Watershed Environmental Hydrology-Hydroclimate Model WEHY-HCM for Modeling Interactive Atmospheric-Hydrologic-Environmental Processes at Watershed Scale

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A Watershed Hydroclimate Model is useful at sparsely-gauged/ungauged watersheds by producing nonexistent atmospheric data as input to the modeling of hydrologic and environmental 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 a regional hydro-climate model (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 Hydroclimate 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.
A Watershed Environmental Hydrology Hydro-Climate Model (WEHY-HCM) is a fully coupled (2-way interaction) Regional Climate model + Watershed Hydrology Model. It models the earth system at watershed scale as a coupled atmospheric-land hydrologic system interacting dynamically through the atmospheric boundary layer.
MM5 and WRF Atmospheric Models

• MM5 (Fifth generation Mesoscale Model) was developed by NCAR (US National Center for Atmospheric Research) and Penn State University, and WRF (Weather Research and Forecasting Model) was developed by NCAR, NOAA/GSD and NOAA/NCEP/EMC;

• Nonhydrostatic 3-D dynamic simulation of atmospheric processes;

• Downscaling and upscaling capabilities;

• Many modeling options for various atmospheric processes.
WEHY-HCM 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.
From Kavvas et al. JHE Nov/Dec 2004 issue
Connection between hillslope and stream

\[ Q_{SF}(t + 1) = Q_{SF}(t) + Q_{exch} + Q_{lateral} \cdot SFGW \]
\[ Q_{GW}(t + 1) = Q_{GW}(t) - Q_{leak} - Q_{exch} + Q_{lateral}(1 - SFGW) \]
Rainfall

MCU#1
MCU#2
MCU#3
MCU#N

Local or regional groundwater aquifer

Reach#1
Reach#2
Reach#3
Reach#4
Reach#5

Runoff

HHP11
Program for Hillslope Hydrologic Processes

SNLG12
Program for Stream Network and Regional Groundwater
Schematic description of Subdivisions and Contributing Areas in a Watershed
At point location scale:

WEHY-HCM uses

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

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

2-d overland sheet flow governing equations with KW approximation

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

2-d subsurface stormflow governing equations

2-d unconfined aquifer flow governing 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.
At the scale of a hillslope:

RPVS soil water flow governing 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 governing 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 physiological characteristics
Green-Ampt model

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

Evolution of soil water saturation under a constant infiltration rate $q_0$
Precipitation

Interception by vegetation

Through Fall

Direct runoff

Infiltration

Groundwater Recharge

Direct Evaporation of Intercepted Water

Transpiration of Root Zone Water

Unsaturated Zone

Snow cover

Snowmelt

Root Zone

Bare Soil Evaporation

Groundwater Table

Sun
Snow Model

- Depth-averaged energy and mass conservation equations
- Can account for varying freezing depth
- 3 snow layers, linear temperature profile
- Unique compared to other available models which use 1 layer
Snow Model – Input Data

Regional Climate Model (3 km resolution)

- Air Temperature
- Relative Humidity
- Wind speed
- Precipitation
- Long-wave Radiation
- Short-wave Radiation

Snow Model

Snow Water Equivalent, Snow Depth, Snowmelt (30 – 100 m resolutions)
Within this framework, a fully-coupled Watershed Hydro-Climate Model (WEHY-HCM) was developed where the atmospheric components of the nonhydrostatic regional model (either MM5 (Fifth Generation Mesoscale Model) or WRF (Weather Research and Forecasting Model) are fully-coupled (two-way interaction) with the Watershed Environmental Hydrology (WEHY) model.
Problem: There is no input precipitation data in Deer Creek.
Available observation stations

- Deer Creek watershed (508km²)
- Big Chico Creek watershed (192km²)
- Upper Butte Creek watershed (407km²)
- Little Chico Creek watershed (78km²)

Elevation [m]:
- 48 - 309
- 309 - 570
- 570 - 831
- 831 - 1091
- 1091 - 1352
- 1352 - 1613
- 1613 - 1874
- 1874 - 2134
- 2134 - 2395

- ●: Discharge stations (CDEC)
- ▲: Precipitation stations (CDEC)
- □: Snow stations (CDEC)

Available observation stations:
- Hourly Precipitation

Map showing the Deer Creek watershed (508km²), Big Chico Creek watershed (192km²), Upper Butte Creek watershed (407km²), and Little Chico Creek watershed (78km²). The map includes symbols for discharge stations, precipitation stations, and snow stations.
WEHY Model
(Watershed Environmental Hydrology Model)
Depiction of four nested grids used for the MM5 simulation of the studied foothills watersheds.
Comparisons of the observed and simulated monthly precipitation at each ground observation station.
Calibration and validation of the WEHY model for river flow discharge

- **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 (2004-2005)

Graph showing discharge and precipitation data over time from October 2004 to October 2005. The graph compares observed data (Obs. (CAR)) and simulated data (Sim. (WEHY)) at Deer Creek. The x-axis represents dates from October 2004 to October 2005, while the y-axis shows discharge in m$^3$/s at DCV and precipitation in mm/h.
Available observation stations

Deer Creek watershed (508 km²)

Big Chico Creek watershed (192 km²)

Upper Butte Creek watershed (407 km²)

Little Chico Creek watershed (78 km²)

Available observation stations:
- Discharge stations (CDEC) - ●
- Precipitation stations (CDEC) - ▲
- Snow stations (CDEC) - □
- Hourly Precipitation - ○

Elevation [m]
- 48 - 309
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Deer Creek watershed (508km²)

Big Chico Creek watershed (192km²)

Upper Butte Creek watershed (407km²)

Little Chico Creek watershed (78km²)
Application of WEHY-HCM to a Sparsely-gauged Watershed

Upper Putah Creek Watershed
Reconstructed Historical Atmospheric Data

Samples of distributed atmospheric components (Feb-2006)

- Precipitation (mm)
- Air temperature (°C)
- Solar radiation (W/m²)
- Wind speed (m/sec)

High elevation
- Heavy cover (hard wood & conifer)

High elevation
- Rarely cover (shrub)

Low elevation
- Open field (grass)
Model Validation with Ground Observed Data (1)  
(Precipitation)

- 4-rain gage station
- 1 weather station (KNO)
- 1 flow gage (PCG)
- Validation periods:  
  (Oct2001 ~ Sep2006)

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<tr>
<th>Station</th>
<th>Nash-Sutcliffe</th>
<th>$r^2$</th>
<th>data</th>
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<td>GNC</td>
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<td>KNO</td>
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Sierra Valley Basin - Foothills

WEHY-HCM
Watershed Environmental Hydrology Hydro-Climate Model

https://www.museumca.org/creeks/z-groundwater.html
Sierra Valley Basin - Foothills

RAINFA LL / SNOWFALL
STREAMS
BEDRO CK RECHARGE
SURFACE RECHARGE ZONE
WELLS

Regional Climate Model (MM5) & Snow Module of WEHY

Hydrologic Module of WEHY
https://www.museumca.org/creeks/z-groundwater.html
Sierra Valley Basin – Aquifer

https://www.museumca.org/creeks/z-groundwater.html
Interception and Evapotranspiration Model

Subsurface Stormflow

Regional Groundwater

Stream Network Flow

Hillslope Processes

Precipitation

Snowfall, Temperature, Wind Speed, Relative Humidity

Rainfall

Unsaturated flow and Infiltration Model

Solar Radiation + Snow Accumulation + Snowmelt Models

Overland flow (Sheet and Rill Flow)

Hillslope Erosion/Sediment, and Nutrient Transport

Hillslope Pesticide Transport

Hillslope Surface/Subsurface/GW Water Temperature

In-stream Erosion/Sediment, and Nutrient Transport

In-stream Pesticide Transport

In-stream Temperature Transport

Parameter values related to Topography, Soil, Land Use Land Cover characteristics

INPUT

OUTPUT

I. HYDROLOGIC MODULE

II. ENVIRONMENTAL MODULE

Streamflow Hydrograph/profile, GW Table Elev/Hydraulic Head

Water temperature at any desired location within a watershed

Sediment and Nutrient load at any desired location within a watershed

Pesticide load at any desired location within a watershed

Soil water content, ET, Inf. rates at any desired location within a watershed

In-stream Erosion/Sediment, and Nutrient Transport

In-stream Temperature Transport

INPUT

OUTPUT
MM5 Domain Nesting for Indian Creek Watershed Model
Reconstructing distributed atmospheric data for validation and for critical hydrologic periods

**Air Temperature**

![Air Temperature Graph]

**Precipitation**

![Precipitation Graph]
Monthly precipitation (mm)
Locations of the field monitoring sites (flow stations, cross sections, wells) over the digital elevation map, DEM (NED)
Derived meadow extent and modeled channel network
Local Groundwater Simulation at Rowland-Charles Reach (Oct 1, 2001 – Sep 30, 2004)
Comparison of model simulated and observed runoff at Doyle Crossing during Oct. 2004 - Sep. 2005
Calibration of the hydrology model during water year 2004

Indian Creek at Taylorsville
Validation of the hydrology model during water year 2005

Indian Creek at Taylorsville
Comparison of model simulated and observed sediment load at Doyle Crossing (Oct. 2004 - Sep. 2005)
Calibration of the stream temperature model during water year 2004

Last Chance Cr. at Doyle Crossing

Flow temperature (°C)

Obs

Sim
Calibration of the stream temperature model during water year 2004
Validation of the stream temperature model during water year 2005

Last Chance Cr. at Doyle Crossing

Flow temperature (oC)

Obs
Sim
Validation of the stream temperature model during water year 2005
Scenario assessment of the impact of meadow land restoration in terms of stream flow and temperature

Scenario: the width of meadow aquifer is 20% increased due to the groundwater level rise by the channel restoration.
Critical period analysis at Pulga station, North Fork, Feather River

Selected historical period (1983-1993)

Annual flow (billion m³)

Insufficient data available

Selected historical period (1983-1993)

Surplus from average (billion m³)
Assessment of the impact of meadow land restoration in terms of stream flow and temperature at **Taylorsville, Indian Cr.**

![Graph showing changes in stream flow and water temperature over time.](Image)

- **Top Graph:**
  - **X-axis:** September years (Sep-82 to Sep-93)
  - **Y-axis:** Difference [(2)-(1)]/Original (1)
  - **Legend:**
    - Difference
    - (1) Original
    - (2) Scenario

- **Bottom Graph:**
  - **X-axis:** September years (Sep-82 to Sep-93)
  - **Y-axis:** Water temperature (1), (2)
  - **Legend:**
    - Difference
    - (1) Original
    - (2) Scenario
Thank you