

# Quick, reproducible and automatic watershed modeling with the SHUD: Essential data, simulation, applications and visualization

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## Motivation

**Quick** - From scratch of the ideal to modeling to analysis and visualization.

**Reproducible** - No need for human intervention.

**Automatic** - User defines the watershed boundary, stream and required resolution, then the program will do the rest.

**Anywhere** - The procedure works for anywhere of the world, with global data services, such as Soil Grids, STRM, ASTER GDEM, USGS GLC, GLDAS, FLDAS.

**Ungaged domain** - Physically-based model is opting to used broad purposes.

**Coupling** - Lake, agriculture, economic, sediment, reaction transport, ...

## Model

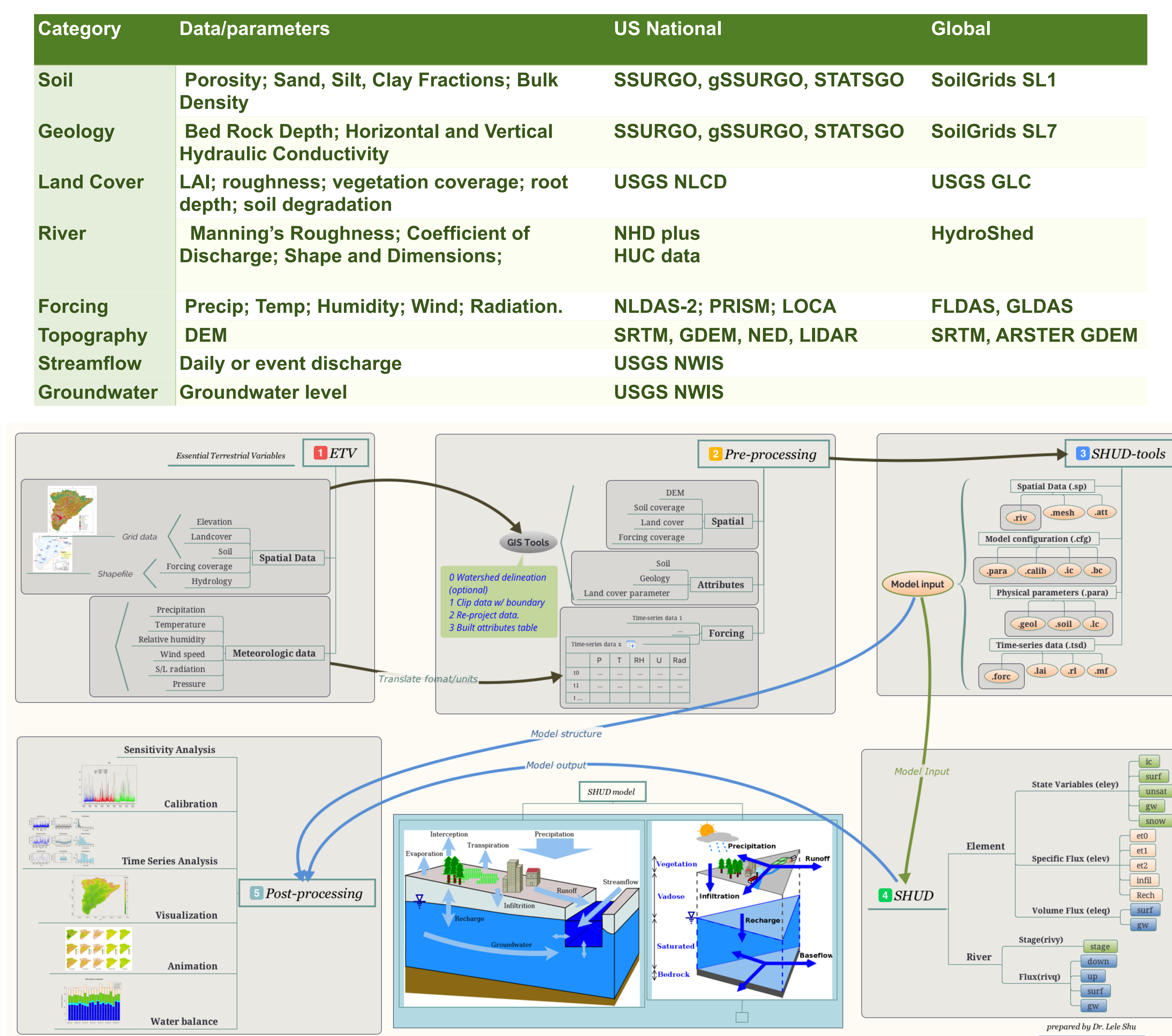
The **Solver for Hydrologic Unstructured Domain** (SHUD - pronounced “**SHOULD**”) is a multi-process, multi-scale hydrological model where major hydrological processes are fully coupled using the semi-discrete Finite Volume Method.

SHUD encapsulates the strategy for the synthesis of multi-state distributed hydrological models using the integral representation of the underlying physical process equations and state variables. As a heritage of **Penn State Integrated Hydrologic Model (PIHM)**, the SHUD model is a continuation of 16 years of PIHM modeling in hydrology and related fields since the release of its first PIHM version (Qu, 2004).

The SHUD is a distributed hydrological model in which the domain is discretized using an unstructured triangular irregular network generated with constraints (geometric and parametric). A local prismatic control volume is formed by the vertical projection of the Delaunay triangles forming each layer of the model.

Physical process	Equation name	Governing equation	Semi-discrete formula from ODE
Interception	Bucket model	$\frac{dS_{ic}}{dt} = P - E_{ic} - P_f$	$\frac{dS_{ic}}{dt} = q_{ic} - E_{ic}$
Snow melt	Temperature Index Model	$\frac{dS_{sm}}{dt} = P - E_{sm} - q_{sm}$	$\frac{dS_{sm}}{dt} = P_{sm} - q_{sm}$
Overland flow	St. Venant Equation (2D)	$\frac{\partial h}{\partial t} + \frac{\partial(hu)}{\partial x} + \frac{\partial(hv)}{\partial y} = q$	$\frac{dS_{of}}{dt} = P_{of} - E_{of} - q_t - \sum_{j=1}^3 \frac{Q_{of}^j}{A_c}$
Unsaturated zone	Richards Equation	$C(\psi) \frac{\partial \psi}{\partial t} = \nabla \cdot (K(\psi) \cdot \nabla(\psi + Z))$	$\frac{dS_{uz}}{dt} = q_t - q_r - E_{sm}$
Groundwater flow	Richards Equation	$C(\psi) \frac{\partial \psi}{\partial t} = \nabla \cdot (K(\psi) \cdot \nabla(\psi + Z))$	$\frac{dS_{gw}}{dt} = q_r - E_{of} - \sum_{j=1}^3 \frac{Q_{gw}^j}{A_c}$
River channel	St. Venant Equation (1D)	$\frac{\partial h}{\partial t} + \frac{\partial(hu)}{\partial x} = q$	$\frac{dS_{rc}}{dt} = \frac{1}{A_c} \left( \sum Q_{of}^j + \sum Q_{gw}^j + \sum Q_{sp}^j + Q_{in} \right)$
Potential ET	Pennman-Monteith Equation	$ET_0 = \frac{\Delta(R_n - G) + \rho_a C_p (T_a - T_w)}{\Delta + \gamma \left( 1 + \frac{u_w}{u_a} \right)}$	$\left( ET_0 = \frac{\Delta(R_n - G) + \rho_a C_p (T_a - T_w)}{\Delta + \gamma \left( 1 + \frac{u_w}{u_a} \right)} \right)_t$

## Deployment



SHUD modeling system workflow

## Benchmark

### V-Catchment

A standard test case for numerical hydrological models to validate **overland flow algorithm** and **model stability**. The specific discharge increases with precipitation until it reaches the maximum discharge rate, which is equal to the precipitation rate. The discharge rate from the side-plane reaches the maximum value earlier than in the river outlet. SHUD can correctly capture the processes in overland flow and channel routing.

### Vauclin Experiment

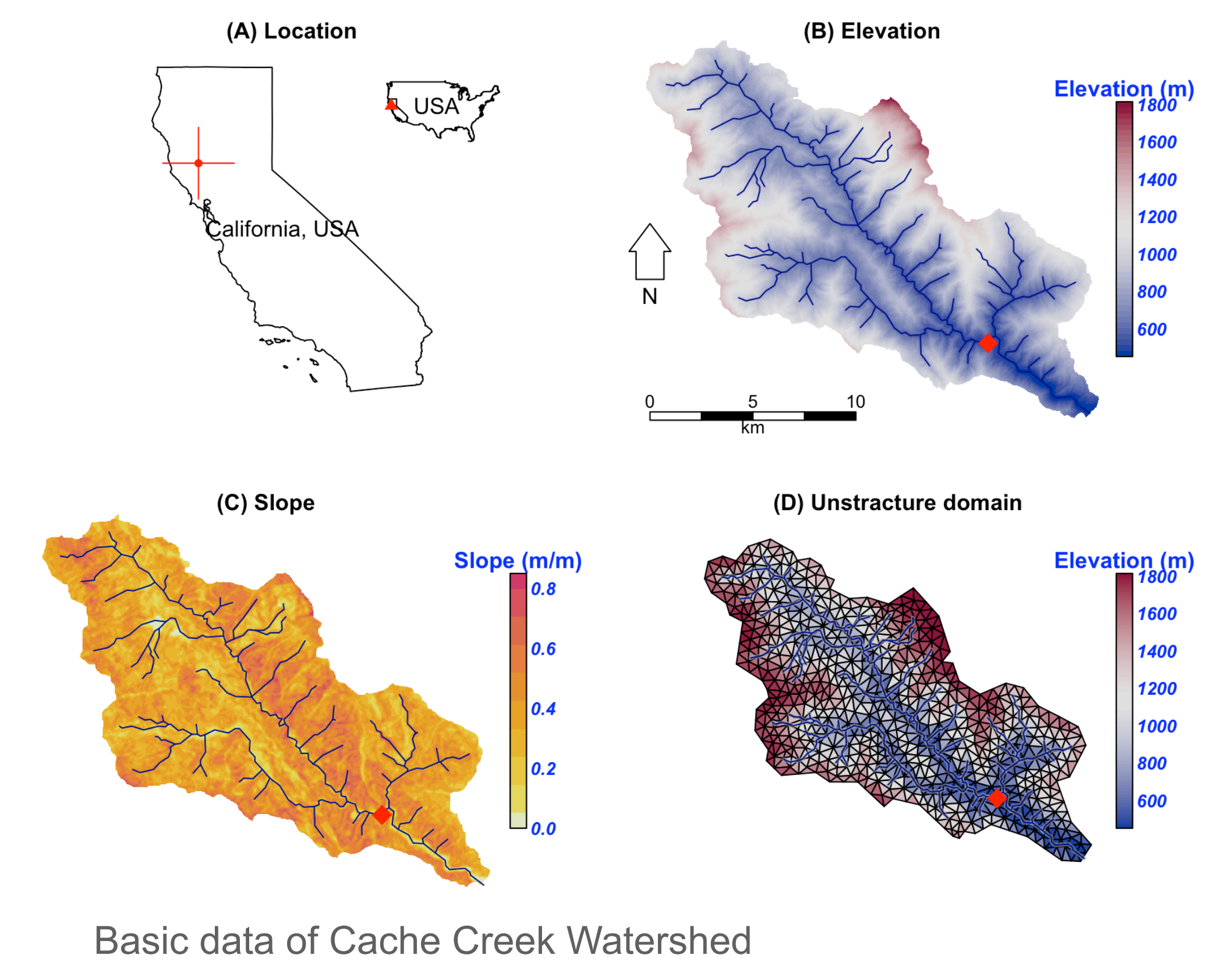
Vauclin's experiment (Vauclin et al., 1979) is designed to assess groundwater table change and soil moisture in the unsaturated layer under precipitation or irrigation.

The SHUD simulated the groundwater table at all four measurement points (2, 4, 6, 8 hr). After calibration, the maximum bias between simulation and Vauclin's observations is 5.5cm, that is comparable to the bias 5.2cm of numerical simulation in Vauclin et al.(1979). The simulations validate the algorithm for infiltration, recharge, and lateral groundwater flow.

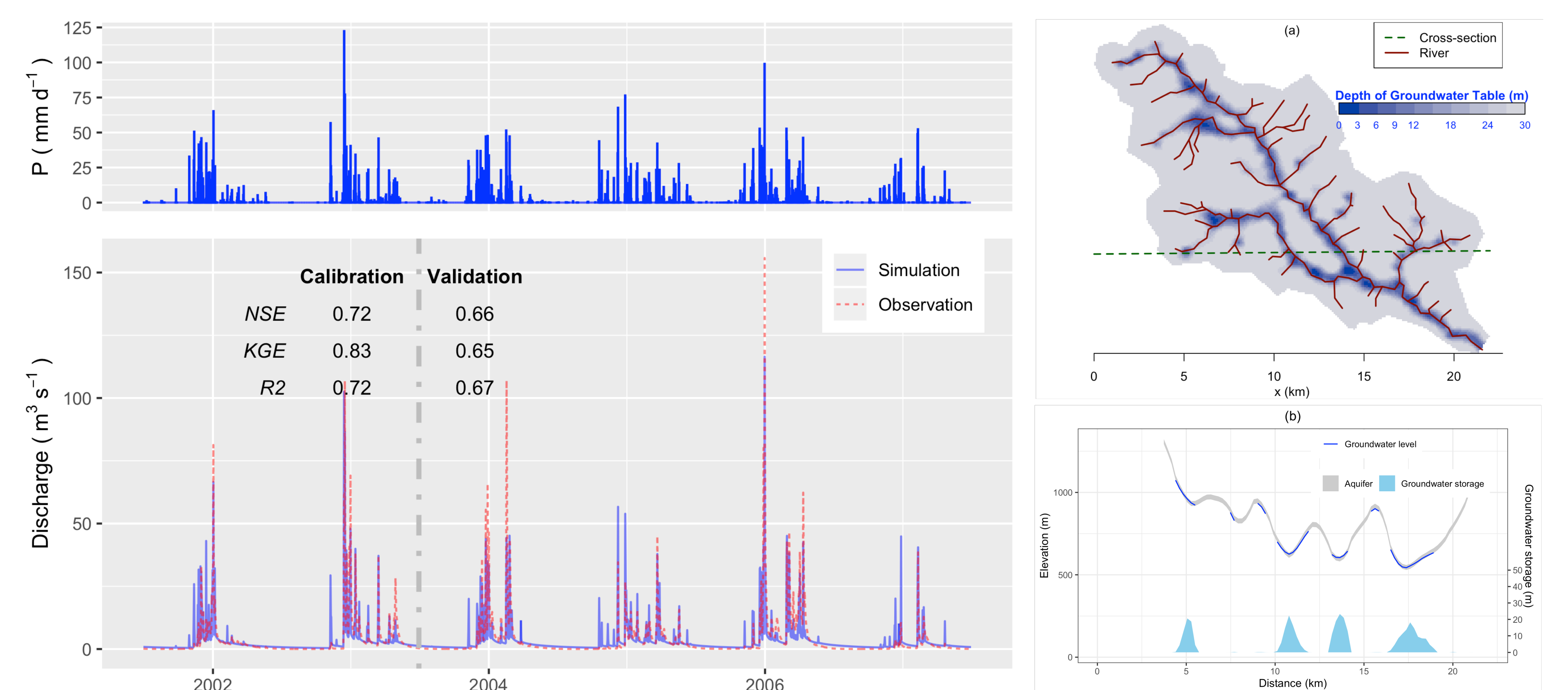
## Applications

### Cache Creek Watershed

A headwater catchment with area 196.4km<sup>2</sup> in the Sacramento Watershed in Northern California. The elevation ranges from 450m to 1800m, with a 0.38m/m average slope and hence a particularly difficult watershed for hydrologic models to simulate. Mean temperature and precipitation was 12.8C and ~817mm, respectively. Precipitation is unevenly distributed through the year.



Basic data of Cache Creek Watershed

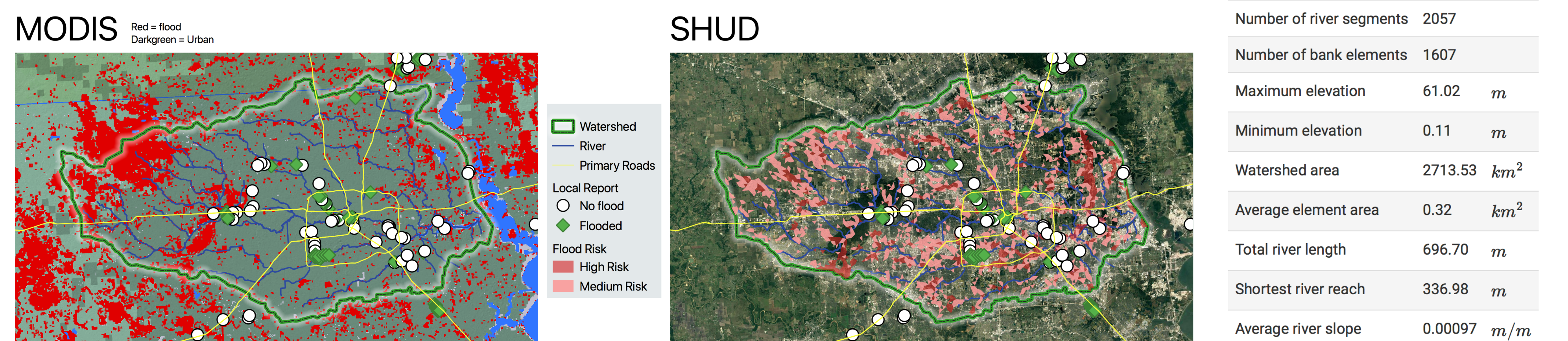


Calibration of simulated discharge against USGS gage station.

Groundwater distribution

### Houston in Harvey Hurricane

This study is to estimate the **inundation area** in Houston, Texas, during Harvey Hurricane from Aug 27 to Sept 3, 2017. Harvey hurricane is one of most costliest U.S. Atlantic hurricanes that cost 125+ billion dollars. The similar costly hurricane is Katrina 2015. Buffalo Bayou River (BBR) watershed encloses Houston city as the modeling boundary. We compare our estimation with MODIS data (from Colorado University) and the local inundation reports. Comparing to the MODIS, SHUD simulations provides higher positive estimation, but less false positive and false negative.



Compare the inundation area from MODIS and preliminary simulation.

## References

1. L. Shu, P. Ullrich, C. Duffy. Solver for Hydrologic Unstructured Domain (SHUD): Numerical modeling of watershed hydrology with the finite element method. Geoscientific Model Development (Submitted)
2. SHUD model: [www.shud.xyz](http://www.shud.xyz) and <https://github.com/SHUD-System/SHUD>
3. SHUD toolbox: <https://github.com/SHUD-System/SHUDtoolbox>
4. AutoSHUD: <https://github.com/SHUD-System/AutoSHUD>

