WATERSHED ENVIRONMENTAL HYDROLOGY (WEHY) MODEL

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Abstract: WEHY model takes a new approach to the modeling of hydrologic processes in order to account for the effect of heterogeneity within natural watersheds. Toward this purpose, the point -scale conservation equations for various hydrologic processes were upscaled in order to obtain their ensemble averaged forms at the scale of the computational grid areas. Over hillslopes these grid areas correspond to areas along a complete transect of a hillslope. The resulting upscaled conservation equations, although they are fundamentally one-dimensional, have the lateral source/sink terms that link them dynamically to other hydrologic component processes. In this manner, these upscaled equations possess the dynamic interaction feature of the standard point scale two dimensional hydrologic conservation equations. A significant computational economy is achieved by the capability of the upscaled equations to compute hydrologic flows over large transactional grid areas versus the necessity of computing hydrologic flows over small grid areas by point-scale equations in order to account for the effect of environmental heterogeneity on flows. The emerging parameters in the upscaled hydrologic conservation equations are areal averages and areal variances/covariances of the original point-scale parameters, thereby quantifying the spatial variation of the original point-scale parameters over a computational grid area, and, thus, the effect of land heterogeneity on hydrologic flows. Also, by requiring only areal average and areal variance/covariance of parameter values over large grid areas, it is possible to achieve very significant economy in parameter estimation. The parameters of the WEHY model are related to the physical properties of the watershed, and can be estimated from readily available information on topography, soils, and vegetation/land cover conditions. The geomorphologic parameters that describe the rilled surface geometry of hillslopes are derived directly from the DEM map of the watershed. The soil hydraulic parameters of the WEHY model require soil texture classification database and/or field investigations. Application of the WEHY model to a California watershed is presented.

INTRODUCTION

Since physically-based models use conservation equations, their resulting parameters make physical sense, and are measurable in the field. Also, since the physically-based model parameters are based upon physical properties (such as the soil hydraulic conductivity being strongly related to soil texture), it is possible to estimate these parameters from the readily available information on regional soil maps , vegetation, topography, geology and land-use conditions. Consequently, it is possible to utilize the physically-based models for hydrologic forecasting and simulations not only in well-gauged watersheds, but also in ungauged or sparsely-gauged watersheds.

All of the current physically-based models use conservation equations which are based on the conservation of mass, momentum and/or energy within a differential control volume which may be considered as the “point scale”. As such, these equations and their parameters are strictly applicable only at a nodal point that is surrounded by a specific grid area within a computational grid mesh over the modeled watershed. Since soils, vegetation, topography, rainfall and other atmospheric inputs are spatially heterogeneous, unless a grid resolution is taken to be very fine (<10 m) it is necessary to resolve the subgrid-scale heterogeneity within each grid area of the computational mesh for a realistic modeling of hydrologic processes over a watershed. In current practice, in order to be able to model the hydrologic and environmental processes over large grid areas (with grid resolution > 500m), and, thereby, reduce substantially the number of parameters to be estimated, the present physically-based models, with their point-scale conservation equations, lump all the subgrid scale heterogeneity into "effective parameters" which can only be obtained by model calibration through fitting the model to historical or experimental hydrologic data.

If one considers a point-scale conservation equation for a particular hydrologic process as a PDE with its point-scale parameters over a computational grid area, then due to the heterogeneity of the land characteristics over such a grid area the point-scale parameters become uncertain within this grid area. Furthermore, the point-scale boundary conditions/forcing functions over a grid area (such as rainfall) become uncertain due to their spatial variation over the area. As such, the original point-scale conservation PDE becomes a stochastic PDE with its point-scale state variable becoming a stochastic variable over an individual computational grid area. One can imagine that each of the parameters, boundary conditions and/or forcing functions, and, thereby, the state variable will have ensembles of possible values they can take within such a heterogeneous grid area, with probability distributions that describe these possible values. One can then argue that one feasible way to describe the evolution of the hydrologic process over an individual heterogeneous computational grid area is to develop the ensemble average form of this conservation equation with its emerging state variable and parameters becoming the ensemble averages of the possible point-scale state variable and parameter values over the grid area, and ensemble variances/covariances which quantify the heterogeneity of the parameters over the grid area. The ensemble average form of the original point-scale equation will now have a scale consistent with that of the modeled grid area, and, as such, it is considered as the upscaled form of the original point-scale conservation equation. The Watershed Environmental HYdrology (WEHY) model, to be discussed in the following, is an attempt to describe the hydrologic processes within a watershed, based upon upscaled hydrologic conservation equations through their ensemble average forms.

A GENERAL DESCRIPTION OF WEHY MODEL

A schematic description of WEHY model is shown in Figure 1. WEHY model subdivides a watershed first into model computational units (MCU) that are delineated from the digital elevation map of the watershed by means of a geographic information system (GIS) analysis (Chen et al. 2004). These MCUs are either individual hillslopes or first-order-watersheds. Their identification and delineation are described in Chen et. al.(2004a). WEHY computes the surface and subsurface hillslope hydrologic processes that take place at these MCUs, in parallel and simultaneously. These computations yield the flow discharges to the stream network and the underlying unconfined groundwater aquifer of the watershed that are in dynamic interaction both with the surface and subsurface hillslope processes at MCUs as well as with each other (as may be seen from Figure 1). These discharged flows are then routed by means of the stream network and the unconfined groundwater aquifer that are in dynamic interaction. In Figure 2 the land surface process components of WEHY model are shown. In its land surface process component, WEHY model describes interception, bare soil evaporation, direct evaporation from ponded water over the plant leaves, and plant transpiration through root water uptake in dynamic interaction with the soil moisture. The land surface component of WEHY, has been reported in detail previously in the literature (eg. Kavvas et al. 1998), and, thereby, will not be discussed further.

In Figure 3 the surface and subsurface flow components of WEHY model at a hillslope (corresponding to a MCU) are shown. It may be noted from Figure 3 that WEHY model can handle both the Hortonian as well as variable source area flow mechanisms. In Figure 3 it is seen that although subsurface soil root zone may not be saturated to the soil surface, Hortonian overland flow may still occur due to ponding of infiltration-excess rainfall/snowmelt water over the land surface. Such Hortonian overland flow which would occur predominantly at bare soil surfaces in arid lands, can then supply water for flow in rills/gullies that neighbor interrill overland flow areas. Meanwhile, in humid, vegetated landscapes rainwater/snowmelt that infiltrates into the soil, moves mainly in the vertical direction within the root zone as unsaturated flow until it encounters a hardened soil layer beneath the plant roots. At this layer the soil hydraulic conductivity decreases drastically to impede vertical soil water flow. Thus, over this soil impeding layer the soil water starts to pond and to saturate soil pores. Once this water reaches sufficient head and hydraulic gradient, it moves downhill as saturated subsurface flow within the soil in a direction approximately parallel to the soil

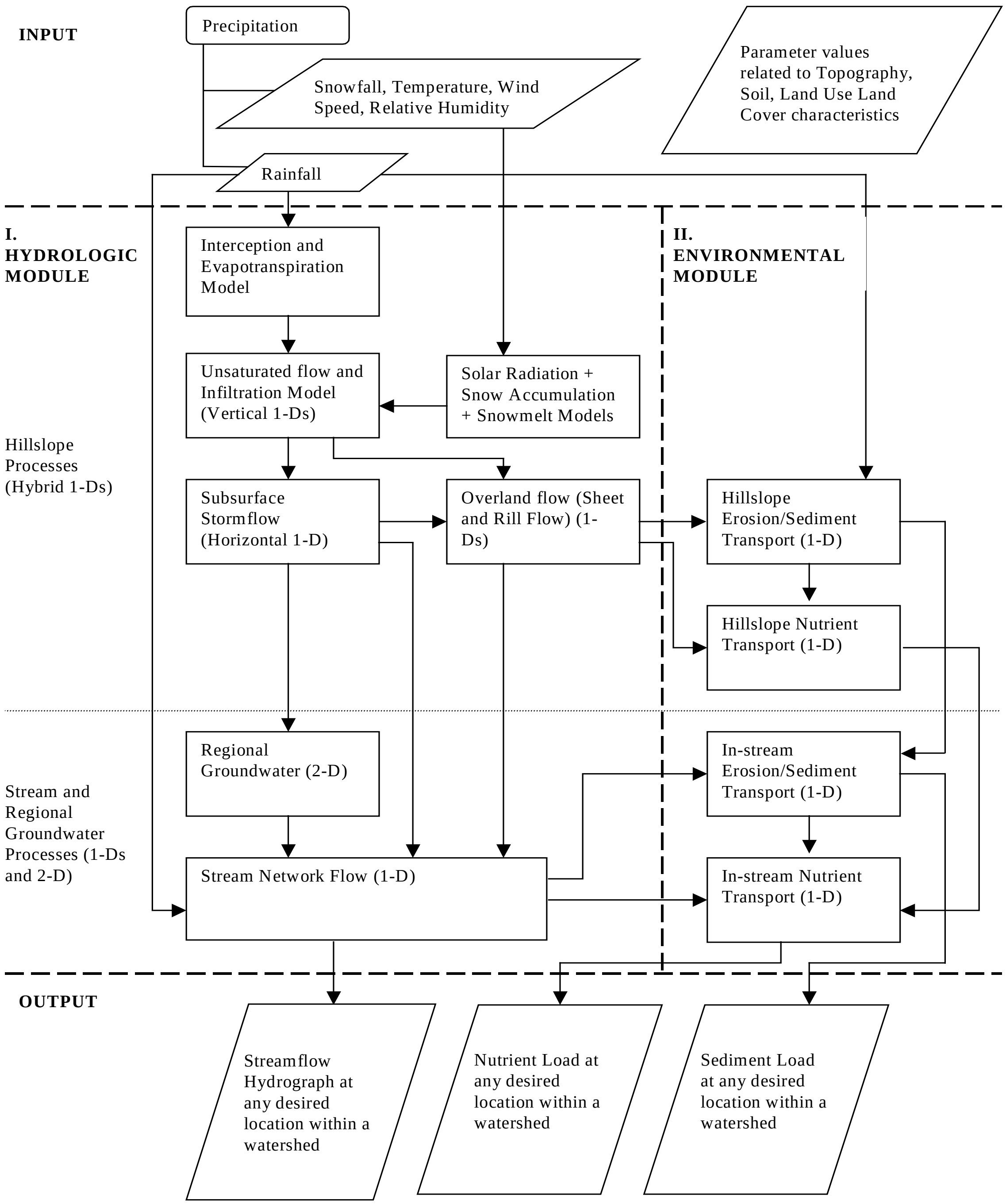

Figure 1. A schematic description of WEHY model

impeding layer. Since the soil impeding layer is oriented approximately in the same direction as the land surface topography, the saturated flow that takes place within the soil above this impeding layer can be about 1000 times faster than the unsaturated soil water flow. Therefore, this saturated soil water flow is known as the “subsurface stormflow” (Dunne, 1978). As described in great detail by Dunne (1978), the subsurface stormflow is a fundamental hydrologic process that a) supplies water for rill/gully flow in

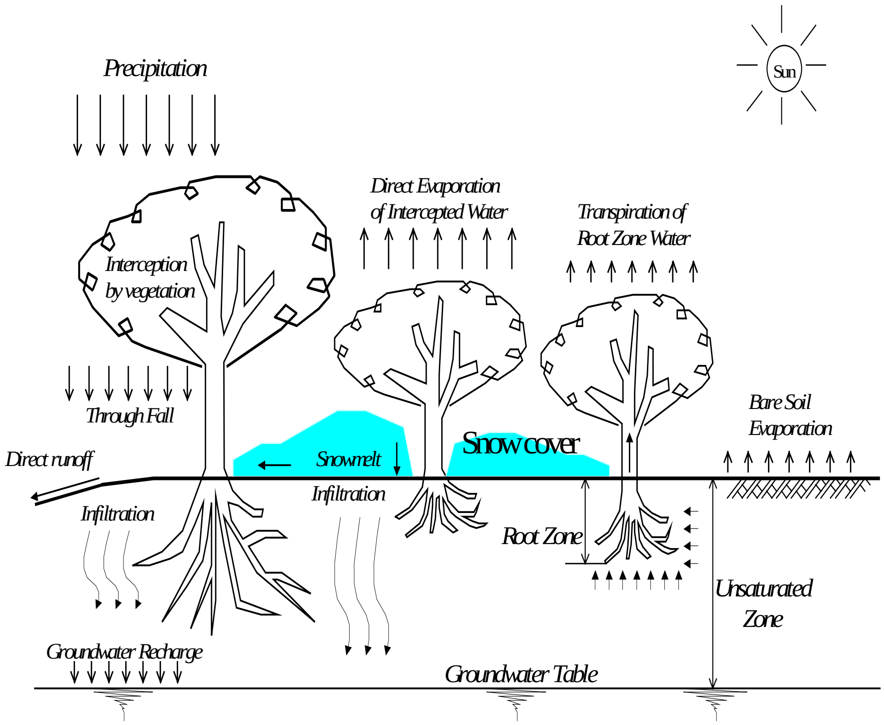

Fig. 2. The description of land surface processes within WEHY model

humid, vegetated landscapes, and b) determines the dynamic location of saturation overland flow in variable source areas. As seen from Figure 3, once the subsurface stormflow water table reaches an elevation that is above the bed elevation of a rill, then under the hydraulic gradient the subsurface stormflow will start discharging into the rill, thus feeding the necessary water for rill flow. Hence, this mechanism renders the case while vegetated land surface may have no overland flow occurring, the rills/gullies over a hillslope may still be flowing in full force during wet periods. As subsurface stormflow continues its travel downslope within a hillslope, it continues to be replenished by vertical unsaturated flow. Then a hillslope location is reached where the capacity of the soil horizon to transmit the subsurface stormflow is exceeded by the stormflow discharge. At this location the part of subsurface stormflow discharge which is in excess of the tranmission capacity of the soil horizon, emerges over the land surface as “return flow” and forms the “saturation overland flow”, as seen in Figure 3. This overland flow is about 1000 times faster than subsurface stormflow (Dunne, 1978), and is the main contributor to flood peak discharge at humid, vegetated landscapes. As seen from Figure 3, from this location where the saturation overland flow starts, onwards the soil is saturated. Hence, the rainwater/snowmelt that falls on this saturated surface, ponds over this surface as “direct precipitation” and amplifies saturation overland flow by joining the return flow. The dynamic extent of this source area, the so-called “variable source area”, is dictated by the location where the subsurface stormflow returns to land surface. WEHY, by modeling explicitly the subsurface stormflow dynamics in terms of upscaled equations, is able to quantify i) the subsurface stormflow-rill flow interaction, and ii) the variable source area flow mechanism.

As seen from Figure 3, since the soil impeding layer is not impermeable, water seeps through this layer and continues its journey as unsaturated flow in the vertical direction through the unsaturated zone beneath the

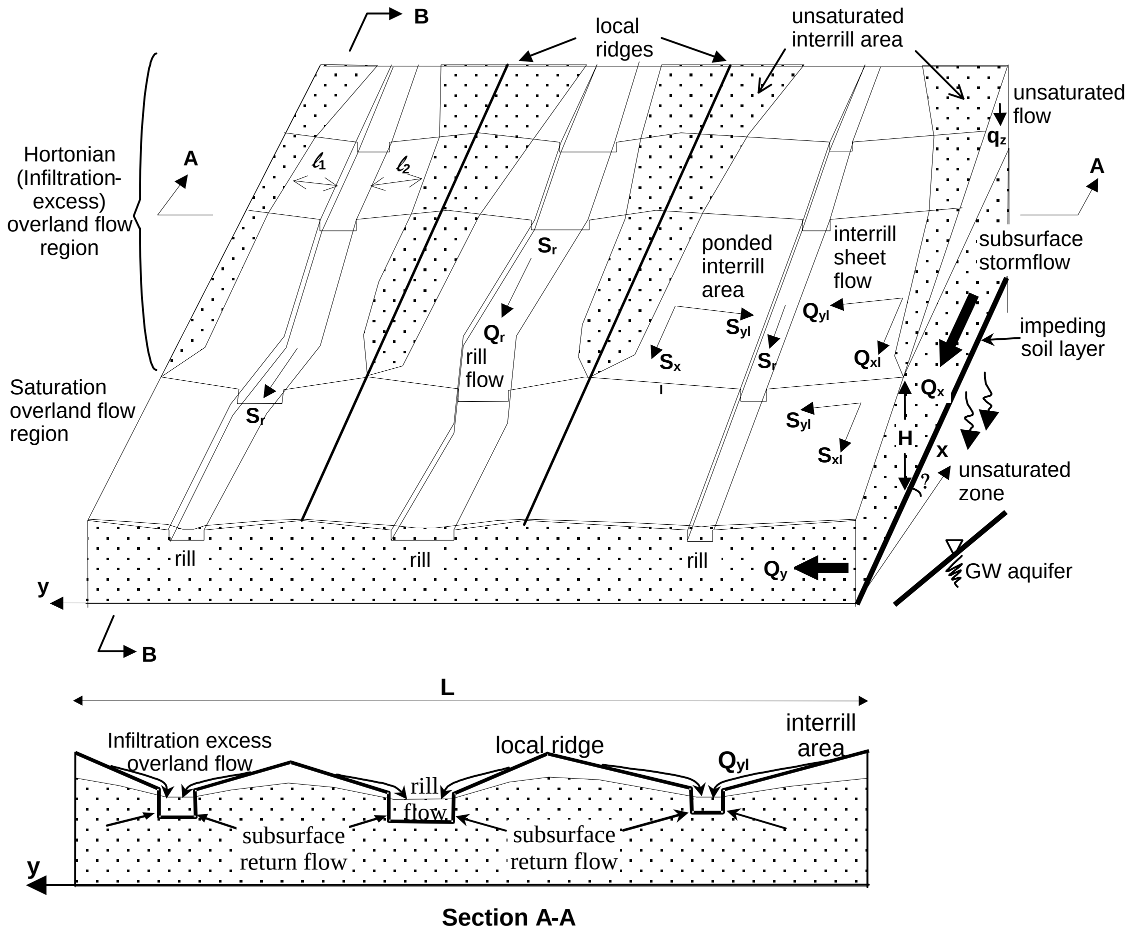

Figure 3. WEHY model's depiction of hillslope surface and subsurface flow processes

soil impeding layer toward an underlying groundwater aquifer. This way a deep unconfined groundwater aquifer may be replenished. Also, since this aquifer borders a stream channel to which a hillslope drains, it provides baseflow discharge to the stream. Since it takes place under very mild hydraulic gradients, the unconfined groundwater flow is very slow, about 1000 times slower than the subsurface stormflow (Dunne, 1978). In this framework, WEHY model conceptualizes water contribution from a hillslope into a neighboring stream channel in terms of a) overland flow (rill flow/sheet flow), b) seepage from subsurface stormflow (which may lead to return overland flow as seen in Figure 3), and c) groundwater baseflow. Once water is discharged from model computational units (MCUs) to the stream network of a watershed, then it is routed by WEHY model within this stream network toward the watershed outlet.

The upscaled conservation equations for the component hydrologic processes of WEHY model were described in detail in Kavvas et. al. (2004), and, due to space limitations, will be deferred to that paper.

APPLICATION OF WEHY MODEL TO CAMP CREEK WATERSHED IN CALIFORNIA

The WEHY model was applied to the Camp Creek subwatershed (162 sq km area) of the Cosumnes River watershed (1388 sq km area) for a water balance study. The location of the Camp Creek watershed is shown in Figure 4. The model parameters were estimated directly from topography, soils, vegetation, land use/land cover data. Some representative results for the development of the GIS system of the model are shown in Figure 5, in terms of the DEM and stream and rill network of the watershed, while a representative result for the estimation of areal statistics of the model parameters is shown in Figure 6 for the areal median and areal log standard deviation of the saturated hydraulic conductivity.

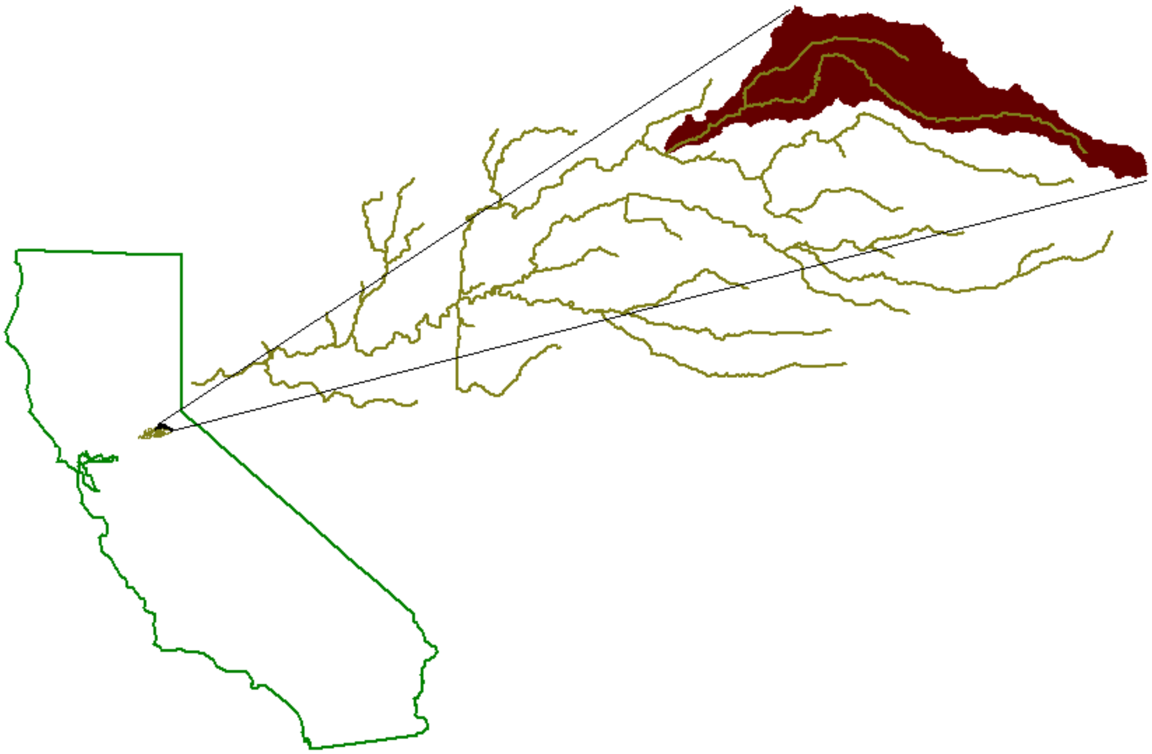

Figure 4. Map of the location of Camp Creek watershed within Cosumnes river watershed in Central California

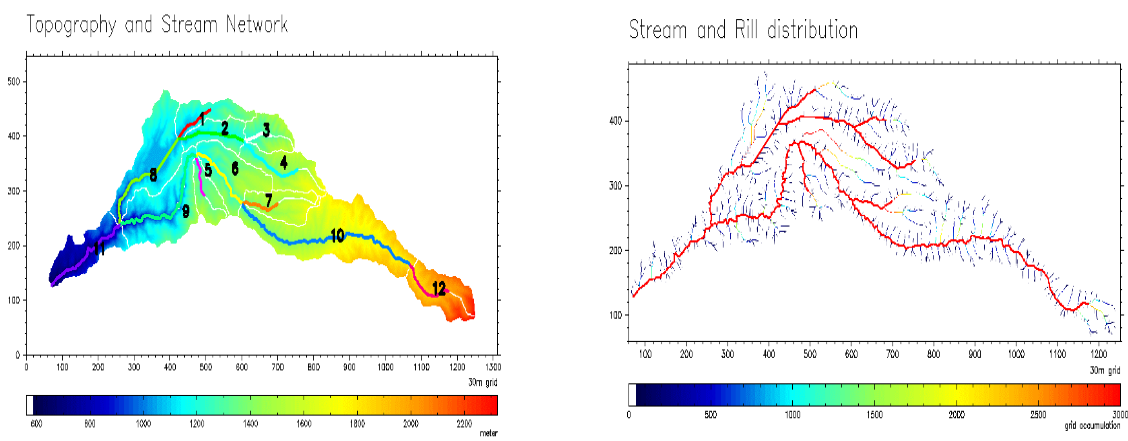

Figure 5. The DEM and the derived stream and rill network of Camp Creek watershed

For its validation, the model simulated the streamflow for the January 1998 period when streamflow data are available. The results of this streamflow simulation against the observations are shown in Figure 7. From Figure 7 it is seen that the WEHY model simulated the observed hourly streamflow at Camp Creek during the month of January 1998 reasonably well. Details of WEHY model's parameter estimation

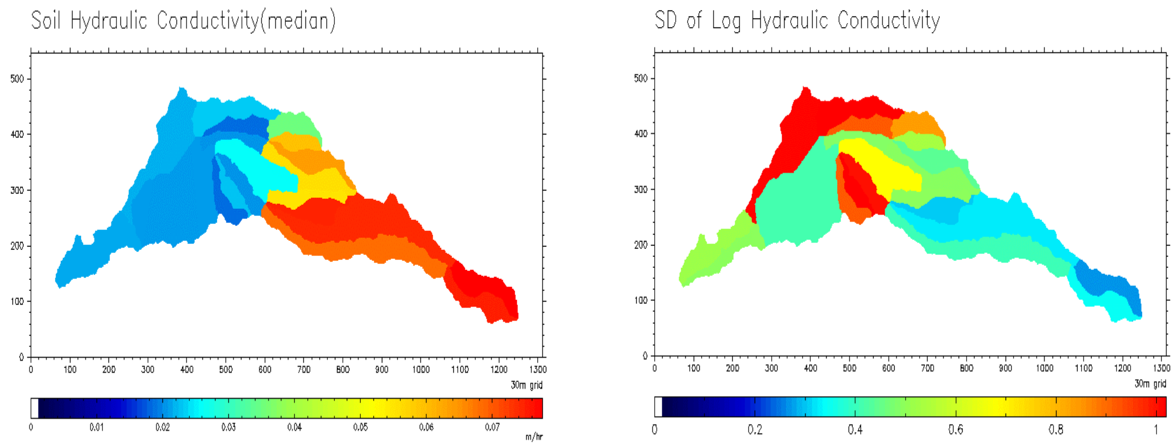

Figure 6. The areal median and areal log standard deviation of saturated soil hydraulic conductivity over the model computational units within Camp Creek watershed

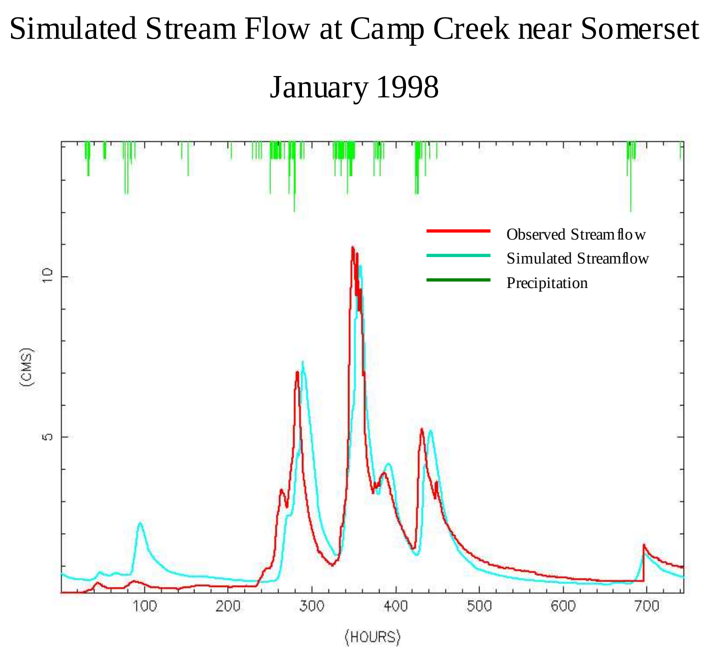

Figure 7. Comparison of the model simulated hourly streamflow against its observed counterpart during January 1998

methodology, along with some detailed results are given in Chen et al. (2004).

DISCUSSION AND CONCLUSION

In this paper, due to space limitations, a brief description of the Watershed Environmental Hydrology (WEHY) model is given. A detailed description of the upscaled conservation equations of the model, along with their derivations, is given in Kavvas et al. (2004). Details of the estimation of the areal statistics of the parameters that are utilized by the model, are given in Chen et al. (2004). The unique feature of WEHY model is that it is based upon upscaled hydrologic conservation equations whose scales are consistent with those of the grid areas they are modeling. By means of this approach significant economy in model parameter estimation and model computations are achieved. Another novel feature of the WEHY model is the estimation of its parameters directly from the existing land data bases. With such estimation approach it is possible to apply the model also to sparsely gauged and ungauged watersheds.

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