer Creek watershed outside the watershed boundaries, it does not seem to represent the precipitation field over the Deer Creek watershed. This is a typical PUB problem, as was discussed earlier.

The main evaluation of the model performance was carried out by visual inspections and statistical analyses of the WEHY-HCM streamflow simulations at the target watersheds during the validation period. **Figures 16 - 19** show the time series of the observed and model simulated daily and monthly mean stream discharge at each observation station during the validation period. From a visual inspection of **Figures 16 - 19** it may be inferred that the WEHY-HCM simulates the daily and monthly streamflows satisfactorily at the target watersheds. Since the WEHY-HCM includes a hillslope process model component, a snow accumulation and melting processes component, and a coupled groundwater flow-river channel routing model component (Kavvas et al., 2012; Kavvas et al., 2004), not only the peak flow discharge but also the flow recession and base flow sections of the hydrograph are simulated well.

Statistical analyses of the modeled streamflows against the corresponding observations were also carried out in order to evaluate the model performance during the validation period. WEHY-HCM's WEHY module streamflow simulation results were evaluated based on various statistical goodness-of-fit criteria, as shown in **Table 3**. The statistical goodness-of-fit criteria, shown in **Table 3,** support the reliability of the simulation results of the model at these watersheds. Especially in Deer Creek watershed (**Figures 16** and **18**), the WEHY-HCM streamflow simulations by means of the model-downscaled precipitation input data during the validation period are better than those model simulations during the

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calibration period that employed the observed precipitation input (from the closest station outside the watershed). From these results, it may be inferred that the WEHY-HCM, employed in this study, performs quite well in general, and can be a useful tool for the flow prediction and watershed hydrology modeling in ungauged or sparsely-gauged watersheds.

Summary and Conclusions

In this study the WEHY-HCM watershed hydro-climate model (Kavvas et al., 2012) which is comprised of MM5 atmospheric model, coupled to the process-based WEHY watershed hydrology model, was applied to Deer Creek, Big Chico Creek, Little Chico Creek, and Butte Creek foothills watersheds in Northern California in order to evaluate the potential of the model for the estimation of runoff from these watersheds where the precipitation/flow data are limited or unavailable. From the results of this application study it is concluded that it is possible to apply WEHY-HCM to the simulation of atmospheric and hydrologic processes over ungauged or sparsely-gauged watersheds, such as the four target watersheds that were investigated in this study. Among the four studied watersheds, Deer Creek watershed and Little Chico Creek watershed have no precipitation station, and Big Chico Creek watershed has only one precipitation station. Also, there are no snow stations in any of the four watersheds although snow is of fundamental importance in the water balances of these watersheds.

By means of the MM5 atmospheric module of WEHY-HCM it was possible to reconstruct the historical atmospheric data at fine time-space resolution over the target watersheds. Hence, even if there is no atmospheric data over a watershed, it is possible to reconstruct such data within the modeling framework of WEHY-HCM. Meanwhile, with the necessary atmospheric inputs provided, it is possible to implement and use the WEHY watershed hydrology module of WEHY-HCM at any ungauged or sparsely-gauged watershed since all of its parameters may be estimated directly from the land features of the watershed.

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Fig 1.pdf

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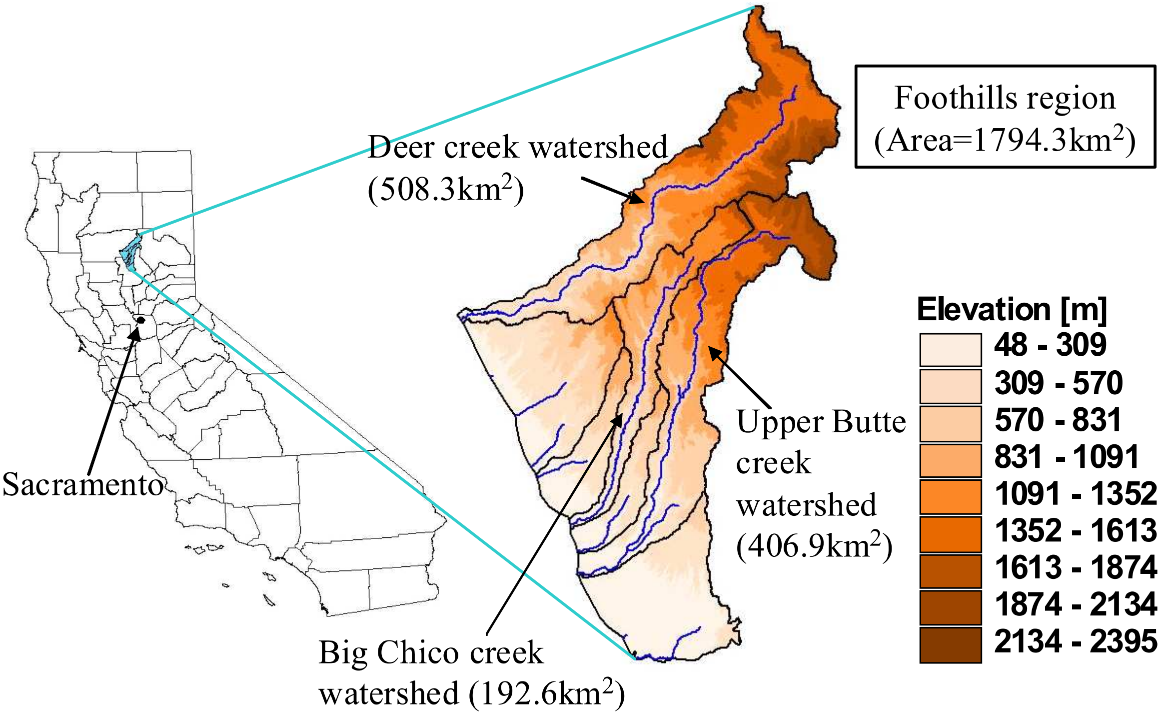

Figure 1- Map of the foothills study region, Northern California: geographic locations and topographic variations

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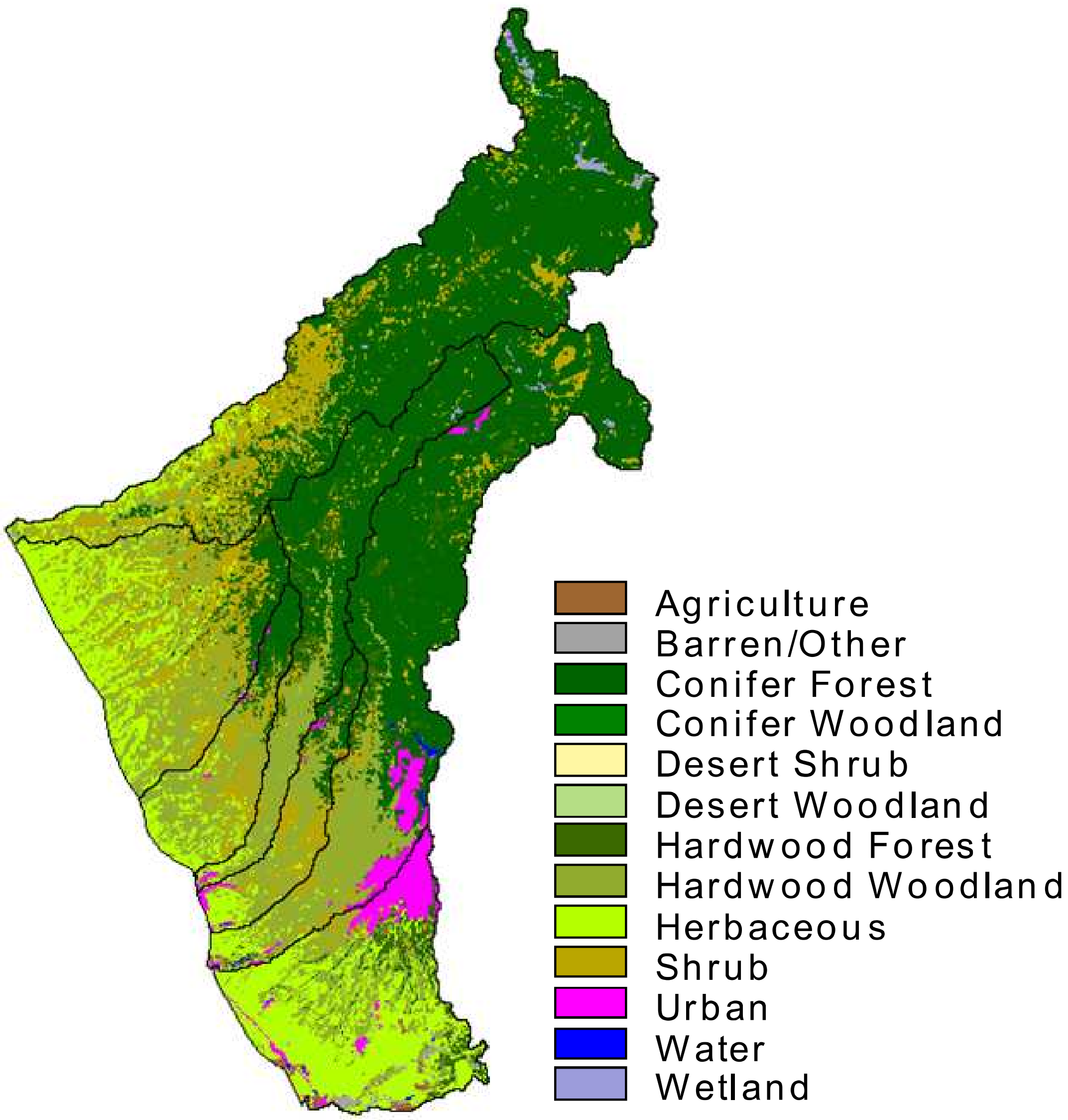

Figure 2- Vegetation and land use/cover map over the studied foothills watersheds

Fig 3.pdf

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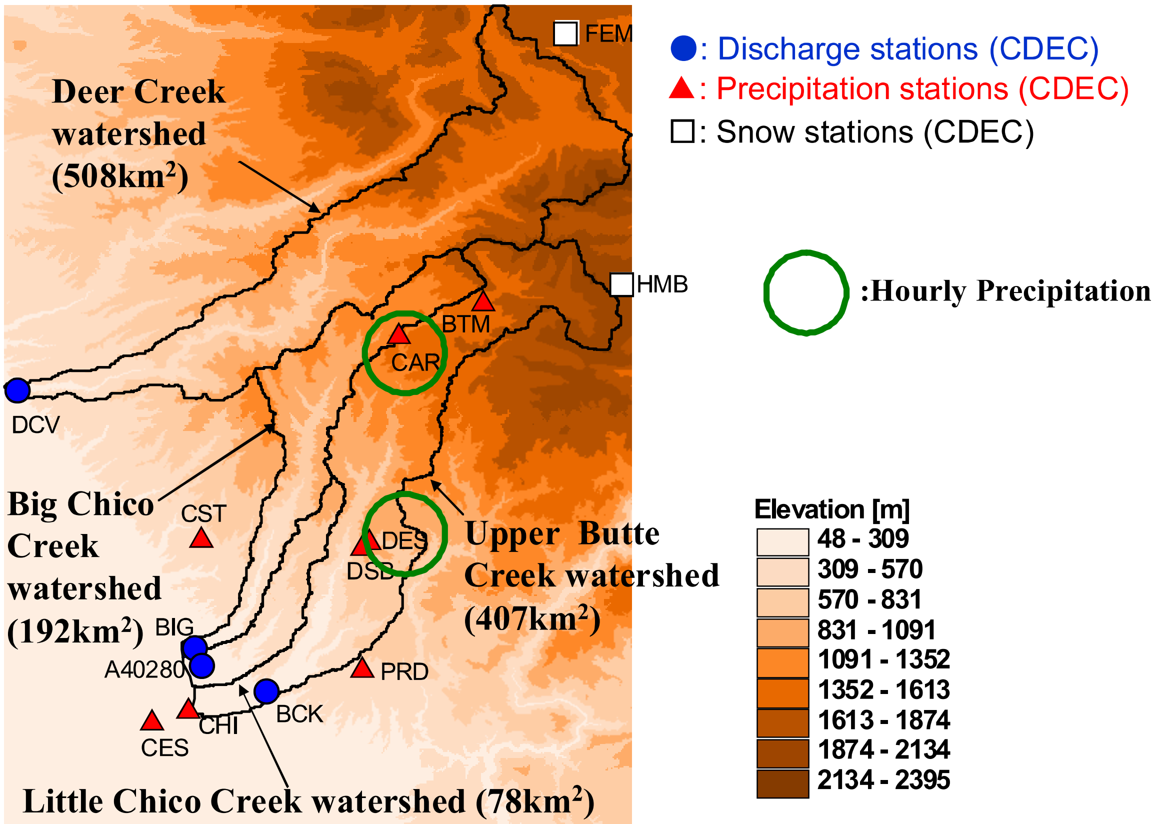

Figure 3- Available observation stations over the study region

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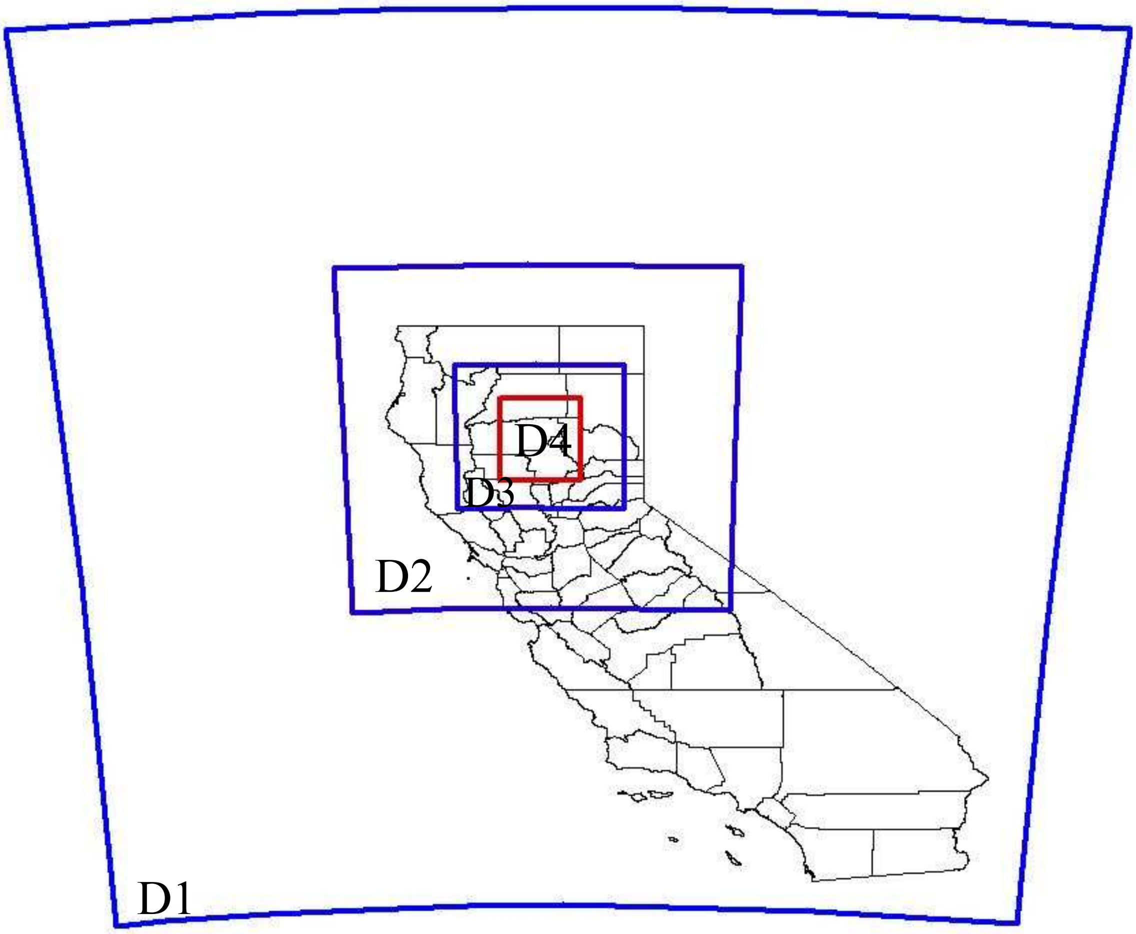

Figure 4- Depiction of four nested grids used for the MM5 simulation of the studied foothills watersheds

Fig 5.pdf

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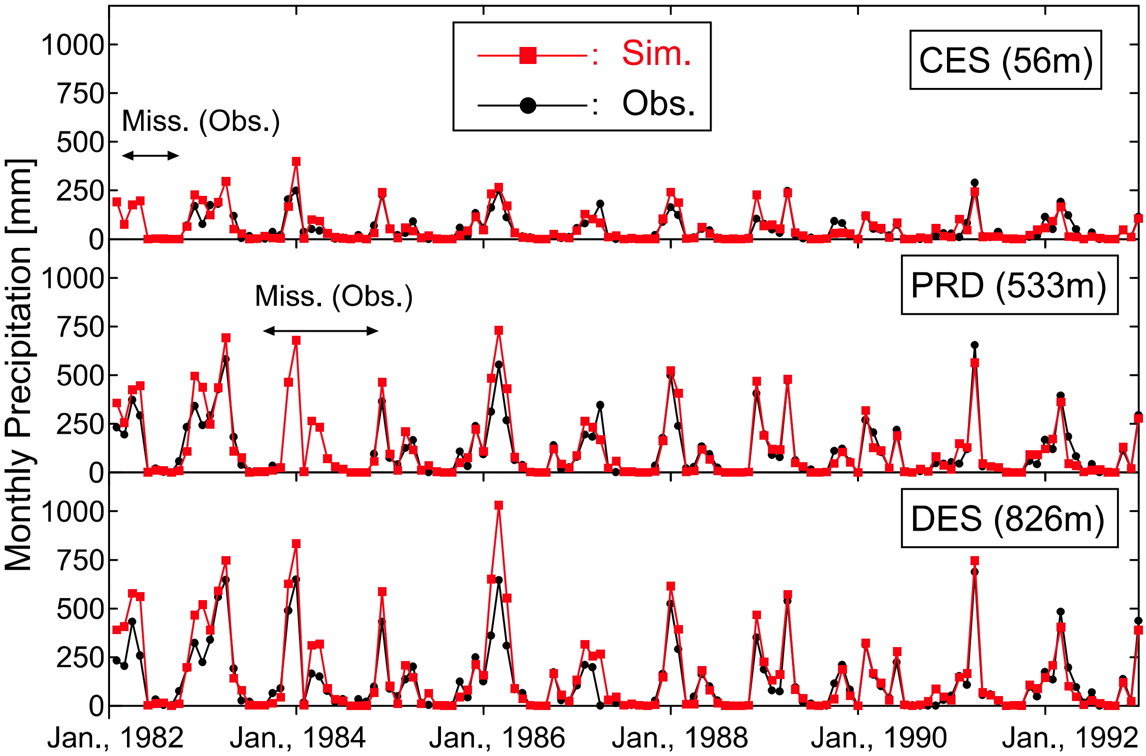

Figure 5- Comparisons of the observed and model simulated monthly precipitation at each observation station during January 1982 - December1992

Fig 6.pdf

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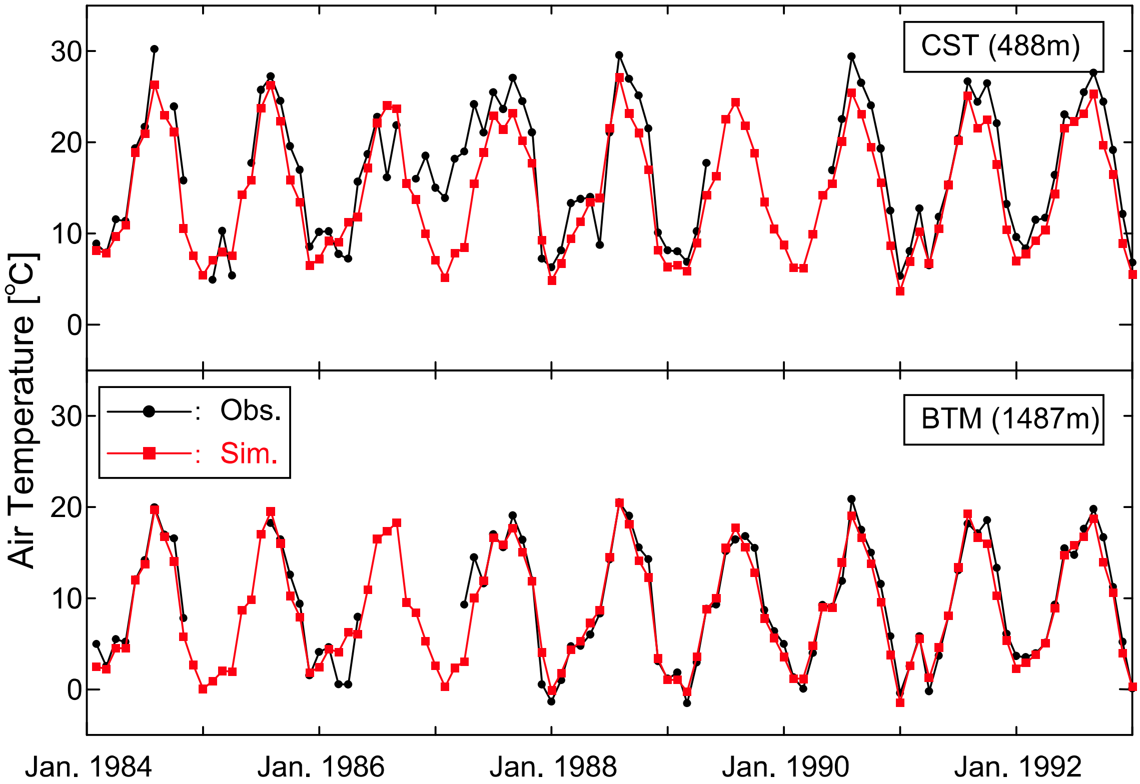

Figure 6- Comparisons of the observed and model simulated monthly mean air temperature at each observation station during January 1984 - December1992

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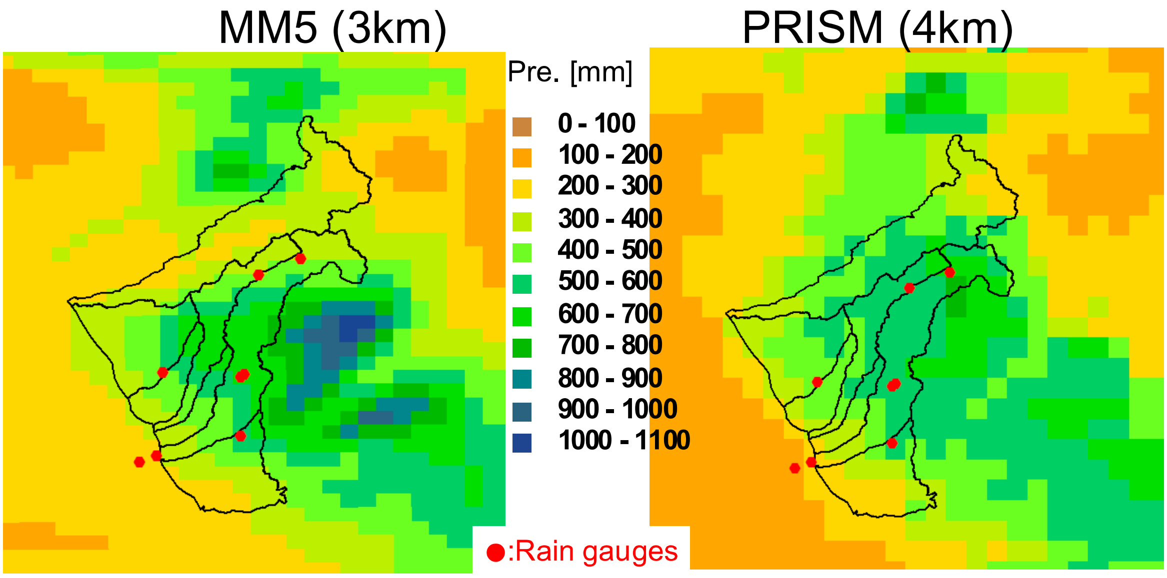

Figure 7- Comparison of model simulated precipitation field and PRISM data over the studied foothills region for December 1987

Fig 8.pdf

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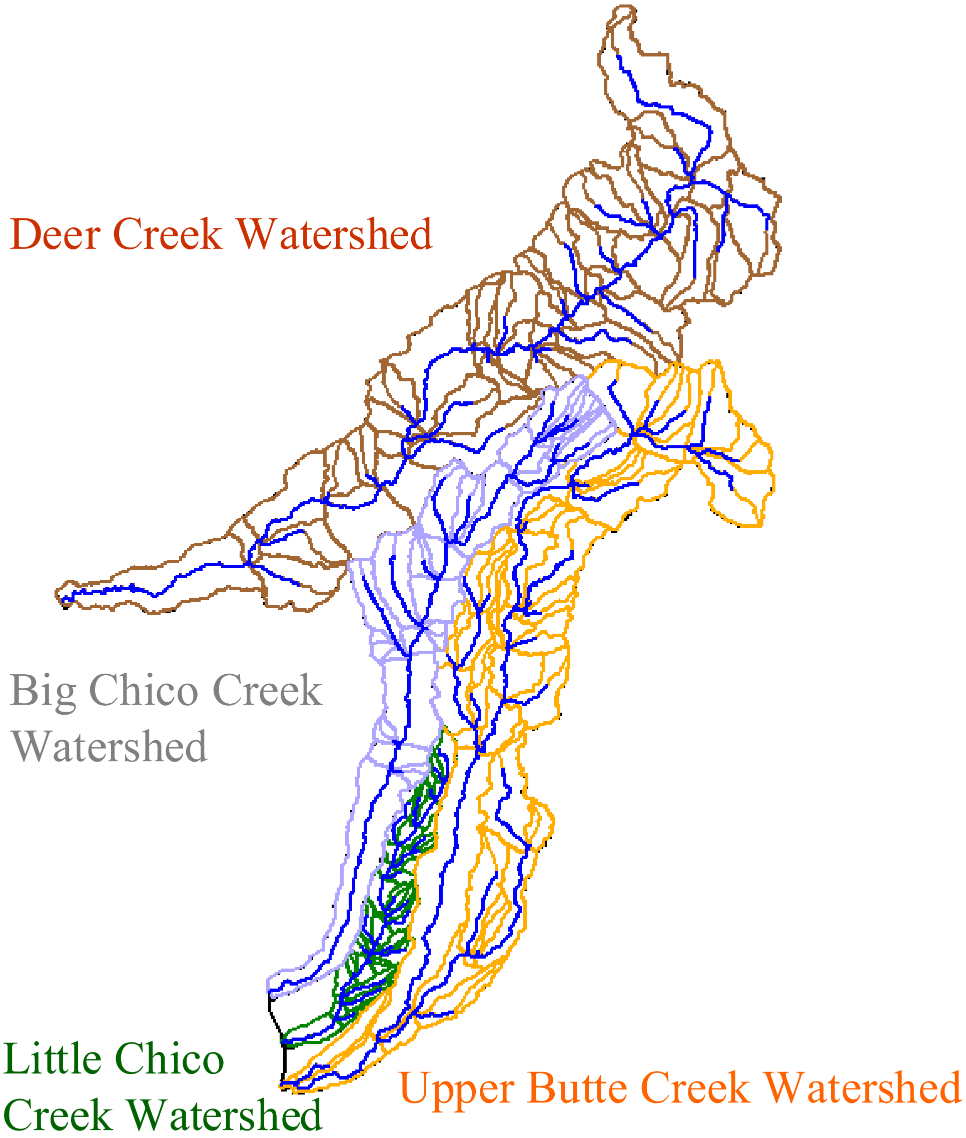

Figure 8- Delineated MCUs map and stream network at each of the studied watersheds

Fig 9.pdf

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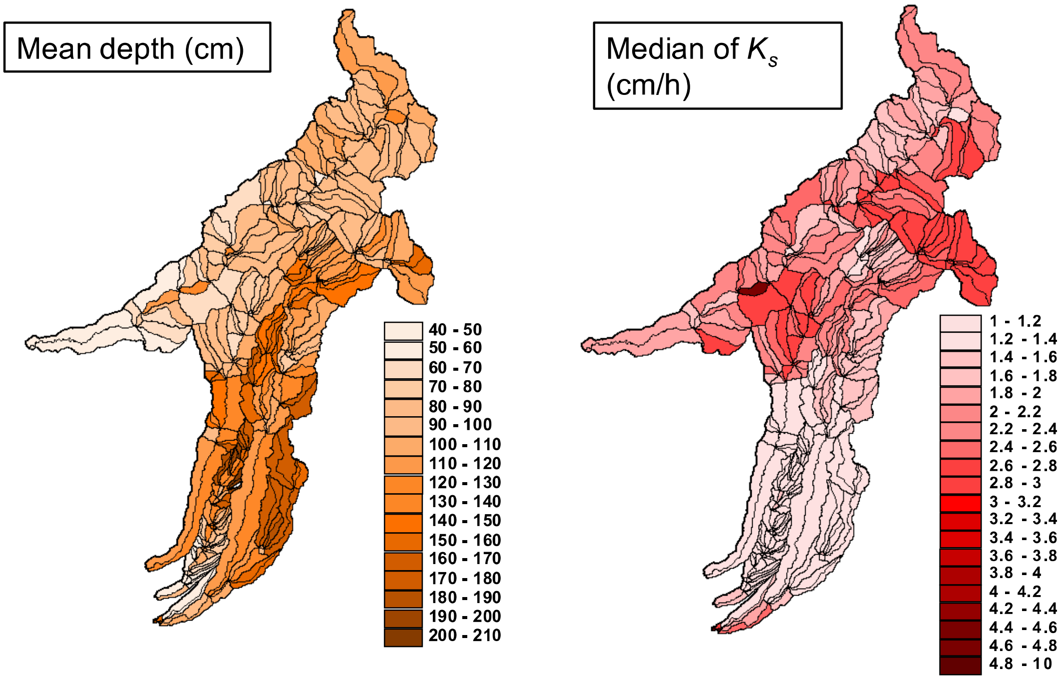

Figure 9 - Mean soil depth and Median of saturated hydraulic conductivity maps in the studied watersheds

Fig 10.pdf

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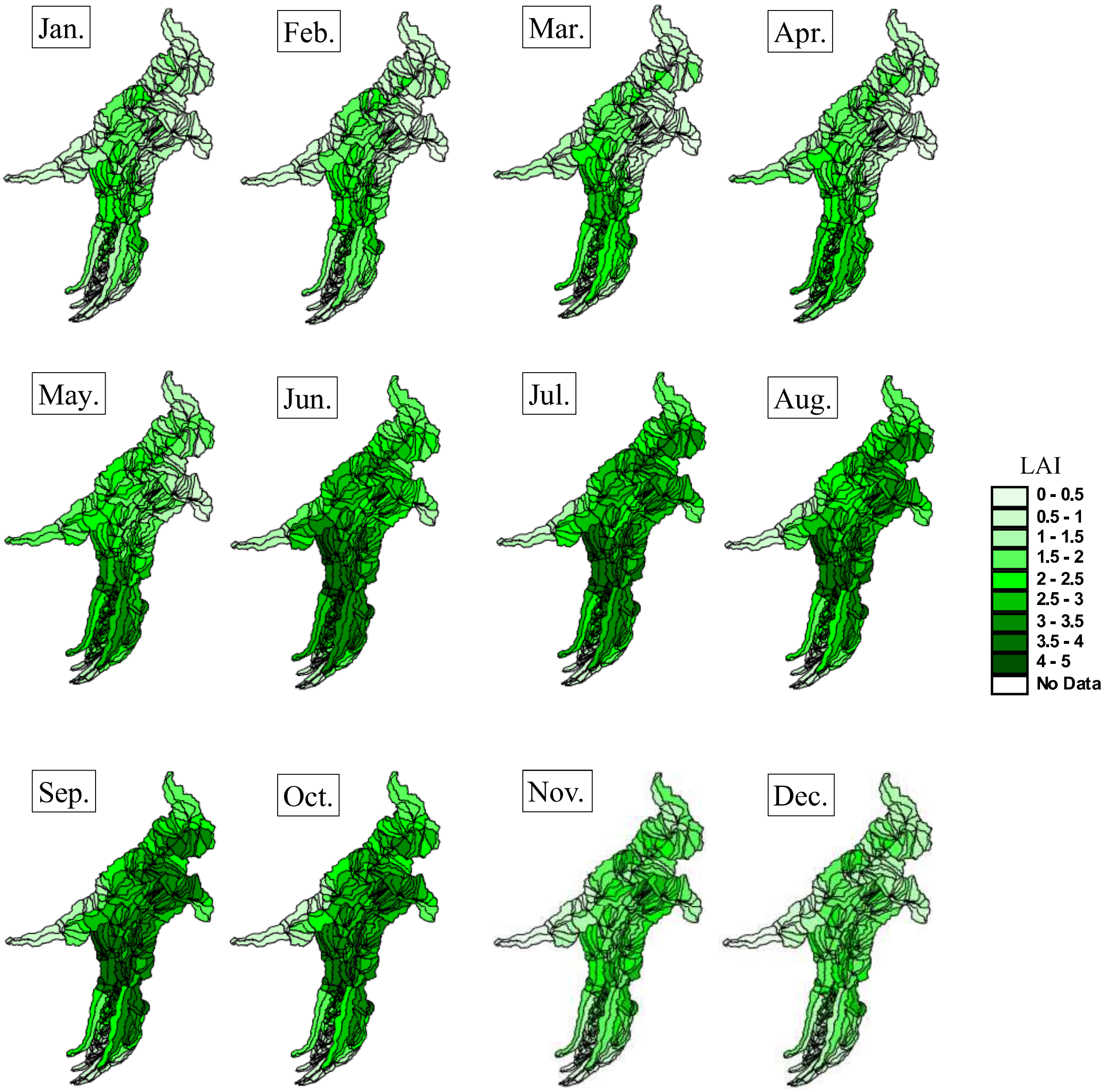

Figure 10 - Monthly mean leaf area index (LAI) maps in the studied watersheds

Fig 11.pdf

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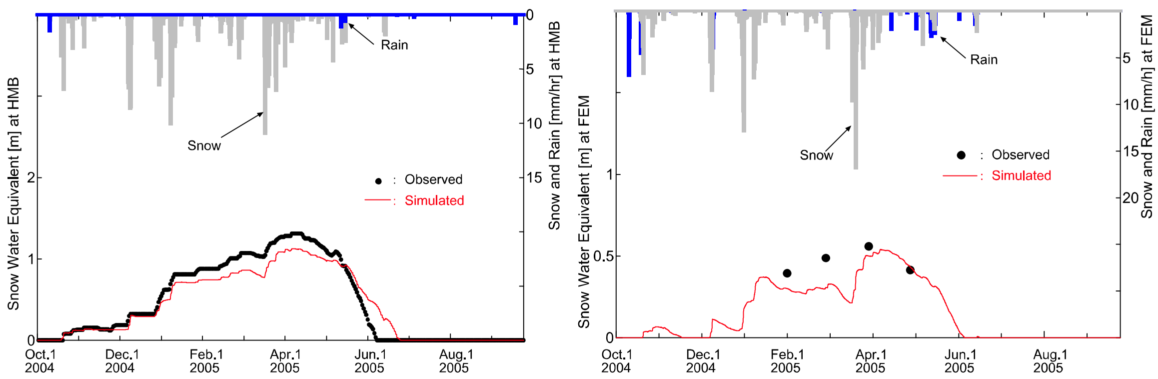

Figure 11 - Time series of the observed and model simulated snow water equivalent at the field observation sites in the study region during October 2004 - September 2005

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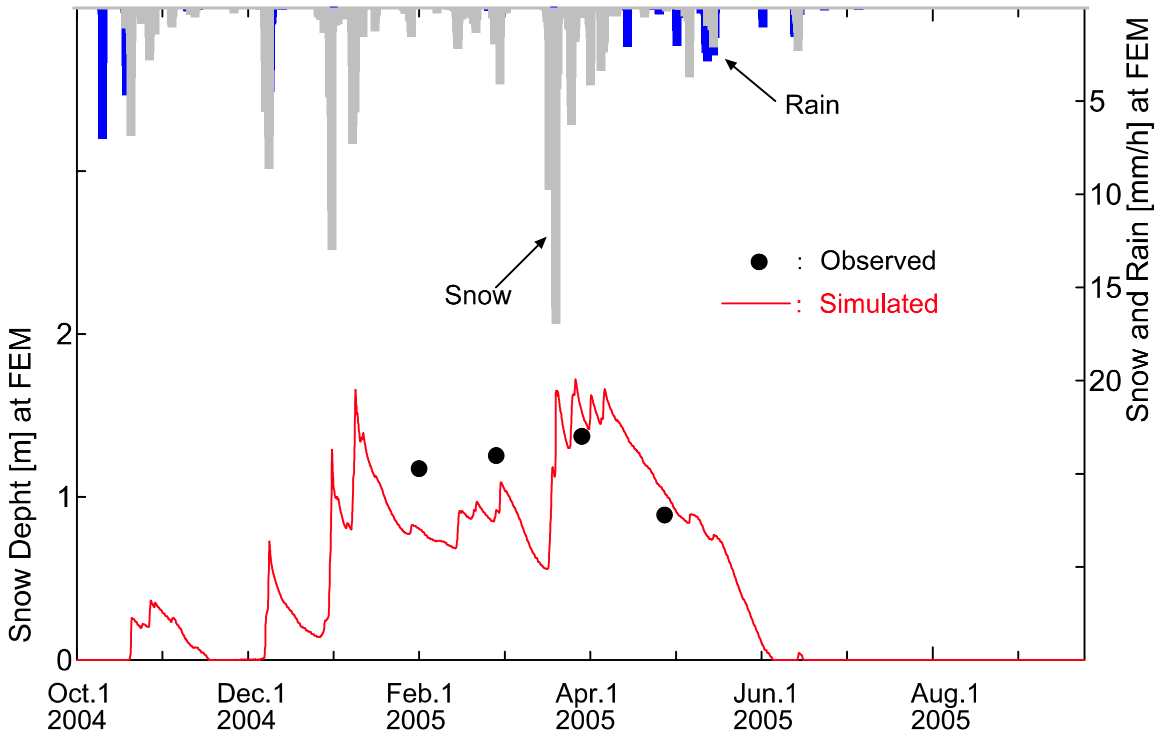

Figure 12 - Time series of the observed and model simulated snow depth at one of the field observation sites in the study region during October 2004 - September 2005

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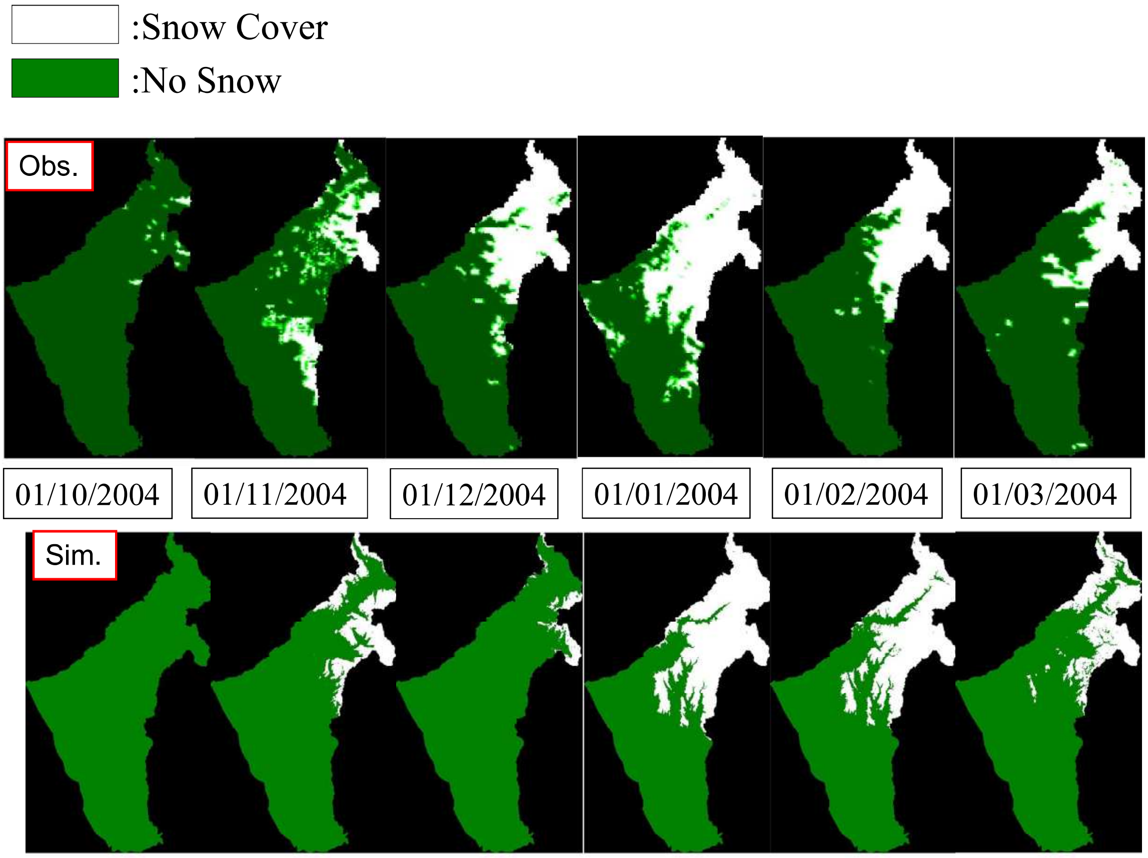

Figure 13 - Model simulated snow cover extent and the maximum snow extent that was derived from MODIS/Terra satellite observation of snow cover at each first day of the month over the study region during October 2004 - March 2005

Fig 14.pdf

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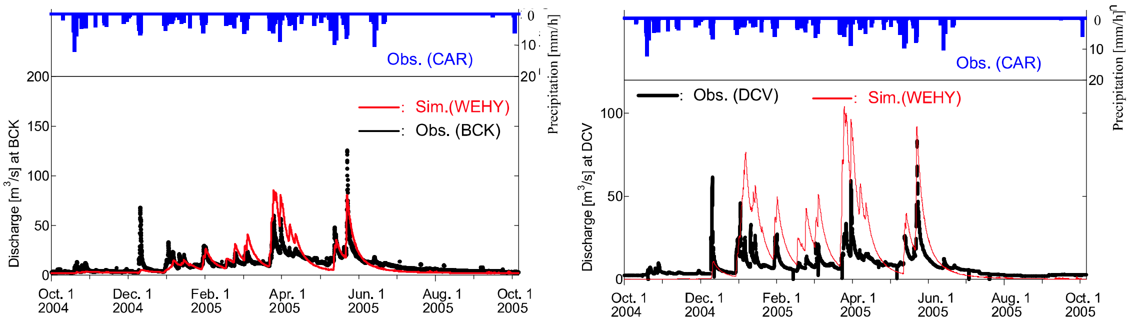

Figure 14- Time series of the observed and model simulated hourly stream discharge at the field observation site of the Butte Creek (Left) and Deer Creek (Right) during October 2004 - September 2005 calibration period

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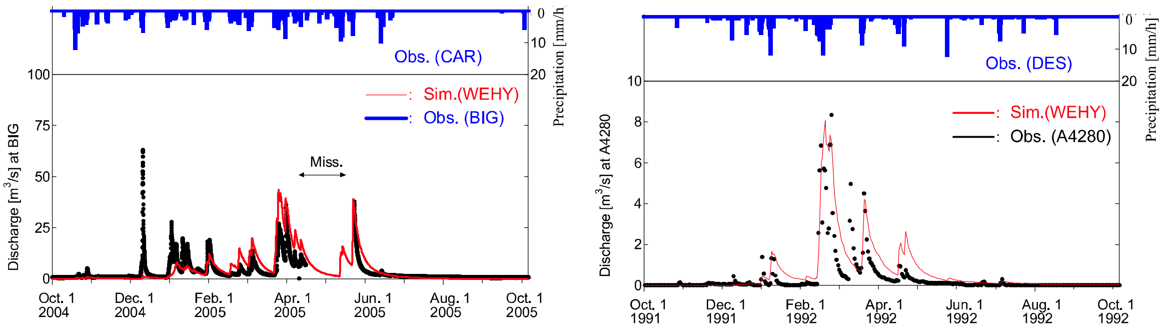

Figure 15- Time series of the observed and model simulated hourly stream discharge at the field observation site of the Big Chico Creek (Left) during October 2004 -September 2005 and Little Chico Creek (Right) during October 1991 - September 1992

Fig 16.pdf

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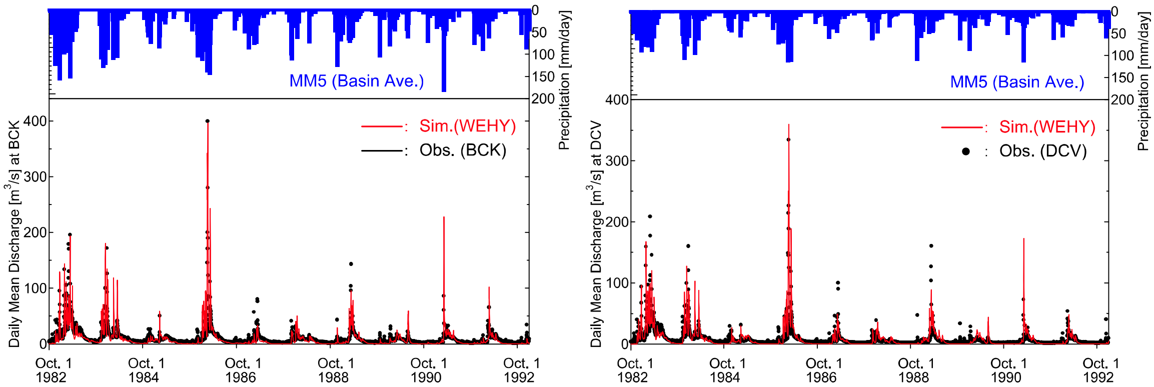

Figure 16- Comparisons of the daily mean discharge between WEHY model simulations and observations at Butte Creek (left) and Deer Creek (right) watersheds during October 1982 - September 1992 validation period

Fig 17.pdf

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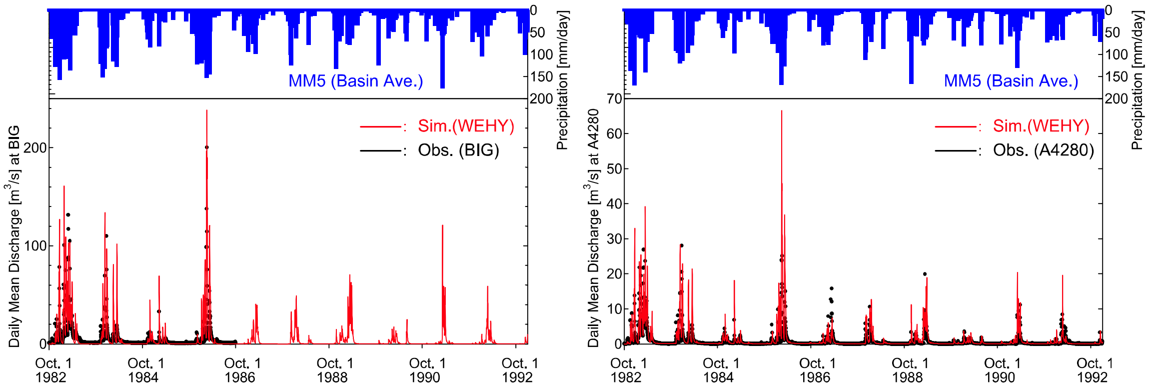

Figure 17- Comparisons of the daily mean discharge between WEHY model simulations and observations at Big Chico Creek (left) and Little Chico (right) watersheds during October 1982 - September 1992 validation period

Fig 18.pdf

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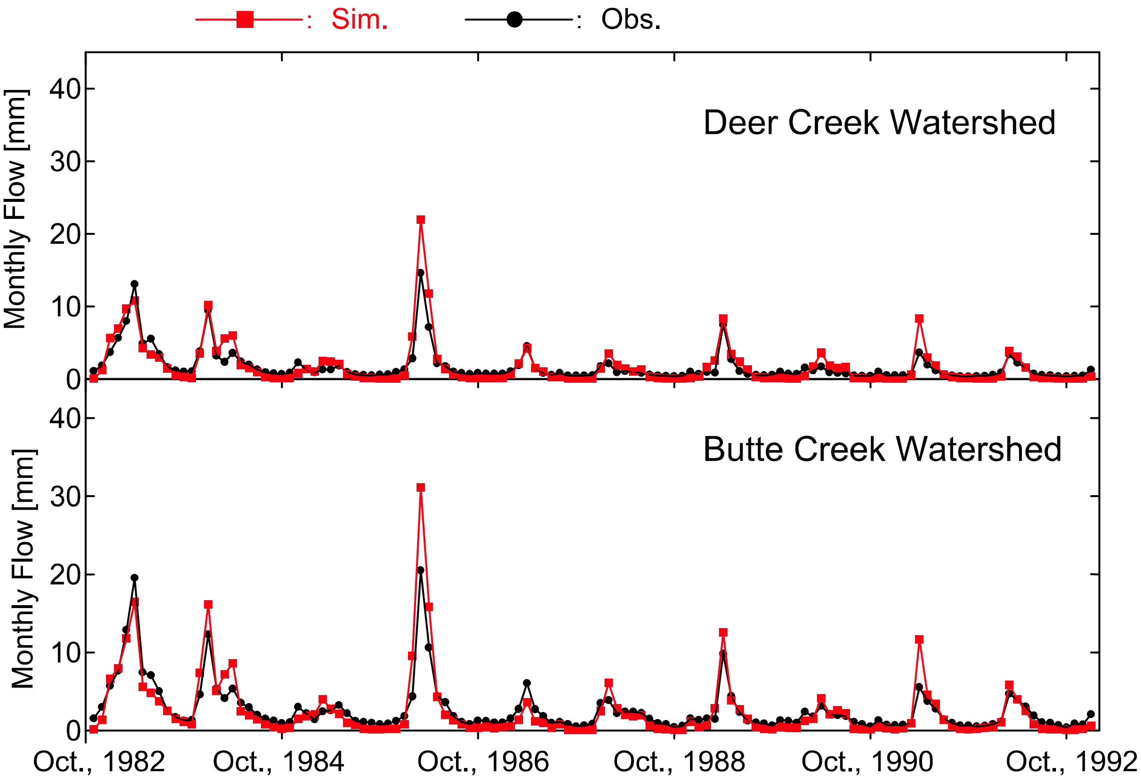

Figure 18- Comparisons of the monthly flow volume between WEHY model simulations and observations at Deer Creek watershed (Upper) and Butte Creek watershed (Lower) during October 1982 - September 1992 validation period

Fig 19.pdf

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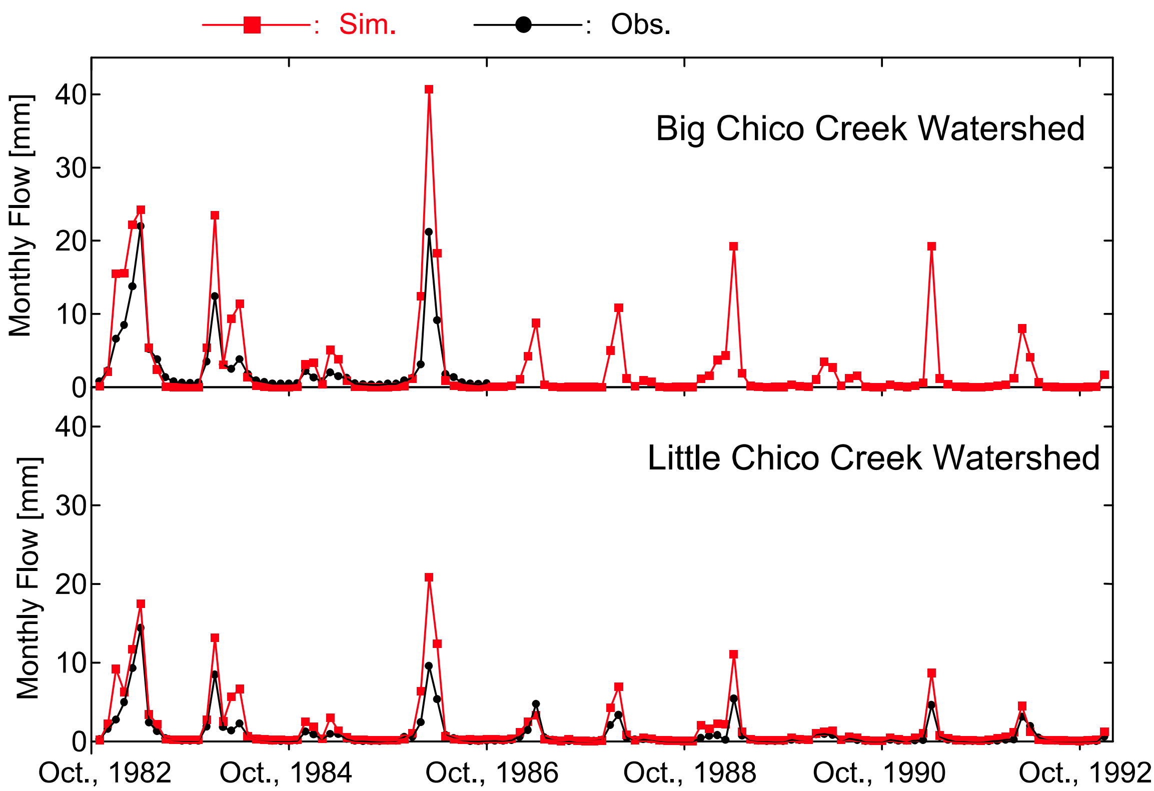

Figure 19- Comparisons of the monthly flow volume between WEHY model simulations and observations at Big Chico Creek watershed (Upper) and Little Chico Creek watershed (Lower) during October 1982 - September 1992 validation period

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Table 1- Nested grid data for the foothills study region of Northern California

Domain	Grid resolution (km)	Number of grids	Domain area (km^2)
1	81	22 × 19	2,742,498
2	27	25 × 22	400,950
3	9	31 × 28	70,308
4	3	52 × 40	18,720

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Table 2- Total number of MCUs at each watershed

Watersheds	Catchment Area (km^2)	Total Number of MCU	Mean MCU Size (km^2)
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

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Table 3- R^2, RMSE, Relative RMSE, Nash-Sutcliffe Efficiency and Chi-square goodness-of-fit statistic values for the simulation results at each studied watershed

Monthly precipitation (Figure 5)					
Station	R^2	RMSE (mm)	Relative RMSE	Nash-Sutcliffe Efficiency	Chi-square calculated ($\chi^2_{0.05}$ = 12.59)
CES	0.77	34.70	0.53	0.70	6.81
PRD	0.89	56.30	0.39	0.83	5.33
DES	0.89	85.30	0.52	0.72	11.38
Monthly mean air temperature (Figure 6)					
Station	R^2	RMSE (mm)	Relative RMSE	Nash-Sutcliffe Efficiency	Chi-square calculated ($\chi^2_{0.05}$ = 12.59)
CST	0.84	3.20	0.46	0.75	8.71
BTM	0.94	1.49	0.23	0.94	10.17
Monthly flow volume (Figure 18 and 19)					
Watershed	R^2	RMSE (mm)	Relative RMSE	Nash-Sutcliffe Efficiency	Chi-square calculated ($\chi^2_{0.05}$ = 12.59)
Big Chico Creek	0.89	4.61	1.60	0.81	11.41
Deer Creek	0.87	1.23	0.67	0.76	6.83
Little Chico Creek	0.88	1.83	1.05	0.59	6.02
Butte Creek	0.87	1.68	0.65	0.83	9.28