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

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Abstract

The Solver of Hydrological Unstructured Domain (SHUD) is an integrated multi-process, multi-scale, multi-timestep hydrologic model where the dominant hydrological processes are fully coupled using the semi-discrete Finite Volume Method. The hydrologic processes in land surface, aquifer and river are fully coupled and solved together. The high spatial and temporal resolution in SHUD provides detailed and reliable hydrologic metrics in a watershed. The SHUD System consists of SHUD (the hydrologic model) and SHUDtoolbox (a data processing tool kit). The new SHUD system provides capabilities for public data downloads, pre-processing, hydrologic modeling, automatic calibration, post-processing and spatial visualization, and is fully open-source and ready for hydrological modelers to use. Here we introduce the philosophy of SHUD, from perceptual to computational structures of watershed hydrology, and select two watersheds (one in Africa and the other in California) as examples to demonstrate the workflow and capabilities of SHUD System. In modeling these examples, we exploit national/global public datasets and exemplify the data management, hydrologic analysis, model calibration and visualization capabilities. This modeling system not only supports quick deployment of hydrologic modeling functionality, but also benefits community modeling in other hydrology-related research fields, such as limnology, agriculture, climate change and Coupled-Natural-Human systems.

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, …

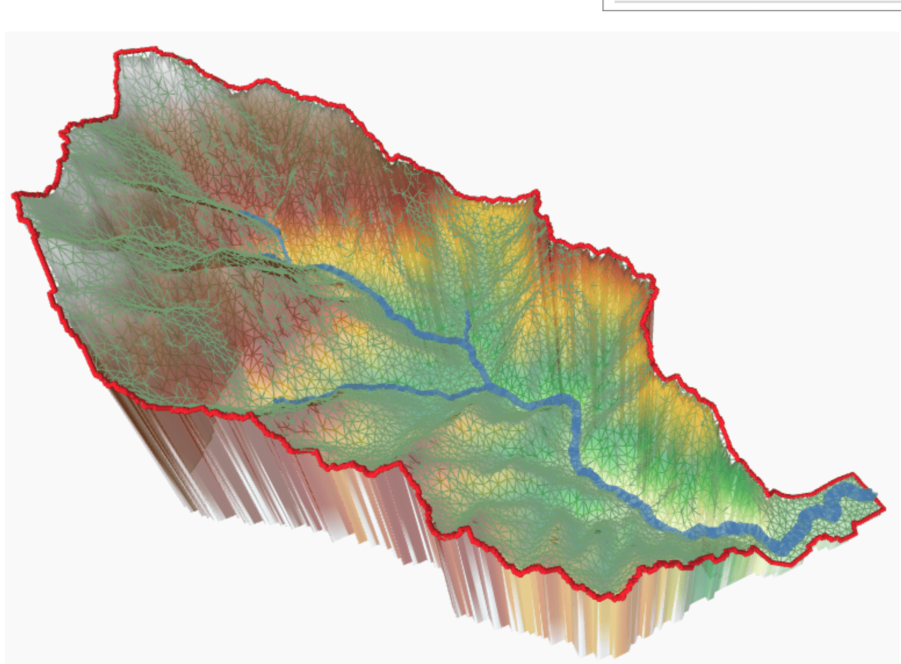
Model

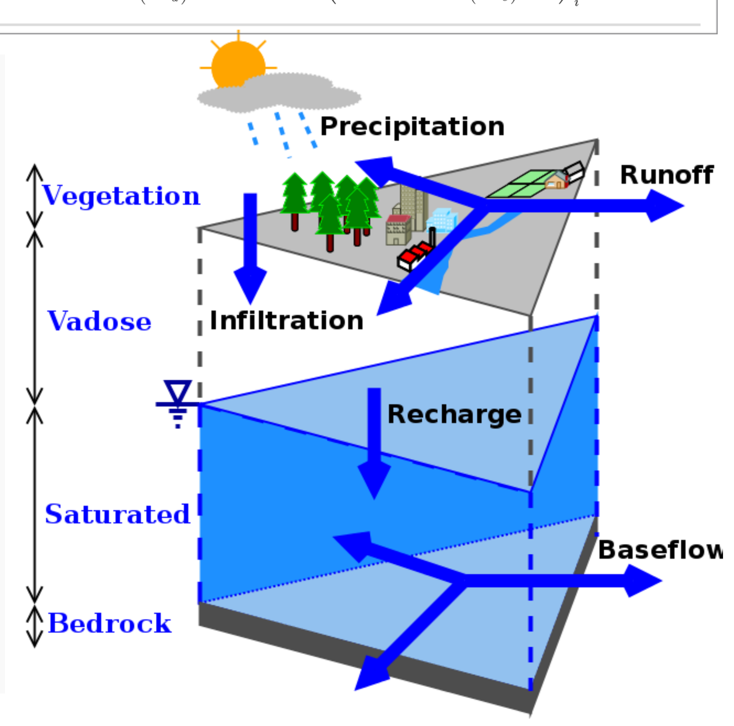
The **Solver for Hydrologic Unstructured Domain** (SHUD - pronounced "**SHOULD**") is a multi-process, multi-scale hydrological model where major hydrological processes are fully coupled using the semi-discrete Finite Volume Method.

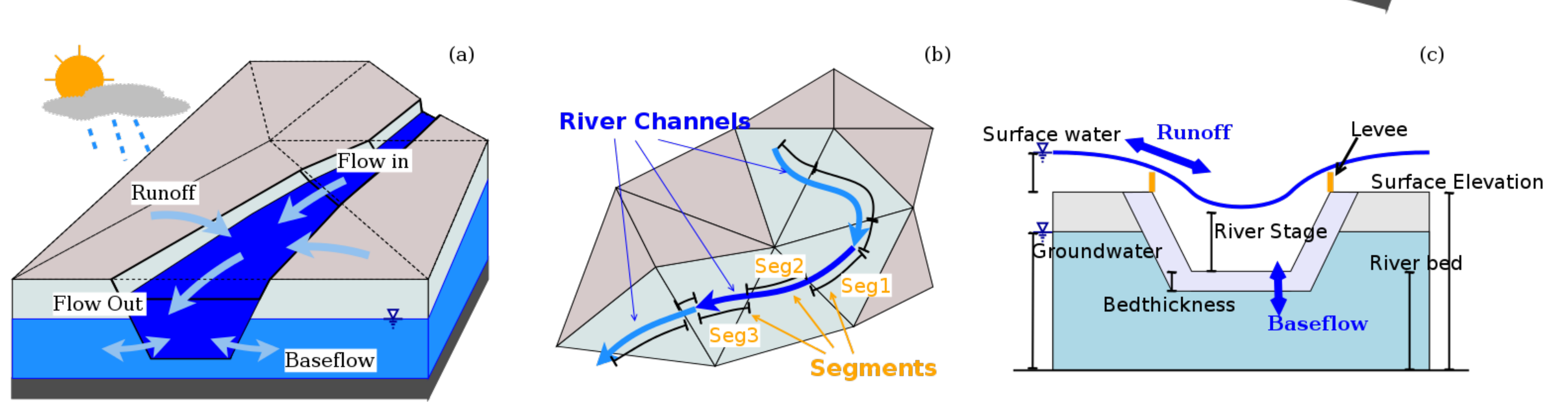
SHUD encapsulates the strategy for the synthesis of multi-state distributed hydrological models using the integral representation of the underlying physical process equations and state variables. As a heritage of **Penn State Integrated Hydrologic Model (PIHM)**, the SHUD model is a continuation of 16 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	$\frac{dS_{ic}}{dt} = P - E_{ic} - P_{tf}$	$\frac{dS_{ic}}{dt} = q_{ic} - E_{ic}$
Snow melt	Temperature Index Model	$\frac{dS_{sn}}{dt} = P - E_{sn} - q_{sm}$	$\frac{dS_{sn}}{dt} = P_{sn} - q_{sn}$
Overland flow	St. Venant Equation (2D)	$\frac{\partial h}{\partial t} + \frac{\partial(uh)}{\partial x} + \frac{\partial(vh)}{\partial y} = q$	$\frac{dy_{sf}}{dt} = P_n - E_{sp} - q_i - \sum_{j=1}^{3} \frac{Q_s^j}{Ae}$
Unsaturated zone	Richards Equation	$C(\psi)\frac{\partial \psi}{\partial t} = \nabla - K(\psi) \cdot \nabla(\psi + Z)$	$s_y \frac{dy_{us}}{dt} = q_i - q_r - E_{sm}$
Groundwater flow	Richards Equation	$C(\psi)\frac{\partial \psi}{\partial t} = \nabla - K(\psi) \cdot \nabla(\psi + Z)$	$s_y \frac{dy_{gw}}{dt} = q_r - E_{tg} - \sum_{j=1}^{3} \frac{Q_g^j}{Ae}$
River channel	St. Venant Equation (1D)	$\frac{\partial h}{\partial t} + \frac{\partial(uh)}{\partial x} = q$	$\frac{dy_{riv}}{dt} = \frac{1}{A_r}\left(\sum Q_{sr}^j + \sum Q_{gr}^j + \sum Q_{up}^j + Q_{dn}\right)$
Potential ET	Penman-Monteith Equation	$ET_0 = \frac{\Delta(R_n - G) + \rho_a C_p \frac{(e_s - e_a)}{r_a}}{\Delta + \gamma\left(1 + \frac{r_z}{r_a}\right)}$	$\left(ET_0 = \frac{\Delta(R_n - G) + \rho_e C_p \frac{(e_t - \epsilon_a)}{r_s}}{\Delta + \gamma\left(1 + \frac{r_s}{r_e}\right)}\right)_i$

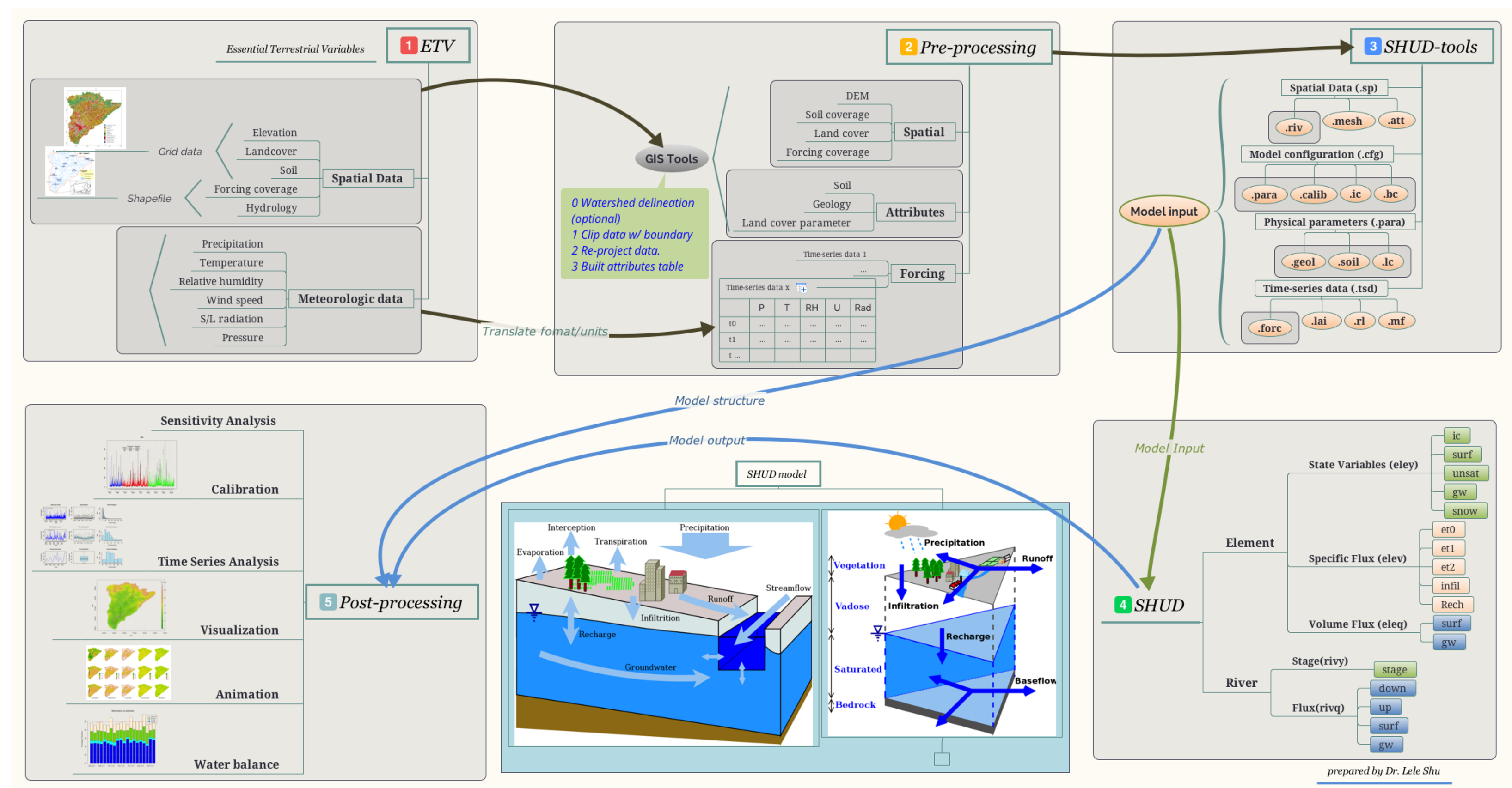






Deployment

Category	Data/parameters	US National	Global
Soil	Porosity; Sand, Silt, Clay Fractions; Bulk Density	SSURGO, gSSURGO, STATSGO	SoilGrids SL1
Geology	Bed Rock Depth; Horizontal and Vertical Hydraulic Conductivity	SSURGO, gSSURGO, STATSGO	SoilGrids SL7
Land Cover	LAI; roughness; vegetation coverage; root depth; soil degradation	USGS NLCD	USGS GLC
River	Manning's Roughness; Coefficient of Discharge; Shape and Dimensions;	NHD plus HUC data	HydroShed
Forcing	Precip; Temp; Humidity; Wind; Radiation.	NLDAS-2; PRISM; LOCA	FLDAS, GLDAS
Topography	DEM	SRTM, GDEM, NED, LIDAR	SRTM, ARSTER GDEM
Streamflow	Daily or event discharge	USGS NWIS	
Groundwater	Groundwater level	USGS NWIS	

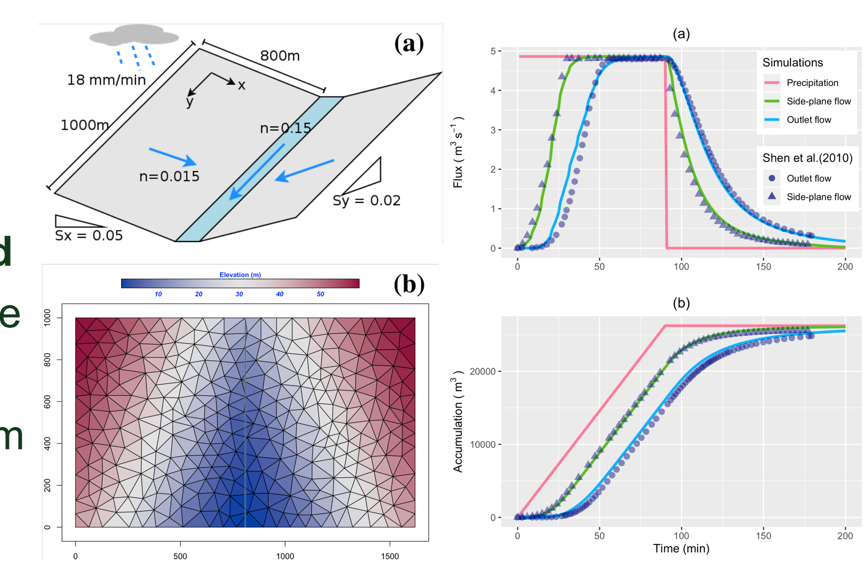


SHUD modeling system workflow

Benchmark

V-Catchment

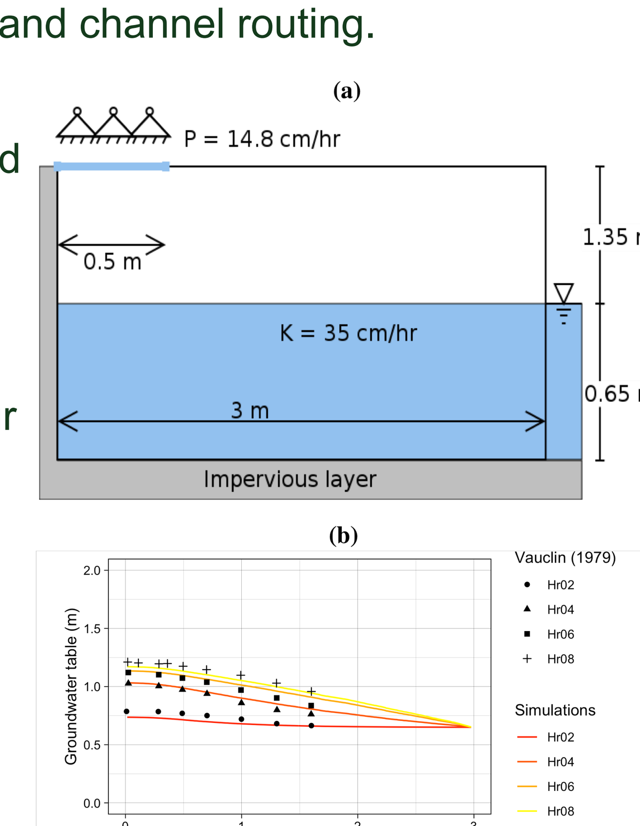
A standard test case for numerical hydrological models to validate **overland flow algorithm** and **model stability**. The specific discharge increases with precipitation until it reaches the maximum discharge rate, which is equal to the precipitation rate. The discharge rate from the side-plane reaches 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.

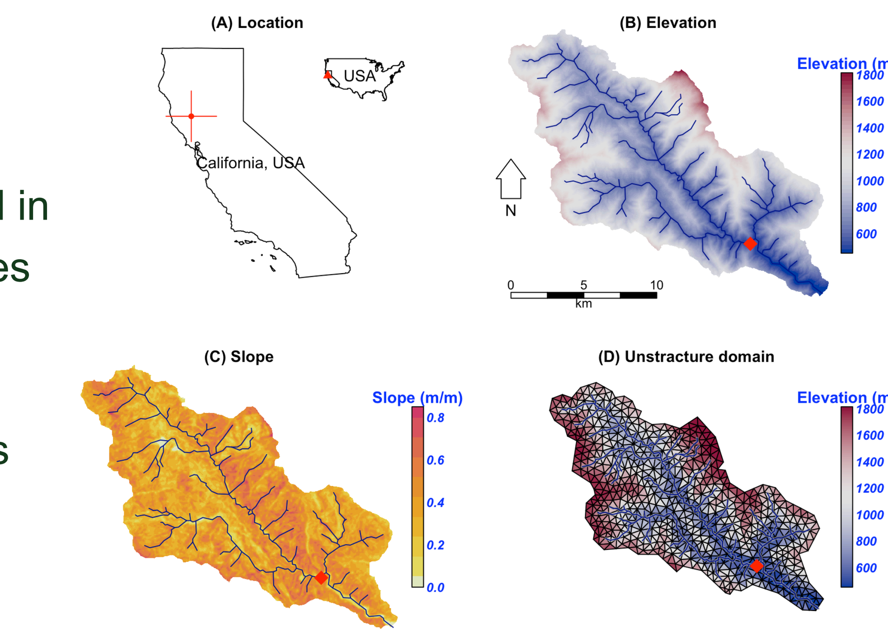
The SHUD simulated the groundwater table at all four measurement points (2, 4, 6, 8 hr). After calibration, the maximum bias between simulation and Vauclin's observations is 5.5cm, that is comparable to the bias 5.2cm of numerical simulation in Vauclin et al.(1979). The simulations validate the algorithm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



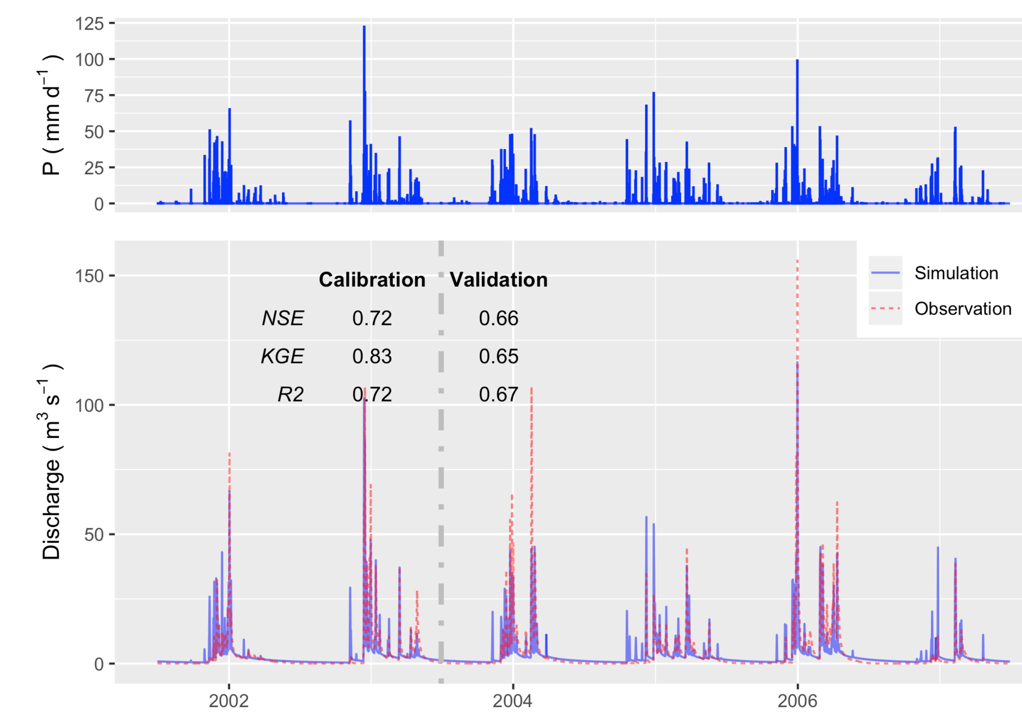
Applications

Cache Creek Watershed

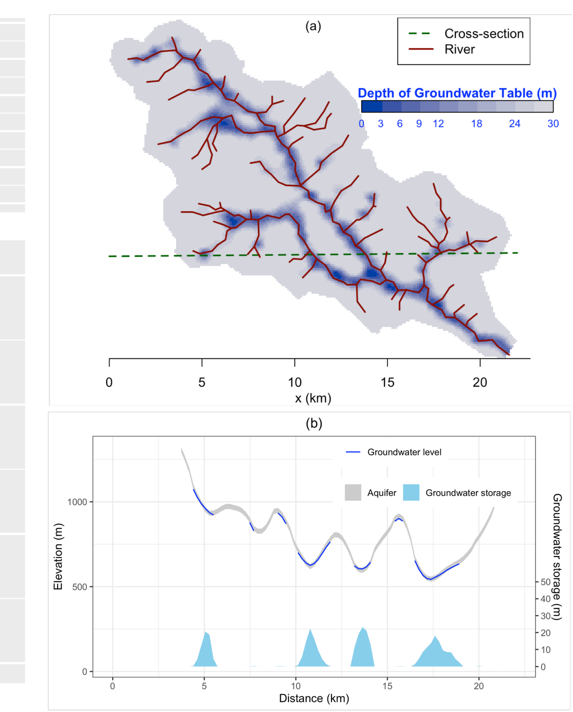
A headwater catchment with area 196.4km² in the Sacramento Watershed in Northern California. The elevation ranges from 450m to 1800m, with a 0.38m/m average slope and hence a particularly difficult watershed for hydrologic models to simulate. Mean temperature and precipitation was 12.8C and ~817mm, respectively. Precipitation is unevenly distributed through the year.



Basic data of Cache Creek Watershed



Calibration of simulated discharge against USGS gage station.

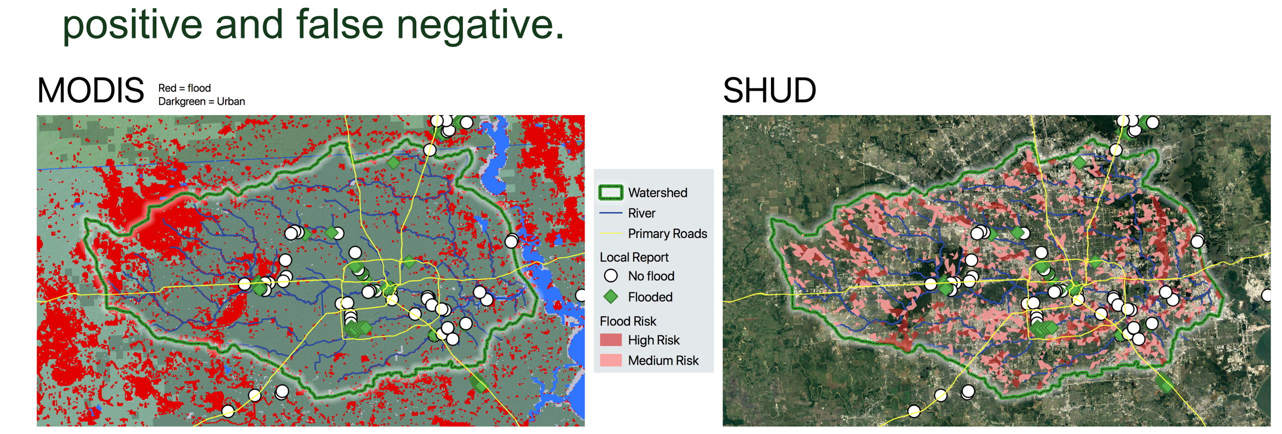


Groundwater distribution

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.

Item	Value	Unit
Number of elements	8571	
Number of river reaches	392	
Number of river order	3	
Number of river segments	2057	
Number of bank elements	1607	
Maximum elevation	61.02	m
Minimum elevation	0.11	m
Watershed area	2713.53	km^2
Average element area	0.32	km^2
Total river length	696.70	m
Shortest river reach	336.98	m
Average river slope	0.00097	m/m



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 and https://github.com/SHUD-System/SHUD
3. SHUD toolbox: https://github.com/SHUD-System/SHUDtoolbox
4. AutoSHUD: https://github.com/SHUD-System/AutoSHUD