**Title**

Mountainous Watershed Modelling with WEHY-HCM: A Case Study from Trinity Watershed in California



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Mountainous Watershed Modelling with WEHY-HCM:
A Case Study from Trinity Watershed in California

By

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# ABSTRACT

This study developed a hydrological model for the Upper Trinity Watershed in California. The Upper Trinity Watershed consists of the portion of the Trinity Watershed upstream of Lewiston Dam and contains both Lewiston and Trinity Lakes. The Upper Trinity Watershed is an important source of water supply in California. Lewiston Lake is used for inter-basin water transfer to the Central Valley region of California for agriculture and municipal use. The watershed model was developed using the Watershed Environmental Hydrology Hydroclimate Model (WEHY-HCM). WEHY-HCM was previously developed over many years in the Hydrological Research Laboratory at UC Davis. WEHY-HCM is a physically-based, numerical, integrated, and distributed modeling system and integrates atmospheric, snowmelt, surface and subsurface flow, and hydraulic processes. WEHY-HCM combines physical equations with spatial relationships and observations such as land use/cover, soil type, and digital elevation model datasets. The primary model output in this study is the streamflow into the Trinity Lake reservoir. The model was calibrated using water years (Oct 1st-Sept 30th) 1997-1999 and was validated using water years 2000-2006. In order to calibrate this model, a program was developed using the evolutionary optimization algorithm differential evolution. The results show that a physically-based, integrated, distributed model is an accurate and effective method for hydrological modeling for the Upper Trinity Watershed. While calibration using a sophisticated algorithm can produce acceptable model results, it was comparable to that obtained by manual calibration in other studies. Automated calibration can produce time savings compared with a manual calibration approach.

# CONTENTS

# I. INTRODUCTION

Water managers seek to solve important large system problems such as water supply, hydropower, and flood control. These problems are governed by complex hydrological processes. A good understanding of hydrological processes is therefore important for water management problems. However, these hydrological processes occur at large and spatially diverse scales. A watershed which drains to a single river may be as large as 1.2 million square miles such as the Mississippi River Basin [1]. Lack of data and detailed knowledge of a region can be a serious challenge for decision making. Hydrological modeling is a useful tool to develop an understanding of a region of interest.

Some important categories of models will be briefly described. Models can be simplified or detailed. They can be conceptual, statistical, or physically-based. Stochastic models have variables with random variation while deterministic models do not. Watershed models can be analytical, empirical, and physical. In general, hydrological models involve some estimation of parameters by calibration from historical data. Some models rely more heavily on this than others. Analytical models use simplifying assumptions to develop closed form solutions [2]. An empirical or statistical model uses relationships derived from observed historical results. Physical models use conservation laws of physics such as conservation of energy, mass, and momentum. These are partial differential equations that can represent processes changing in three-dimensional space and time. Physical models are initial and boundary value problems which can be solved with numerical methods.

An additional demarcation of models is that between lumped and distributed models. Lumped models treat the watershed as a homogenous unit and do not account for spatial distributions of parameters and variables. This makes them a one-dimensional model. Distributed models are two-dimensional or three-dimensional and account for spatial variations in variables, parameters, and processes [2]. There are several methods for representing spatial variation in hydrological models including triangle irregular network (TIN), rectangular grid, plane and channel segments i.e. hillslopes, explicit depth, and depth separation into saturated and unsaturated zones. Distributed watershed models can model different processes within the model domain such as subsurface flow, overland flow, channel flow, evapotranspiration, and snow processes [3].

Many models have been developed which simulate processes in a watershed. The earliest models go back to the 19$^{th}$ century. Mulvany's rational method from 1850 was the first published mathematical model to relate rainfall intensity to peak stream discharge [4], [5]. Later work by Sherman published work in 1932 on the unit hydrograph which relate excess rainfall to runoff [4], [6]. Other work developed models for individual processes important to watershed hydrology such as Green-Ampt infiltration, Horton's work on infiltration to estimate rainfall excess and overland flow, Penman's and later Monteith's work on evapotranspiration, and the Soil Conservation Services Curve Number method to estimate runoff accounting for abstraction [4], [7], [8], [9], [10], [11], [12].

The arrival of the computing age allowed for more ambitious modelling of watersheds. The Stanford Watershed Model (previously SWM now HSPF) by Crawford and Linsley in 1966 was probably the first attempt to model the entire hydrological cycle [4], [13]. Numerous computer based hydrologic models have been developed since then such as the Hydrologic Engineering Center (HEC-1) model, National Weather Service River Forecast System (NWSRFC), Storm

Water Management Model (SWMM), Systeme Hydrologique European (SHE) Model, and TOPMODEL [4], [14], [15], [16], [17], [18]. Versions of many of these are still in use.

The Watershed Environmental Hydrology Hydroclimate Model (WEHY-HCM) is a physically-based, distributed, deterministic, watershed scale model presented in 2004 [19]. WEHY-HCM was developed at UC Davis by the Hydrologic Research Laboratory. WEHY-HCM couples atmospheric, snow, hydrological, and hydraulic models. WEHY-HCM uses many land observation datasets to parameterize models without relying significantly on pure calibration to fit the model simulations to observations. It uses a unique method of accounting for spatial heterogeneity by upscaling point-scale to ensemble averaged forms applied at the hillslope scale [19]. Further it uses a spatially horizontally averaged rectangular profile variable saturation (RPVS) flow model for infiltration and flow [20]. WEHY-HCM was chosen as the model for this study.


**Figure 1: Full extent of Trinity Watershed** [21]

Trinity River Watershed is located in northern California within Trinity and Humboldt counties. It is shown as Figure 1. The Trinity River flows through the watershed entering the Klamath River as a major tributary before flowing out to the Pacific. The Trinity River is dammed by Trinity Dam

(Figure 2) forming Trinity Lake, and downstream a smaller dam named Lewiston Dam forms Lewiston Lake. Trinity Lake is a major storage reservoir for flows diverted by the Central Valley Project (CVP) to the Sacramento River. Lewiston Lake is the diversion point for inter-basin water transfers to the Sacramento River by way of the Clear Creek Tunnel and Whiskeytown Lake[22].

**Figure 2: Trinity Dam** [23]

Due to its relevance for water supply and the Sacramento River, this upstream portion of the Trinity River Watershed is the target for hydrological modeling in this study. Trinity Watershed was subdivided into the Upper Trinity Watershed which has an area of 1859 $km^2$ (718 $mi^2$) with an outlet at Lewiston Lake. This delineation is shown as Figure 3.

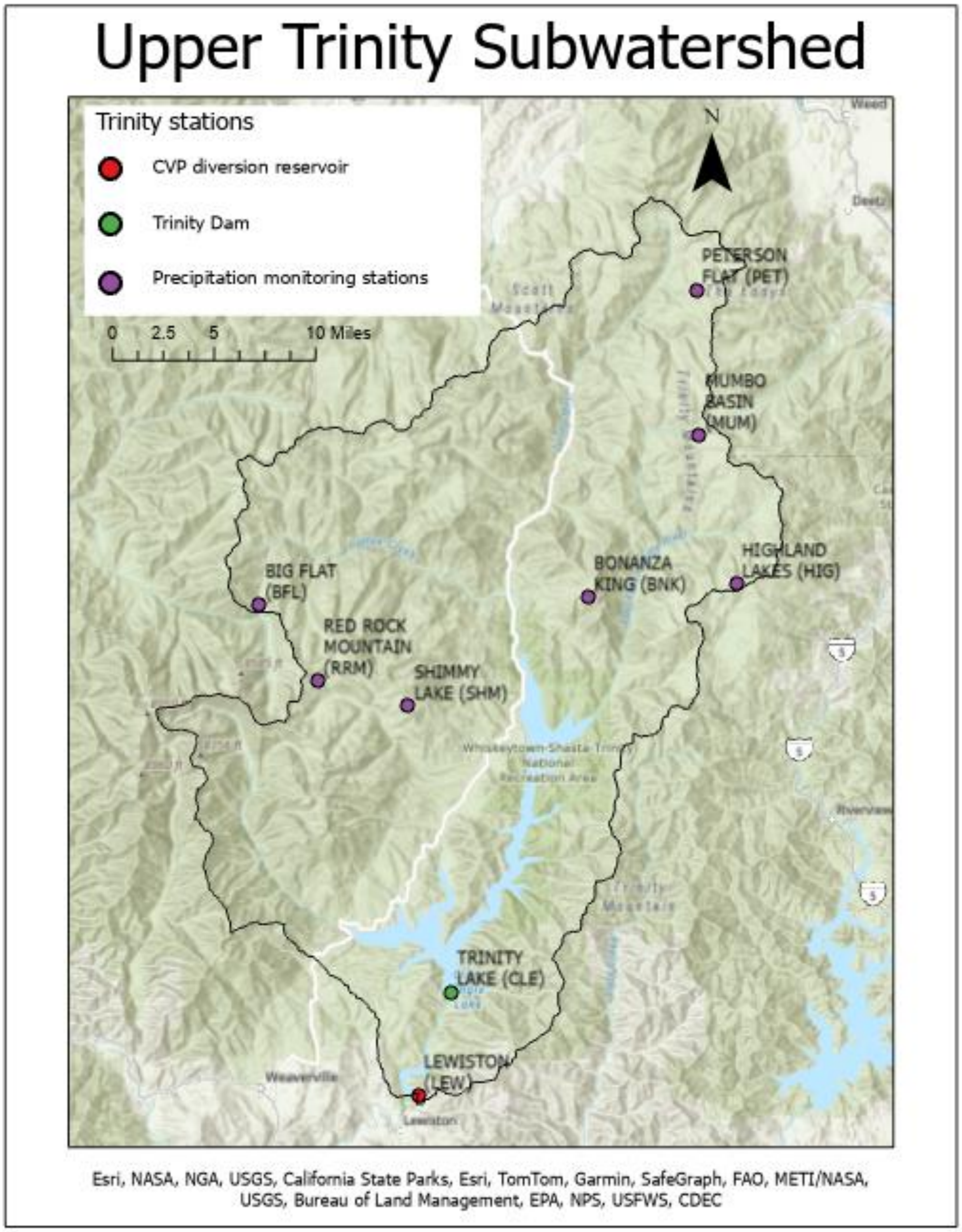
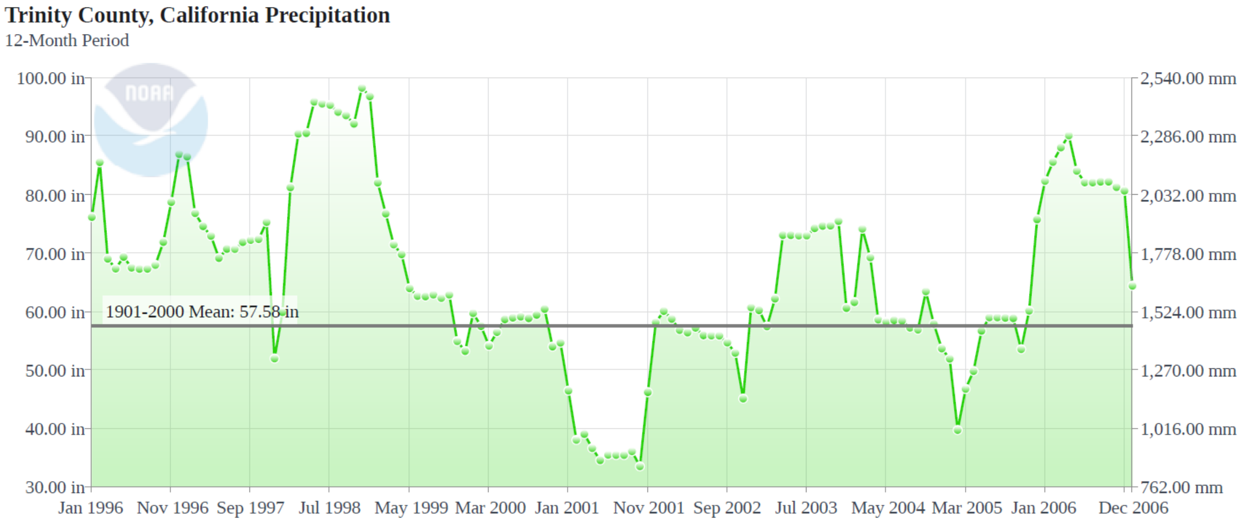



**Figure 3: WEHY Model domain and observation stations in the Upper Trinity Watershed. Trinity Lake is the observation station for the Trinity Reservoir.**

California's climatology is important to this Trinity modeling study. California has a mediterranian climate with intraannual varaibility, wet winters and dry summers.  It also experiences interannual variablilty with multiyear high or low precipitation periods. This can be seen in Figures 4. Figure 4 shows the monthly precipitation totals over Trinity County for the 1997-2006 study periodand the monthly precipitation totals over an extended record from 1895-2024. Only rarely is the precipitation at the mean value.



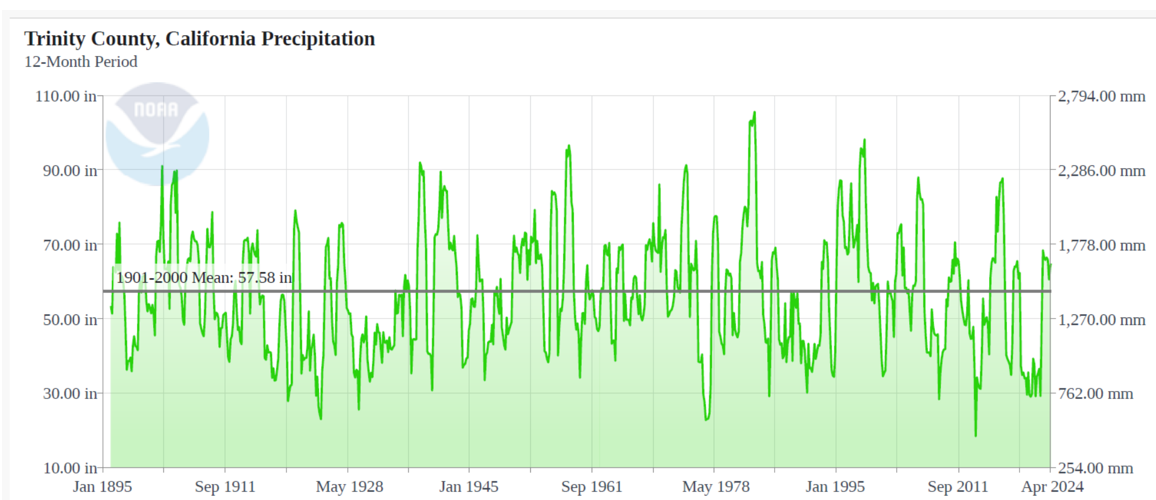




**Figure 4: Water years 1997-2006(top) & 1895-2024(bottom) Precipitation Trinity County timeseries.** [24]

It has a north-south distribution of precipitation with a greater portion falling in the north and less in the south. It also has a mountanous terrain which drives orographic uplift and precipitation of moist air masses such as from atmospheric rivers. Figure 5 shows the statewide distribution of precipitation. Some northern coastal areas receive more than 100 inches annaully on average while some southern desert regions receive 5 inches or less.

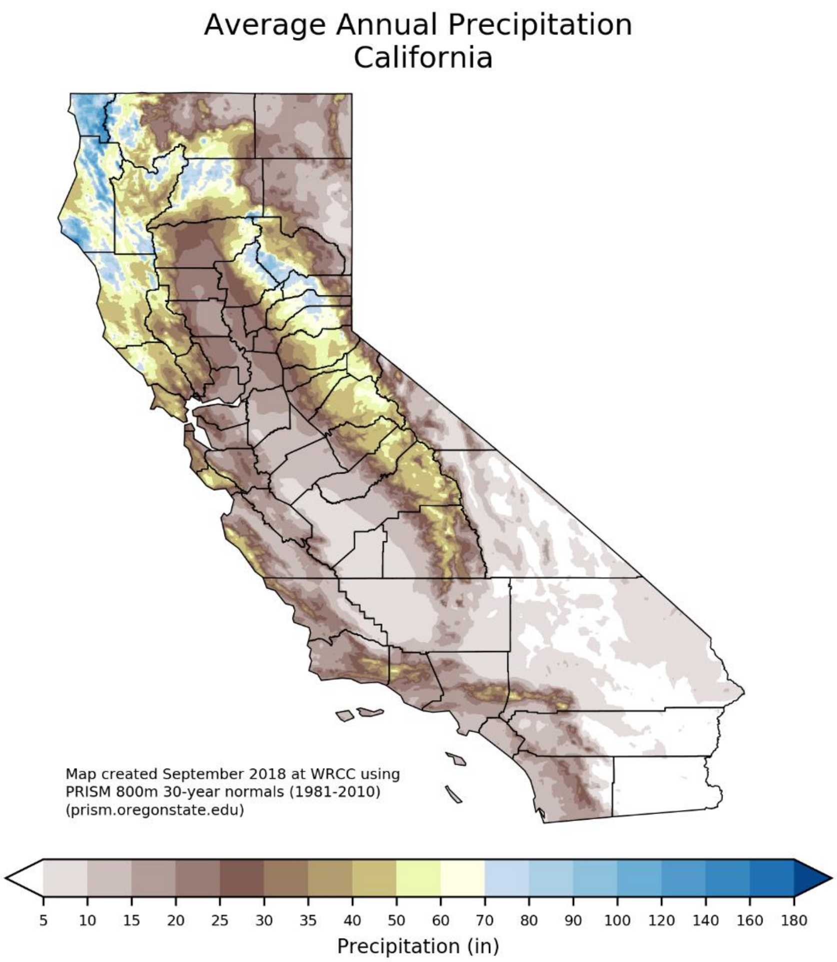



**Figure 5: California average annual precipitation.** [25]

Some previous hydrological models have described the Trinity Watershed. To the authors knowledge, no previous study has implemented a physically-based, spatially distributed, watershed scale model for the Trinity Watershed. One previous study modelled the Sacramento Basin using Water Evaluation and Planning Version 21 (WEAP21) but this model is primarily a water planning model [26]. It uses some Land Use Land Cover (LULC) information but with a much coarser representation of Trinity and other watersheds based on United States Geological Survey (USGS) 8-digit Hydrologic Unit Codes (HUC 8). The WEAP21 model used 54 sub-catchments to describe the entire Sacramento Basin. This may have represented the Upper Trinity Watershed with somewhere between one and three computational units. Conversely, this WEHY-HCM study modelled the Upper Trinity watershed using 64 Model Computational Units (MCUs). Importantly WEHY-HCM uses a DEM dataset to delineate hillslope scale MCUs accounting for much more spatial variability in geomorphology. Further the WEAP21 used only a monthly time step while this WEHY-HCM uses an hourly timestep that was daily averaged to compare with daily observations.

Currently Trinity reservoir operations rely on California Nevada River Forecast Center (CNRFC) for real time flow forecasts. CNRFC uses the Hydrologic Ensemble Forecast System (HEFS). The hydrological model uses only three meteorological inputs: precipitation, air temperature at two meters, and freezing level [27]. The Meteorologic Ensemble Forecast Processor (MEFP) is used to generate an ensemble of this forcing input for use by the hydrologic model at the 6-hour time step. This hydrologic model divides the Upper Trinity Watershed into three subbasin model regions[28]. This model uses the Snow-17 model, the Sacramento Soil Moisture Accounting (SAC-SMA) model, and the Unit Hydrograph model. The Snow-17 model is a one-dimensional, conceptual, lumped model which uses temperature and precipitation to model snow accumulation and loss [29]. The Sacramento Soil Moisture Accounting model is a one-dimensional, conceptual, lumped model that simulates soil water storage and surface and subsurface flow[27]. This is done by dividing each subbasin into lower and upper depth layers with several storage zones and flow pathways between them to represent different hydrological processes. The Unit Hydrograph model is then used to route the computed surface flow from the different subbasins to the outlet stream. The unit hydrograph is unique to each watershed and needs to be developed empirically. A Unit Hydrograph describes the hydrological response of a watershed to a standard one inch or cm of rain fall, applied uniformly to a watershed over a specified time. It can be used to convert the 6-hour runoff time series from each subbasin into a 1-hour streamflow timeseries for the watershed [27].

CNRFC does not use the hydrological component of HEFS, known as Ensemble Postprocessor because of performance issues. CNRFC also recognizes some issues with the MEFP component. It models temperature using only 6-hour timestep and daily maximum and minimum temperatures. This approach can work sufficiently for normal diurnal cycles but encounters problems during situations of more rapid weather changes. The effect can be to misidentify the type of precipitation negatively affecting forecasting results [27]. Additionally, if the historical and present conditions are very different because of some extreme weather conditions then MEFP performance will be affected [27]. The MEFP also has a tendency to underestimate extreme precipitation events, a form of type II bias [27].

Conversely WEHY-HCM operates at a finer space and time resolution able to better capture short term and spatially distributed weather. It uses geophysical observations rather than relying largely on calibration of unknown parameters between conceptual storage zones. Further it does not rely on historical statistics which are unreliable for future use because of climate change. While

WEHY-HCM involves some calibration, it is not entirely reliant on it. Models that rely more heavily on calibration from historical observations are more limited in this respect.

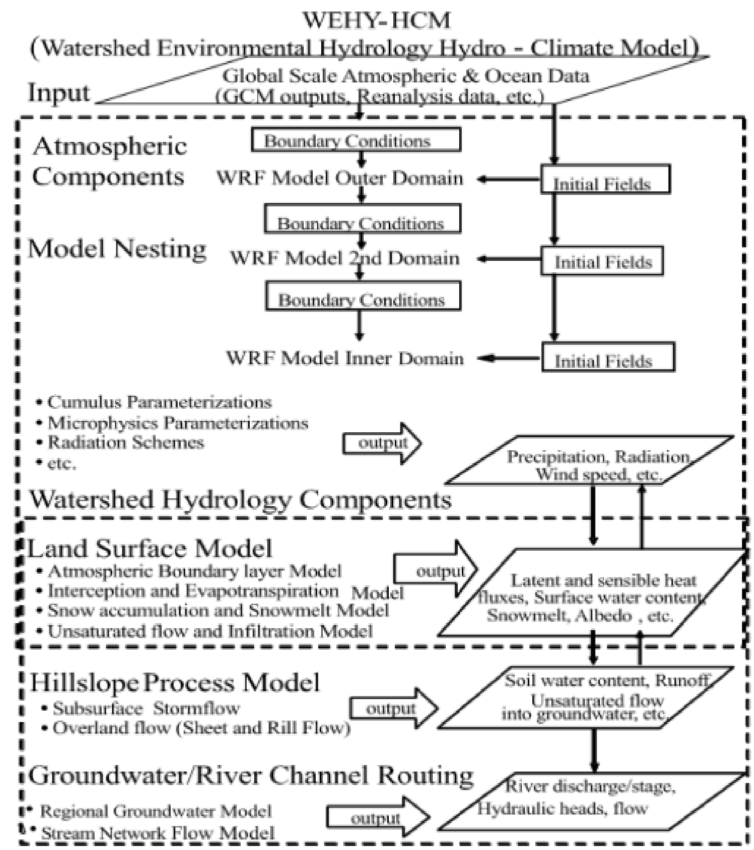
This study aims to apply the WEHY-HCM model to the Trinity Subwatershed where no comparable model has been applied. Further this study will apply a novel automated calibration technique using an evolutionary algorithm which has not been used with WEHY-HCM before. This will expand knowledge of the use of physically-based modelling in general and WEHY-HCM in particular.

# II. METHODOLOGY

## A. Model System Overview

The Watershed Environmental Hydrology Hydroclimate Model (WEHY-HCM) is a physically-based, deterministic, numerical, integrated, distributed, watershed scale model [19]. This model was developed over many years by members of the UC Davis Hydrologic Research Laboratory. WEHY couples atmospheric, snow, surface and subsurface flows, and hydraulic processes. Figure 6 is an overview diagram of the WEHY-HCM. Since dominant time scales of these processes are different from one another, the model uses different time steps for different processes. The model domain is developed using several geomorphological datasets.

WEHY-HCM uses upscaled, areal averaged, governing equations using parameter values of areal mean, areal variance, and areal covariance at the hillslope scale. This approach avoids the need to estimate parameters at many model nodes that is employed in models that use point scale governing equations [20] . A watershed model was developed for the Upper Trinity watershed using WEHY-HCM for the purpose of this study.




Model components of WEHY-HCM watershed hydro-climate model

**Figure 6: WEHY-HCM model overview** [20]

## B. Atmospheric Components

WEHY-HCM is a coupled atmospheric-hydrologic model. Atmospheric processes are important to the hydrological cycle. WEHY-HCM uses inputs developed with the Weather Research and

Forecasting (WRF) Model 3.9.1 [30]. WRF is a mesoscale numerical weather prediction model used for atmospheric research and forecasting [31]. This study used the Climate Forecast System Reanalysis (CSFR) dataset. CFSR is a global reanalysis dataset that useful for the study of historical hydro-climate [32]. Atmospheric variable fields such as precipitation, radiation, mixing ratio, surface pressure, wind velocity, air temperature, and potential temperature are acquired from a CSFR dataset and are used in WEHY-HCM. However, this Trinity modeling study required a finer resolution dataset developed by dynamical downscaling by the UC Davis Hydrologic Research Lab using WRF to generate 9 km resolution atmospheric variable fields over the Sacramento Basin in California. The downscaling used Stony-Brook University Scheme for micro physics, New Simplified Arakawa-Schubert Scheme for cumulus option, Revised MM5 Monin-Obukhov Scheme for surface layer physics, Unified Noah Land Surface Model for surface physics, New Goddard Shortwave and Longwave Schemes for radiation, and the Bougeault–Lacarrere Scheme for the planetary boundary layer which is designed for orographic induced turbulence [33]. It is important to note that the model domain is at the scale of a watershed with its hydrologic response units being tens of hillslopes.

### C. Land Surface Model

The land surface hydrologic flow components of WEHY-HCM include five models which describe the processes which convey moisture and heat between the atmosphere and the land surface. These include an atmospheric surface layer model, a heat balance model, vegetation model, evapotranspiration model, and the soil water flow infiltration and runoff model. These processes make up a nonlinear system which has interactions among different components. As such, WEHY-HCM solves these equations simultaneously for the moisture and heat fluxes between the atmosphere and land surface at the hillslope scale [8]. Figure 7 below shows many of the processes that are handled by the land surface model component.

The surface layer affects the heat and moisture fluxes at the land atmosphere interface which is important to mass and energy balances within and between the watershed and its surroundings. The surface layer model uses Monin-Obukhov similarity theory (MOST) to describe the vertical fluxes and profiles of temperature, wind velocity, and specific humidity between the lowest level of atmospheric model at around 50 m and the ground surface roughness height. MOST is an empirical model developed for homogenous flat terrain and is not strictly validated for complex or mountainous terrain. Mountain terrain may induce air motions not well described by MOST [34], [35]. This may be a source of error in some areas of Upper Trinity Watershed.

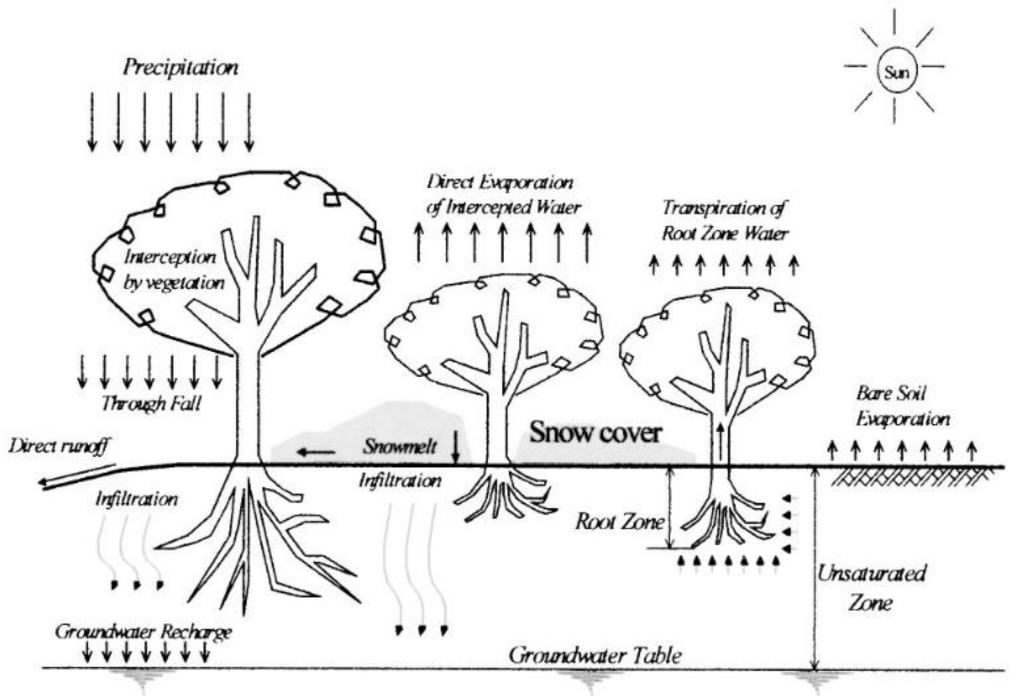



**Figure 7: Land Surface Model Processes** [19]

The vegetation and evapotranspiration models account for the interception of a portion of precipitation by vegetation and both the direct evaporation to the atmosphere or throughfall to the surface. Evapotranspiration deals with the moisture flux from plants or ground surface. The heat balance model accounts for heat fluxes between the atmosphere and surface domains. The soil water flow component accounts for occurrence of infiltration and runoff as well as soil moisture conditions and flow. WEHY-HCM links this model component with other important model component processes such as overland flow, subsurface stormflow, and regional groundwater [20].

The snow model component deals with snow accumulation by precipitation and snow drift as well as snowmelt [20]. These are important in mountainous watersheds such as Trinity where a significant quantity of precipitation occurs as snow in higher elevation areas. This snow does not immediately enter the stream system. Rather much of it is stored throughout the cold winter season only melting as temperatures rise in spring and summer. The model must therefore account for this snowmelt effect.

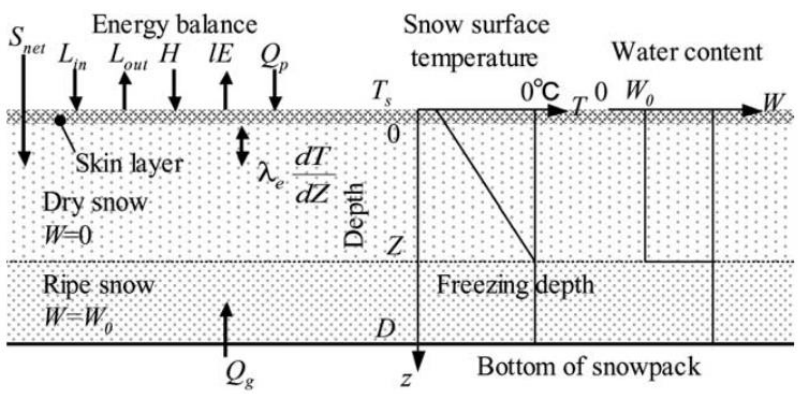



**Figure 8: Snow model Processes** [36]

The snow model is a physically-based model that uses one-dimensional vertically integrated governing equations for mass, density, and energy balances. The energy balance equation accounts for variable effects on solar radiation from topographic slope/aspect effects and models snow with three layers; a surface skin layer, an active upper layer, and an inactive lower layer [36]. The boundary between the active and inactive layer varies with time according to the energy balance and is known as the freezing depth. The snow temperature profile is taken as linear as shown in Figure 8. This approximation was validated in field experiments [36]. The point scale one-dimensional equations are numerically upscaled and solved over the model domain rendering them a spatially distributed model for snow depth, snow water content, and snowmelt.

WEHY-HCM uses a spatially horizontally averaged rectangular profile variable saturation (RPVS) soil water model**.** The RPVS model does not assume that soil surface saturation is reached during a rain event as do many popular models such as Green-Ampt and Horton. The RPVS model allows an equilibrium between a rainfall rate and soil water content to be reached before soil surface saturation (ponding). This is a more realistic model for infiltration and runoff calculation. This model is based on a depth integrated continuity equation which addresses the depth wise variability of soil.

The RPVS model addresses spatial variability in soil water content profiles by spatial averaging of infiltration/soil water flow. This uses soil survey observation of hydraulic conductivity mean and variance for numerous soil patches within a watershed. This allows the calculation of upscaled ensemble-averaged soil water flux by integration with a probability density function while assuming hydraulic conductivity is lognormally distributed. This is incorporated with the boundary layer model for the calculation of heat and vapor fluxes to the atmosphere as well as infiltration/runoff [19] [8].

Specifically, the equations the WEHY model used at the point location scale include:

> "one-dimensional vertically integrated soil water flow equations with rectangular profile variable saturation approximation, two-dimensional overland sheet flow equations with the Kinematic Wave approximation, one-dimensional rill/gully channel flow equations with the Kinematic Wave approximation, two-dimensional subsurface stormflow equations, two-dimensional unconfined aquifer flow (Boussinesq) equation" [20] .

## D. Hillslope

WEHY-HCM incorporates models for hydrological processes that occur at the hillslope level and uses hillslopes as Model Computational Units (MCU). WEHY-HCM uses ensemble areal averaging and areal variance and covariance of point scale parameters to represent hillslope scale processes in each MCU. The datasets are linked at the hillslope scale. The MCUs used for Trinity in this study can be seen in Figure 10.

Flow is modelled at the level of the hillslope as a linked interactive process between sheet flow, rill flow, and subsurface stormflow. Sheet flow occurs as a sheet of moisture on the surface. Rill flow occurs in small channels along the surface which are fed by return flows from the subsurface and from overland flow. Subsurface stormflow occurs in the downhill direction within the ground but above an impeding layer as saturated flow. This subsurface stormflow can remerge on the surface as a return flow. These processes and other processes modelled by WEHY-HCM are depicted in Figure 9. In order to provide computational savings while maintaining performance, sheet flow and subsurface flow are represented as quasi-two-dimensional processes. This is done by averaging the two-dimensional sheet flow equation and two-dimensional subsurface stormflow equation in the transverse direction to develop one-dimensional equations which have lateral flow components[19].

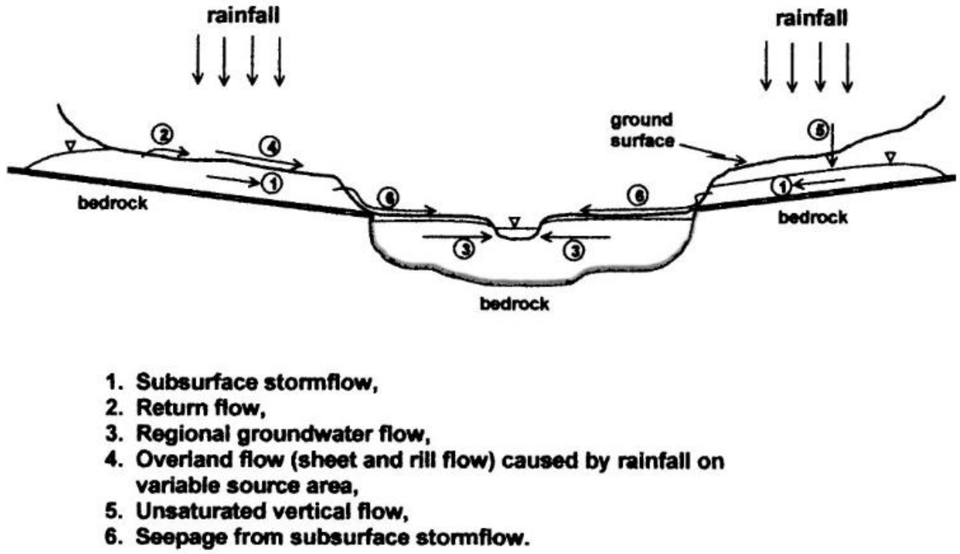



**Figure 9: Hillslope Processes** [19]

## E. Groundwater and River Channel Routing

Finally, a Groundwater and River Channel Routing module is run which models stream network flow and groundwater flow. Regional groundwater flow is modeled as two-dimensional transient saturated, horizontal flow under the Dupuit–Forchheimer assumption [4]. Stream reaches are fed from groundwater and from hillslope processes after which the streamflows are routed through the network via one dimensional diffusion wave equations using Chezy's formula [19]. Hydrographs are produced for the stream reaches in the watershed.

# III. DATA

WEHY-HCM uses several land observation datasets from land survey and satellite. A digital Elevation Map (DEM) dataset from satellite observations available from US Geological Survey (USGS) were used to generate slope and aspect land surface data layers which are Figures 11 and 12 respectively. The one arc second resolution dataset were resized to 40 m over the watershed model domain. The DEM dataset along with generated model computational units (MCU) used for this study, are shown in Figure 10.

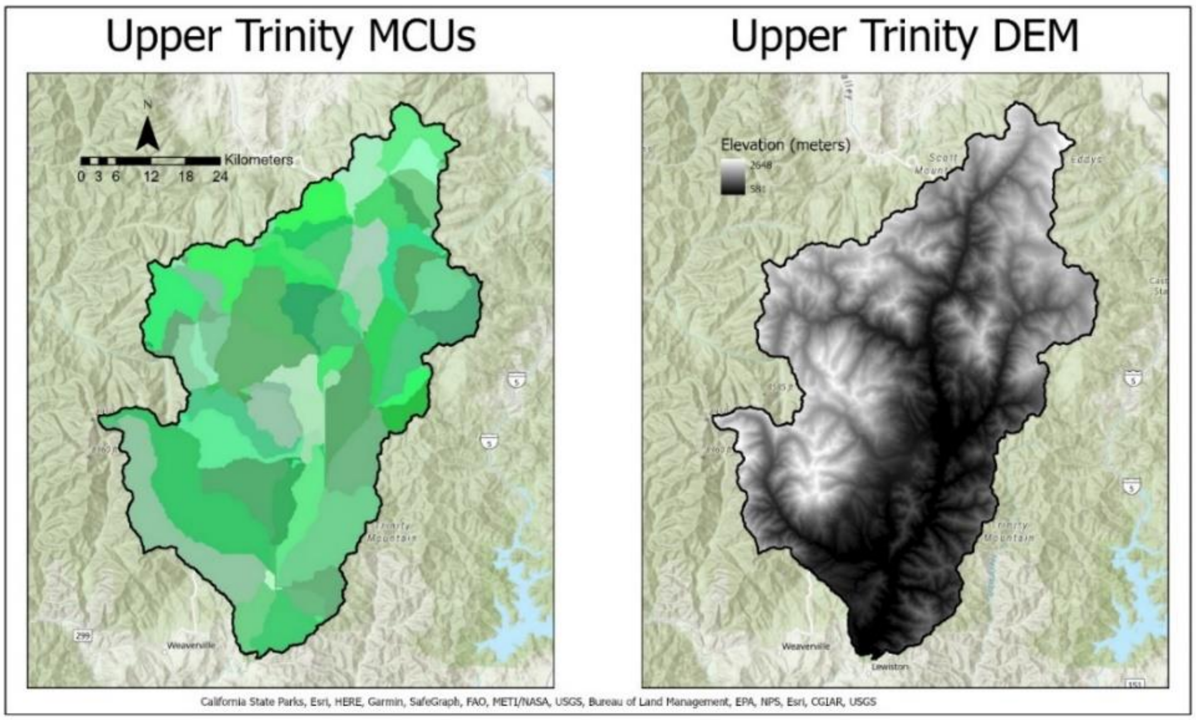



**Figure 10: (a) Model Computational Units (MCU), each shade is a different unit; and (b) Digital Elevation Model (DEM) layers used in Trinity model development.**

This study used a soil dataset from Soil Survey Geographic Database (SSURGO) which were collected by the National Cooperative Soil Survey[37]. This included direct observations of soil patches during field surveys and lab analysis of soil samples and is depicted as Figure 13. This study also used the 2006 Fire and Resources Assessment land use-land cover dataset from Cal Forest and Fire which is depicted in Figure 14. The datasets were coupled at the hillslope scale model computation unit.

For calibration and validation, WEHY-HCM streamflow results were compared with Trinity Full Natural Flow dataset obtained at California Data Exchange Center (CDEC). Full Natural Flow is a computed value which found by a mass balance summation of change in storage, releases, pumping, and evaporation according to the Bureau of Reclamation [38]. This is a daily time step dataset which represents the flow in an unimpaired watershed. This dataset is useful for a basin like Trinity which has a major dam and thus does not behave as an undeveloped basin.

The present study makes use of 1997-2006 observations and simulations in accordance with a larger lab objective resulting in a good representation of the watershed during that time period which is still applicable today. It could be updated further to better represent the present with a more recent land use land cover dataset and weather simulations or ever future projections.

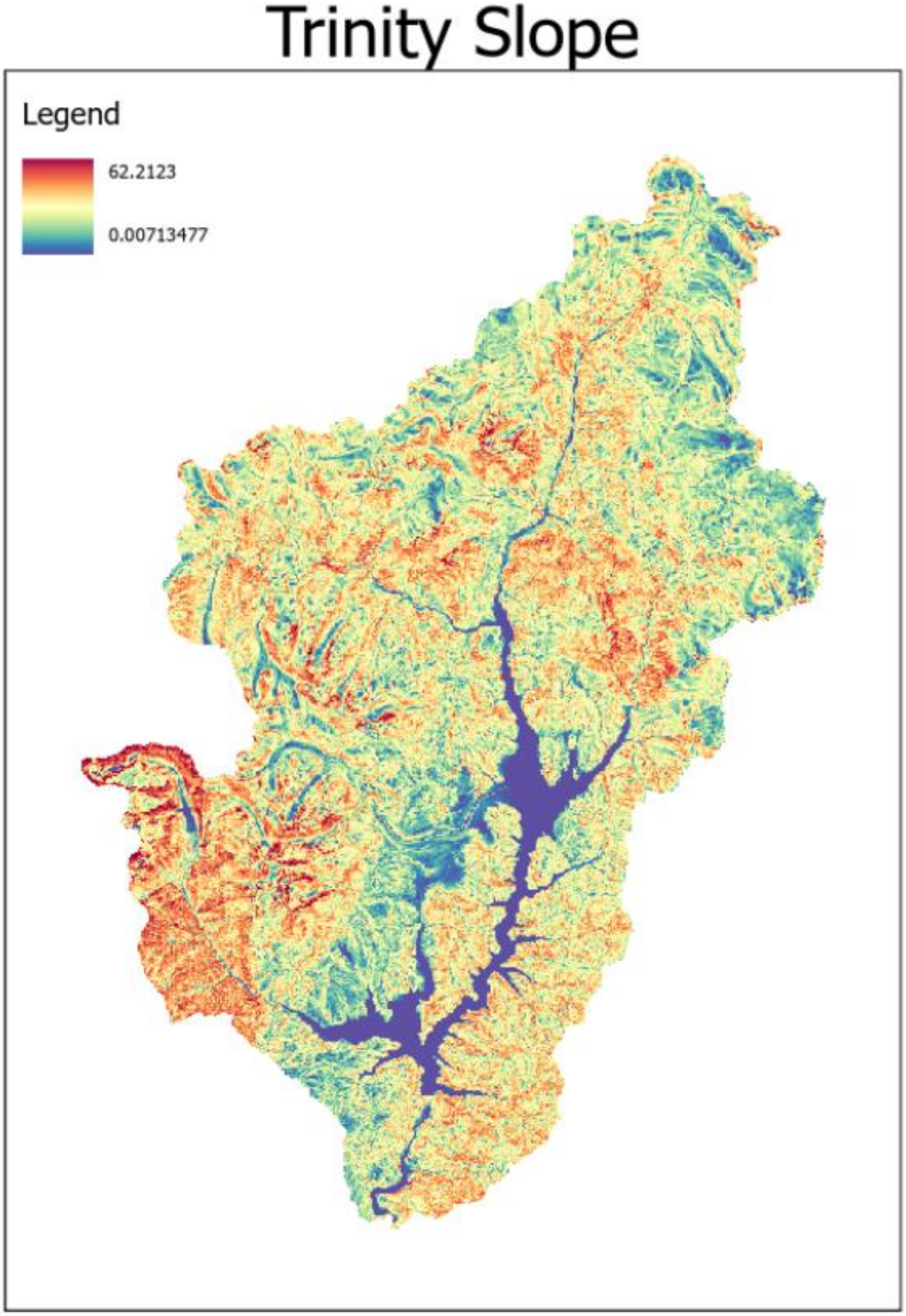



**Figure 11: Slope of land surface in the Trinity Subwatershed.**

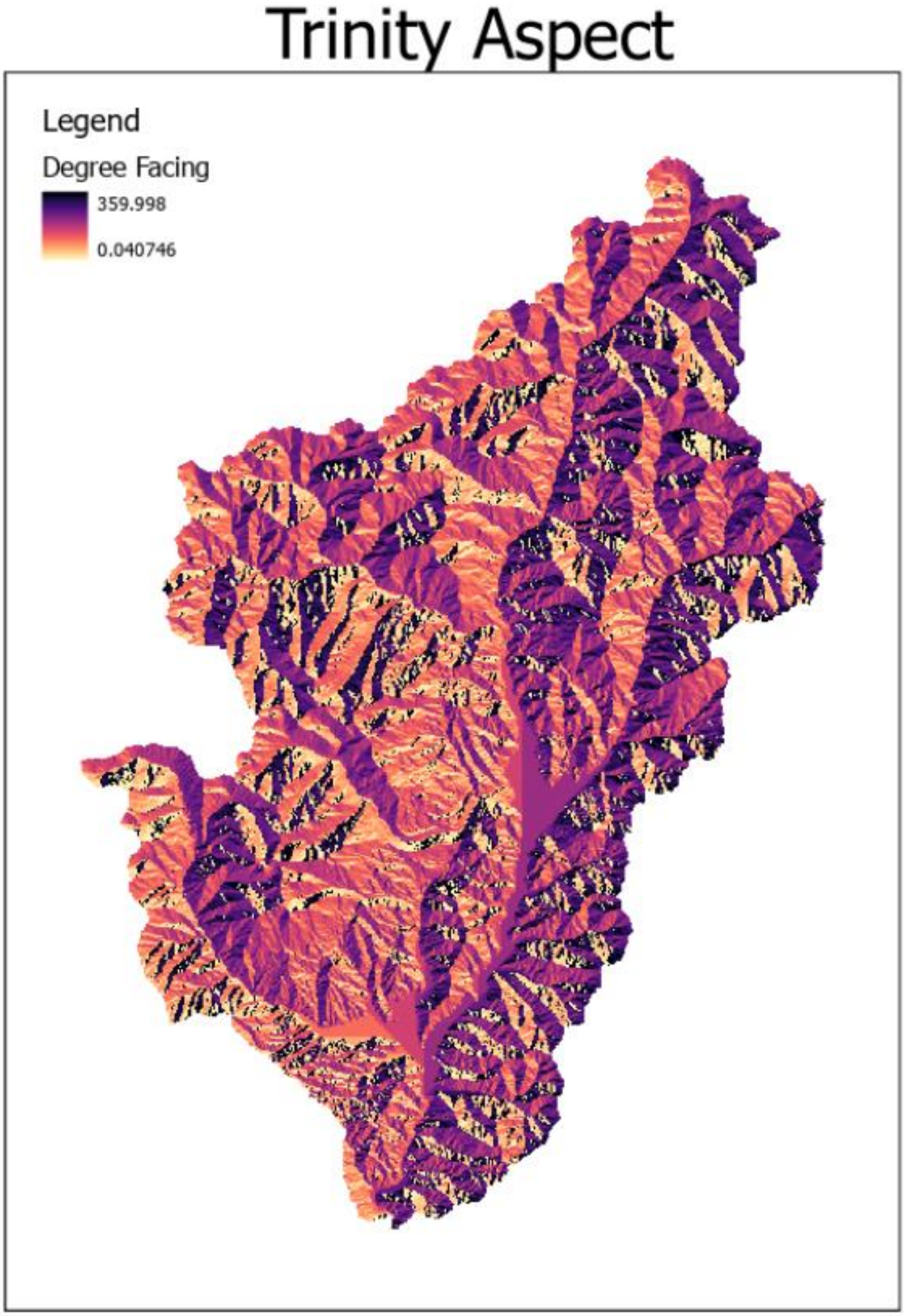



**Figure 12: Aspect or compass facing of land surface in the Trinity Subwatershed.**

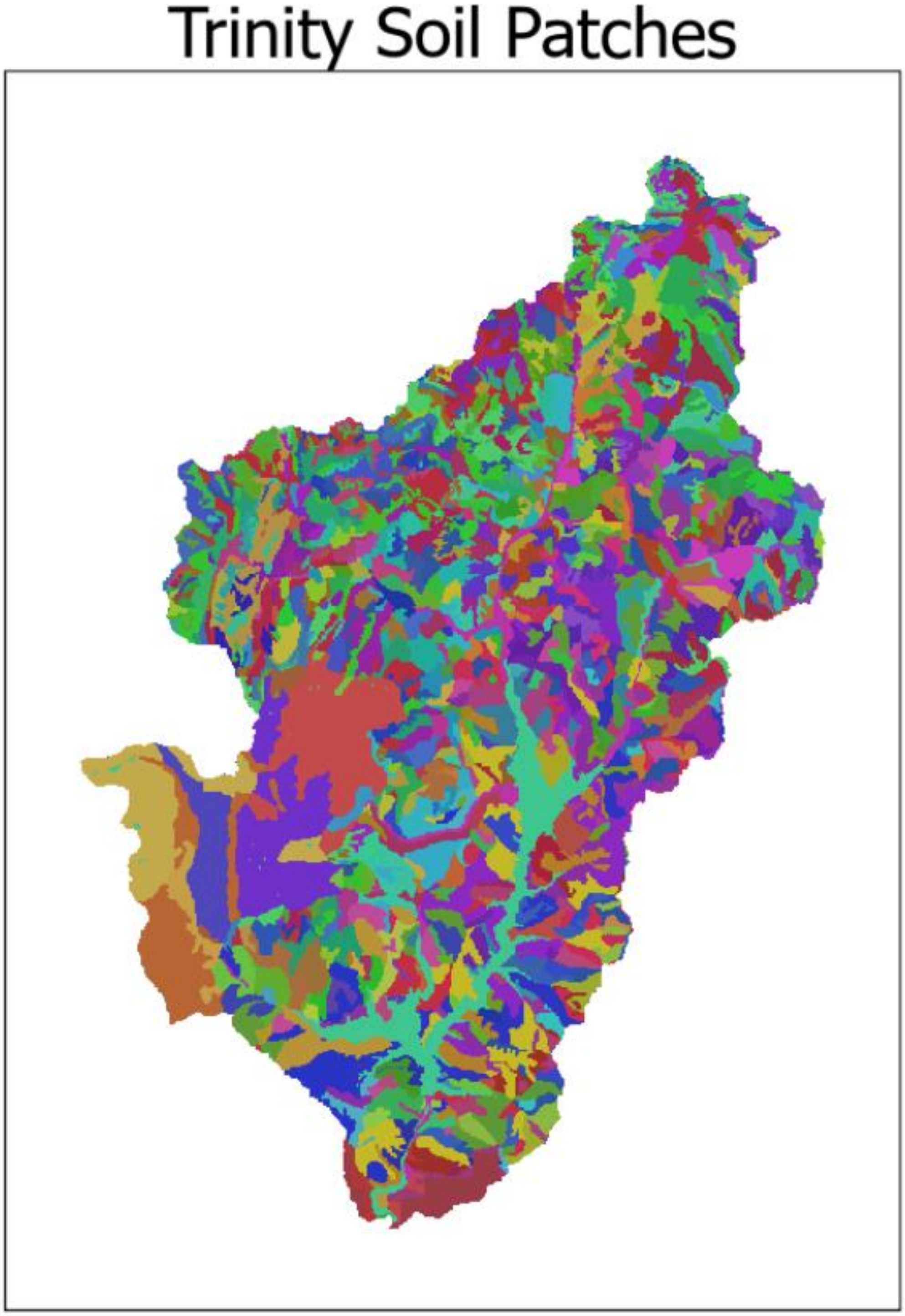



**Figure 13: Soil patches the Trinity Subwatershed. There are 247 different patches with unique soil parameter statistics obtained by field survey.**

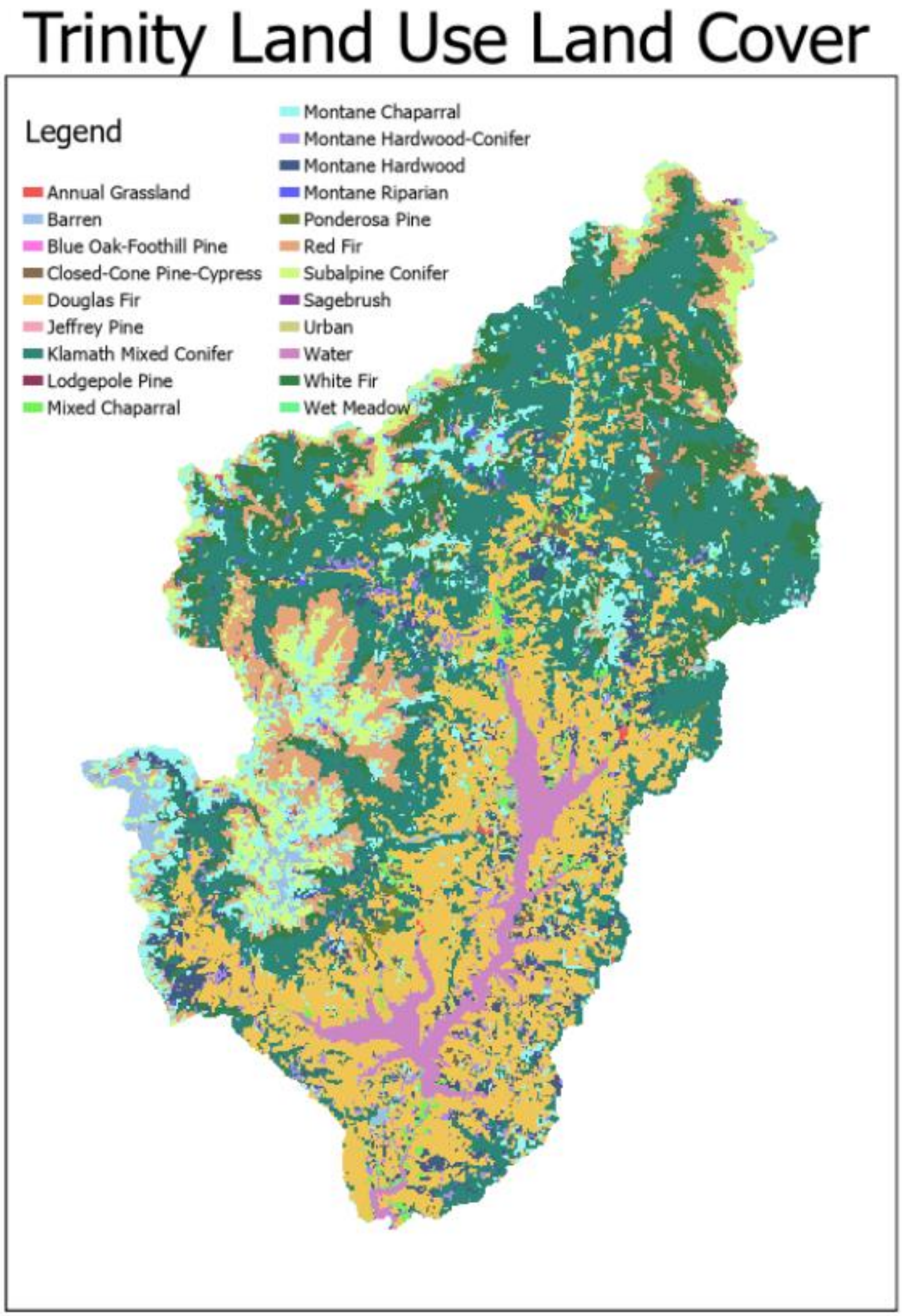



**Figure 14: Land Use Land Cover in Trinity Subwatershed.**

# IV. CALIBRATION PROGRAM

WEHY-HCM uses several land observation datasets for model parameterization. As such, it does not rely entirely on calibration to observed streamflow. However, some calibration of parameters can improve model performance. The usual approach with WEHY-HCM was a manual calibration of parameters. This approach has been effective in previous studies[39]. As a new contribution, this study developed a calibration program to assist model calibration for Trinity Subwatershed for this study. This calibration program was written using python and uses the evolutionary algorithm SciPy differential evolution. This program calibrated the global parameters used in WEHY-HCM. Parameters calibrated were either scaling factors on observed land parameters or were physical equation parameters which are not observed that are used for calibration. All parameters were optimized within realistic ranges to increase the model performance. For calibration and validation, the model streamflow was compared to the Full Natural Flow at Trinity Lake (CLE) station from CDEC. The calibrated parameters were chosen as those which are important to the hydro-climate processes. The parameters that were calibrated included soil depth, soil hydraulic conductivity, albedo, aerodynamic roughness length, length of channel influence, Manning's roughness, and transmissivity of groundwater. Soil depth, hydraulic conductivity, channel influence, and transmissivity are important for groundwater surface water interactions. Albedo and aerodynamic roughness length affect the heat and moisture fluxes from the hillslopes to the atmosphere. Manning's roughness affects flow within channels. The calibration parameters, their calibration range, and calibration results are included in Table 1.

**Table 1: Calibration Parameter Summary**

| Parameter | Default (x0) | Calibration Range | Calibration Result |
|---|---|---|---|
| Soil depth adjusting factor | 1 | (0.5,2) | 1.26 |
| Soil hydraulic conductivity adjusting factor | 1 | (0.5,2) | 1.67 |
| Albedo summer | 0.2 | (0.14,0.26) | 0.24 |
| Albedo winter | 0.8 | (0.64,0.96) | 0.94 |
| Roughness length summer (m) | 0.5 | (0.2,0.6) | 0.37 |
| Roughness length winter (m) | 0.1 | (0.5,0.1) | 0.38 |
| Length of influence of the channel in the unconfined aquifer (m) | 50 | (10,500) | 433 |
| Global factor-Manning's roughness coefficient | 1 | (0.7,1.3) | 1.08 |
| Global factor of transmissivity of groundwater | 1 | (0.01,10) | 3.10 |

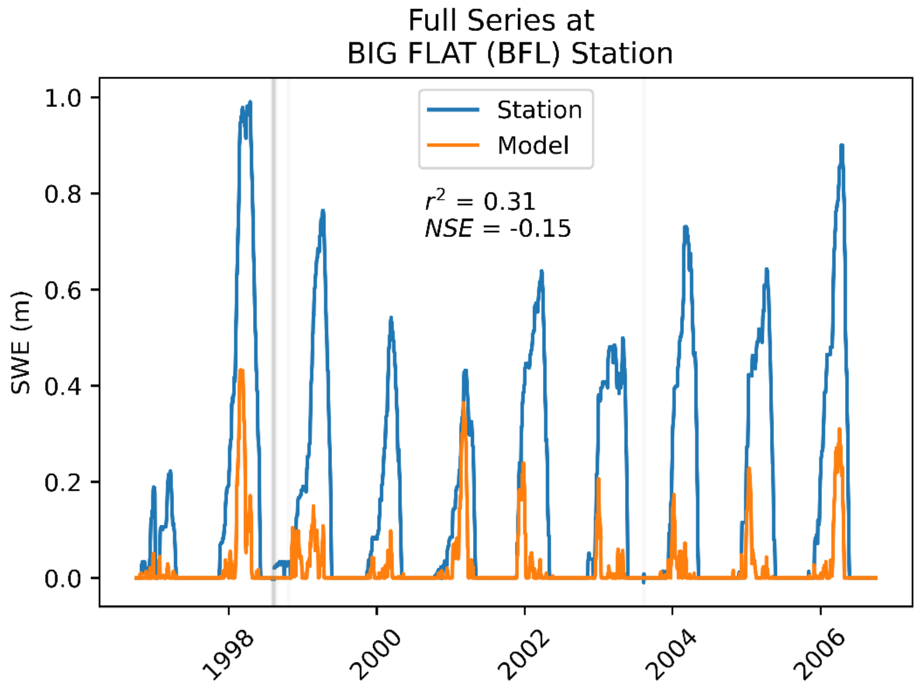
Differential evolution is an optimization method which employs an evolutionary algorithm to develop optimal solutions iteratively. The candidate solutions are mutated by cross breeding with each other favoring the best parameter configurations with time in an evolutionary fashion. The result is a convergence on an optimal solution over time while being able to search a large problem space [40] . This method is also helpful in that it does not require derivatives and can be applied to complex multivariate functions such as are found in a hydro climate model. It does however require many evaluations. As such the program was run on a research computing cluster using multiprocessing. The calibration program is included in Appendix A. At completion of the model run the results were then assessed with the Nash-Sutcliffe efficiency (NSE) for goodness of fit. NSE is a statistic commonly used to evaluate hydrological models which considers the ratio of model error variance to observation variance. The value can range from 1 for a perfect model to -infinity for a very poor model. An NSE of zero means a model performs as well as the mean observed discharge [41]. There are different views on what value represents an acceptable or unacceptable NSE. A comparative study of statistical evaluation of watershed models found an

NSE > 0.5 of to be satisfactory [42]. The developed calibration method in this study for the Upper Trinity watershed can be applied to the calibration of WEHY-HCM over any watershed. As such, it is a valuable development in the application of WEHY-HCM at any watershed around the world. In fact, this method could be applied to the calibration of other regional hydroclimate models.

# V. RESULTS/ANALYSIS

## A. Calibration and validation of the snow model

The snow model was evaluated in comparison to observations at seven monitoring stations operated by the US Bureau of Reclamation. These stations are shown in Figure 3 above and have coverage throughout a study period covering water years 1997 to 2006. The revised daily snow water equivalent (SWE) dataset was used for evaluation. Missing or erroneous negative values were excluded. Water years 1997-1999 were used for model calibration and water years 2000-2006 were used for validation. Average $r^2$ for calibration years was 0.86 while the average $r^2$ for validation years was 0.80. Average NSE was 0.74 for calibration and 0.69 for validation. For the full range of water years (1997-2006), the NSE was 0.72 and the $r^2$ was 0.82. Figures 15-18 display results at the seven stations for 1997-2006. These show generally good alignment between the snow model and snow observations. The seasonal snow accumulation and snow melt cycle is clearly shown in Figures 15-18. Additional snow figures are available in Appendix B. The scores indicate the snow model in the Upper Trinity River Basin shows satisfactory performance. Model comparisons at most stations typically had excellent scores of 0.8 and above. Model performance at Big Flat (BFL) station had poor results with an NSE of -0.15. This might be explained by the surrounding terrain which was a large flat valley which could create local effects which were not accounted for in the model. It is possible that the atmospheric, boundary, or surface layer models failed to account for the spatial distribution of snow in this valley because of its unique characteristics. The Big Flat Valley runs around 9 km north-south on the western edge of the Upper Trinity watershed. Approximately 2 km of the valley is included in the Upper Trinity River Watershed model domain. The large southern portion of the valley was part of a different watershed which flows directly to the Klamath River via the South Fork Salmon River without entering the Trinity River or reservoir and was therefore not included in this modeling study. It is possible that the snow accumulated in the Trinity portion because of some mountain advection effects which carried snow from the South Fork Salmon River portion of the valley or elsewhere while this was not well represented by WRF or WEHY. Advection of falling snow can affect the distribution of snow on the land surface in mountain regions [43]. Valley breeze effects driven by differential heating of the north-south running Big Flat Valley could explain the discrepancy. The southward facing northern portion of the valley could receive more heating during the day which could drive local uplift and subsequent advection from the southern portion of the valley. Further study would be necessary to explore this in the Trinity Subwatershed.



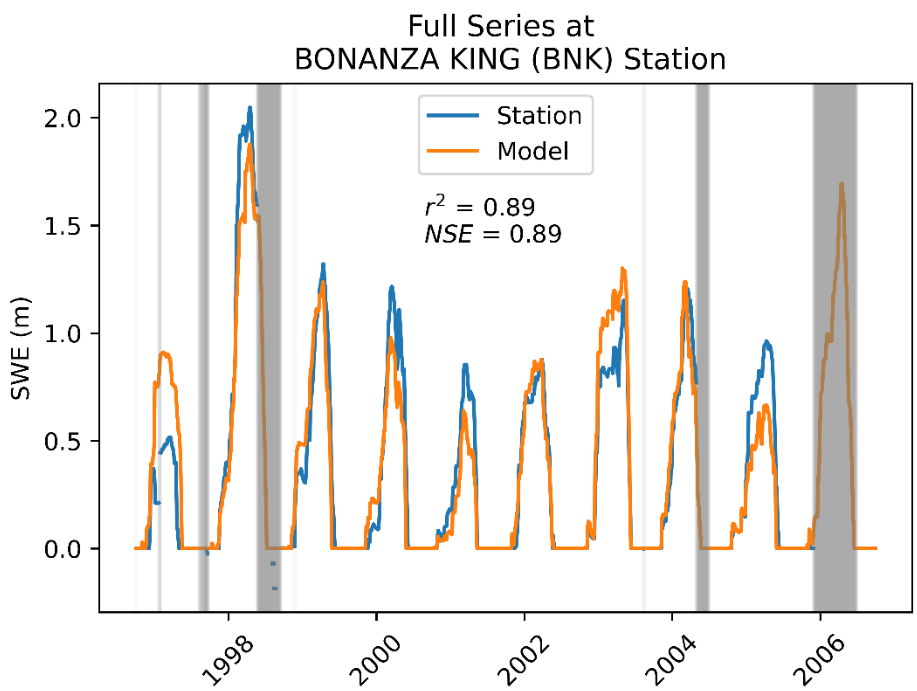




**Figure 15: Daily snow water equivalent timeseries comparisons between observations and snow model simulations for full date range from 1997-2006 at stations BFL and BNK. The grey shaded area represents missing or faulty data.**

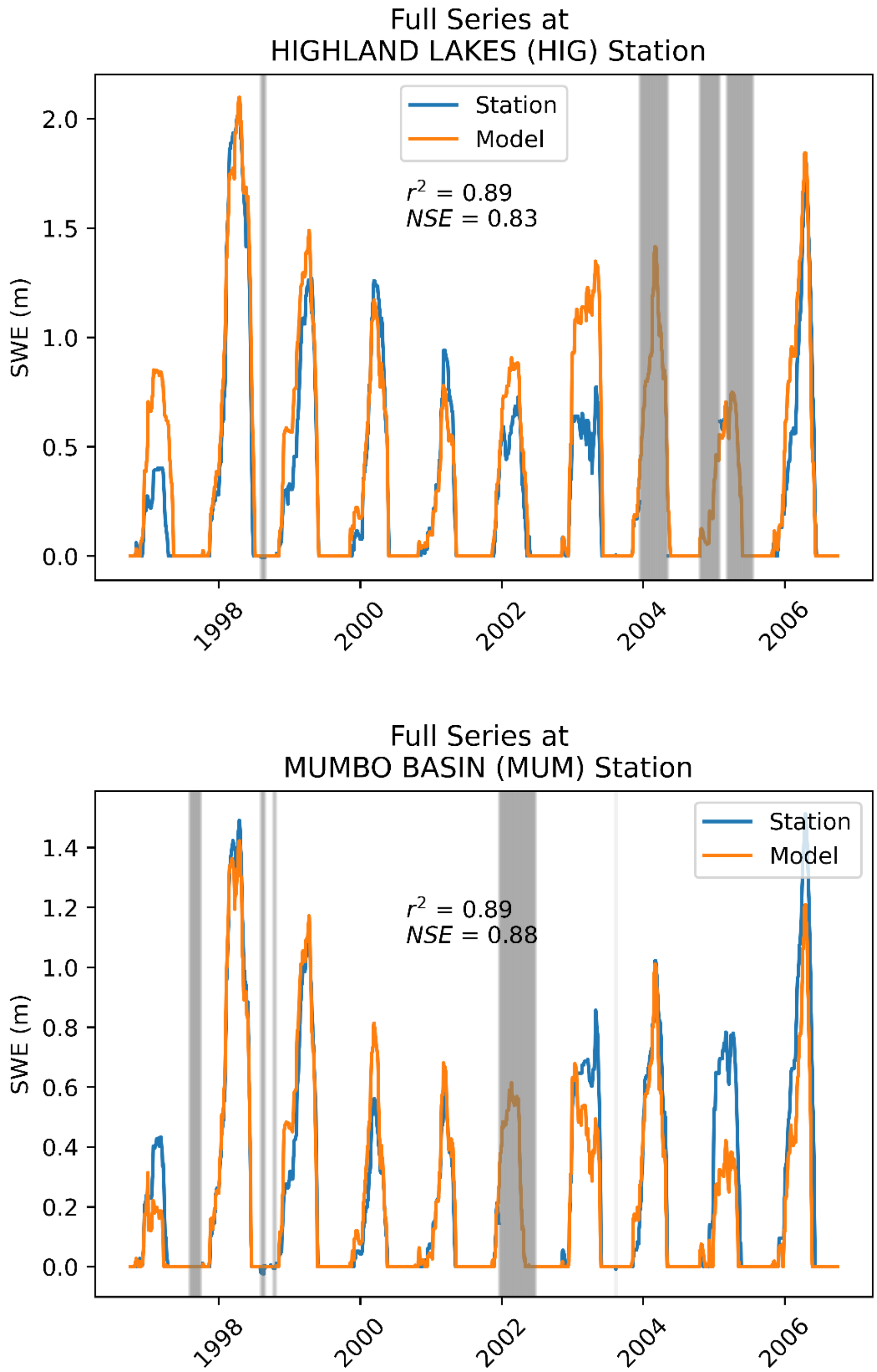



**Figure 16: Daily snow water equivalent timeseries comparisons between observations and snow model simulations for full date range from 1997-2006 at stations HIG and MUM. The grey shaded area represents missing or faulty data.**

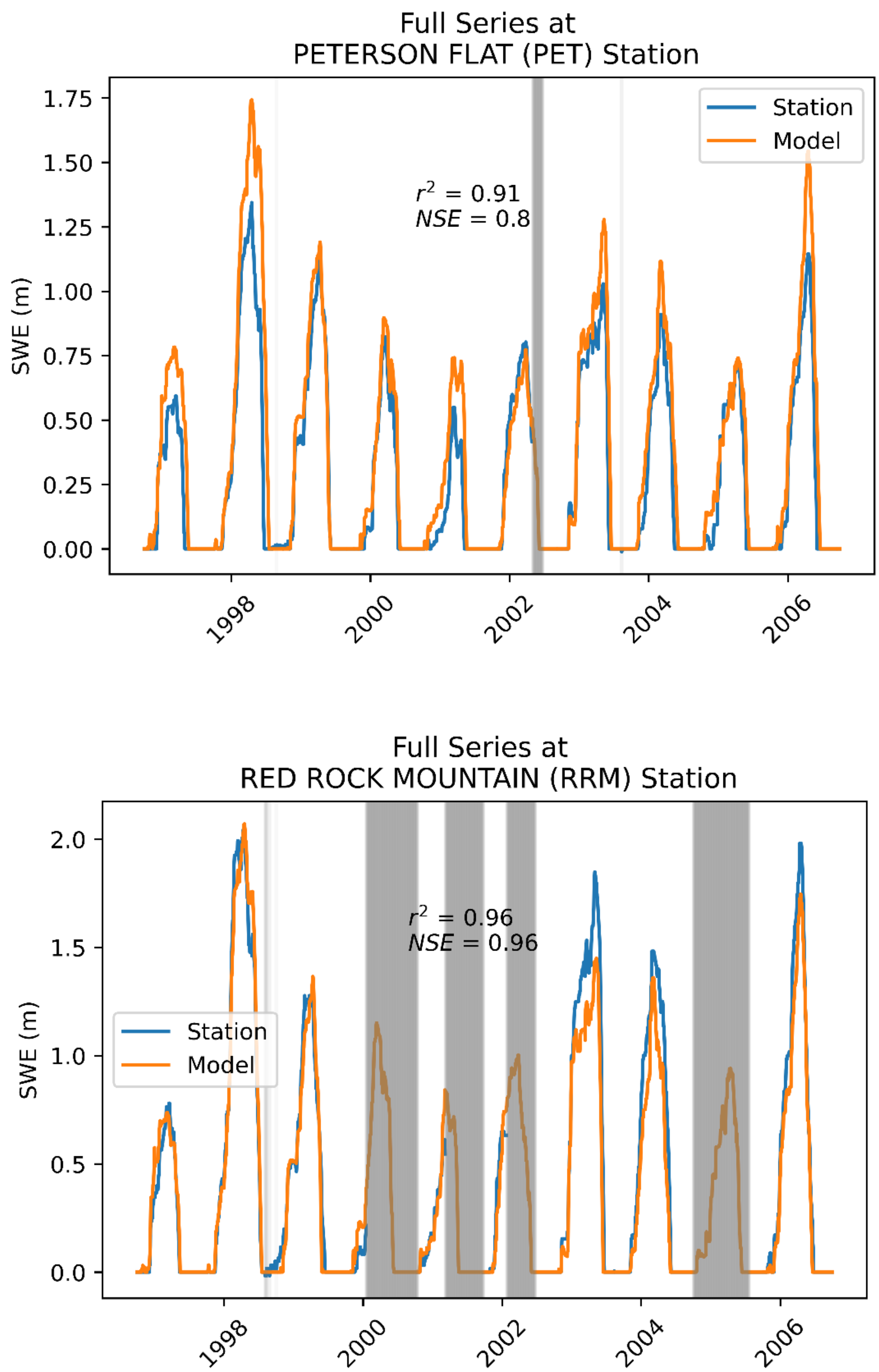



**Figure 17: Daily snow water equivalent timeseries comparisons between observations and snow model simulations for full date range from 1997-2006 at stations PET and RRM. The grey shaded area represents missing or faulty data.**

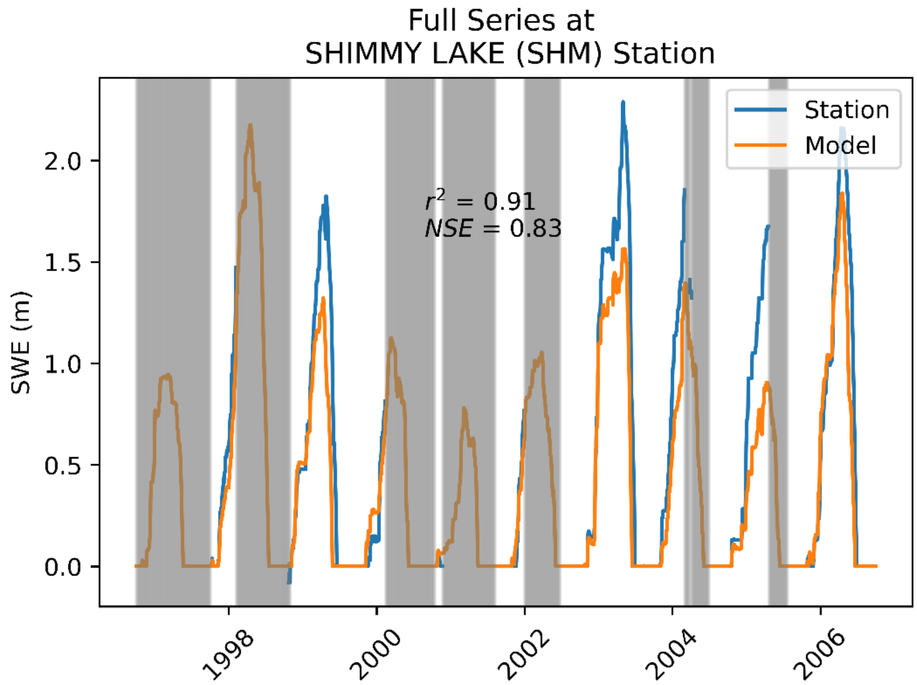



**Figure 18: Daily snow water equivalent timeseries comparisons between observations and snow model simulations for full date range from 1997-2006 at station SHM. The grey shaded area represents missing or faulty data.**

## B. Calibration and Validation of WEHY model

A WEHY model was developed for the Upper Trinity Subwatershed. The three-year period of 1997-1999 water years was used for calibration. The six-year period of water years 2000-2006 was used for validation of the model. Calibration was conducted using a calibration program as described in Section IV. While this approach produced the best calibration results for Trinity, they were not clearly superior to manual calibration as done in previous studies [39], [44], [45]. However, there is a time savings benefit acquired by use of the calibration program as hours of manual calibration are automated with this program. This can be easily applied to other watersheds. The calibrated model had a modest but effective improvement in performance over the uncalibrated model. The uncalibrated daily full time series had an $r^2$ of 0.67 and NSE of 0.65. With calibration, the daily time step $r^2$ value was 0.71 and the NSE was 0.69. The daily time series is presented as Figure 19. The results are comparable or improved for the weekly time step and monthly time step for both calibrated and uncalibrated models as seen in Tables 2 – 5 and Figure 20 and 21. A weekly or monthly timestep would be acceptable for Upper Trinity Subwatershed where the primary concern is water supply. The weekly time step $r^2$ value was 0.75 and the NSE was 0.73. The monthly time step $r^2$ value was 0.72 and the NSE was 0.69. Model results for the uncalibrated and calibrated full time series are presented as Figures 19-24. Additional streamflow figures are included in Appendix C.

One possible explanation for the performance of the calibration period compared with the validation period is that the calibration period includes two large peak flows greater that 1000 cubic meters per second (CMS) which are well represented by the model, giving good performance, whereas the validation period does not have such large peaks. Looking at the precipitation in Figure 4 it is clear that the calibration period had relatively more precipitation compared with the validation period. The Oct 1996 – Sept 1999 calibration period was largely above the historical mean. The Oct 1999-Sept 2006 validation period was more variable with wet and dry years. The calibration may have favored parameters which worked well in the wet calibration period to match these high peaks flows without similarly improving the more variable validation years. This would explain the slight difference in performance improvement between the calibration and validation periods shown in Table 2 – 4. Further performance improvements might be obtained from calibrating for more low flow water years.

A good physical understanding of the watershed is also important for calibration. Early calibration was impaired by accounting for the model in an unphysical way, using a stream reach created during delineation which did not represent the actual geomorphology in the basin. This occurred because the DEM dataset was interpreted during watershed delineation to create a flat stream reach across what is actually the flat surface of the reservoir. This unphysical stream reach does not exist in reality but the earlier model version produced greater error from its inclusion in the model. When the model was adjusted to negate this unphysical reach by using a summation of stream reach inflows into the reservoir instead, a significant gain in performance was obtained.

Table 2: R-squared values for uncalibrated WEHY model

| | 1997-1999 calibration | 2000-2006 validation | 1997-2006 full series |
|---|---|---|---|
| daily | 0.77 | 0.58 | 0.67 |
| weekly | 0.84 | 0.61 | 0.72 |
| monthly | 0.78 | 0.62 | 0.68 |

Table 3: NSE values for uncalibrated WEHY model

| | 1997-1999 calibration | 2000-2006 validation | 1997-2006 full series |
|---|---|---|---|
| daily | 0.77 | 0.51 | 0.65 |
| weekly | 0.84 | 0.59 | 0.71 |
| monthly | 0.76 | 0.62 | 0.68 |

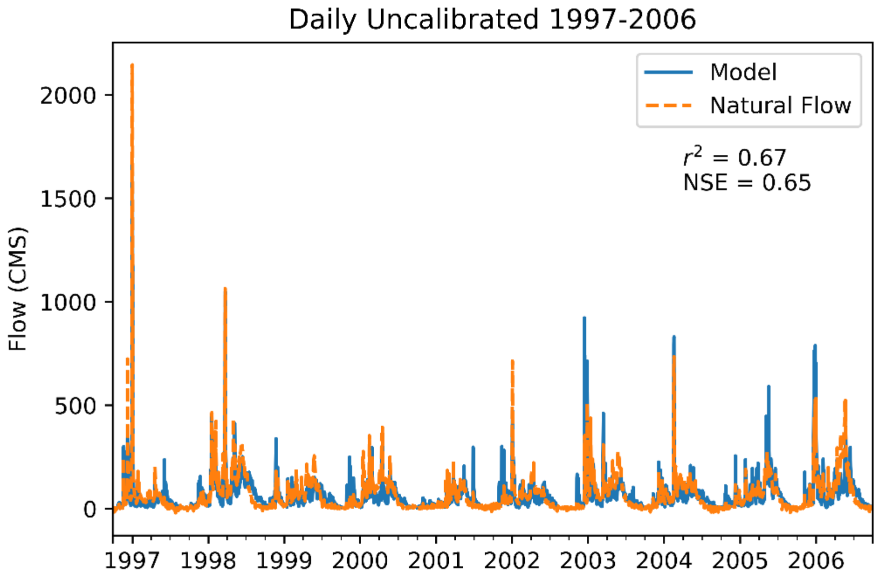
Table 4: R-squared values for calibrated WEHY model

| | 1997-1999 calibration | 2000-2006 validation | 1997-2006 full series |
|---|---|---|---|
| daily | 0.83 | 0.60 | 0.71 |
| weekly | 0.87 | 0.64 | 0.75 |
| monthly | 0.83 | 0.66 | 0.72 |

Table 5: NSE values for calibrated WEHY model

| | 1997-1999 calibration | 2000-2006 validation | 1997-2006 full series |
|---|---|---|---|
| daily | 0.82 | 0.54 | 0.69 |
| weekly | 0.85 | 0.61 | 0.73 |
| monthly | 0.77 | 0.63 | 0.69 |

## C. Uncalibrated WEHY model



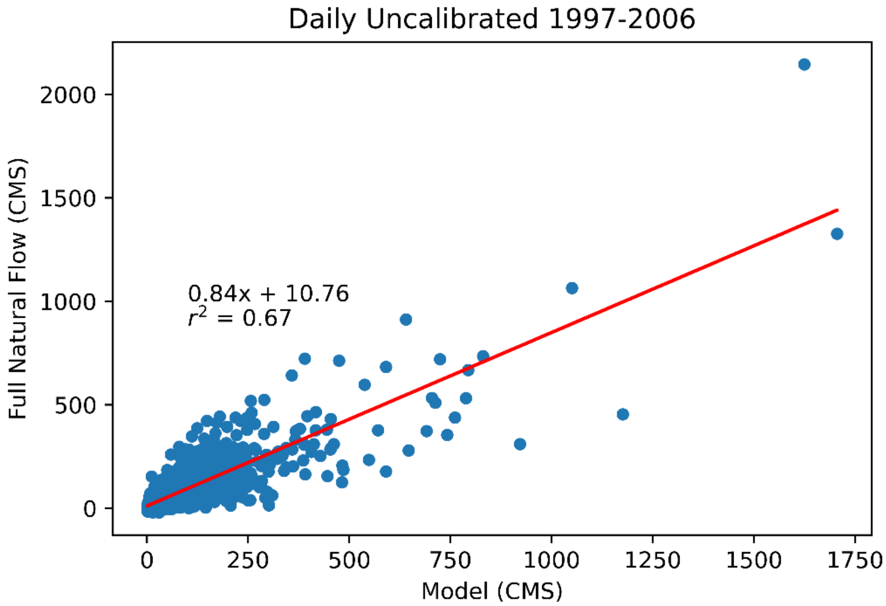
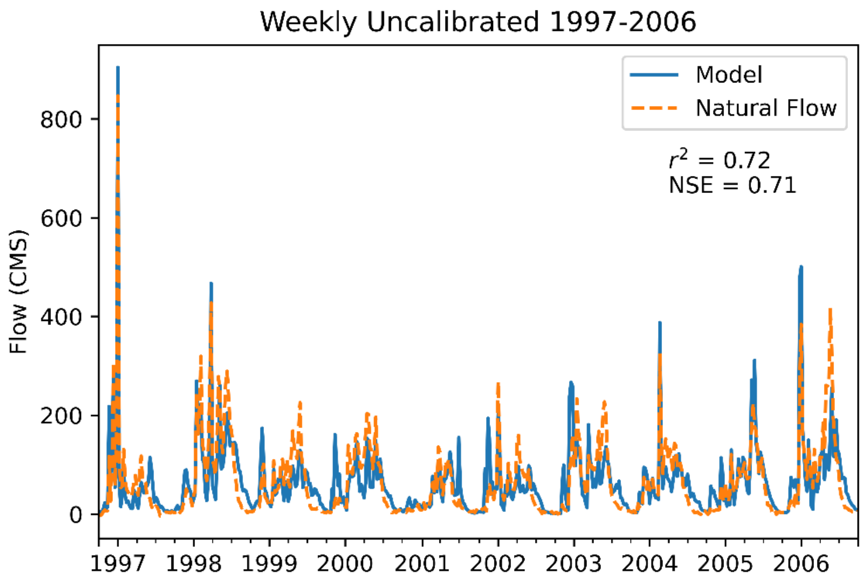




**Figure 19: (Top) The uncalibrated daily mean discharge time series for the full time period (1997-2006). (Bottom) The scatter plot of daily mean discharge between uncalibrated WEHY simulation and observed natural flow for the full period.**



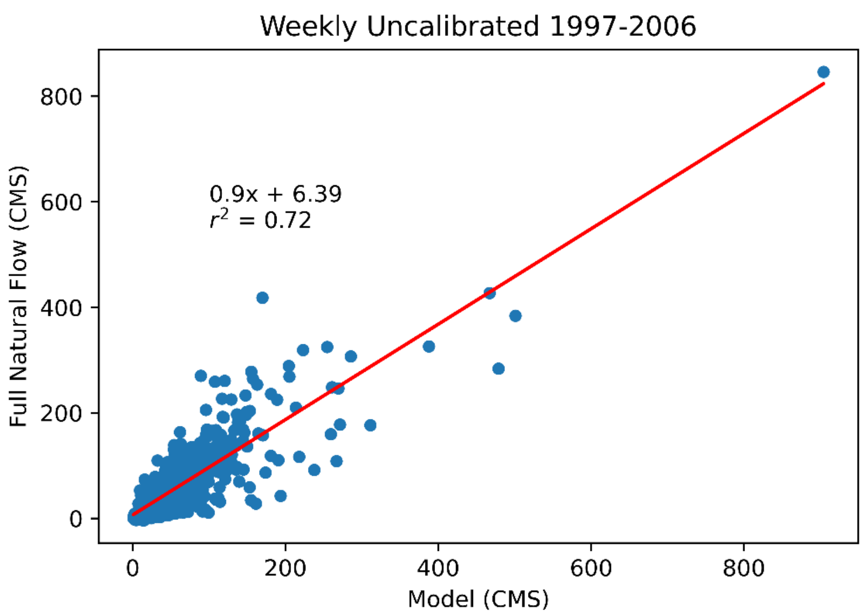
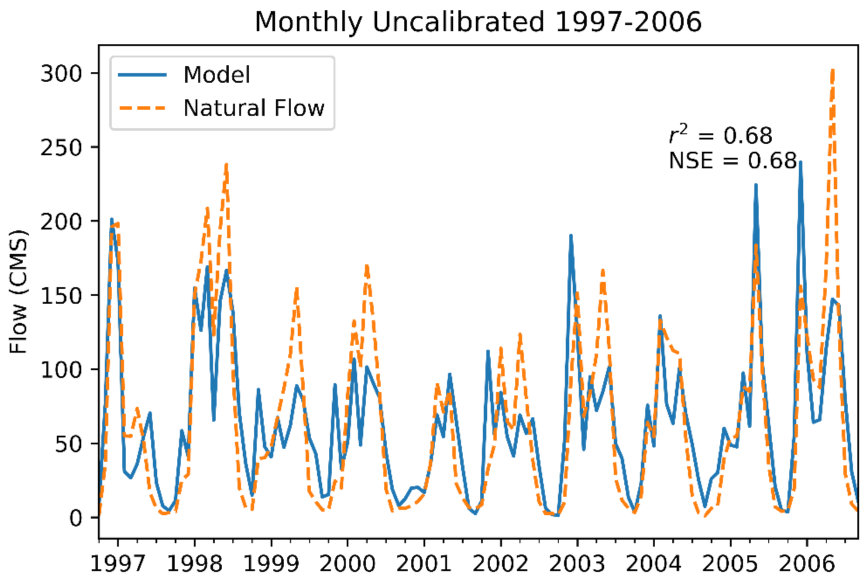




**Figure 20: (Top) The uncalibrated weekly mean discharge time series for the full time period (1997-2006). (Bottom) The scatter plot of weekly mean discharge between uncalibrated WEHY simulation and observed natural flow for the full period.**



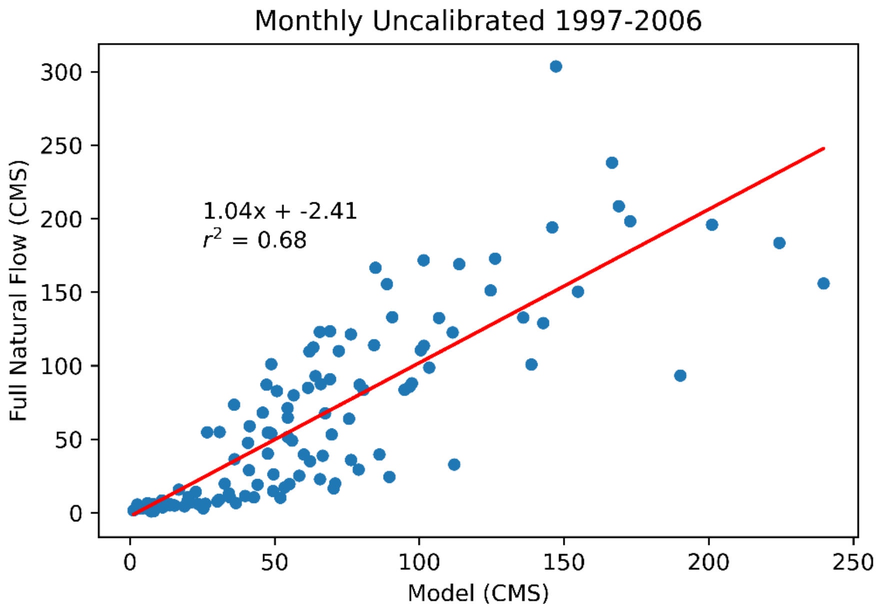
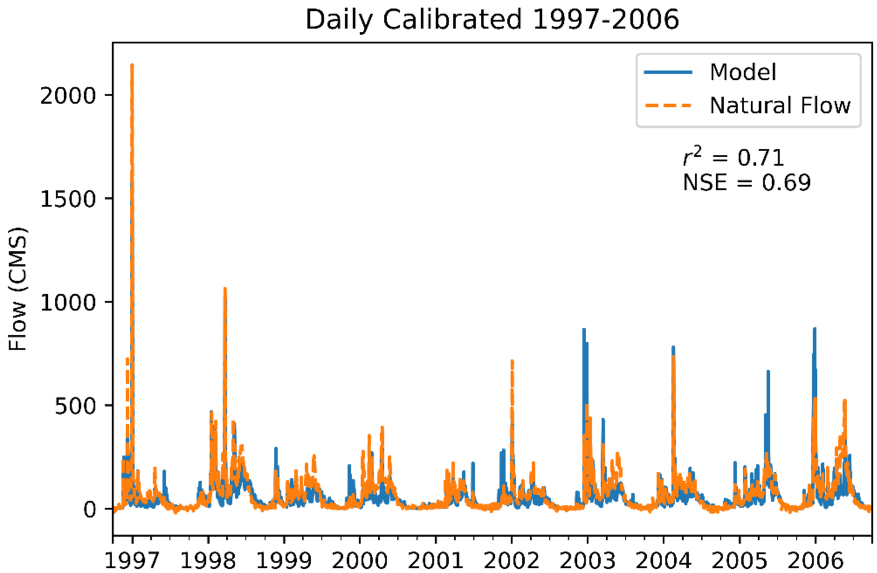




**Figure 21: (Top) The uncalibrated monthly mean discharge time series for the full time period (1997-2006). (Bottom) The scatter plot of monthly mean discharge between uncalibrated WEHY simulation and observed natural flow for the full period.**

## D. Calibrated WEHY Model



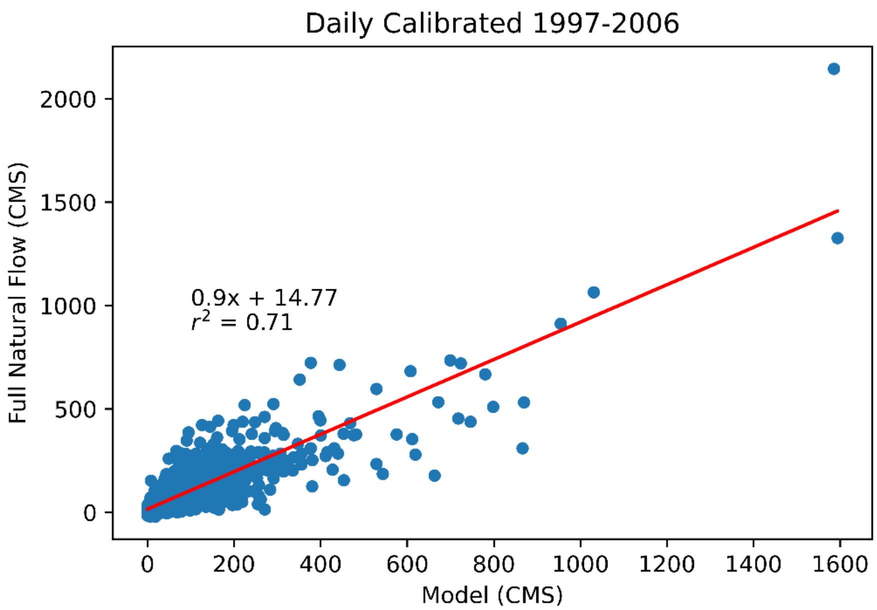
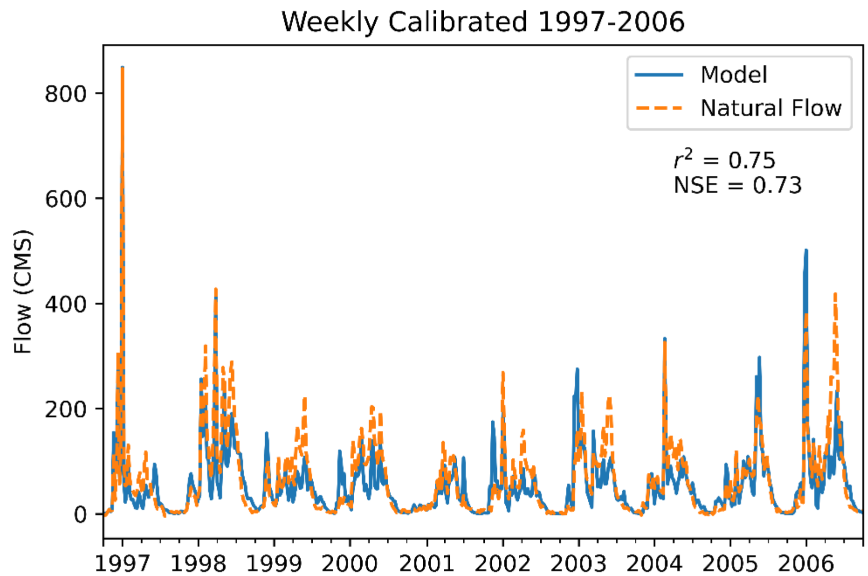




**Figure 22: (Top) The calibrated daily mean discharge time series for the full time period (1997-2006). (Bottom) The scatter plot of daily mean discharge between calibrated WEHY simulation and observed natural flow for the full period.**



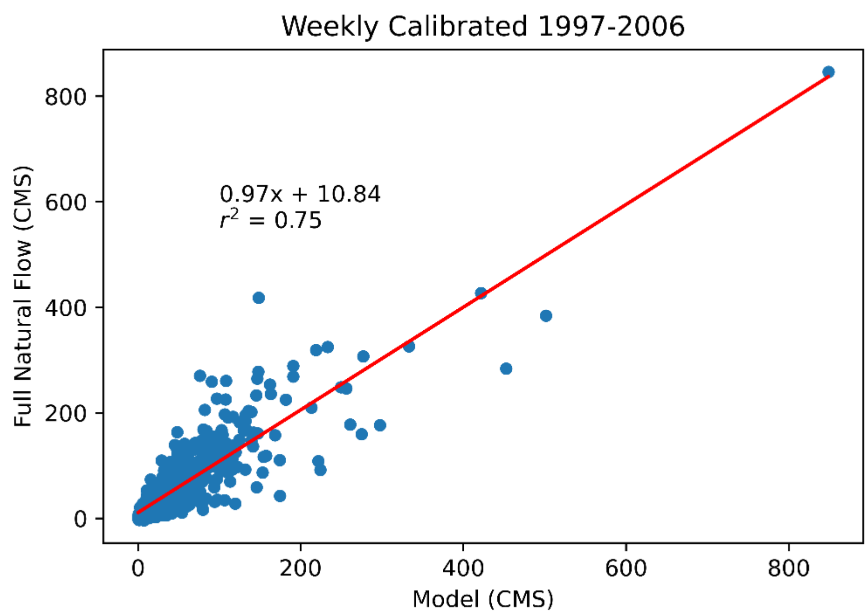
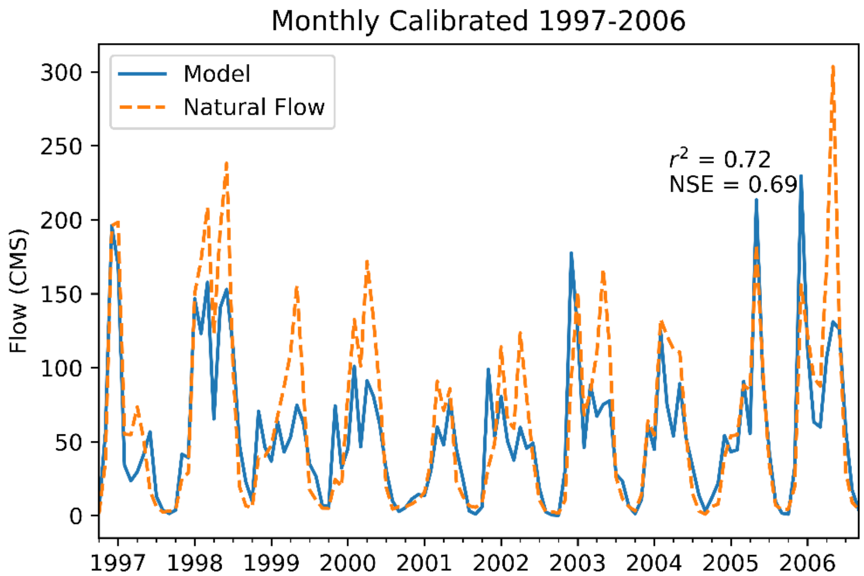




**Figure 23: (Top) The calibrated weekly mean discharge time series for the full time period (1997-2006). (Bottom) The scatter plot of weekly mean discharge between calibrated WEHY simulation and observed natural flow for the full period.**



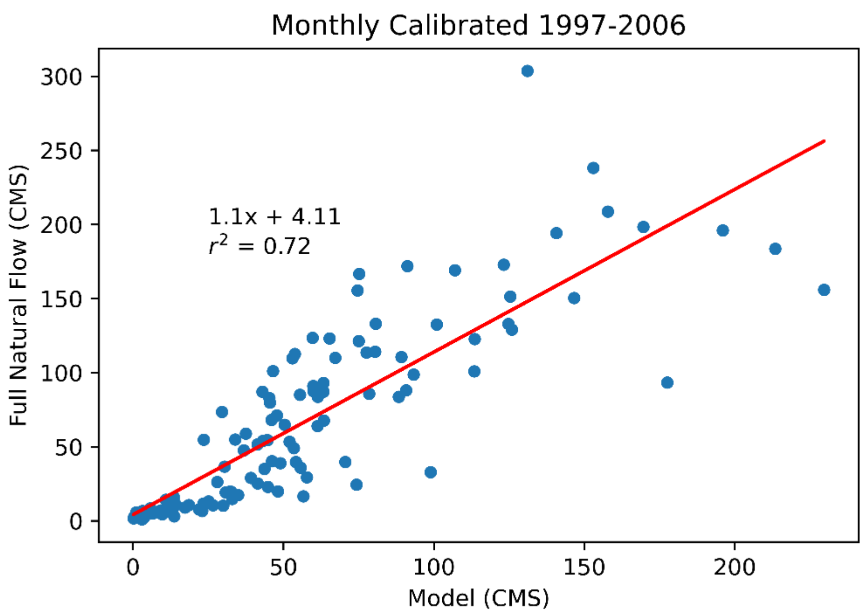




**Figure 24: (Top) The calibrated monthly mean discharge time series for the full time period (1997-2006). (Bottom) The scatter plot of monthly mean discharge between calibrated WEHY simulation and observed natural flow for the full period.**

## E. WEHY Model and Basin Integrated Precipitation

To provide a basis for comparison with WEHY model, the basin integrated precipitation was computed using the CFSR dataset at a daily, weekly, and monthly timestep. These are presented as Figures 25-27. This precipitation was immediately routed to streamflow and compared with the full natural flow. The NSE and $r^2$ values for WEHY are significantly better than for model simulations based on the basin integrated CFSR as seen in Table 6. For model simulations based on the basin integrated CFSR the NSE scores are all less than 0 meaning that just taking the average streamflow over the entire 1997-2006 period would produce better results in terms of model error variance. The results show that model simulations based on the basin integrated precipitation are a poor representation of the hydrology of the basin at every time resolution. This is because total precipitation over a basin is not immediately converted to streamflow. There are many physical mechanisms which delay stream flow developments in natural basins. Flow paths for surface and groundwater flows as displayed in Figure 9 are much slower than precipitation. Some moisture is lost from the basin by evapotranspiration or is held for long periods in aquifers or in the soil pores. The hydrology of the Upper Trinity Subwatershed is strongly affected by an annual snowfall/snowmelt cycle because of California's mediterranean climate and mountainous terrain. Significant seasonal precipitation occurs as snow in winter which remains in mountain areas until spring temperature rise drives snowmelt. While the WEHY model accounts for these processes, the model simulations based on the basin integrated precipitation approach ignores it entirely, converting everything to streamflow immediately. The weakness of this is illustrated clearly in the monthly model simulations based on the basin integrated CFSR Figure 27. The streamflow of the model simulations based on the basin integrated CFSR method precedes the full natural flow observation by several months each year because there is no accounting for snow. The observations show substantial streamflow throughout the spring and into early summer driven by snowmelt. With model simulations based on the basin integrated CFSR there is no snow accumulation and no snowmelt resulting in much lower spring and summer flows.

Table 6: NSE and R-squared values for calibrated WEHY model and model simulations based on the basin integrated CFSR

| | WEHY model | Model simulations based on the basin integrated precipitation CFSR |
|---|---|---|
| Daily NSE | 0.69 | -5.89 |
| Weekly NSE | 0.73 | -2.18 |
| Monthly NSE | 0.69 | -2.10 |
| Daily R-squared | 0.71 | 0.16 |
| Weekly R-squared | 0.75 | 0.24 |
| Monthly R-squared | 0.72 | 0.21 |

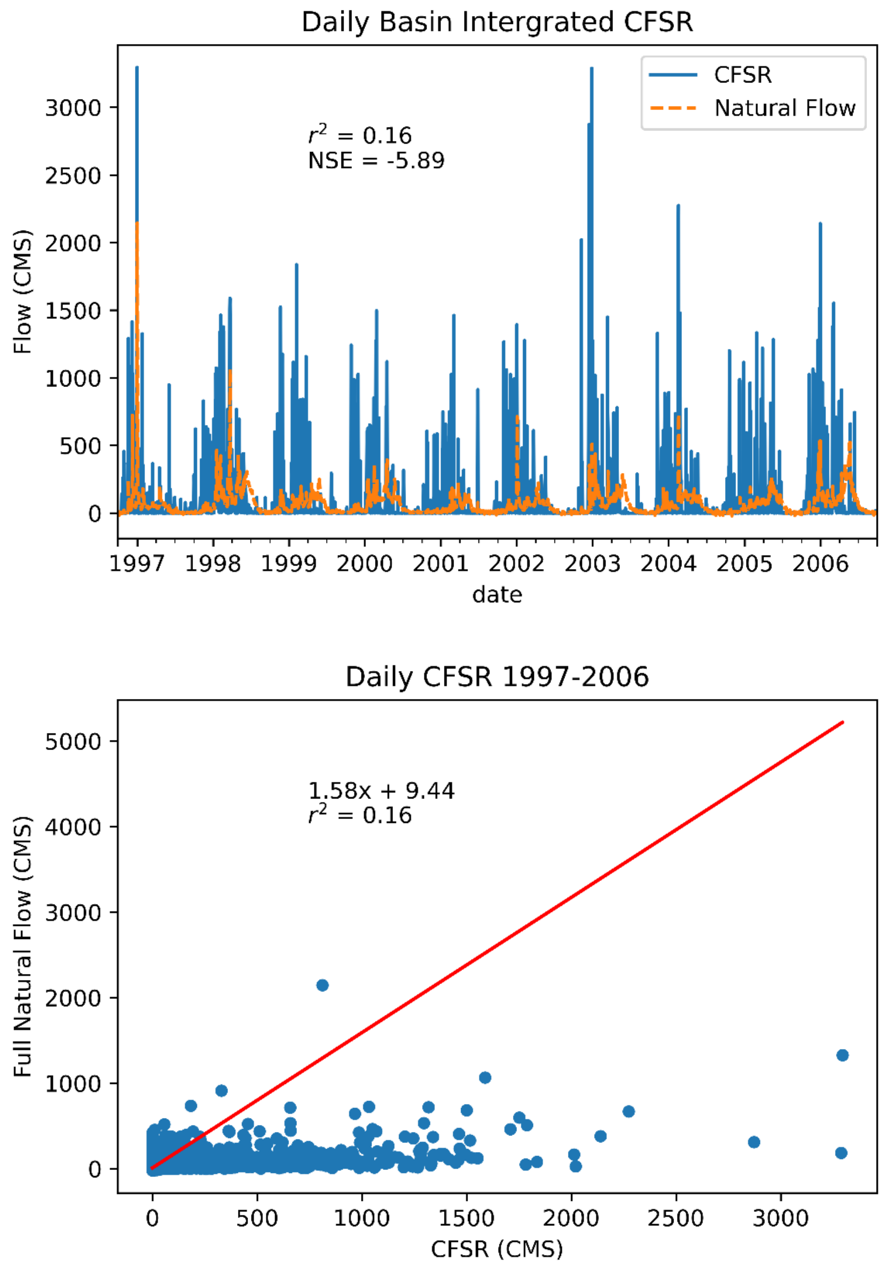
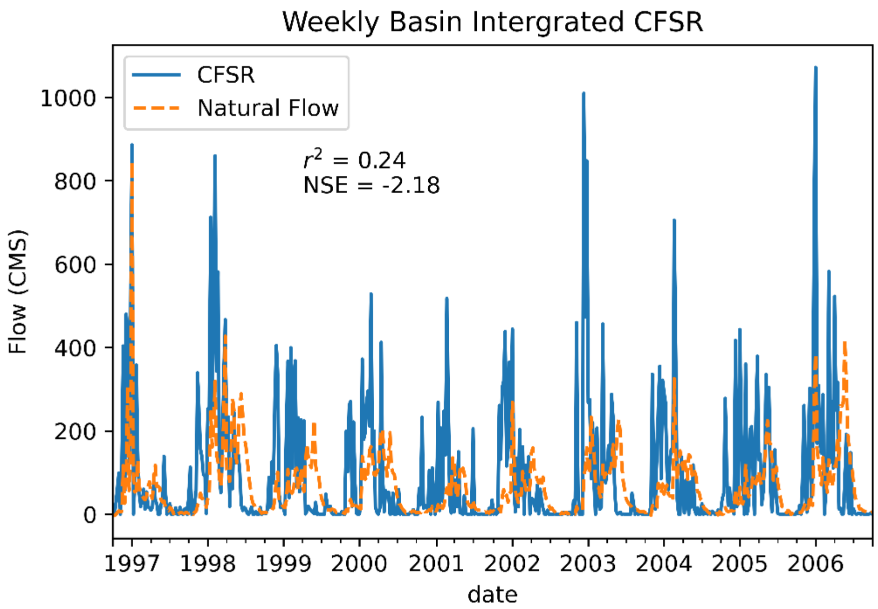



**Figure 25: (Top) The model simulations based on the basin integrated CFSR daily discharge time series for the full time period (1997-2006). (Bottom) The scatter plot of daily discharge between model simulations based on the basin integrated CFSR simulation and observed natural flow for the full period.**



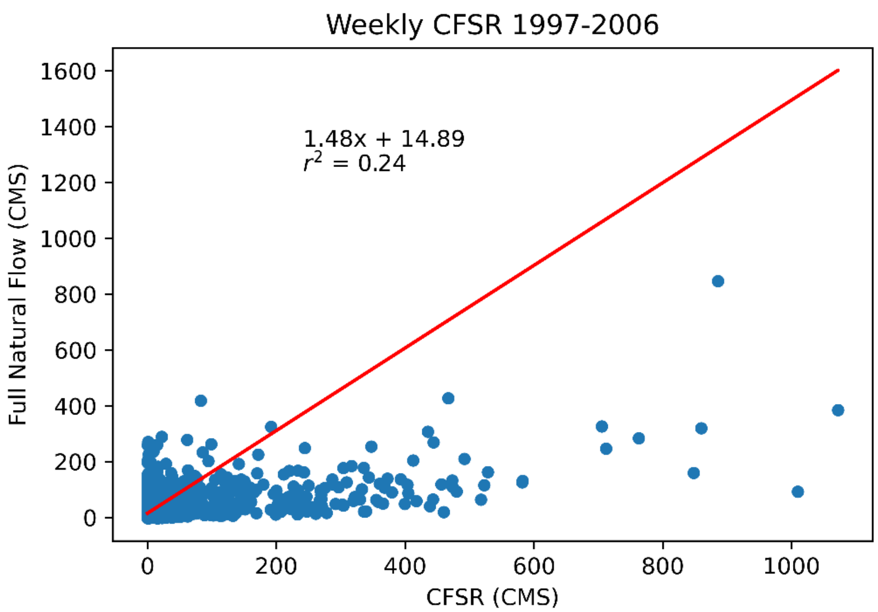
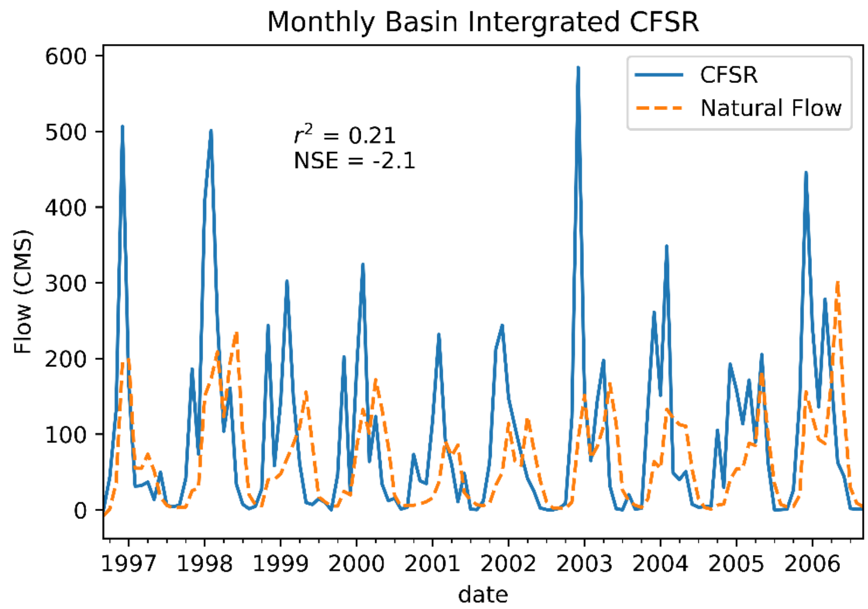




**Figure 26: (Top) The model simulations based on the basin integrated CFSR weekly discharge time series for the full time period (1997-2006). (Bottom) The scatter plot of weekly discharge between model simulations based on the basin integrated CFSR simulation and observed natural flow for the full period.**



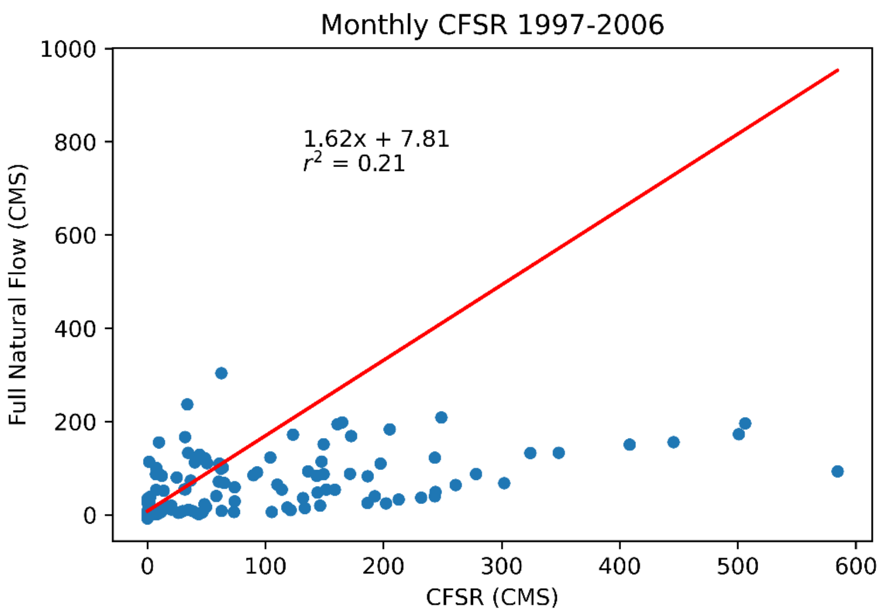




**Figure 27: (Top) The model simulations based on the basin integrated CFSR monthly discharge time series for the full time period (1997-2006). (Bottom) The scatter plot of monthly discharge between model simulations based on the basin integrated CFSR simulation and observed natural flow for the full period.**

# VI. DISCUSSION/CONCLUSIONS

A WEHY-HCM model was developed for the Trinity Subwatershed. In order to calibrate this model, a program was developed using the evolutionary optimization algorithm differential evolution. The performance of the snow module was acceptable. Average snow NSE was 0.74 for calibration years and 0.69 for validation years. Average $r^2$ for calibration years was 0.86 while the average $r^2$ for validation years was 0.80. For the full range of water years (1997-2006), the NSE was 0.72 and the $r^2$ was 0.82. The performance of the WEHY-HCM model streamflow compared with the Full Natural Flow dataset was also acceptable. For daily timestep calibration the $r^2$ value is 0.83 and the NSE is 0.82. The daily time step validation for $r^2$ is 0.60 and the NSE is 0.54. The calibrated model full time series at daily time scale had an $r^2$ of 0.71 and NSE of 0.69. This compares favorably against using model simulations based on the basin integrated precipitation method using CFSR which had poor results because it does not account for any physical hydrological processes such as surface and subsurface flow pathways, seasonal snow accumulation and snowmelt, evapotranspiration, and soil moisture.

The Upper Trinity WEHY-HCM model captured important elements of the hydrology of the watershed. The WEHY-HCM model represented the seasonal fluctuation of water quite well. The low and high flow periods are synchronous. The major flood peak of January 1997 is well represented in the model as are many others. Some of the peak flows particularly from the validation are less well represented. This is possibly a result of calibration favoring some parameter settings which may not have translated as well to the validation period. It should be noted that only three years were used for calibration compared with seven for validation. If more years of flow observations were used to calibrate further, performance improvements may be obtained.

An interesting and important point is that without any calibration of parameters, the WEHY-HCM model had an NSE of 0.65 and $r^2$ of 0.67 which is already an acceptable hydrological model performance [42]. This is due to the WEHY-HCM being based on good physical representation of the watershed and actual land observations rather than pure calibration of unknown parameters. However, calibration is done where streamflow datasets are available to increase performance as much as possible.

There are sources of error in the model which need to be considered. Each model is an imperfect but useful representation of physical reality. The structure of WEHY-HCM is such that the output of one model is fed as an input into subsequent models. The CSFR dataset and WRF downscaled atmospheric model can have errors which affect downstream models such as the snow and hydrological models. The observation dataset can also have errors such as bad or missing data. One erroneous high flow data point was discovered and verified with CDEC through this study. WEHY itself can also have errors from model parameterizations. During early model calibration, an unphysical stream reach was included in the model which negatively affected model performance. This was discovered using a physical understanding of hydrological flow in the watershed. When the model was adjusted to account for flow in a more physically realistic way, model performance was improved.

In conclusion, WEHY-HCM is an effective tool to model a watershed. The results show that a physically-based, integrated, distributed model is an accurate and effective method for hydrological modeling for the Upper Trinity Watershed. Using conservation laws and extensive land observations is a good starting point for model development that is not reliant on historical statistical information which is made unreliable by climate change. Land observations can be updated as needed. The laws of physics do not change. Without extensive calibration, or any calibration in some cases such as in this Trinity study, a model can be developed with acceptable performance using WEHY-HCM. By calibrating with moderate variation from those observations, improved model performance can be obtained as has been done in this study.

In order to calibrate this model, a program was developed using the evolutionary optimization algorithm differential evolution. This approach produced the best calibration results for the Trinity Subwatershed. However these results were not clearly superior to a manual calibration approach in previous watershed hydrology modelling studies [39], [44], [45]. However, there is a time savings benefit acquired by use of the calibration program as hours of manual calibration are automated with this program. This can be easily applied to other watersheds in California and beyond.

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# VIII. APPENDIX

## A. Calibration Program

```
WEHY Trinity Calibration v2

Python script

"""



import subprocess

import pandas as pd

import numpy as np



import tempfile

import shutil



import os



from scipy.optimize import differential_evolution

import sys
```

```
def nse(obs,model):
    return 1-(np.sum((obs-model)**2)/np.sum((obs-np.mean(obs))**2))


def WEHY_calibration(param):
    styear='1997'
    enyear='1999'
    IC ='1996'

    alfsdp, alfKs, albedos0, albedow0, roughs0, roughw0, LG_EXCH, F_CMN, F_TRNS= param

    homedir='/home/benjamin/Trinity/Trinity_calibration/'
    os.chdir(homedir)

    #make the dir

    temp_dir=tempfile.TemporaryDirectory(dir='/home/benjamin/Trinity/Trinity_calibration/')
    tempdir=temp_dir.name
```

```
    os.chdir(tempdir)

    #copy files

    shutil.copytree('/home/benjamin/Trinity/Trinity_calibration/WEHY', tempdir, dirs_exist_ok = True)

    #use dir here
    with open(tempdir+r"/tw/parameters/WEHY.control", 'w') as f:
        f.write('&DXNTcontrol\n')
        f.write('    alfsdp = {},\n'.format(alfsdp))
        f.write('    alfKs = {},\n'.format(alfKs))
        f.write('    albedos0 = {},\n'.format(albedos0))
        f.write('    albedow0 = {},\n'.format(albedow0))
        f.write('    roughs0 = {},\n'.format(roughs0))
        f.write('    roughw0 = {},\n'.format(roughw0))
        f.write('/\n')
        f.write('!')
        f.close()
```

```
with open(tempdir+r"/tw/parameters/R_ch_para.txt",'r') as file:
  data=file.readlines()



  data[3]="0.0001    0.2       0.8       0.002   {}       1         {}       1         1         {}       1
       \n".format(LG_EXCH, F_CMN, F_TRNS)


with open(tempdir+r"/tw/parameters/R_ch_para.txt", 'w') as f2:
  f2.writelines(data)
  f2.close()


args0=[tempdir+'/scr/main_wehy_cold.sh', IC, IC]
p0=subprocess.Popen(args0)
p0.wait()



args=[tempdir+'/scr/main_wehy_hot.sh', styear, enyear]
p1=subprocess.Popen(args)
```

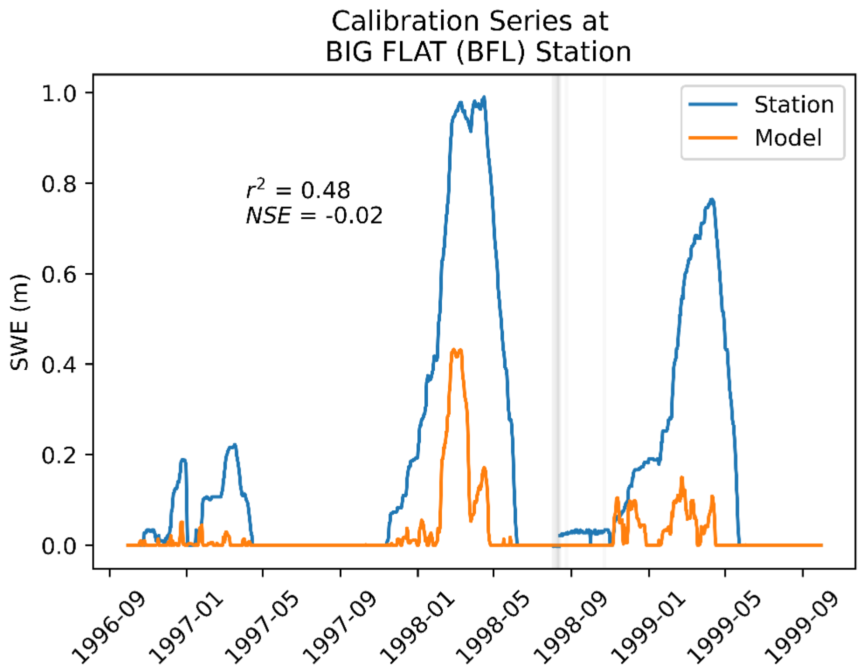
```
    p1.wait()



    path1997=tempdir+r'/tw/output_1997'
    path1998=tempdir+r'/tw/output_1998'
    path1999=tempdir+r'/tw/output_1999'

model_data_1997=pd.read_csv(path1997+r"/R_hydro_out.csv",skiprows=10,skipfooter=17,usecols=[0,19,27,29,30,65,82],header=0,names=['dates','bot20','bot28','bot30','bot31','up5','up23'],engine='python')

model_data_1998=pd.read_csv(path1998+r"/R_hydro_out.csv",skiprows=10,skipfooter=17,usecols=[0,19,27,29,30,65,82],header=0,names=['dates','bot20','bot28','bot30','bot31','up5','up23'],engine='python')

model_data_1999=pd.read_csv(path1999+r"/R_hydro_out.csv",skiprows=10,skipfooter=17,usecols=[0,19,27,29,30,65,82],header=0,names=['dates','bot20','bot28','bot30','bot31','up5','up23'],engine='python')
```

```
model_plot_1997=np.average(((model_data_1997['up5']+model_data_1997['up23']+model_data
_1997['bot20']+model_data_1997['bot28']+model_data_1997['bot30']+model_data_1997['bot31']
).values).reshape(-1, 24), axis=1)

model_plot_1998=np.average(((model_data_1998['up5']+model_data_1998['up23']+model_data
_1998['bot20']+model_data_1998['bot28']+model_data_1998['bot30']+model_data_1998['bot31']
).values).reshape(-1, 24), axis=1)

model_plot_1999=np.average(((model_data_1999['up5']+model_data_1999['up23']+model_data
_1999['bot20']+model_data_1999['bot28']+model_data_1999['bot30']+model_data_1999['bot31']
).values).reshape(-1, 24), axis=1)


    obs_csv_1997=pd.read_excel(path1997+r'/CLE_8.xlsx', usecols=['OBS DATE','VALUE'])
    obs_csv_1998=pd.read_excel(path1998+r'/CLE_8.xlsx', usecols=['OBS DATE','VALUE'])
    obs_csv_1999=pd.read_excel(path1999+r'/CLE_8.xlsx', usecols=['OBS DATE','VALUE'])

    obs_plot_1997=pd.to_numeric(obs_csv_1997['VALUE'].str.replace(',', ''))*0.028316847
    obs_plot_1998=pd.to_numeric(obs_csv_1998['VALUE'].str.replace(',', ''))*0.028316847
```

```
    obs_plot_1999=pd.to_numeric(obs_csv_1999['VALUE'].str.replace(',', ''))*0.028316847


    model=np.concatenate([model_plot_1997,model_plot_1998,model_plot_1999])
    natural=np.concatenate([obs_plot_1997[:-1],obs_plot_1998[:-1],obs_plot_1999[:-1]])
    natural[natural<0]=0


    NSE=nse(natural,model)
    dif=abs(1-NSE)
    temp_dir.cleanup()
    return dif


bounds=[(0.5,2),(0.5,2),(0.14,0.26),(0.64,0.96),(0.2,0.6),(0.5,0.1),(10,500),(0.7,1.3),(0.01,10)]


WEHY_calibration_result=differential_evolution(WEHY_calibration, bounds, maxiter=50, workers=20, polish=False, updating='deferred',popsize=20)



opt_parameters=WEHY_calibration_result.x
```

```
min_dif=WEHY_calibration_result.fun

best_nse=1-min_dif

print('best parameters are ',opt_parameters)

print('best nse is ',best_nse)



opt_string=str(opt_parameters)

nse_string=str(best_nse)



f = open("/home/benjamin/Trinity/Trinity_calibration/results.txt", "w")

f.write('best parameters are '+opt_string)

f.write('best nse is '+nse_string)

f.close()



sys.stdout.flush
```

## B. Snow Figures



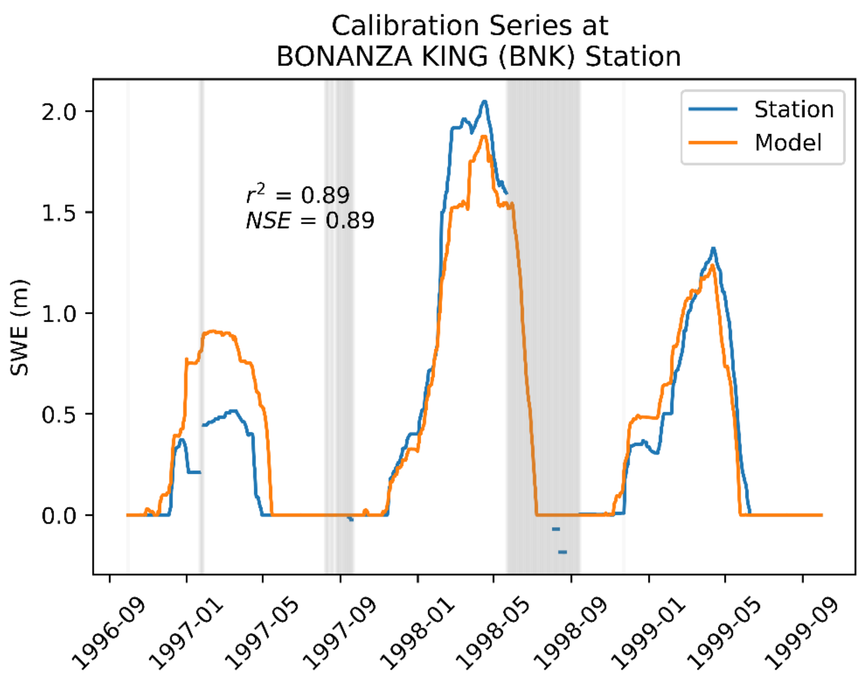
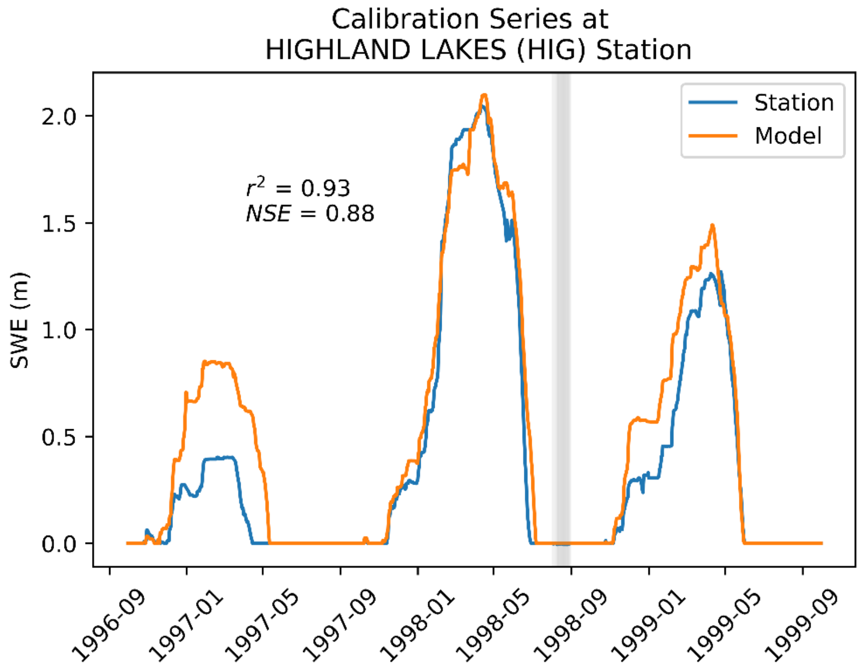




**Figure B1: Daily snow water equivalent timeseries comparisons between observations and snow model calibration simulations for 1997-1999 at stations BFL and BNK. The grey shaded area represents missing or faulty data.**



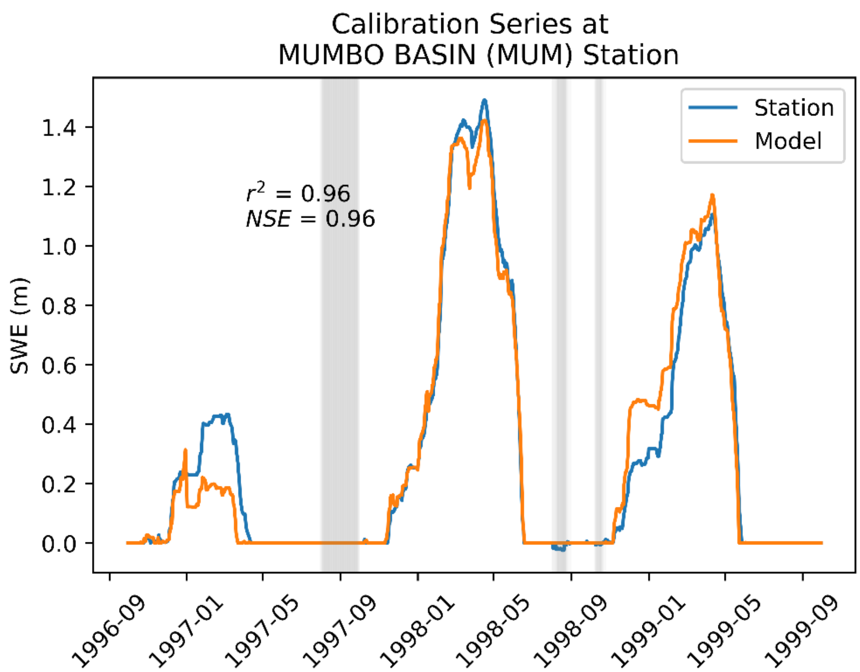
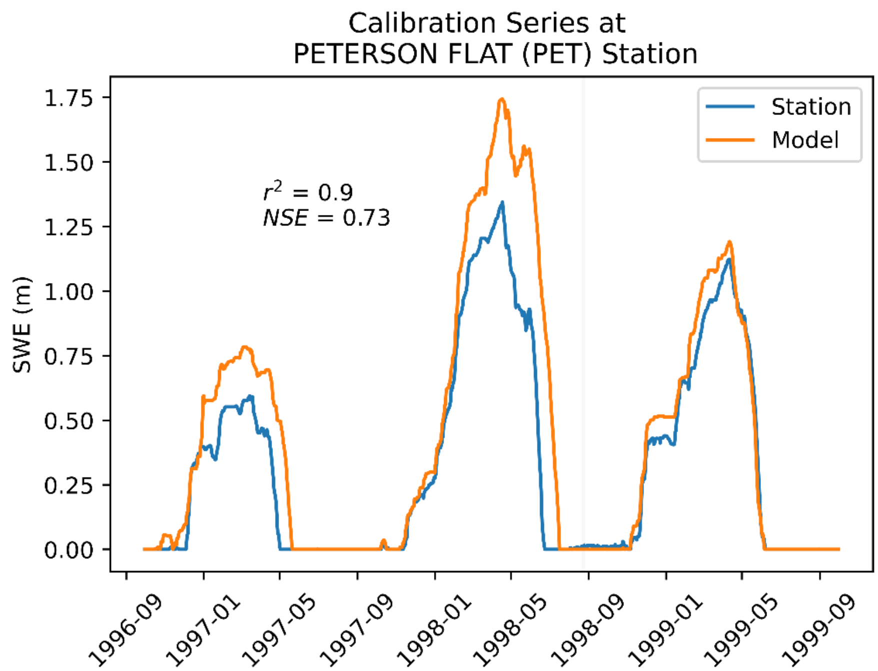




**Figure B2: Daily snow water equivalent timeseries comparisons between observations and snow model calibration simulations for 1997-1999 at stations HIG and MUM. The grey shaded area represents missing or faulty data.**



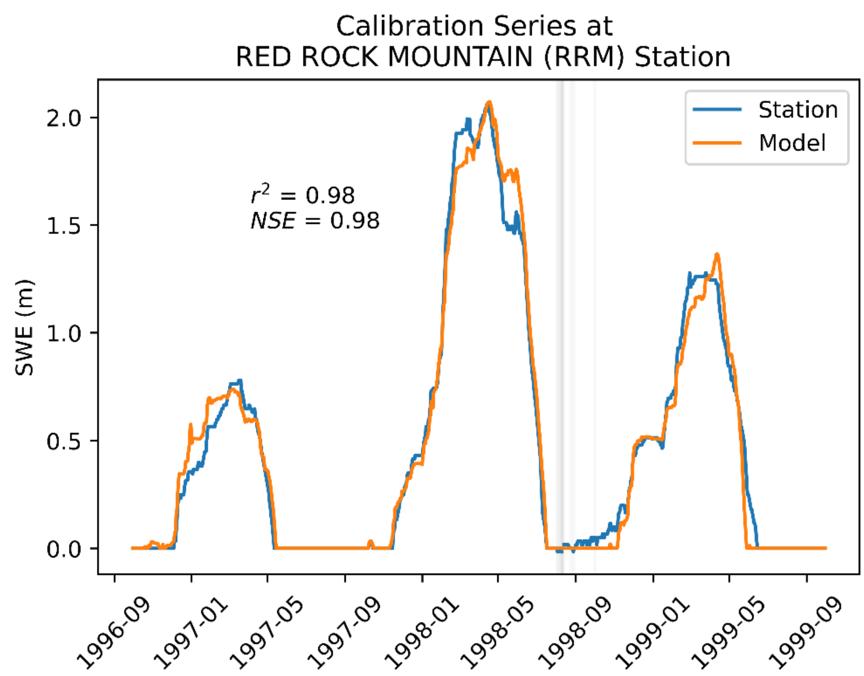




**Figure B3: Daily snow water equivalent timeseries comparisons between observations and snow model calibration simulations for 1997-1999 at stations PET and RRM. The grey shaded area represents missing or faulty data.**

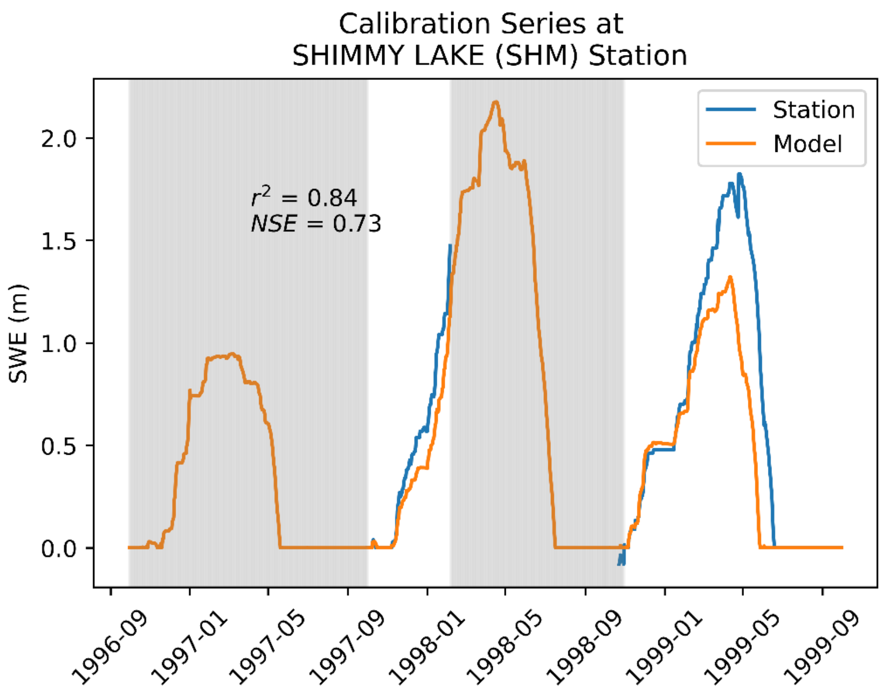



**Figure B4: Daily snow water equivalent timeseries comparisons between observations and snow model calibration simulations for 1997-1999 at station SHM. The grey shaded area represents missing or faulty data.**

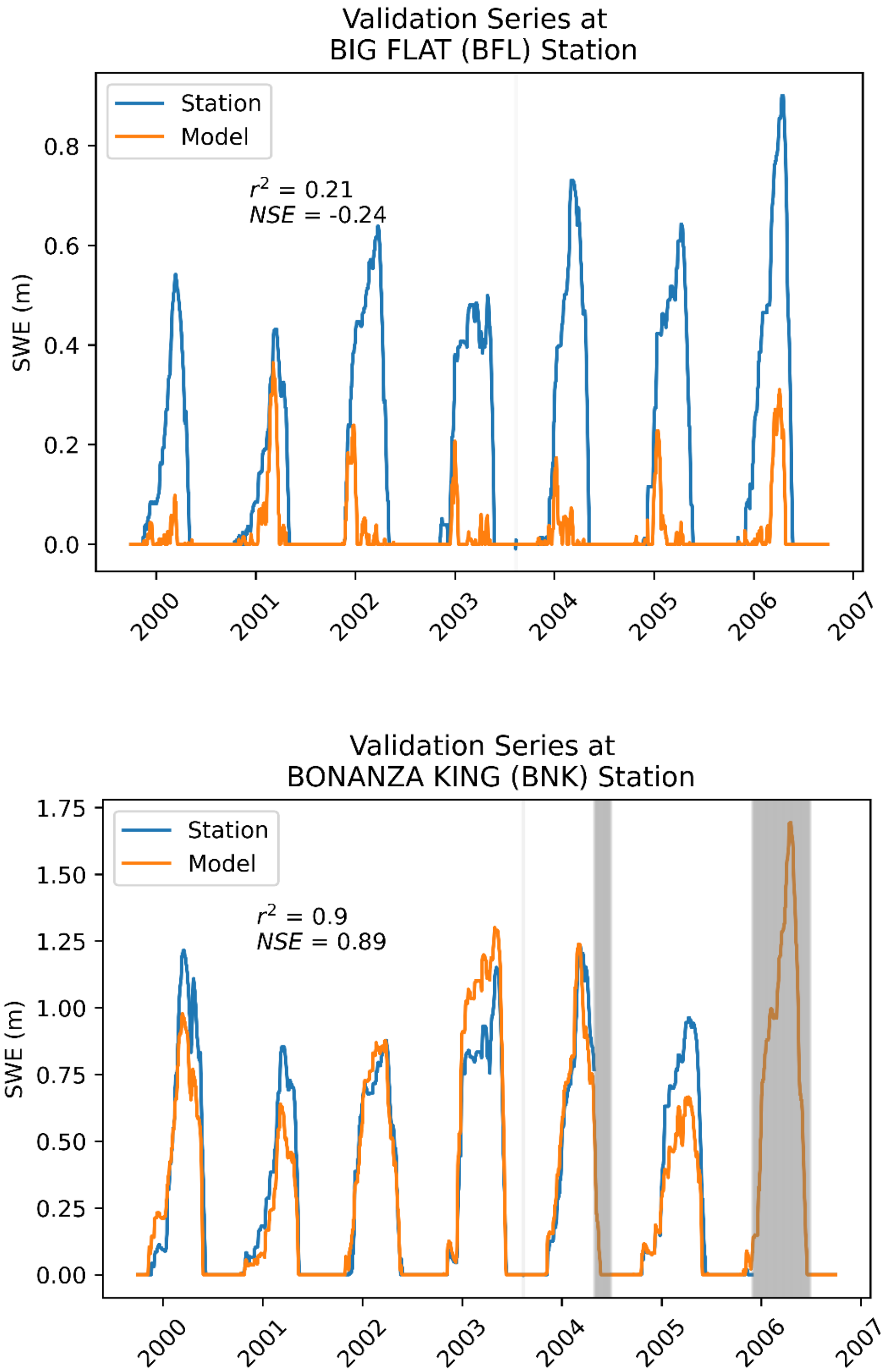
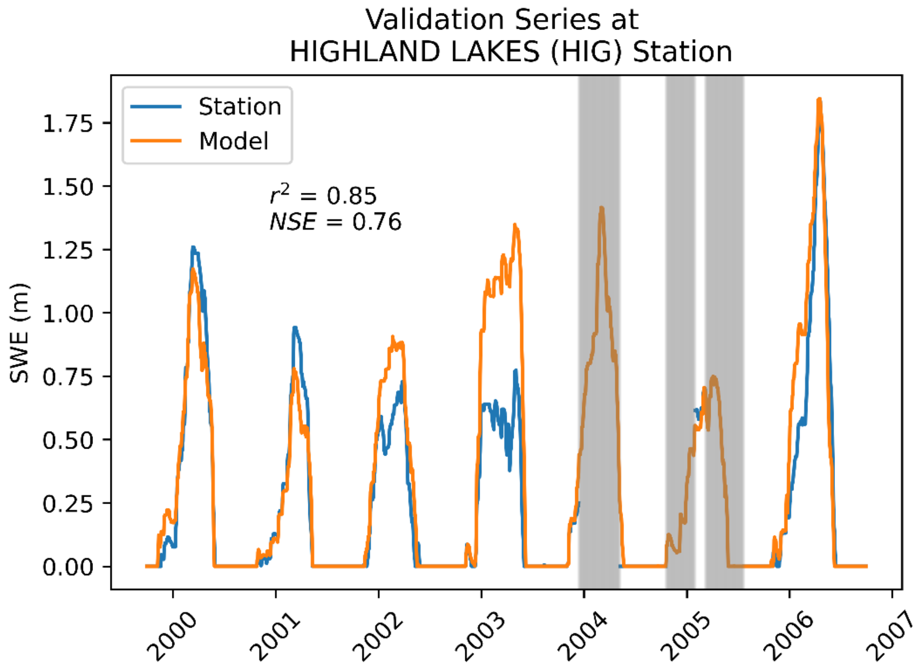



**Figure B5: Daily snow water equivalent timeseries comparisons between observations and snow model validation simulations for 2000-2006 at stations BFL and BNK. The grey shaded area represents missing or faulty data.**



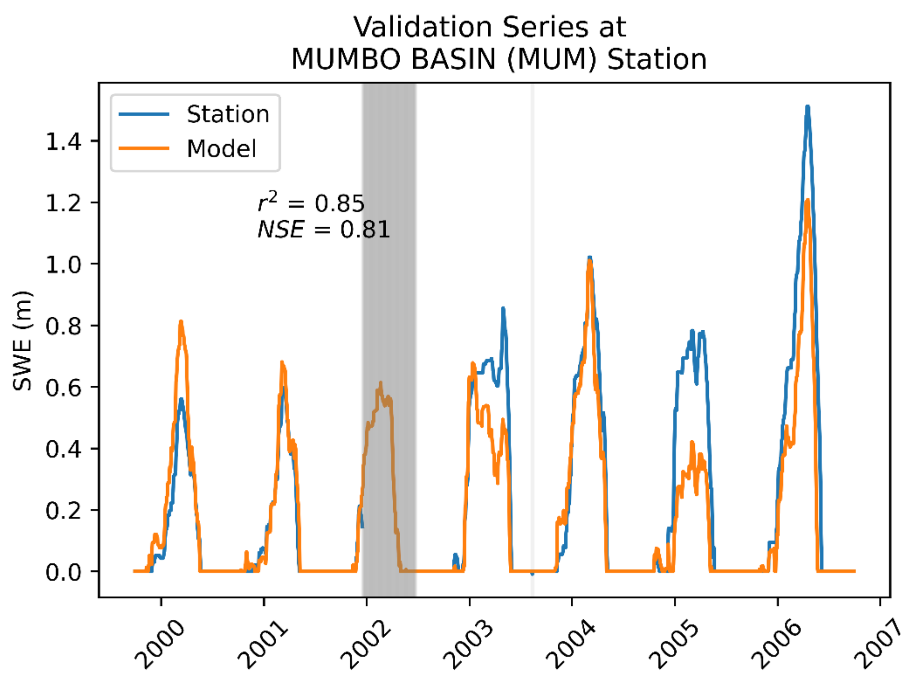
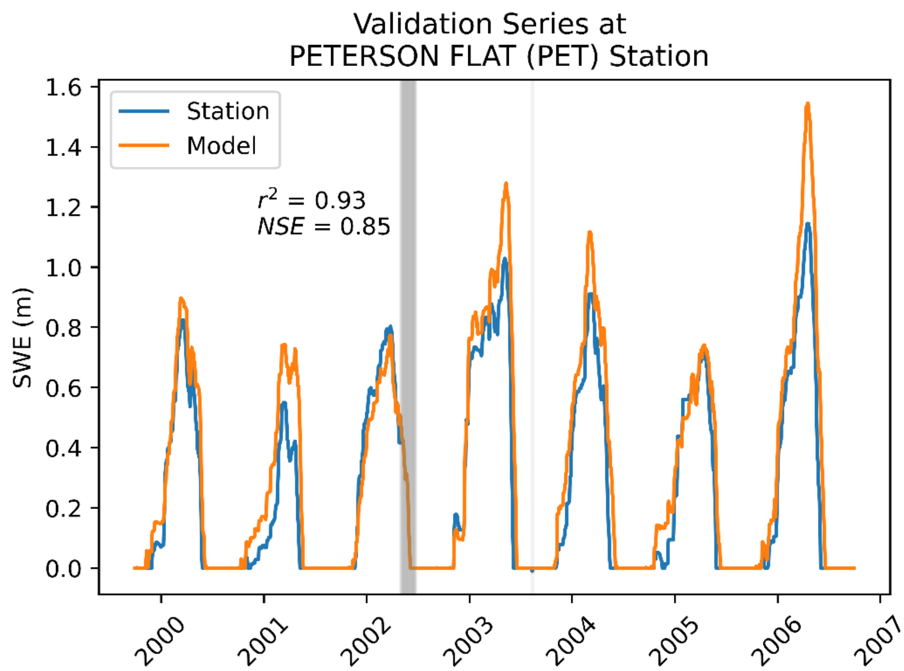




**Figure B6: Daily snow water equivalent timeseries comparisons between observations and snow model validation simulations for 2000-2006 at stations HIG and MUM. The grey shaded area represents missing or faulty data.**



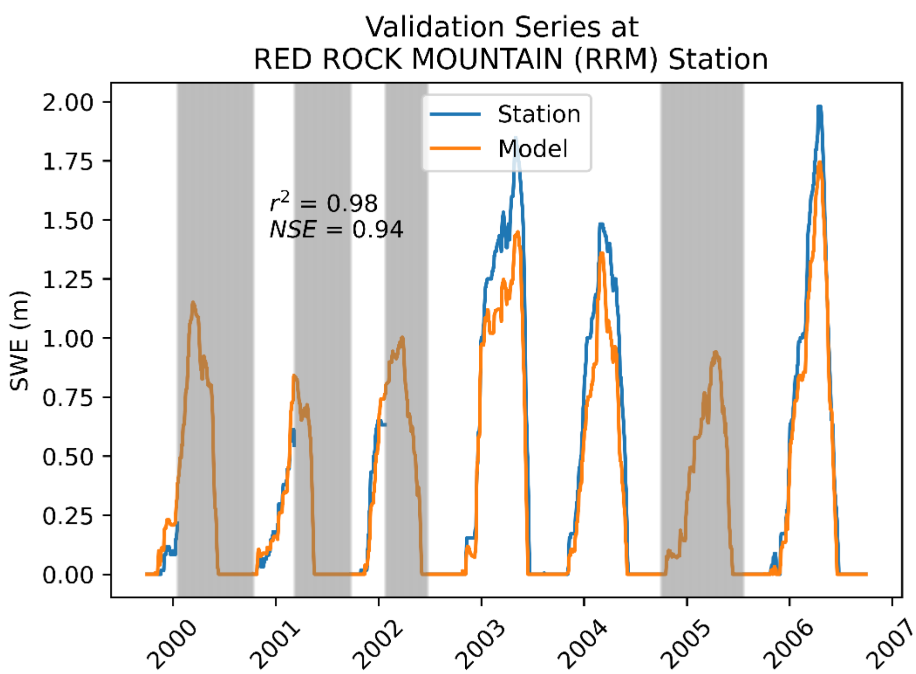




**Figure B7: Daily snow water equivalent timeseries comparisons between observations and snow model validation simulations for 2000-2006 at stations PET and RRM. The grey shaded area represents missing or faulty data.**

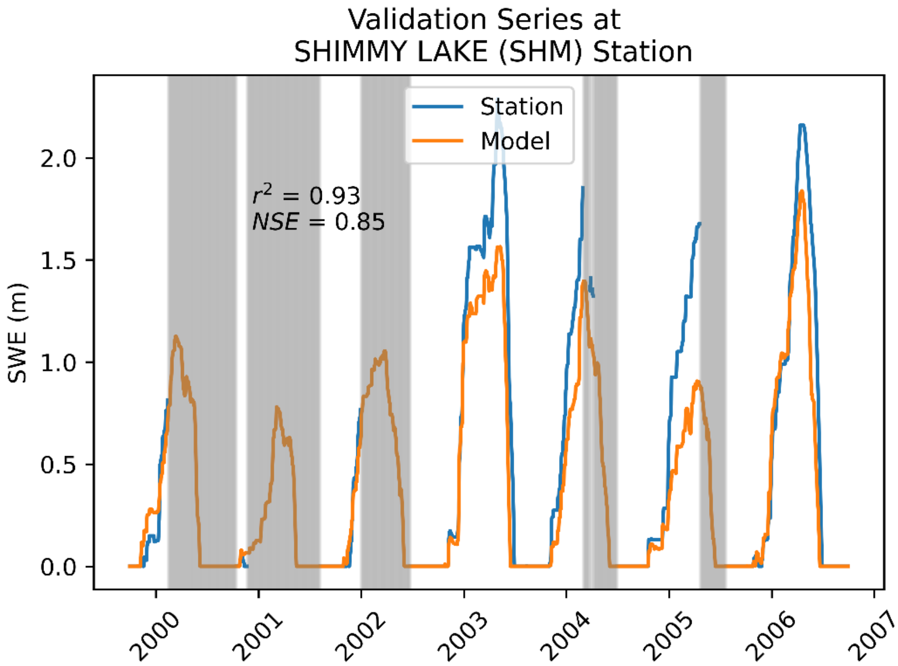
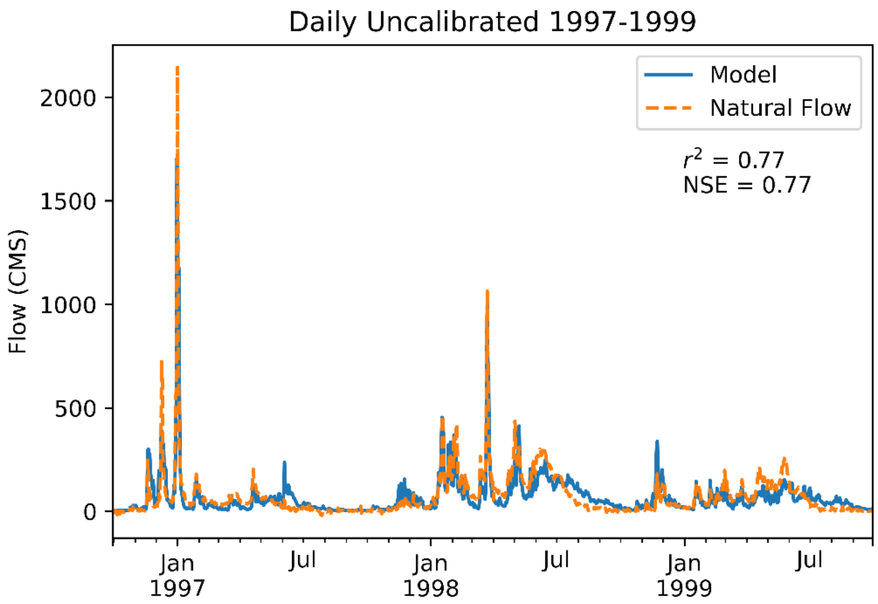



**Figure B8: Daily snow water equivalent timeseries comparisons between observations and snow model validation simulations for 2000-2006 at station SHM. The grey shaded area represents missing or faulty data.**

## C. Streamflow Figures



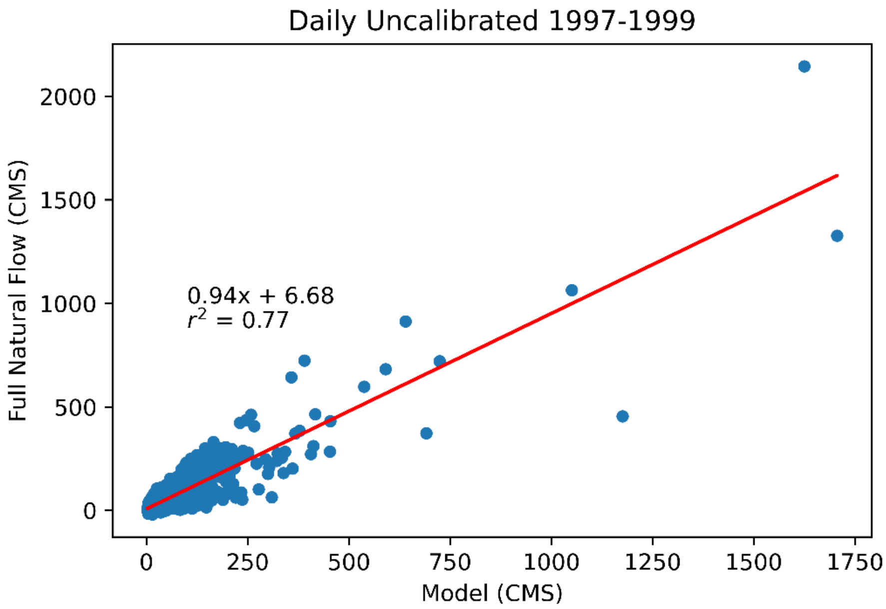




**Figure C1: (Top) The uncalibrated daily mean discharge time series for the calibration period (1997-1999). (Bottom) The scatter plot of daily mean discharge between uncalibrated WEHY simulation and observed natural flow for the calibration period.**

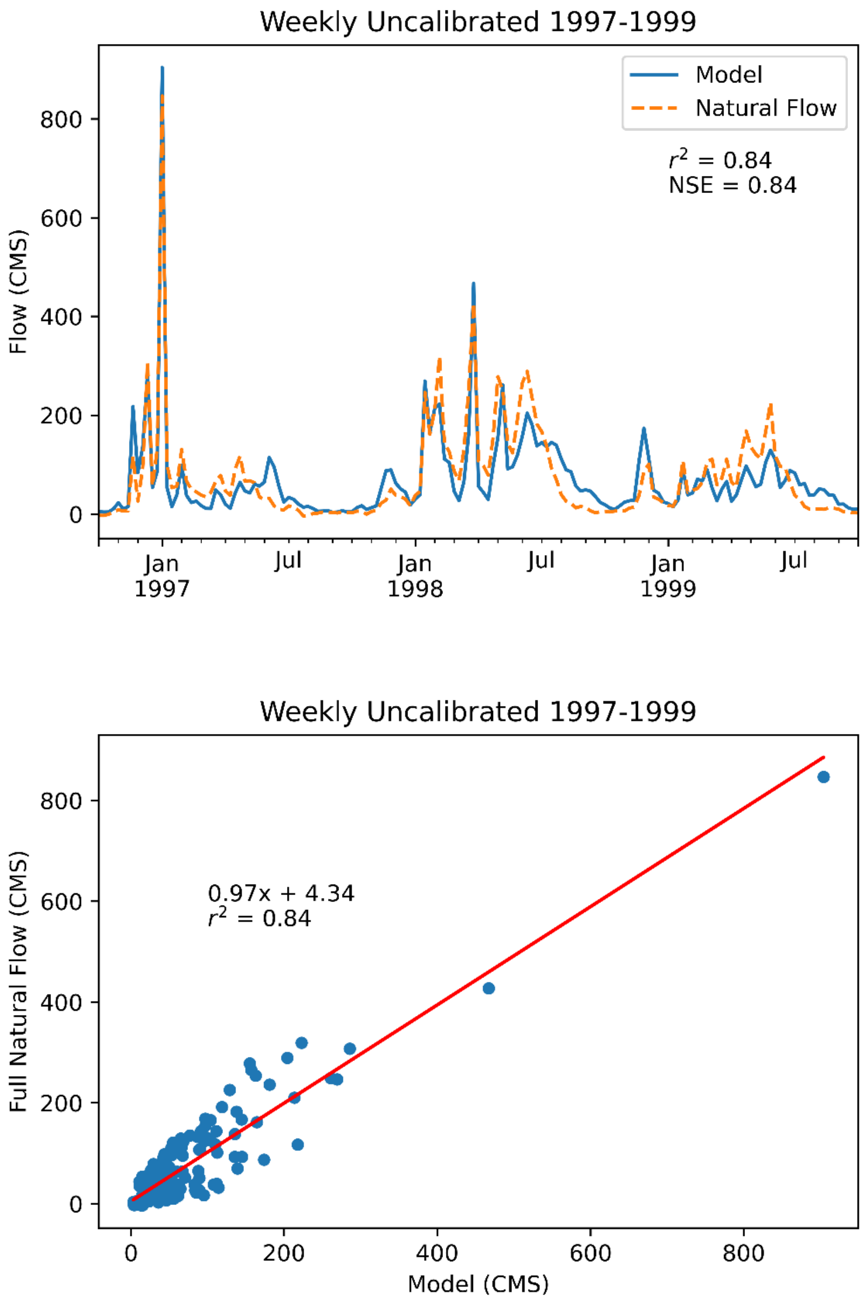
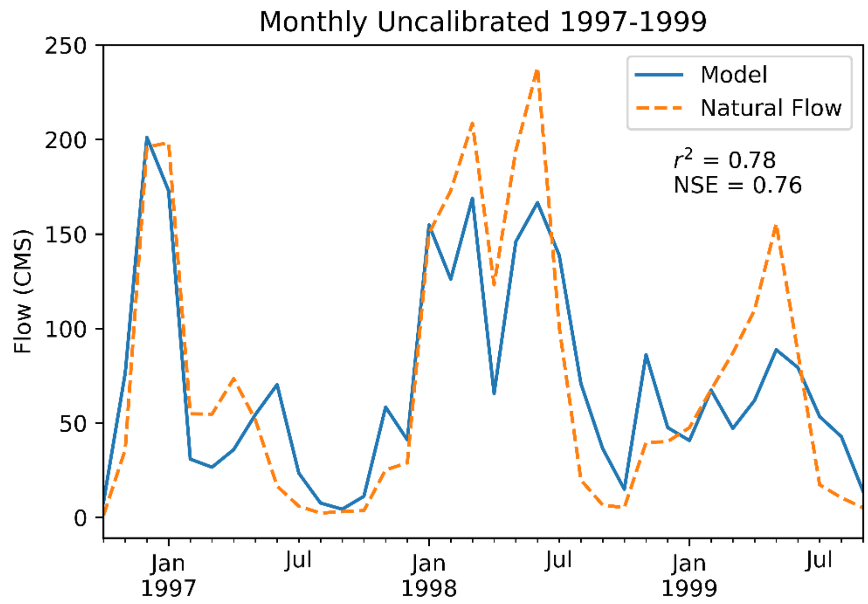



**Figure C2: (Top) The uncalibrated weekly mean discharge time series for the calibration period (1997-1999). (Bottom) The scatter plot of weekly mean discharge between uncalibrated WEHY simulation and observed natural flow for the calibration period.**



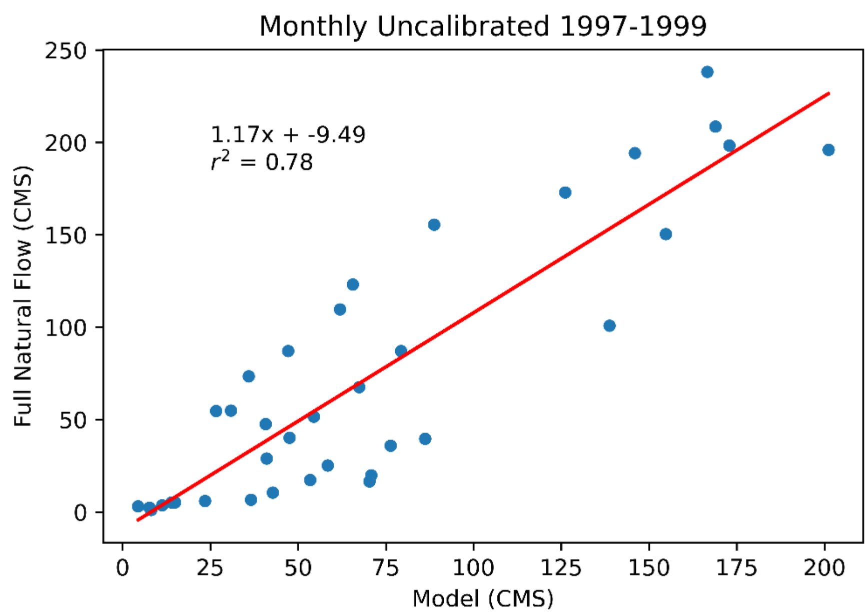
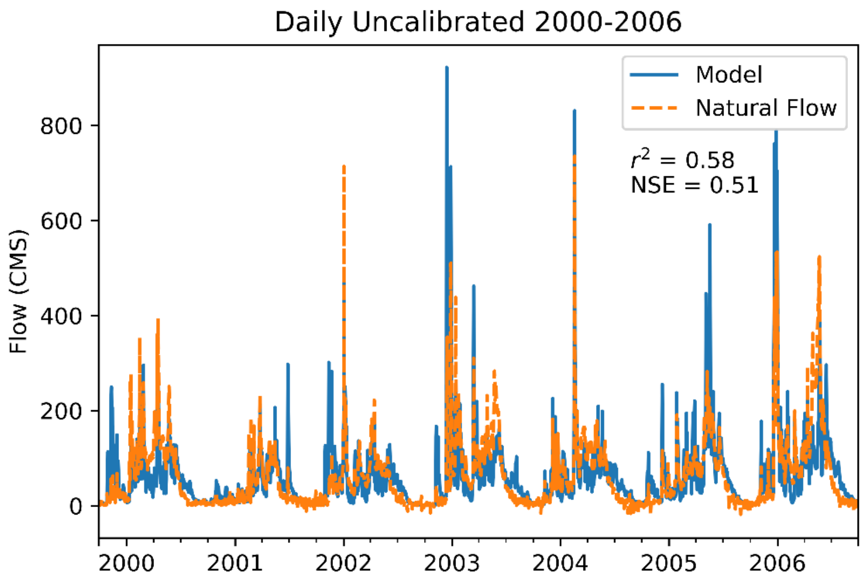




**Figure C3: (Top) The uncalibrated monthly mean discharge time series for the calibration period (1997-1999). (Bottom) The scatter plot of monthly mean discharge between uncalibrated WEHY simulation and observed natural flow for the calibration period.**



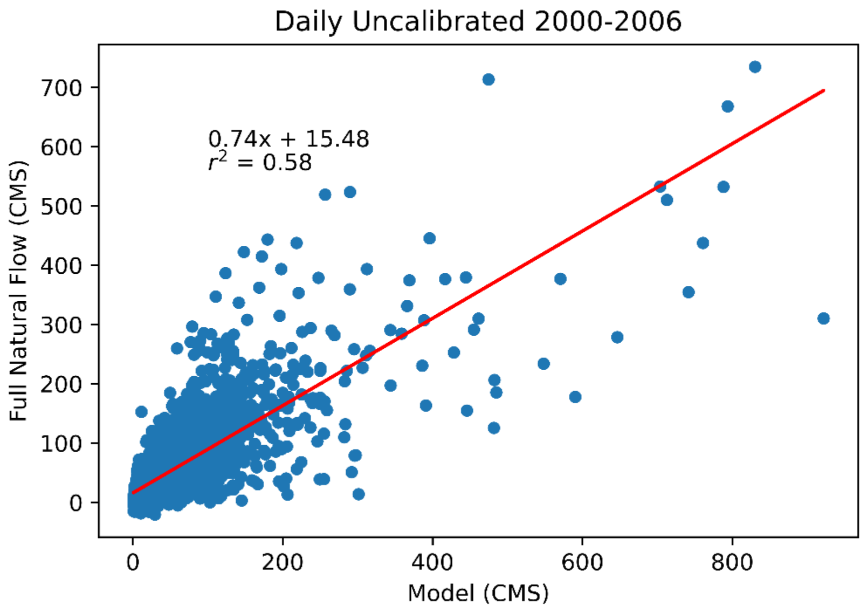
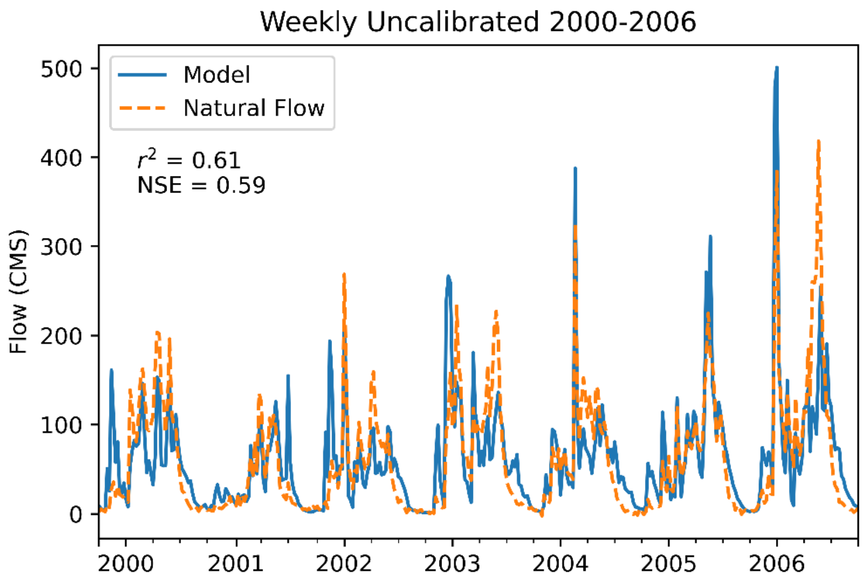




**Figure C4: (Top) The uncalibrated daily mean discharge time series for the validation period (2000-2006). (Bottom) The scatter plot of daily mean discharge between uncalibrated WEHY simulation and observed natural flow for the validation period.**



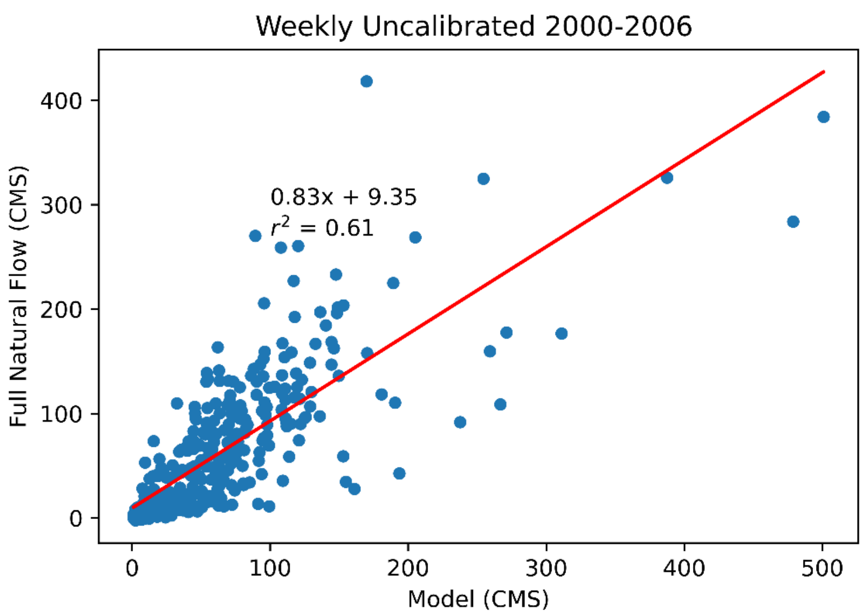
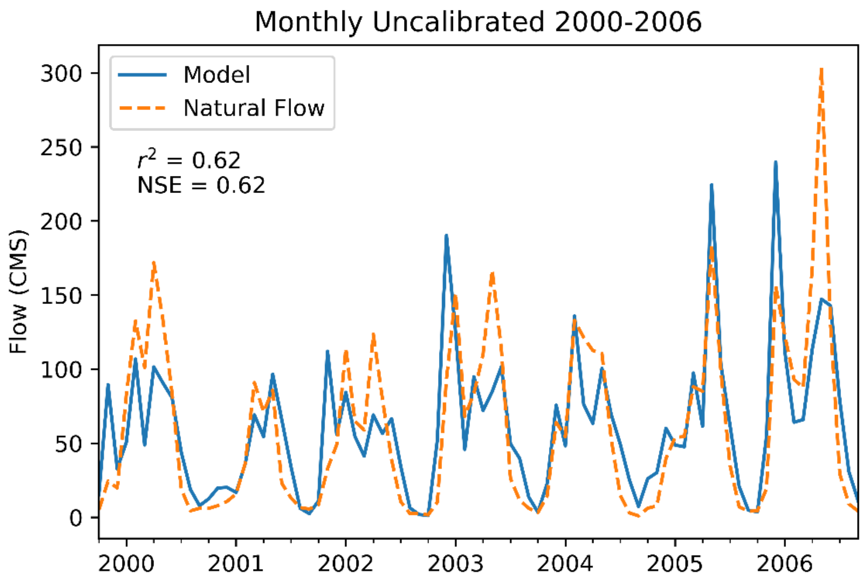




**Figure C5: (Top) The uncalibrated weekly mean discharge time series for the validation period (2000-2006). (Bottom) The scatter plot of weekly mean discharge between uncalibrated WEHY simulation and observed natural flow for the validation period.**



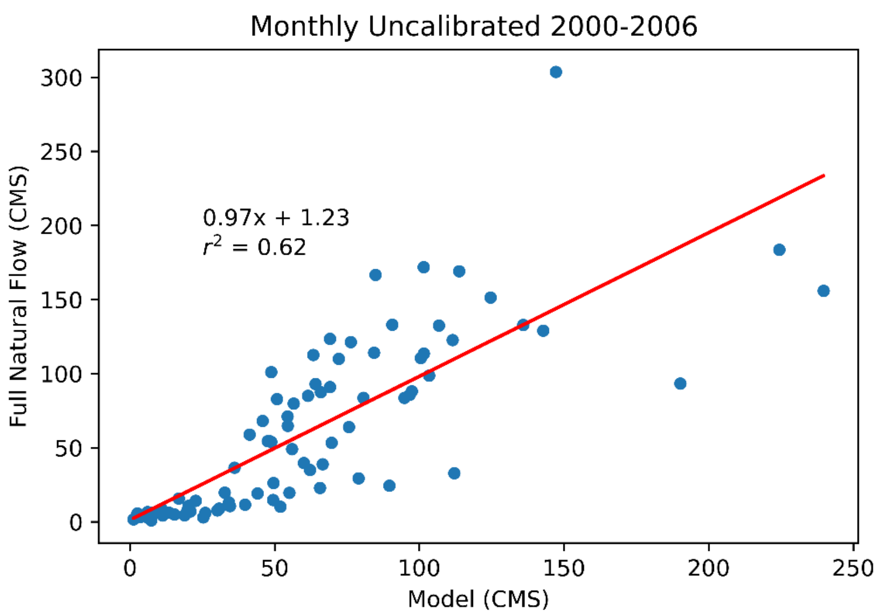
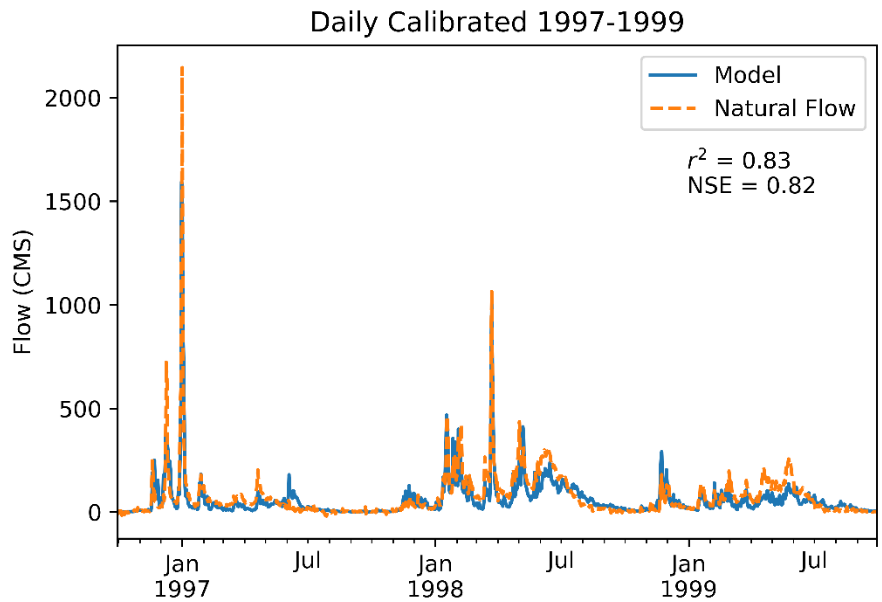




**Figure C6: (Top) The uncalibrated monthly mean discharge time series for the validation period (2000-2006). (Bottom) The scatter plot of monthly mean discharge between uncalibrated WEHY simulation and observed natural flow for the validation period.**



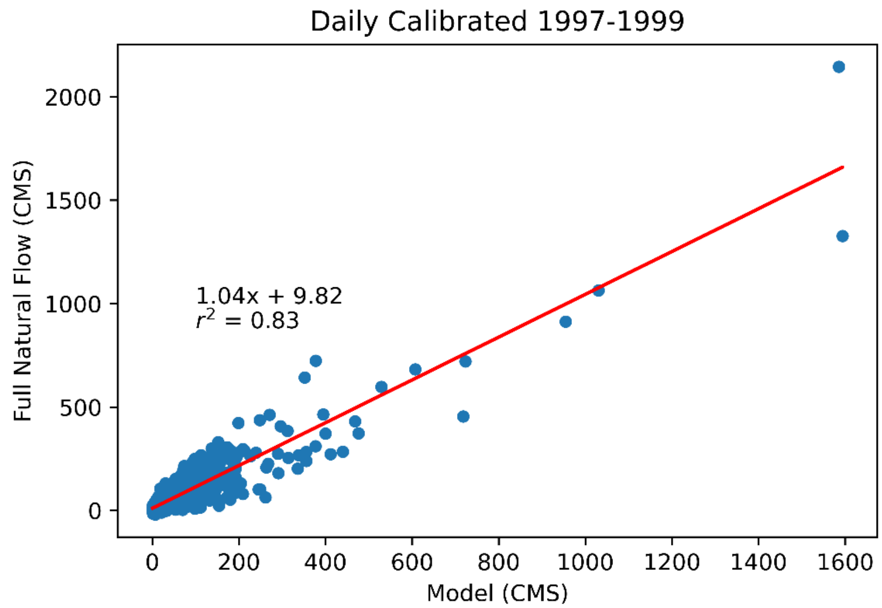




**Figure C7: (Top) The calibrated daily mean discharge time series for the calibration period (1997-1999). (Bottom) The scatter plot of daily mean discharge between calibrated WEHY simulation and observed natural flow for the calibration period.**

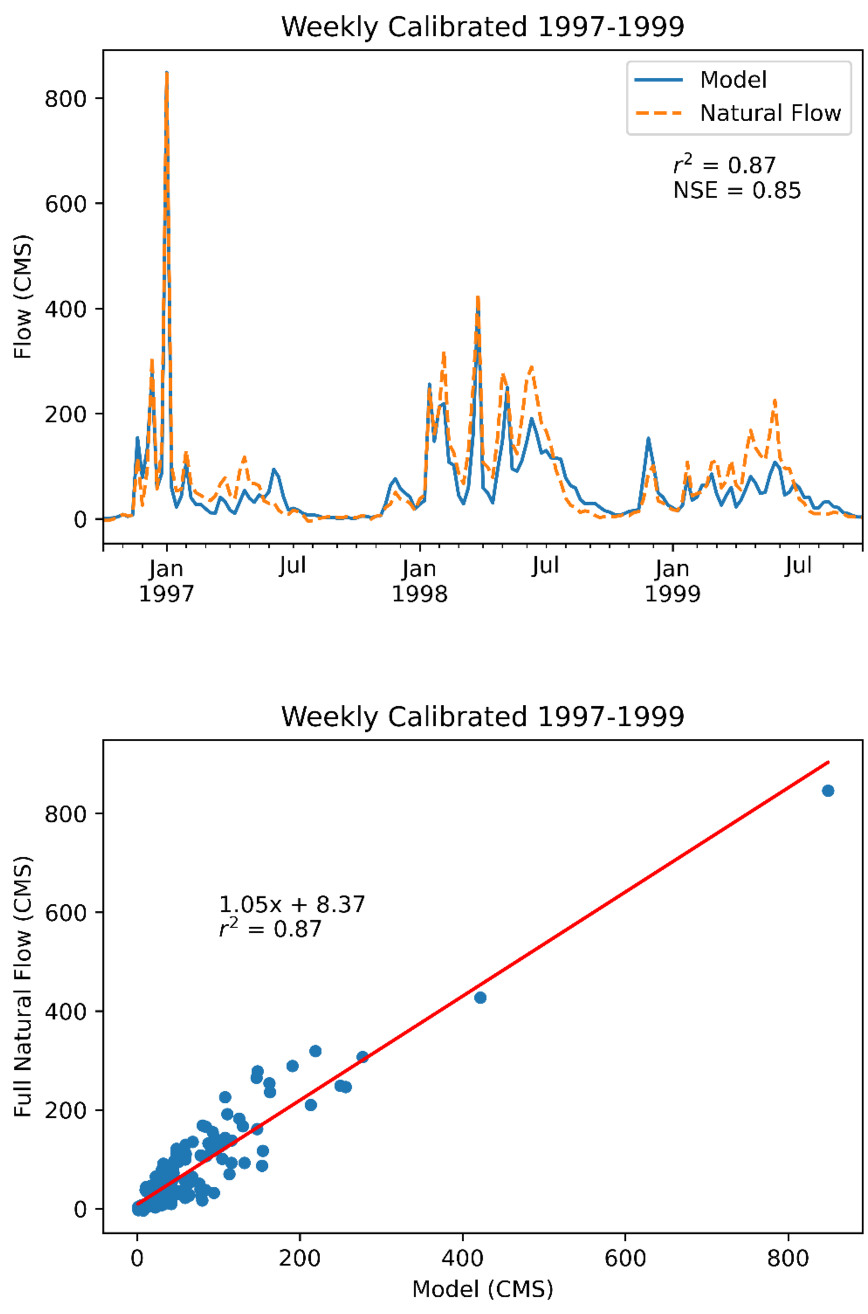
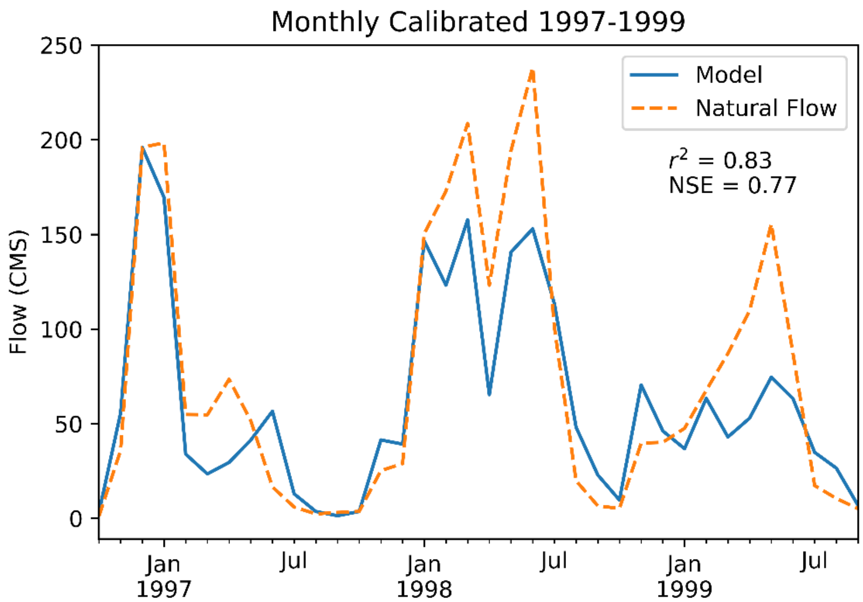



**Figure C8: (Top) The calibrated weekly mean discharge time series for the calibration period (1997-1999). (Bottom) The scatter plot of weekly mean discharge between calibrated WEHY simulation and observed natural flow for the calibration period.**



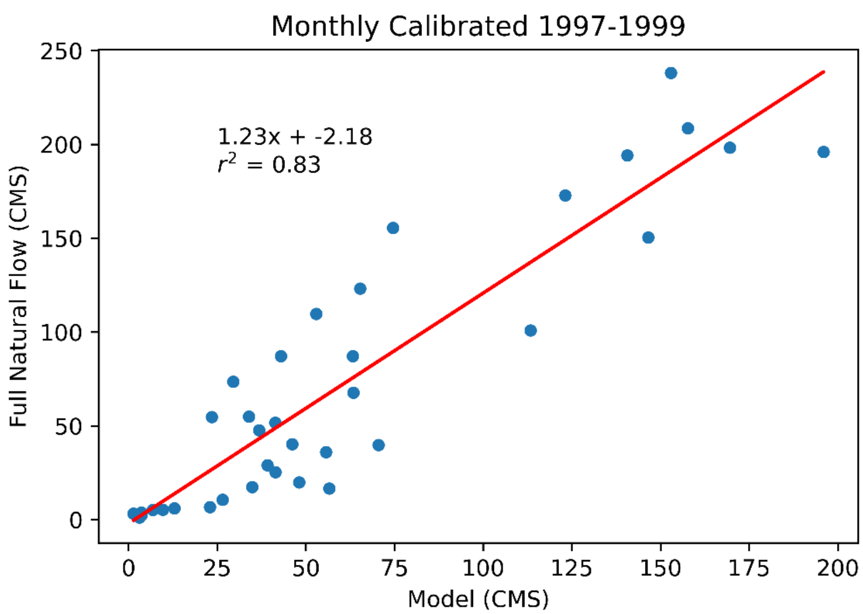
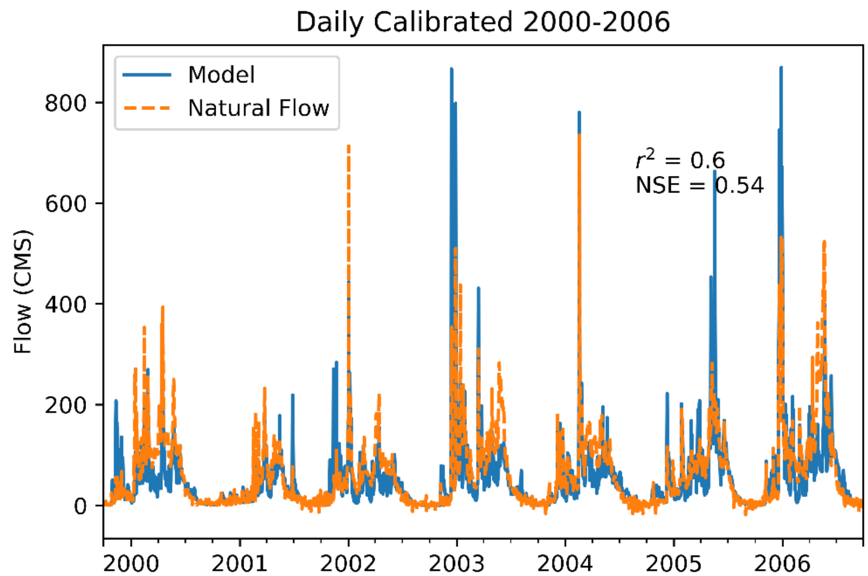




**Figure C9: (Top) The calibrated monthly mean discharge time series for the calibration period (1997-1999). (Bottom) The scatter plot of monthly mean discharge between calibrated WEHY simulation and observed natural flow for the calibration period.**



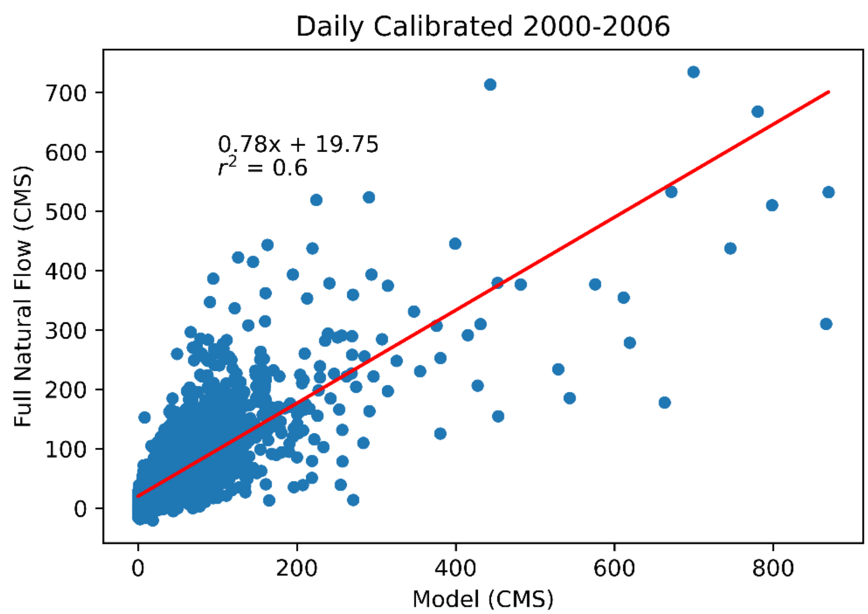
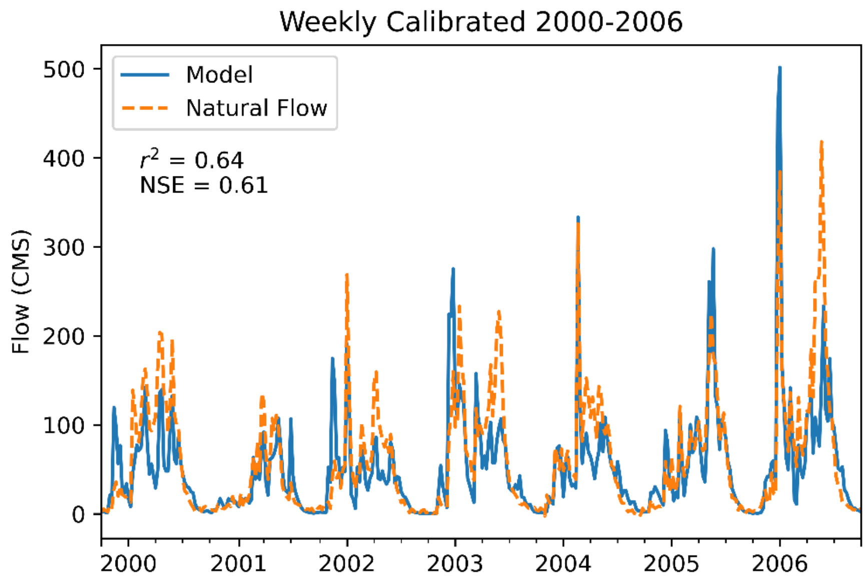




**Figure C10: (Top) The calibrated daily mean discharge time series for the validation period (2000-2006). (Bottom) The scatter plot of daily mean discharge between calibrated WEHY simulation and observed natural flow for the validation period.**



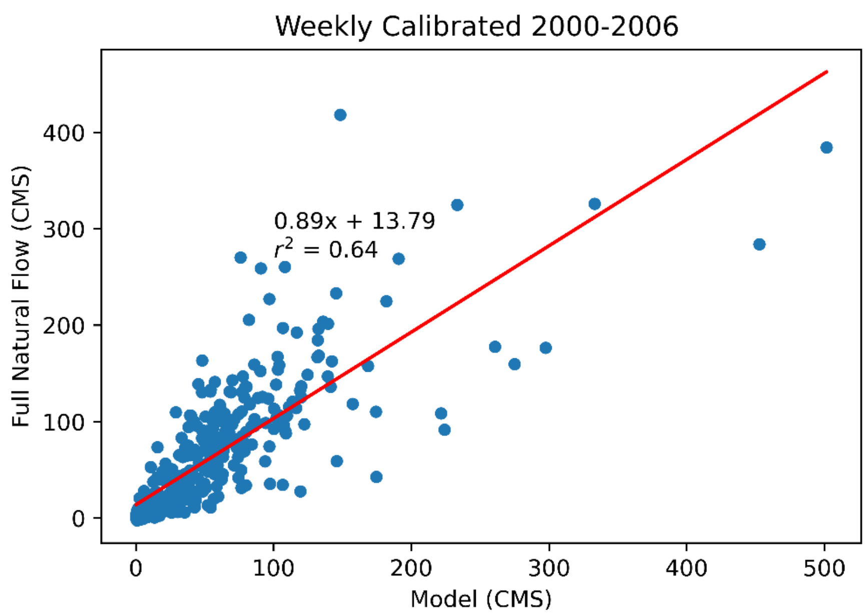
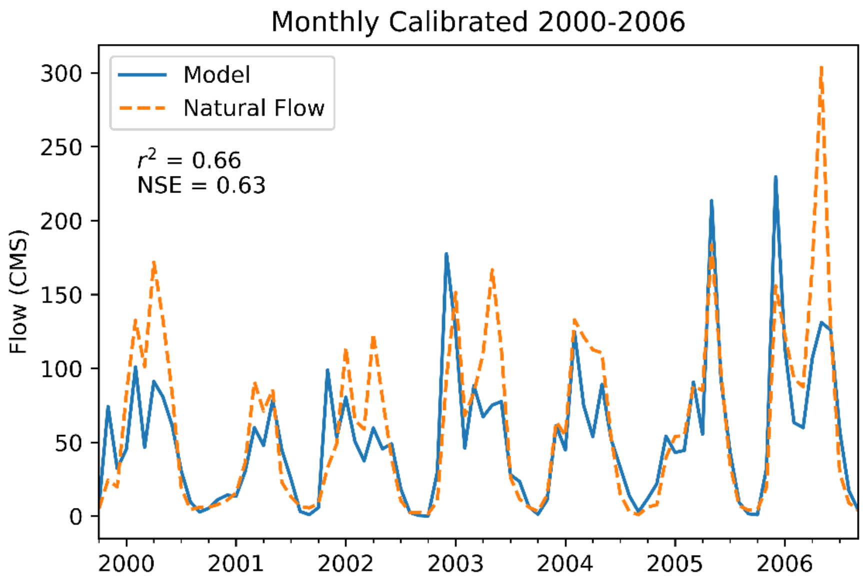




**Figure C11: (Top) The calibrated weekly mean discharge time series for the validation period (2000-2006). (Bottom) The scatter plot of weekly mean discharge between calibrated WEHY simulation and observed natural flow for the validation period.**



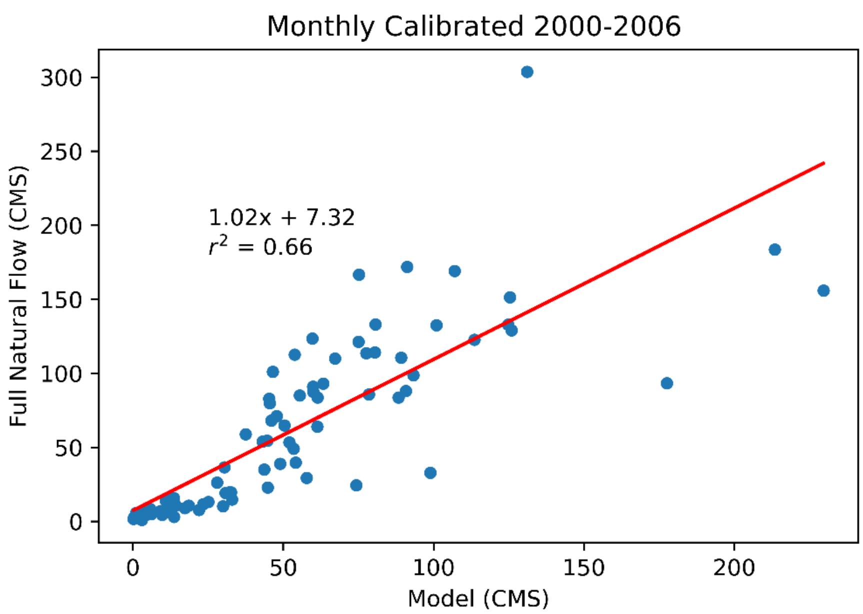




**Figure C12: (Top) The calibrated monthly mean discharge time series for the validation period (2000-2006). (Bottom) The scatter plot of monthly mean discharge between calibrated WEHY simulation and observed natural flow for the validation period.**