Integrating remotely-sensed data into hydrological/water quality models

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ROBERT B. ANNIS WATER RESOURCES INSTITUTE

Trans-Atlantic Training 2023 (Brno, CZ)
30 June 2023

Education and Experience

- Ph.D. (2015)
    - Biosystems and Agricultural Engineering
      Michigan State University
- Postdoctoral fellow (2015-2019)
    - National Exposure Research Laboratory
      Office of Research and Development
      U.S. Environmental Protection Agency
- Assistant Professor (2019-present)
    - Annis Water Resources Institute
      Grand Valley State University

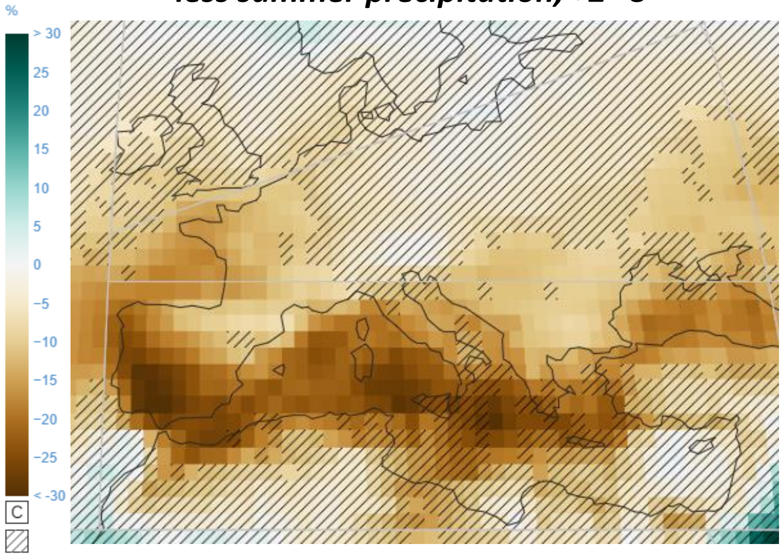
MICHIGAN STATE UNIVERSITY

UNITED STATES ENVIRONMENTAL PROTECTION AGENCY

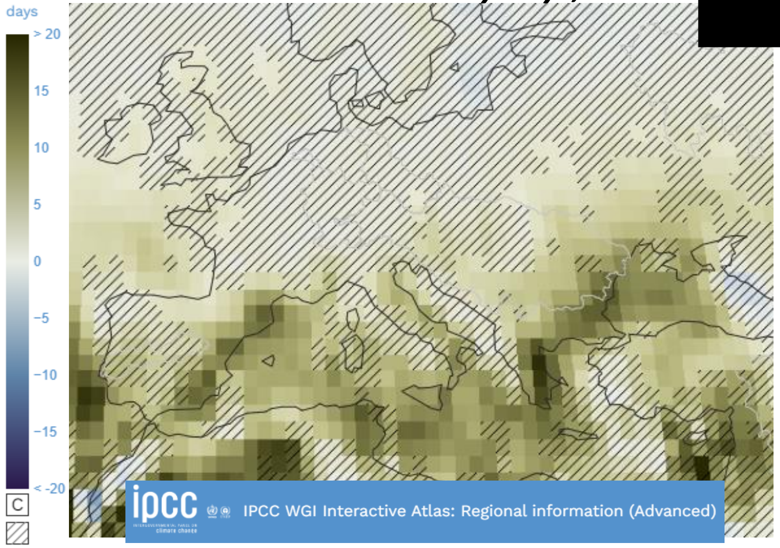
W.G. Jackson at AWRI's Lake Michigan Center

Water scarcity in the Serbian Danube: Agricultural land use and irrigation

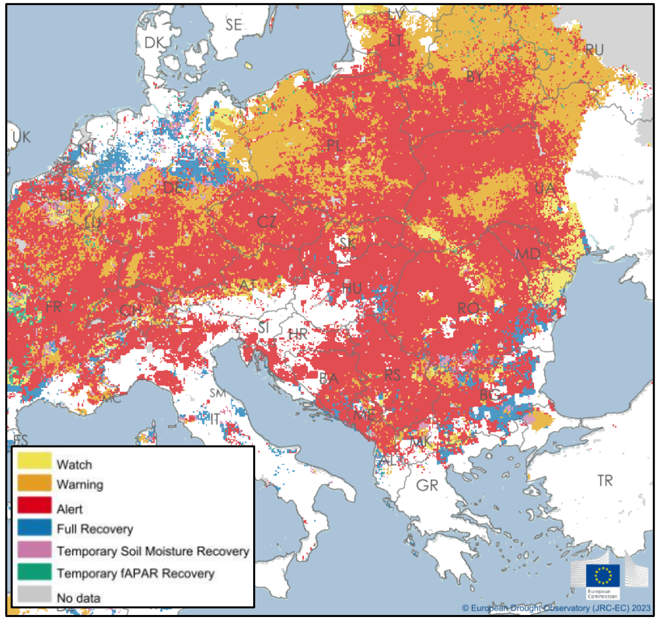
less summer precipitation, +2° C



more consecutive dry days, +2° C



More frequent droughts



Crop choice and rotation changes?

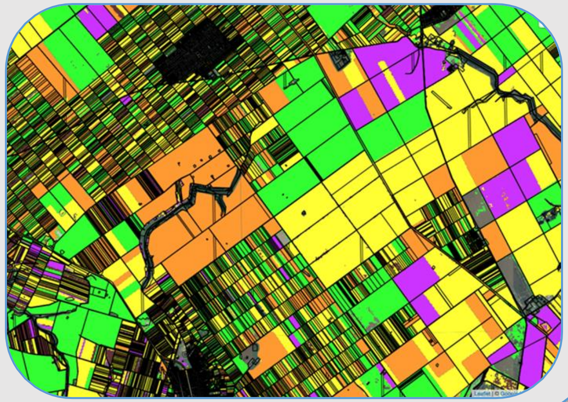
Water scarcity

Irrigation expansion

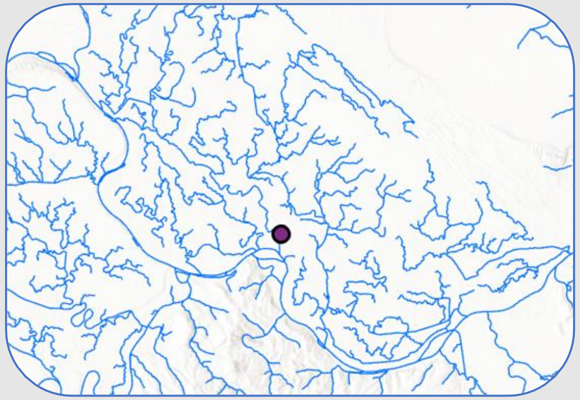
NASA LCLUC Grant #80NSSC22K0467

Water scarcity in the Serbian Danube: Agricultural land use and irrigation

Remote Sensing
- Crop mapping
- Irrigated agriculture
- Evapotranspiration



Hydrological/crop modeling
- Water balance
- Crop yield
- Historical and future



Economic models + decisions
- Crop choice
- Irrigation investment
- Historical + future

Lecture Objectives/Outcomes

1. Describe the relationship between LCLUC and the hydrological cycle

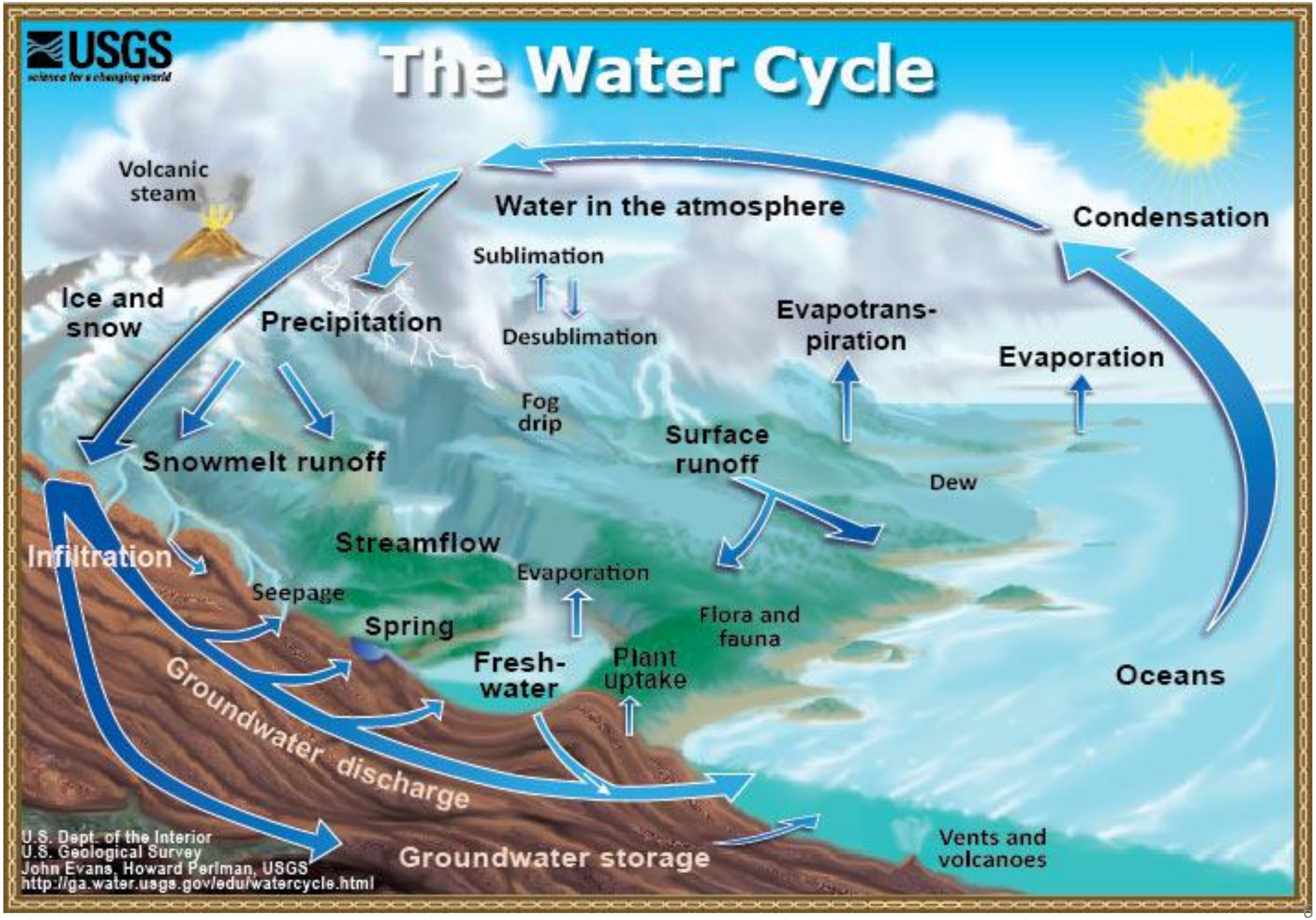
2. Understand the role of remote sensing data in hydrological model development and assessment

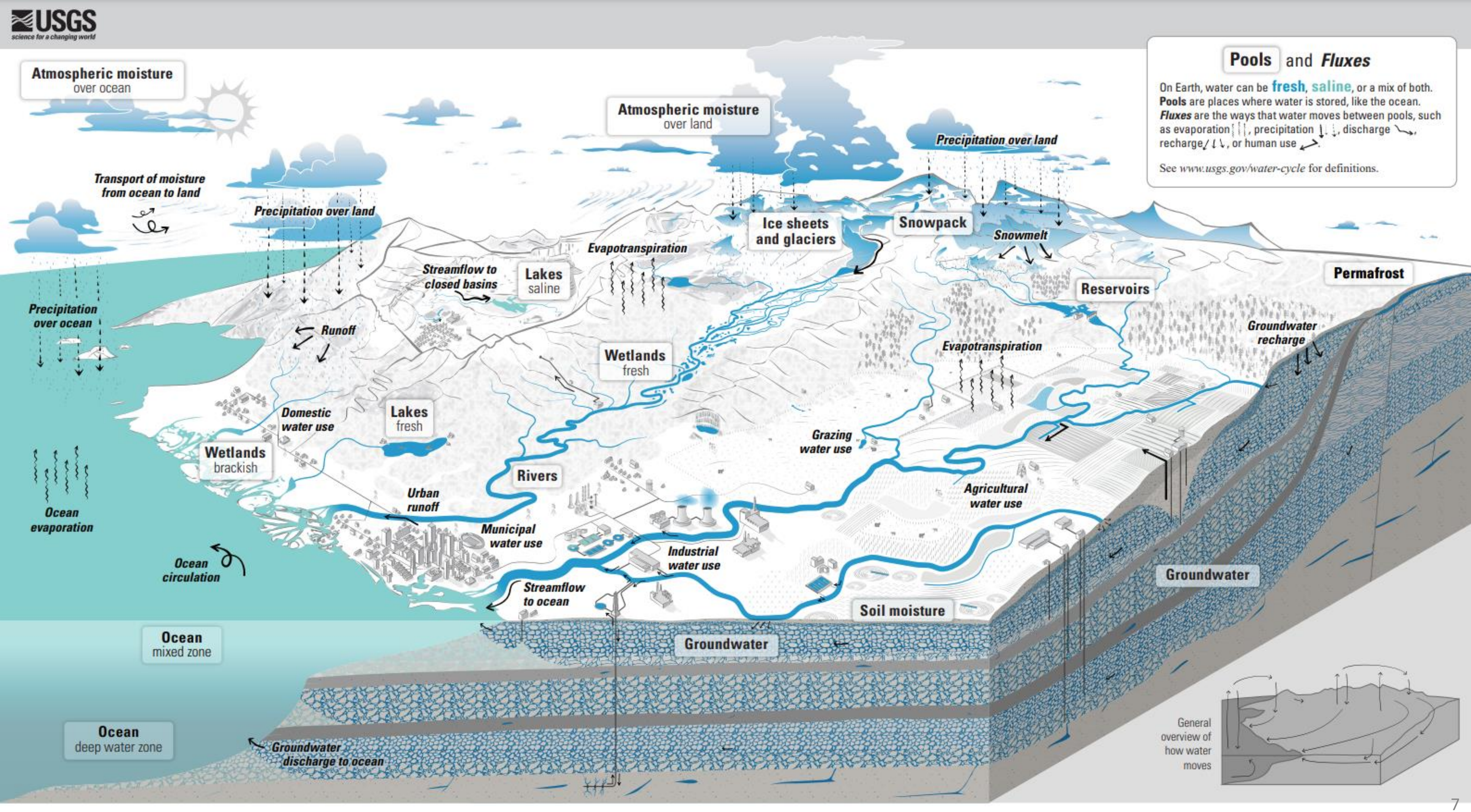
3. Describe hydrological modeling concepts and build a hydrological model

4. Build communication/understanding of hydrology and hydrological modeling concepts – ***modelers are the users of the data you produce!***

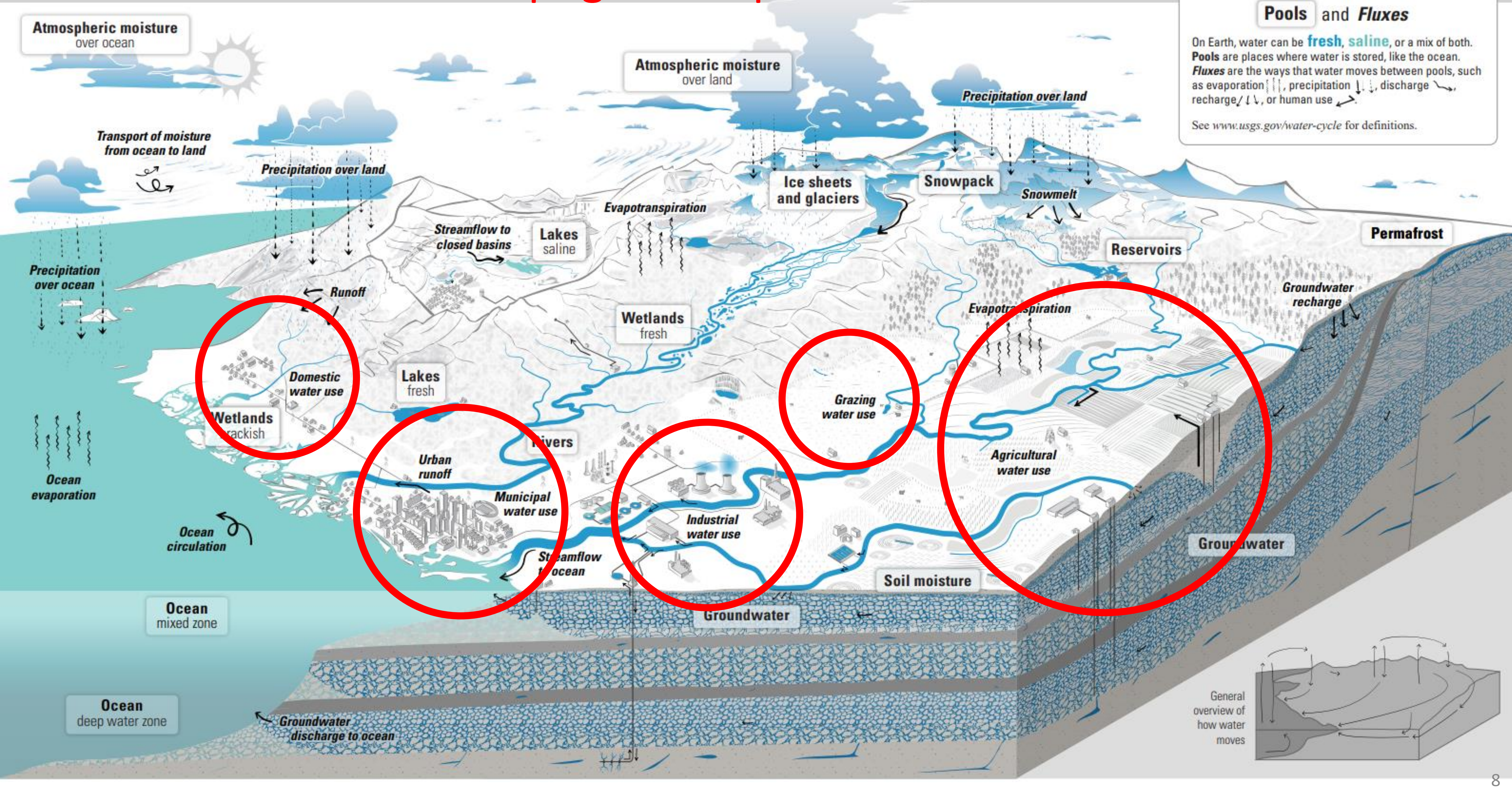
The classic water cycle diagram…

What is missing?

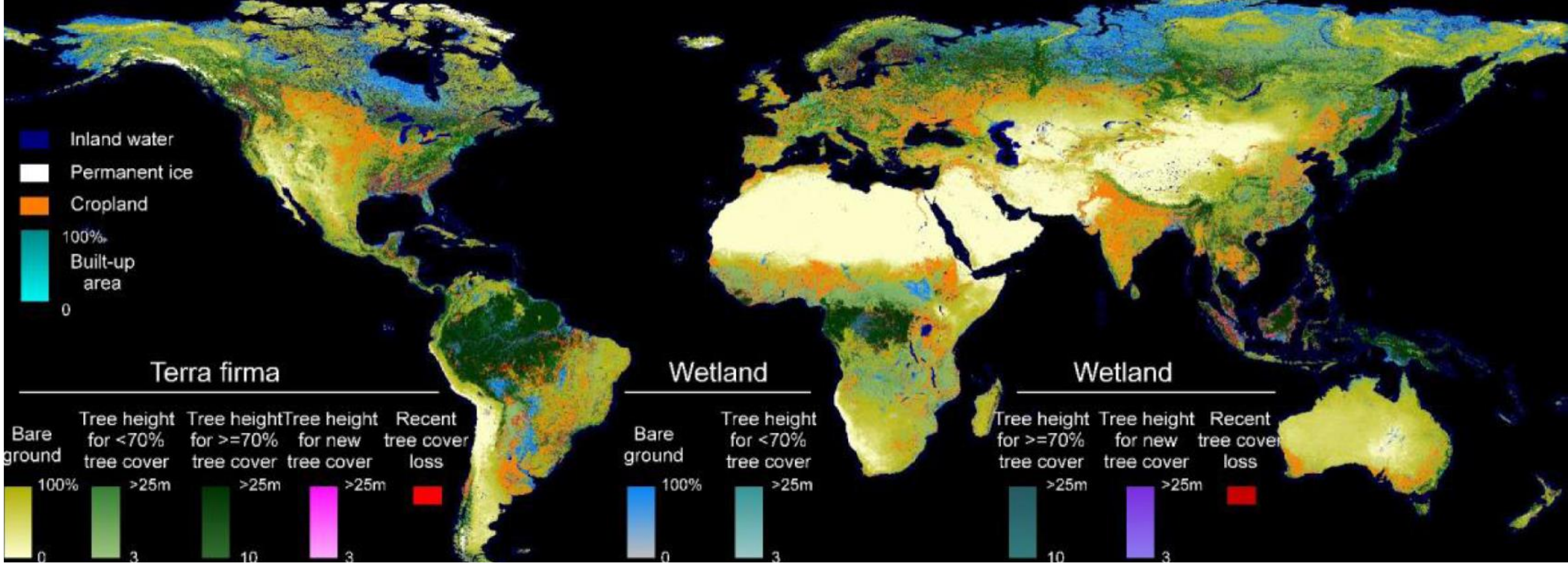



USGS
science for a changing world
Atmospheric moisture
over ocean
Atmospheric moisture
over land
Pools and Fluxes
On Earth, water can be fresh, saline, or a mix of both.
Pools are places where water is stored, like the ocean.
Fluxes are the ways that water moves between pools, such as evaporation, precipitation, discharge, recharge, or human use.
See www.usgs.gov/water-cycle for definitions.
Transport of moisture
from ocean to land
Precipitation over land
Precipitation over land
Precipitation
over ocean
Ice sheets
and glaciers
Snowpack
Snowmelt
Evapotranspiration
Streamflow to
closed basins
Lakes
saline
Permafrost
Reservoirs
Runoff
Wetlands
fresh
Evapotranspiration
Groundwater
recharge
Domestic
water use
Lakes
fresh
Wetlands
brackish
Grazing
water use
Rivers
Urban
runoff
Agricultural
water use
Ocean
evaporation
Municipal
water use
Industrial
water use
Ocean
circulation
Streamflow
to ocean
Groundwater
Soil moisture
Groundwater
Ocean
mixed zone
Ocean
deep water zone
Groundwater
discharge to ocean
General
overview of
how water
moves

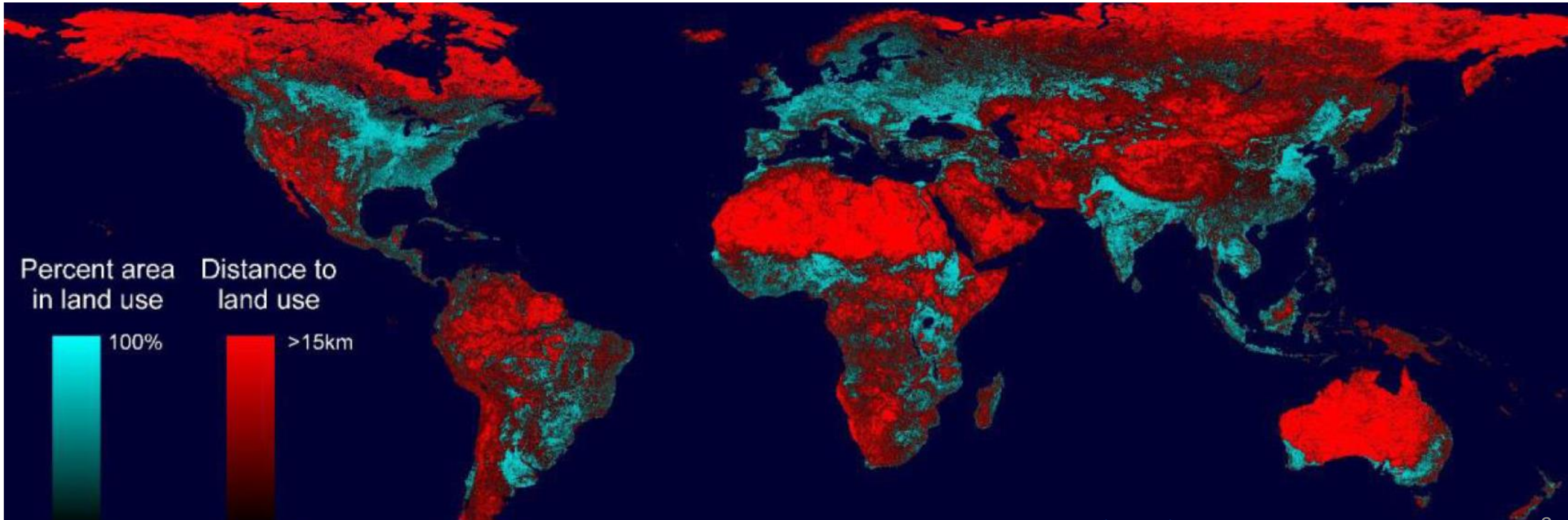
Direct anthropogenic impacts related to land use



Land cover and land use (2019)



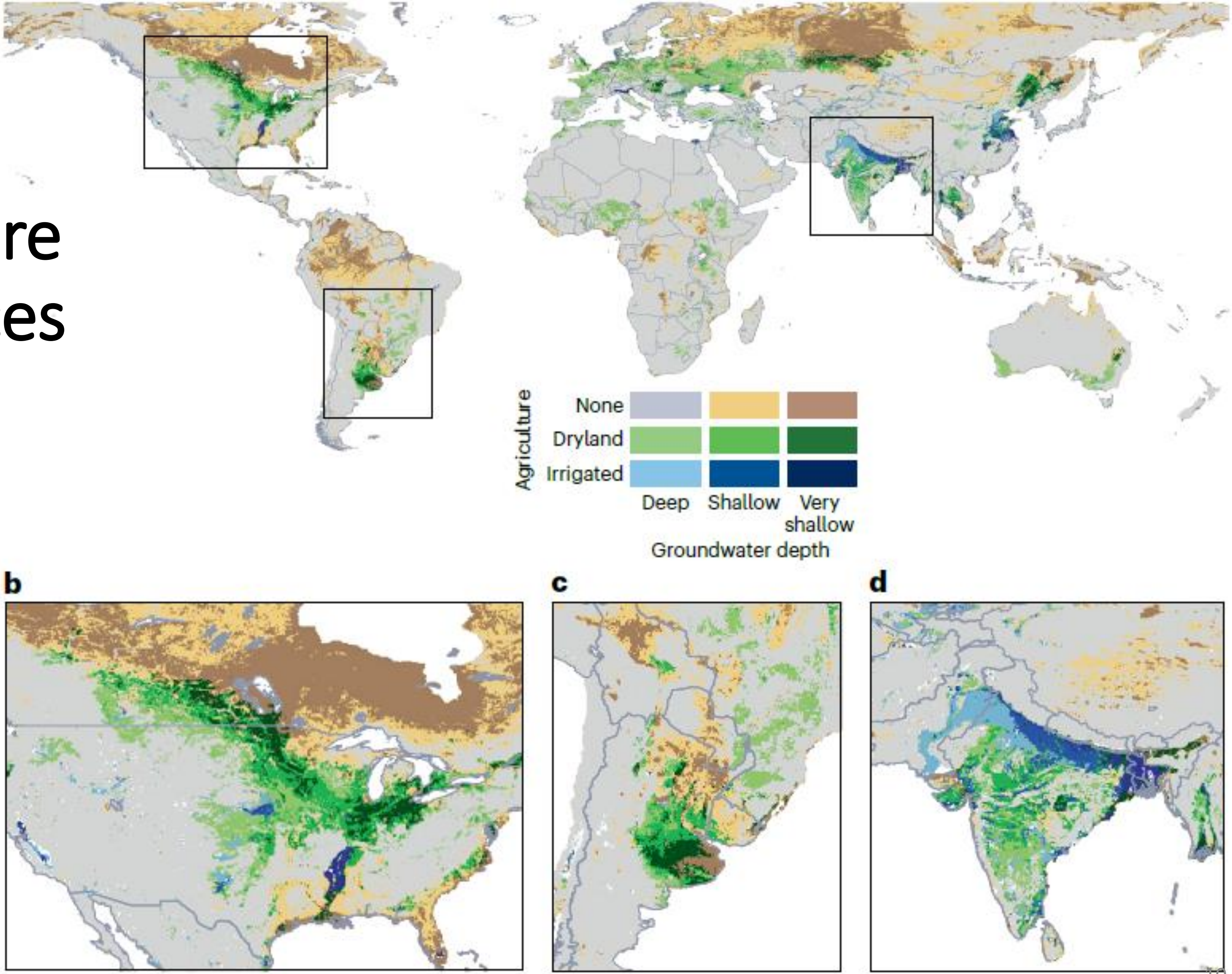
Land use extent / Distance to use



[Hansen et al. (2022) *Environmental Research Letters*]

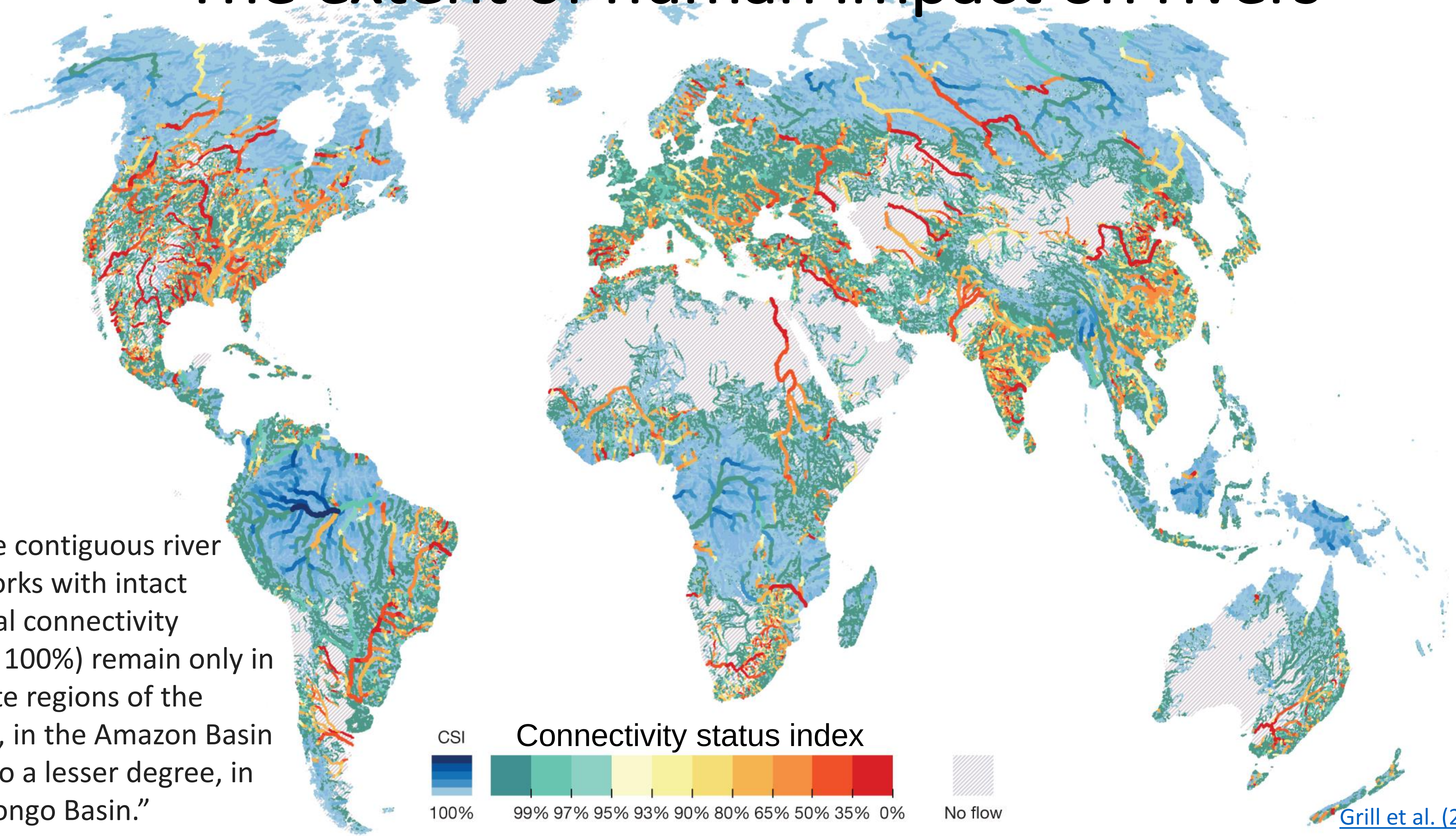
The relationship between agriculture and water resources

"Human intervention affects water resources directly through water use such as for **irrigation, which accounts for 70% of global water withdrawal and 90% of water consumption** (Siebert et al. 2010). Many hotspots of water scarcity globally correspond to intensively irrigated areas…"



Scanlon et al. (2023) Nature Reviews Earth and Environment

The extent of human impact on rivers



"Large contiguous river networks with intact natural connectivity (CSI = 100%) remain only in remote regions of the Arctic, in the Amazon Basin and, to a lesser degree, in the Congo Basin."

[Grill et al. (2019) *Nature*](#)

Change and impacts on the hydrological cycle

Drivers of change

- Global warming
- Deforestation
- Urbanization
- Agriculture
- Grazing
- Wildland fire
- Reservoir construction
- Invasive species
- Mining/extractive industry

Fluxes and pools

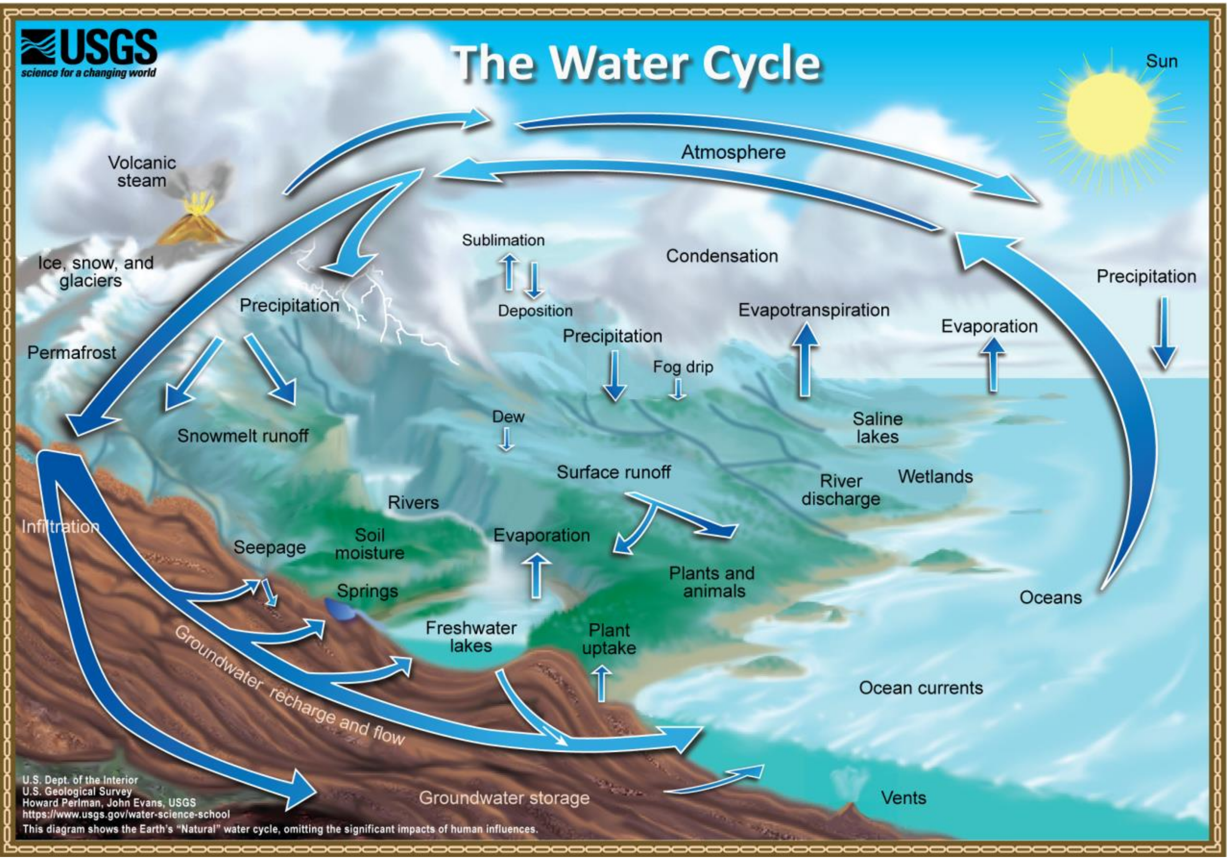
- Surface runoff
- Soil moisture
- Groundwater
- Evapotranspiration
- Streamflow
- Lakes + wetlands

Water Quality

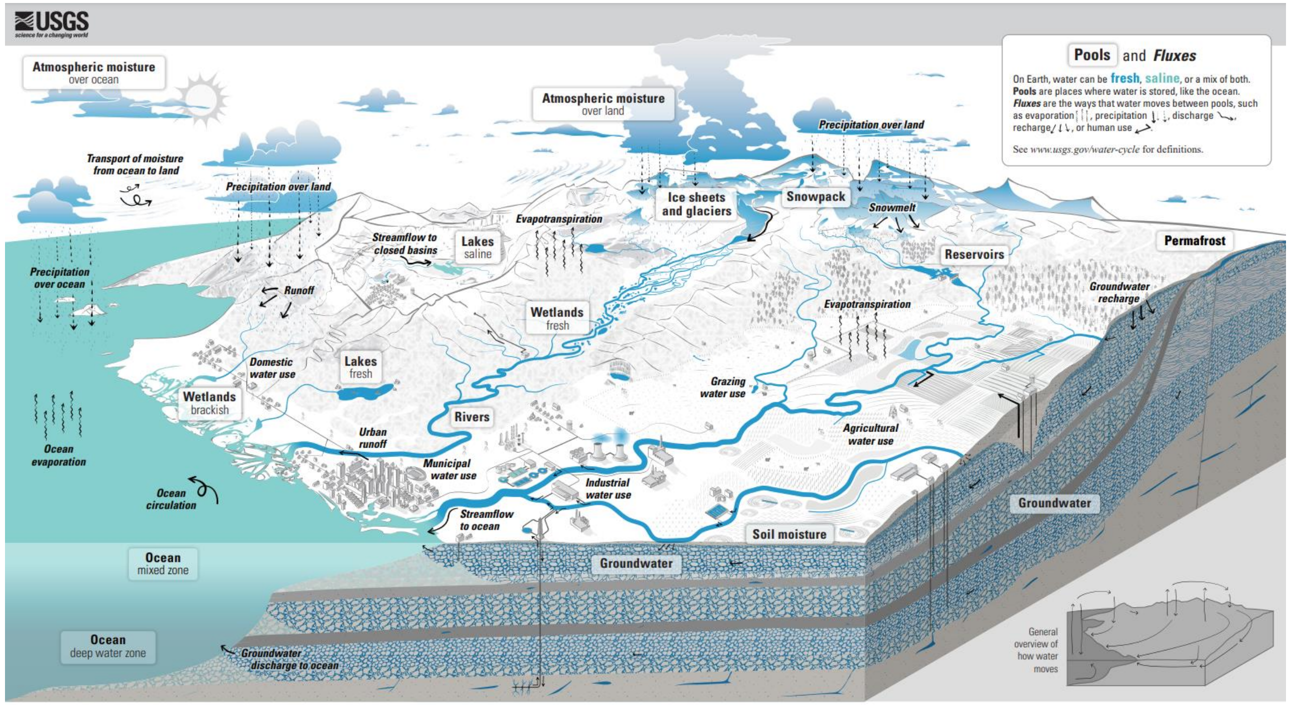
- Sediment
- Nutrients
- Pesticides
- Heavy metals
- Fecal coliform bacteria

To understand change, we need to know the natural (reference) condition

REFERENCE

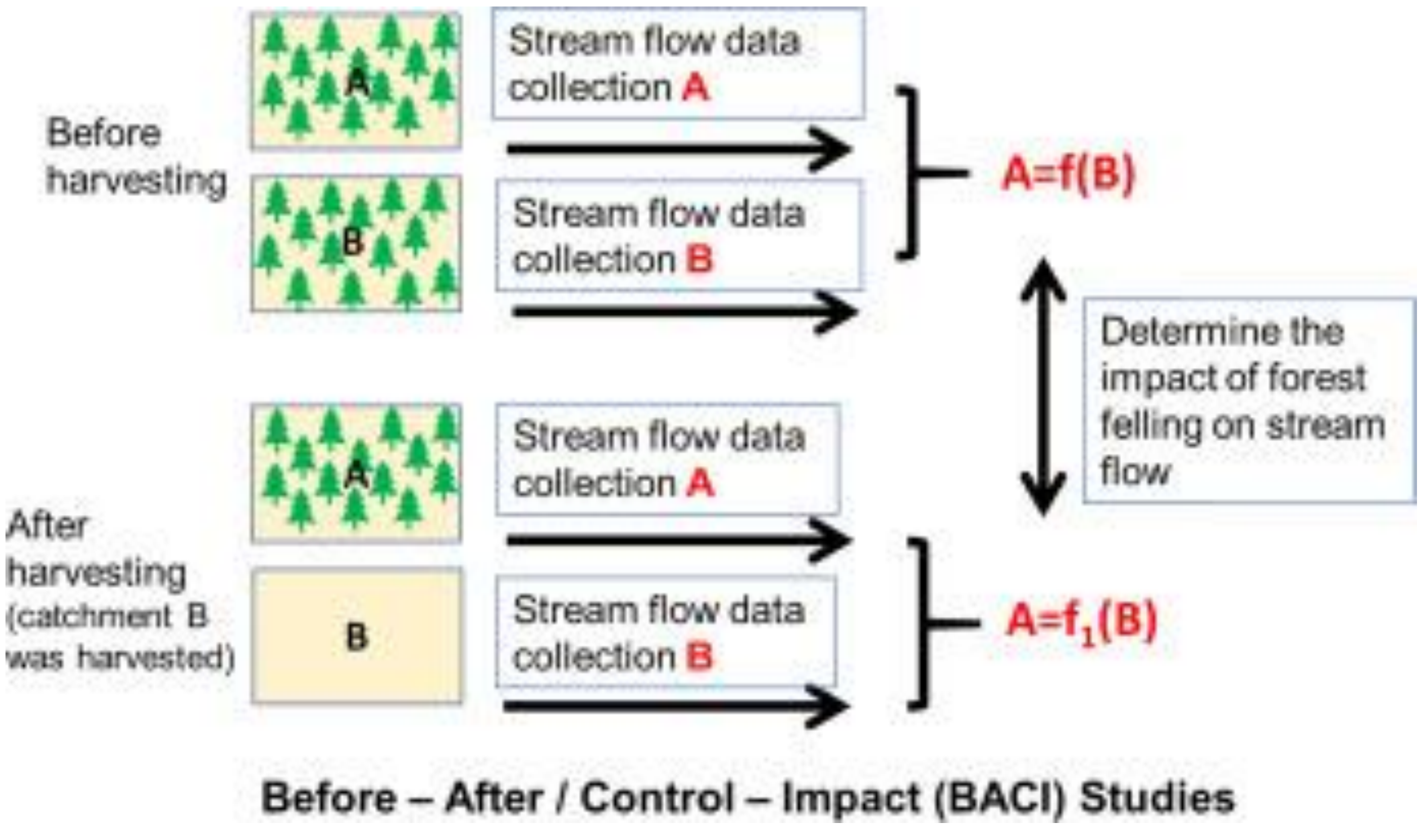


IMPACT



How to quantify effect of change? Study design

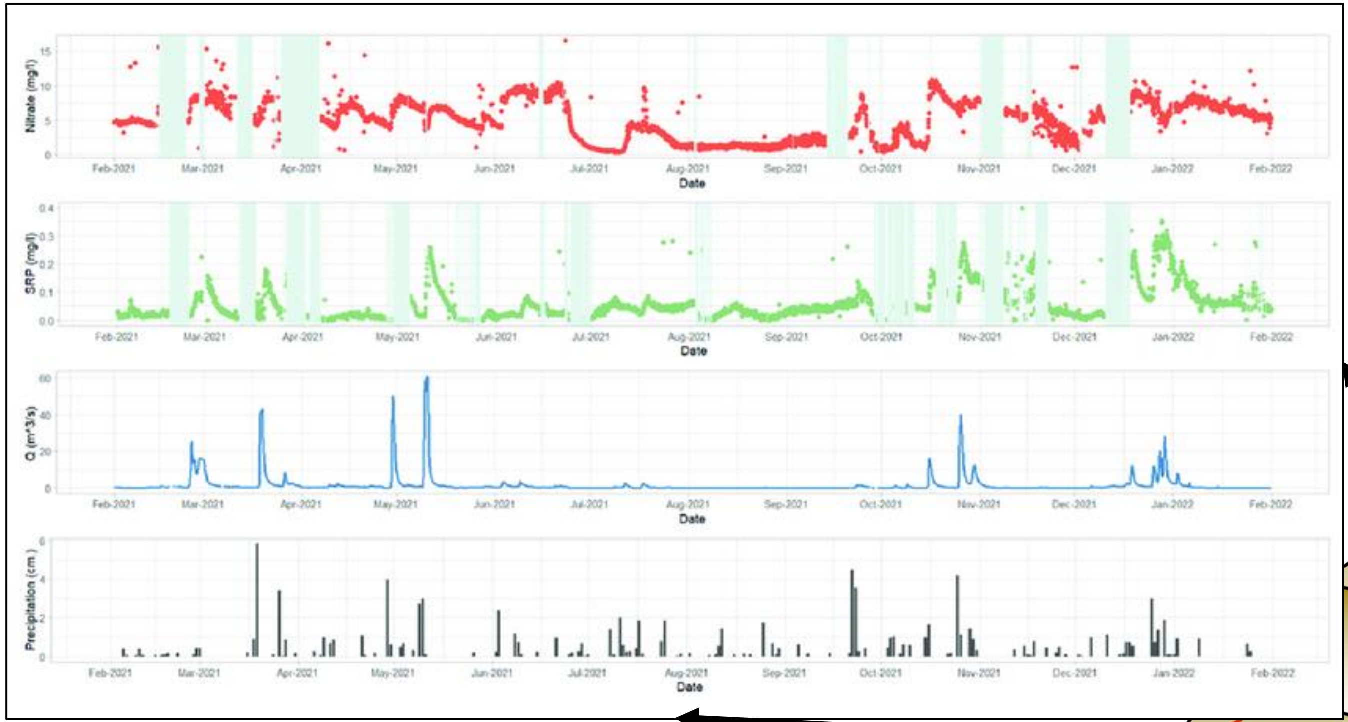
- Before-after change
  - Observed or future projection
- Control-impact
  - paired catchments
- Before-after control-impact



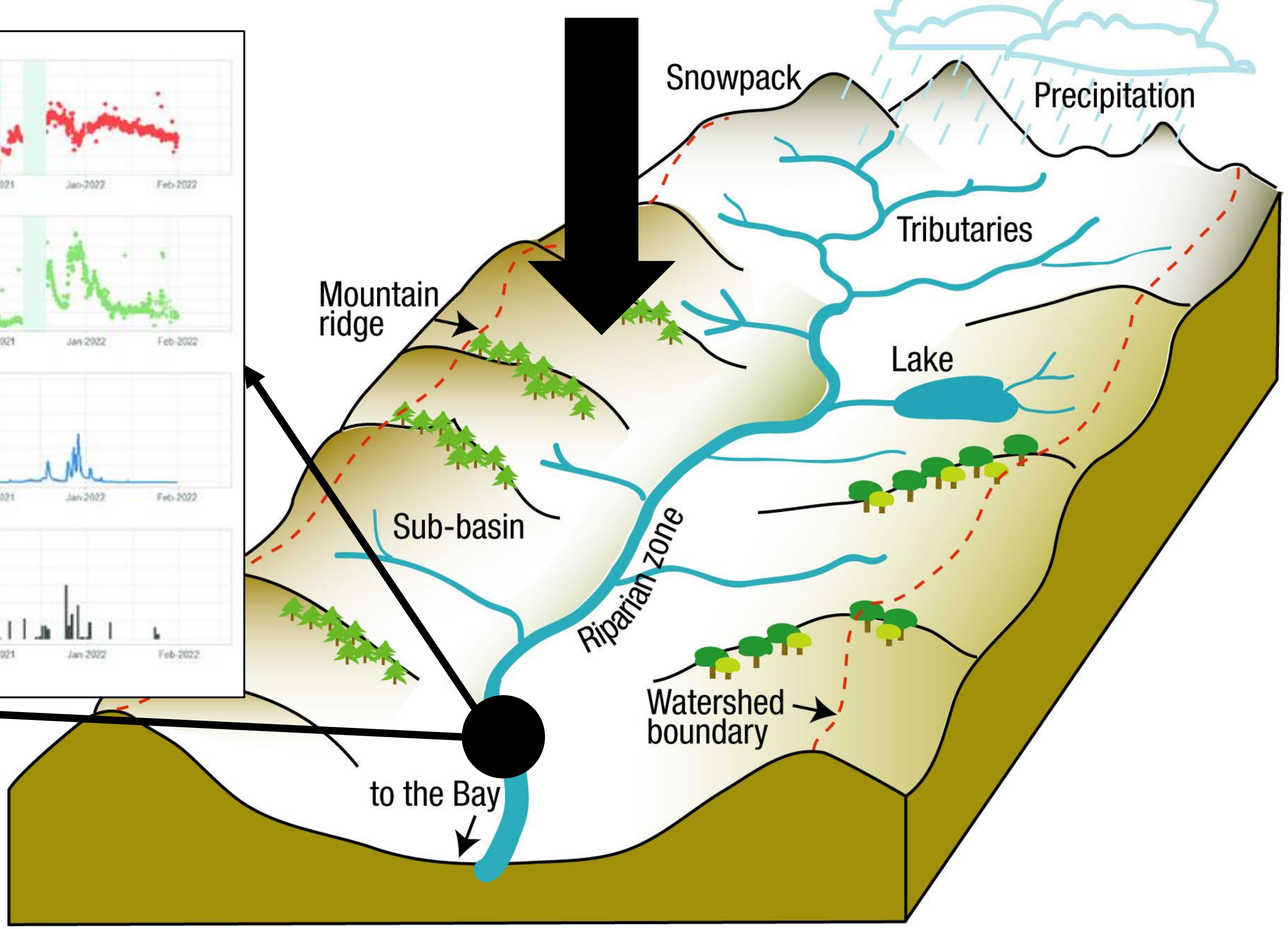
Xiao et al. 2022 *Sci Tot Env*

Connecting LCLUC to hydrology and water quality

Time series discharge and water quality
in-situ measurements

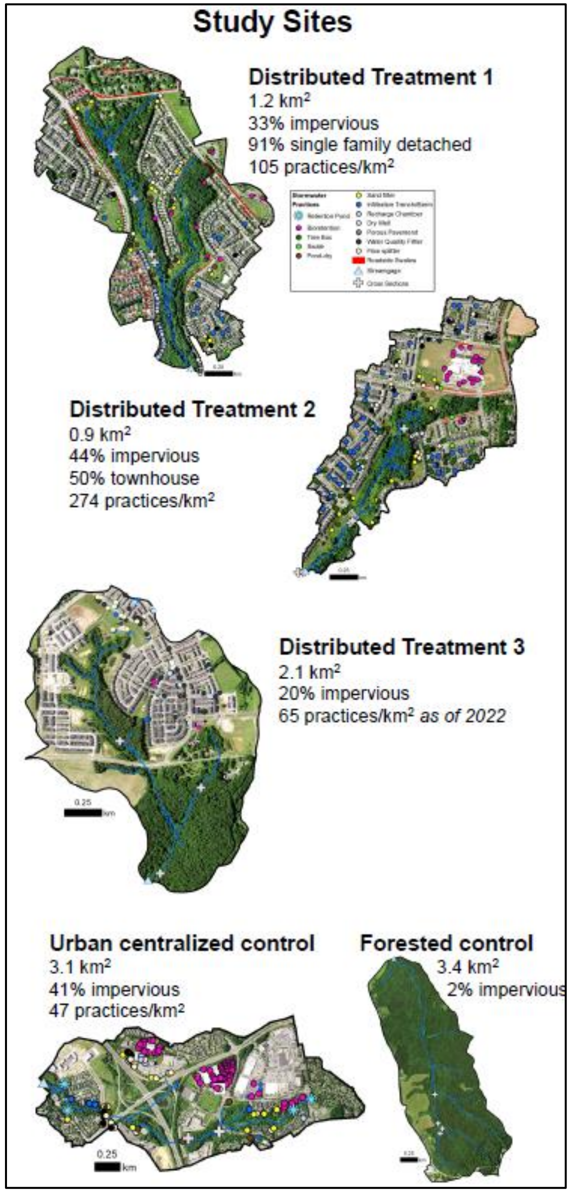


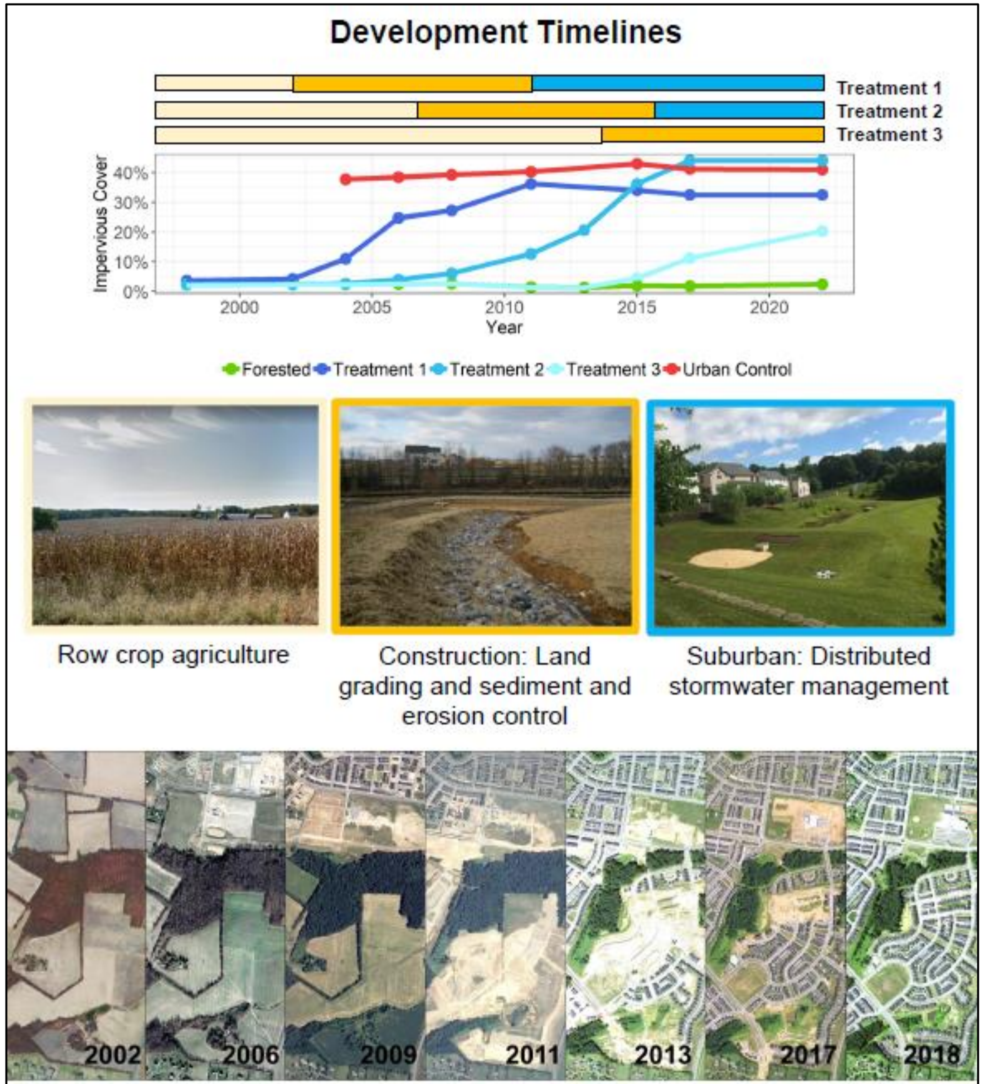
Observe/model change



Urbanization

- How does urbanization alter the water balance?
- Do mitigation measures (stormwater control) reduce the impacts of urbanization?

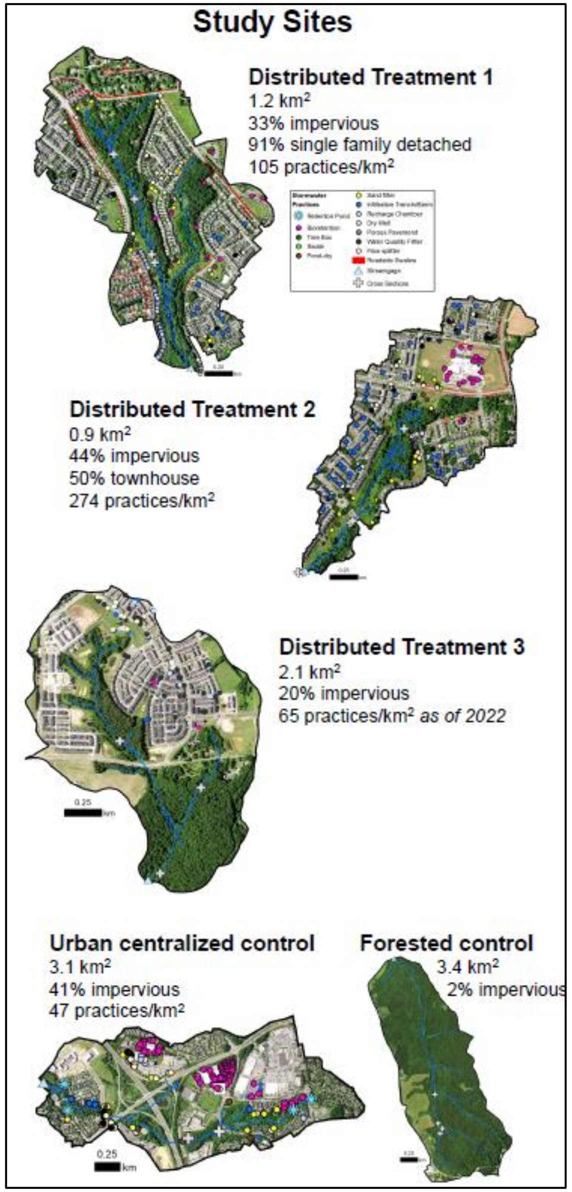


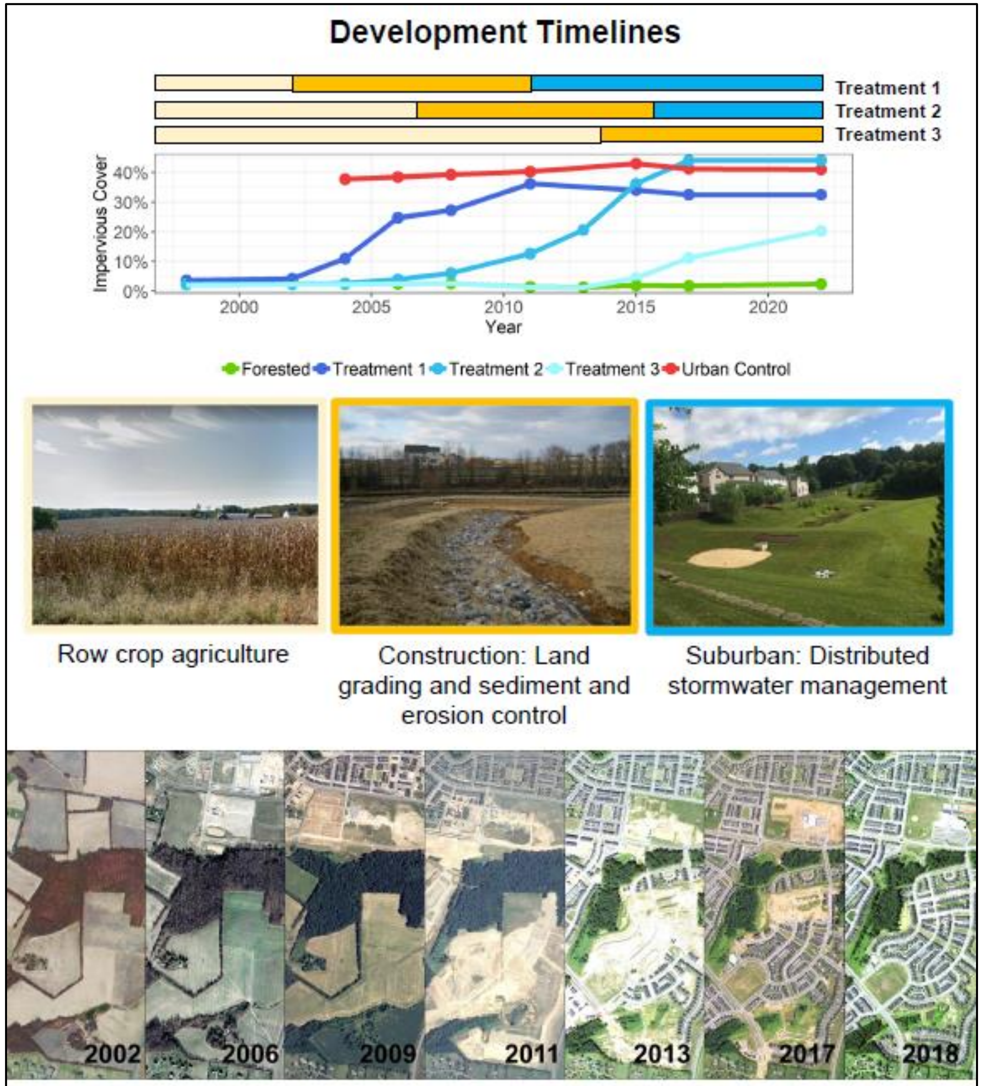


Land cover changes were tracked using data from the National Agriculture Imagery Program (NAIP) and orthoimagery.

Hopkins et al. (2022a) *Freshwater Sci*; *(2020) Hydrol Proc*

Urbanization ↑ runoff ↑ peak discharge ↓ baseflow ↓ water quality





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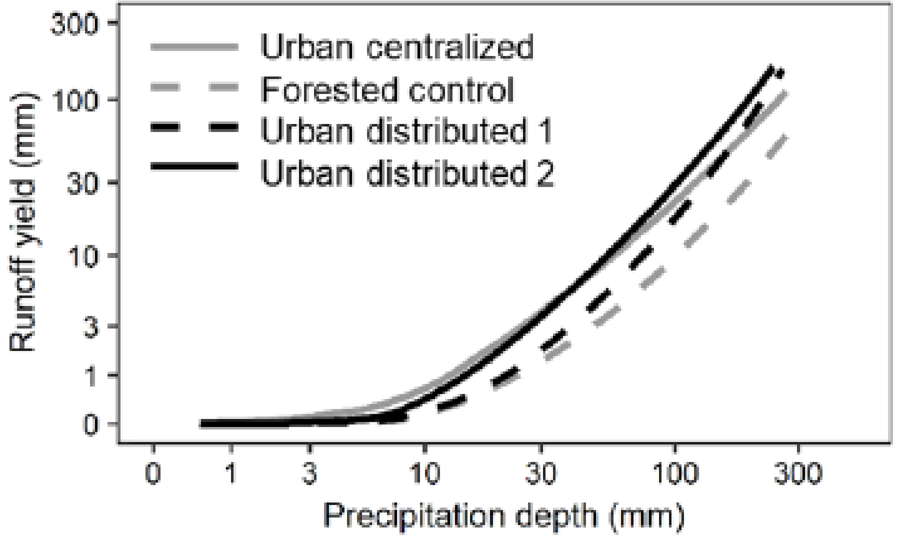
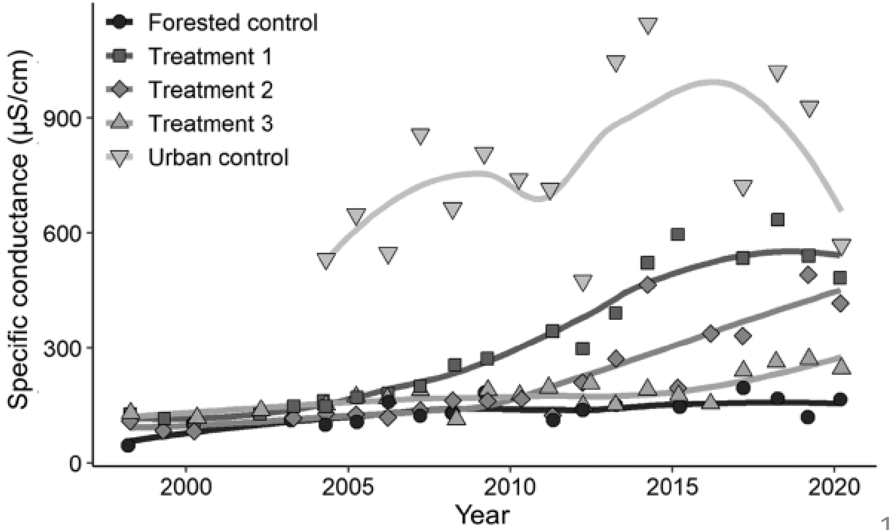


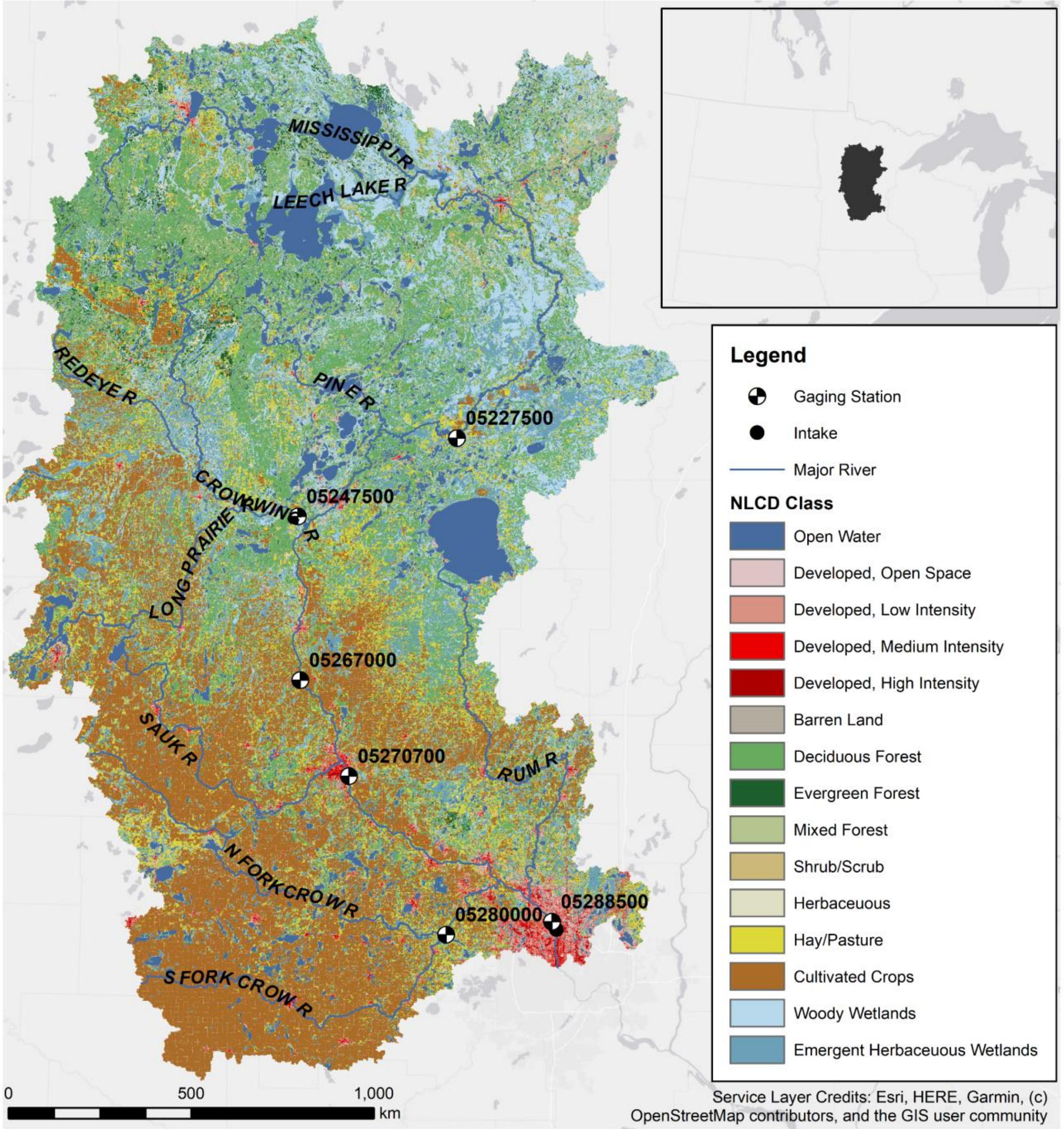


Hopkins et al. (2022a) *Freshwater Sci*; *(2020) Hydrol Proc*

Drinking water

Minneapolis Water Treatment and Distribution

- *Processes:* 21 billion gal/year of raw water from the Mississippi River headwaters
- *Serves:* > 500,000 people
- ***Concerns:* agricultural expansion, population growth, urbanization, climate change**



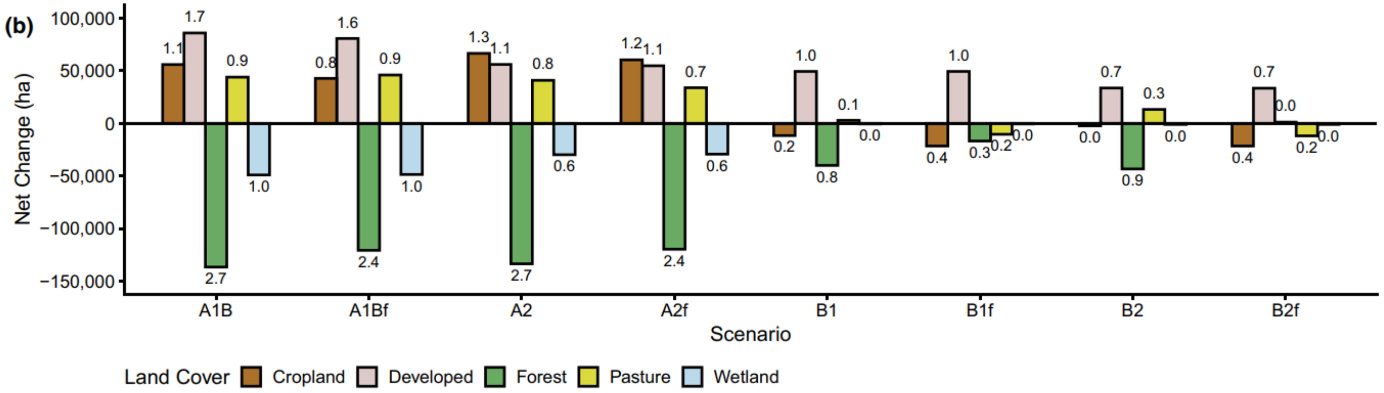
Woznicki et al. (2023) *J. Am. Water Res Assoc*

Drinking water

Coupled land use change and hydrological modeling

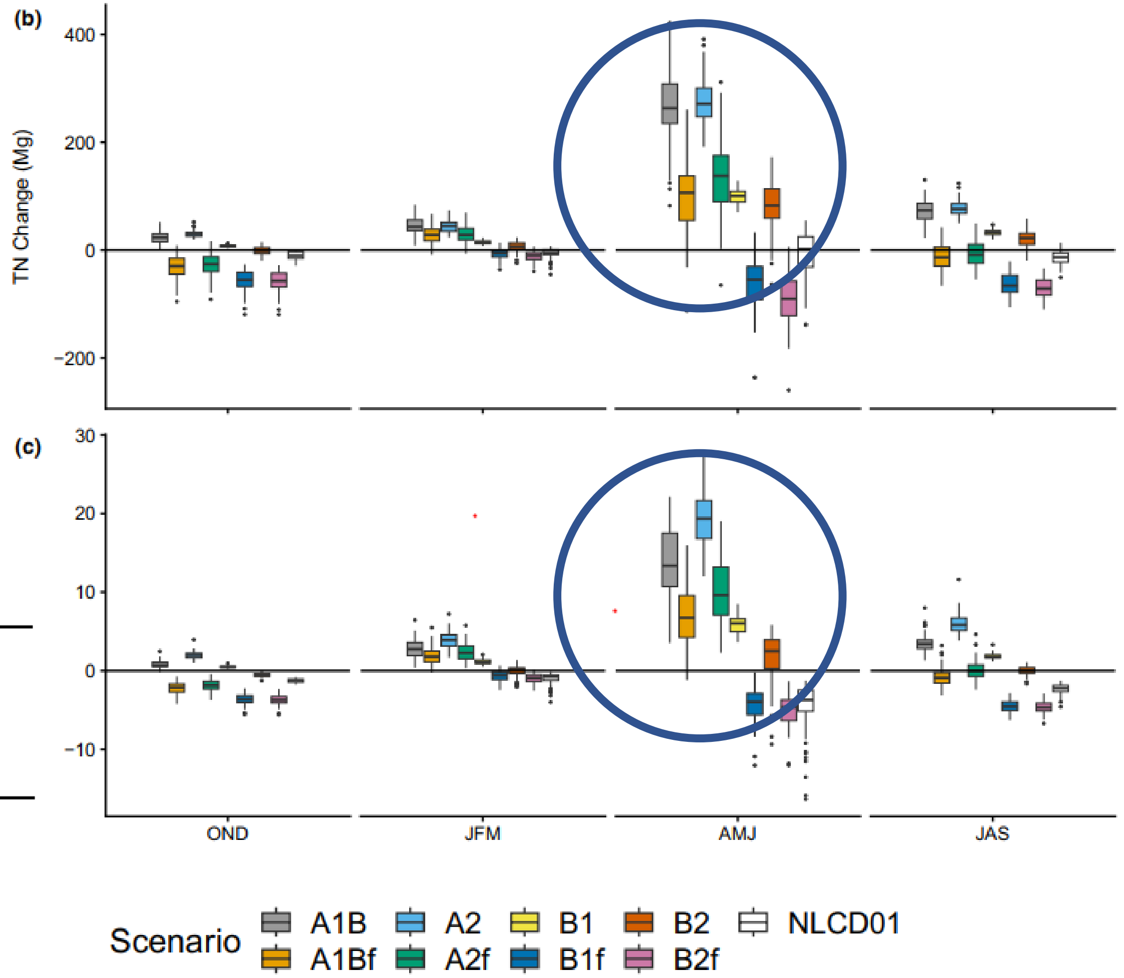
LCLUC by 2050:

- Forest loss to agriculture in headwaters
- Agriculture loss to expansion of Minneapolis urban footprint associated with population growth



Water quality changes by 2050:

- Raw water nutrient loads increase in more extreme forest loss scenarios
- Impact is greatest in early growing season
- Greater water treatment costs



[Woznicki et al. (2023) *J. Am. Water Res Assoc*](#)

Forest hydrology: bark beetle infestation

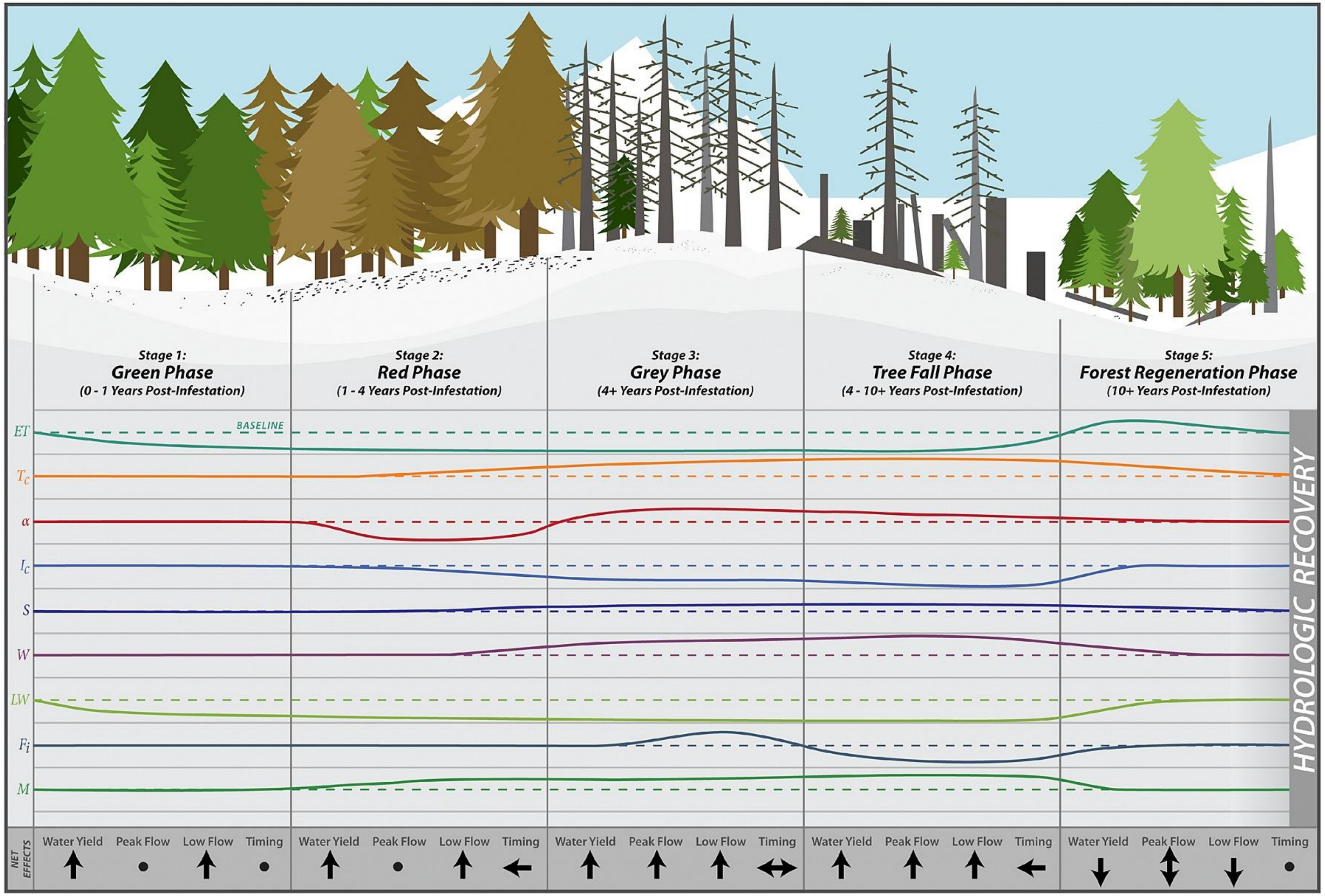
Infestation-induced tree death mapped using RS (some examples)

- Barta et al. (2022)
- Dalponte et al. (2022)
- Fernandez-Carillo et al. (2020)

Hydrological impacts:

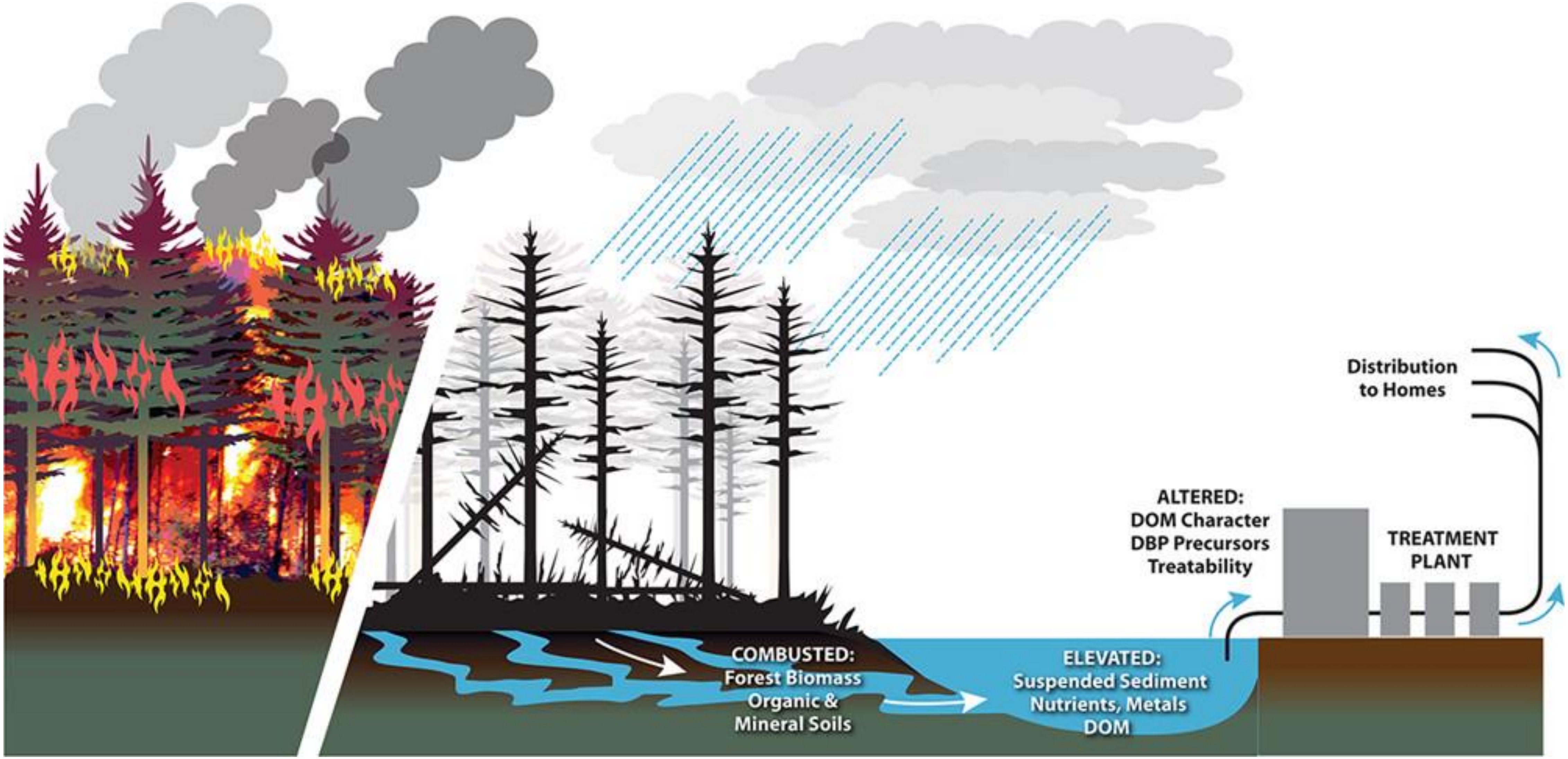
- Transpiration ↓
- Canopy interception ↓
- Baseflow ↑
- Peak flow ↑
- Soil evaporation ↑

Phases of infestation and hydrologic changes

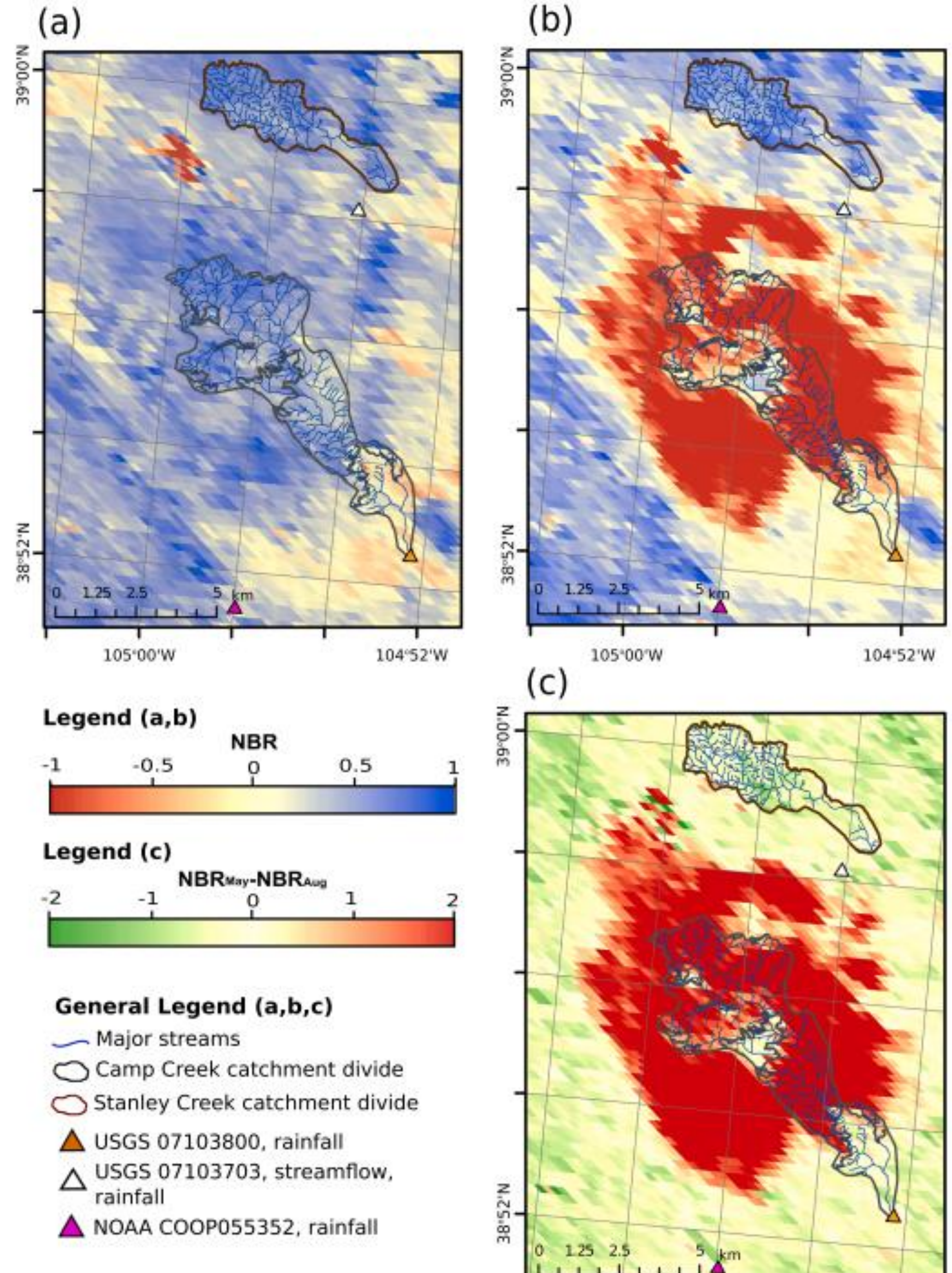


Pugh and Gordon (2013) *Hydrological Processes*

Post-wildfire hydrology: ↑ runoff ↑ erosion ↓ water quality



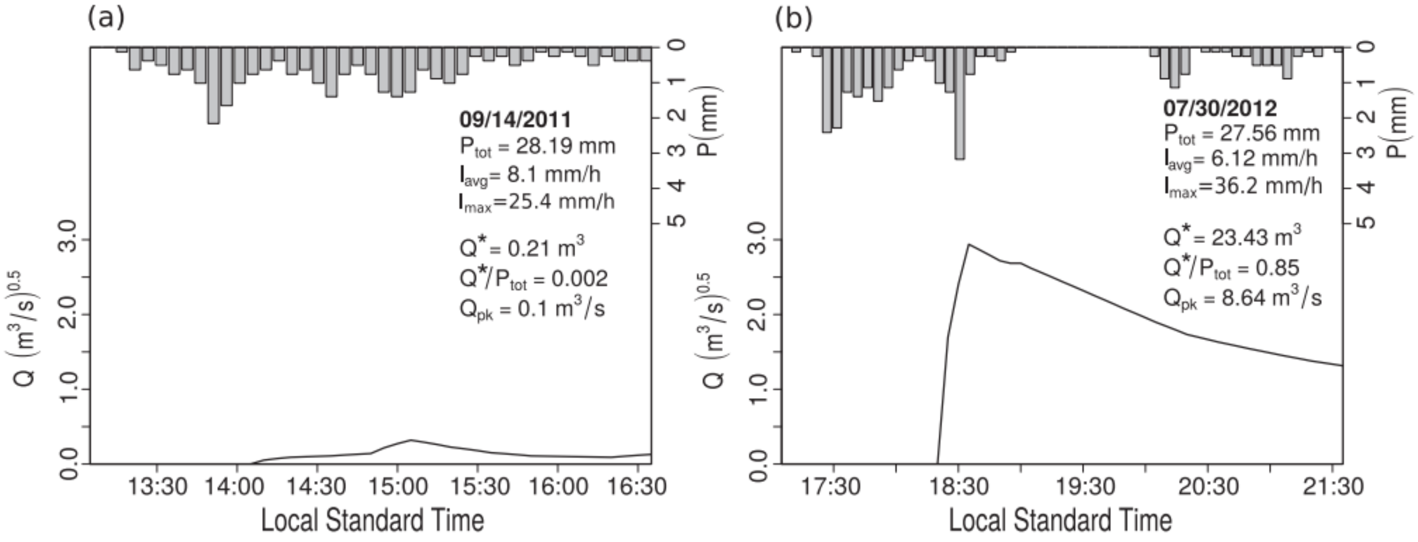
Hohner et al. (2019) *Acc. Chem. Res*

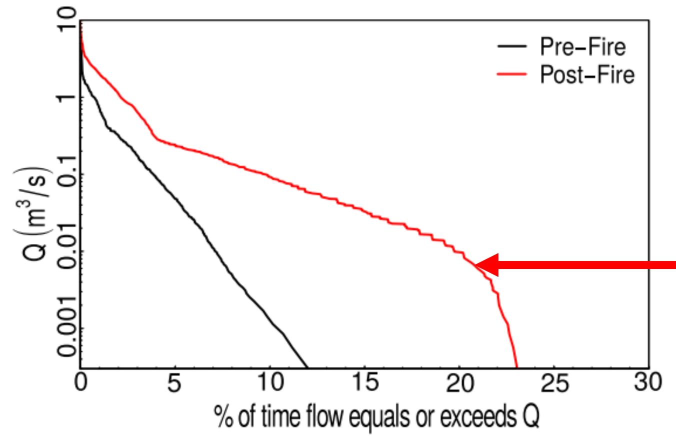


Post-wildfire hydrology

Linking ***normalized burn ratio (NBR, MODIS MOD13Q1)*** to pre- and post-fire rainfall-runoff events

Pre-fire runoff event **Post-fire runoff event**



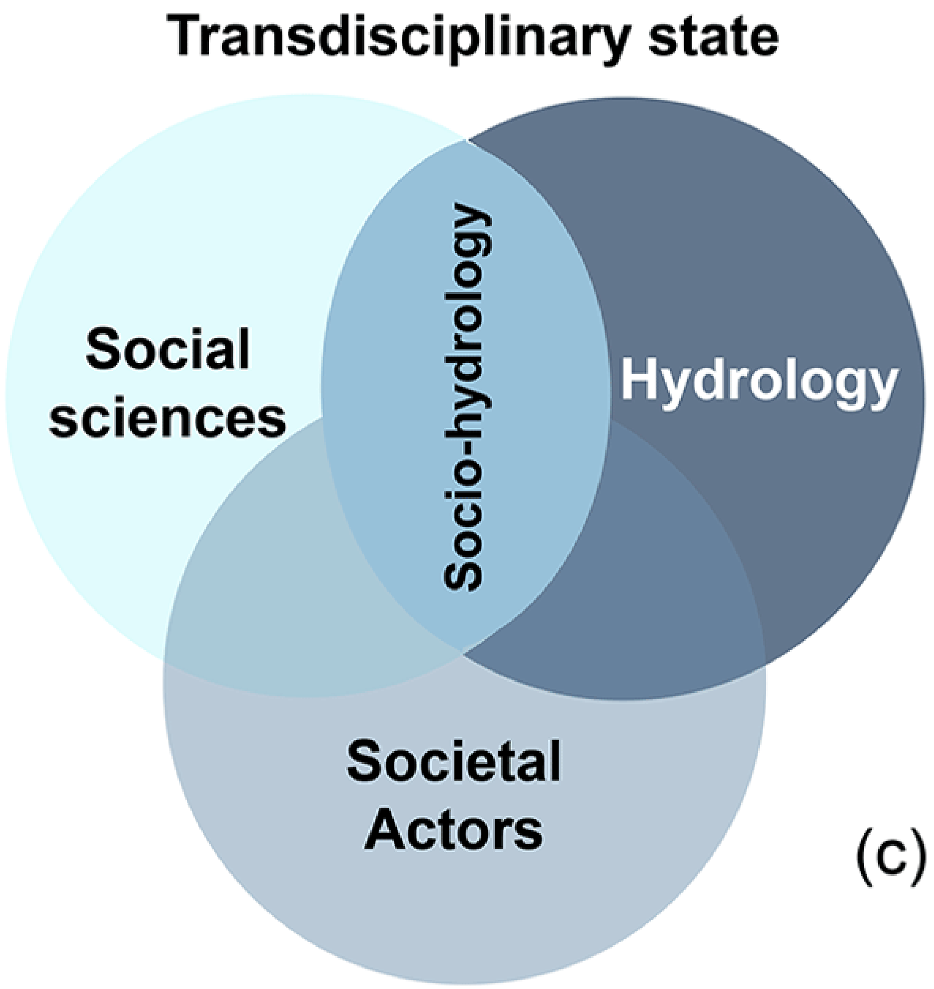


All parts of flow regime affected

[Moreno et al. (2020) J Hydrol]

Socio-hydrology and interdisciplinary studies

"Socio-hydrology can deal with a range of **policy-relevant questions**… while hydrology alone cannot address these questions as it **fails to consider how anthropogenic activities** affect natural hazards, and vice versa (Di Baldassarre et al., 2021)"

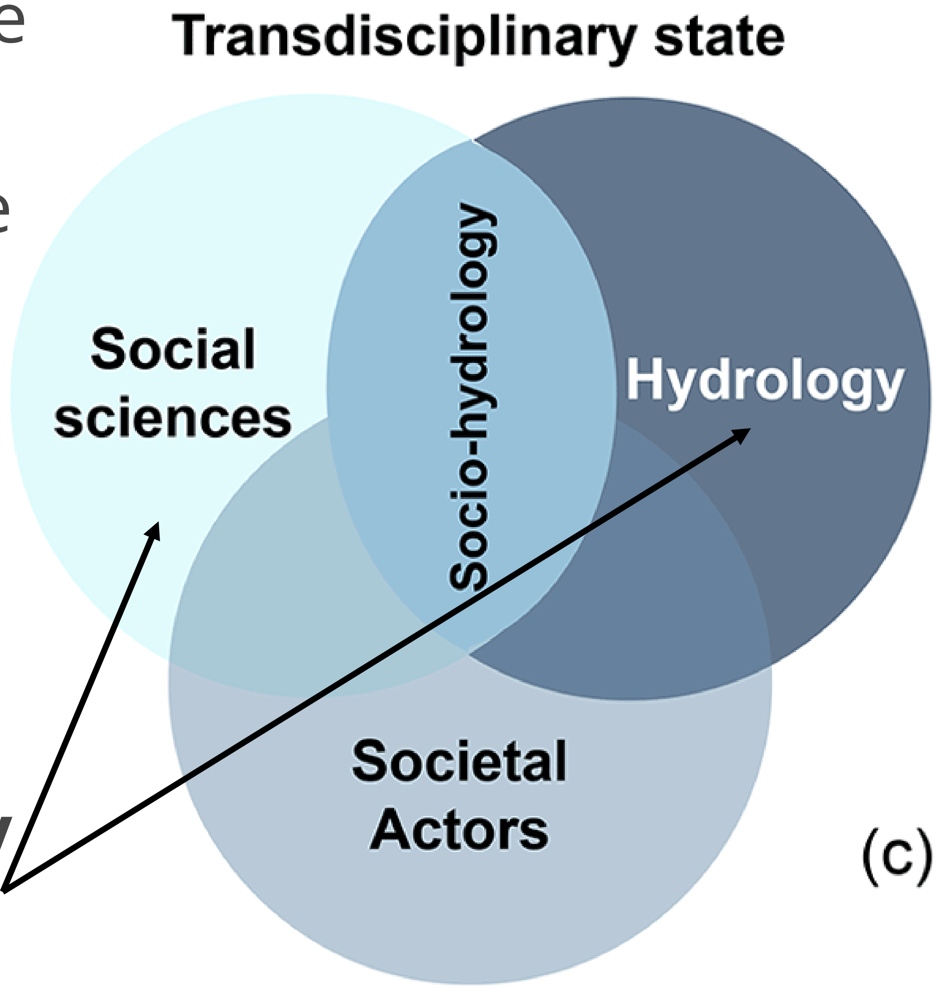


Vanelli et al. (2022) *HESS*

Socio-hydrology and interdisciplinary studies

“Socio-hydrology can deal with a range of **policy-relevant questions**… while hydrology alone cannot address these questions as it **fails to consider how anthropogenic activities** affect natural hazards, and vice versa (Di Baldassarre et al., 2021)”

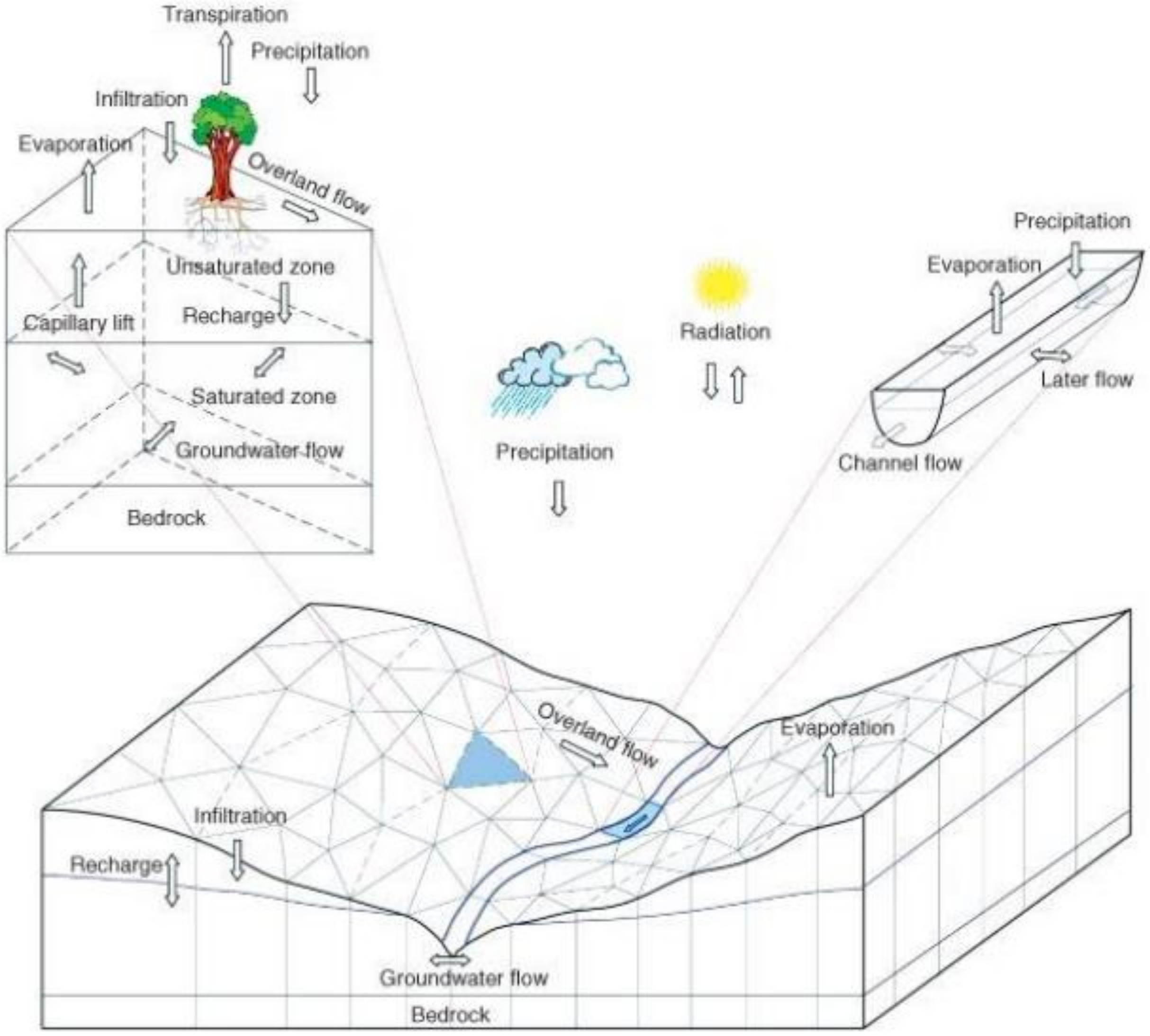
Remote sensing can (and does) play a direct role in socio-hydrology



Vanelli et al. (2022) *HESS*

Hydrological modeling: model specifications

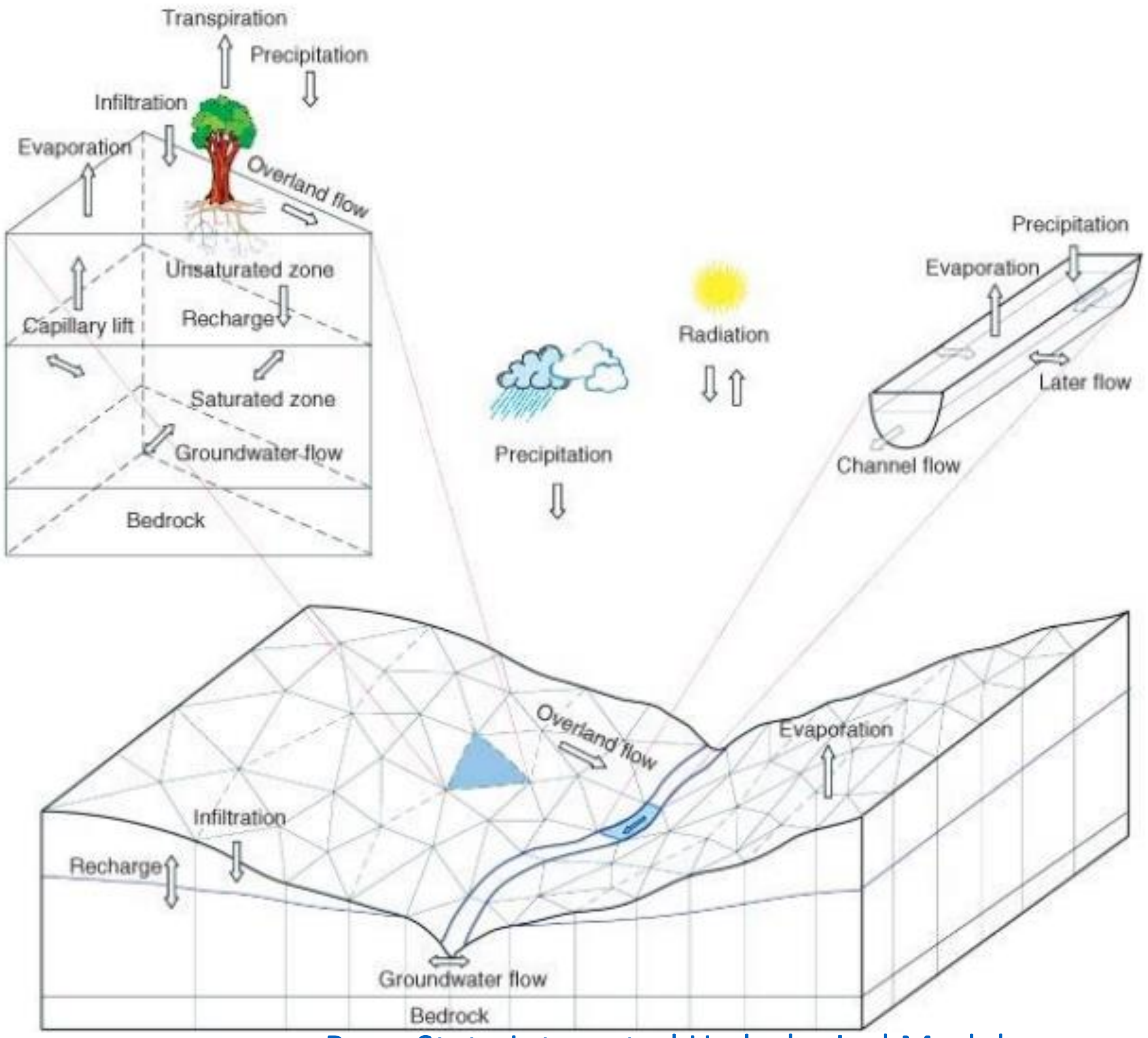
- *Simulation type*
  - Event (single-storm)
  - Continuous (long-term)
- *Physical representation?*
  - Empirical/statistical
  - Conceptual
  - Process or physics-based
- *Spatial structure*
  - Lumped
  - Semi-distributed
  - Distributed



[Penn State Integrated Hydrological Model]

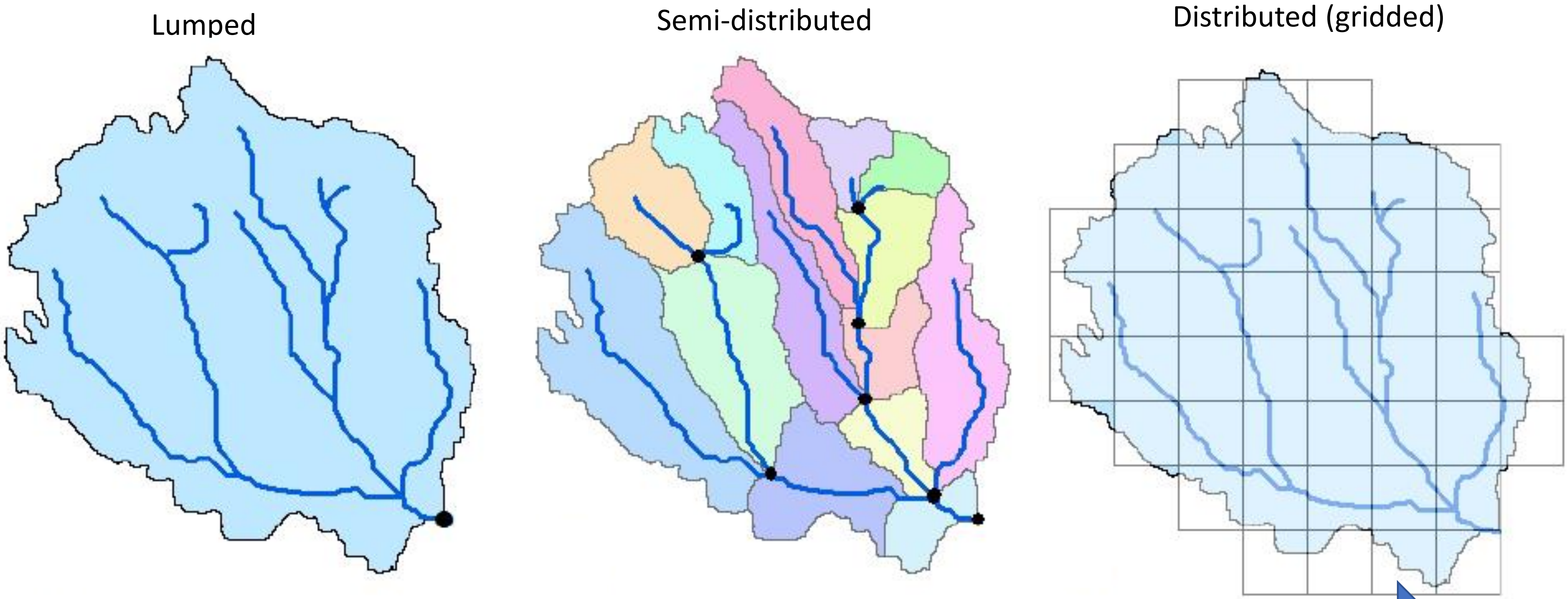
Hydrological modeling: key processes

- Overland flow
- Soil water/moisture
- Capillary lift
- Evaporation and transpiration
- Groundwater recharge
- Groundwater flow



[Penn State Integrated Hydrological Model]

Model spatial structure: rainfall-runoff models

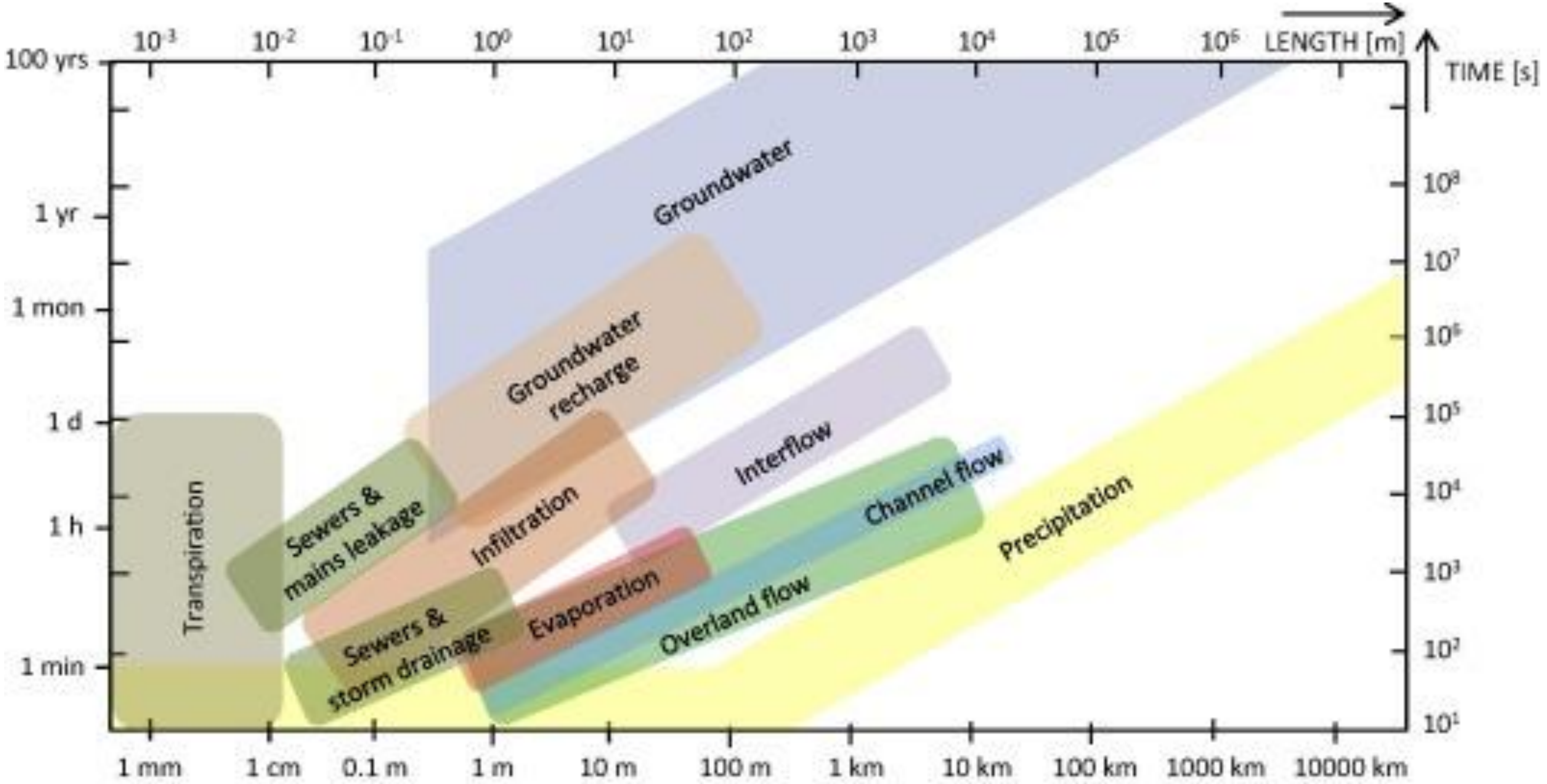


INCREASINGLY DETAILED REPRESENTATION OF SPATIAL PROCESSES

Sitterson et al. (2017))

Process spatial and temporal scales

Important processes in the region of interest affect model choices and model setup



Spatial and temporal scales of hydrological processes in urban areas, Elga et al. (2015) *J Hydrol*)

Model spatial and temporal scales

Soil moisture models → hillslope models → catchment models → global hydrological models

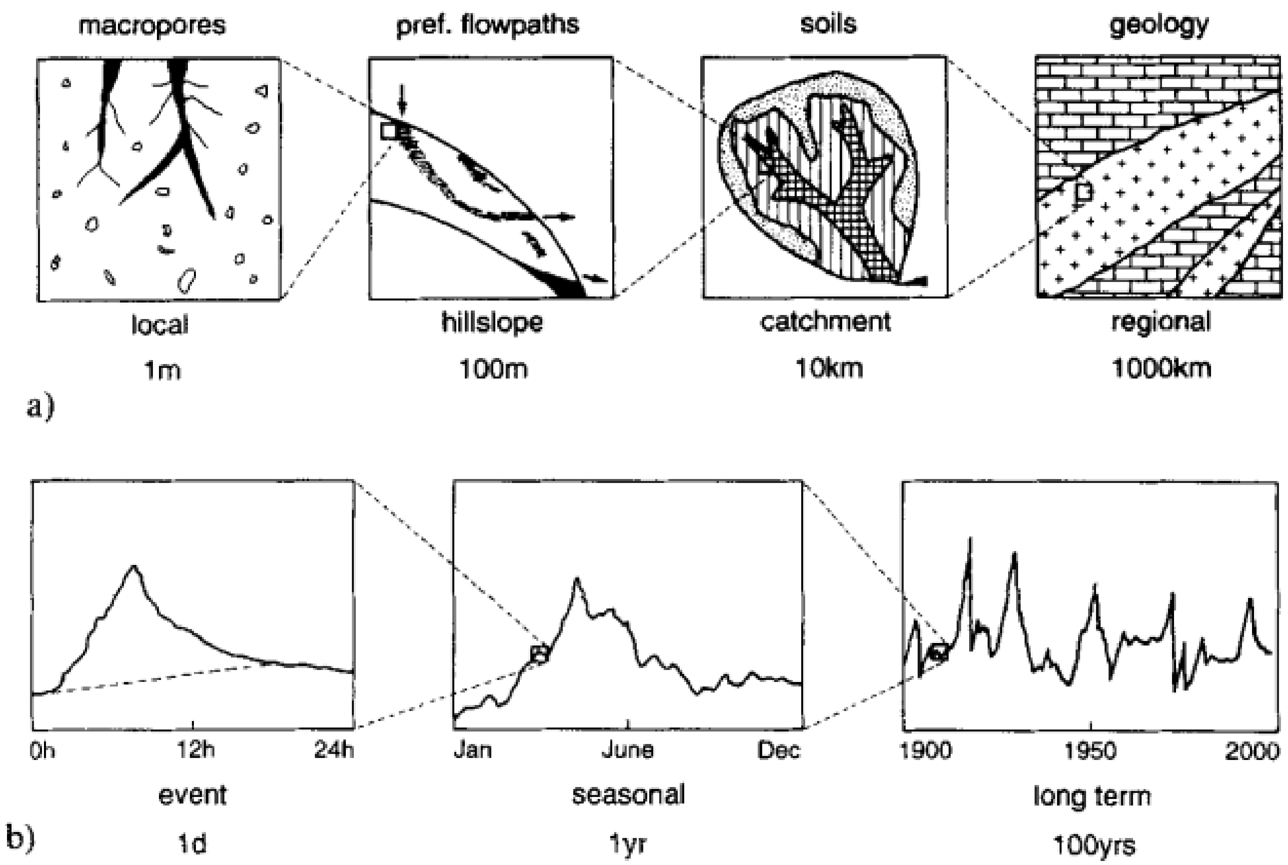
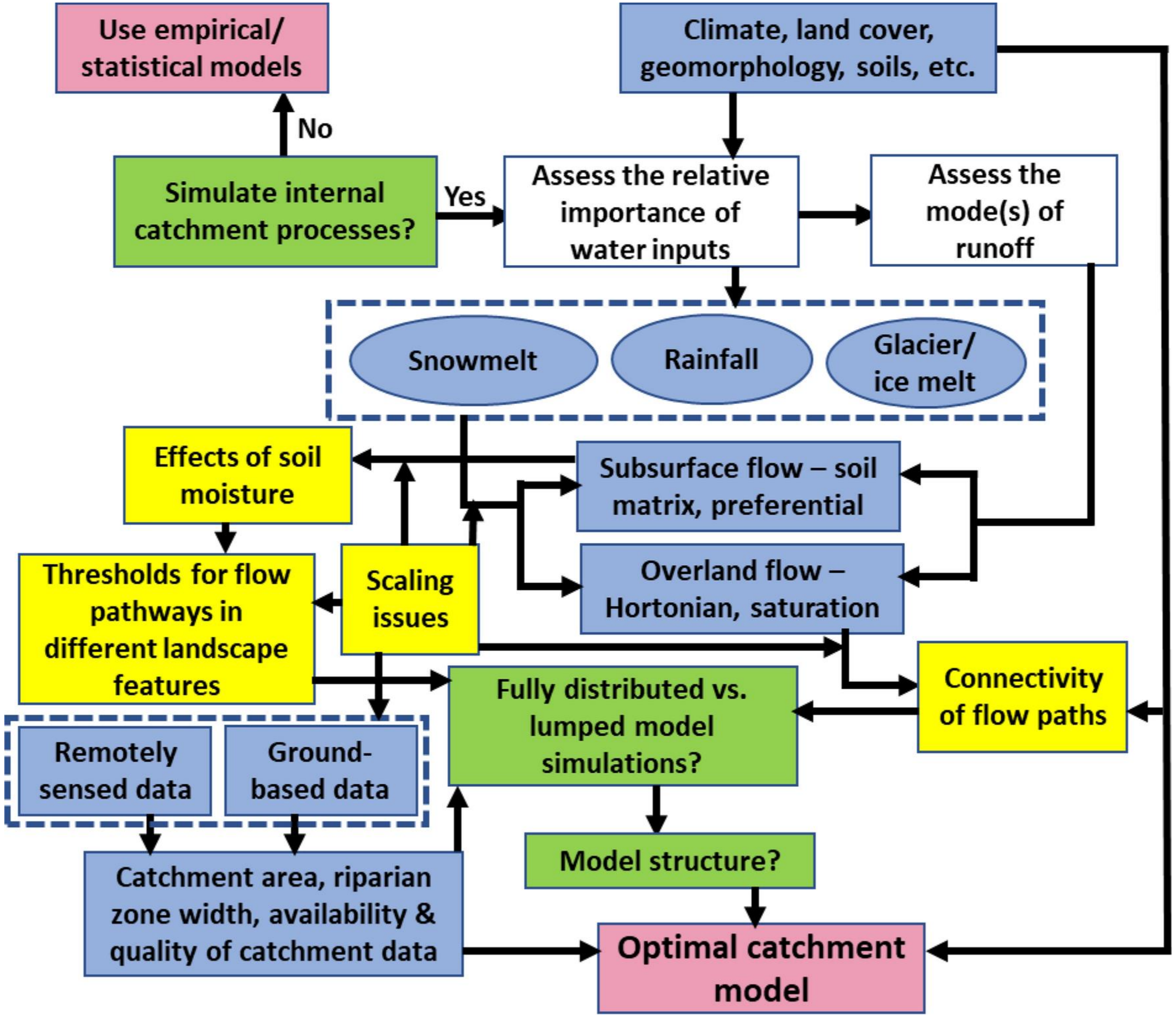


Figure 6. Heterogeneity (variability) of catchments and hydrological processes at a range of (a) space scales and (b) time-scales

Bloschl and Sivapalan (1995) *Hyd Proc*

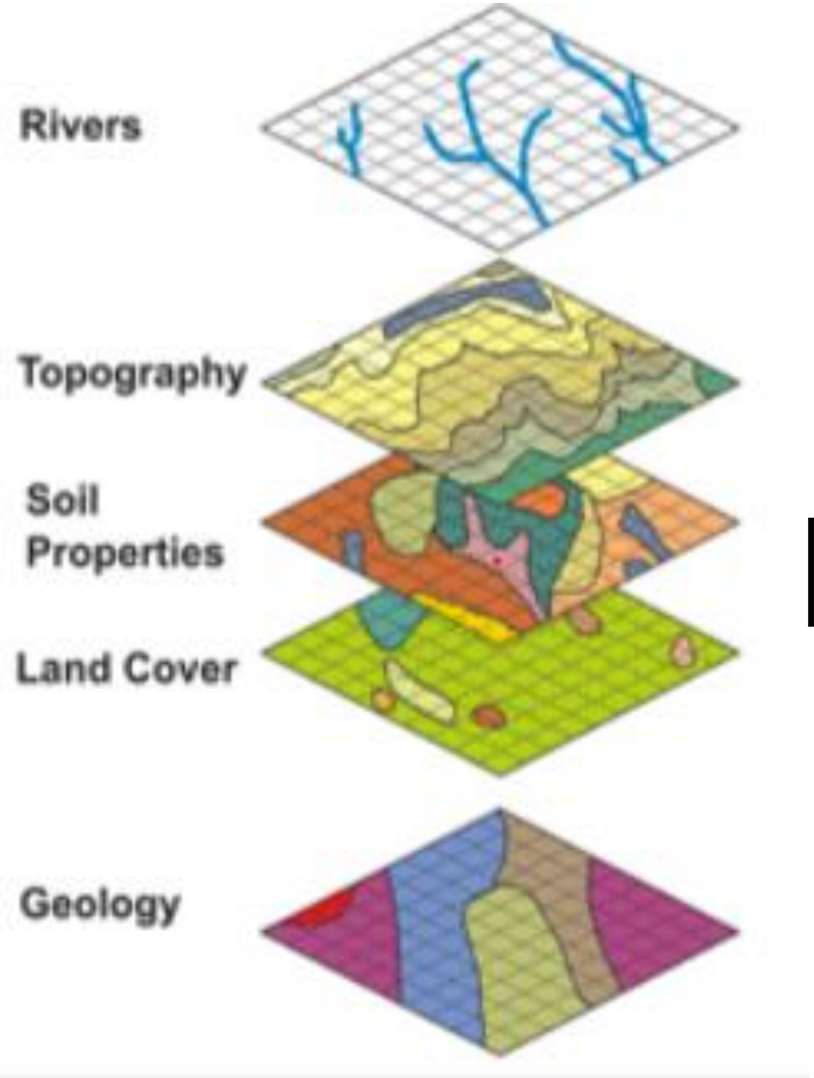
Robust hydrological process representation

- Data requirements (blue)
- Objectives (white)
- Decision points (green)
- Model selection (pink)
- Improvements in model development (yellow)



[Sidle (2021) *Geoscience Letters*]

Model parameterization: an inverse problem



DATA TO PARAMETERS
representing key physical/conceptual processes

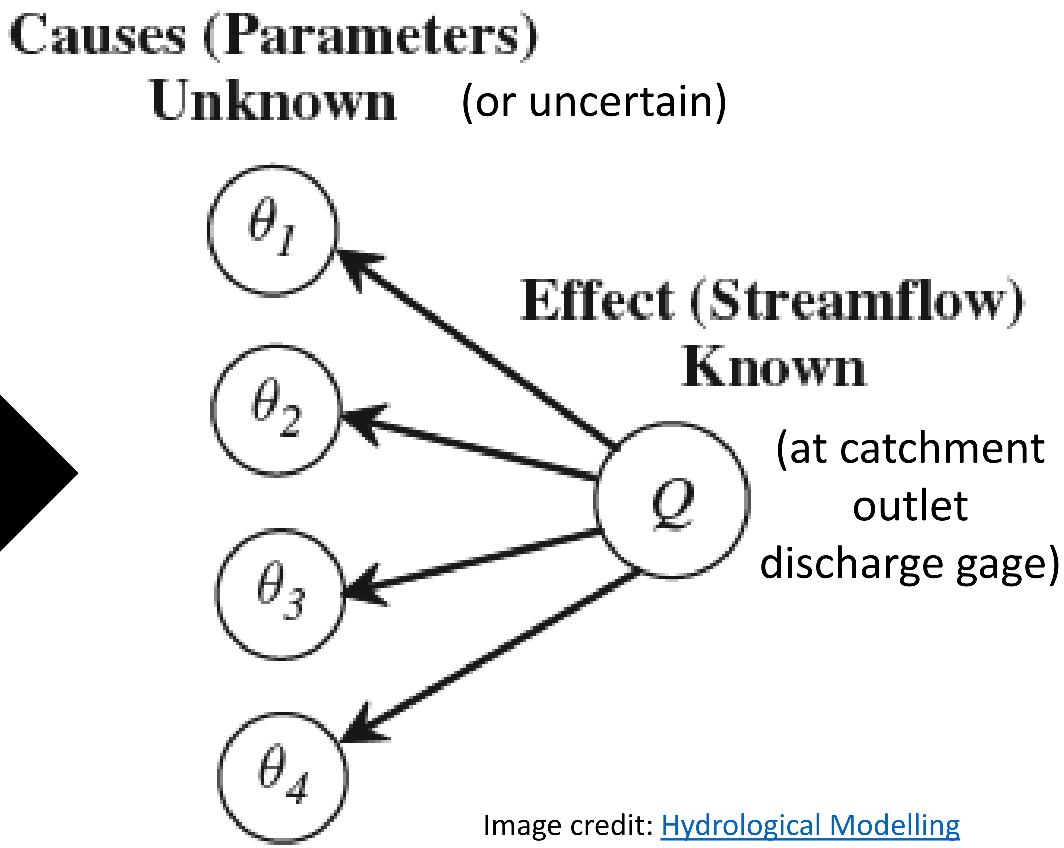


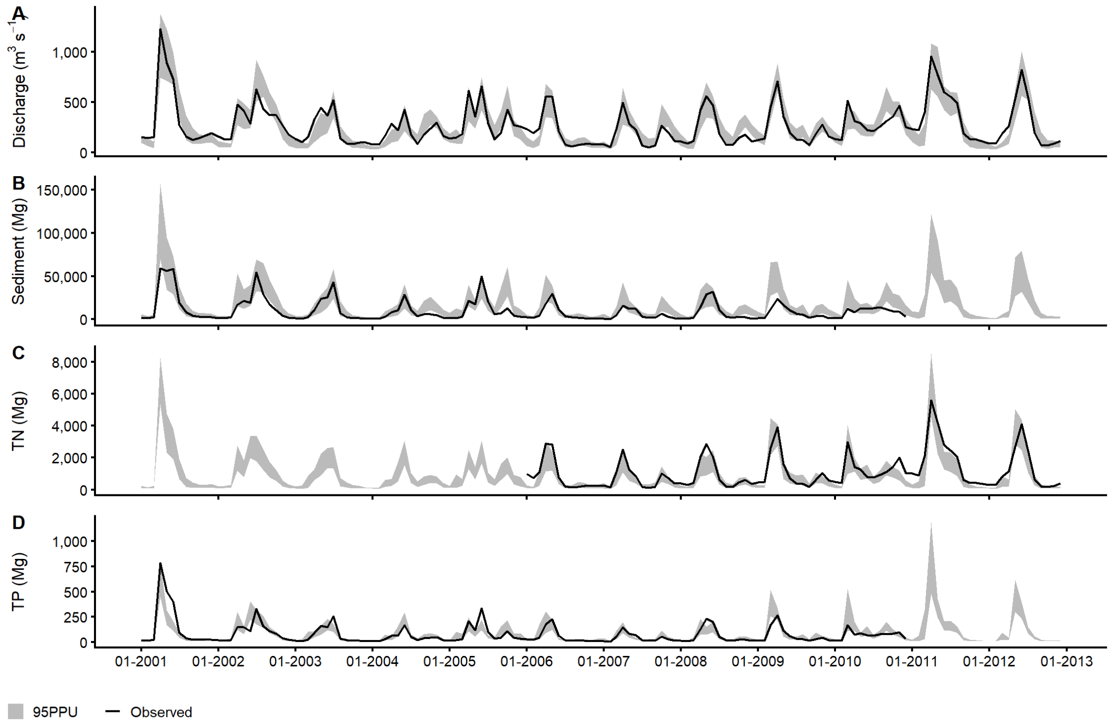
Image credit: Hydrological Modelling and the Water Cycle (2008). Sooroshian et al. (eds)

Calibration/Uncertainty Analysis

- Model assessment: How well does the model capture reality?

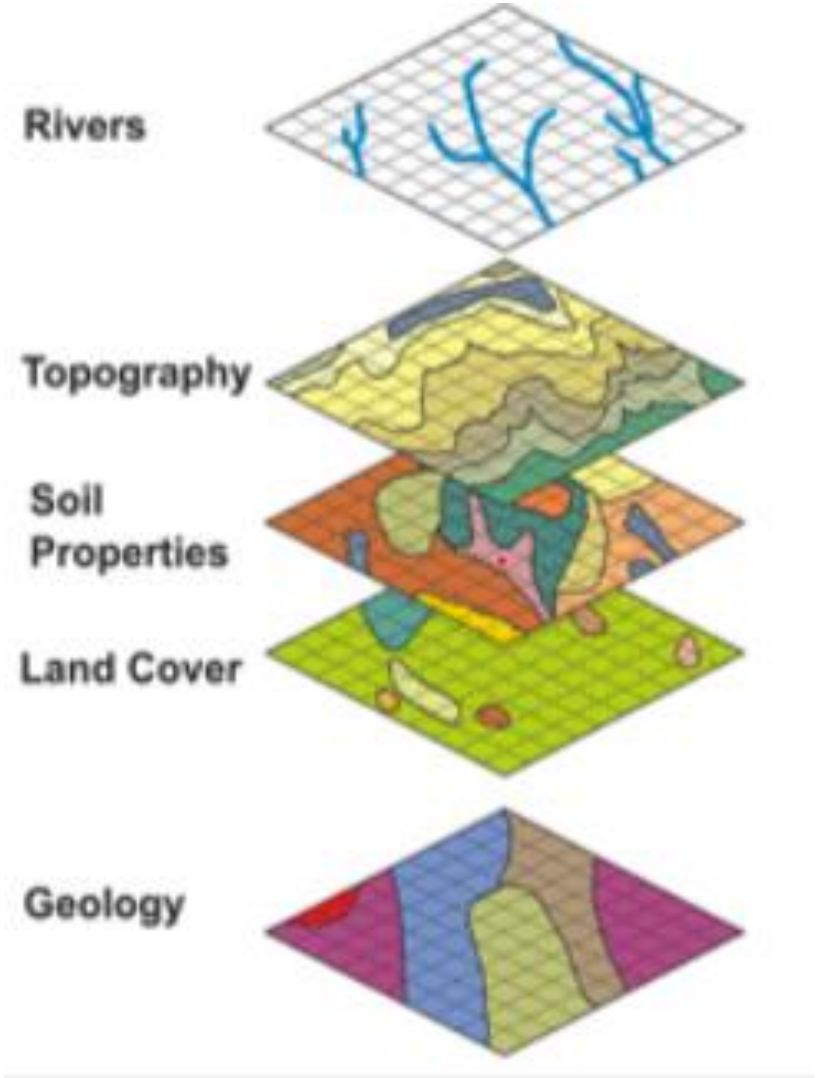
- Assessment options using measurements:
  1. River discharge at catchment outlet
     - Global Runoff Data Centre (GRDC) data
  2. Catchment internal processes (spatial)
     - Evapotranspiration (RS)
     - Depth to water table (wells or coarse country datasets)
     - Crop yield (country datasets/ RS?)
  - 1 & 2 (best option)

Observations vs. simulation

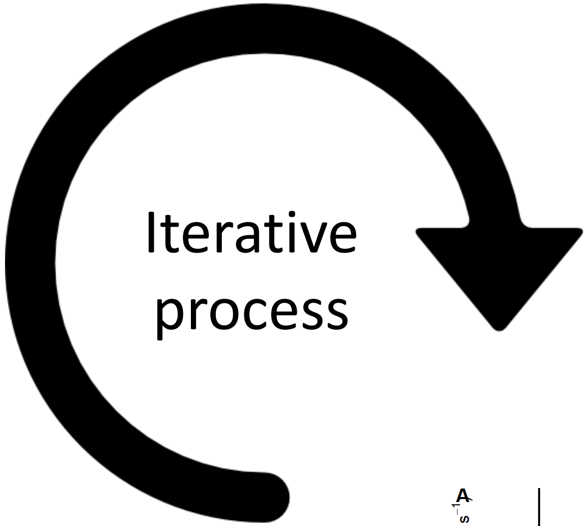


Woznicki et al. (2023) *JAWRA (Supplemental)*

Model parameterization: an inverse problem



ADJUST PARAMETER VALUES to maximize agreement between simulation and observation



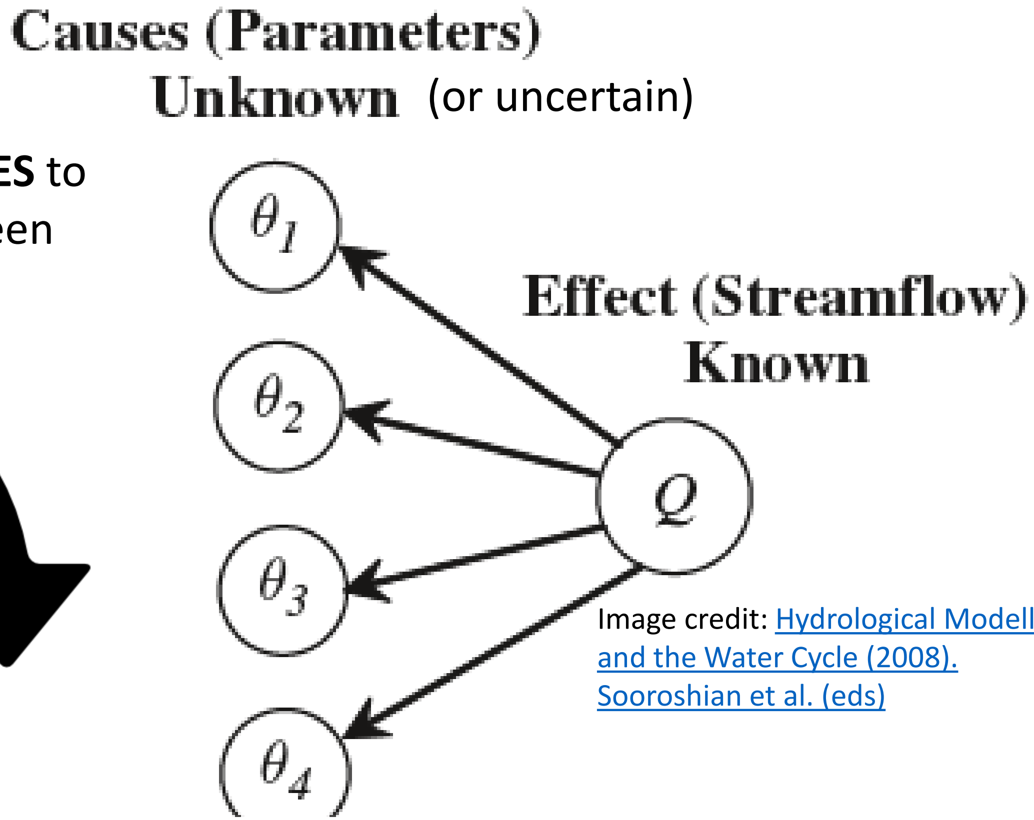
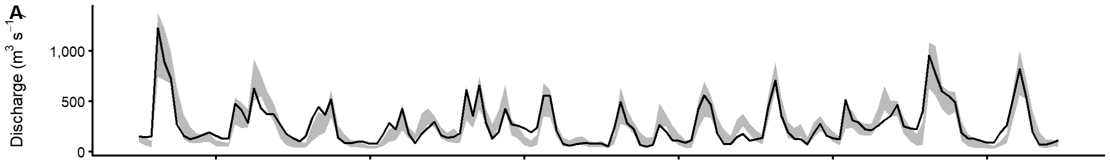


Image credit: [Hydrological Modelling and the Water Cycle (2008). Sooroshian et al. (eds)]



Remote sensing datasets used in hydrology studies

*****Not a complete list!

Can be used in forcing, assimilation, parameterization (initial conditions/physical processes), and/or model calibration/evaluation (depending on the data)

- Precipitation (TRMM, GPM)
- Surface water extent (Landsat, MODIS, Sentinel-1, Sentinel-2, VHR)
- Land cover/land use (Landsat, MODIS, Sentinel-1, Sentinel-2, VHR)
- Soil moisture (GRACE, SMAP, Sentinel-1)
- Terrestrial water storage (GRACE, GRACE-FO)
- Evapotranspiration (MODIS, Landsat, AVHRR)
- Surface water elevation (SWOT, ICESat-2)

Soil and Water Assessment Tool (SWAT / SWAT+)

- **Components:**
  - Land-based hydrological cycle
  - Channel processes and routing
  - Plant growth
  - Land management practices
  - Erosion
  - Nutrient cycles and transport

- **Characteristics:**
  - Continuous (long-term)
  - Semi-distributed
  - Hybrid: physical process information coupled with conceptual and empirical algorithms

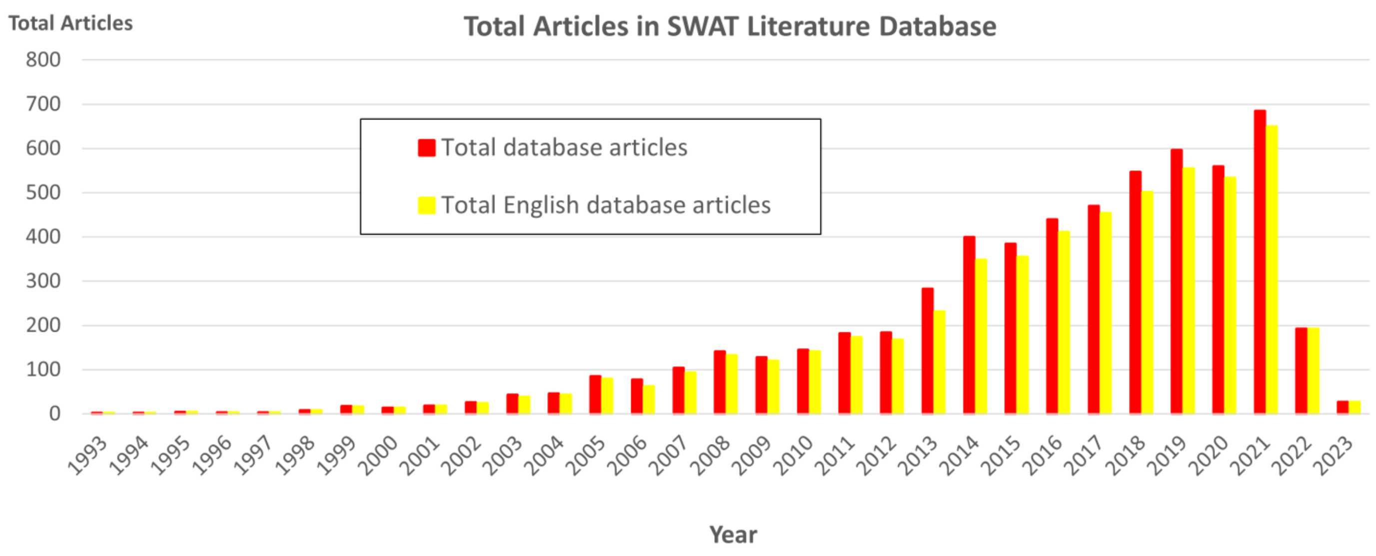
https://swat.tamu.edu/software/plus/

Soil and Water Assessment Tool (SWAT / SWAT+)

- "Comprehensive tool for simulating streamflow and pollutant transport across a wide range of spatial and temporal scales, environmental conditions, land management practices, and land use and climate change scenarios" (Bieger et al. 2016)

- **Components:**
  - Land-based hydrological cycle
  - Channel processes and routing
  - Plant growth
  - ***Land management practices***
  - Erosion
  - Nutrient cycles and transport
- **Open-source code**
- **Can be coupled with complex groundwater models**

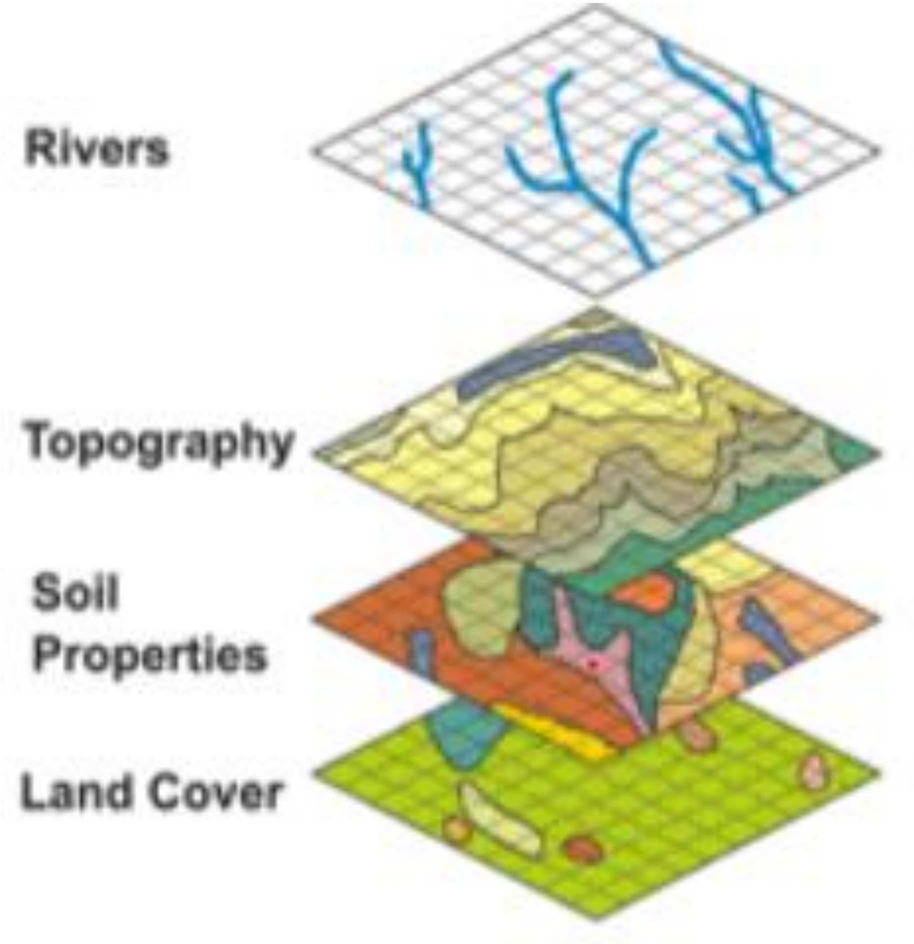
~5900 peer-reviewed articles using SWAT as of March 2023



SWAT Publication Database

SWAT+ Data Requirements

- Digital elevation model (DEM)
- Soil raster with database of key parameters
  - E.g., Sand/Silt/Clay, hydraulic conductivity, bulk density, etc.
- Land cover / land use map
- Daily weather (tabular with coordinates)
- Other (optional, dependent on catchment):
  - Reservoir volumes and operation
  - Common crop rotations and land management



Spatial representation in SWAT+

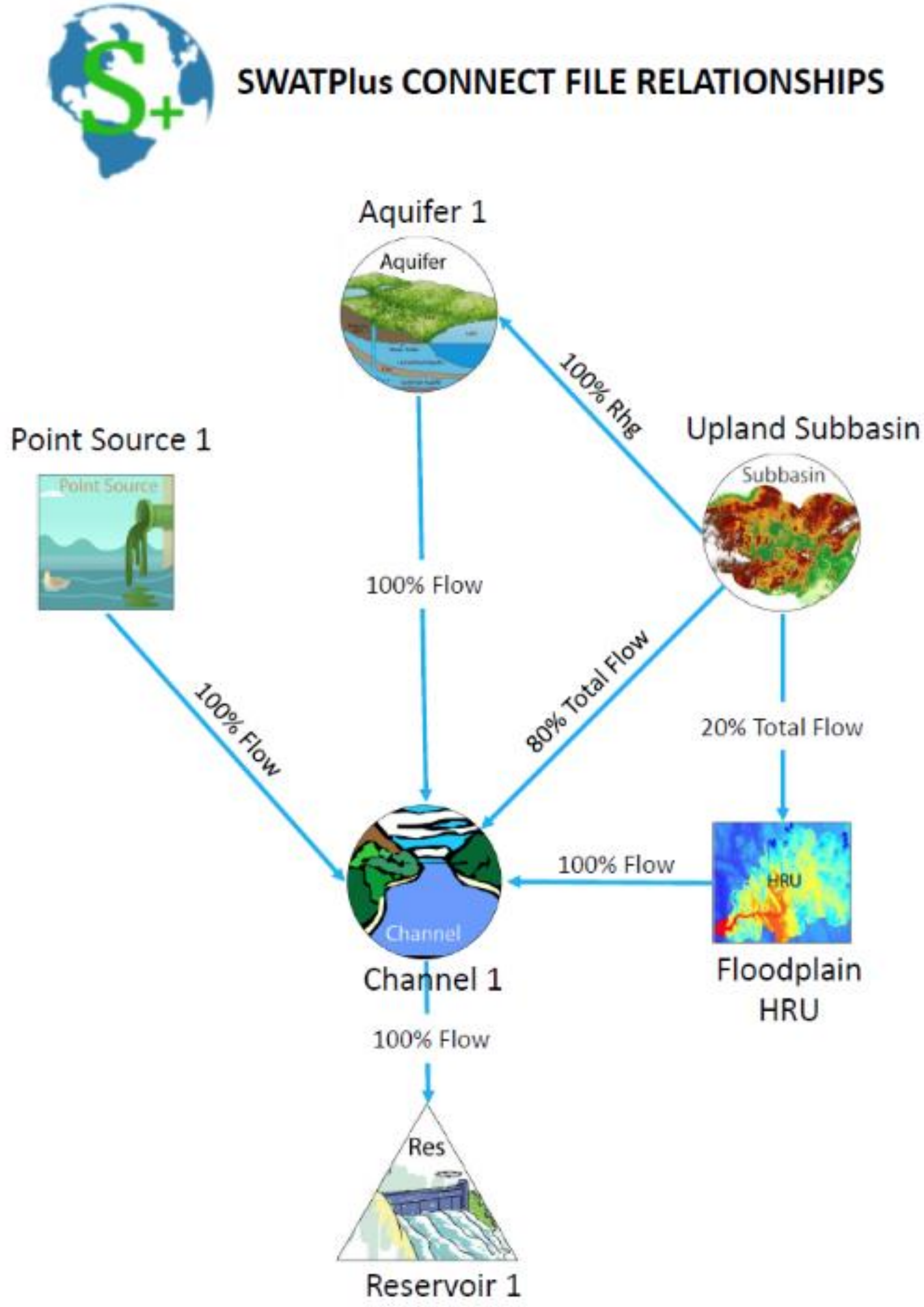
- Many spatial objects in SWAT+ with variety of connections for flow routing:

a) Upland to floodplain to river channel (runo

b) Upland to aquifer (recharge)

c) Channel to reservoir (river flow)

d) Withdrawal from reservoir to upland (irrigation)



https://swatplus.gitbook.io/docs/user/editor/inputs/connections

Overview of modeling process in SWAT+

1. Catchment/watershed delineation (digital elevation model)

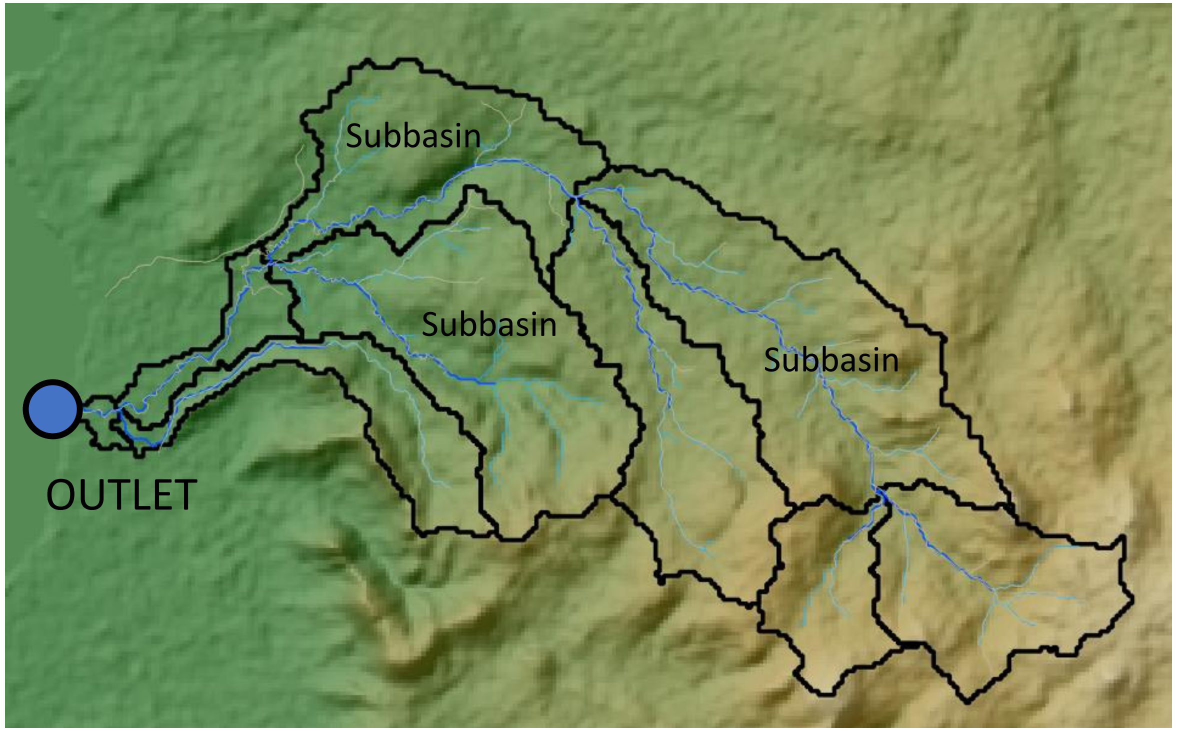
2. Landscape characterization = Landscape units (LSUs)

3. Hydrologic response units (HRUs) definition

4. Weather inputs (daily precipitation, temperature, rel. humidity, wind speed, solar radiation)
5. Other (optional decision tables):
    1. Parameterize agricultural/forestry management operations
    2. Initialize reservoir operations

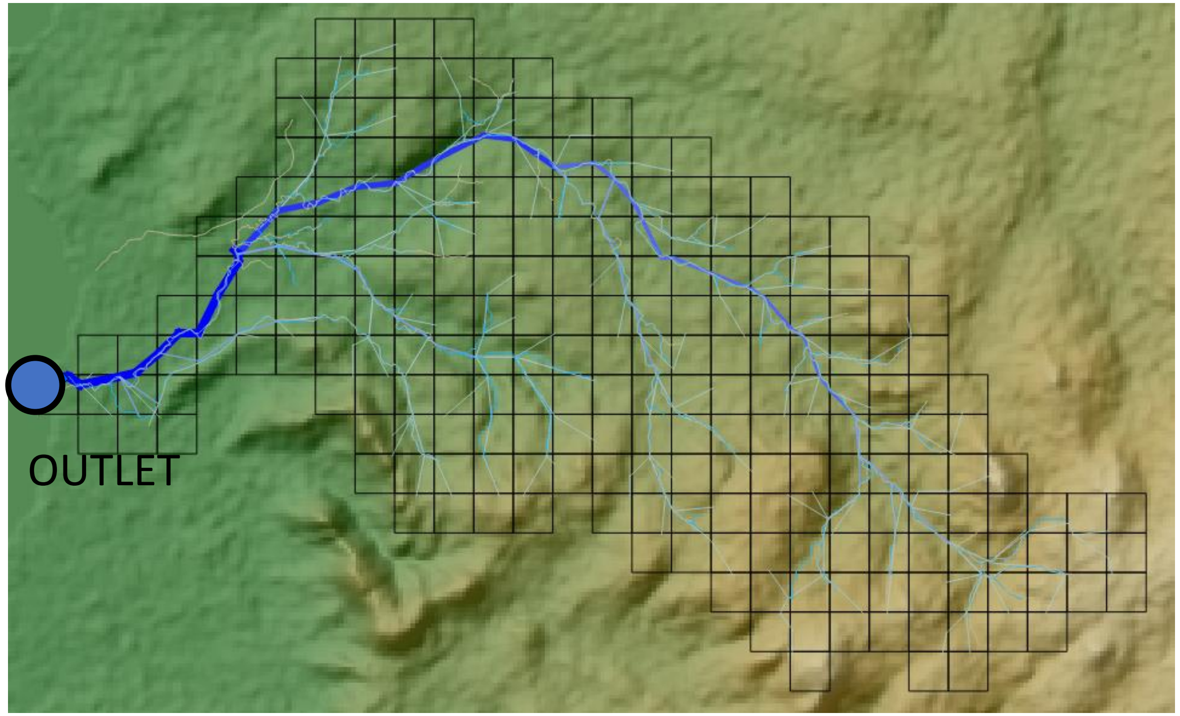
Watershed/catchment delineation (drainage based)

- Requires digital elevation model (DEM) and (optional) stream network shapefile
- Calculates flow direction and flow accumulation based on a defined outlet/pour point
- Defines catchment boundary
- Defines subcatchments based on stream network



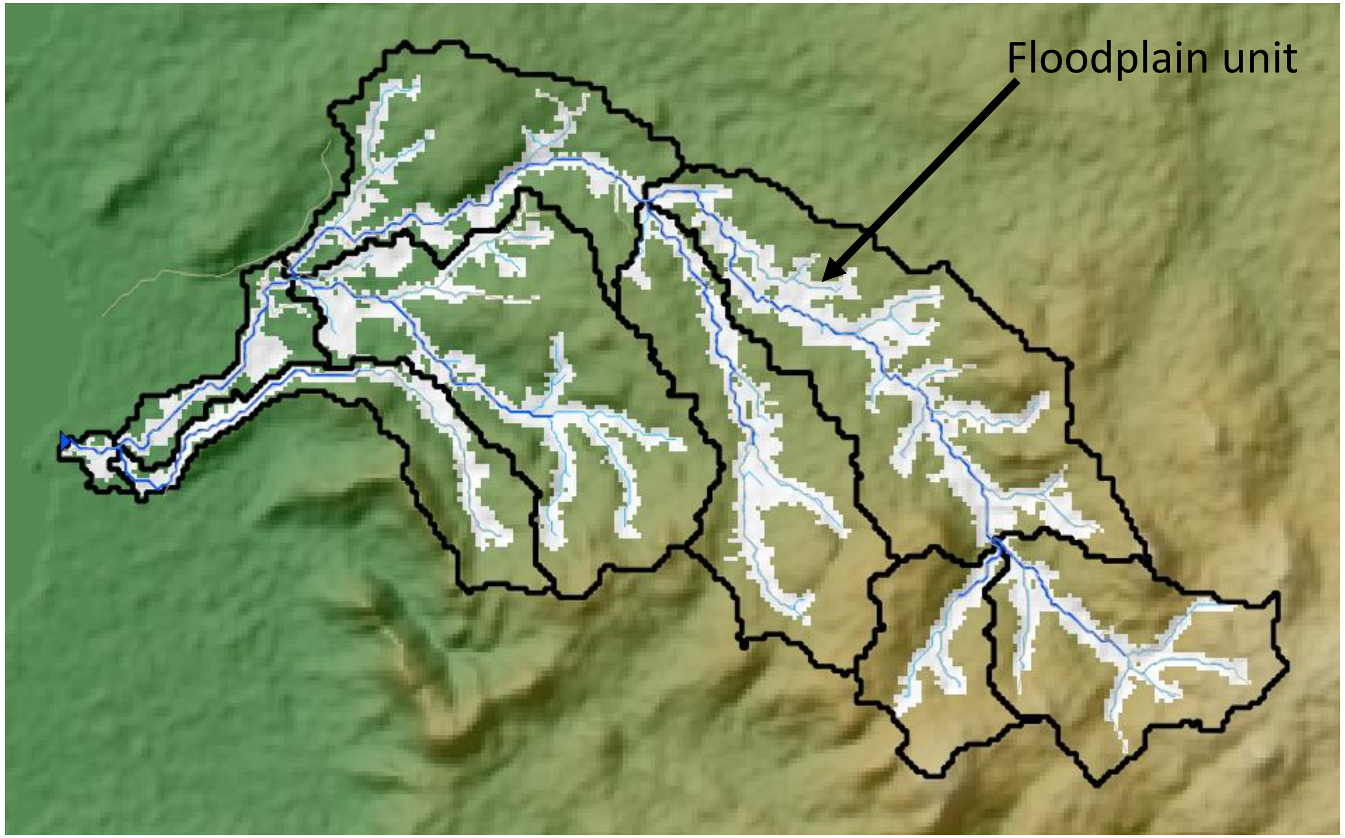
Watershed/catchment delineation (grid-based)

- Requires digital elevation model (DEM) and (optional) stream network shapefile
- Calculates flow direction and flow accumulation based on a defined outlet
- Defines catchment boundary
- Defines grid cells and attaches them to stream network



Calculate landscape units (LSUs)

- Partition catchment into floodplain and upland units
- Multiple methods
  - Buffer (e.g. 25 m)
  - DEM-based using low points on the landscape



Hydrologic response unit (HRU) definition

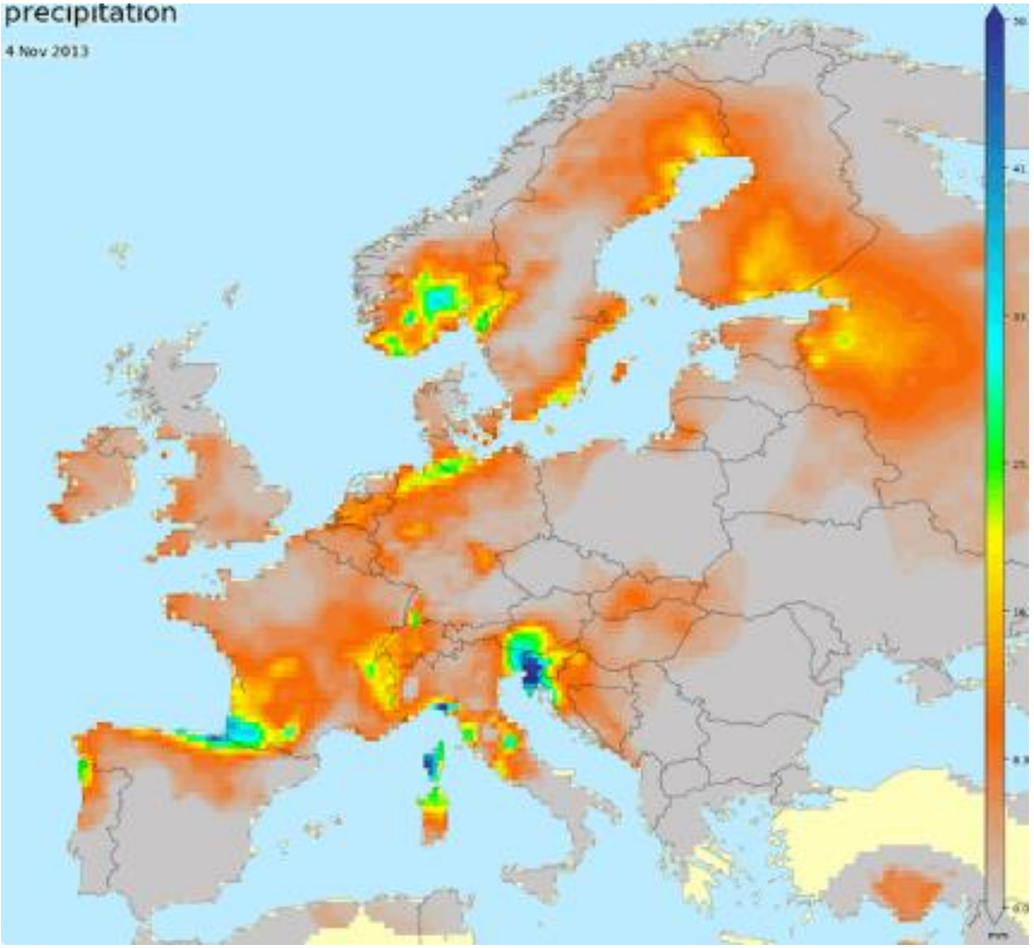
- Each HRU has uniform land use/soil/slope/land management
- Lumped aspatial units with subbasin or grid cell
- Computationally efficient
- User defined level of aggregation
- Model is param

Credit: Amin Zettam

Ingest daily weather data

- Precipitation
- Minimum and maximum temperature
- Relative humidity*
- Wind speed*
- Solar radiation*

*Not required, SWAT+ weather generator (WGEN) can create based on long-term global weather generator database

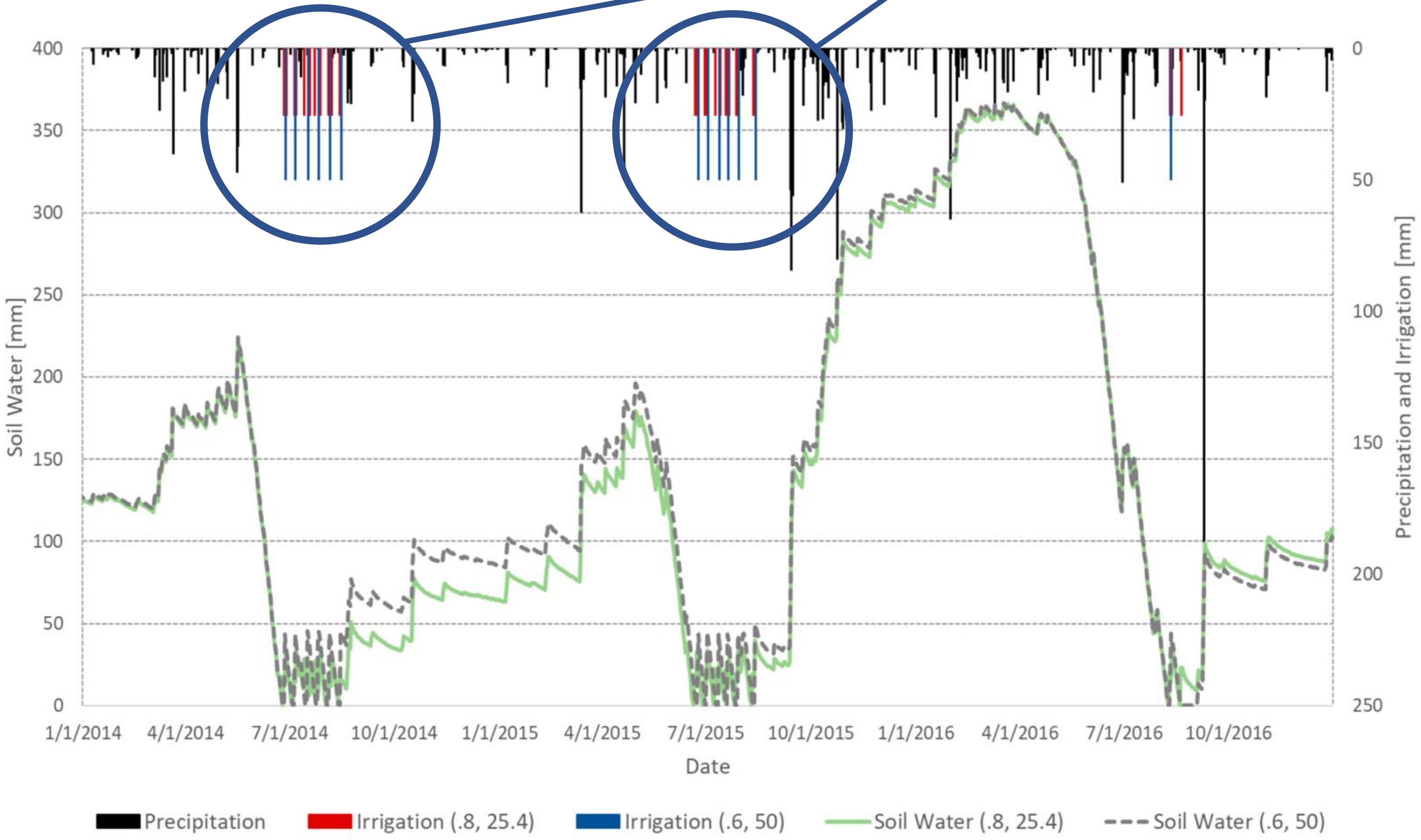


[E-OBS daily gridded meteorological data for Europe from 1950 to present derived from in-situ observations]

Other model components

- Agricultural decisions
  - Irrigation
  - Planting and harvesting
  - Rotations
  - Tillage
- Reservoir operations
- Water withdrawals
- Point source discharges

Irrigation based on soil water thresholds



Arnold et al. (2018) *Water*

Upcoming NASA Applied Remote Sensing Training Program (ARSET) session

- Pre-fire land cover mapping
- Watershed delineation
- Post-fire burn severity
- Pre- and post-fire hydrology/water quality modeling with SWAT

TRAINING

ARSET - Assessing the Impacts of Fires on Watershed Health

PROGRAM AREA: WILDFIRES DISASTERS ECOLOGICAL CONSERVATION WATER RESOURCES

HOME / JOIN THE MISSION / TRAINING

DESCRIPTION

This advanced-level training will focus on using remote sensing observations for monitoring post-fire impacts on watershed health, building off the ARSET training offered in 2021: Satellite Observations and Tools for Fire Risk, Detection, and Analysis. Specifically, this training will highlight uses of NASA Earth observations (EO) for pre-fire land cover mapping, watershed delineation and stream mapping, post-fire burn severity mapping, and pre- and post-fire riverine and freshwater water quality. This three-part training will highlight case studies that use remote sensing data for assessing the impacts of fires on watersheds. This training will also provide participants with hands-on exercises for using NASA EO for these assessments within the Soil Water Assessment Tool (SWAT) and Google Earth Engine.

[AGENDA]

DETAILS

July 6, 2023 - July 13, 2023

LANGUAGE(S): English

TRAINING TYPE: Online Training

LEVEL: Advanced

TRAINING SOURCE: ARSET

Acknowledgements

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Grand Valley State University
Robert B. Annis Water Resources Institute

NASA LCLUC

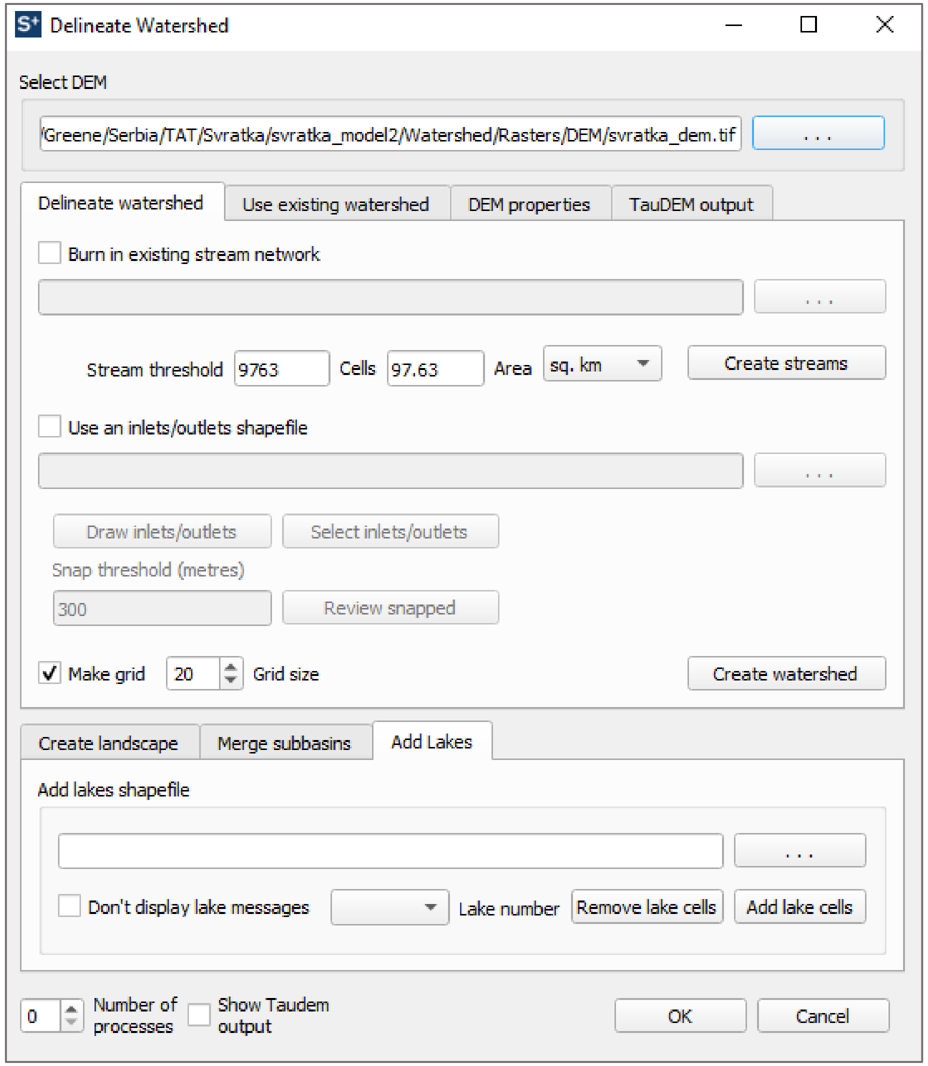
Grant #80NSSC22K0467

SWAT Walkthrough – Setup

- QGIS > Plugins > Install Plugins > Install SWAT+
- Click SWAT+ tool, S+, in the top-right of the QGIS toolbar
- Create **New Project** > select directory > *svratka_model*
- **Delineate Watershed**

SWAT Walkthrough – Delineate Watershed

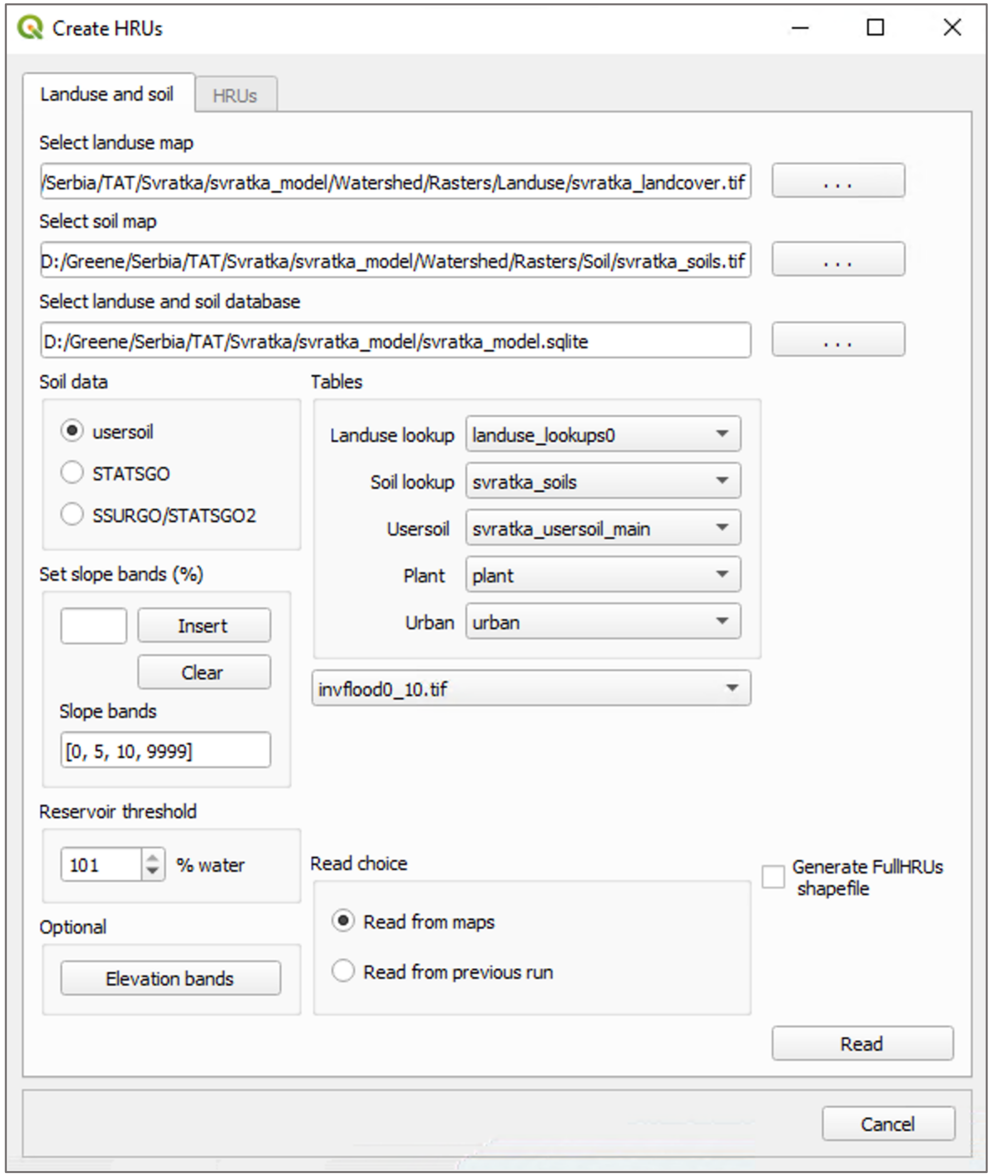
- Select DEM > *Model_Inputs/DEM/svratka_dem.tif*
- Uncheck **Burn in existing stream network**
- **Create streams**
- Leave inlets/outlets unchecked
- Check **Make grid**, enter 20, click **Create watershed**
- **Create landscape** > **Create** > DEM inversion with 9763 cells & 0.10 slope > **Create** > **Done**
- Click **OK**



SWAT Walkthrough – Create HRUs

Landuse and soil

- Select landuse map > *Landcover/svratka_landcover.tif*
- Select soil map > *HWSD/svratka_soils.tif*
- Leave landuse and soil database as default
- Soil data > **usersoil**
- Tables > Landuse lookup > *Landcover/landuse_lookups.csv*
- Tables > Soil lookup > *HWSD/svratka_soils.csv*
- Tables > Usersoil > *HWSD/svratka_usersoil_main.csv,* **then** *svratka_usersoil_layers.csv*

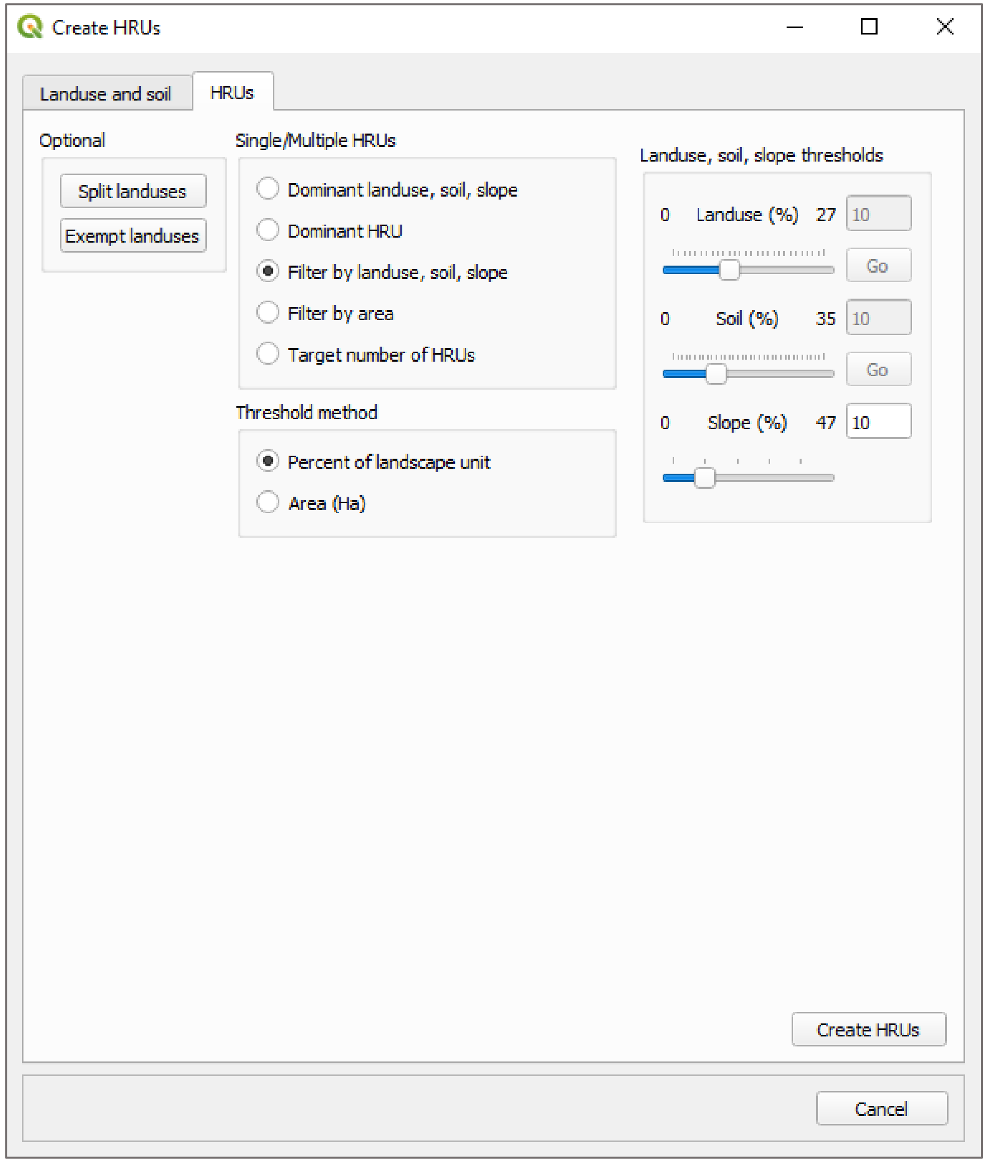


SWAT Walkthrough – Create HRUs (cont.)

- Set slope bands at 5 and 10%
- Reservoir threshold and elevation bands will be left as the default
- Enter *invflood_10.tif* in the floodplain map dropdown
- Select **Read from maps** and **Read**

HRUs

- In HRUs tab, select **Filter by landuse, soil, slope**
- Landuse = 10% > **Go**
- Soil = 10% > **Go**
- Slope = 10% > **Create HRUs**



SWAT Walkthrough – Run SWAT+

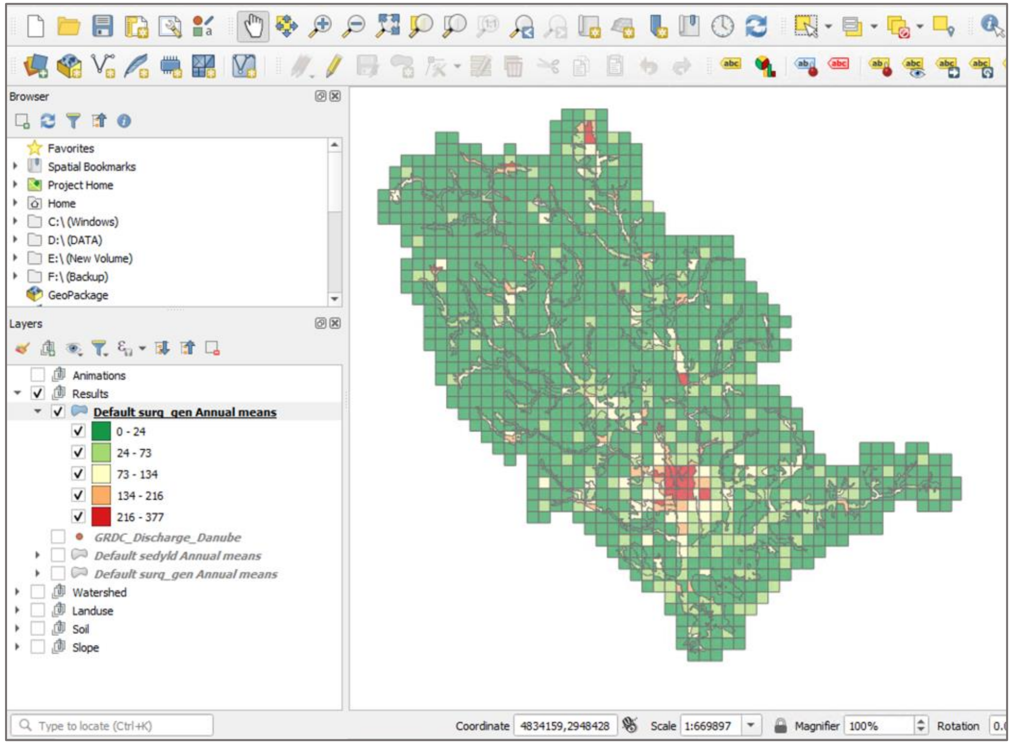
- Click **Edit Inputs and Run SWAT+, Start**
- Click **Edit SWAT+ Inputs,**
- Weather Generator > Import Data > **Start**
- Weather Stations > Import Data > *Weather* > **Start**
- Click **Run SWAT+,**
- Simulation period = 2018-2022
- Output to print > warm-up period = 2 years
- Select only the outputs displayed to the right. **Save Settings & Run Selected**

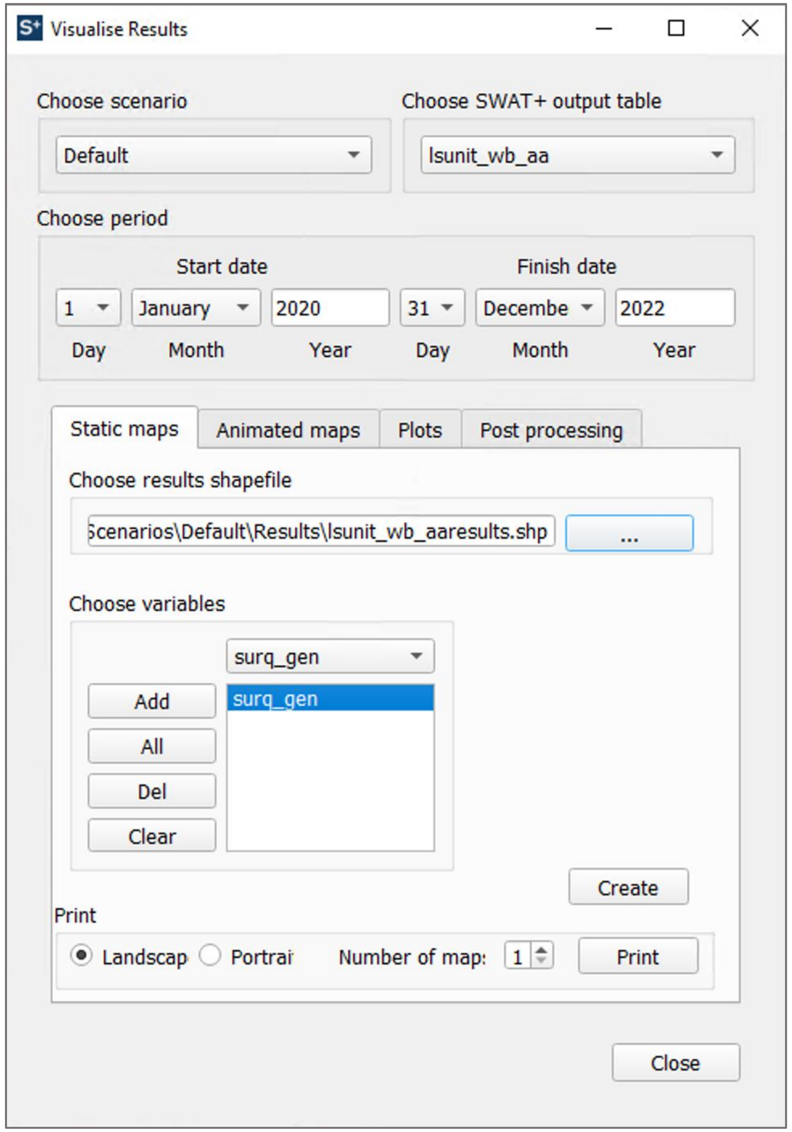
Outputs to Select

	Daily	Monthly	Yearly	Average	Outputs
Model Components					
Channel		✓	✓	✓	channel_sd channel_sdmorph
Water Balance					
Basin					basin_wb
Landscape Unit			✓	✓	lsunit_wb
HRU					hru_wb
Losses					
Basin					basin_ls
Landscape Unit				✓	lsunit_ls
HRU					hru_ls

SWAT Walkthrough – Visualize: Map

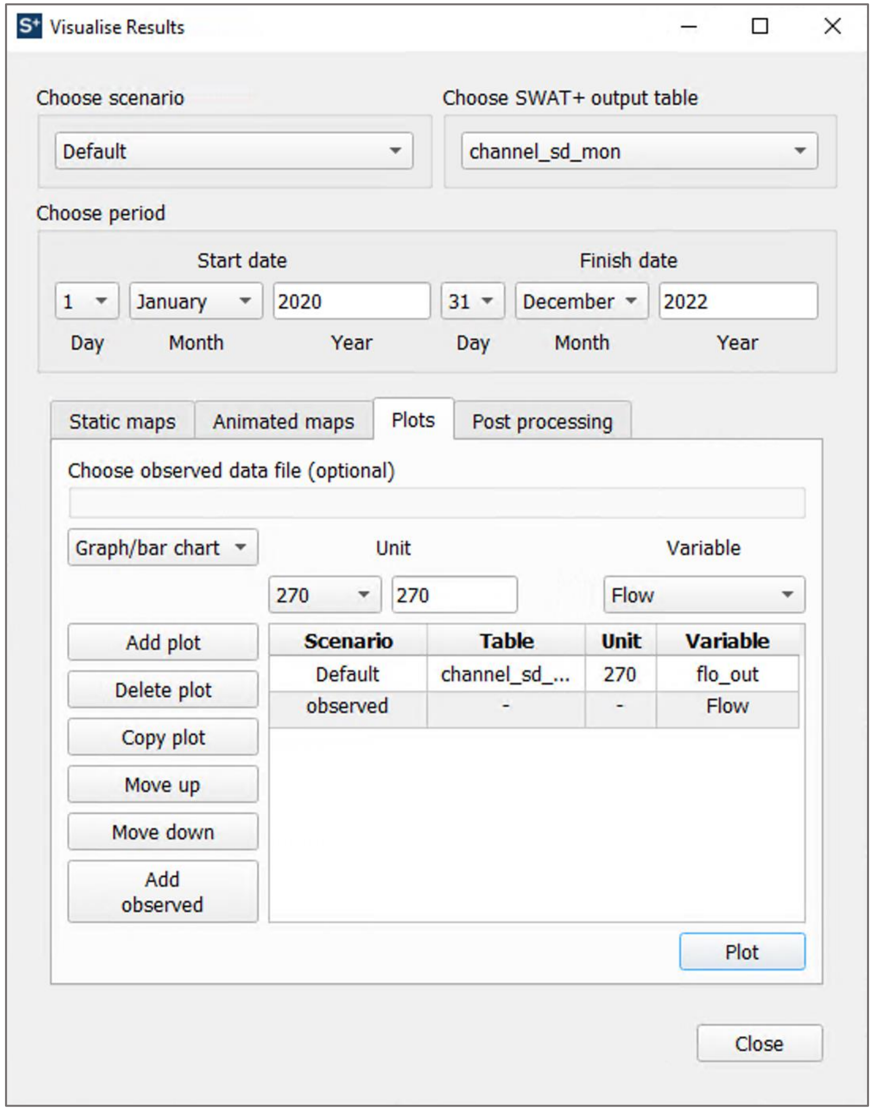
- Click **Visualize**
- Choose SWAT+ output table > *lsunit_wb_aa*
- Static maps > Choose variables > *surq_gen* > **Add** > **Create**



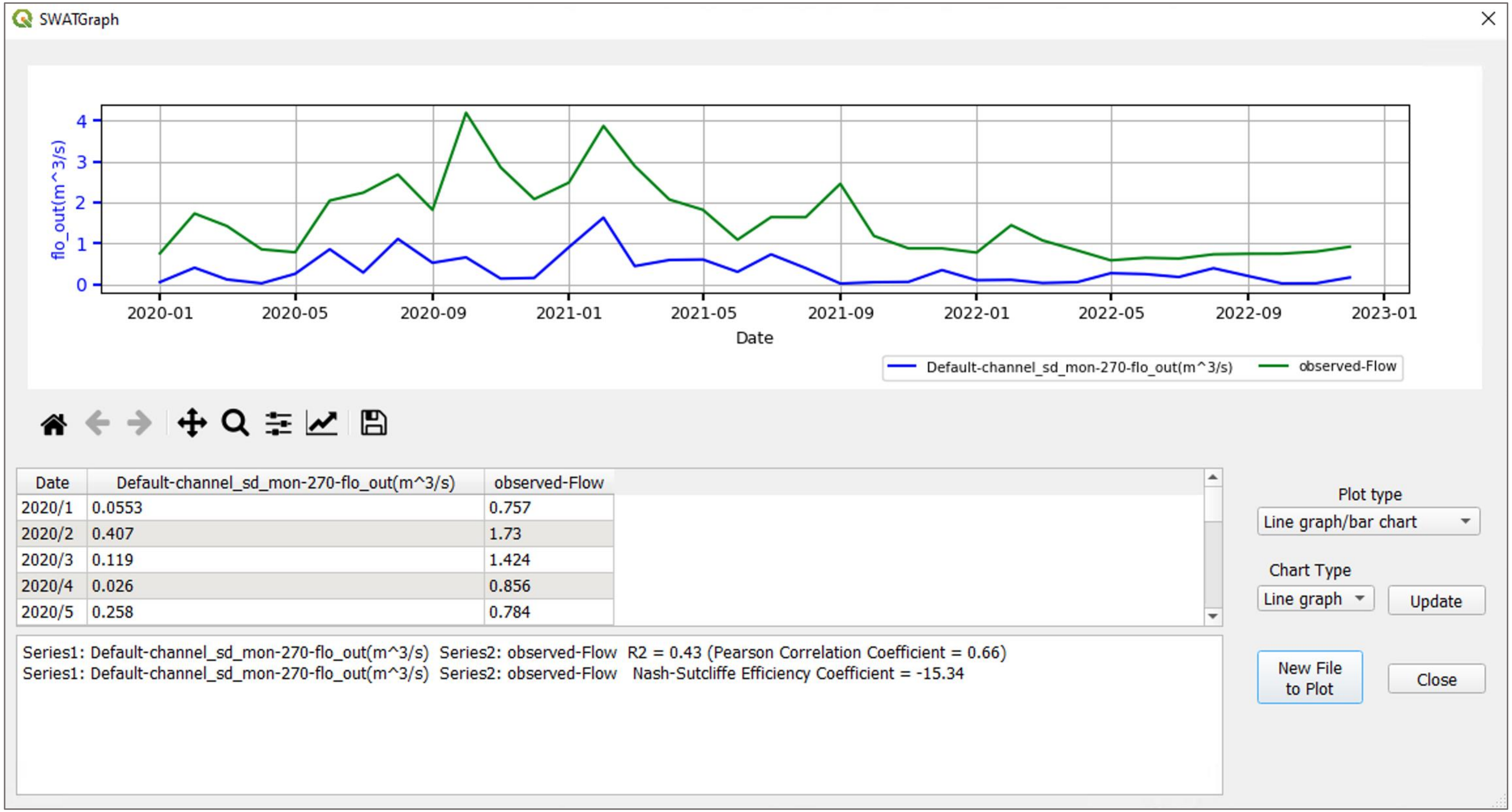


SWAT Walkthrough – Visualize: Time Series

- Click **Visualize**
- Choose SWAT+ output table > *channel_sd_mon*
- Plots > Choose observed data file > *GRDC_Stations/6142260_observedFlow.csv*
- Plot type > **Graph/bar chart**
- Unit > 270
- Variable > *flo_out* > **Add plot**
- **Add observed**
- **Plot**
- Create CSV filename, *svratka_flow_plot* > **Save**



SWAT Walkthrough – Visualize: Time Series



SWAT Walkthrough – Landcover Change Example

- Create a secondary SWAT+ project using the same parameters except the landuse map
- In **Create HRUs** > Select landuse map > *Landcover/landcover_change.tif*
- In Visualize Results > Choose SWAT+ output table > *lsunit_ls_aa*
- Choose variables > *sedyld* > **Add** > **Create**
- Compare these *sedyld* results to the original project's *sedyld* results
  - Note changes in sediment yield in the Northeast corner where "reforestation" occurred