Watershed Environment Hydrology Model coupled with Hydro-climate Model (WEHY-HCM): Coupled Modeling of Atmospheric-Hydrologic Processes at Watershed Scale

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A Watershed Hydro-climate Model (WEHY-HCM) is useful

at sparsely-gauged/ungauged watersheds

by producing nonexistent atmospheric data

as input to the modeling of hydrologic processes

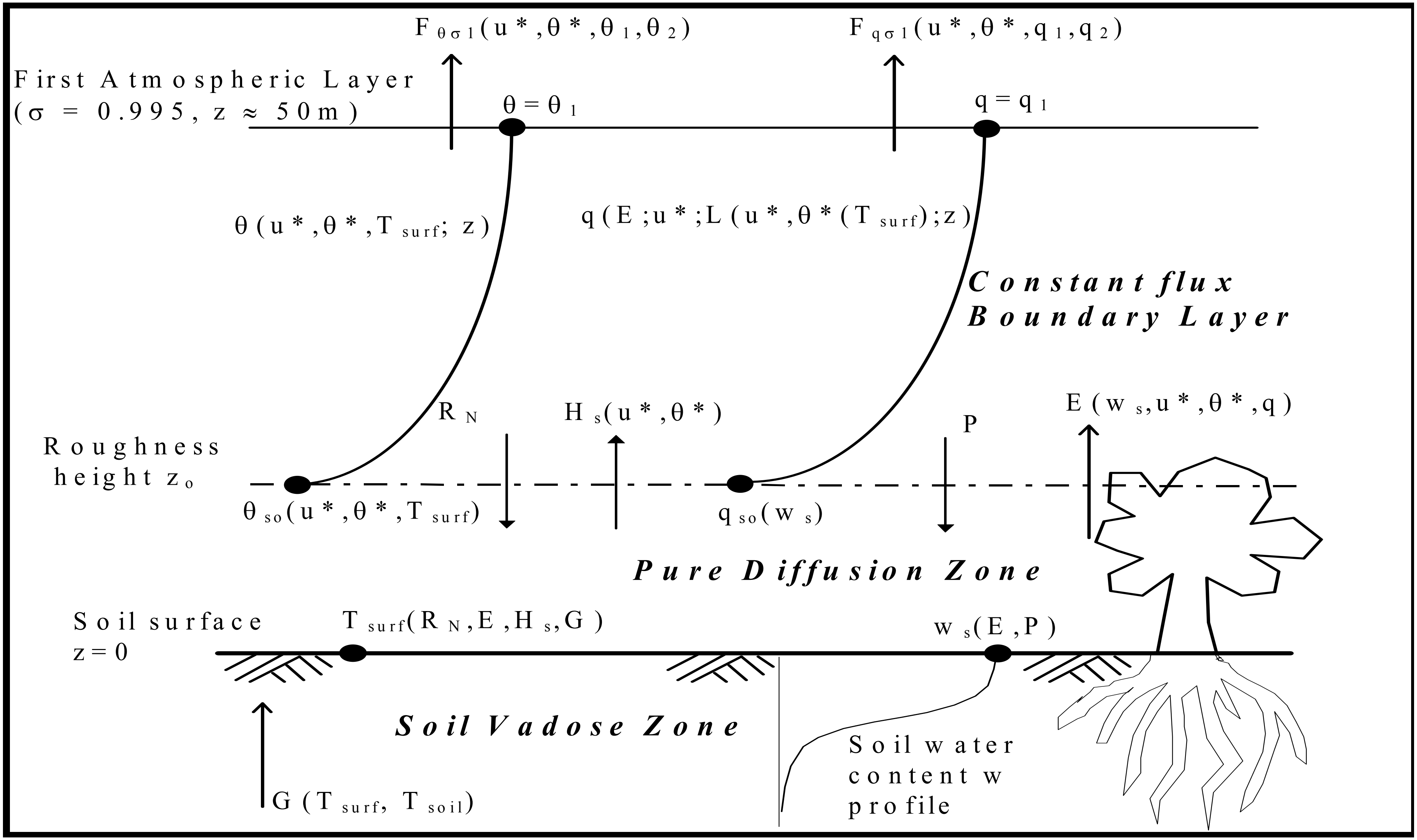
at such watersheds.

It models the earth system

at watershed scale

as a coupled atmospheric-land hydrologic system

interacting dynamically through the atmospheric boundary layer.



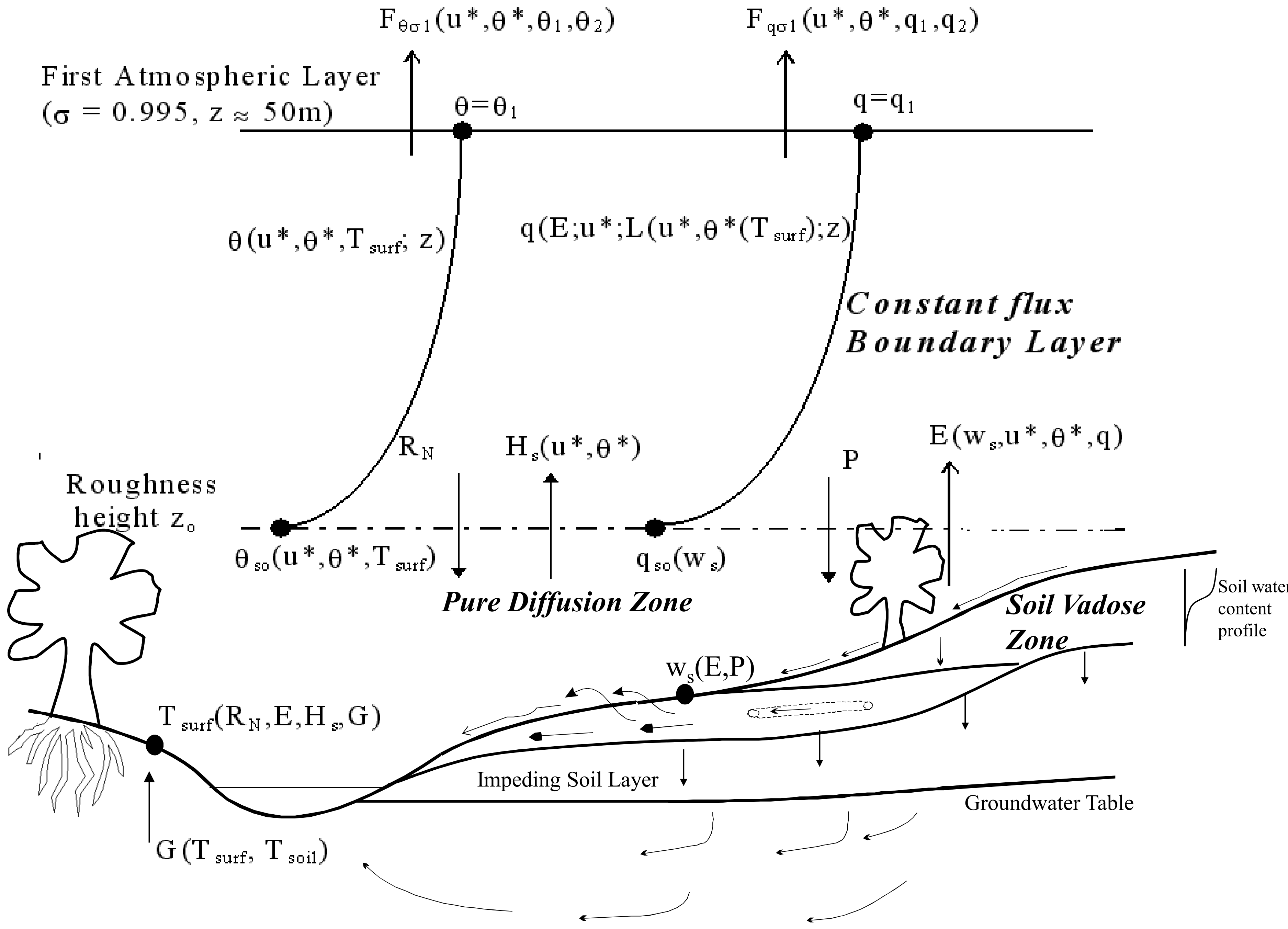
Interactive evolution of atmospheric processes aloft, atmospheric planetary boundary layer, and land surface processes in WEHY-HCM
(From Kavvas et al. (1998), Journal of Hydrological Sciences, IAHS)

As opposed to a standard Regional Hydroclimate Model (RegHCM)
which takes vegetation/soil patches as its fundamental modeling units
a Watershed Hydro-climate Model (WEHY-HCM)
takes hillslopes as its fundamental modeling units.

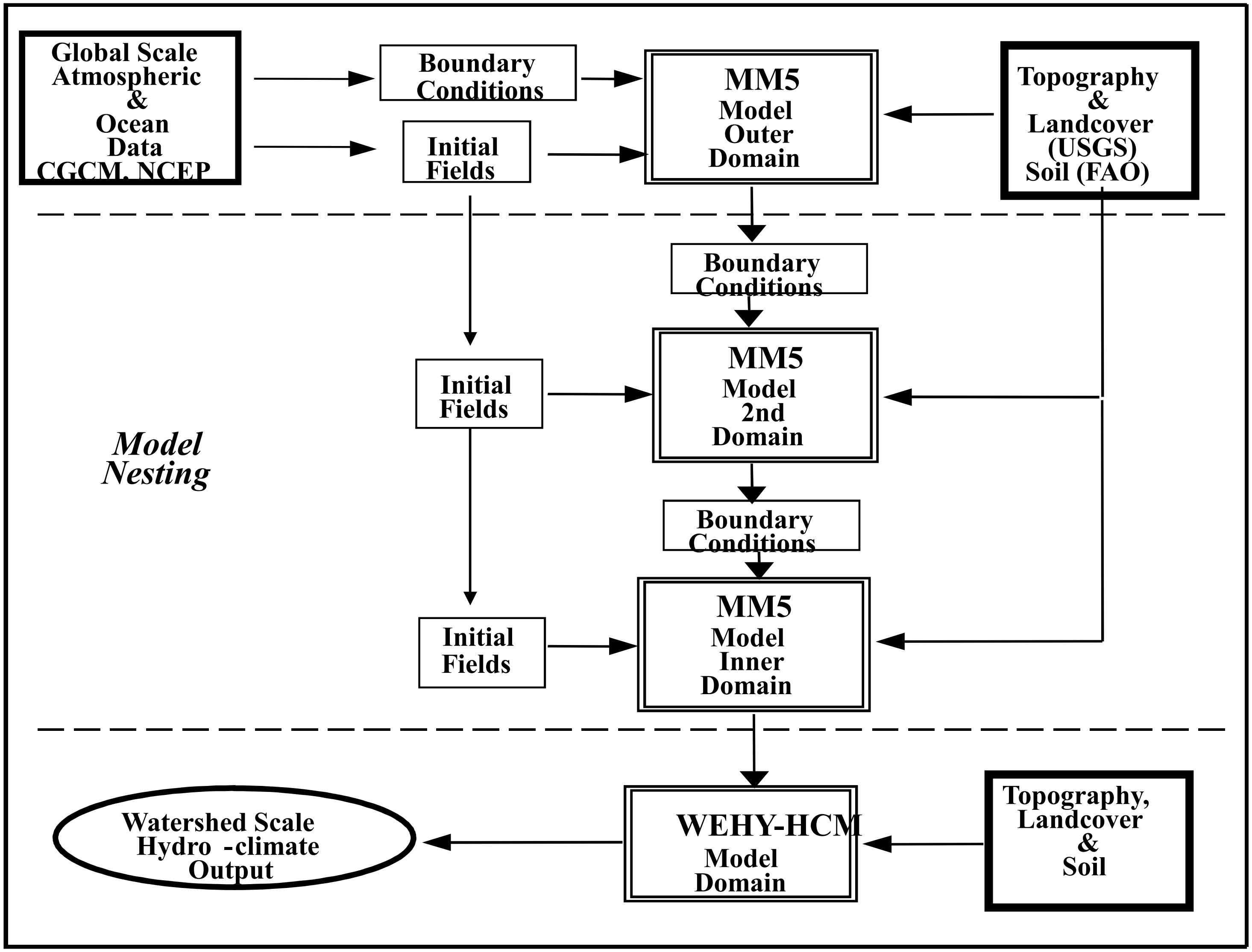
As such
it models the vertical interactions with the atmosphere
(precipitation, radiation, wind, sensible heat flux, evaporation/ET,
soil water flow)
and

lateral hydrologic processes
(subsurface stormflow, overland flow, groundwater flow)
at hillslope scale

mostly as
hillslope-scale averages.



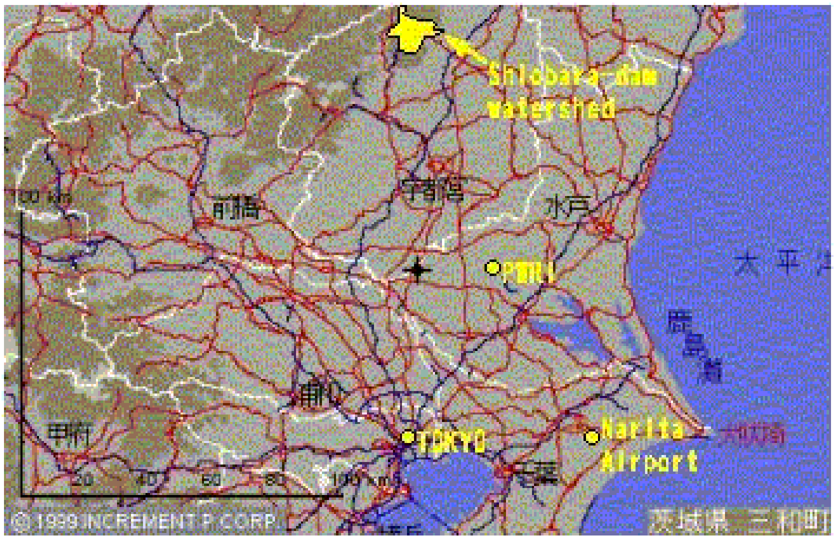
$F_{\theta\sigma 1}(u^*, \theta^*, \theta_1, \theta_2)$
$F_{q\sigma 1}(u^*, \theta^*, q_1, q_2)$
First Atmospheric Layer
(σ = 0.995, z ≈ 50m)
$\theta = \theta_1$
$q = q_1$
$\theta(u^*, \theta^*, T_{surf}; z)$
$q(E; u^*; L(u^*, \theta^*(T_{surf}); z)$
Constant flux Boundary Layer
R_N
$H_s(u^*, \theta^*)$
P
$E(w_s, u^*, \theta^*, q)$
Roughness height z_o
$\theta_{so}(u^*, \theta^*, T_{surf})$
$q_{so}(w_s)$
Pure Diffusion Zone
Soil Vadose Zone
Soil water content profile
$w_s(E,P)$
$T_{surf}(R_N, E, H_s, G)$
Impeding Soil Layer
Groundwater Table
$G(T_{surf}, T_{soil})$

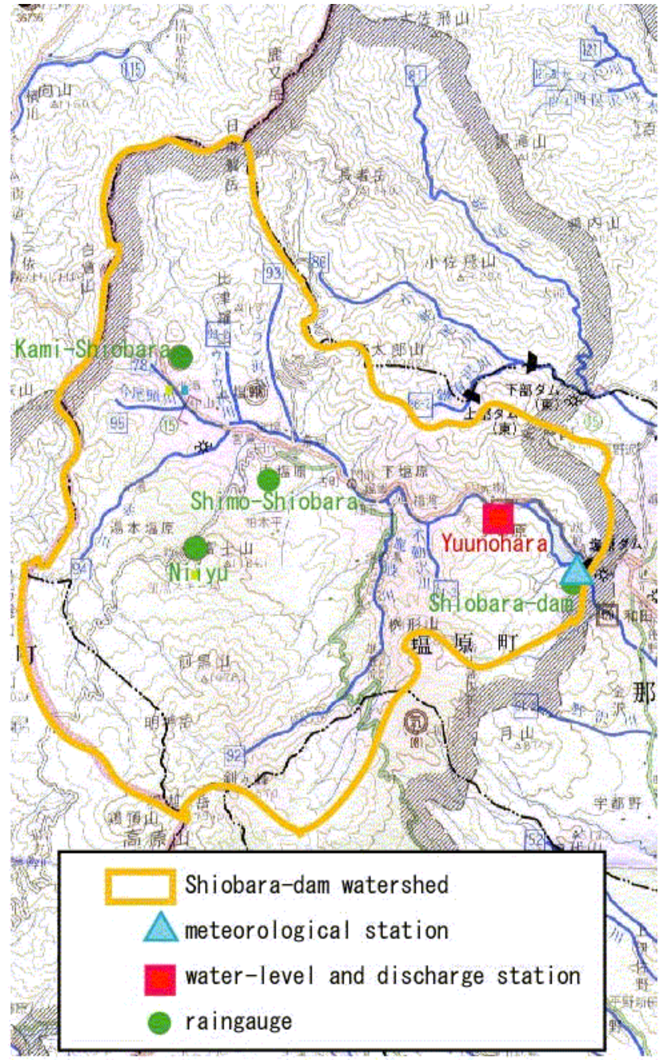


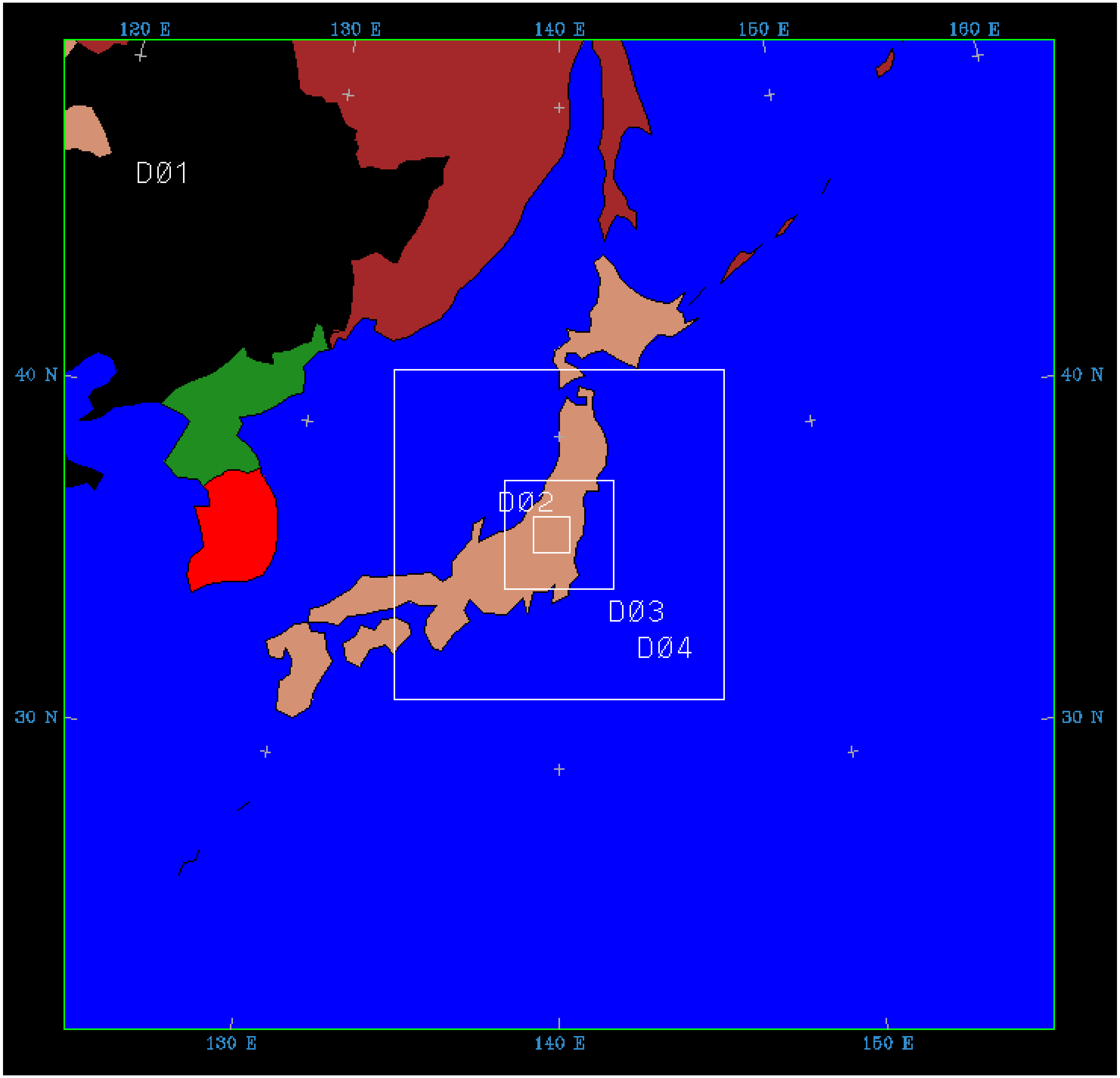
NCEP: stands for United States National Center for Environmental Prediction;
USGS: United States Geological Survey;
FAO: Food and Agriculture Organization of the United Nations;
CGCM: Canadian General Circulation Model

MM5 Model

- 5^{th} generation mesoscale model from NCAR/Penn State Univ.
- Nonhydrostatic 3D simulations of atmospheric motions possible
- Nested grid capabilities economize downscaling computations
- Multiple schemes available for atmospheric processes (e.g. boundary layer, convection, precipitation, radiation, etc)


Shiobara-dam
watershed
宇都宮
前橋
水戸
PWRI
鹿島灘
甲府
TOKYO
Narita
Airport
千葉
© 1999 INCREMENT P CORP.


Kami-Shiobara
Shimo-Shiobara
Niiyu
Yuunohara
Shiobara-dam
塩原町
Shiobara-dam watershed
meteorological station
water-level and discharge station
raingauge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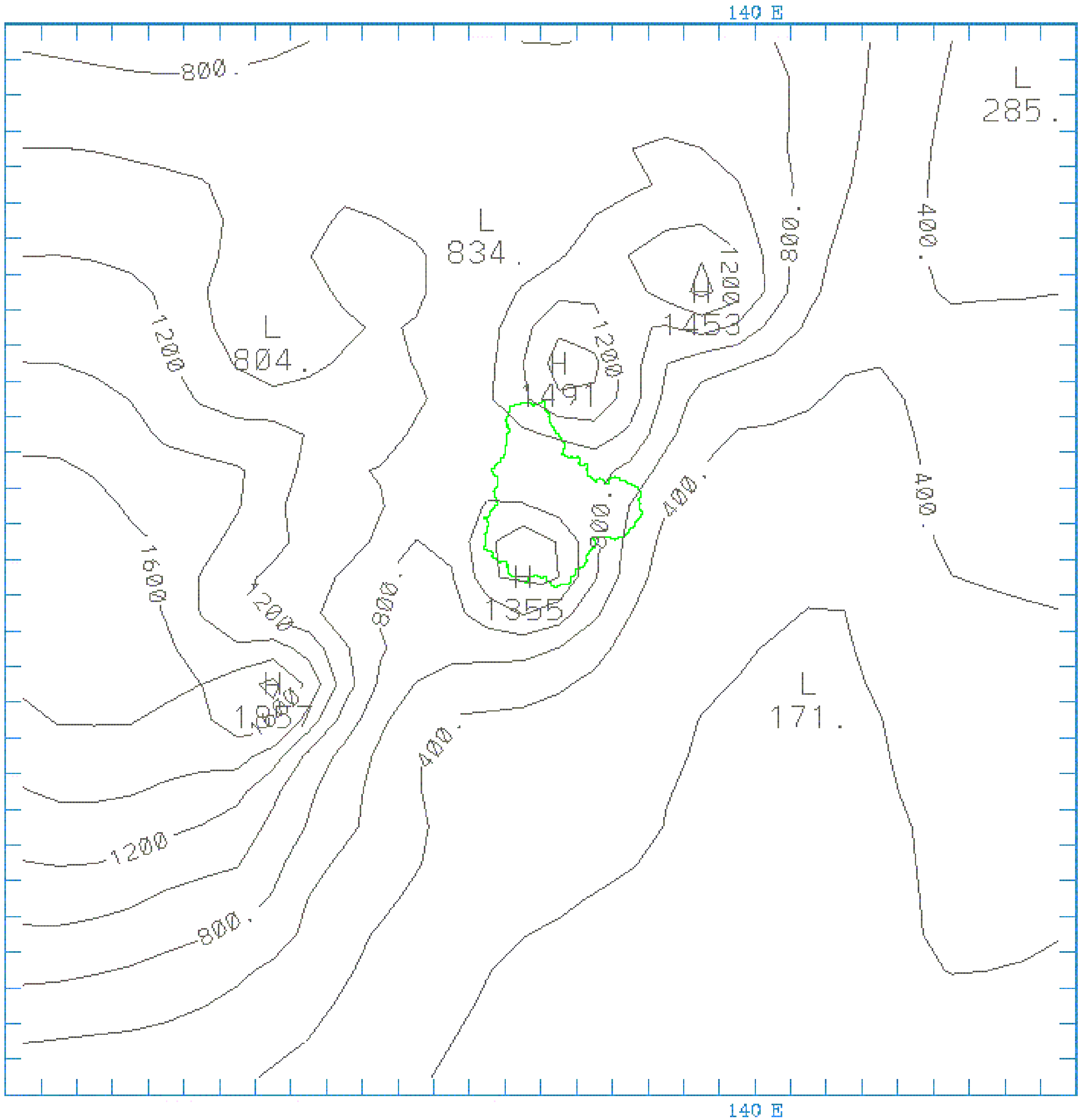

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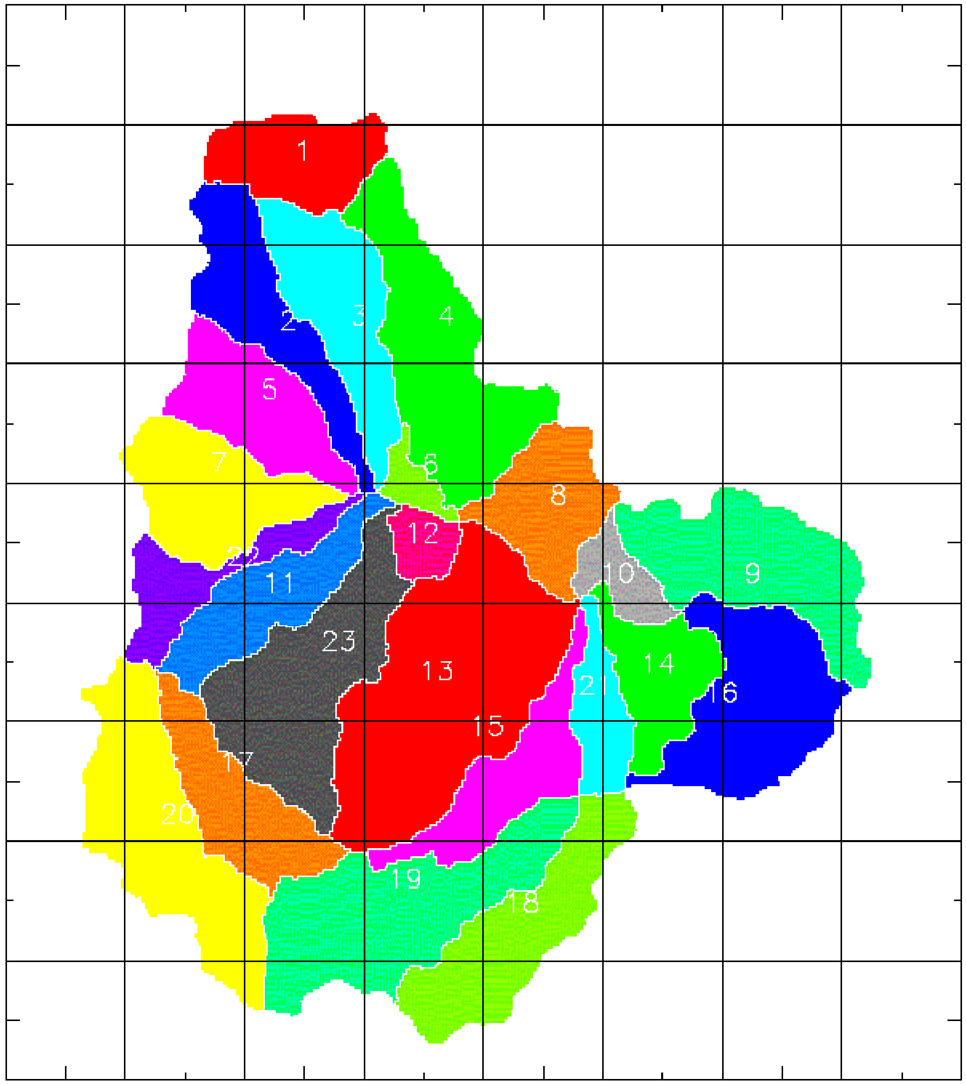
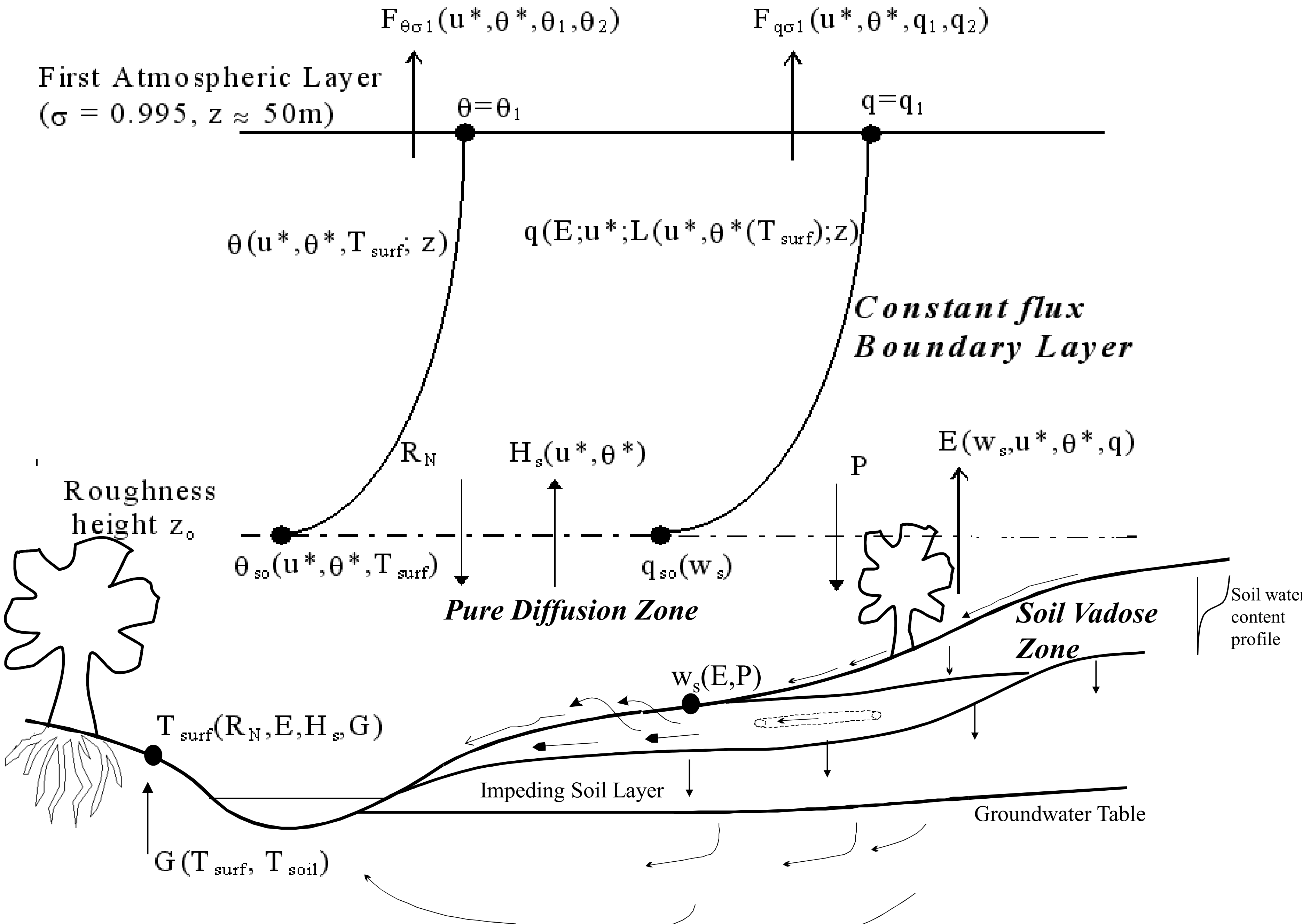


Transformation of spatially-distributed precipitation data from the MM5 grids to the computational units (MCUs) of WEHY-HCM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content
profile
$w_s(E,P)$
$T_{surf}(R_N, E, H_s, G)$
Impeding Soil Layer
Groundwater Table
$G(T_{surf}, T_{soil})$

At point location scale:

WEHY-HCM uses

1-d vertically-integrated soil water flow conservation equations with rectangular profile variable saturation approximation,

1-d vertically-integrated snow conservation equations (mass, density, thermodynamics),

2-d overland sheet flow conservation equations with KW approximation

1-d rill/gully channel flow conservation equations with KW approximation

2-d subsurface stormflow conservation equations

2-d unconfined aquifer flow (Boussinesq) equation

Then at a transverse section of a hillslope:

2-d overland sheet flow equation and 2-d subsurface stormflow equation are averaged in the transverse direction

to render

1-d sheet flow equation with a lateral flow component

and

1-d subsurface stormflow equation with a lateral flow component

to

the neighboring rills/gullies over the hillslope.

Transverse averaging of 2-D subsurface stormflow:
(Kavvas et al., JHE 2004)

$$Q_x(x,y) = -H(x,y)\cos\theta \cdot K(x,y)\left(\frac{\partial H(x,y)\cos\theta}{\partial x} + \sin\theta\right)$$

$$Q_y(x,y) = -H(x,y)\cos\theta \cdot K(x,y)\frac{\partial H(x,y)\cos\theta}{\partial y}$$

where Q_x and Q_y are the discharge rates per unit width in x (longitudinal) and y (transverse) directions, respectively. θ is the slope angle of the impeding soil layer in the x direction, H is the vertical depth of the subsurface stormflow, and K(x,y) is the hydraulic conductivity.

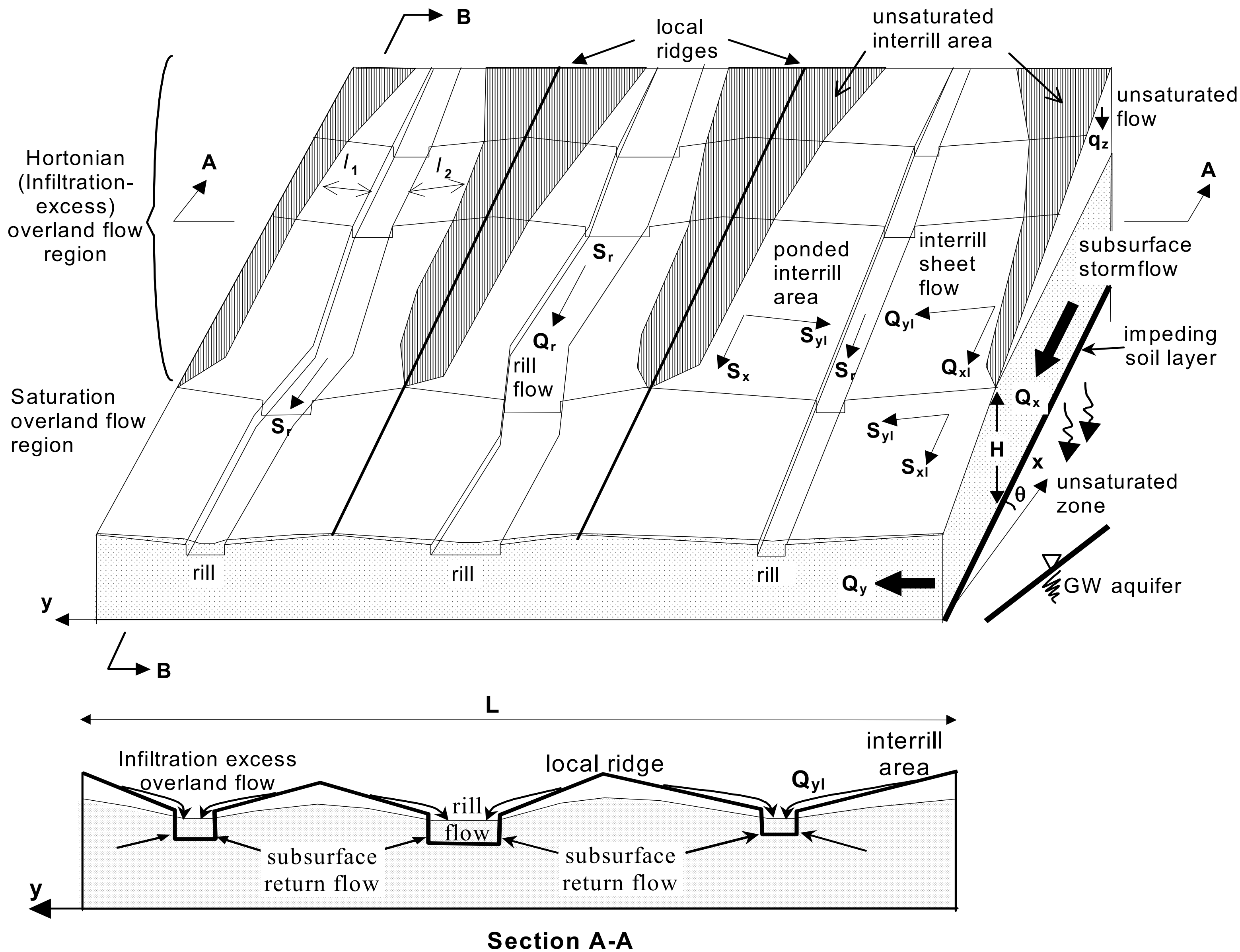
The continuity equation which describes the flow in the subsurface stormflow domain, becomes

$$\frac{\partial}{\partial x}Q_x(x,y) + \frac{\partial}{\partial y}Q_y(x,y) + w_h\frac{\partial H(x,y)}{\partial t} = q(x,y,t)$$

Integrating the continuity equation along the hillslope transect in y-transverse direction yields

$$\frac{\partial\langle Q_x\rangle L}{\partial x} + Q_y(x,y)\Big|_{y=0}^{y=L} + w_h\frac{\partial\langle H\rangle L}{\partial t} = \langle q\rangle L$$

where L is the hillslope width in y-direction, and represents the net lateral fluxes in y-direction as subsurface return flow to rills, modeling the supply of water from subsurface stormflow to the rills in vegetated, humid regions.



From Kavvas et al. JHE Nov/Dec 2004 issue

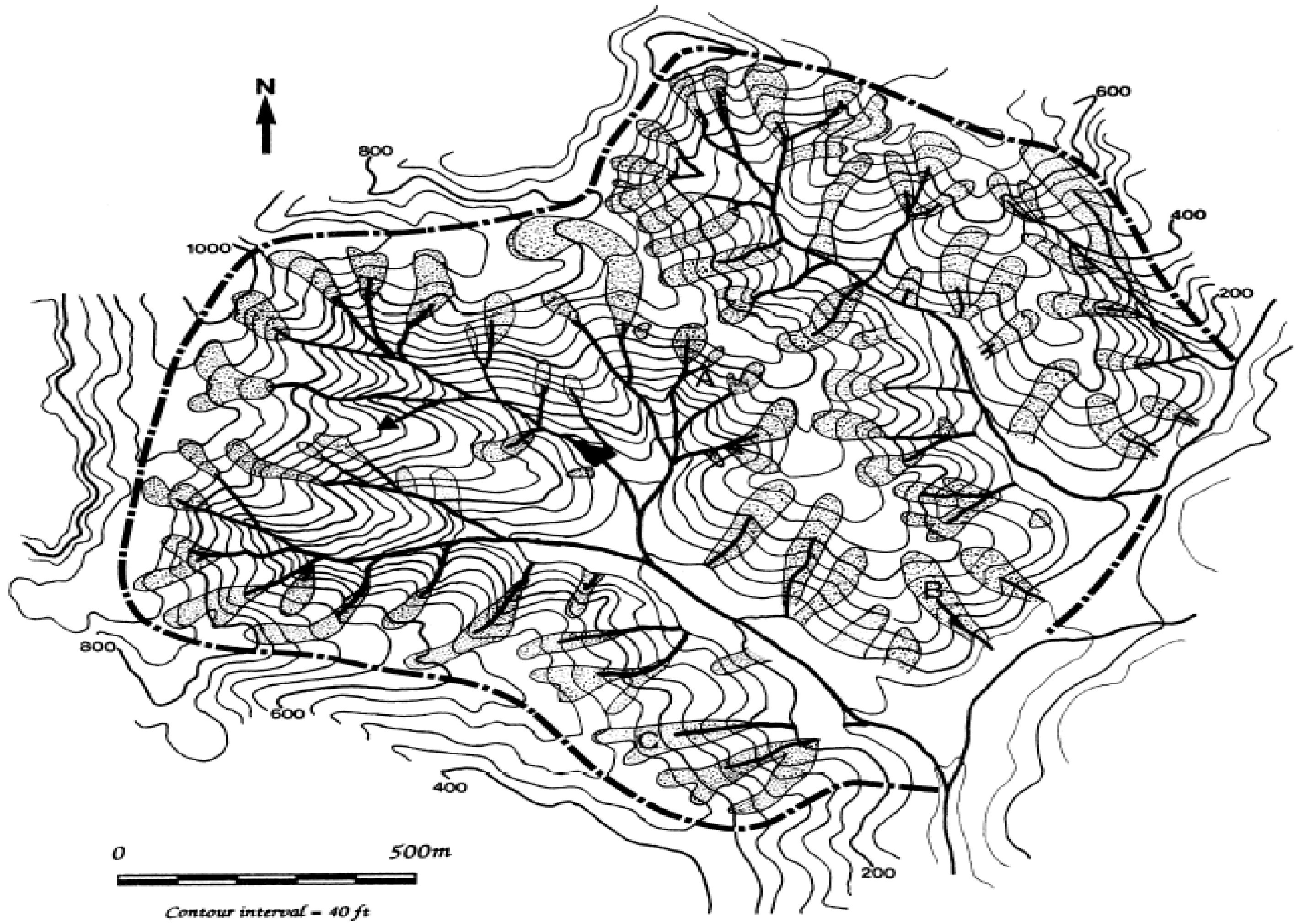


Fig. 3. Channels and colluvial deposits in the study area. Both continuous and discontinuous channels are indicated by heavy black lines and the approximate extent of colluvial deposits are indicated by the stippled areas. Small triangle in middle left of the figure represents a channel head associated with a road drainage culvert. The black pattern in the area near center of figure denotes a man-made pond. Capital letters indicate channel heads shown in detail in Figures 4, 5*a*, and 6*a*.

From D.R.Montgomery and W.E.Dietrich (1989). "Source areas, drainage density and channel initiation", WRR, 25(8), 1907-1918

At a 2 km^2 area near San Francisco, California

At the scale of a hillslope:

RPVS soil water flow conservation equations are ensemble averaged with respect to saturated hydraulic conductivity random field;

Transverse-averaged sheet overland flow equation is further ensemble-averaged wrt roughness and bedslope;

Transverse-averaged subsurface stormflow equation is further ensemble-averaged wrt saturated hydraulic conductivity;

Vertically-integrated snow conservation equations are further averaged with respect to aspect ratio;

Bare soil evaporation and ET from vegetation are modeled by aerodynamic formulation in order to incorporate the evolution of atmospheric boundary layer, soil water flow and plant physical characteristics

WEHY-HCM hydrology model component

- Interception module
- Areally-averaged snow accumulation and snowmelt module
- Evapotranspiration, sensible heat flux for computation of these fluxes as areally-averaged quantities (wrt Monin-Obukhov ABL and soil water flow and heat flow at a hillslope area)
- Short wave/long wave radiation equations
- Areally averaged soil water flow and soil heat flow equations
- Areally-averaged subsurface stormflow
- Computes infiltration, exfiltration, soil water content profile, soil water storage, interception, subsurface stormflow, groundwater flow, direct runoff volume, soil temperature at each hilllslope of the modeled watershed

Within this framework,

a fully-coupled Watershed Hydro-Climate Model (WEHY-HCM)

was developed

where

the **atmospheric components of** the nonhydrostatic regional model

NCAR MM5 (Fifth Generation Mesoscale Model)

were

fully-coupled (two-way interaction)

with

the **Watershed Environmental Hydrology (WEHY) model**

A fundamental issue in the infiltration/unsaturated flow modeling:

It is not necessary for soil surface to reach saturation (ponding) during rainfall over vegetated land surfaces !!

Soil water flow can reach an equilibrium with the infiltrating rainfall rate at a soil water content significantly below porosity!!!

However, many popular soil water flow models (such as Green-Ampt model, Horton model, Phillip model, etc.) assume that the soil surface must reach saturation at some time after the start of rainfall.

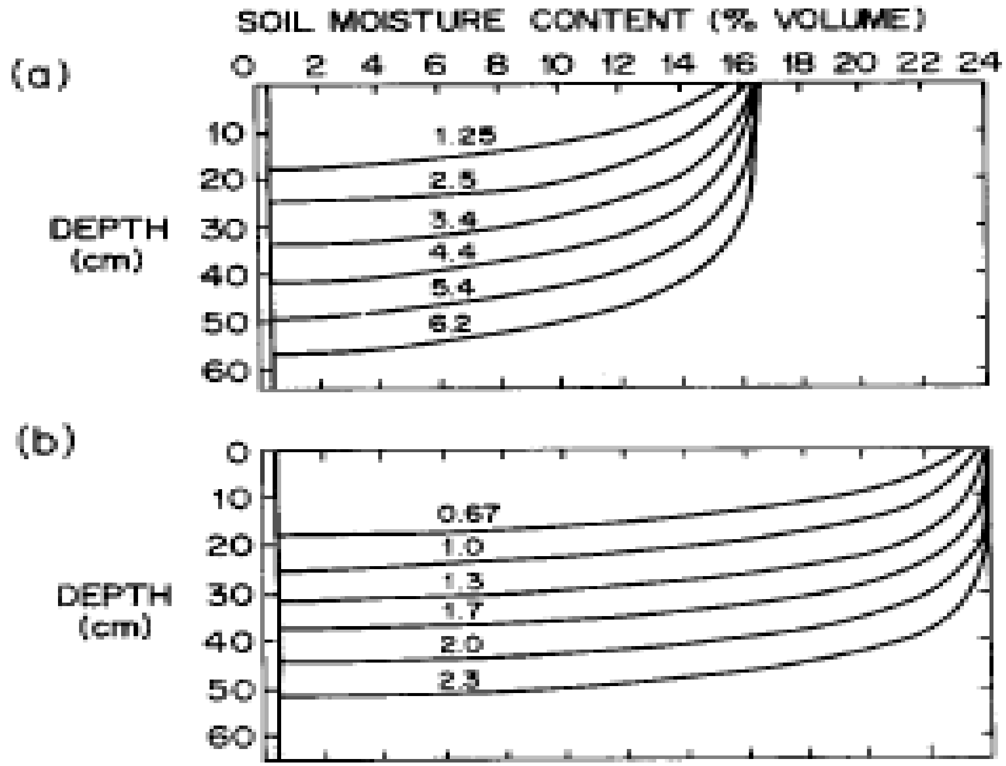
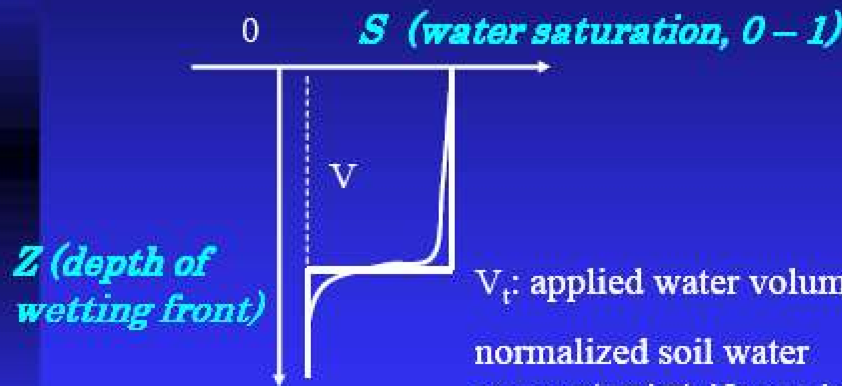


Figure 7.9 Changes of soil moisture with depth during infiltration in initially air-dry sand. Saturation moisture content for this soil is 38%. Figures on the curves indicate the duration of infiltration, in hours.
(a), Ratio of rainfall intensity to the saturated hydraulic conductivity of the soil = 0·026; (b), Ratio of rainfall intensity to the saturated conductivity of the soil = 0·098
(after Rubin, 1966)

From T.Dunne (1978). "Field studies of hillslope flow processes", Chp.7 in *Hillslope Hydrology*, ed. by M.J. Kirkby

Assumption of rectangular soil water saturation profile



V_t: applied water volume,

normalized soil water storage(=S*Z) if no rainfall excess

The issue of soil layers:

Many land surface models (especially popular in RegHCMs and GCMs of atmospheric scientists) take soil with a fixed number of layers, analogous to the description of the atmosphere in terms of many layers.

However, unlike atmosphere, the locations of soil layers are not fixed!!!

The depths of soil layers will vary from one soil survey area to the next soil survey area.

Over a hillslope (MCU of WEHY-HCM) there may be several soil patches with different number of soil layers with differing depths.

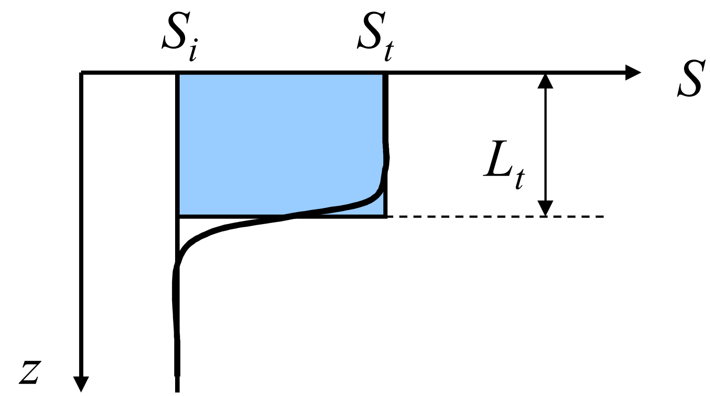
WHAT TO DO ????

One solution:

Average the soil water conservation equations with respect to depth, based on soil survey information at a hillslope

With this depthwise-integrated conservation equations approach
the soil survey information on soil layers and soil textures can be directly utilized within these
depthwise integrated equations.

Point-location-scale RPVS (Rectangular Profile Variable Saturation) Model



It is based upon depth-integrated continuity and Darcy equations at a soil column .

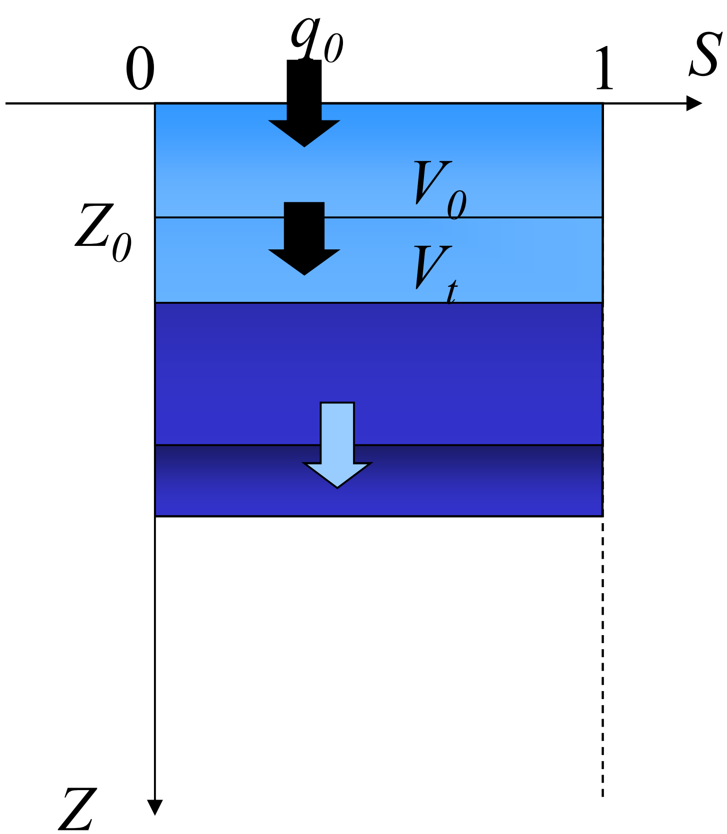
Depth-integrated continuity equation which accounts for root water uptake:

$$\frac{\partial}{\partial t}\left[(\theta_s-\theta_r)(S_t-S_i)L_t\right]=q(0,t)-q(L_t,t)-h_{vt}E_p$$

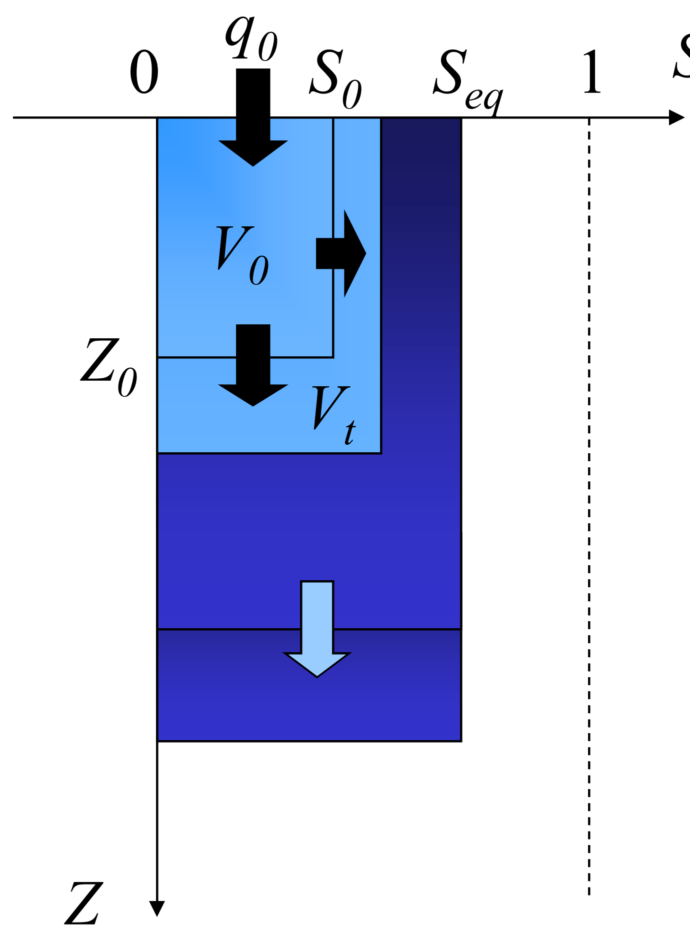
Depth-integrated Darcy's law:

$$\int_0^{L_t} q_z(z,t)dz = K_{sat}\cdot K_r(S_t)\cdot L_t + K_{sat}\cdot\left[\Phi_r(S_t)-\Phi_r(S_i)\right]$$

Green-Ampt model

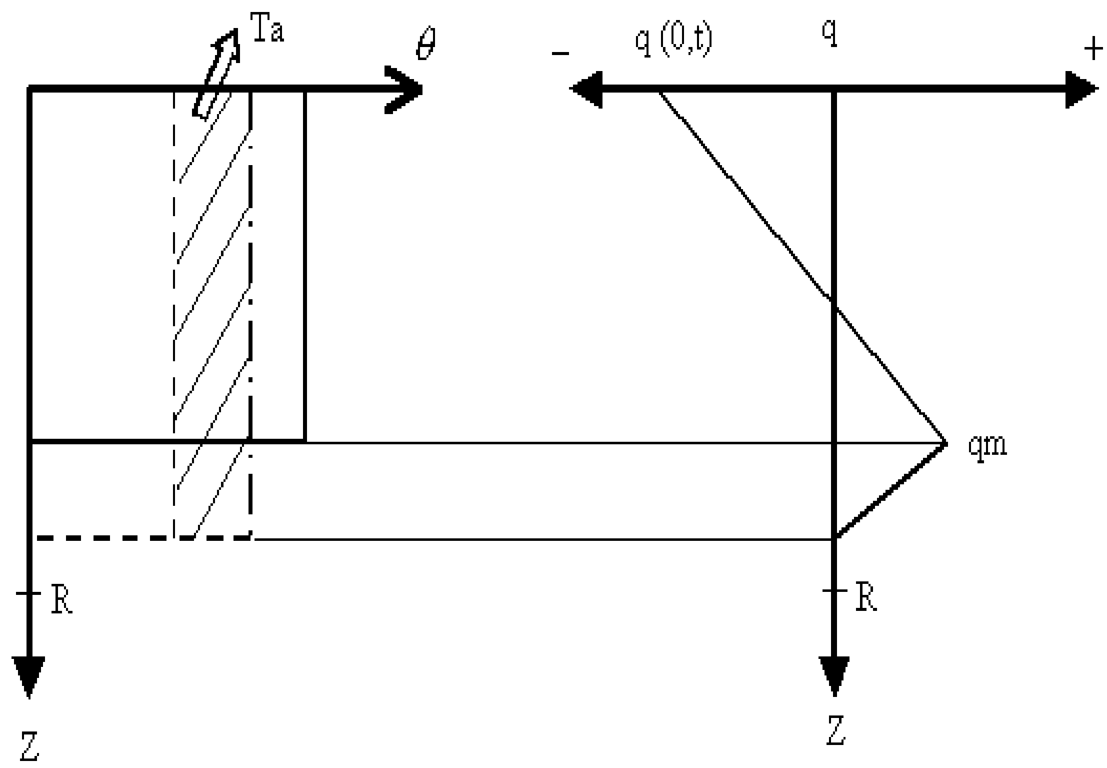


Rectangular Profile Variable Saturation (RPVS) model (Chen et al. WRR 1994)



Evolution of soil water saturation under a constant infiltration rate q_0

Modeling soil water dynamics under bare soil evaporation and soil water redistribution
(from Kim et al., JHE 2004)



The issue of land heterogeneity:

Most prominently, saturated hydraulic conductivity,
and to a lesser extent, porosity
are random fields over even a 15m X 20m field soil.
(Based on experimental observations at UCDavis Campbell track
field site by Rolston et al. 1995)

As such,
the point-location-scale Richards Equation
is not effective
in modeling soil water flow at hillslope scale (Chen et al. 1994)

Chen et al. (WRR, April 1994) have developed
exact analytical expressions for

ensemble averaged soil water flow conservation equations

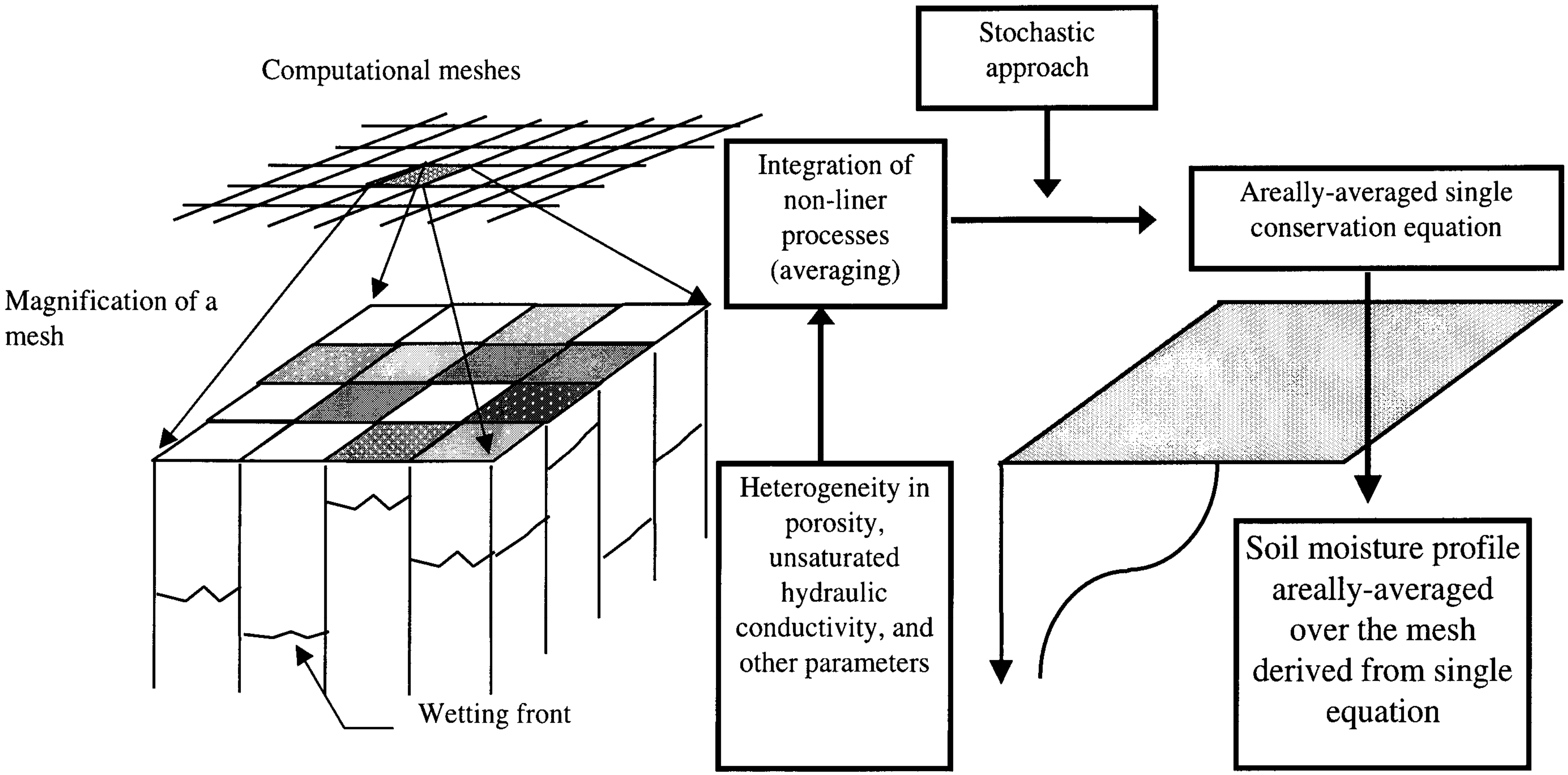
with the rectangular, variably saturated soil water content profiles approximation

under ponded, infiltration and evapotranspiration boundary conditions

(**Rectangular Profile Variable Saturation (RPVS) Model**)
(Chen et al. 1994; Kavvas et al., JHE 2004; Kim et al. JHE 2005)

where **saturated hydraulic conductivity**
is taken to be a random field

Concept of areal-averaging of soil water profiles in a MCU in WEHY-HCM based on Rectangular Profile Variable Saturation (RPVS) Model (Chen et al., 1994a,b)

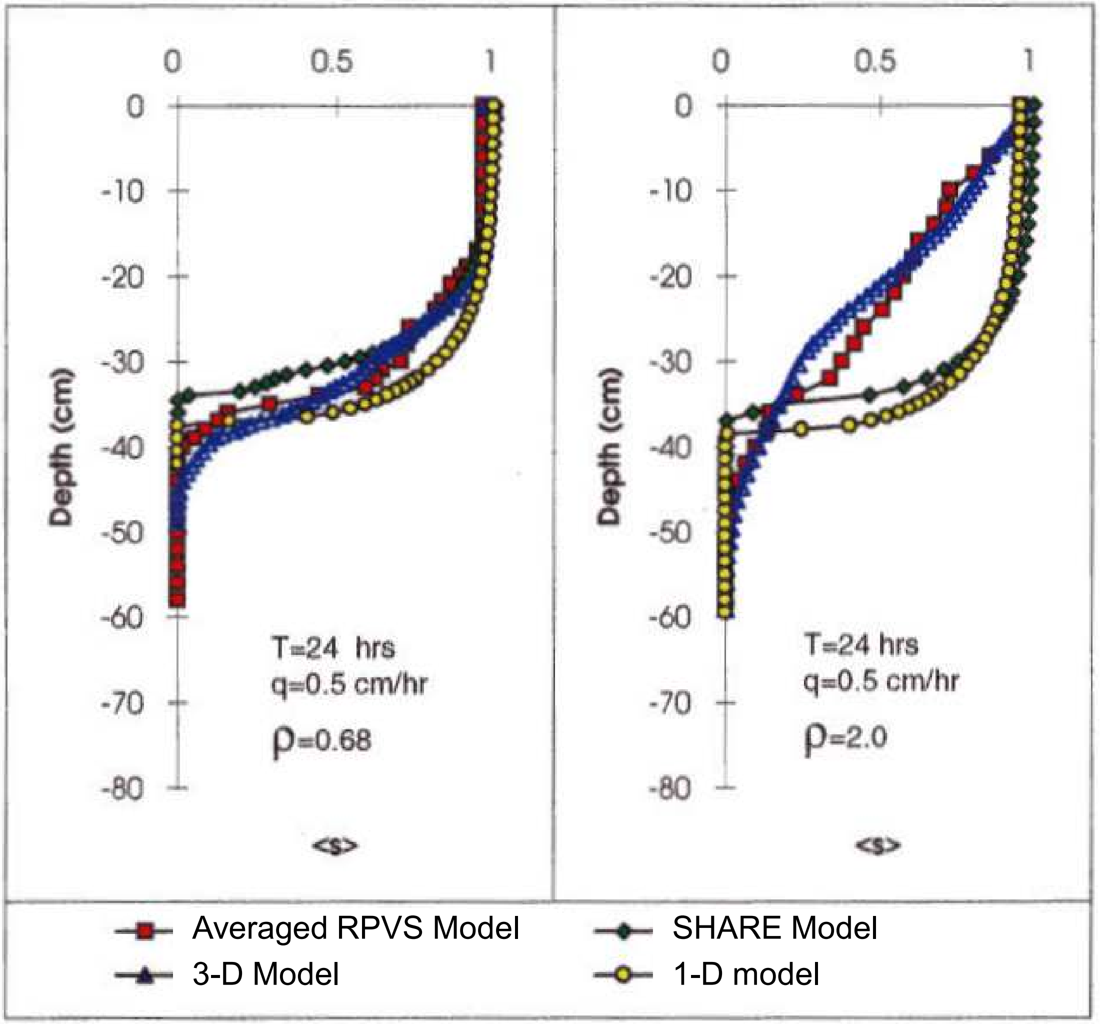


Numerical model of 3-d Richards equation with

Grid Network	= 10m x 10m x 2m
Horizontal grid size	= 1 m
Vertical grid size	= variable (~cm)

was used (Chen et al.,WRR, 1994) to simulate a 3-d soil moisture field under infiltration boundary conditions, starting from vertically uniform soil moisture condition. Then the simulated soil moisture field was horizontally averaged in order to obtain areally-averaged soil moisture content profiles at different times.

These areally-averaged soil moisture profiles were compared with those, predicted by areally-averaged RPVS model (Rect.Prof.) and by a second-order regular perturbation closure to areally-averaged 1-d Richards equation.



0
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1
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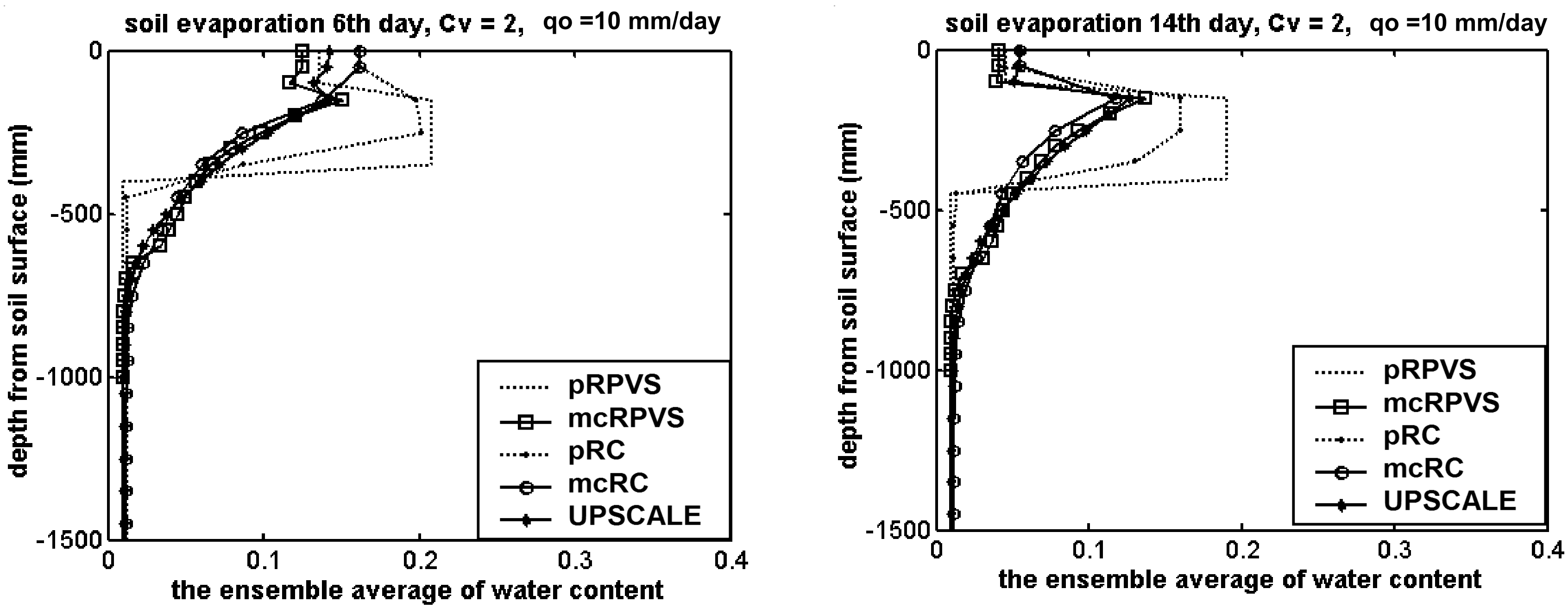
-20
-30
-40
-50
-60
-70
-80
Depth (cm)
T=24 hrs
q=0.5 cm/hr
ρ=0.68
<s>
T=24 hrs
q=0.5 cm/hr
ρ=2.0
<s>
Averaged RPVS Model
SHARE Model
3-D Model
1-D model



The temporal evolution of the ensemble average of vertical soil water content profile in the case of **bare soil evaporation** within a highly heterogeneous soil (Cv of log K_s =2).

Hillslope area-averaged RPVS (Rectangular Profile Variably Saturated)

model equations (Chen et al. 1994; Kavvas et al. 2004; Kim et al. 2005)

were then incorporated into the

aerodynamic formulae (utilizing Monin-Obukhov similarity theory)

in order to

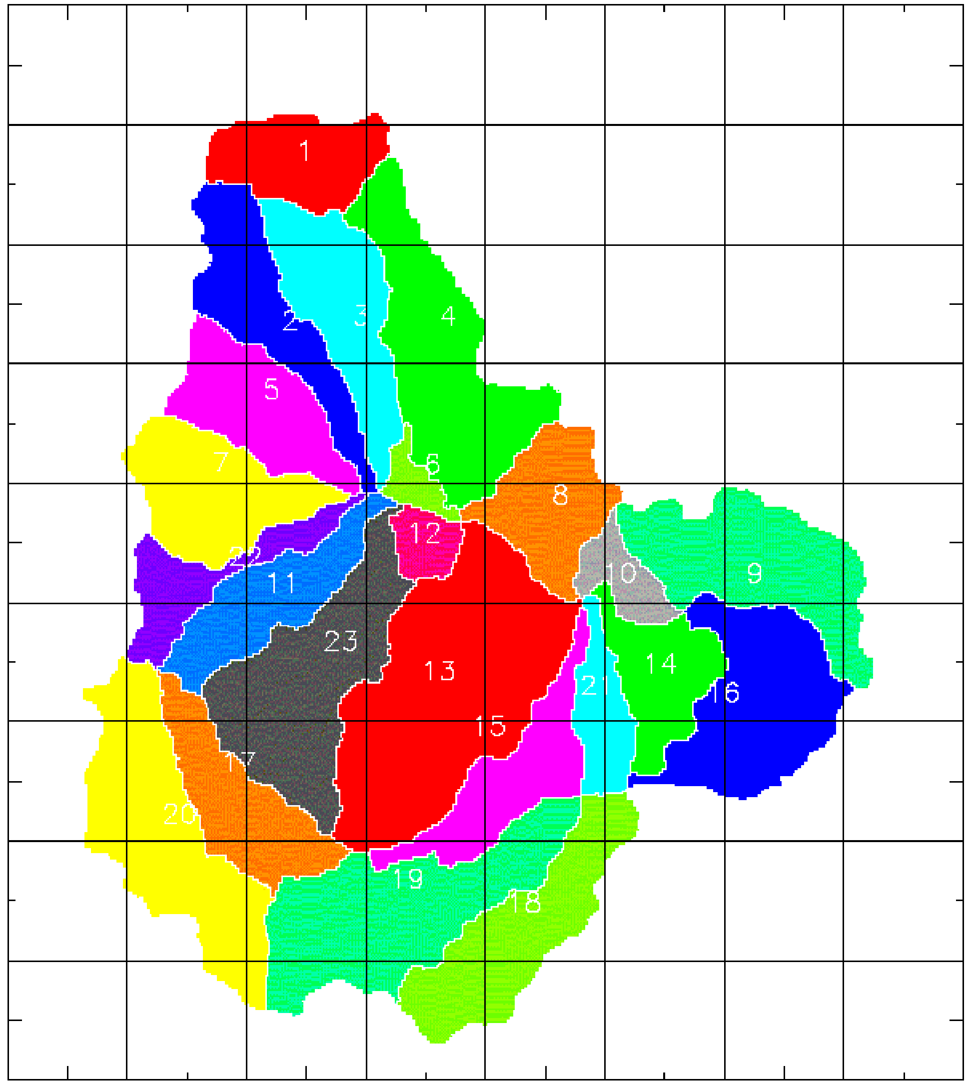
calculate vapor fluxes and sensible heat fluxes

from

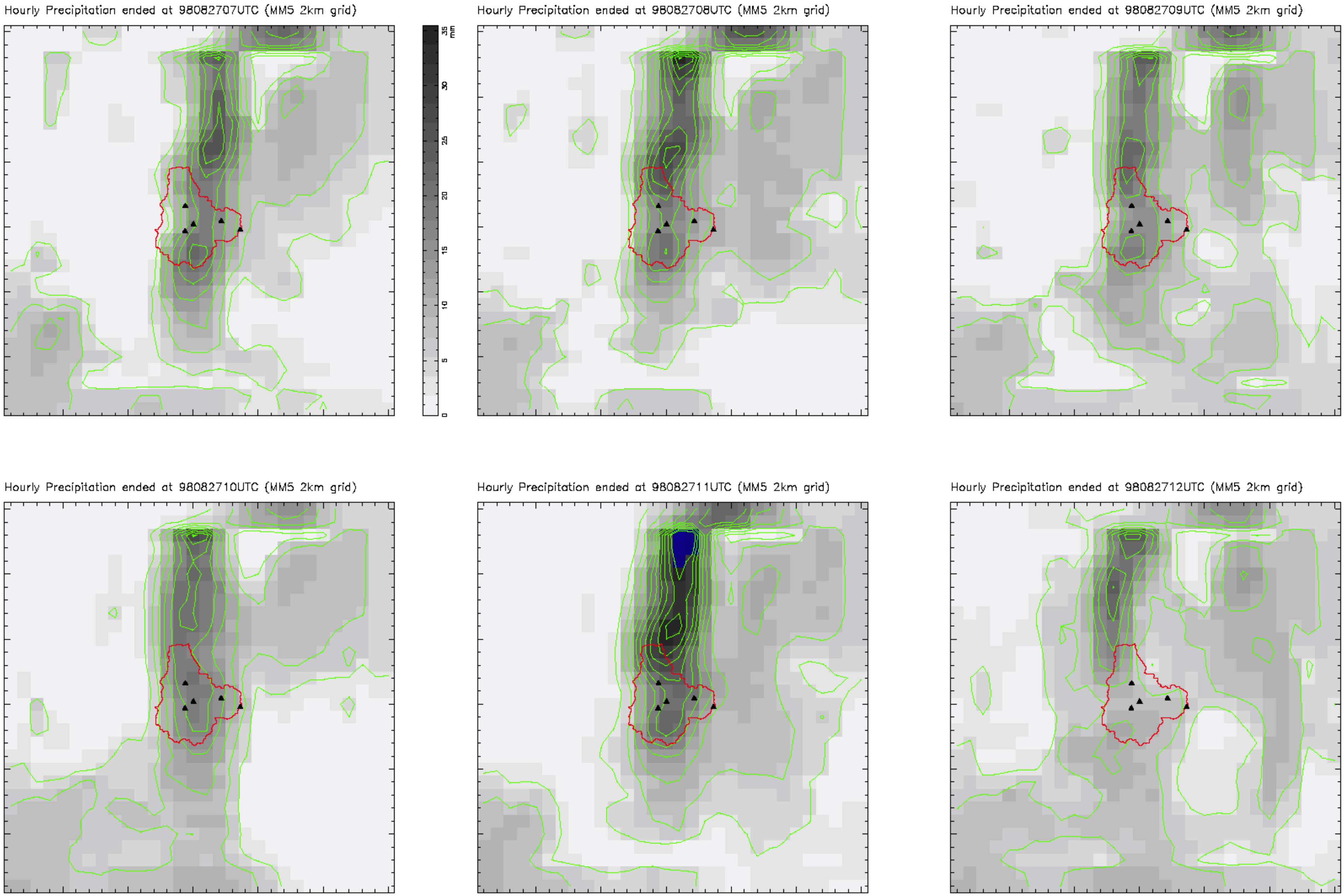
each hillslope land surface of a watershed

to

the atmosphere



Transformation of spatially-distributed precipitation data from the MM5 grids to the computational units (MCUs) of WEHY-HCM


Hourly Precipitation ended at 98082707UTC (MM5 2km grid)
Hourly Precipitation ended at 98082708UTC (MM5 2km grid)
Hourly Precipitation ended at 98082709UTC (MM5 2km grid)
Hourly Precipitation ended at 98082710UTC (MM5 2km grid)
Hourly Precipitation ended at 98082711UTC (MM5 2km grid)
Hourly Precipitation ended at 98082712UTC (MM5 2km grid)
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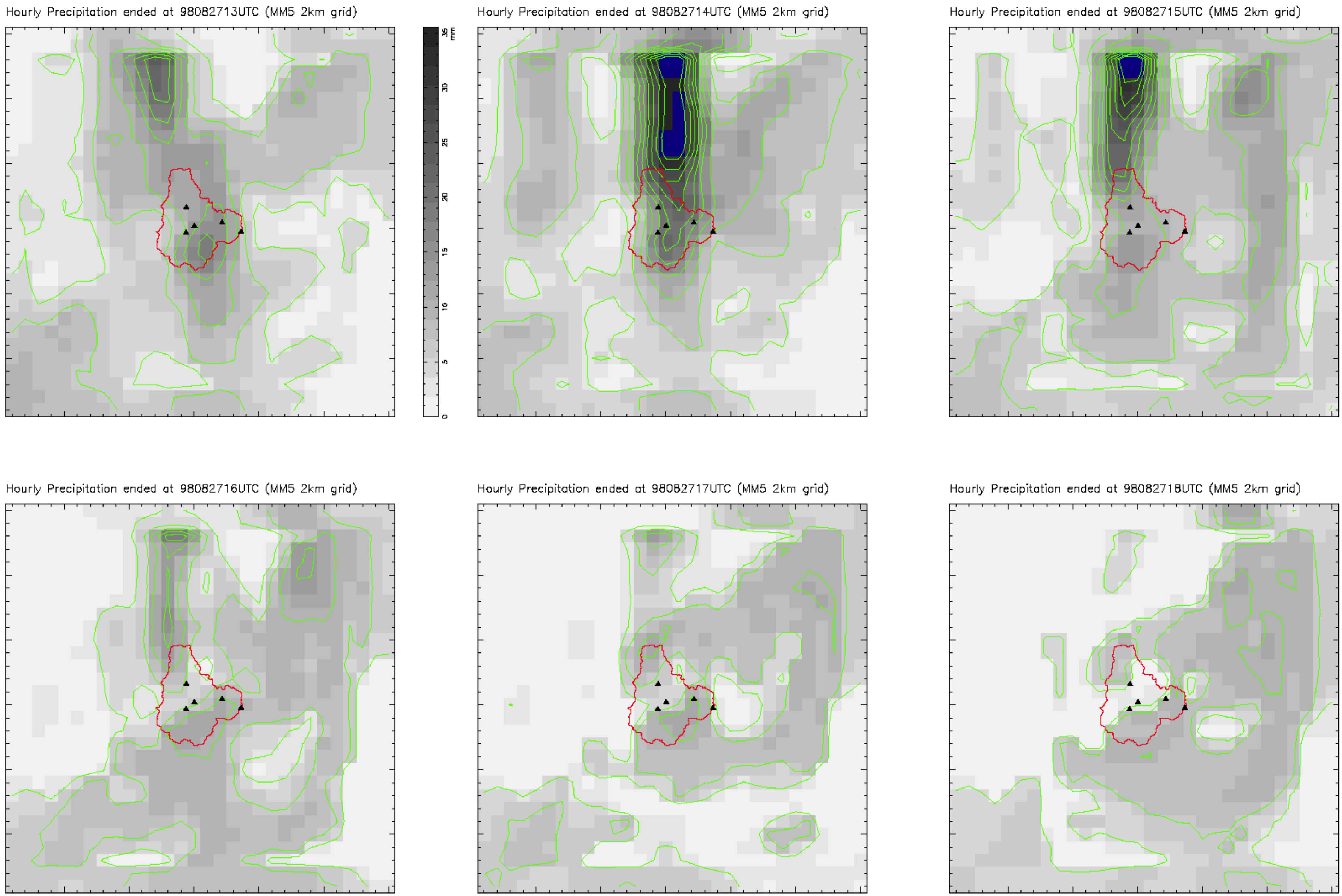
Hourly Precipitation ended at 98082713UTC (MM5 2km grid)
Hourly Precipitation ended at 98082714UTC (MM5 2km grid)
Hourly Precipitation ended at 98082715UTC (MM5 2km grid)
Hourly Precipitation ended at 98082716UTC (MM5 2km grid)
Hourly Precipitation ended at 98082717UTC (MM5 2km grid)
Hourly Precipitation ended at 98082718UTC (MM5 2km grid)
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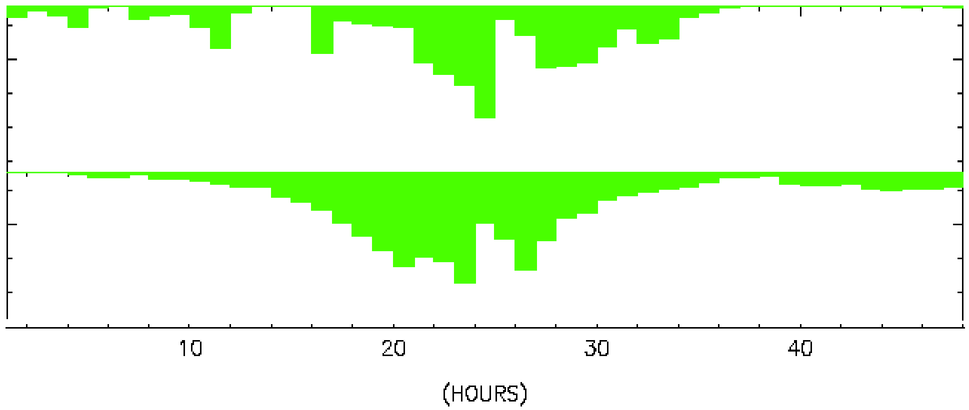
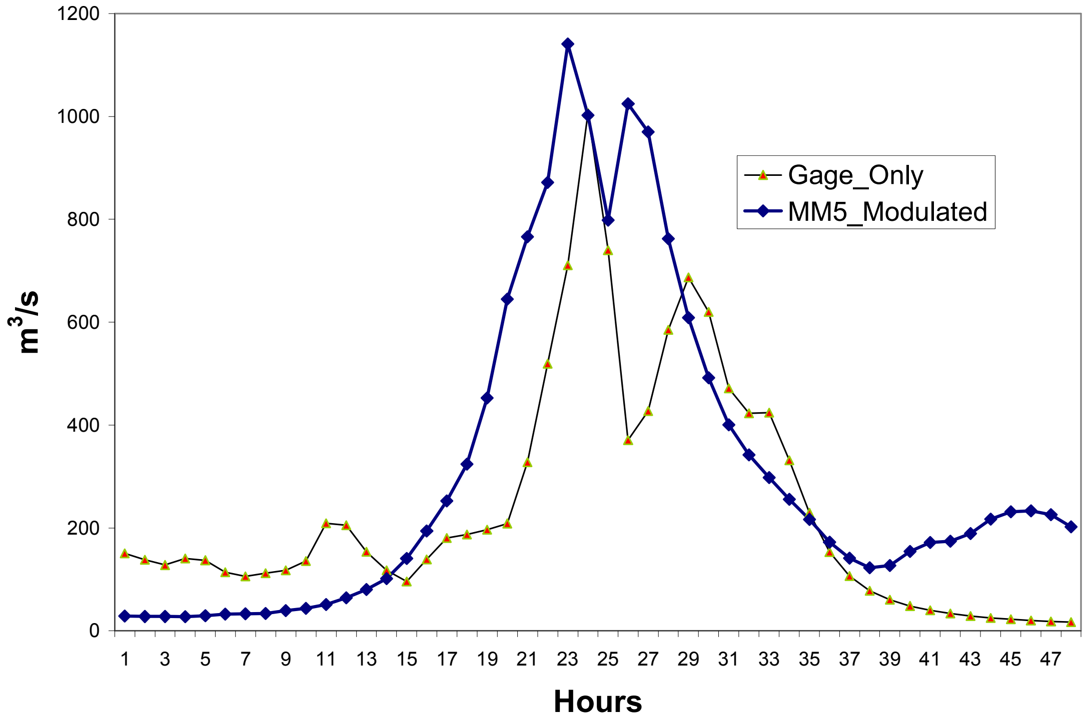


Observed basin average rainfall

versus

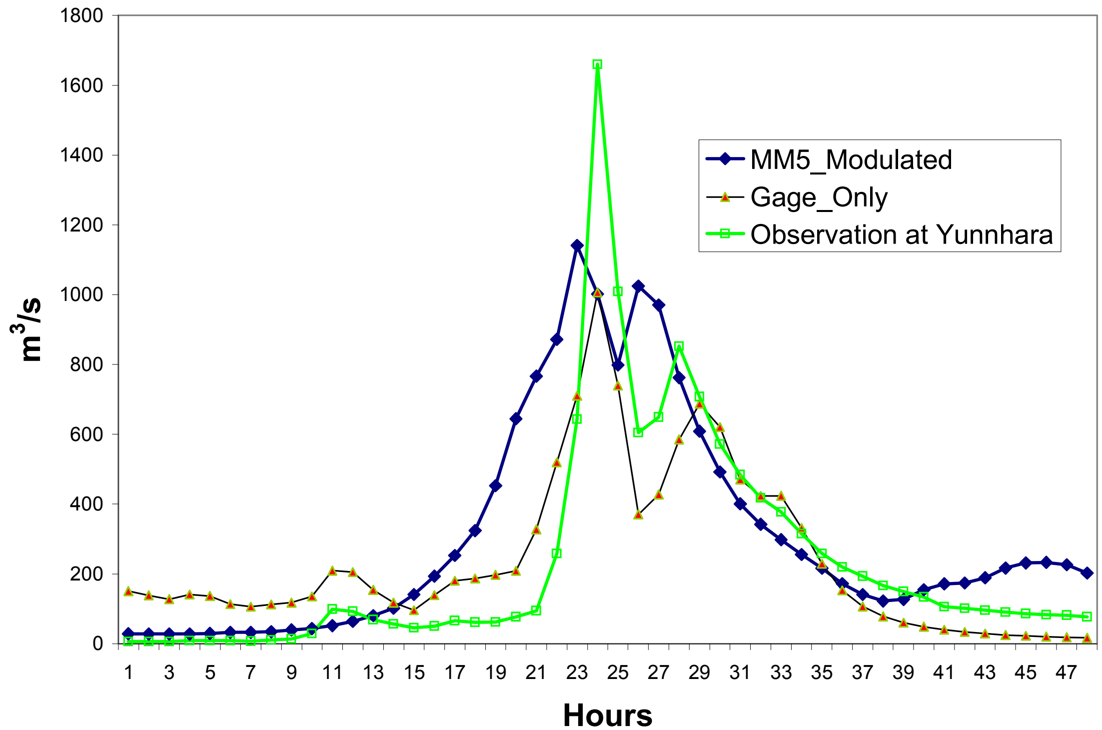
48-hour ahead predicted basin average rainfall by MM5-ISM



Comparison of runoff forecasts based upon raingage observations,

versus

runoff forecasts based upon MM5-ISM predicted rainfall



Comparison of observed runoff at Yuunohara station
versus
runoff forecasts based upon raingage observations
and
runoff forecasts based upon MM5-ISM rainfall forecasts
.

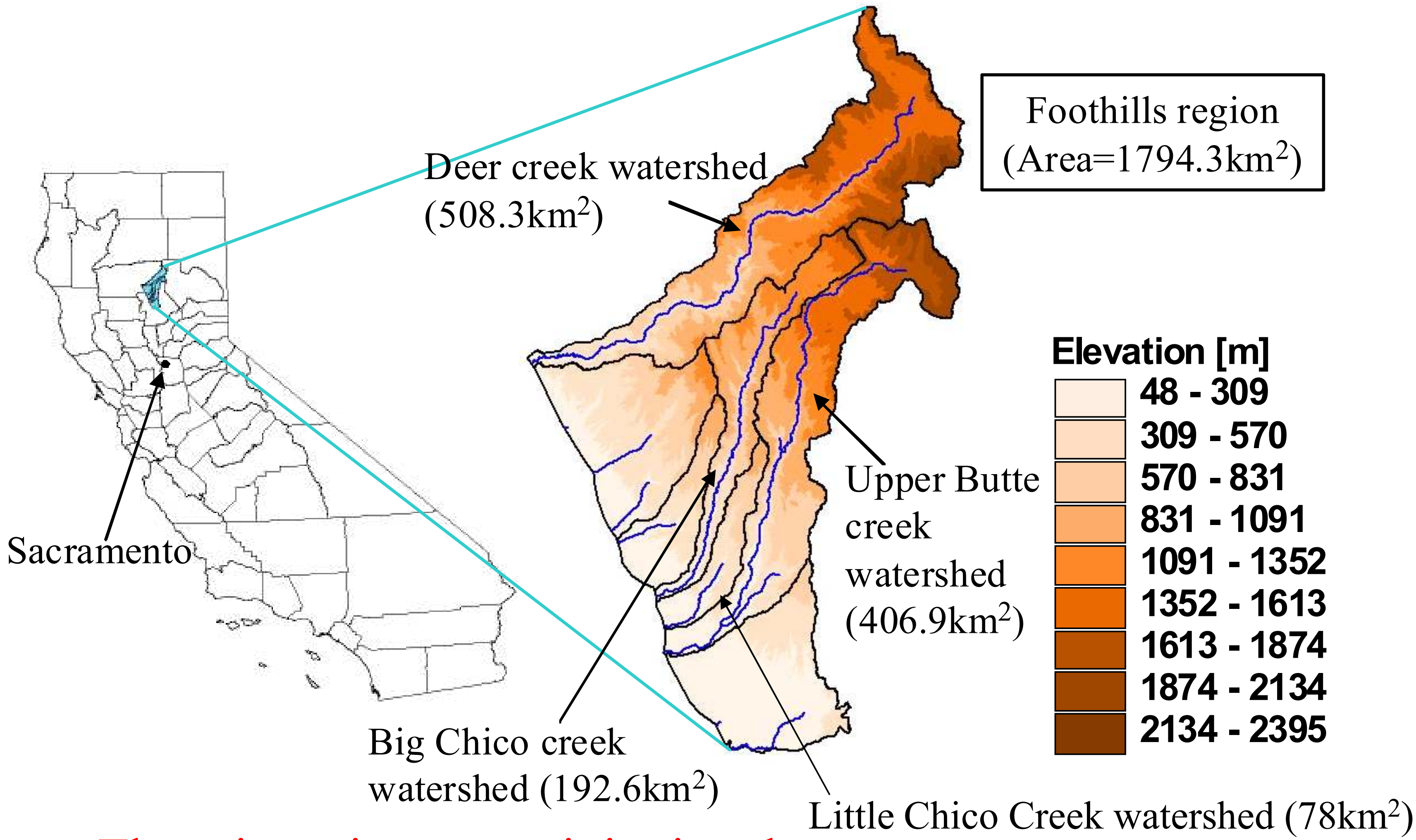
Application of WEHY-HCM to Ungauged watersheds

In order to overcome
PUB (Predictions in Ungauged Basins) problem,

WEHY-HCM

was applied to ungauged watersheds

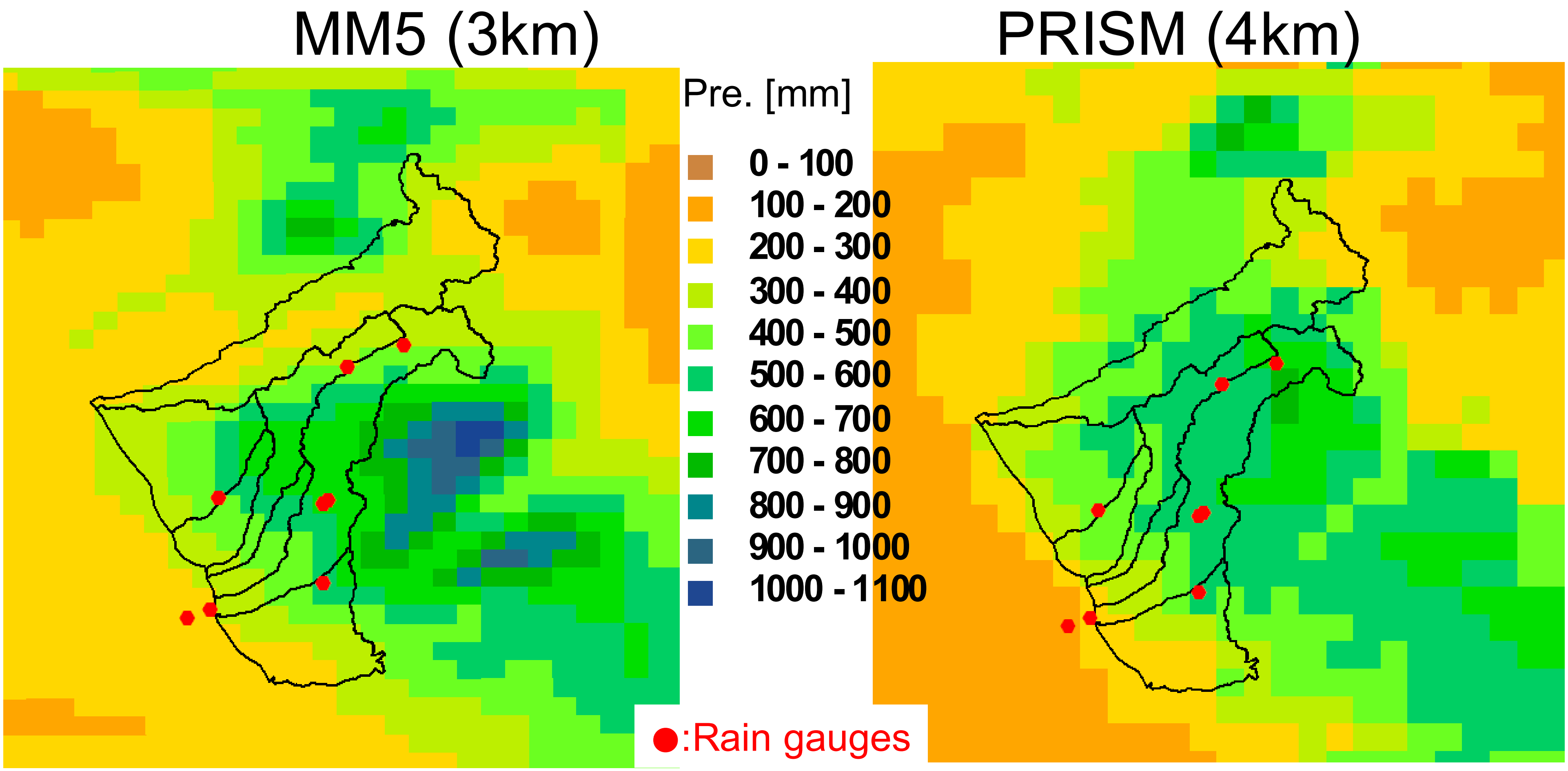
Application Area



There is no input precipitation data in Deer Creek and Big Chico Creek watersheds

MM5 VS PRISM (Monthly Pre.)

Comparison of the PRISM and simulated monthly precipitation fields over the foothills region



Dec. 1987

Calibration and validation of the WEHY model

- Calibration period: 2004 - 2005

→ Input precipitation data: **Observed**

- Validation period: 1982 - 1992 (Dry and Wet periods)

→ Input precipitation data: **Reconstructed**

- Calibration factors:

  Chezy coefficients for hillslope surfaces [$m^{1/2}/s$]

  Initial soil moisture conditions of simulations

Calibration Results

period: 2004 - 2005

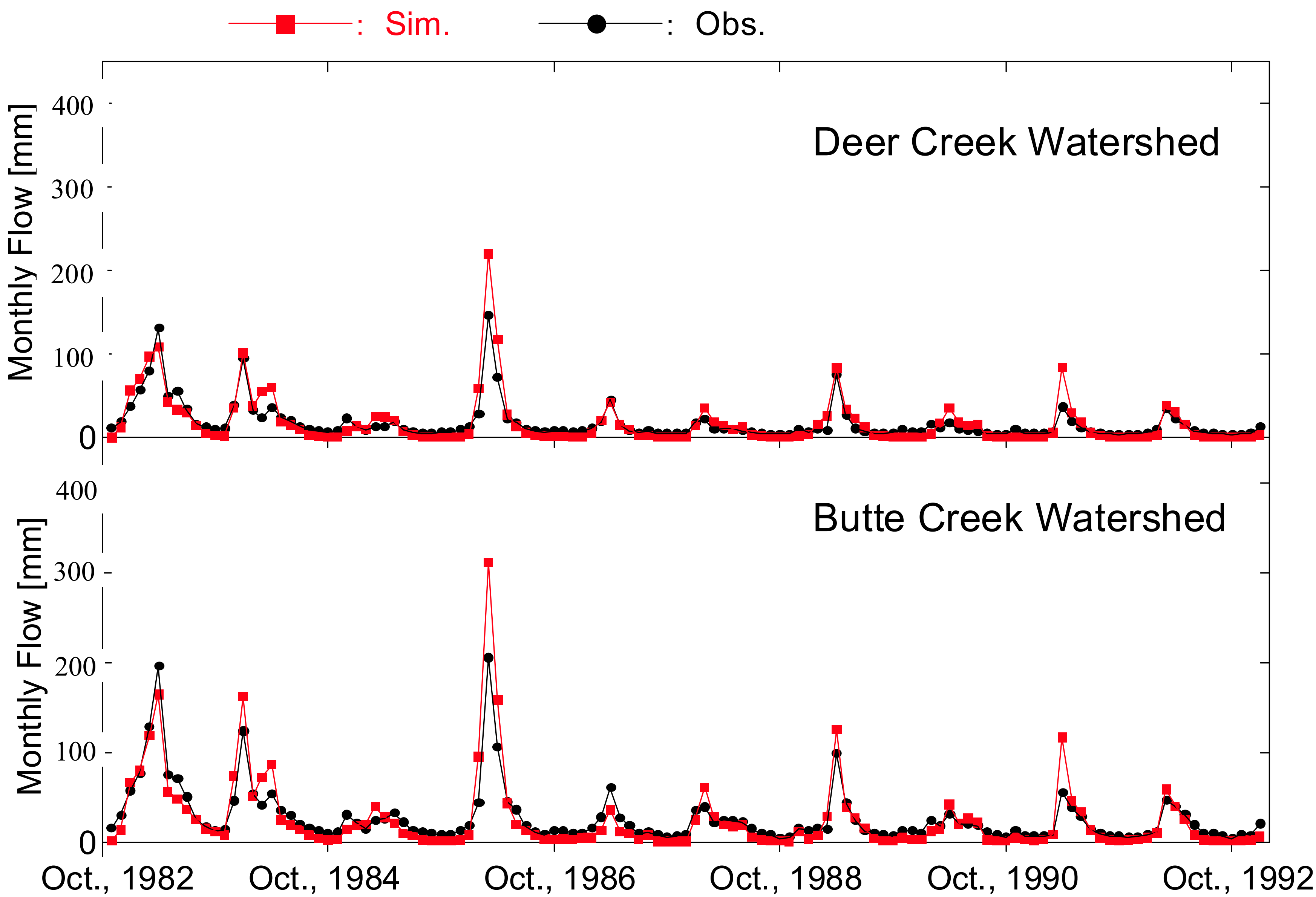
→ Input precipitation data: **Observed**

Validation Results

period: 1982 - 1992

→ Input precipitation data: **Reconstructed**

Sim. VS Obs. (Monthly)

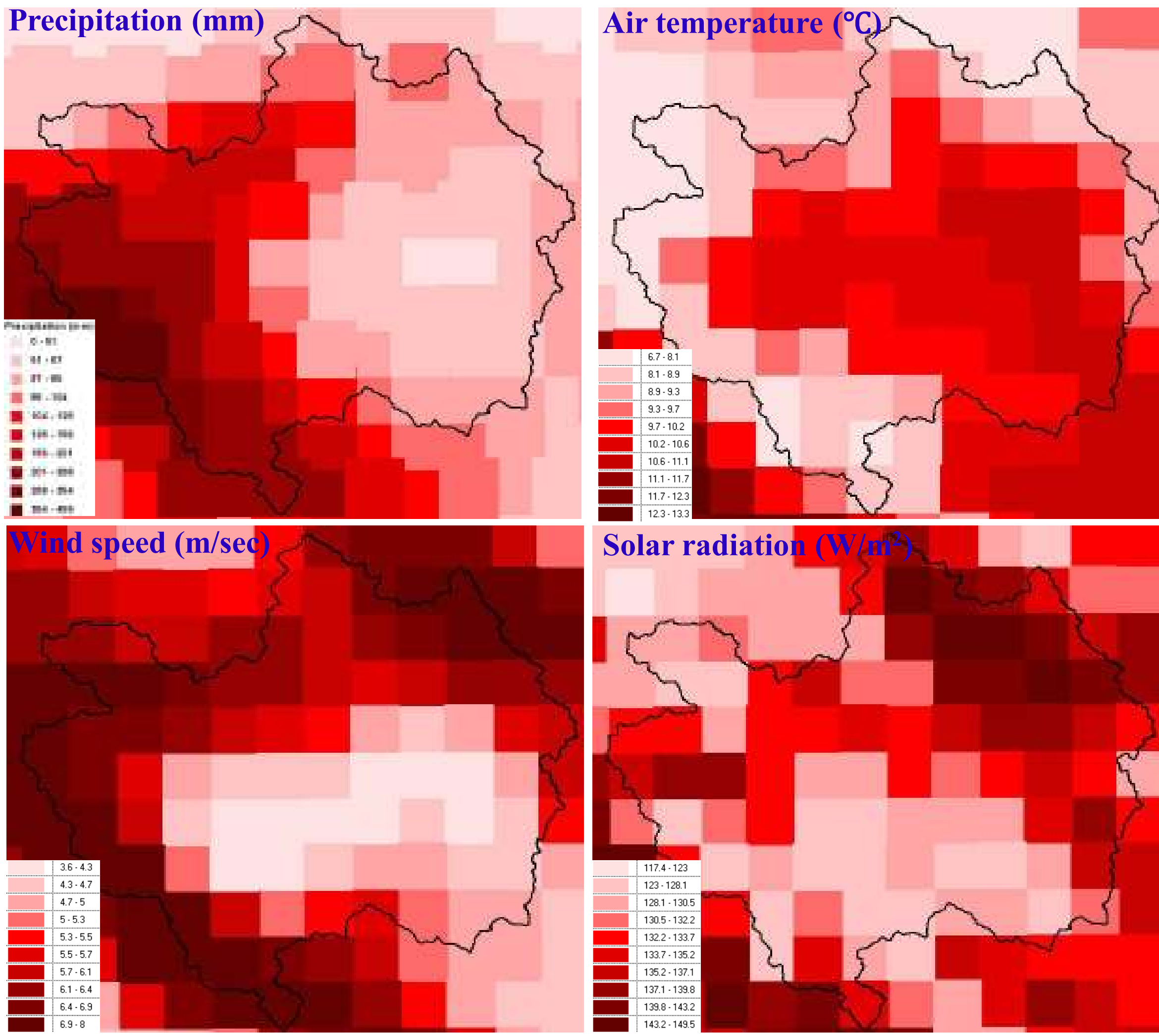


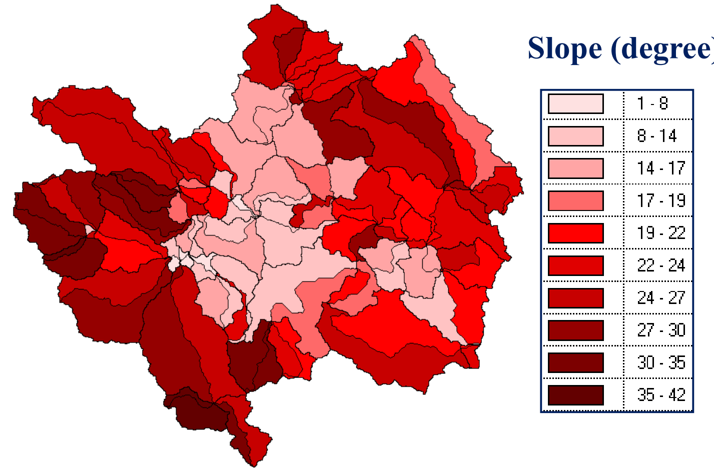
Application of WEHY-HCM to a Unique Topography and Heterogeneous Watershed

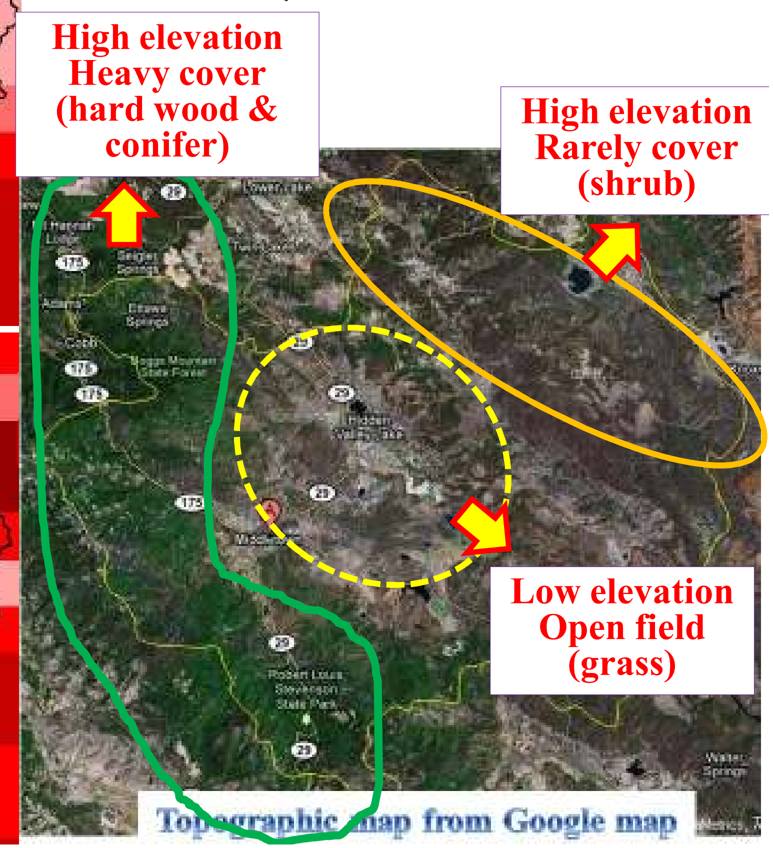
Upper Putah Creek Watershed

Reconstructed Historical Atmospheric Data

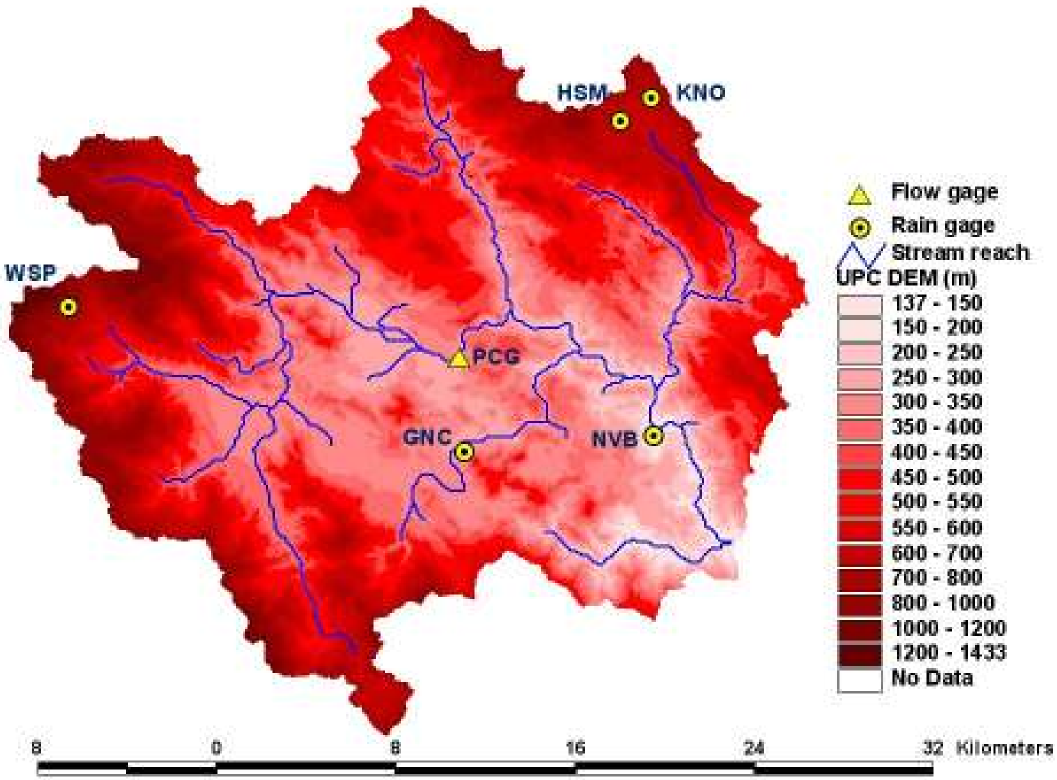
Samples of distributed atmospheric components (Feb-2006)







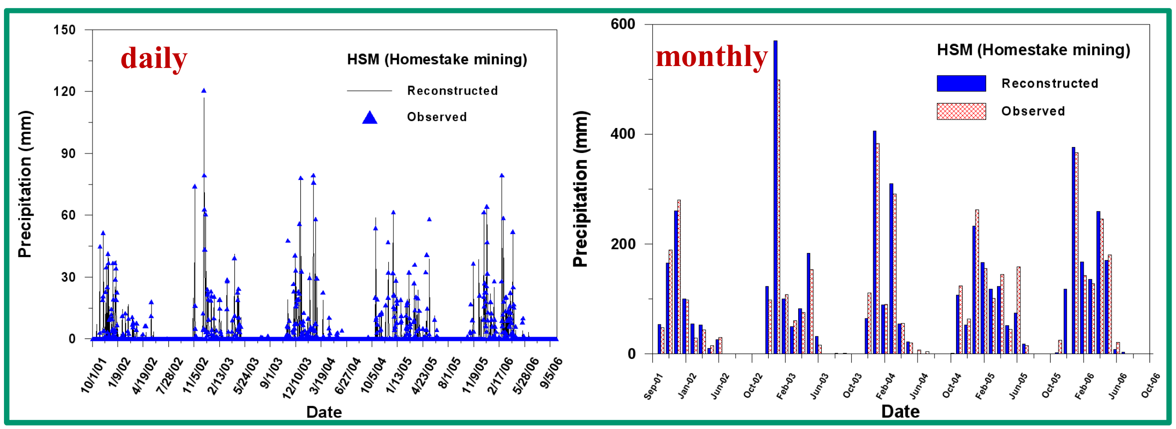
Model Validation with Ground Observed Data (1) (Precipitation, Air temperature)



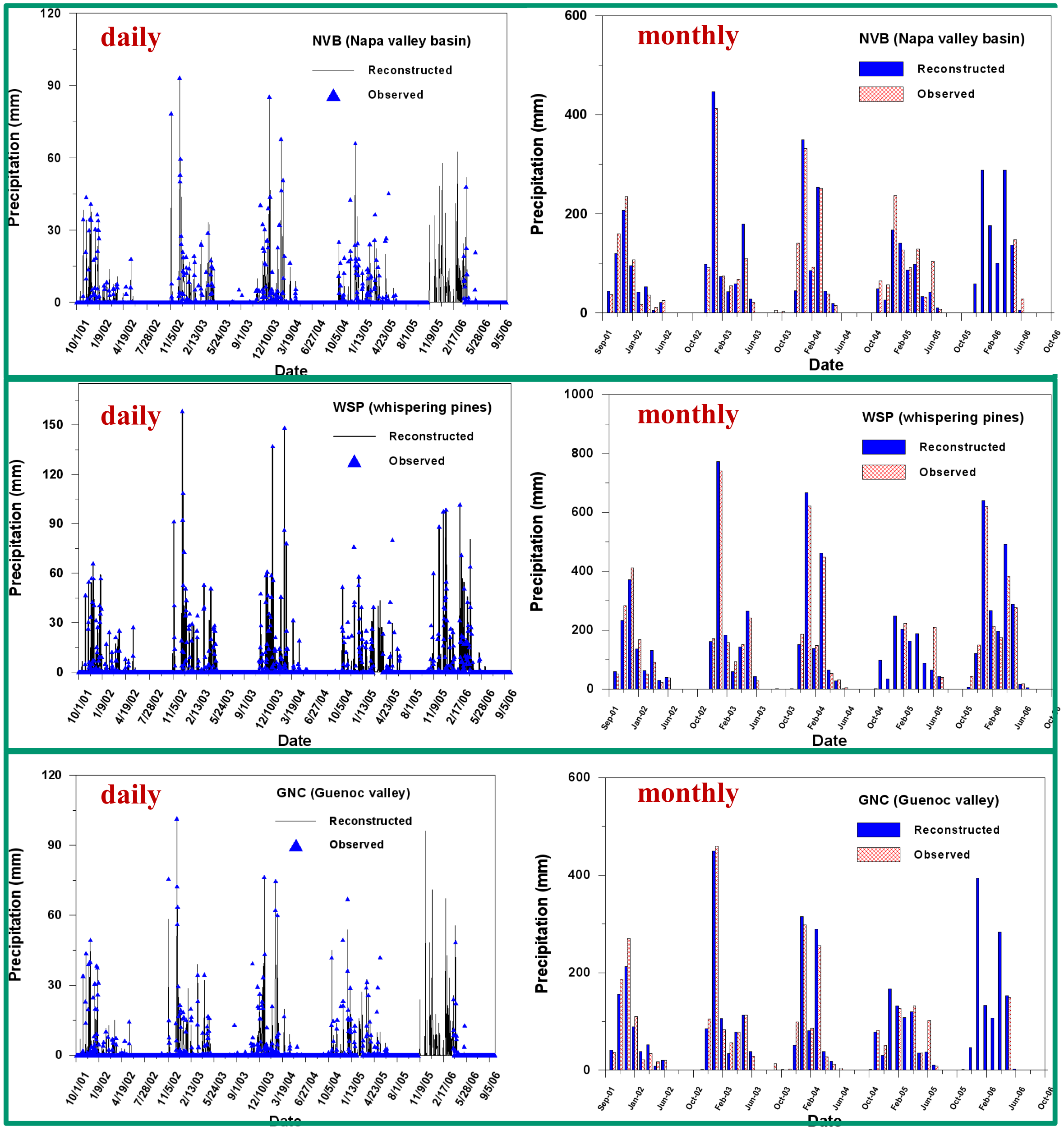
- 4-rain gage station
- 1 weather station (KNO)
- 1 flow gage (PCG)
- Validation periods :

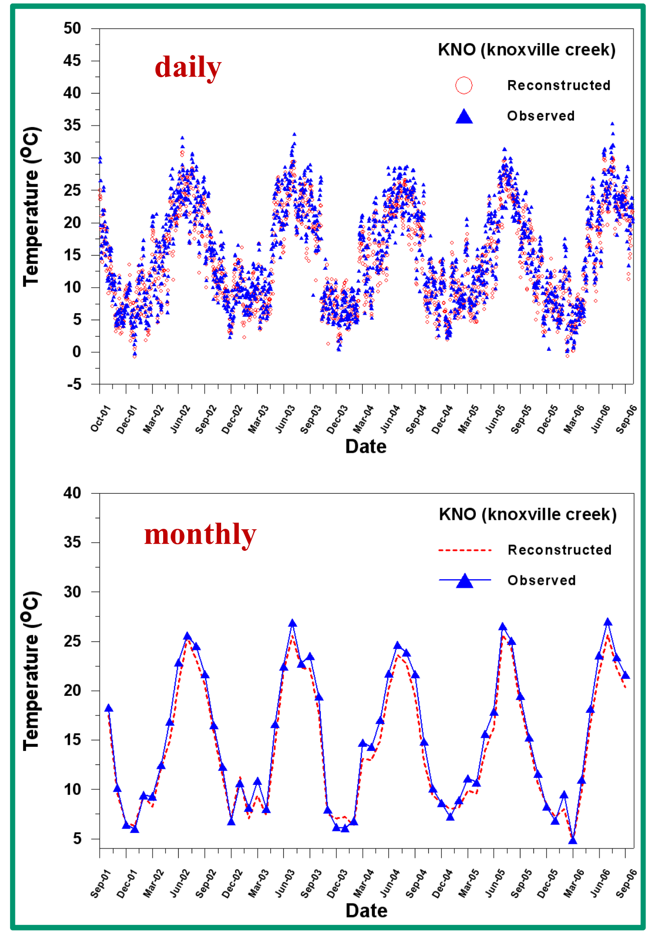
  (Oct2001 ~ Sep2006)

Station	Nash-Sutcliffe	r^2	data
WSP	0.87	0.87	daily precip.
	0.97	0.97	monthly precip.
GNC	0.83	0.83	daily precip.
	0.96	0.97	monthly precip.
NVB	0.78	0.78	daily precip.
	0.93	0.93	monthly precip.
HSM	0.88	0.88	daily precip.
	0.97	0.97	monthly precip.
KNO	0.98	0.90	daily air temp.
	0.97	0.99	monthly air temp.



Model Validation with Ground Observed Data (2) (Precipitation, Air temperature)

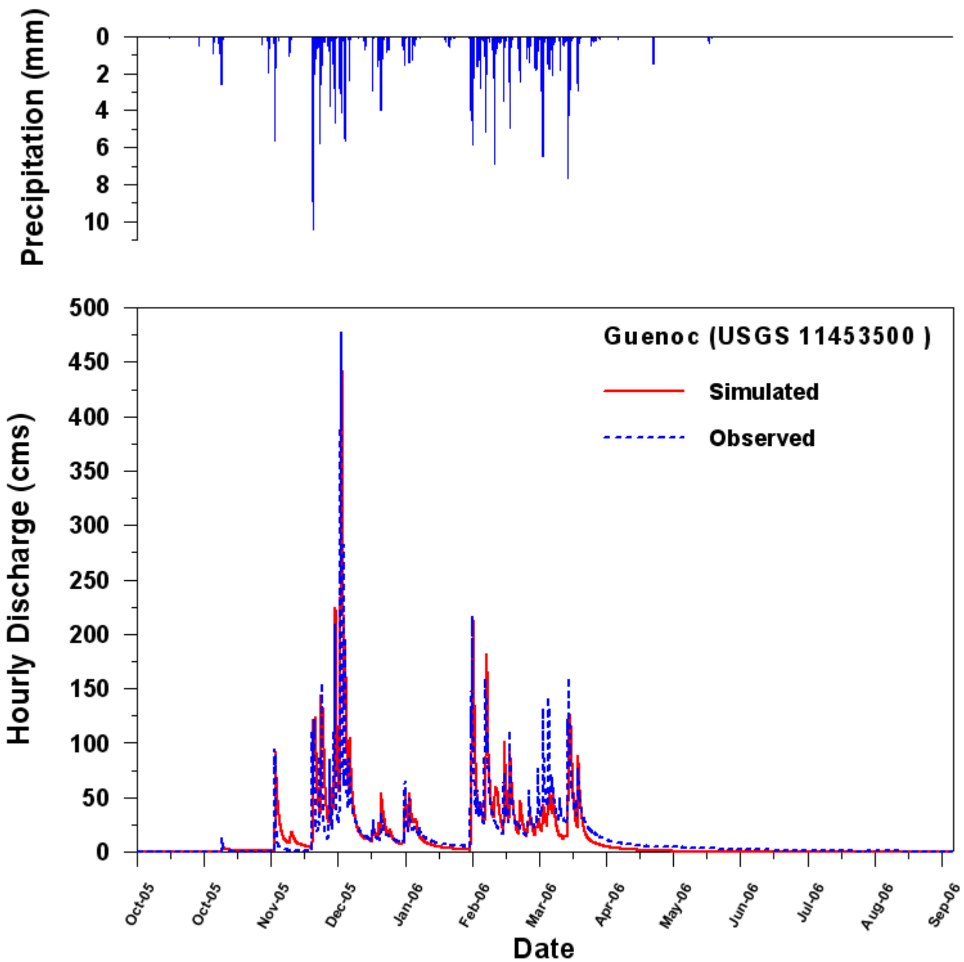




Model Calibration and Validation (Discharge, Hourly)

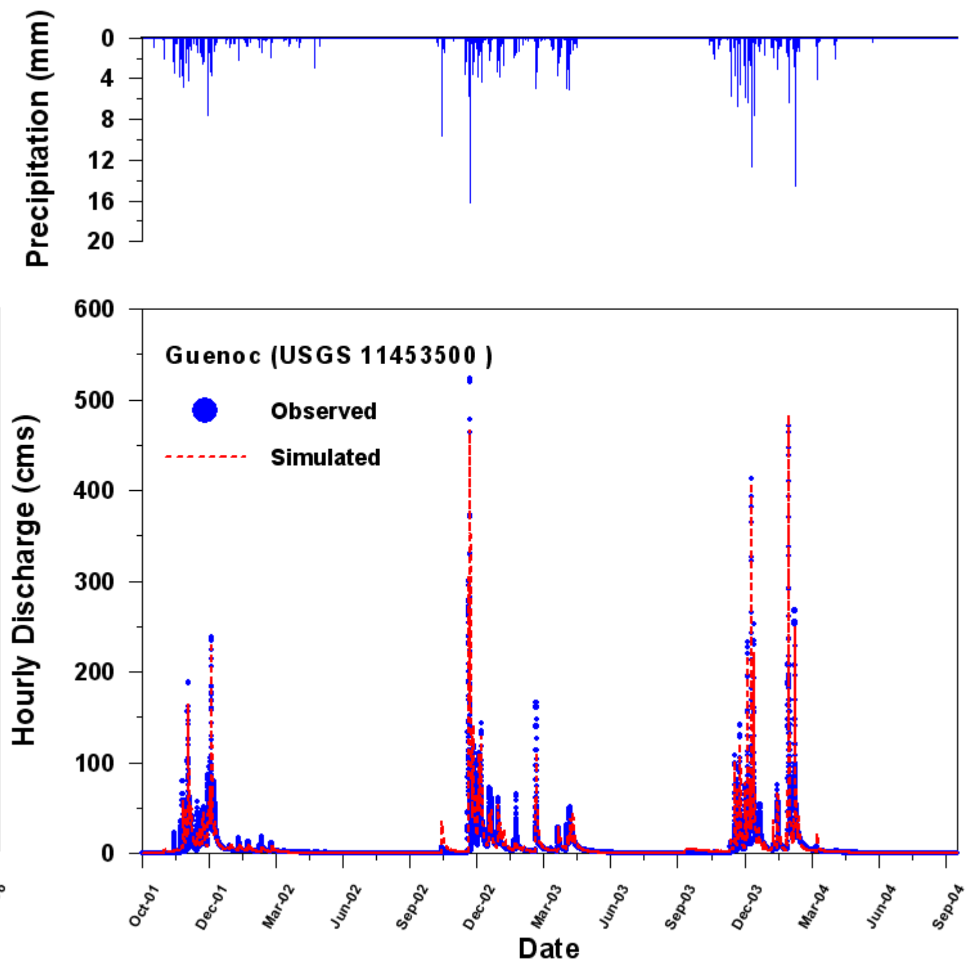
Calibration periods

(Oct2005 ~ Sep2006)



Validation periods

(Oct2001 ~ Sep2004)



Thank you