# Integrated Hydrological Modeling Practices and Uncertainty Analysis

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Texas A&M AgriLife Research
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국립한밭대학교 HANBAT NATIONAL UNIVERSITY

*Overview:*

This workshop aims to provide a better understanding of the principles of hydrologic cycle and water budgets and to teach the fundamental principle and structure of a widely used integrated hydrologic model, SWAT-MODFLOW, with hands-on exercises for use in assessing spatio-temporal patterns of water resources and fluxes. It will also cover general procedures of model development, implementation, evaluation, and optimization.

*Course Objectives:*

Upon successful completion of this workshop, students will be able to (1) understand the fundamental principles of each model (SWAT, MODFLOW, and SWAT-MODFLOW); (2) construct a SWAT-MODFLOW model; (3) perform a simulation with various configurations; (4) evaluate and visualize simulation results; and (5) perform model optimization. Students will learn to work with a graphical user interface, QSWATMOD, and an automatic optimization framework with Jupyter notebooks.

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*Course Preparation:*

Please bring a laptop running Windows OS (higher than Windows 10, preferably) to use for the workshop exercises. You will be contacted by the instructor with files to download prior to the course.

- Pre-requisites (nice to have; not required):
  - Basic understanding of Python
  - Basic understanding of Jupyter Notebook
  - Basic understanding of SWAT and MODFLOW
- Introductions:
  - The mathematics and theory
  - Learning by doing
  - Please speak up! Everyone learns from discussion
  - Work in pairs
  - Python, GUIs, and all that

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# 수문지질학 | Hydrogeology

- 물의 분포 및 수지
- 물의 순환 (지표수 / 지하수의 흐름)
- 연구사례
  - 토지관리국 (Bureau of Land Management)
  - 국제자연보호협회 (The Nature Conservancy) 유역관리 사례
  - 중금속관련 모델링 적용사례
- 현재 진행중인 과제

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- **About 71 percent** of the Earth's surface is water-covered, and the oceans hold about **97.5 percent** of all Earth's water.

*- 출처: 네이버지식*

- **About 71 percent** of the Earth's surface is water-covered, and the oceans hold about **97.5 percent** of all Earth's water.

*- 출처: 네이버지식*

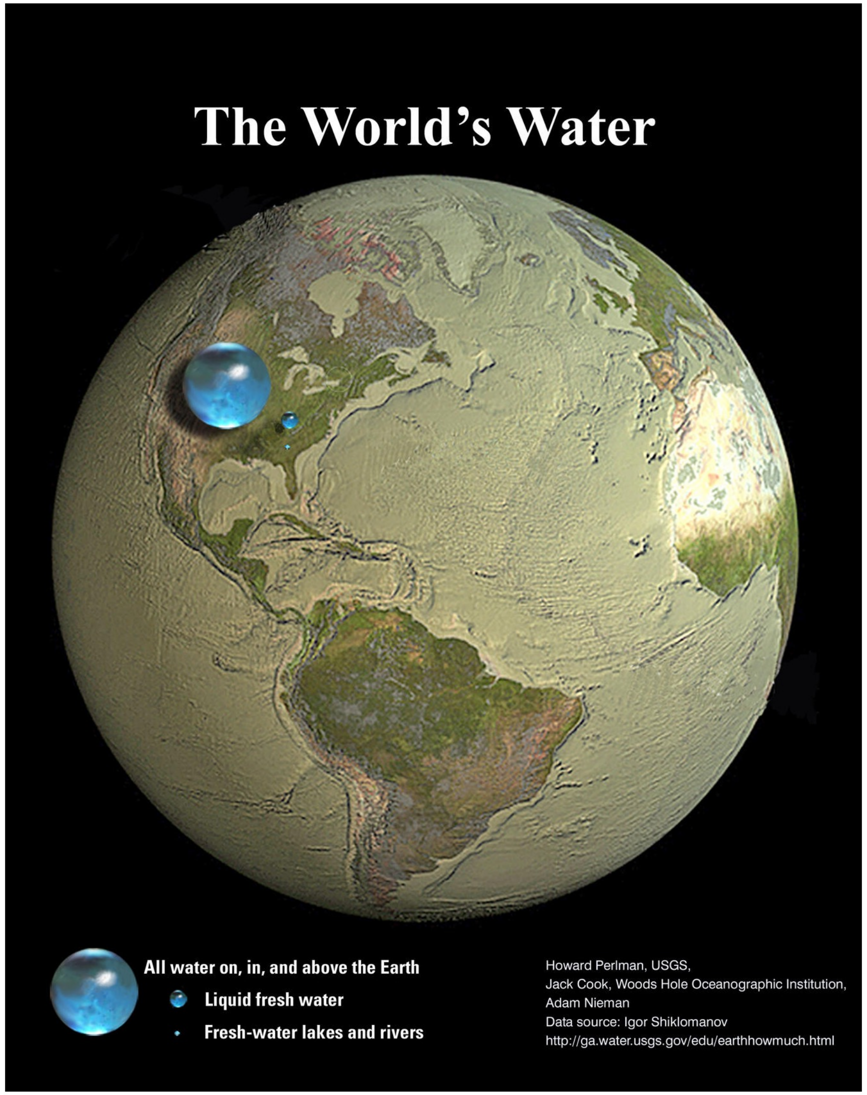
*333 million cubic miles (1.4 billion km$^3$)*

*1.388004548e+21 Liters*

usgs.gov/media/images/all-earths-water-a-single-sphere

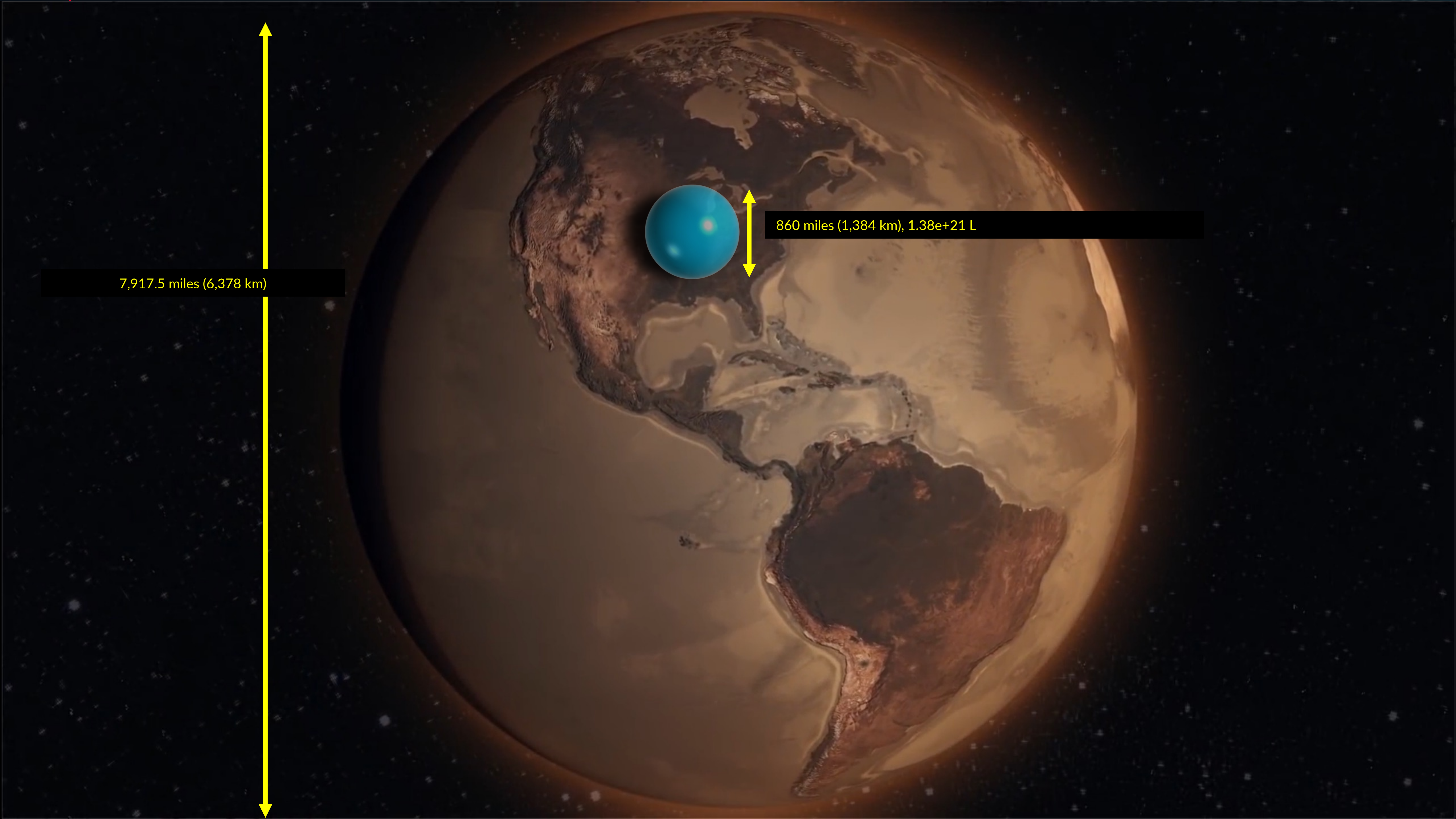
## All of Earth's water in a single sphere!

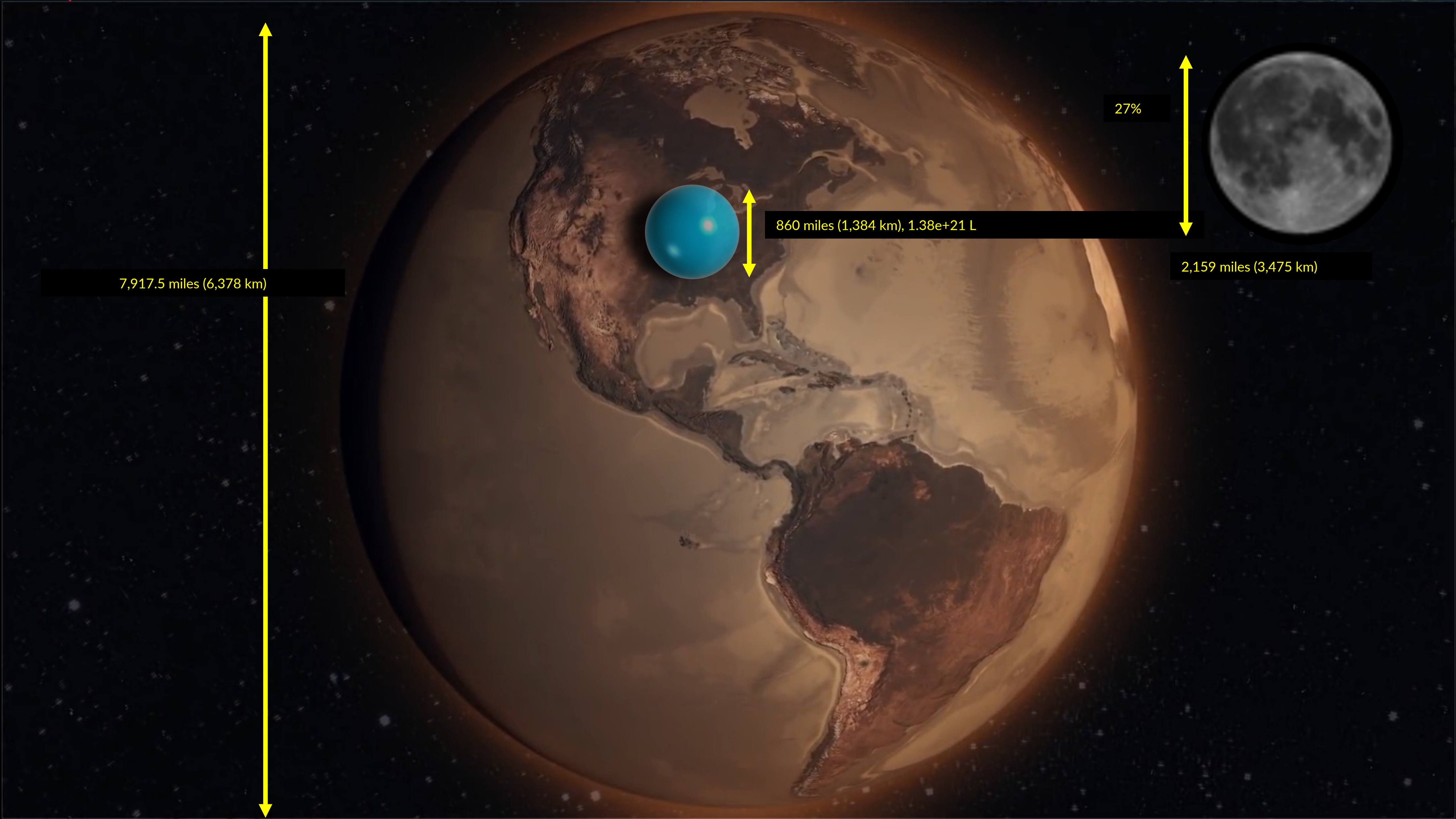
By Water Science School JULY 16, 2019

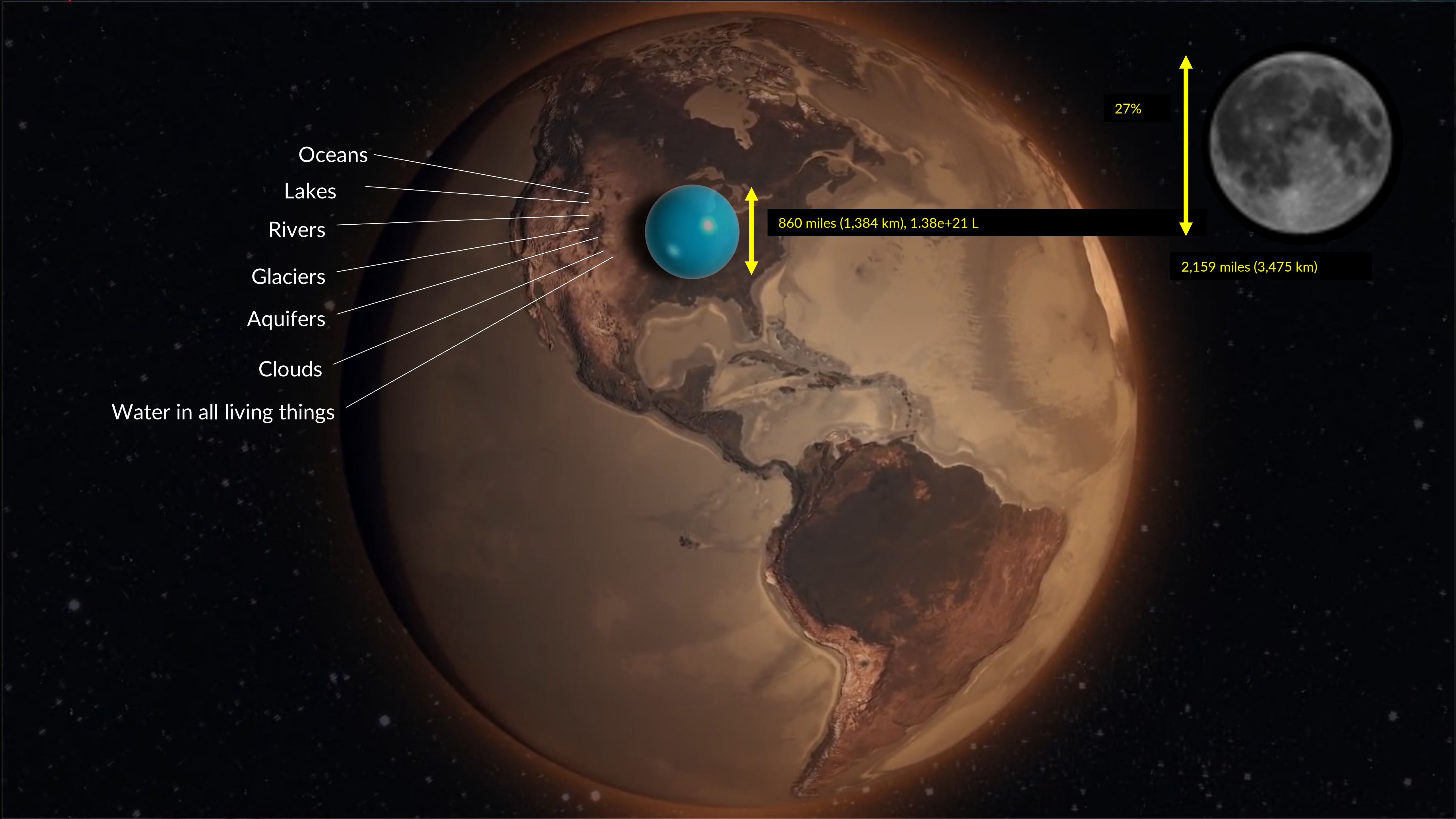


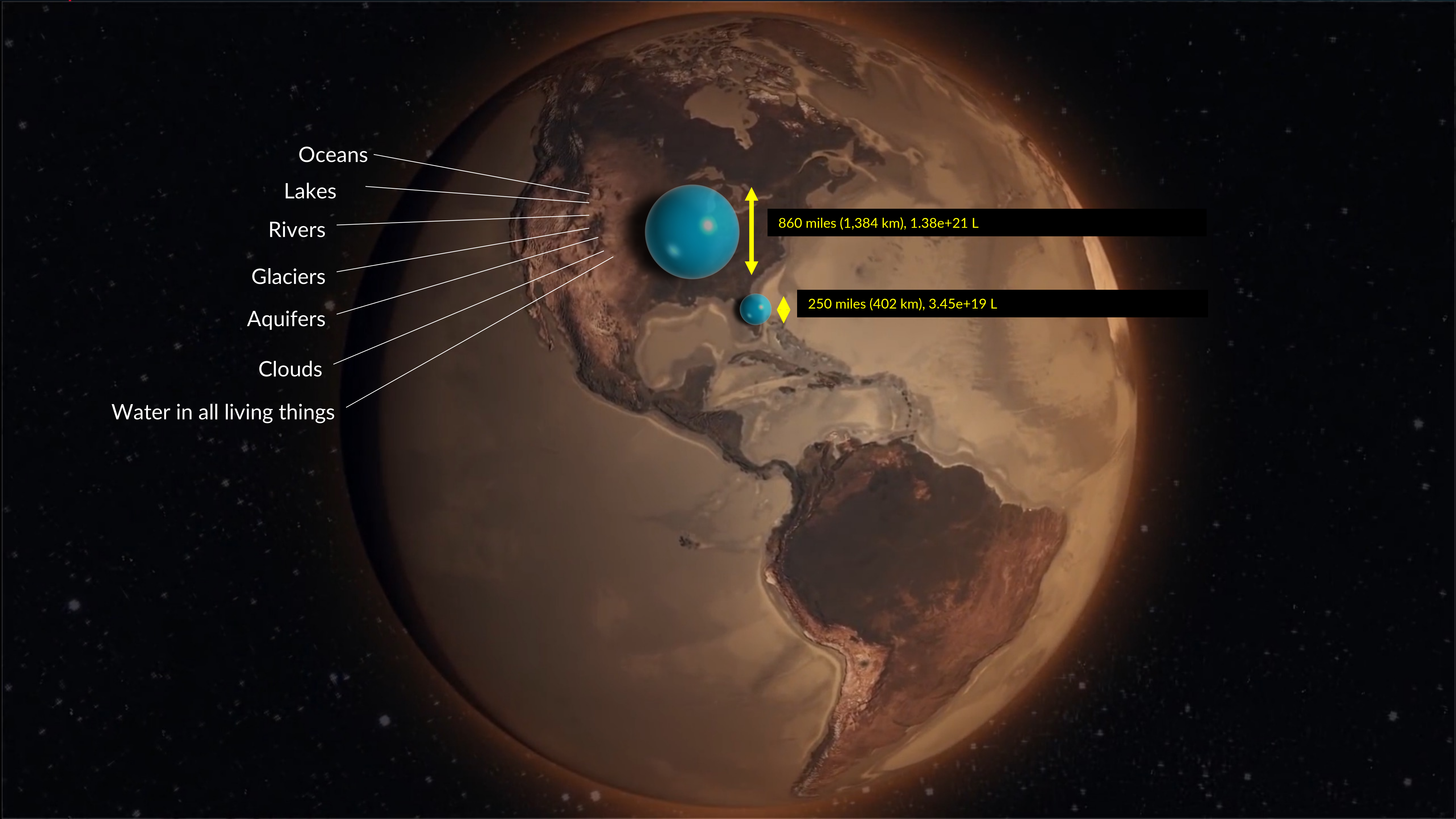

Original Thumbnail Medium

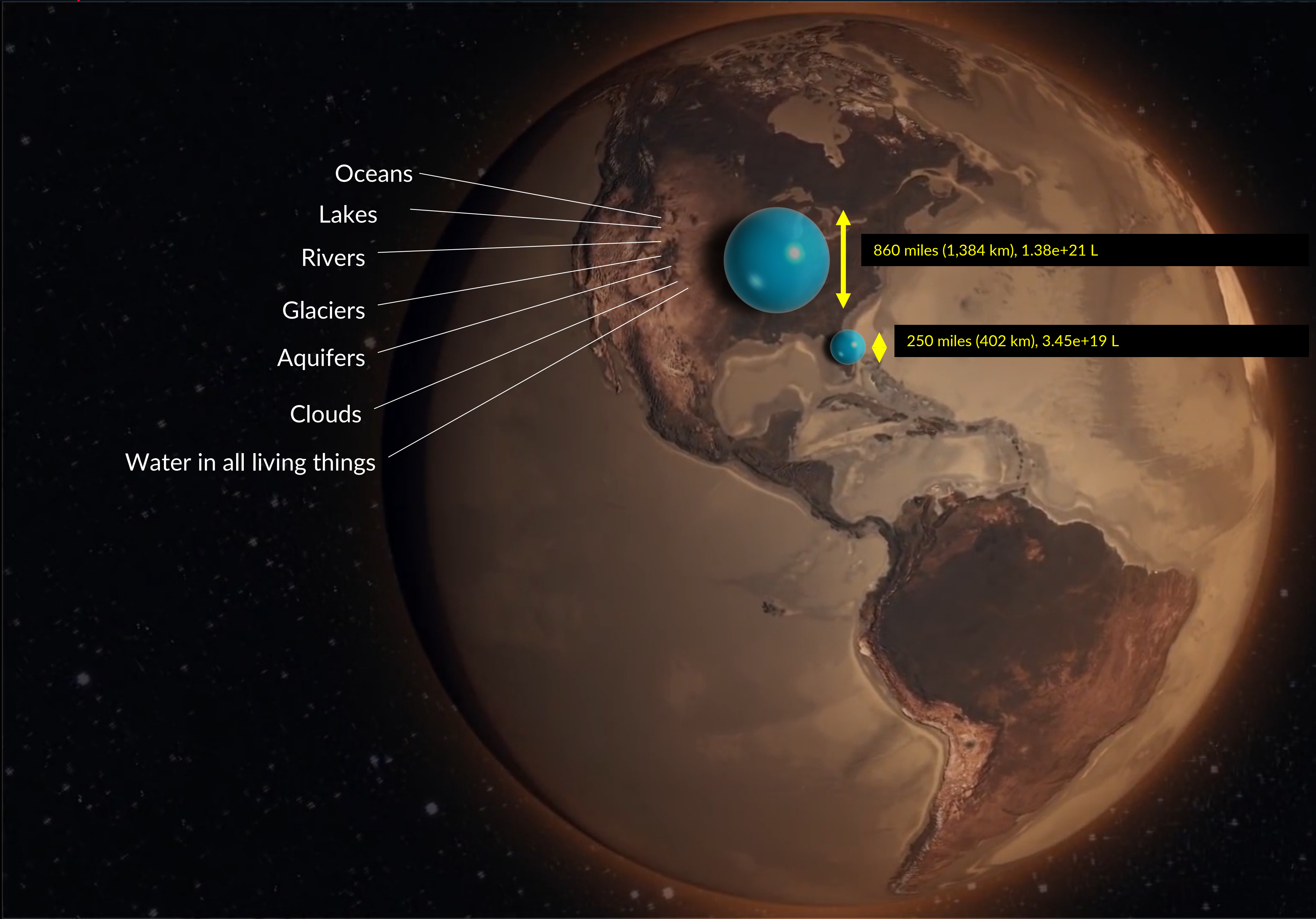
https://www.usgs.gov/media/images/all-earths-water-a-single-sphere


860 miles (1,384 km), 1.38e+21 L
7,917.5 miles (6,378 km)


27%
860 miles (1,384 km), 1.38e+21 L
2,159 miles (3,475 km)
7,917.5 miles (6,378 km)


Oceans
Lakes
Rivers
Glaciers
Aquifers
Clouds
Water in all living things
860 miles (1,384 km), 1.38e+21 L
27%
2,159 miles (3,475 km)


Oceans
Lakes
Rivers
Glaciers
Aquifers
Clouds
Water in all living things
860 miles (1,384 km), 1.38e+21 L
250 miles (402 km), 3.45e+19 L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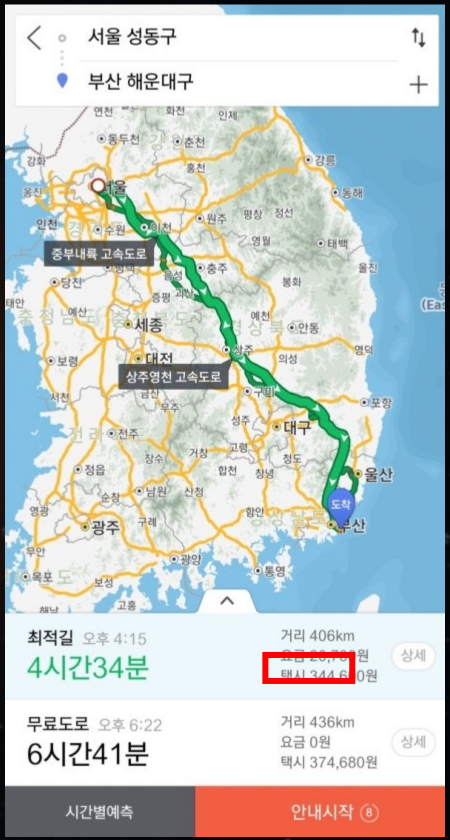
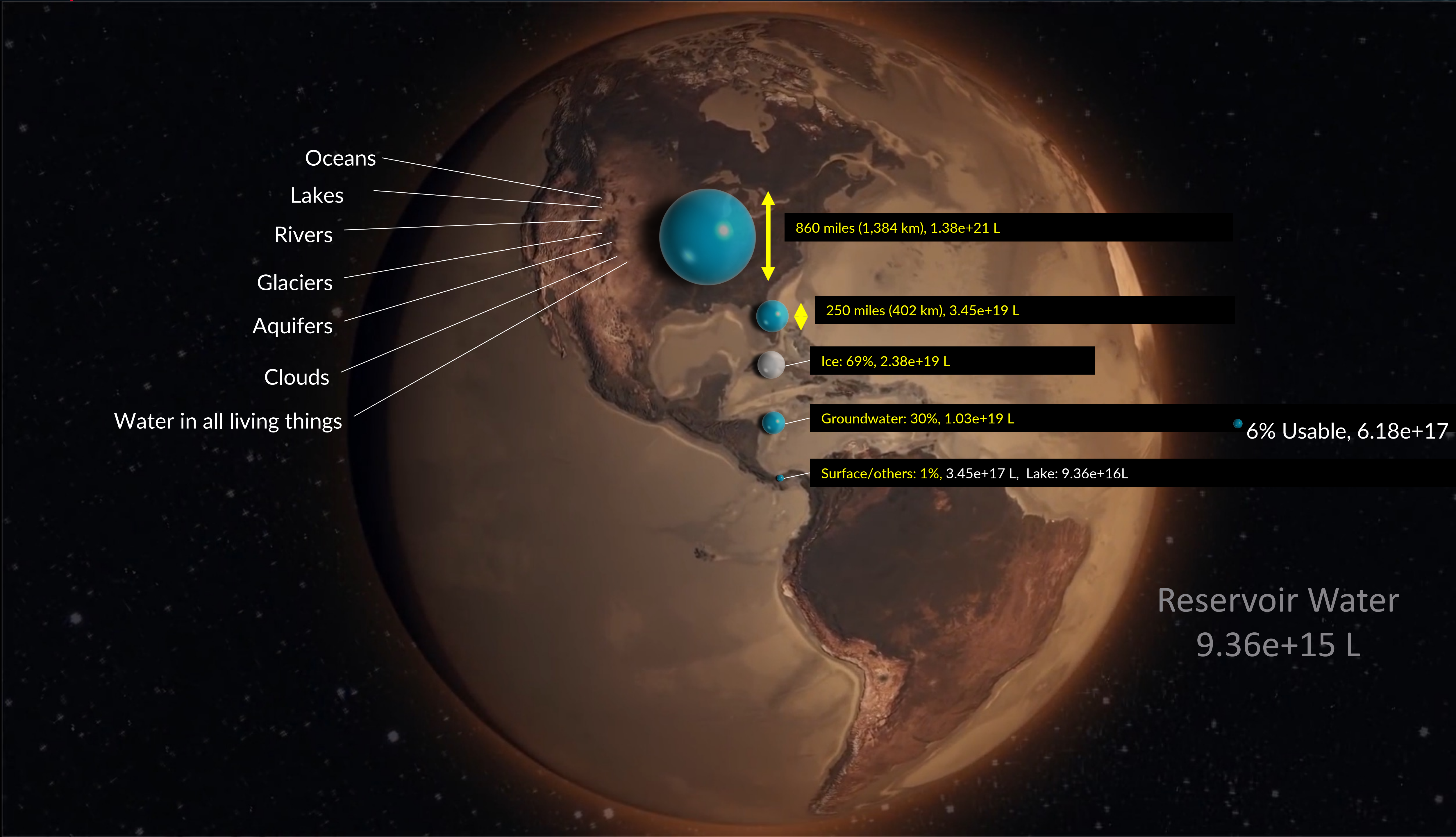

서울 성동구
부산 해운대구
중부내륙 고속도로
상주영천 고속도로
최적길 오후 4:15
4시간34분
거리 406km
상세
무료도로 오후 6:22
6시간41분
거리 436km
요금 0원
택시 374,680원
상세
시간별예측
안내시작


Oceans
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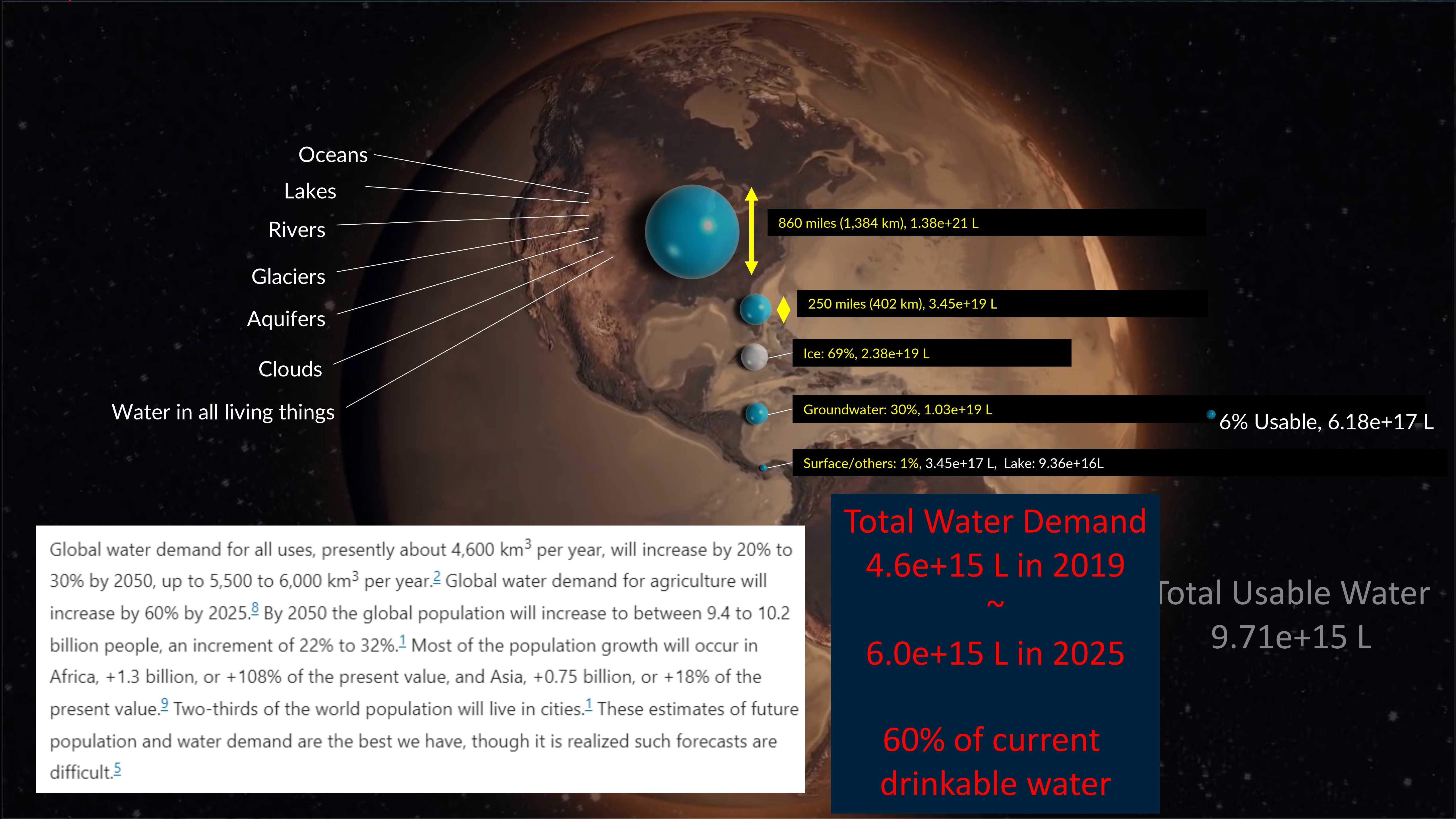
Water in all living things
860 miles (1,384 km), 1.38e+21 L
250 miles (402 km), 3.45e+19 L
Ice: 69%, 2.38e+19 L
Groundwater: 30%, 1.03e+19 L
6% Usable, 6.18e+17 L
Surface/others: 1%, 3.45e+17 L, Lake: 9.36e+16L
Reservoir Water
9.36e+15 L



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Global water demand for all uses, presently about 4,600 $km^3$ per year, will increase by 20% to 30% by 2050, up to 5,500 to 6,000 $km^3$ per year.[2] Global water demand for agriculture will increase by 60% by 2025.[8] By 2050 the global population will increase to between 9.4 to 10.2 billion people, an increment of 22% to 32%.[1] Most of the population growth will occur in Africa, +1.3 billion, or +108% of the present value, and Asia, +0.75 billion, or +18% of the present value.[9] Two-thirds of the world population will live in cities.[1] These estimates of future population and water demand are the best we have, though it is realized such forecasts are difficult.[5]
Total Water Demand
4.6e+15 L in 2019
~
6.0e+15 L in 2025
60% of current drinkable water
Total Usable Water
9.71e+15 L

# WATER USAGE | Korea

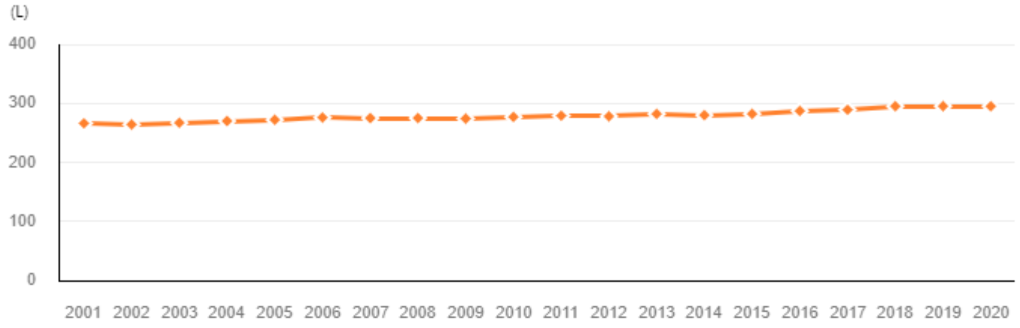
## 1인당 물사용량

· 최근 갱신일 : 2022-01-14 (입력 예정일 : 2023-01-31)

### 그래프

범례전체해제 패턴 적용 다운로드

1인당 일평균 물사용량




**출처:** 환경부, 「상수도통계」

* 자료 : 환경부, 「상수도통계」 각 연도

**주석:** 1) 1인당 일평균 물사용량 = {(유수량 - 분수량) ÷ 급수인구} ÷ 365.

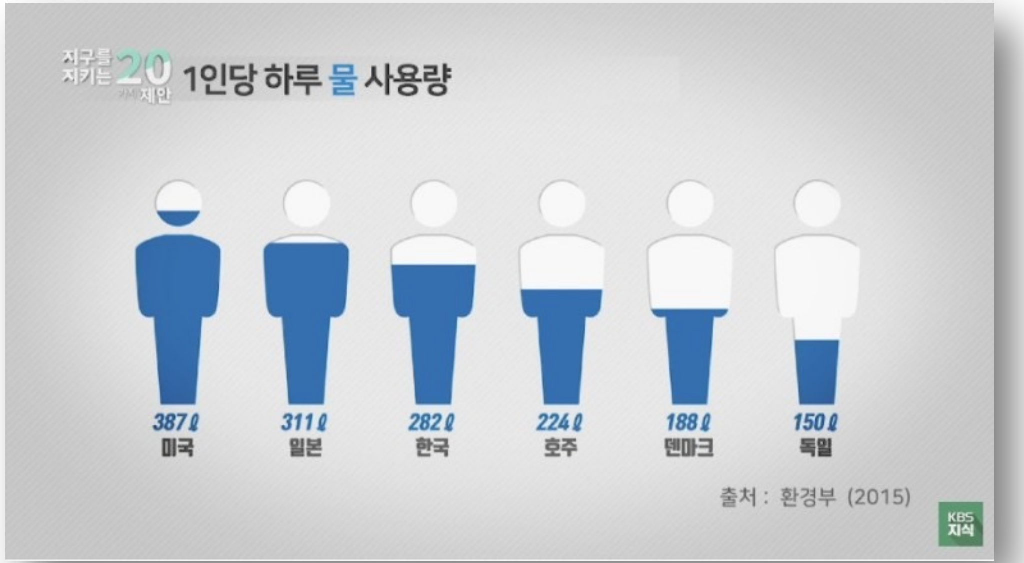
### 통계표

연간 총급수량과 1인당 일평균 물사용량

시계열조회 엑셀 증감비교

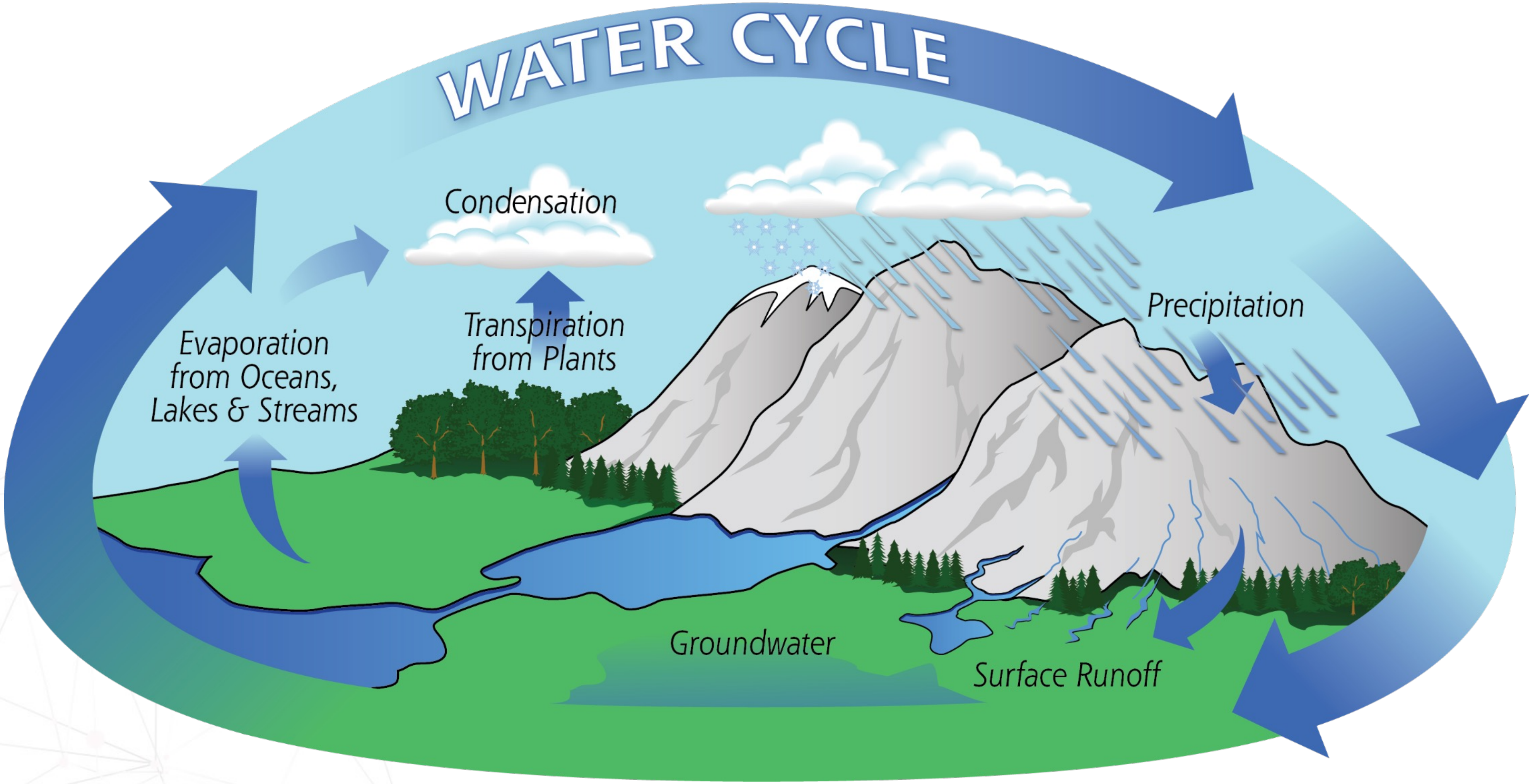
[단위 : 백만 ㎥, L]

| | 2009 | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 | 2019 | 2020 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 연간 총급수량(백만 ㎥) | 5,760 | 5,910 | 6,021 | 6,029 | 6,159 | 6,214 | 6,279 | 6,419 | 6,492 | 6,656 | 6,666 | 6,651 |
| 1인당 일평균 물사용량(L) | 274 | 277 | 279 | 278 | 282 | 280 | 282 | 287 | 289 | 295 | 295 | 295 |

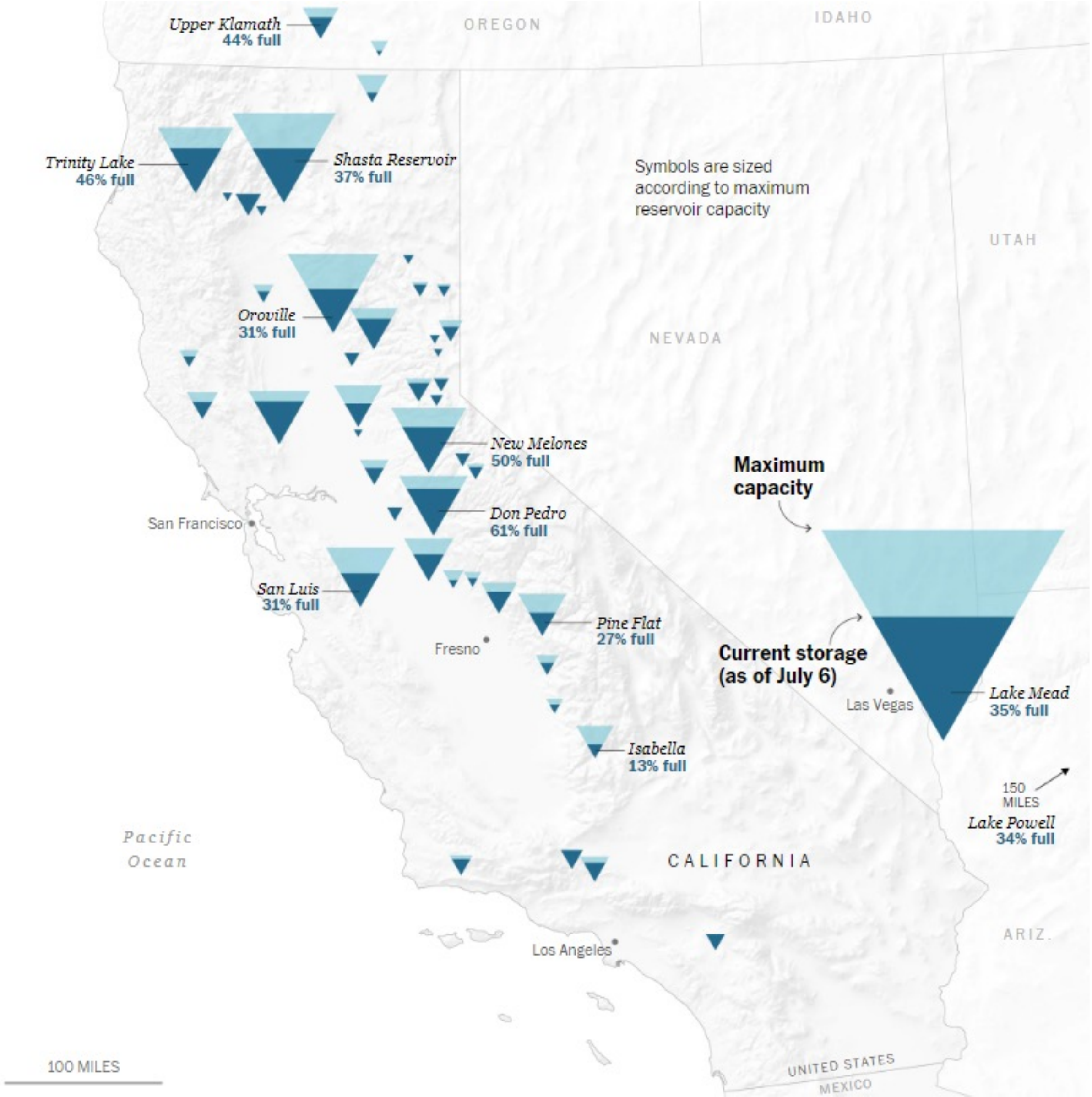


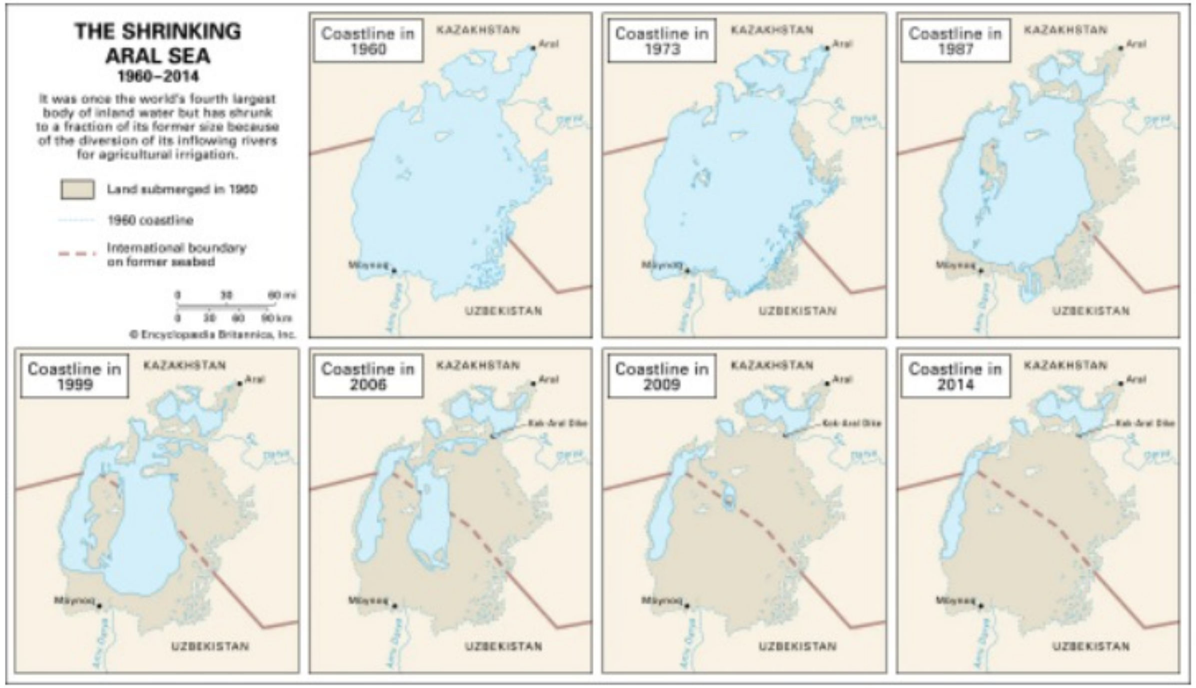

1.8 L X 164

# HYDROLOGIC CYCLE



# HYDROLOGIC CYCLE




The Aral Sea was an endorheic lake lying between Kazakhstan in the north and Uzbekistan in the south which began shrinking in the 1960s and had largely dried up by the 2010s.

*Source: The Washington Post in July 2019*

# HYDROLOGIC CYCLE


From left to right: Dr. Joseph Poland posing with a telephone pole indicating land surface elevation in 1925 compared to 1977; buckling of the Delta-Mendota Canal due to land subsidence in the area; land-subsidence fissure at the Fort Irwin National Training Center; hydrologist Michelle Sneed posing at a location in the Central Valley with signs indicating land surface elevation in 1965 compared to 2013.

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# HYDROLOGIC CYCLE

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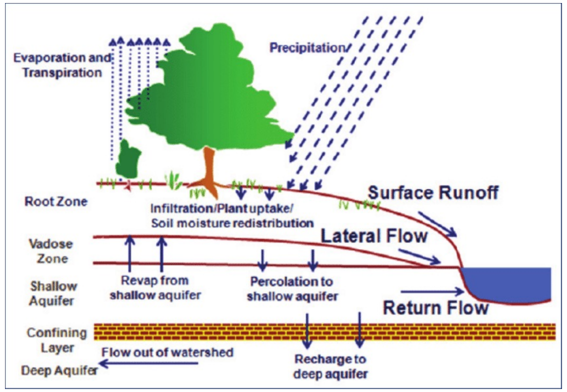
# WHAT IS THE BEST SOLUTION?

- Education
- Monitoring
- Tool Development

# Methods | Watershed/field scales Agroecosystem Models



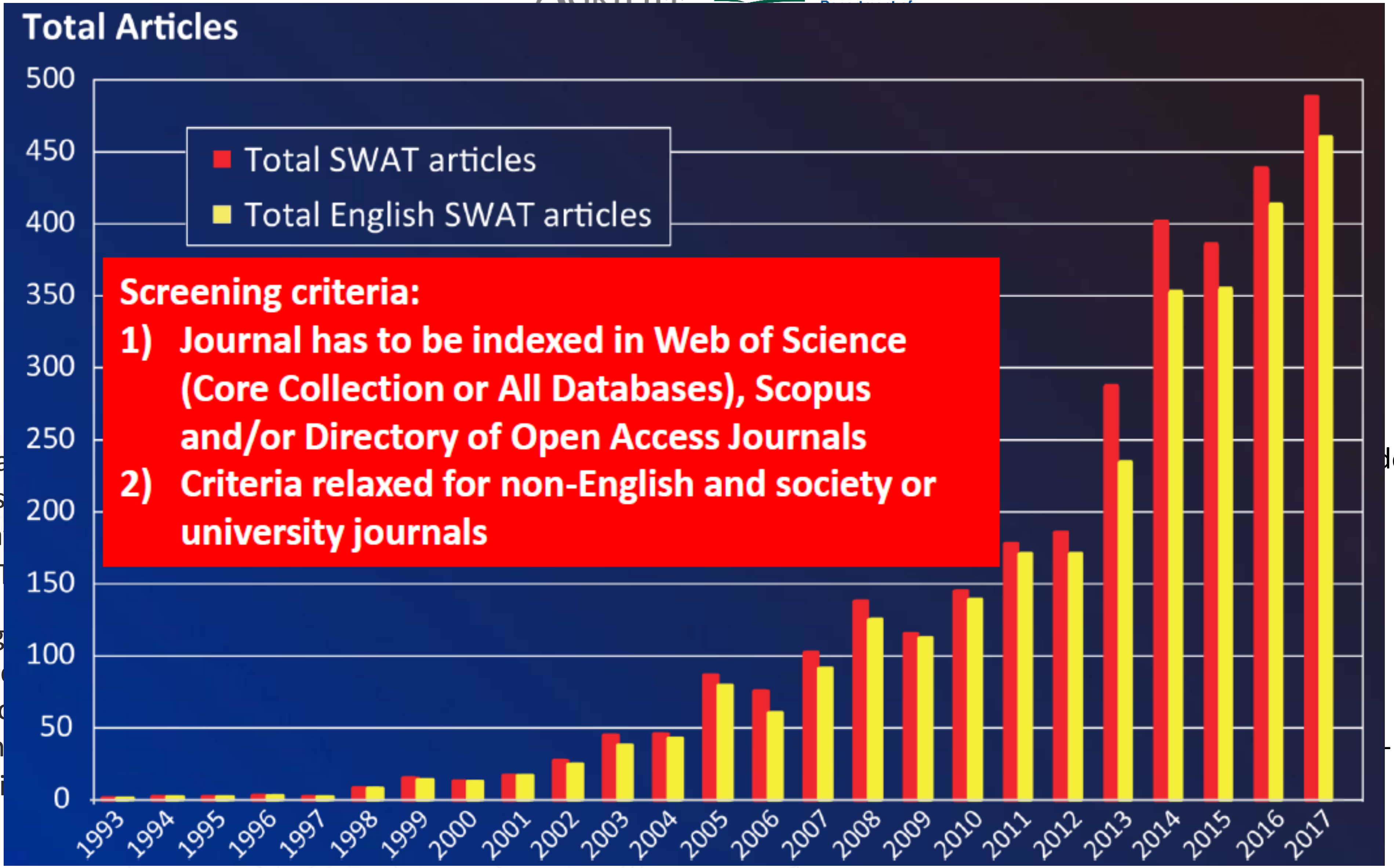



$$SW_t = SW_o + \sum_{i=1}^{n}(R_{day} - Q_{surf} - E_a - w_{seep} - Q_{gw})$$

- SWAT is a public domain software enabled model actively supported by the USDA Agricultural Research Service at the Blackland Research & Extension Center in Temple, Texas, USA.
- Hydrologic components: weather, surface runoff, return flow, percolation, evapotranspiration, transmission losses, pond and reservoir storage, crop growth and irrigation, groundwater flow, reach routing, nutrient and pesticide loading, and water transfer.

- The Agricultural Policy / Environmental eXtender (APEX) model was developed and included
  - crop growth algorithms
  - nutrient cycling in the soil profile
  - nutrient transport and
  - loading to streams in surface runoff, soil lateral flow, and groundwater flow, and in-stream transport.

# Methods | Watershed/field scales Agroecosystem Models




- SWAT is a ... der
actively s...
Service a...
Temple, T...

- Hydrolog...
flow, perc...
losses, po...
irrigation...
and pesti...

# Methods | Watershed/field scales Agroecosystem Models



swat.tamu.edu/conferences/

SWAT Soil & Water Assessment Tool

Software Docs Data Workshops Conferences Publication

## Past Conferences

See presentations and photos from our past SWAT conferences below.

### 2024 - Strasbourg, France


### 2024 - Ifrane, Morocco

### 2023 - Aarhus, Denmark


### 2022 - Prague, Czech Republic


### 2019 - Vienna, Austria


### 2019 - Siem Reap, Cambodia

### 2018 - Chennai, India

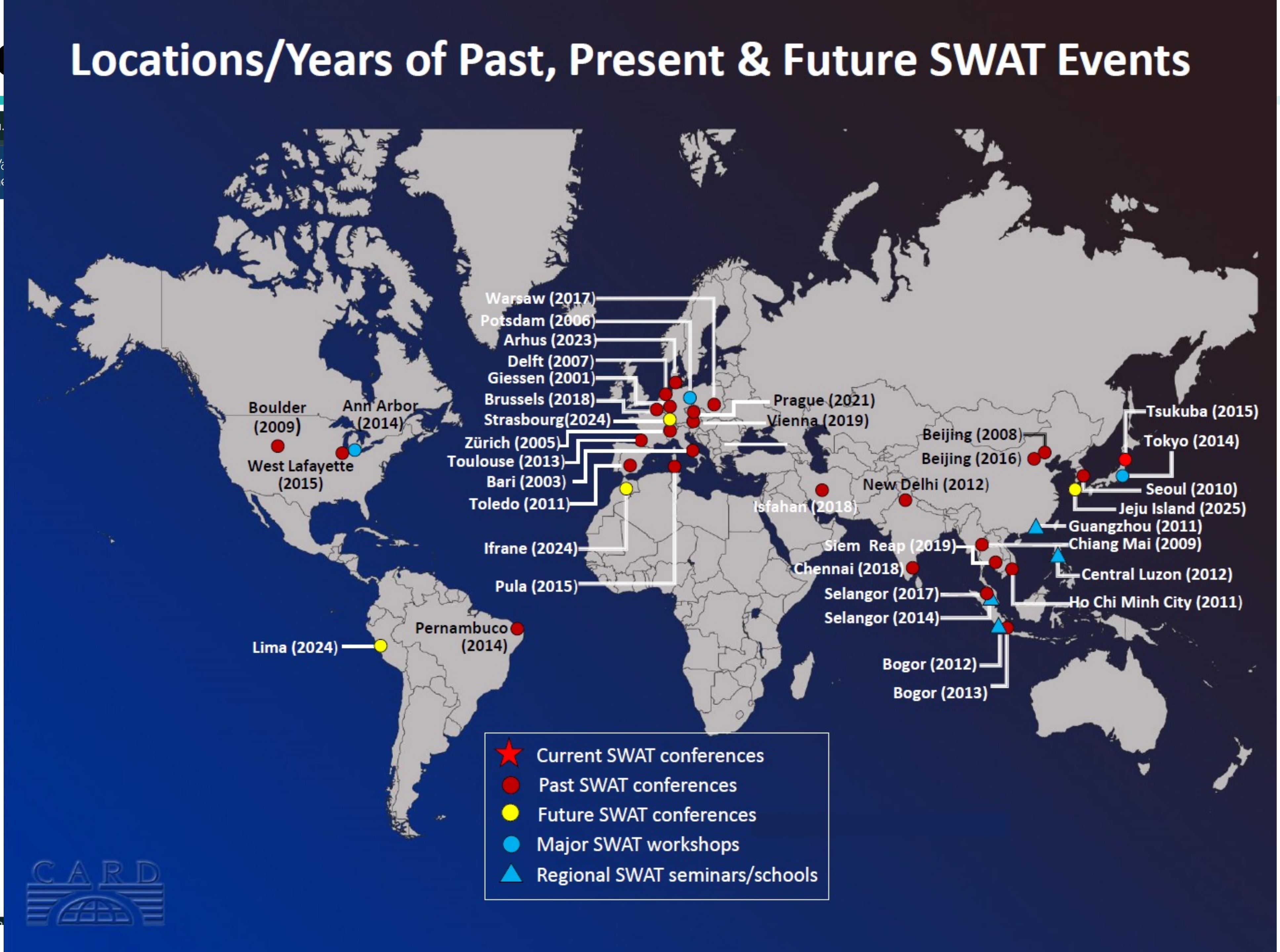

### 2018 - Brussels, Belgium


### 2017 - Warsaw, Poland

# Metho

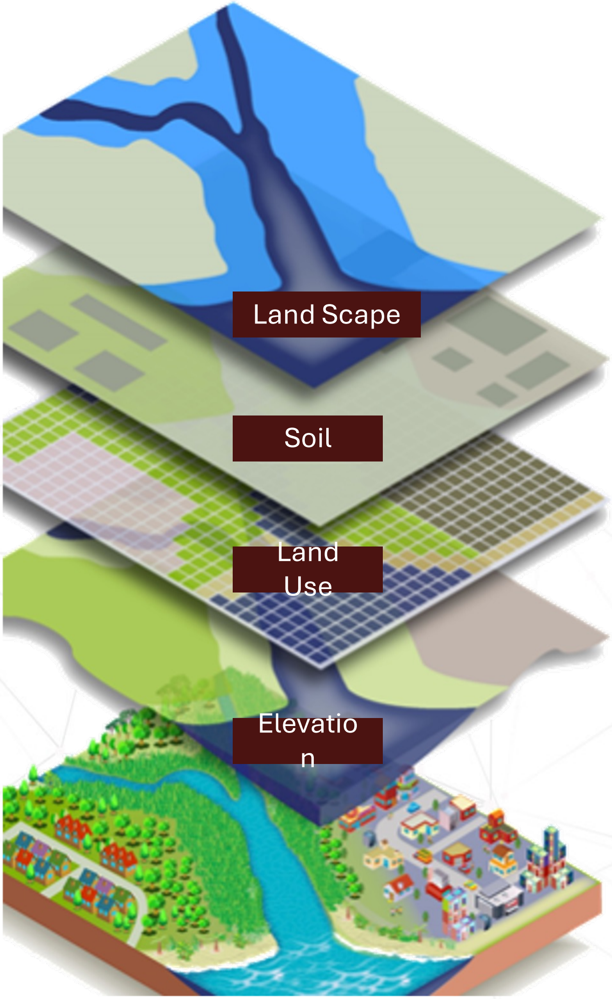



swat.tamu.
SWAT Soil & Wa
Assessme


Locations/Years of Past, Present & Future SWAT Events
Boulder (2009)
Ann Arbor (2014)
West Lafayette (2015)
Warsaw (2017)
Potsdam (2006)
Arhus (2023)
Delft (2007)
Giessen (2001)
Brussels (2018)
Strasbourg(2024)
Zürich (2005)
Toulouse (2013)
Bari (2003)
Toledo (2011)
Ifrane (2024)
Pula (2015)
Prague (2021)
Vienna (2019)
Pernambuco (2014)
Lima (2024)
Isfahan (2018)
New Delhi (2012)
Beijing (2008)
Beijing (2016)
Tsukuba (2015)
Tokyo (2014)
Seoul (2010)
Jeju Island (2025)
Guangzhou (2011)
Chiang Mai (2009)
Siem Reap (2019)
Chennai (2018)
Central Luzon (2012)
Selangor (2017)
Selangor (2014)
Ho Chi Minh City (2011)
Bogor (2012)
Bogor (2013)
Current SWAT conferences
Past SWAT conferences
Future SWAT conferences
Major SWAT workshops
Regional SWAT seminars/schools
CARD

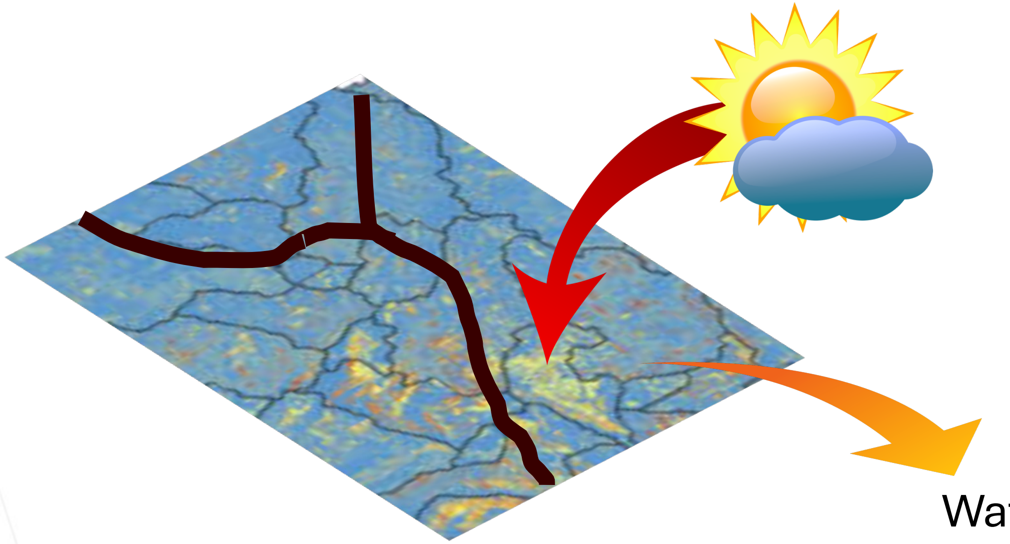
**SWAT-** Soil and Water Analysis Tool

Semi-distributed watershed scale ecosystem model




**Watershed** → **Subbasins** → **HRUs**

Areas of unique properties



Water cycle components

Nutrient transport

Crop growth

# HAWQS

## Hydrologic and Water Quality System

hawqs.tamu.edu

TEXAS A&M AGRILIFE RESEARCH

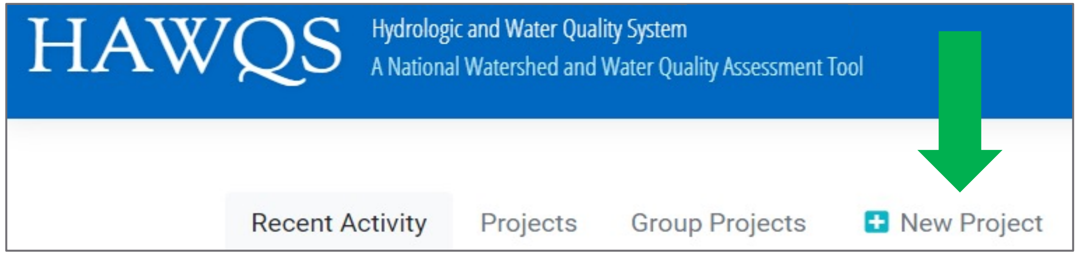
UNITED STATES ENVIRONMENTAL PROTECTION AGENCY

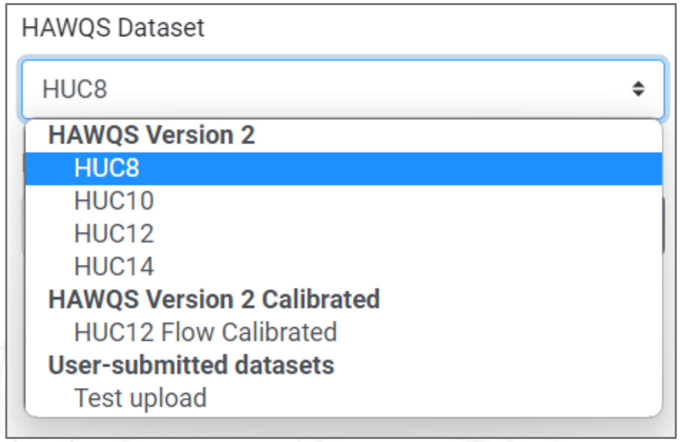
USDA ars Agricultural Research Service

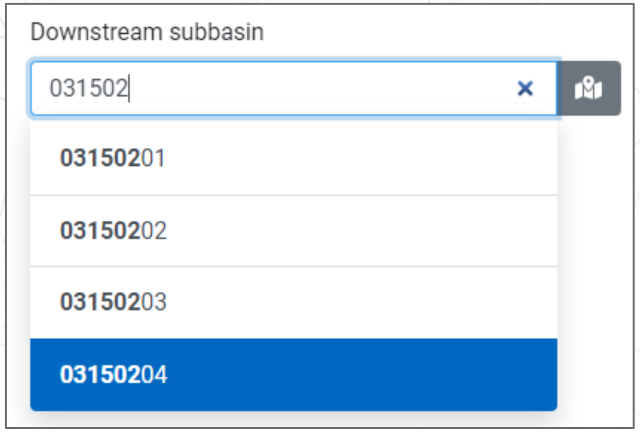
# Federally Approved Input Datasets

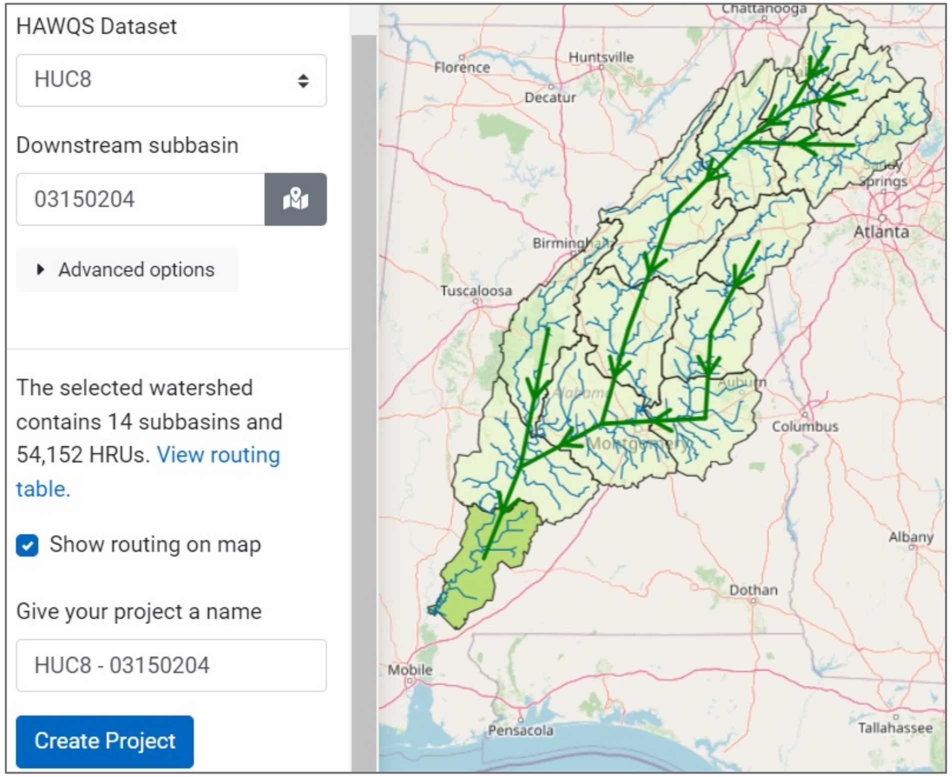
| Input Dataset | Source | Specifications |
|---|---|---|
| Weather | PRISM | 1981 – 2020 (gridded) |
| | NEXRAD | 2005 – 2020 (gridded) |
| Soil | USDA National Resources Conservation Service (NRCS) Soil Survey Geographic (SSURGO) Database | 2018 |
| | USDA NRCS State Soil Geographic (STATSGO) Database | 2018 |
| Land Use | National Land Cover Database (NLCD) | 2016 |
| | USDA National Agricultural Statistics Service (NASS) Cropland Data Layer (CDL) | 2014 – 2017 |
| | USDA NASS Fields | 2006 – 2010 |
| | U.S. Fish and Wildlife Service (FWI) National Wetlands Inventory (NWI) | 2018 |
| Aerial Deposition | National Atmospheric Deposition Program (NADP) | 1980 – 2020 (monthly) |
| Watershed Boundaries | EPA NHDPlus v2 | 2019 |
| Stream Networks | EPA NHDPlus v2 | 2019 |
| Elevation | USGS National Elevation Dataset (NED) | 2018 (10-meter DEM) |
| Point Sources | EPA Hypoxia Task Force (HTF) | 2019 |
| | EPA Integrated Compliance Information System National Pollutant Discharge Elimination System (ICIS-NPDES) | 2019 |
| Management Data | USDA NRCS crop management zone data | 2010 |
| Ponds, Potholes, and | U.S. Army Corps of Engineers (USACE) National Inventory of Dams | 2018 |

# SWAT Model setup- just a few clicks away



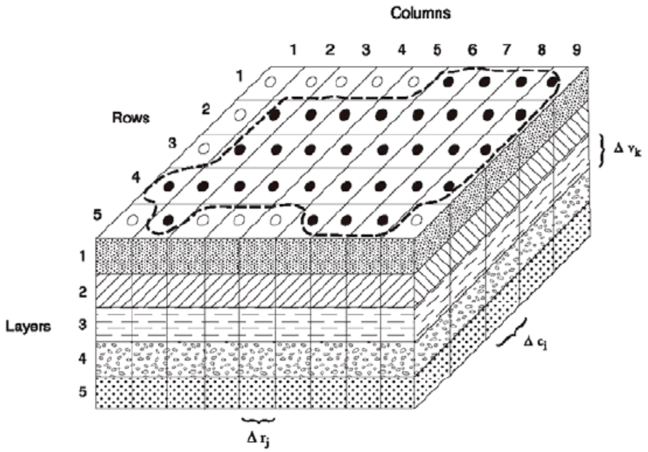




| Spatial Scale | Total Subbasins | Average Subbasin Area | | Average Number of HRUs per HUC |
|---|---|---|---|---|
| | | km$^2$ | mi$^2$ | |
| HUC8 | 2,112 | 3,690 | 1,425 | 2,920 |
| HUC10 | 15,301 | 509 | 200 | 680 |
| HUC12 | 79,836 | 98 | 38 | 229 |
| HUC14 | 352,847 | 22 | 8 | 89 |

# INTERNATIONAL HAWQS PLATFORMS

- South Africa (HAMSA)
  [*hamsa.hawqs.tamu.edu*]
- Pernambuco Brazil (SUPer)
  [*super.hawqs.tamu.edu*]
- Hydrologic Unit Model for InDia (HUMID)
  [*bhuvan.nrcs.gov.in*]
- Global HAWQS
  [*global.hawqs.tamu.edu*]
- Coming Soon: Ukraine, Nepal

# HYDROLOGIC MODEL | MODFLOW




*developed and maintained by*

**Partial Differential Equation**: develop water balance for each point (cell) in the aquifer

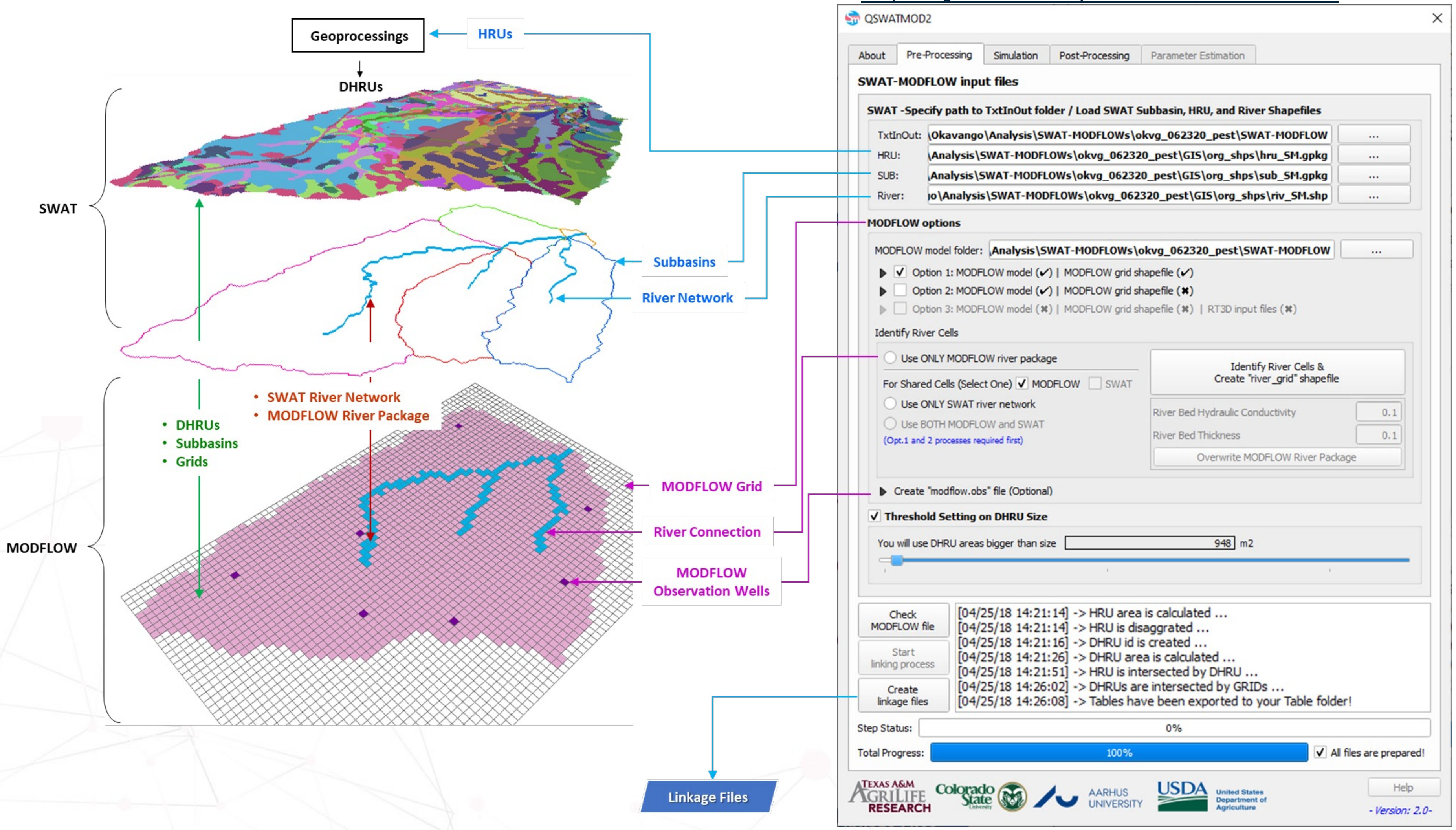
$$\frac{\partial}{\partial x}\left(hK_x\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(hK_y\frac{\partial h}{\partial y}\right)+Q_{rech}-Q_{pump}-Q_{ET}=S_y\frac{\partial h}{\partial t}$$

- MODFLOW is the U.S. Geological Survey modular finite-difference flow model
  - solve the groundwater flow equation,
  - simulate the flow of groundwater through aquifers.
- The source code is free public domain software,[1] written primarily in Fortran, and can compile and run on Microsoft Windows or Unix-like operating systems.

# HYDROLOGIC MODEL | Integrated Model

## SWAT-MODFLOW MODEL LINKING

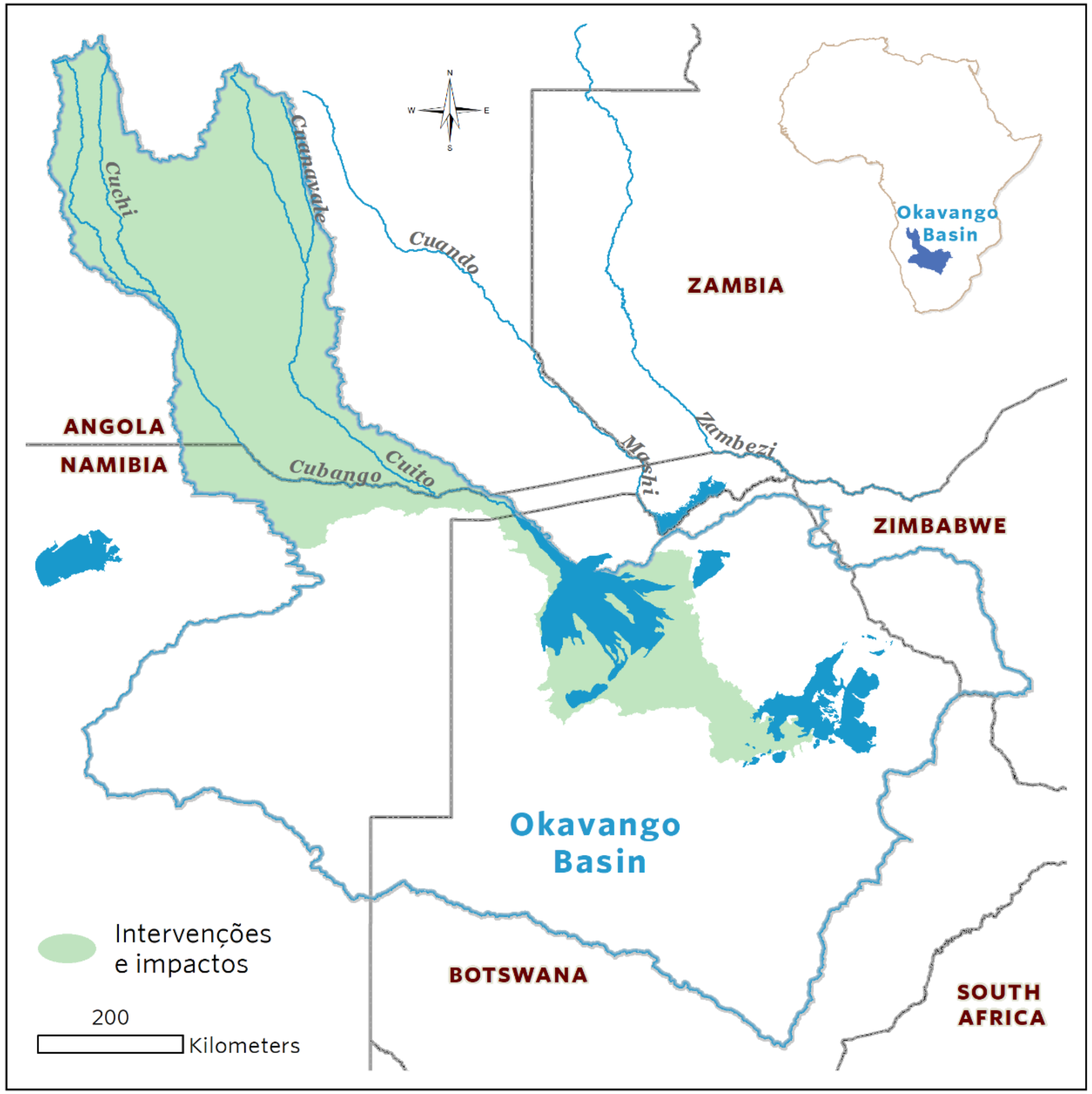
(https://github.com/spark-brc/QSWATMOD2)



# CASE I

# Okavango River Watershed

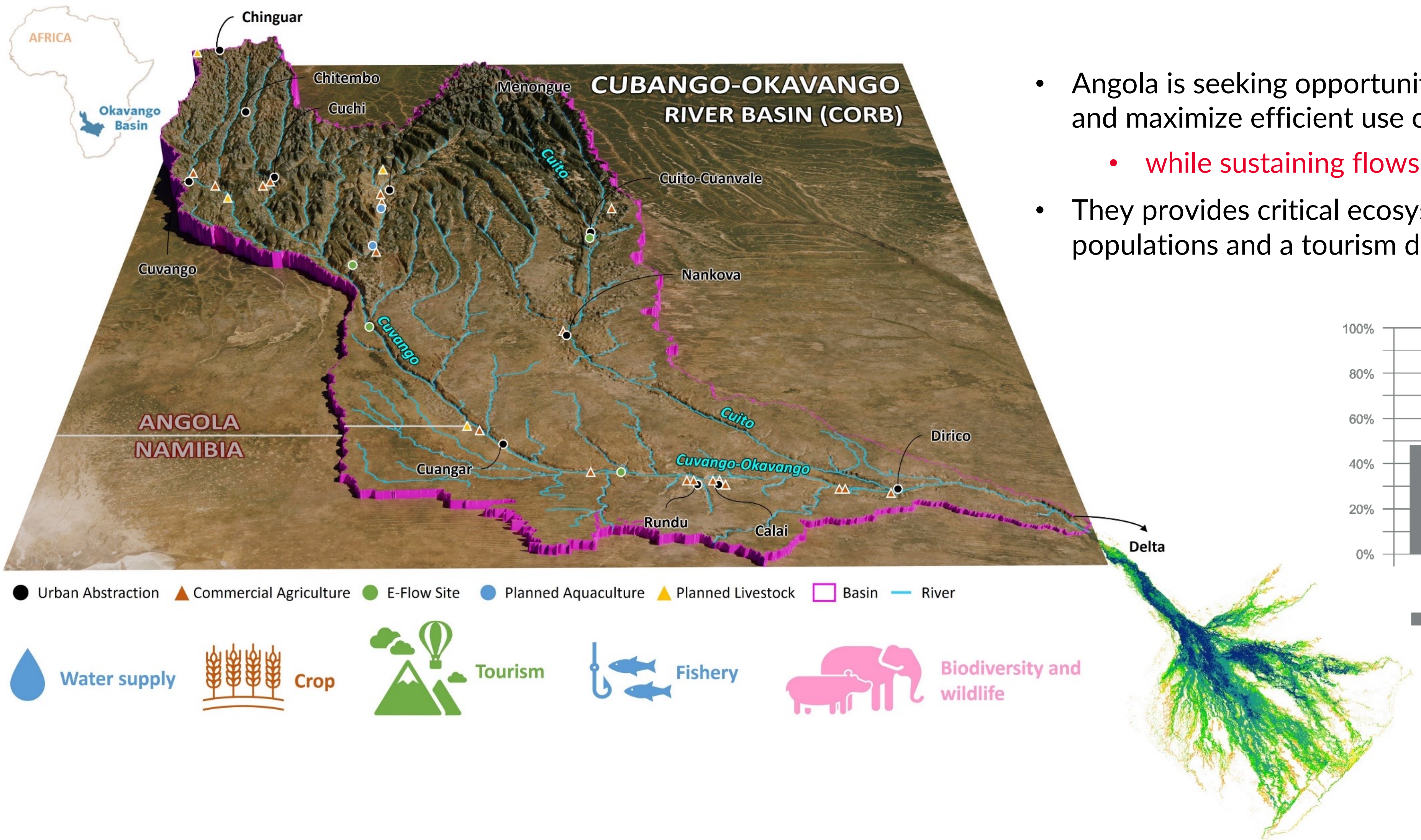
# CASE I | Okavango River Watershed



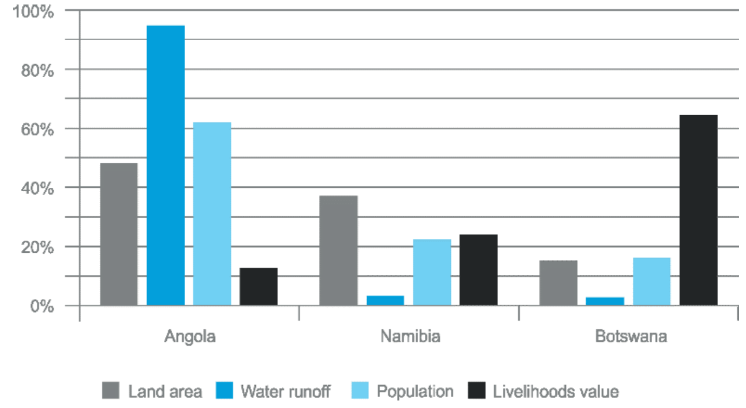

- Amidst the sands of the Kalahari desert, an oasis exists in the form of the Okavango River Basin
- The basin stretches across three countries (Angola, Namibia, and Botswana) and is one of the most biodiverse regions in Africa.
- The Okavango is home to the world's largest remaining elephant population and many other endangered species.
- The basin provides critical water resources to over a million people.

- Basin Area: 232,028 km$^2$
- Delta Area: 6,000 – 12,000 km$^2$

# CASE I | Okavango River Watershed




- Angola is seeking opportunities to intensify agricultural production and maximize efficient use of the abundant water resources.
  - while sustaining flows and sediment to the Okavango Delta
- They provides critical ecosystem services for sustaining wildlife populations and a tourism dependent local economy.



# CASE I | Okavango River Watershed

## Business As Usual (BAU)

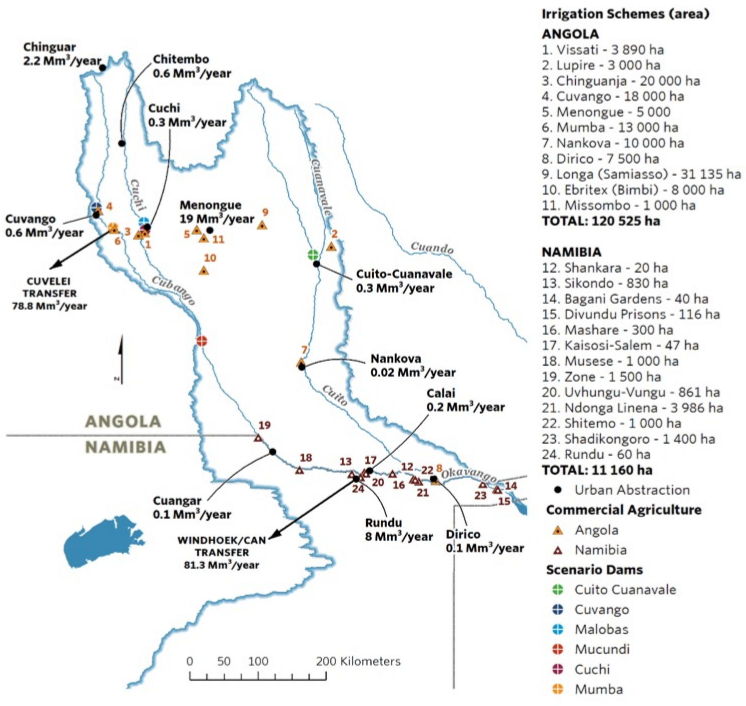



*Figure 12: Cubango-Okavango River Basin Fund Business as Usual scenario*

- **Hydropower development**
  - Mucundi – 104.3 MW
  - Malobas – 53.3 MW
  - Cuito-Cuanavale – 16.2 MW
  - Cuvango – 27.6 MW
- **Commercial irrigated agriculture**
  - Angola – 120,525 ha
  - Namibia –11,160 ha
- **Irrigation storage**
  - Cuchi and Mumba storage dams
- **Domestic water supplies**
  - 31.5 Mm³ per annum for 10 cities in Angola and Rundu
- **Water transfers**
  - 81.3 Mm³ per annum for Central Areas of Namibia
  - 78.8 Mm³ Cuvelai River basin in Angola
- **Land use change**
  - Converted to small-scale agriculture
    - 102,940 ha of miombo woodlands
    - 3,240 ha of riparian vegetation
  - 67,318 ha miombo woodlands degraded
  - 87,030 ha of additional urban

## Resilient Development (RD)

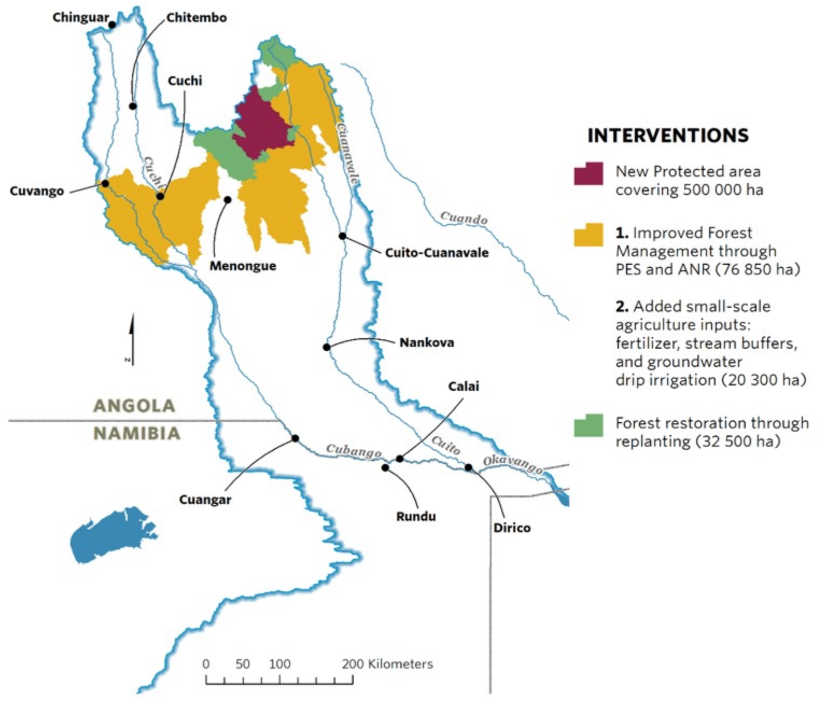


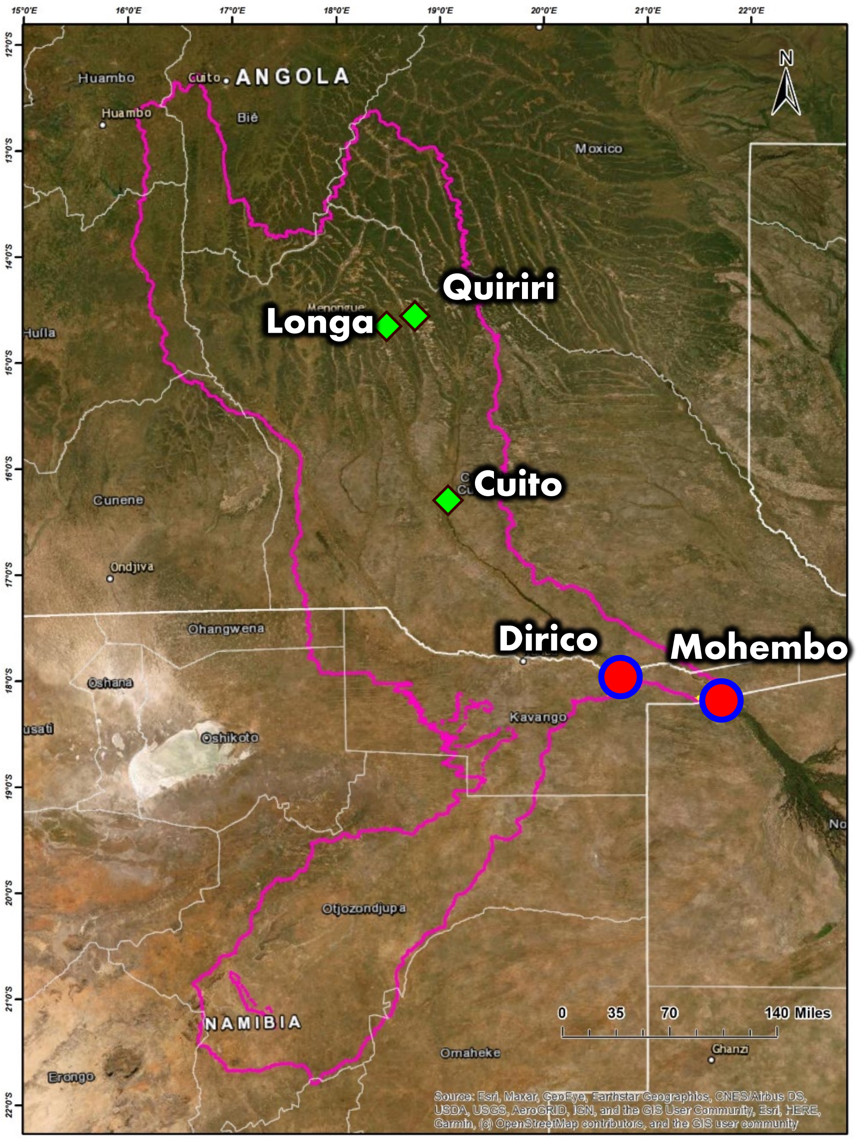

*Figure 15: Landscape Scale Interventions*

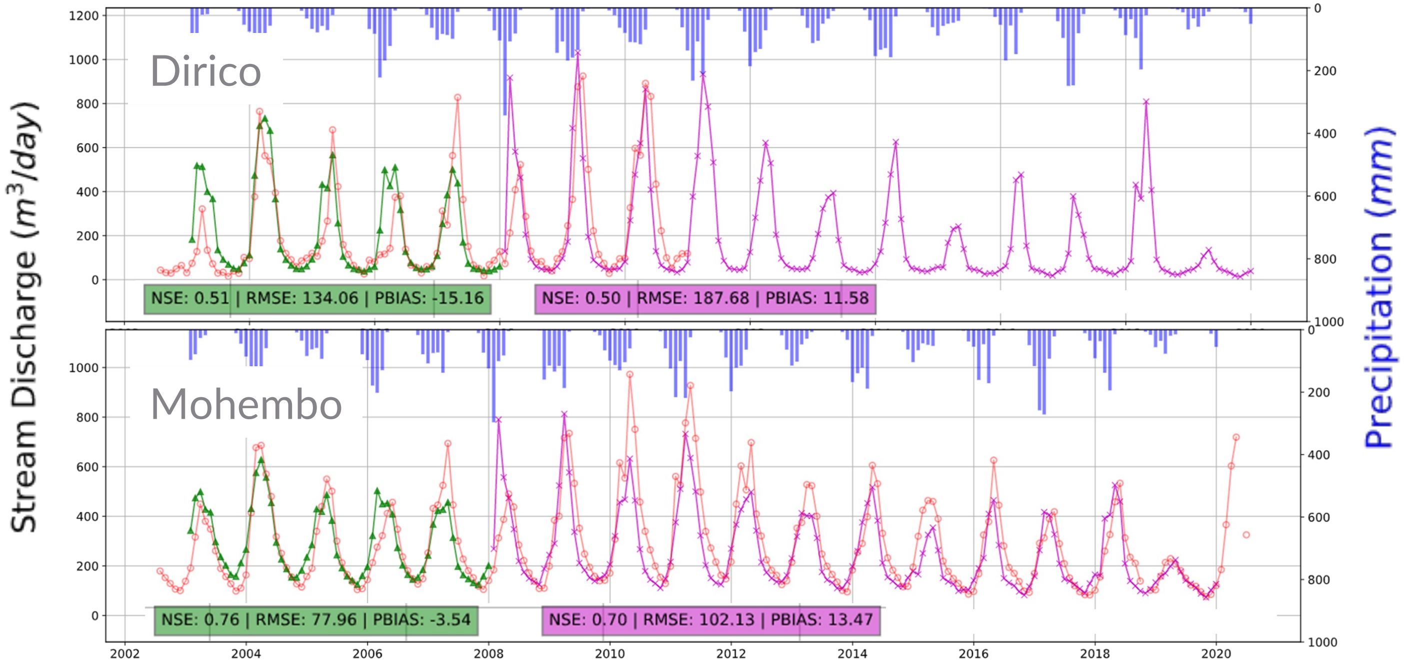
- **No hydropower development**
- **109,356 ha Improved, avoided, or restored miombo woodlands**
- **No irrigation storage**
- **Domestic water supplies**
  - 20.7 Mm³ per annum for 10 cities in Angola and Rundu
- **Water transfers**
  - 67.1 Mm³ per annum for Central Areas of Namibia
- **Commercial irrigated agriculture**
  - Angola – 55,060 ha
  - Namibia –11,160 ha
- **Land use change**
  - Converted to small-scale agriculture
    - 84,088 ha of miombo woodlands
    - 0 ha of riparian vegetation
  - 61,145 ha miombo woodlands degraded
  - 87,030 ha of additional urban

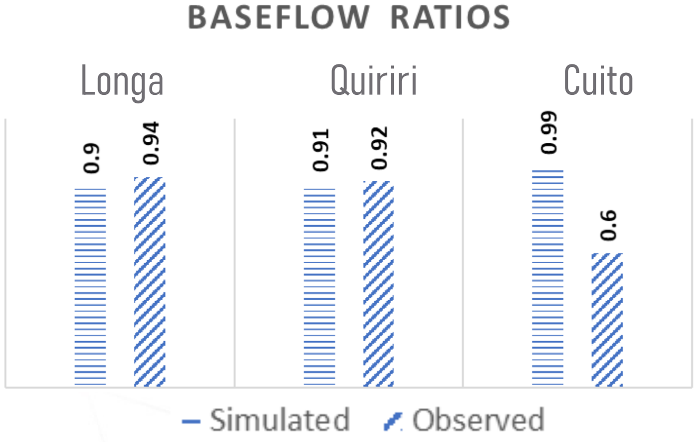
## Climate Scenarios

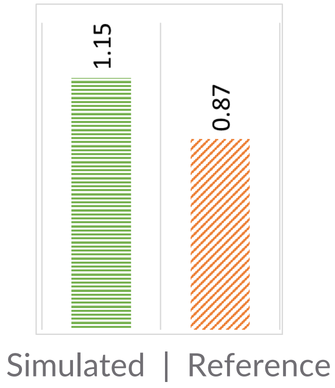
- CMIP 6 for SSP245 and SSP585
- Four climate models selected
  - INM-CM5-0 - Wetting across the basin, weak temperature rise
  - NorESM2-LM - Weak wetting in the north, no change in the south, moderate temperature rise
  - UKESM1-0-LL - Weak drying across the basin, high temperature rise
  - FGOALS-g3 - Drying, strong in the north, weaker in the south, moderate temperature rise.

# CASE I | Okavango River Watershed



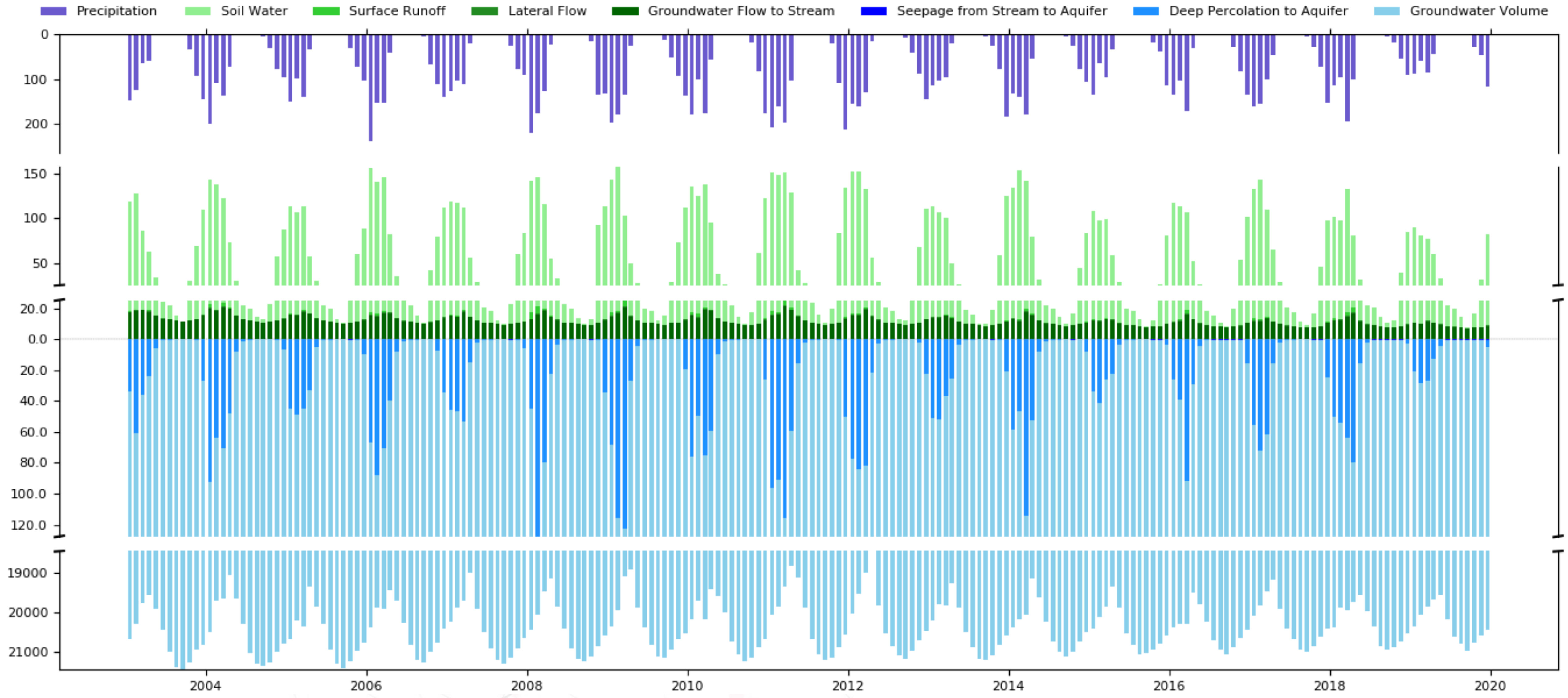




## Yearly Sediment Yields (million tons/year)

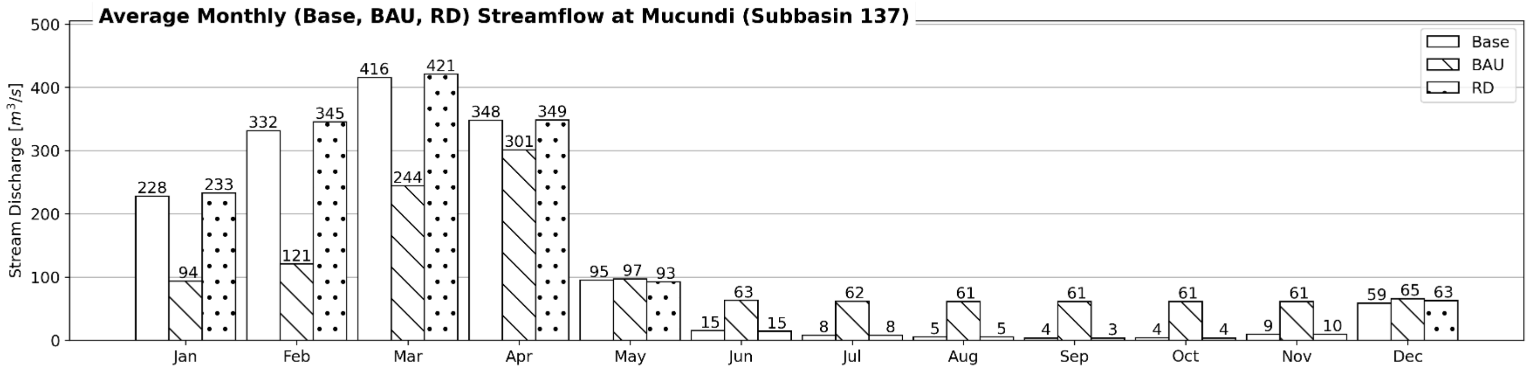
Garstang et al. (1998) and Milzow et al.(2009) estimated yearly sediment yields delivered to the Okavango Delta to be 0.87 million tons/year.

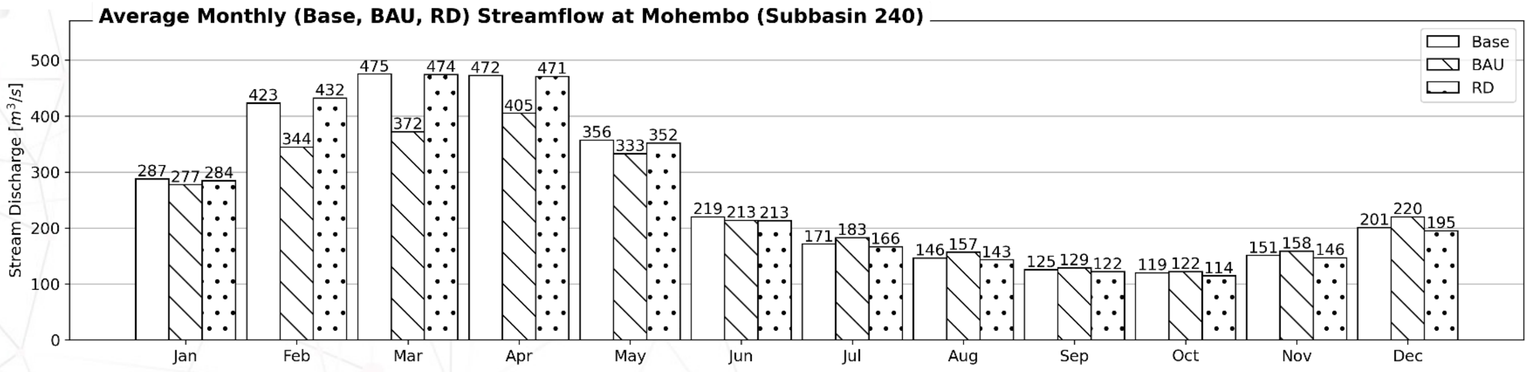
# CASE I | Okavango River Watershed

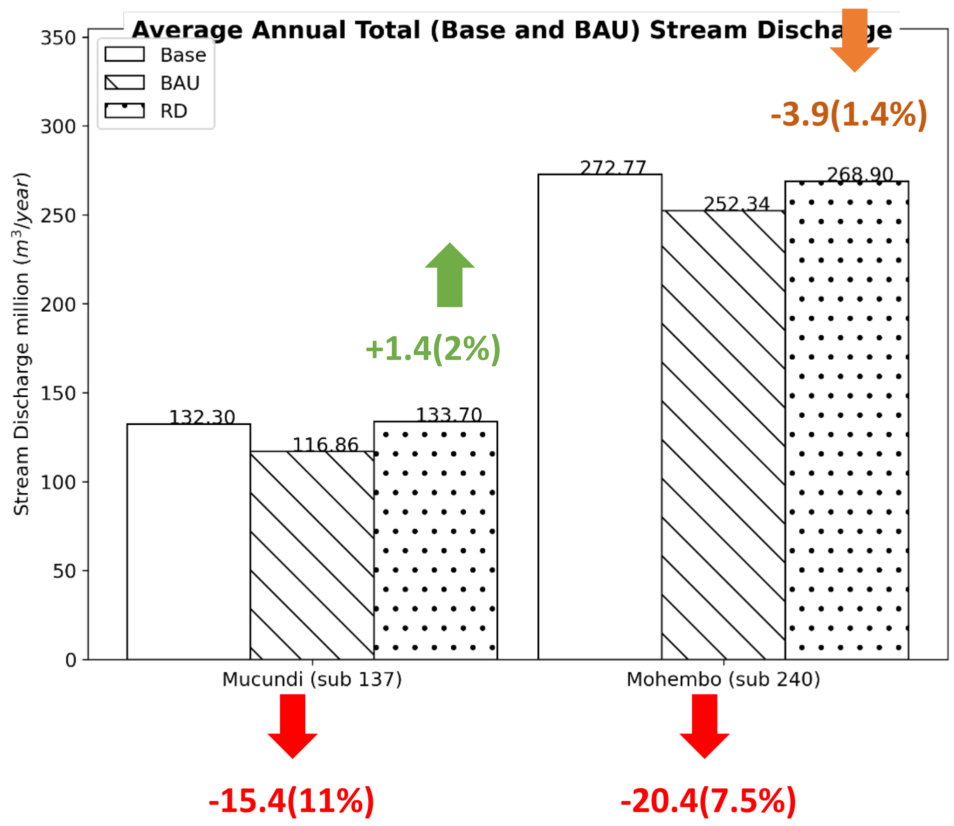


# BAU & RD SCENARIOS | Stream Discharge



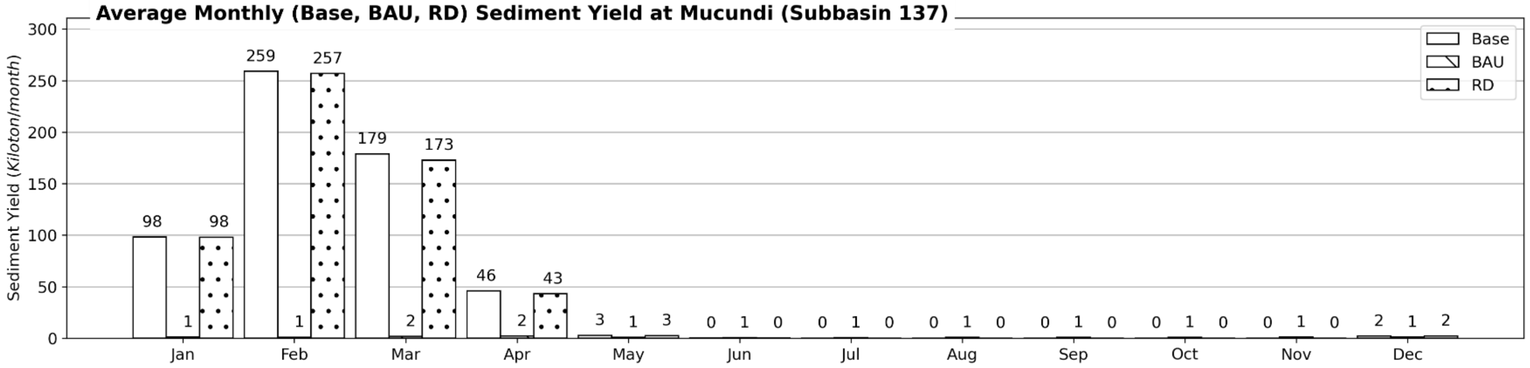


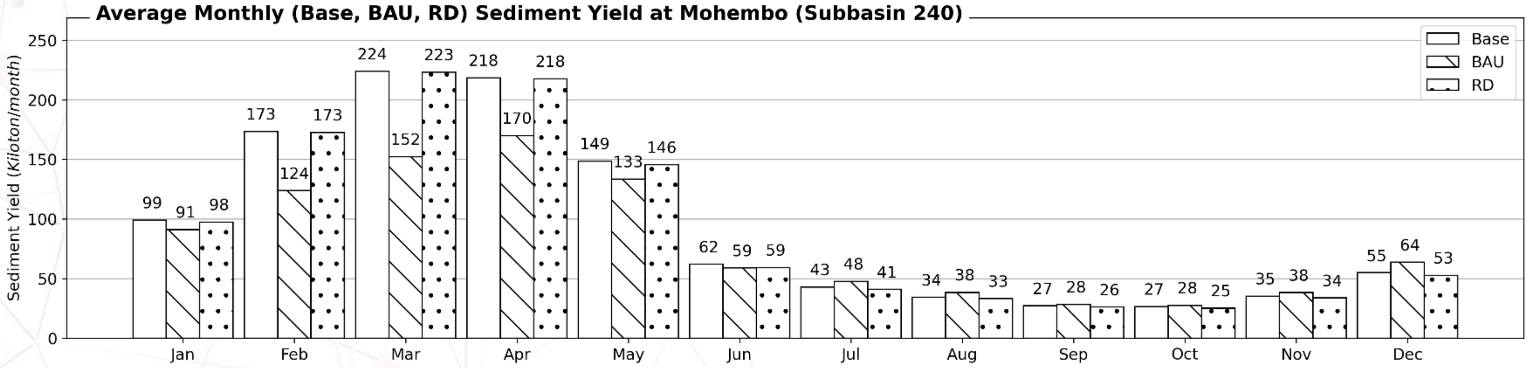



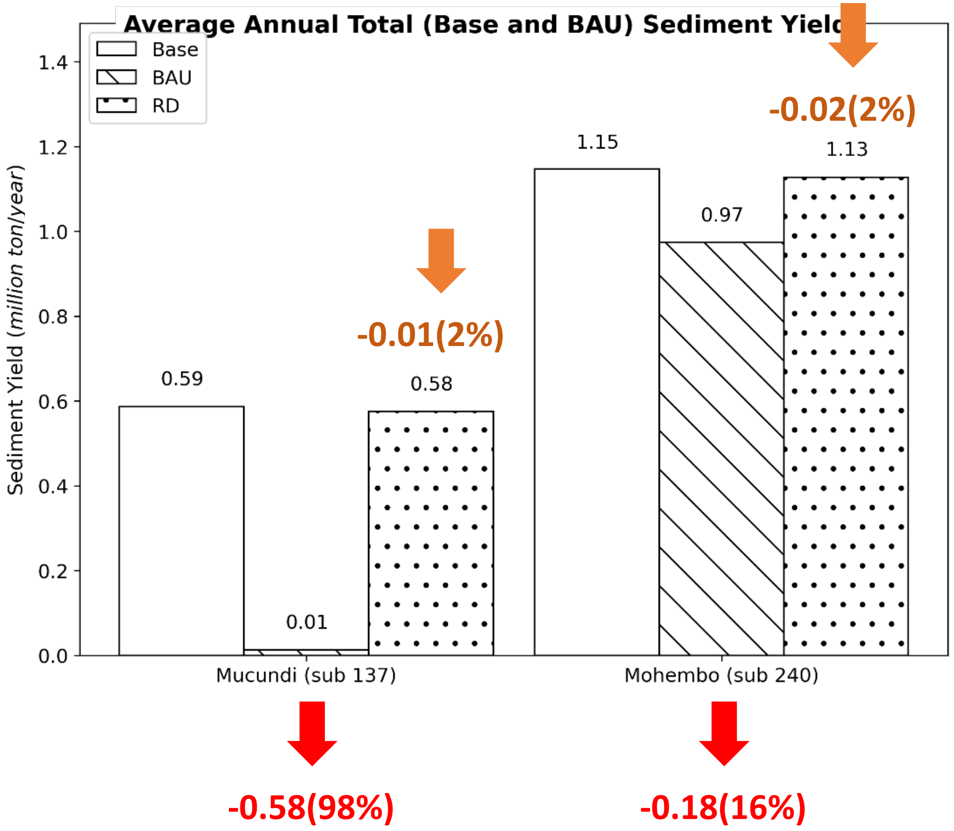



# BAU & RD SCENARIOS | Sediment Yield



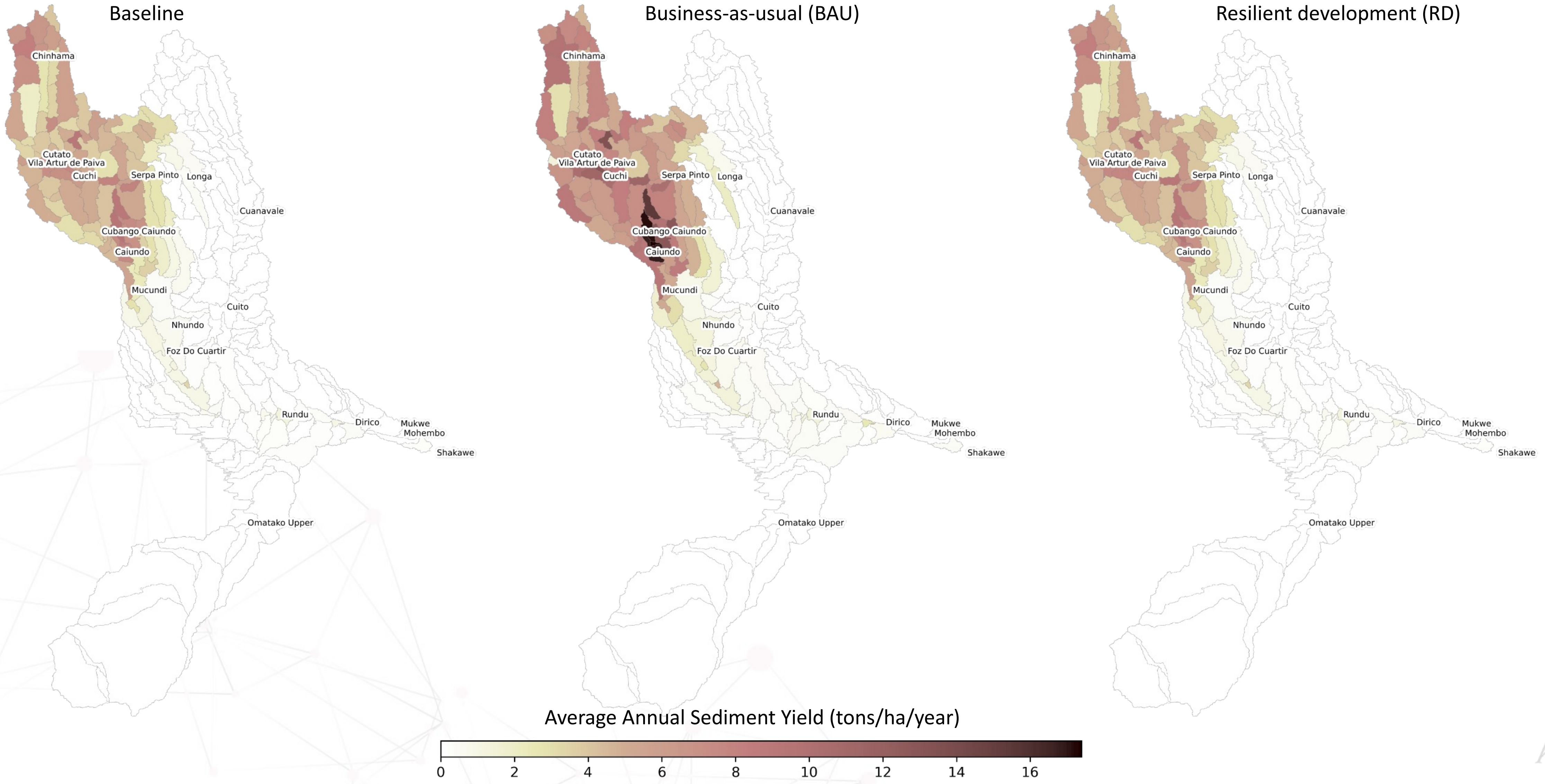


# BAU & RD SCENARIOS | Soil Loss



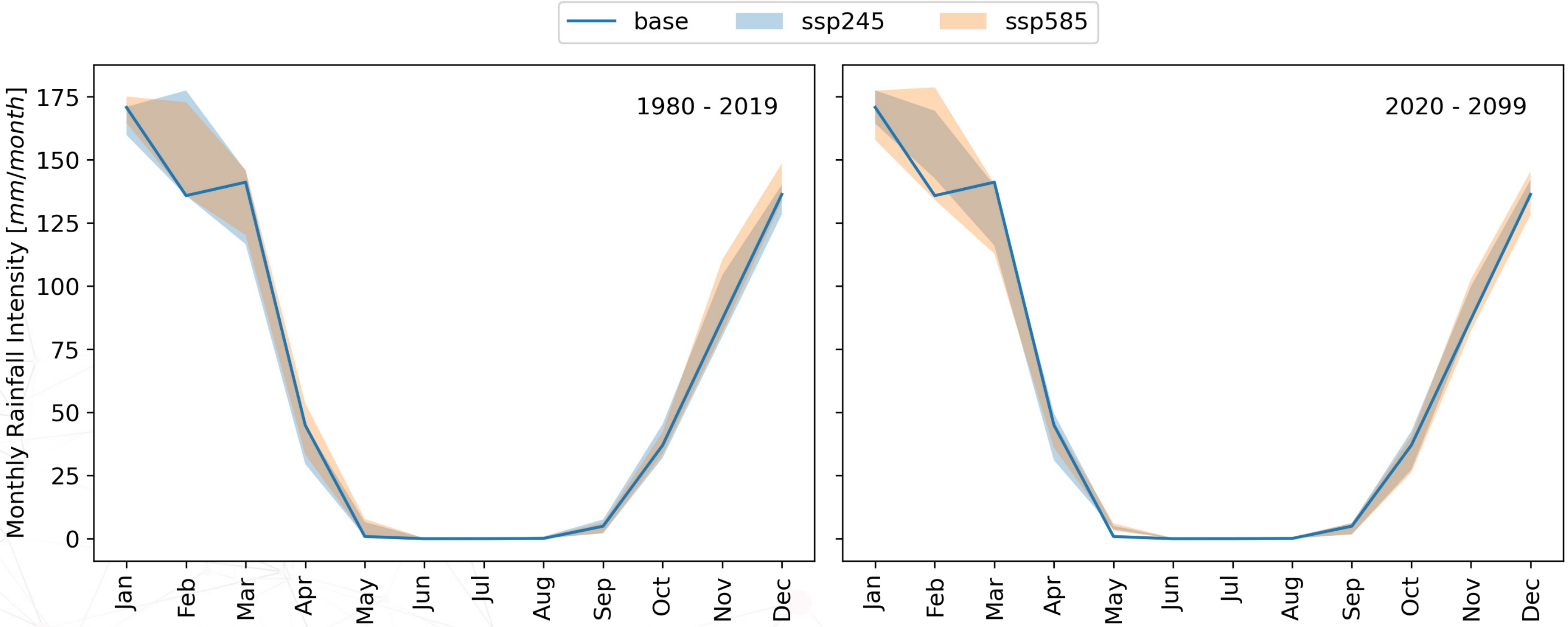


# BAU & RD SCENARIOS | Soil losses in BAU and RD Scenarios relative to Baseline



# CLIMATE SCENARIOS | SSP 245 and SSP 585 for 2020 -2099

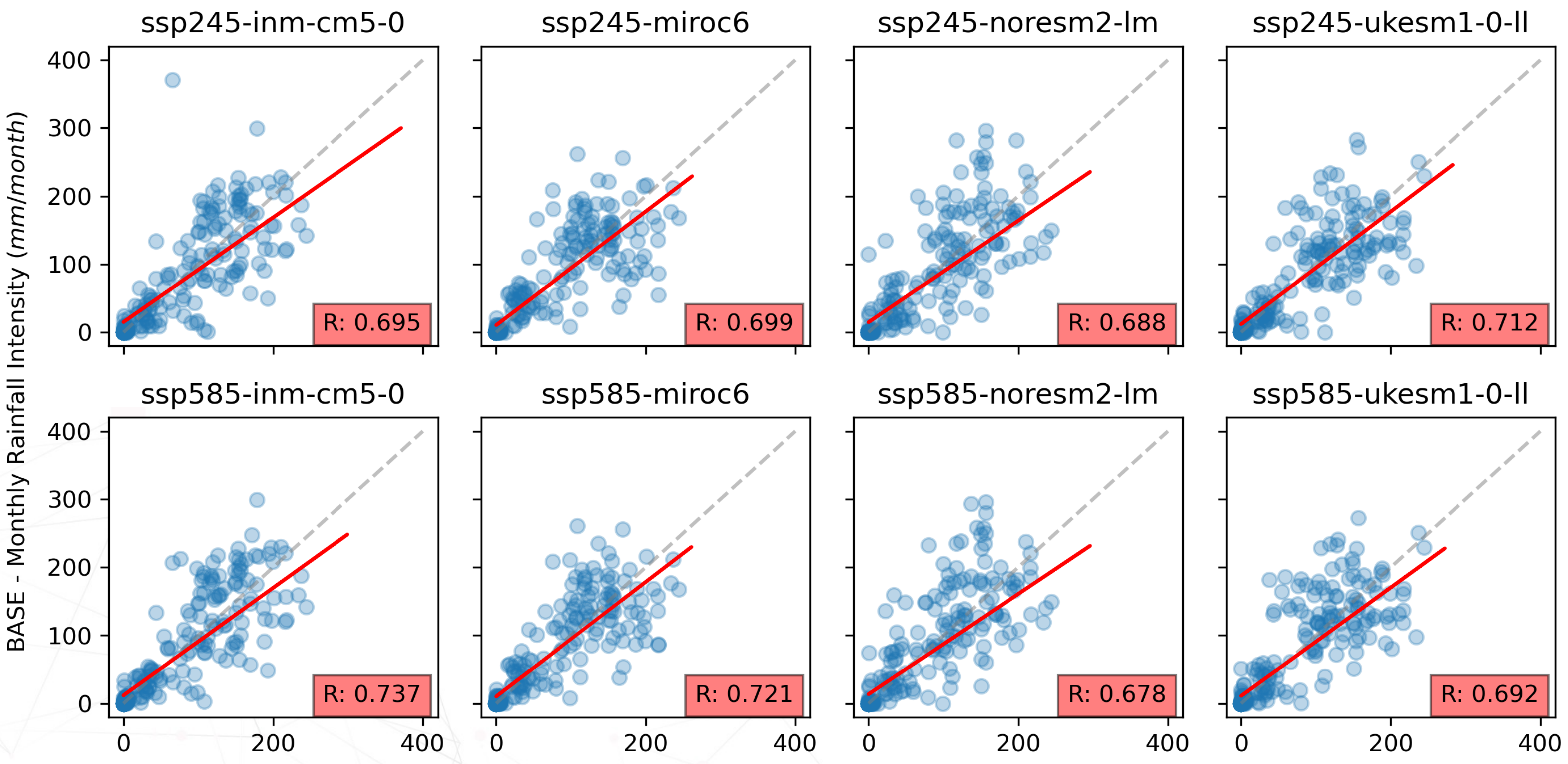





* Base rainfall ranges from 1980 to 2019 in future monthly rainfall data.

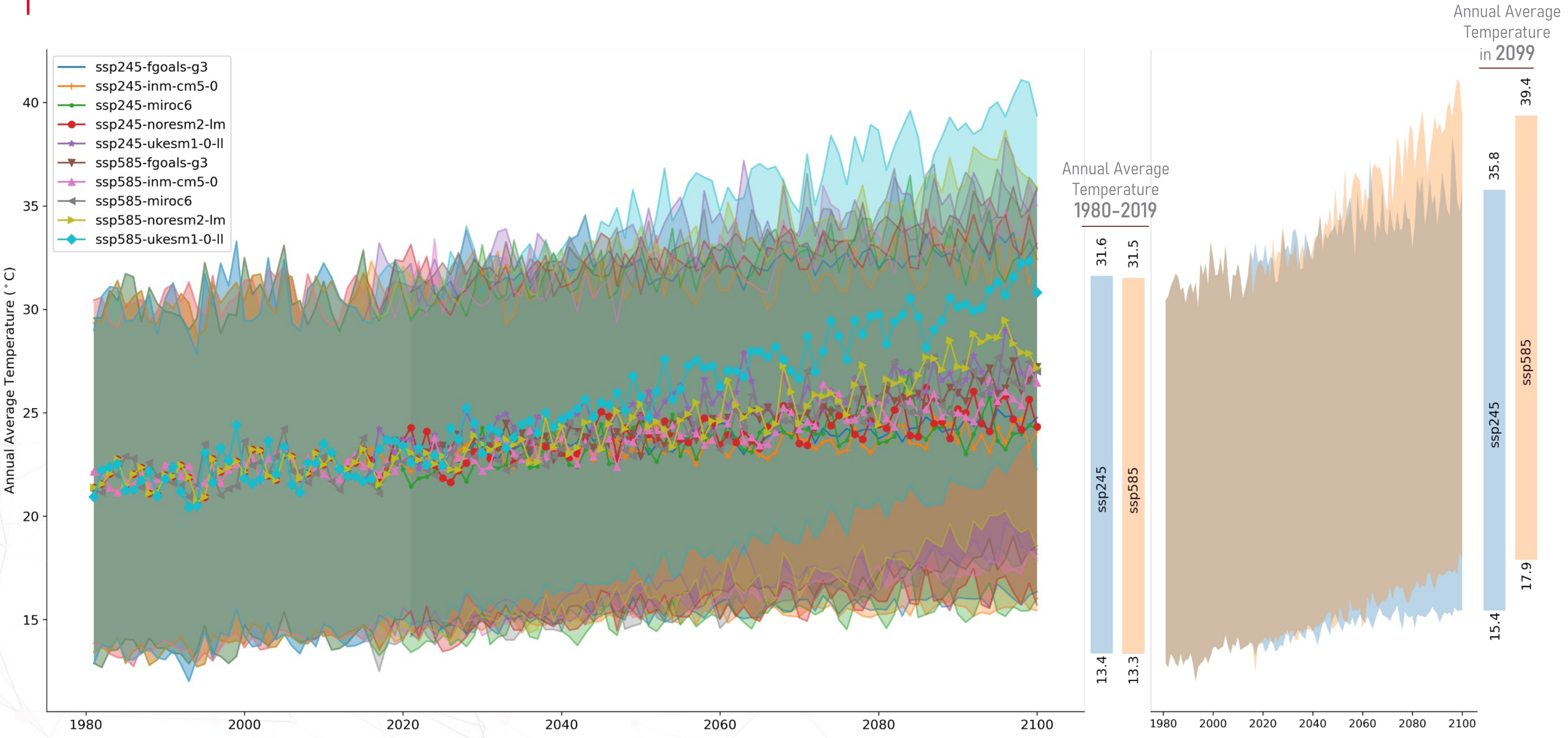
# CLIMATE SCENARIOS | Comparison of Based and Scenario Monthly Rainfall from 2000 - 2019





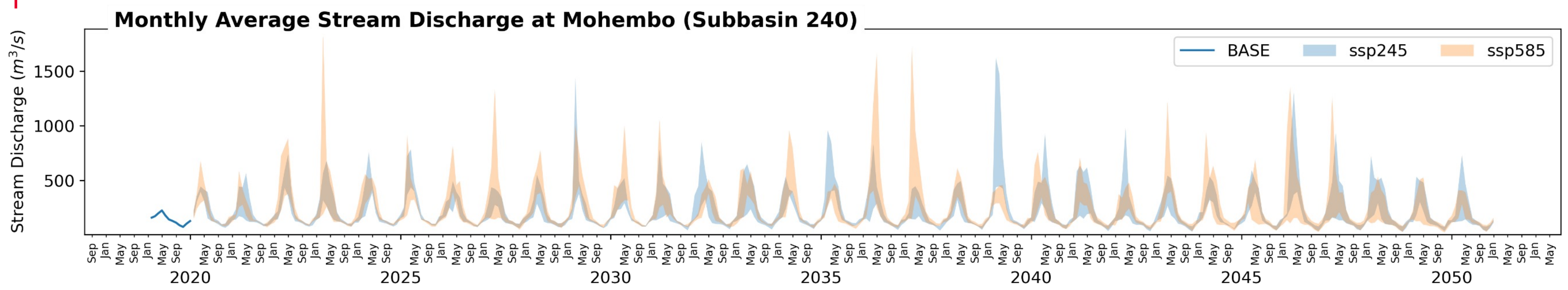
# FUTURE TEMPERATURE | Annual Maximum and Minimum Air Temperatures (°C) during Historical (1980-2019) and Future Period (2020-2099)

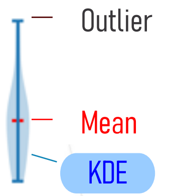




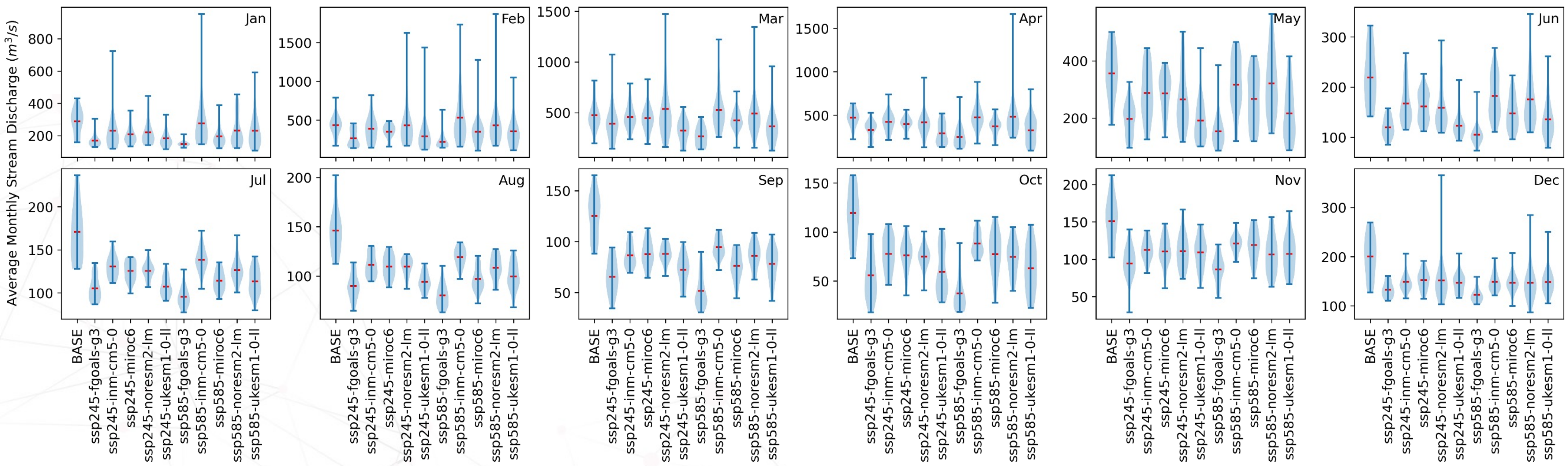
# PROJECTED STREAM DISCHARGE | Monthly Average Stream Discharge (m3/s) in Base Model from 2003-2019 and under Scenario SSP 245 and SSP 585 from 2020 - 2050





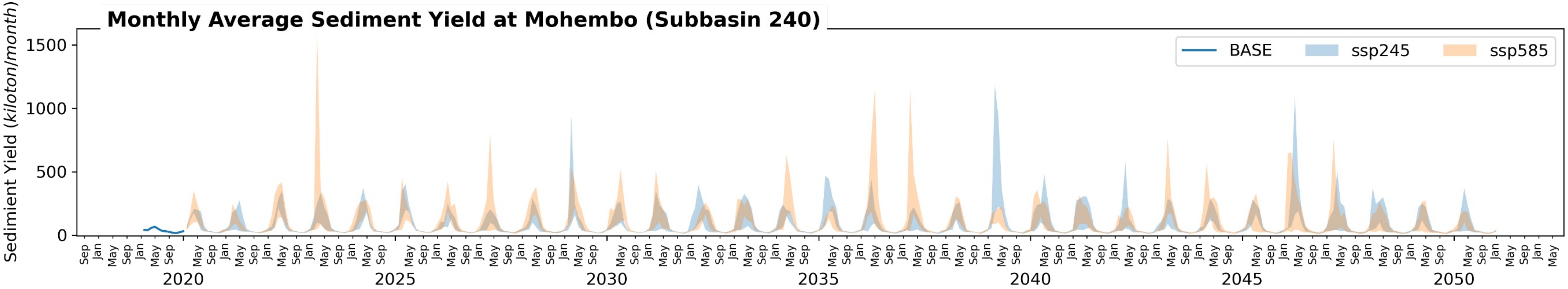

* KDE: Kernel density estimation (KDE) to compute an empirical distribution of the sample

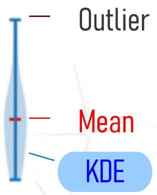


# PROJECTED SEDIMENT YIELD

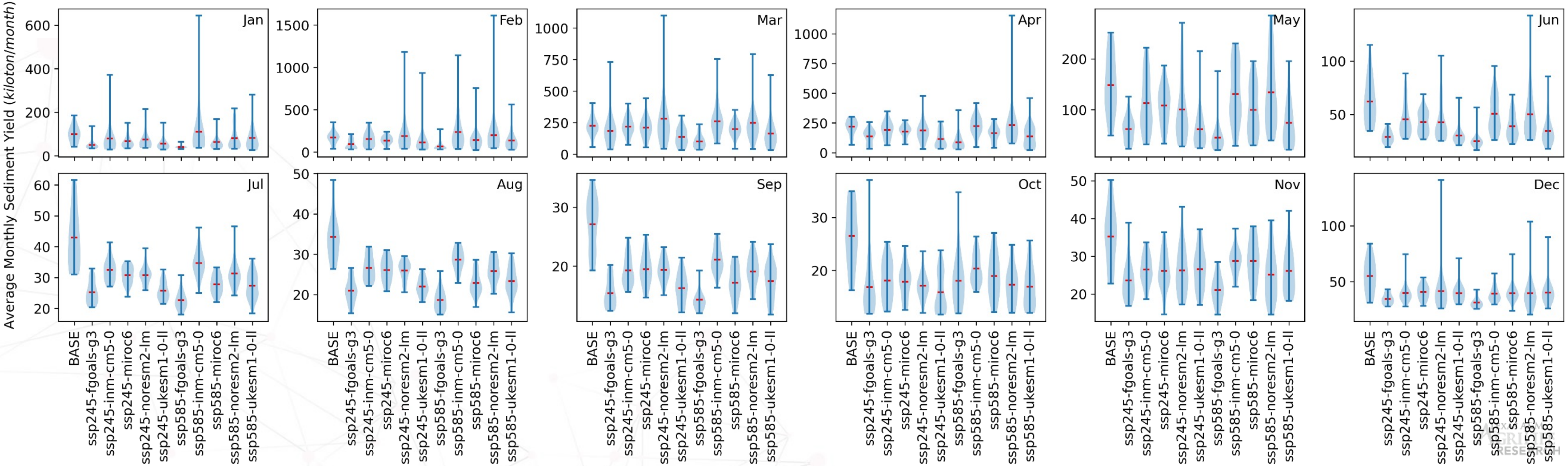
## Monthly Sediment Yield (kiloton/month) in Base Model from 2003-2019 and under Scenario SSP 245 and SSP 585 from 2020 - 2050






* KDE: Kernel density estimation (KDE) to compute an empirical distribution of the sample



# SUMMARY & CONCLUSION

- **Hydrology of the CORB**
  - Groundwater return flow is dominant in channel flow
  - Significant water from floodplain wetlands recharges shallow aquifers
- Management Scenarios
  - BAU: Agricultural intensification, dam construction, and domestic use of water reduce streamflow by 7.5% and sediment delivery to the Delta by 7.5% and 16%, respectively
  - BAU: Soil loss increases up to 100% (or 8 t/ha/yr) in Cubango and may reduce the service life of the Mucundi reservoir
  - RD: Flow volume and sediment delivery to the Delta are sustained well with <2% reduction over the baseline scenario
- Climate Scenarios
  - No distinctive trend in hydrologic responses between SSP scenarios
  - High variability in rainfall intensity results in extreme events during wet months
  - Elevated temperatures promote higher evapotranspiration and cause to reduce streamflow

# CASE II

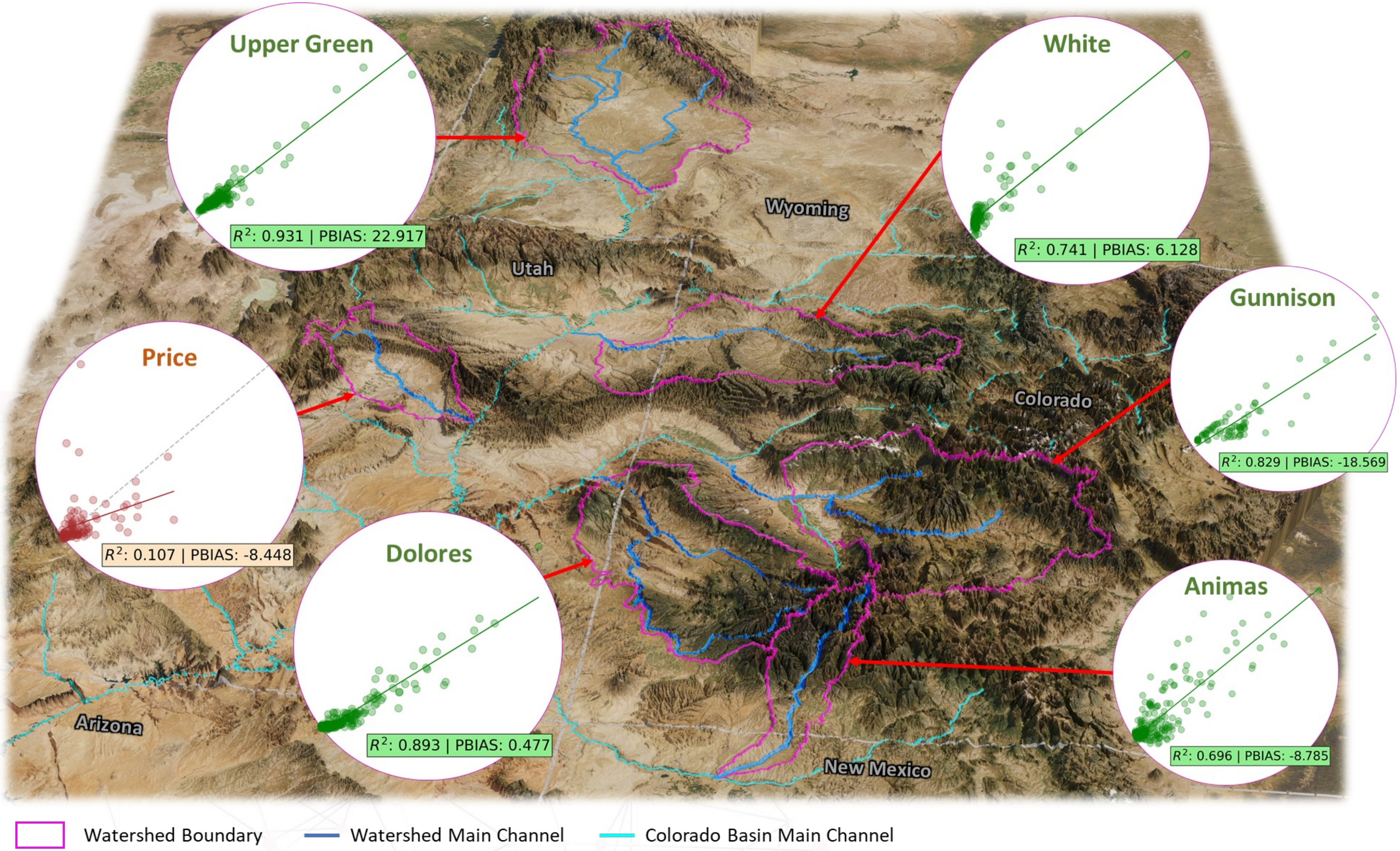
# Colorado River Basins

# (Bureau of Land Management)

# MODEL PERFORMANCE

## $R^2$ for Simulated and Observed Stream Discharge





# MODEL PERFORMANCE

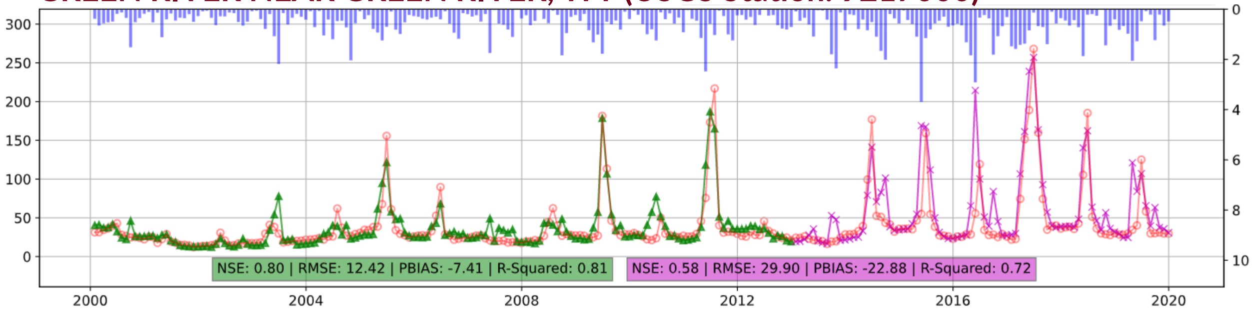
## └ Hydrographs for Simulated and Observed Stream Discharge



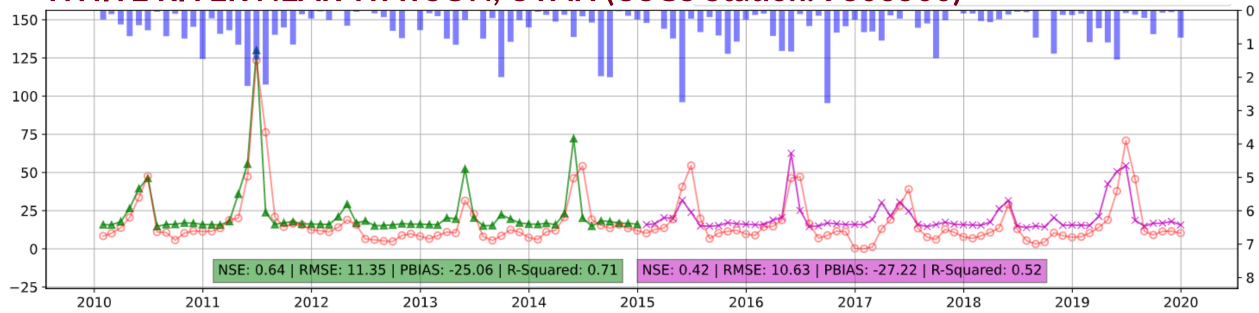
Calibrated | Validated | Observed | Precipitation

1st Y axis: Stream Discharge ($m^3/s$) | 2nd Y axis: Precipitation (mm)

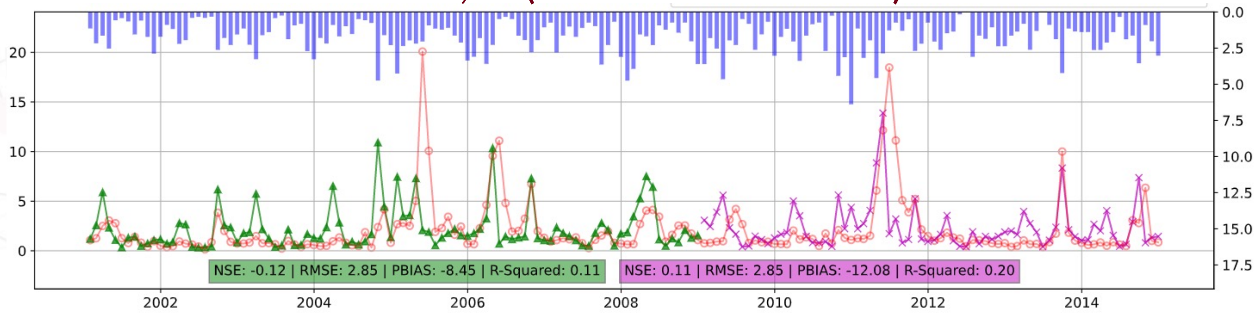
### GREEN RIVER NEAR GREEN RIVER, WY (USGS Station: 9217000)



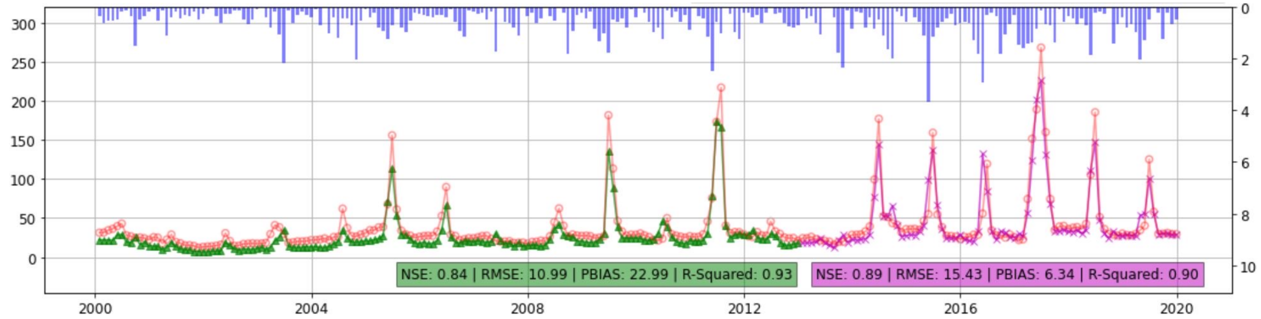

### WHITE RIVER NEAR WATSON, UTAH (USGS Station: 9306500)



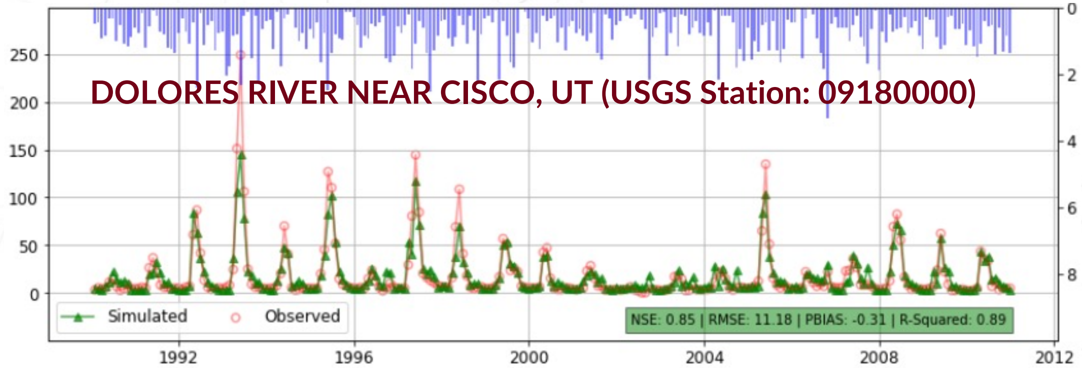

### PRICE RIVER AT WOODSIDE, UT (USGS Station: 09314500)



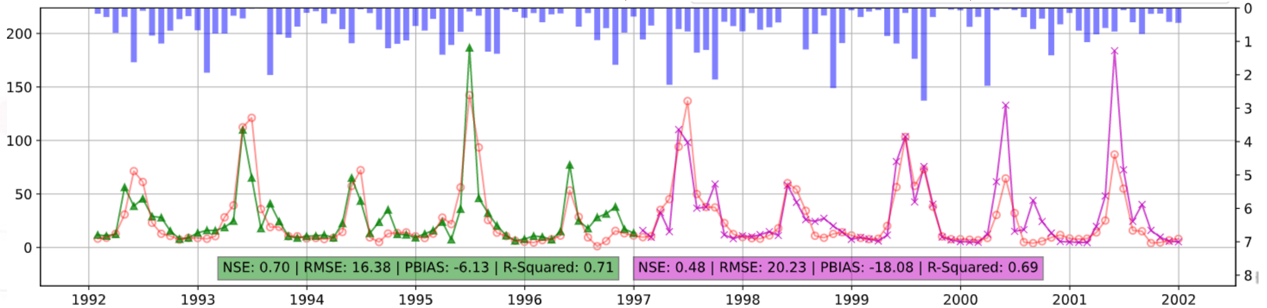

### GUNNISON RIVER AT DELTA, CO (USGS Station: 09144250)




### DOLORES RIVER NEAR CISCO, UT (USGS Station: 09180000)




### ANIMAS RIVER AT FARMINGTON, NM (USGS Station: 9364500)

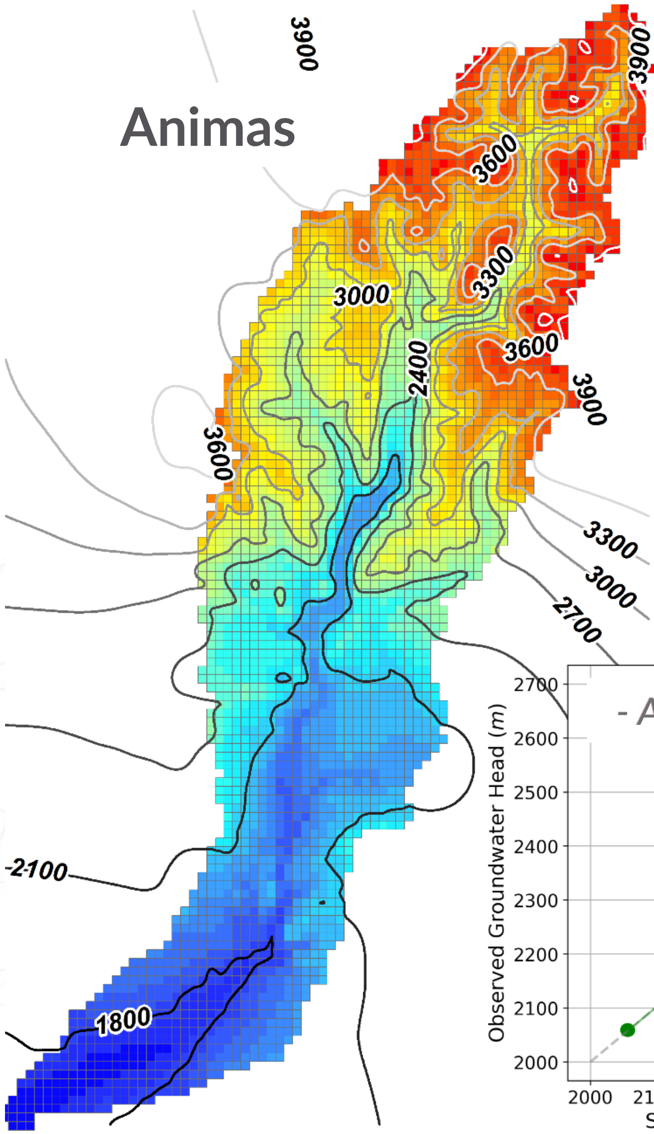


# MODEL PERFORMANCE

## Comparison of Simulated and Observed Water Table Elevation



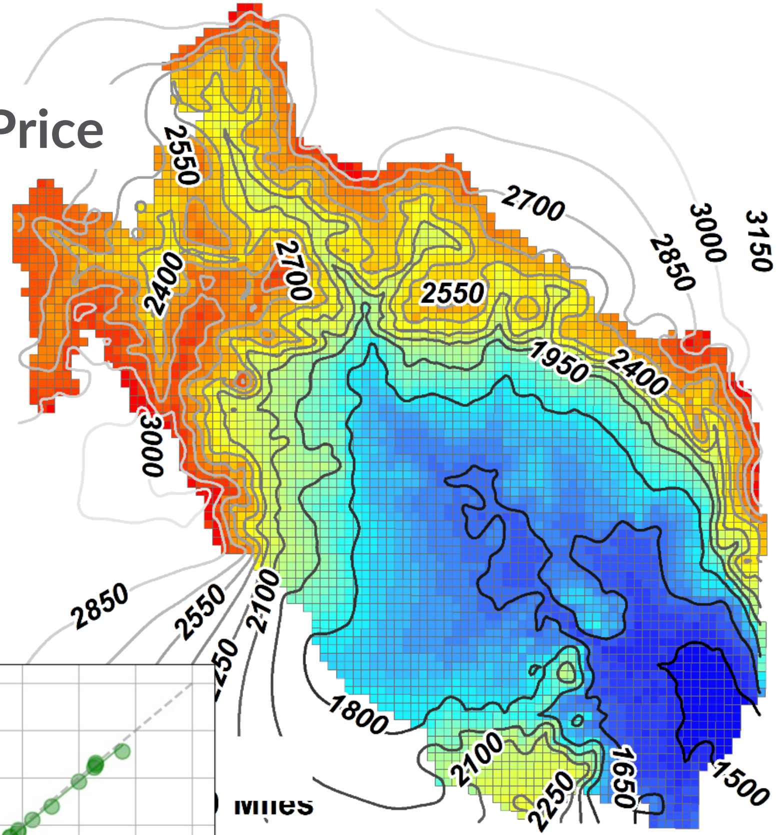
Animas

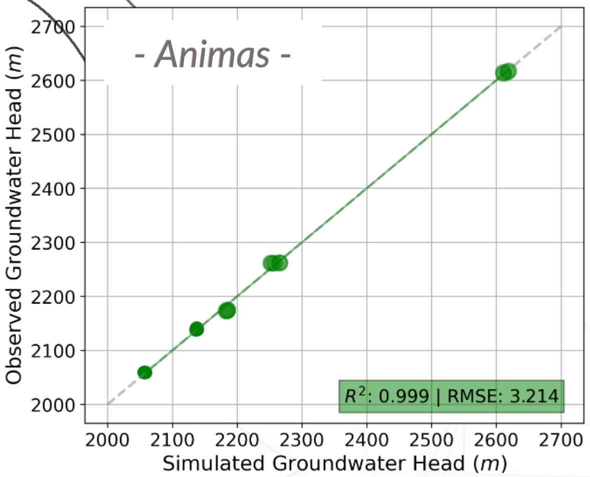


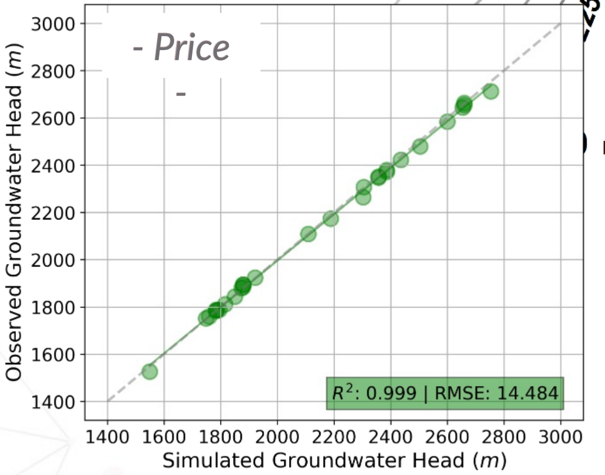

**Water Table Elevation (m)**

| | Minimum | Maximum |
|---|---|---|
| Animas | 1,622 | 4,047 |
| Price | 1,492 | 3,059 |

Price



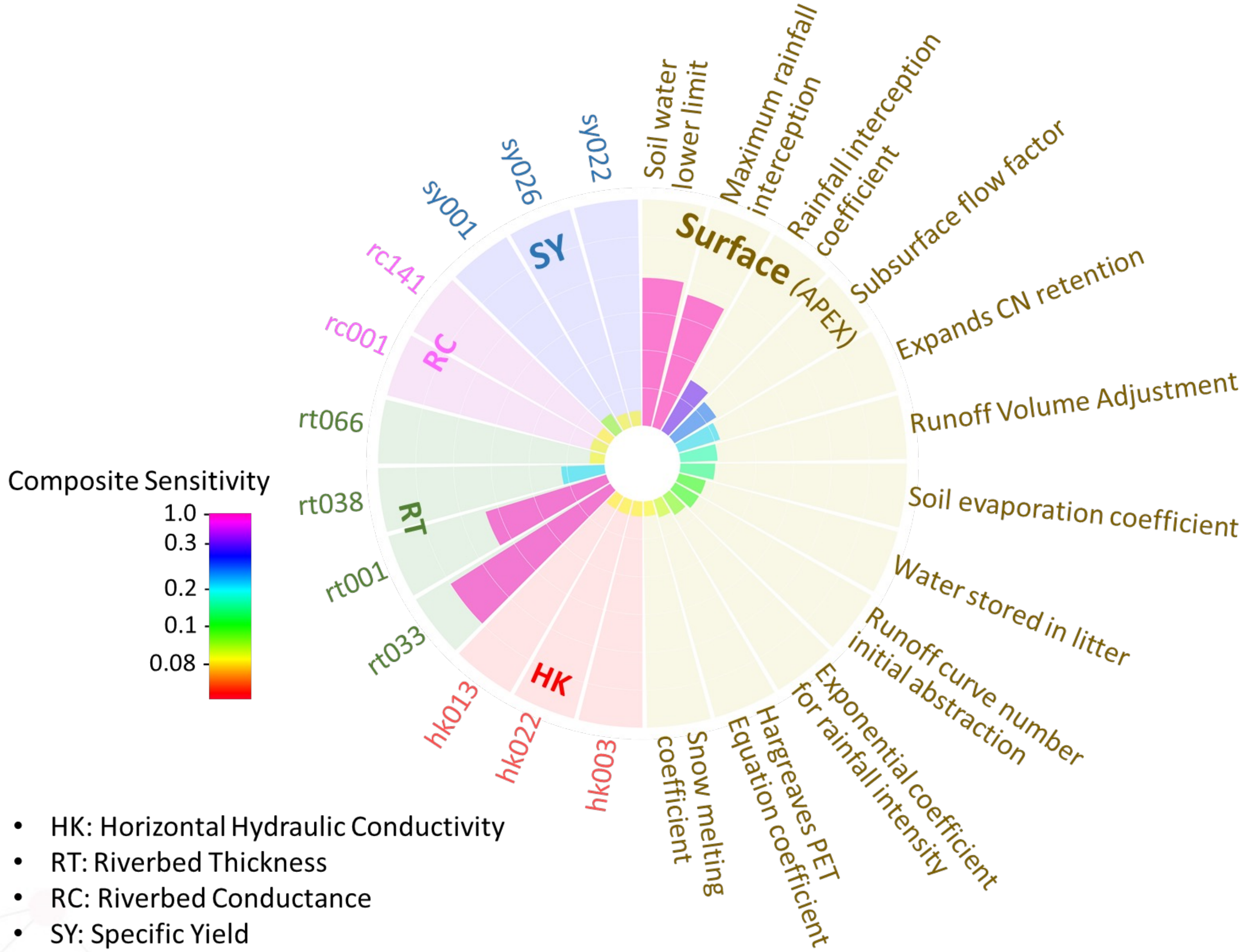



# MODEL PERFORMANCE

## └ Sensitivity Analysis



- 40 ~ 150 parameters were used for each model optimization.
- Auto-calibration was performed using Python scripts and model-independent Parameter ESTimation utilities (PEST).
- USGS streamgage data and groundwater level were used.
- In general, riverbed thickness from MODFLOW and soil water limit from APEX were estimated to be highly sensitive to groundwater level and stream discharge.



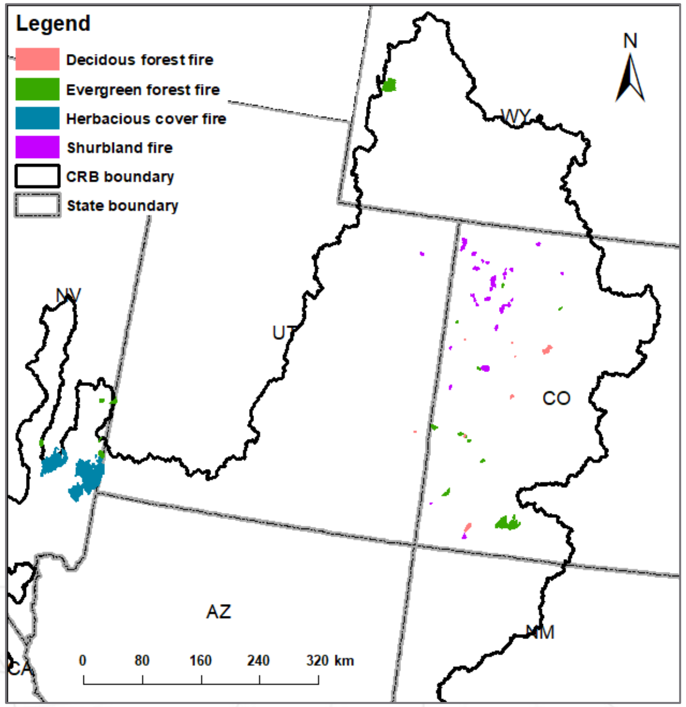

- HK: Horizontal Hydraulic Conductivity
- RT: Riverbed Thickness
- RC: Riverbed Conductance
- SY: Specific Yield

: Dolores Watershed

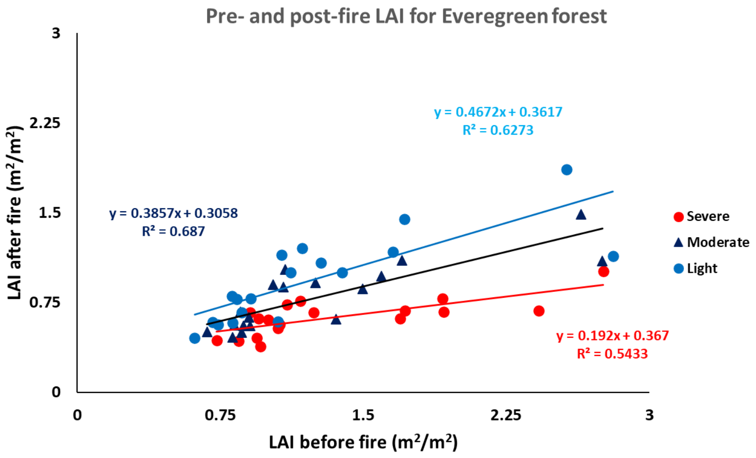
# WILDFIRE ASSESSMENT IN APEX MODEL

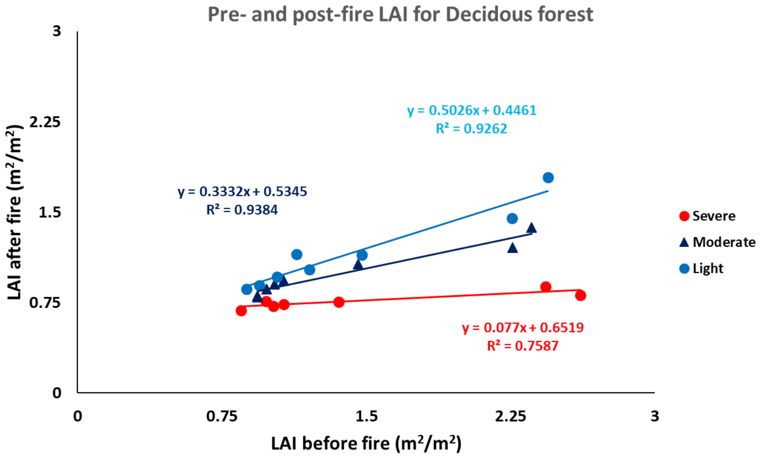
## Landsat-based pre-and post-fire LAI synthesis

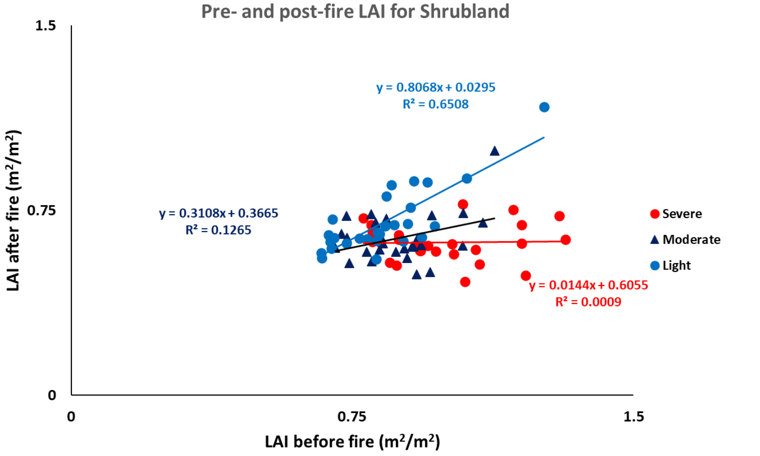





Historical wildfire event locations used in the analyses




Among over 5000 fire events reported since 1974, about 100 were selected for analysis based on the following criteria:

- >10,000 acres
- 2000 or later
- Within UCRB
- Availability of cloud-free Landsat data within 1-month pre- and post-fire period

- Several 30m*30m pixels Landsat 7 images were analyzed in Google Earth Engine to compute fire burn severity indices (Severe, Moderate and light) and explore the pre- and post-fire LAI for dominant landcover types across CRB

→ The post-fire LAI illustrates the biomass loss extent which has serious implications to surface runoff processes, salt and sediment loads to streams

# WILDFIRE ASSESSMENT IN APEX MODEL

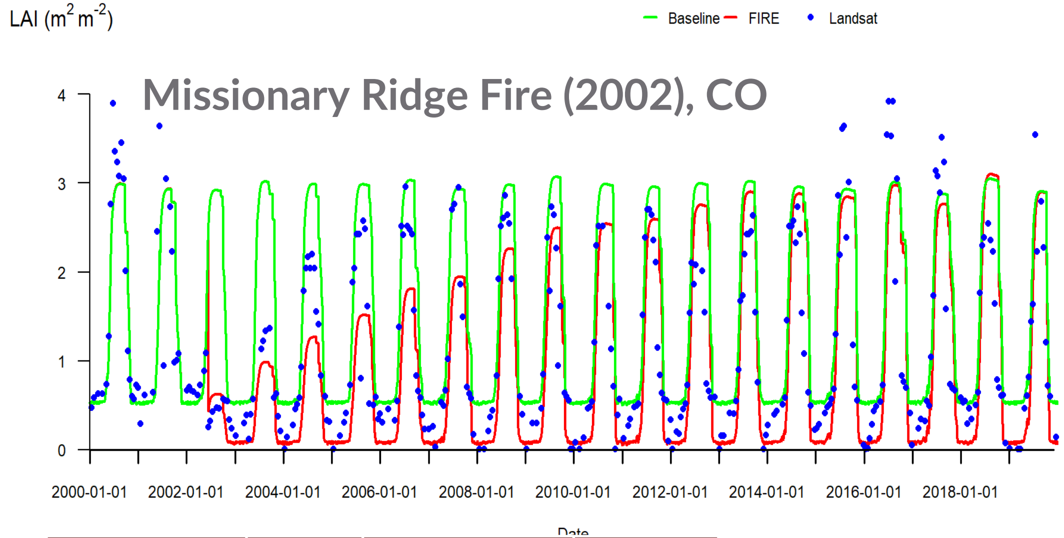
## └ Wildfire simulation in APEX

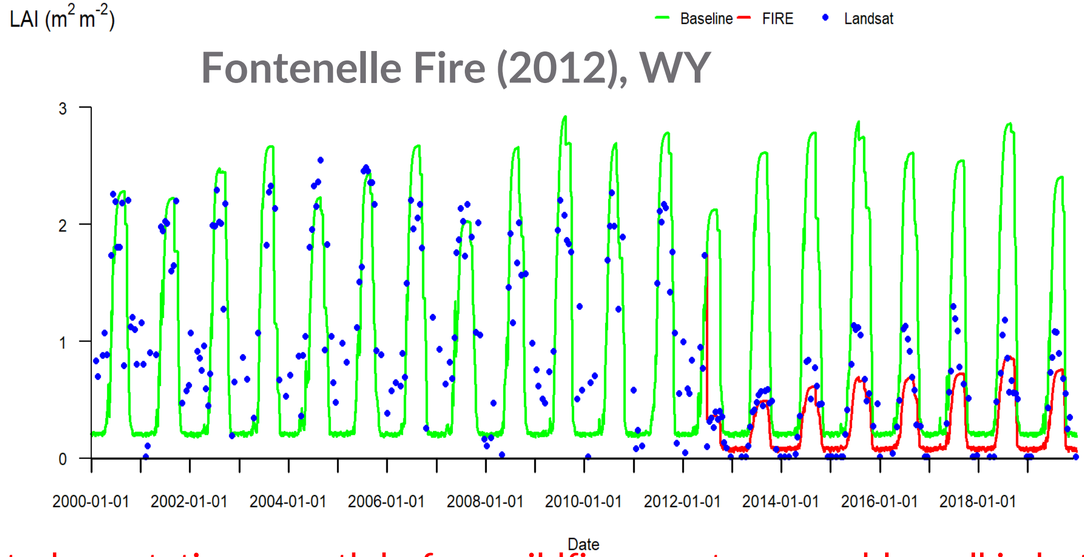


- APEX has a number of operation that is relevant to wildfire

✓ Burn operation: mainly remove biomass >> reduce LAI depending on fire severity

✓ Thinning: reduce the density of plant population




| | Before | Short-term | Long-Term |
|---|---|---|---|
| Upper Green watershed , WY | | | |
| RMSE | 0.57 | 0.14 | 0.23 |
| R2 | 0.7 | 0.72 | 0.71 |
| Animas watershed, CO | | | |
| RMSE | 0.62 | 0.45 | 0.64 |
| R2 | 0.69 | 0.75 | 0.66 |

✓ APEX simulated vegetation growth before wildfire event reasonably well in both Animas and Upper Green watersheds

✓ APEX can simulate the wildfire impact on vegetation cover using the burn and thinning operations in the short-term

✓ The model requires field data and information of restoration activities to accurately simulate long-term vegetation recovery

# Data-Driven Application

# DATA-DRIVEN APPLICATION

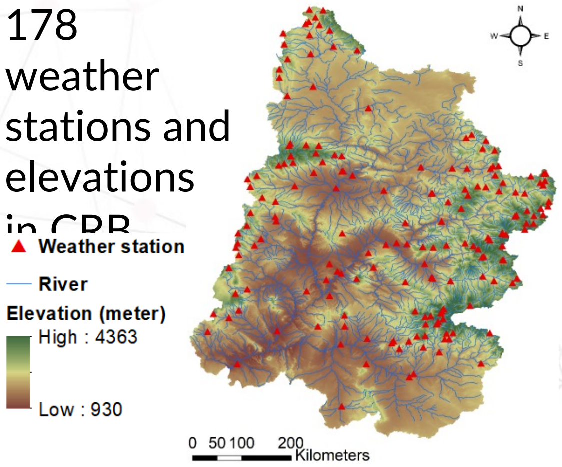
## └ Spatio-Temporal Evaluation of Satellite-based Precipitation Products



- BACKGROUND and PURPOSES
  - Satellite-based remote sensors (RS) provided continuous and seamless data that can overcome the limitation of ground-based precipitation.
  - Evaluation of RS-based precipitation over snowfall-dominated complex mountainous regions (i.e., CBR) for hydrological applications.

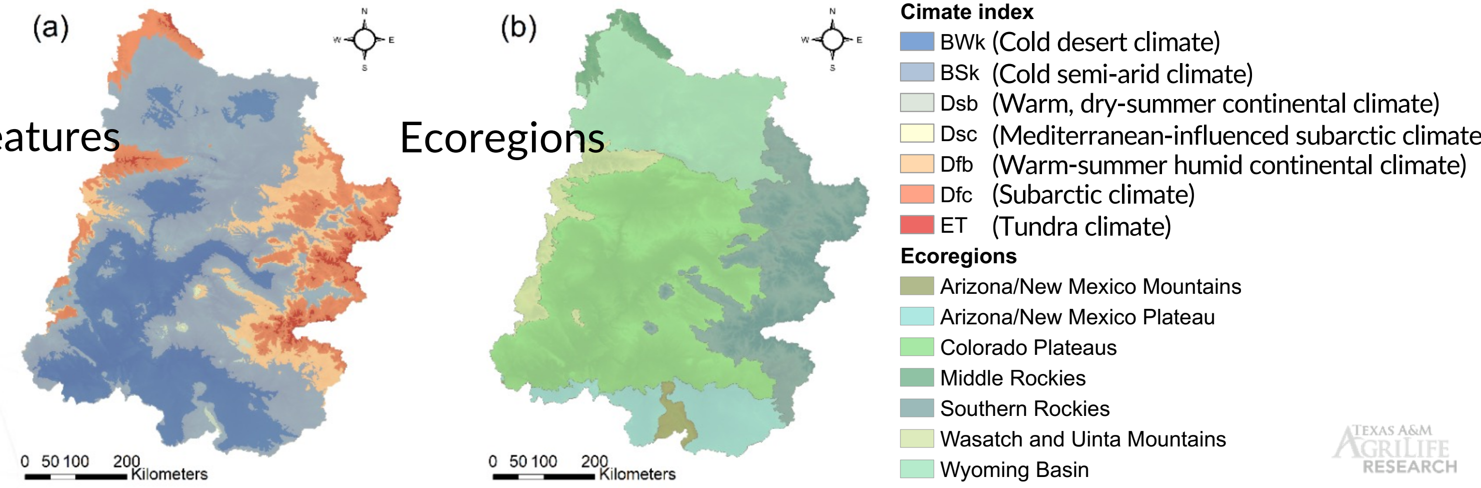
- METHODS and DATA
  - Three RS-based daily precipitation products (TRMM, PERSIANN, CHIRPS) were evaluated by comparing with 178 ground stations in CRB.
  - Six statistical metrics were used for evaluations.
  - Uncertainty of products was investigated according to different elevation, climate, and ecological features in CRB.
  - Daily precipitation data for 20 years (2000 – 2019) were evaluated.

178 weather stations and elevations in CRB




Climate features

Ecoregions



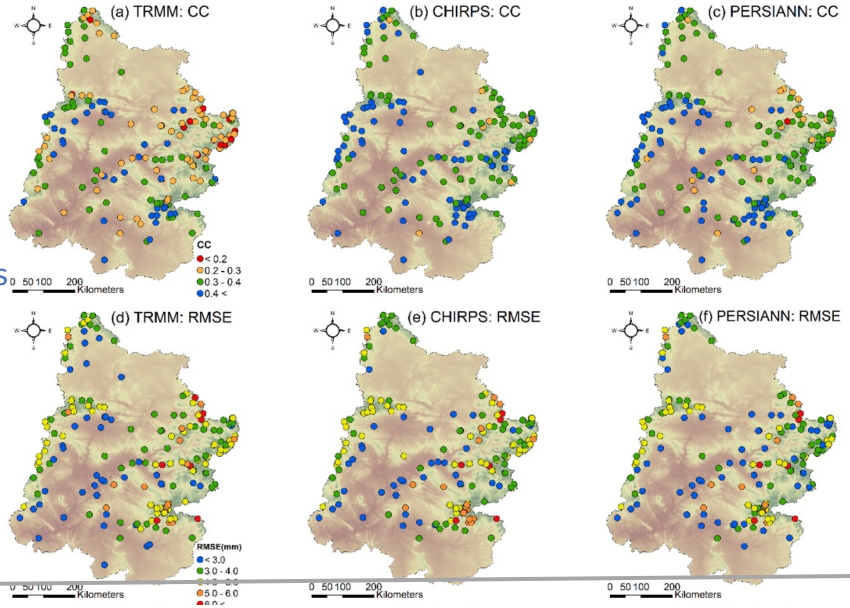

TEXAS A&M AGRILIFE RESEARCH

# DATA-DRIVEN APPLICATION

## └ Spatio-Temporal Evaluation of Satellite-based Precipitation Products

- Spatial distribution CC and RMSE over CRB.

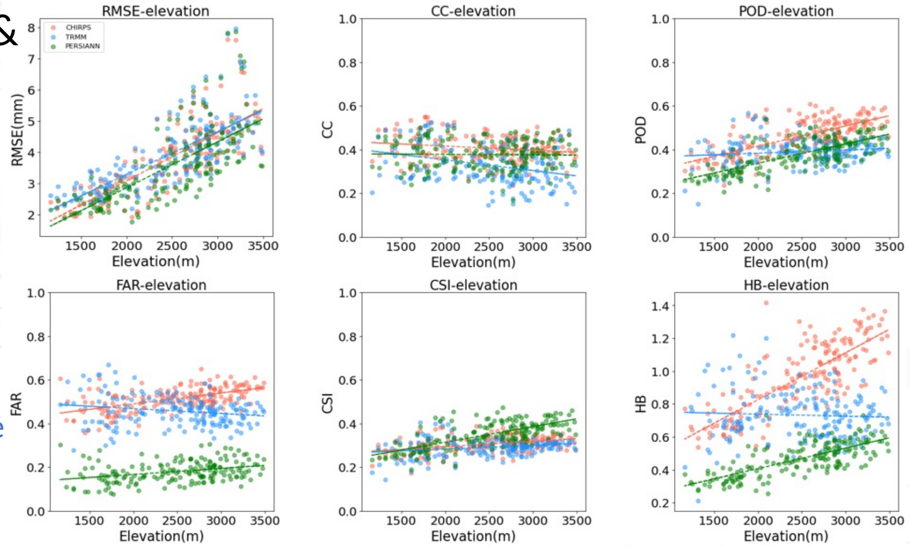
✓ Poor quality in terms of CC and RMSE metrics in mountainous areas than in lower altitude areas

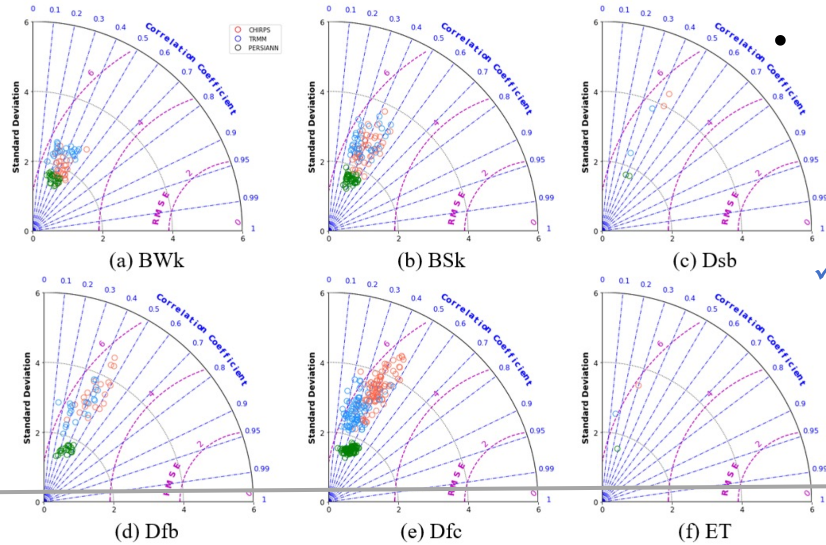



- Uncertainty & Elevation

✓ RMSE has strongly correlated with elevation variability

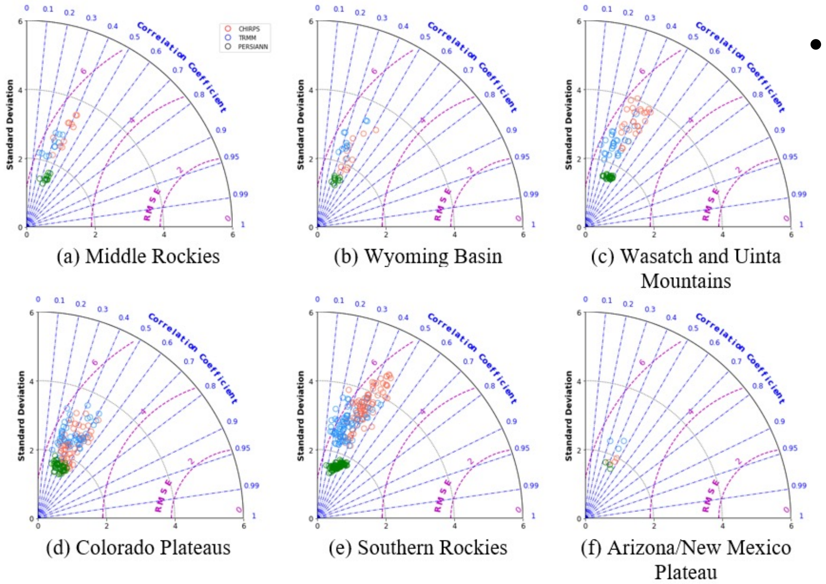
✓ TRMM was very insensitive to the elevation variability




- Uncertainty & Climate features

✓ All three products have similar patterns of metrics for each climate feature and ecoregion




- Uncertainty & Ecoregions

# DATA-DRIVEN APPLICATION

## └ Development of Wildfire Severity Prediction Model using Machine Learning Approach

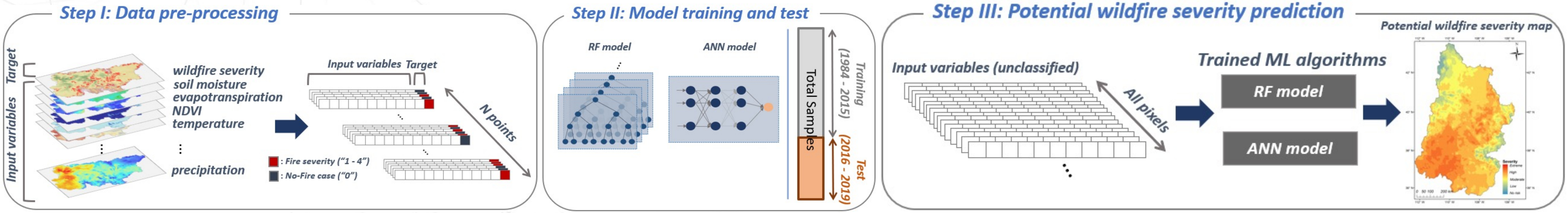
- BACKGROUND and PURPOSES
  - Wildfire severity is linked to multiple environmental conditions such as weather, soil, land property, fuels, and others.
  - Machine learning can be a novel approach to predict wildfire severity with various environmental conditions.
  - Prediction of potential wildfire severity in CRB using machine learning algorithms and relationship between severity and environmental conditions.

$$NBR = \frac{NIR - SWIR}{NIR + SWIR}$$

$\uparrow NBR$ : healthy vegetation

$\downarrow NBR$ : bare ground or burnt area

- METHODS and DATA
  - Grid-based spatial environment datasets (4 x 4 km) were used as inputs of Artificial Neural Networks (ANN), Random Forest (RF) models.
  - Data: Precipitation, temperature, soil moisture, NDVI, evapotranspiration, wind speed, drought conditions, etc.
  - The difference between the pre-fire and post-fire NBR (dNBR or ΔNBR) was used to calculate the burn severity (from MTBS website; https://mtbs.gov).

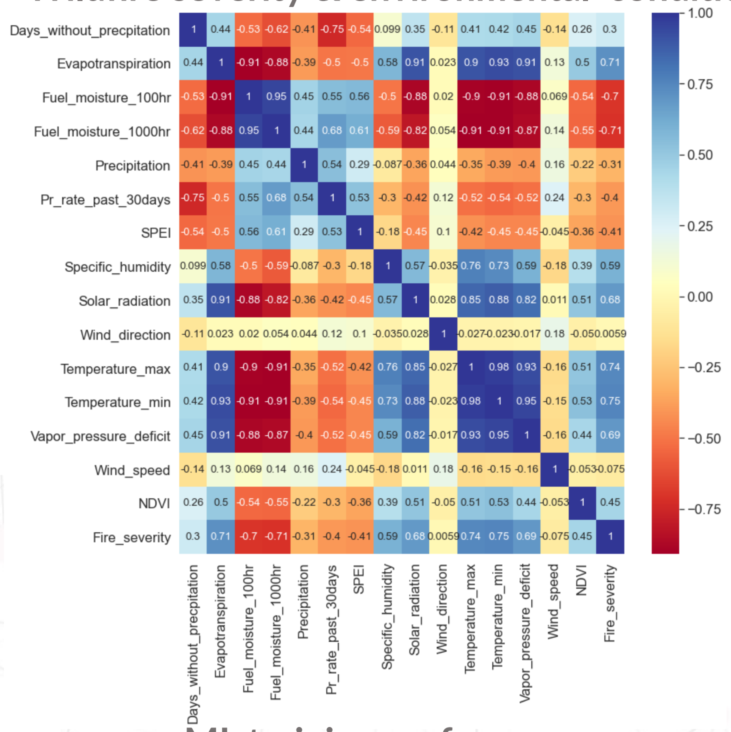


# DATA-DRIVEN APPLICATION

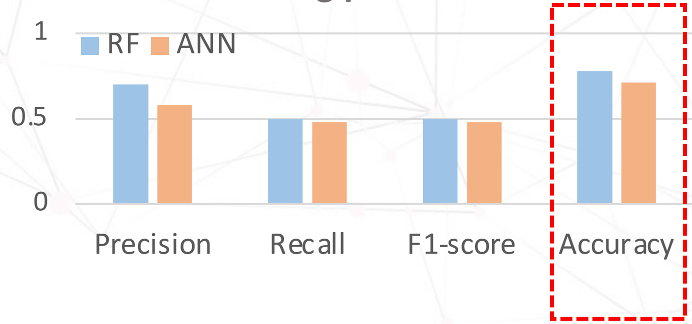
## └ Development of Wildfire Severity Prediction Model using Machine Learning Approach



### Wildfire severity & environmental conditions

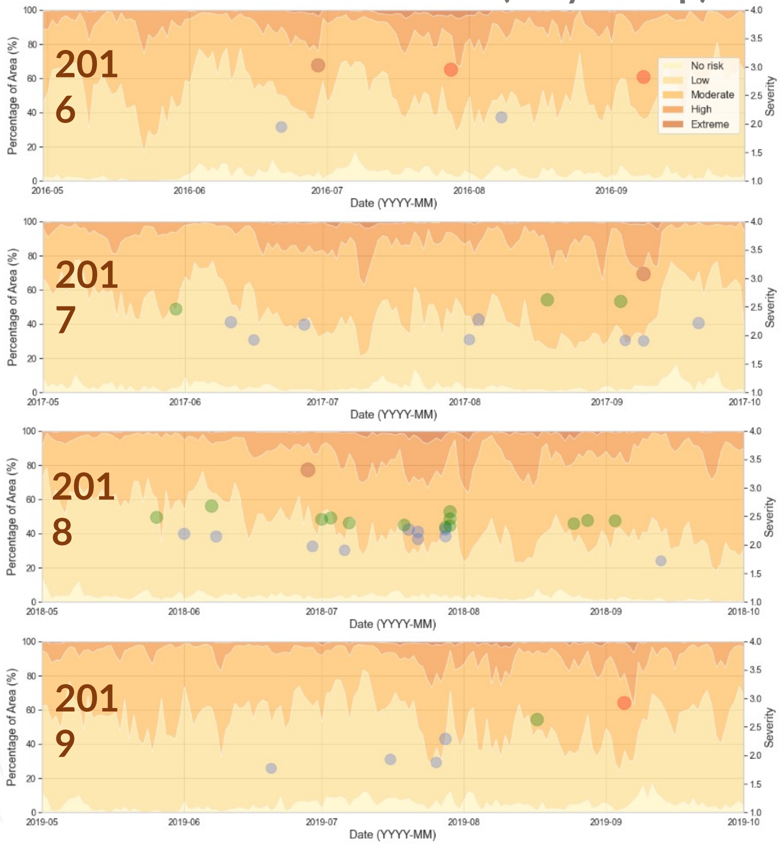



### ML training performances



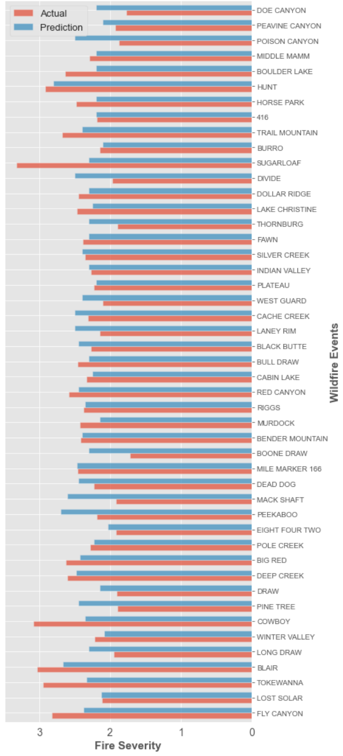

### Prediction results of wildfire severity from 2016 to 2019 in CRB

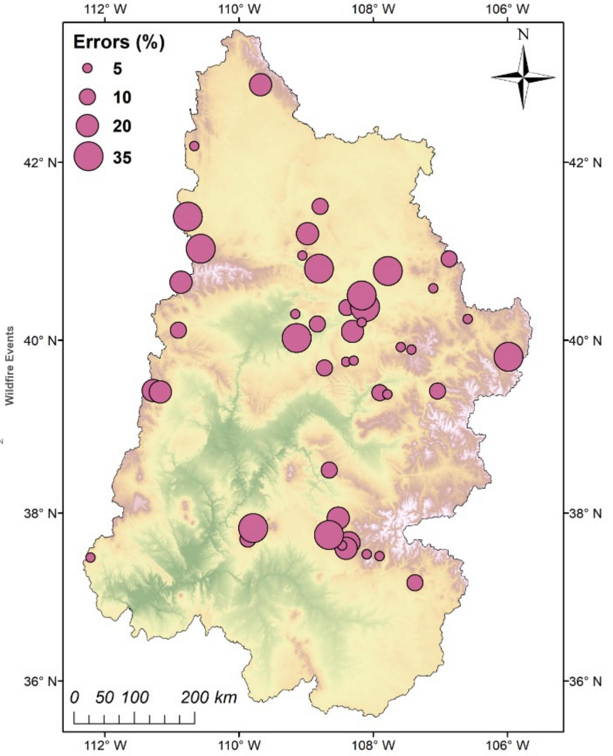
### Percent area coverage for wildfire categories based on their severities (May to Sep)




- The circle indicates the wildfire severity of 47 actual wildfire events. Brown, red, green, blue indicate extreme, high, moderate, and low severity cases, respectively

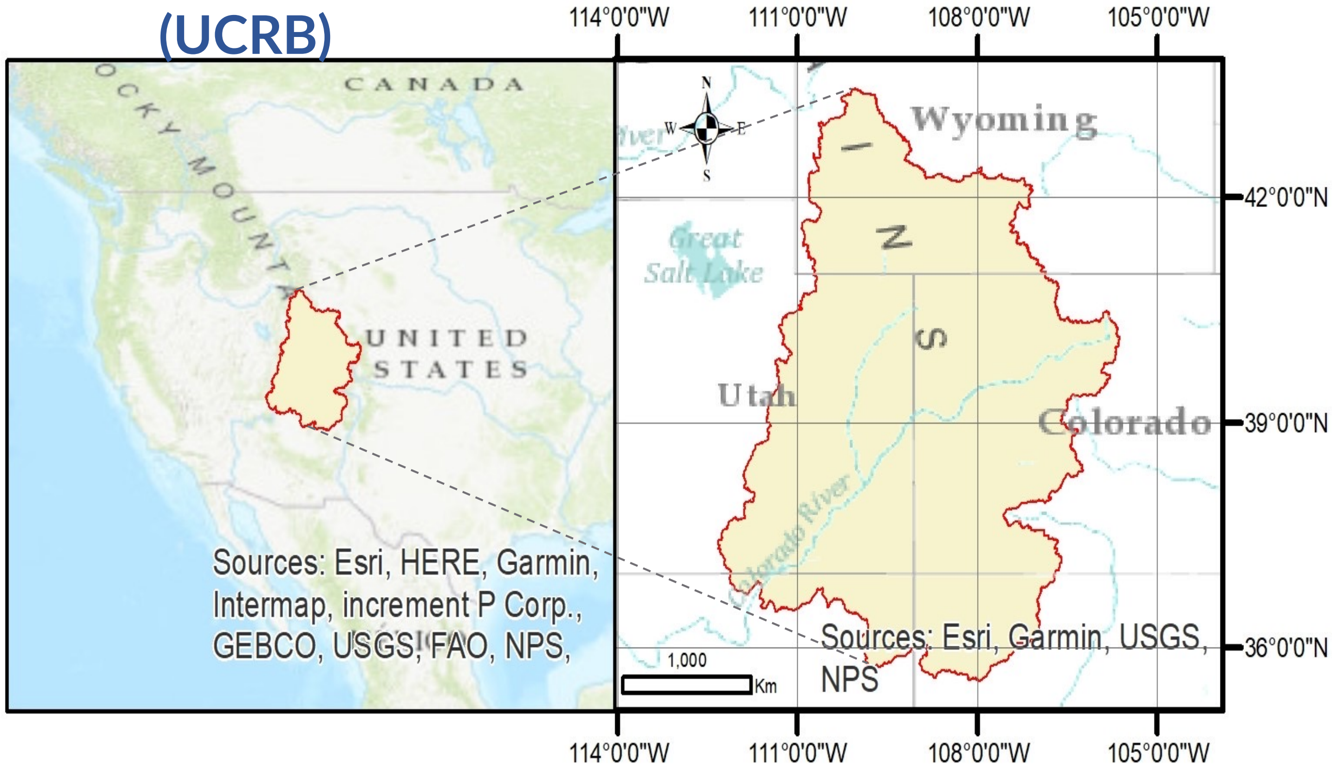
### Comparison with actual 47 wildfire events




- (Left panel) Comparison of wildfire severity predicted from the RF model with 47 actual wildfire events. (Right panel) Location and errors in prediction results of 47 wildfire events in the CRB.

## ○ Drought in the Upper Colorado River Basin (UCRB)




Since 2000, the Colorado River Basin (CRB) has experienced the driest 16-year period in over 100 years of historical natural flows. This period also ranks as the fifth driest 16-year period in the last 1,200 years (Bureau of Reclamation, 2015).

- The Colorado River and its tributaries provide water to nearly 40 million people for municipal use, supply water to irrigate nearly 5.5 million acres of land (Bureau of Reclamation, 2012).
- The UCRB is facing an increased demand for water along with rising temperatures and ongoing drought

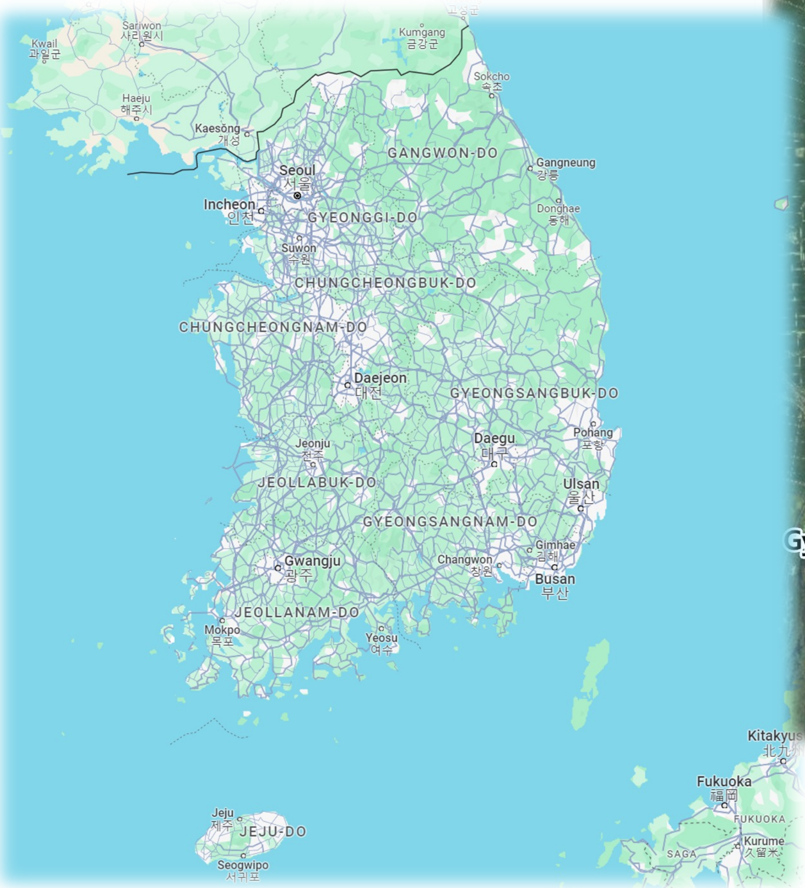
Lake Powell, created with the 1963 completion of Glen Canyon Dam, is the upper basin's largest reservoir on the Colorado River. Credit: EcoFlight

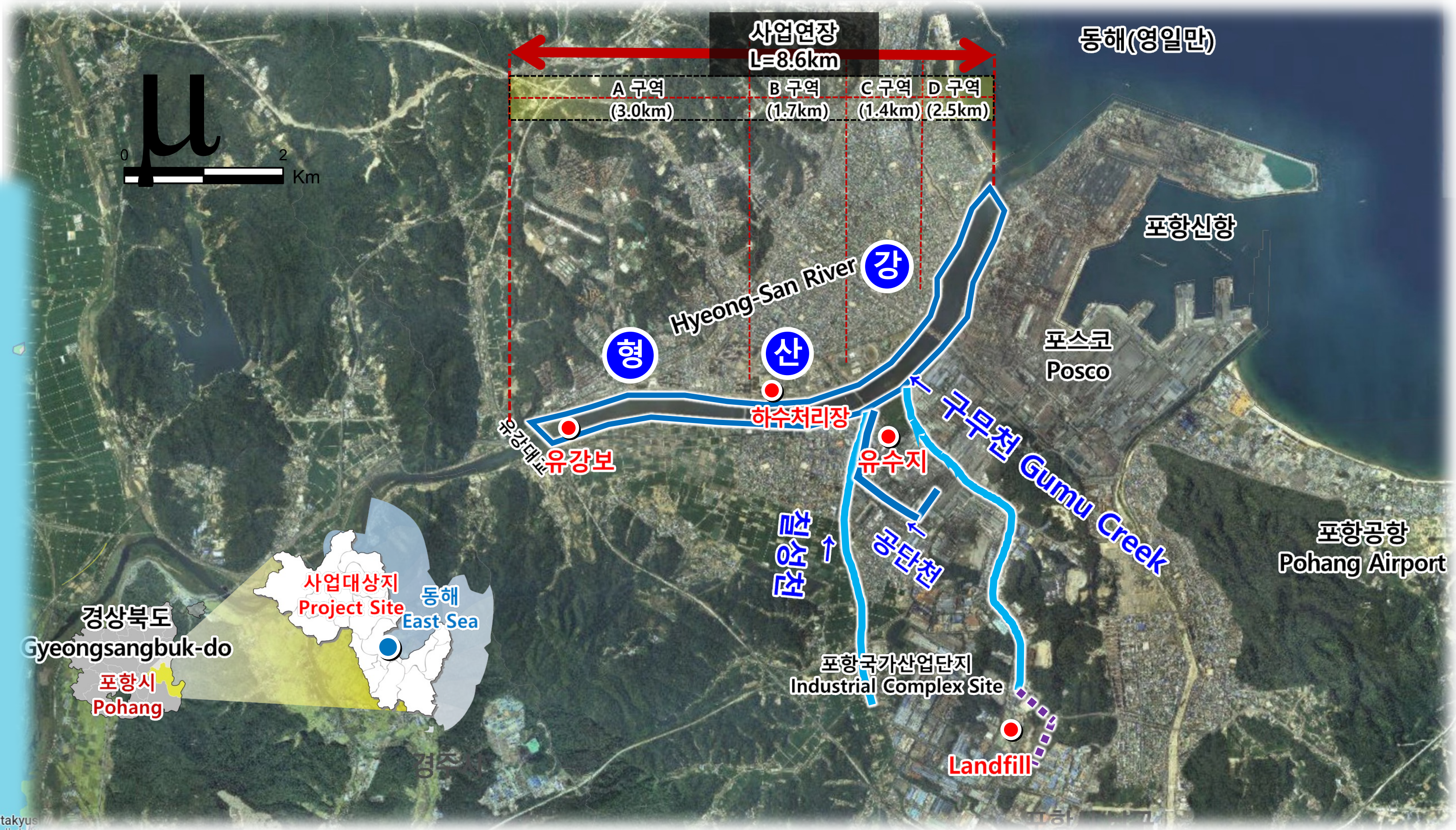
# CASE III

# Gumu Creek Watershed

# (South Korea)

# Backgrounds | Overview of Pohang, South Korea




- Heavy metal contamination in aquatic systems is a serious concern.
  - neurological and reproductive issues
- Our case study focuses on Gunm Creek located in a prominent steel industrial city in the southeastern coast of South Korea.

# Backgrounds





- Around 30 years ago in June 1994, the dike of an industrial waste landfill collapsed
- 120,000 tons of toxic waste from the 300,000 tons buried at the site spilled into the nearby Gumu Stream

# Backgrounds | Overview of Pohang, South Korea




Korean J. Limnol. 43 (1) : 150~160 (2010)

형산강 수계의 수질 특성

김 유 표 · 안 광 국*
(충남대학교 생명과학과)

Character
Guk An*
Biotechn

Atmos. Chem. Phys., 16, 10215–10228, 2016
www.atmos-chem-phys.net/16/10215/2016/
doi:10.5194/acp-16-10215-2016


Atmospheric Chemistry and Physics
Open Access

Characteristics of total gaseous mercury (TGM) concentrations in an industrial complex in South Korea: impacts from local sources

Yong-Seok Seo[1,2]
Young Kim[1], He
Seung-Muk Yi[1,2]

Environ Monit Assess (2018) 190: 274
https://doi.org/10.1007/s10661-018-6624-4

CrossMark

Total mercury, methyl mercury, and heavy metal concentrations in Hyeongsan River and its tributaries in Pohang city, South Korea

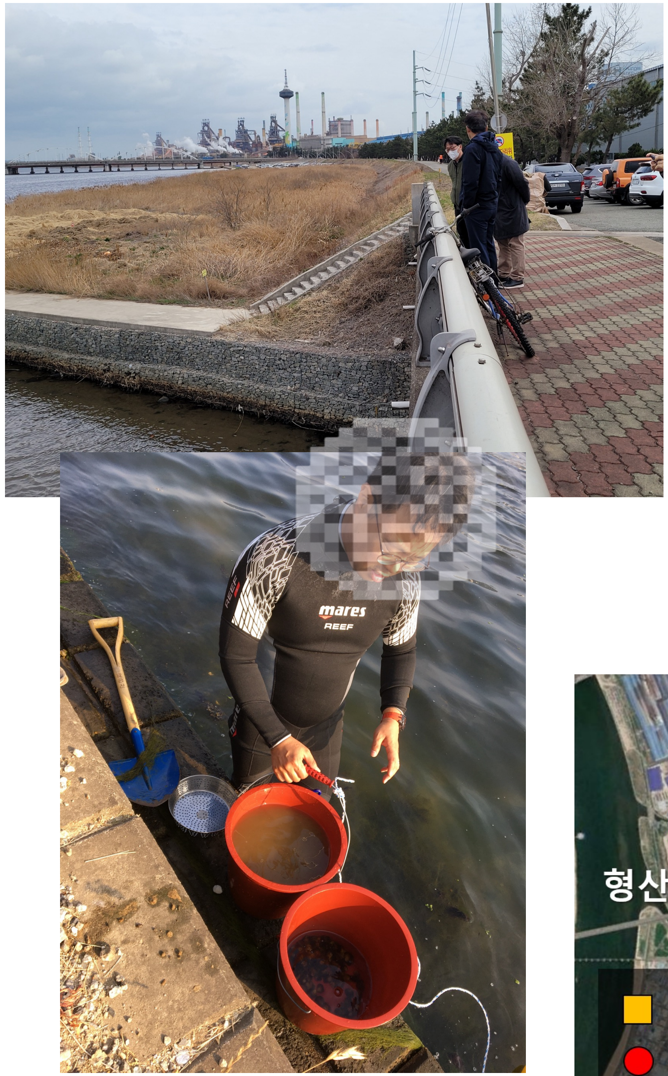
Mark Xavier Bailon · Anneschel Sheehan David · Yeongeon Park · Eunhee Kim · Yongseok Hong

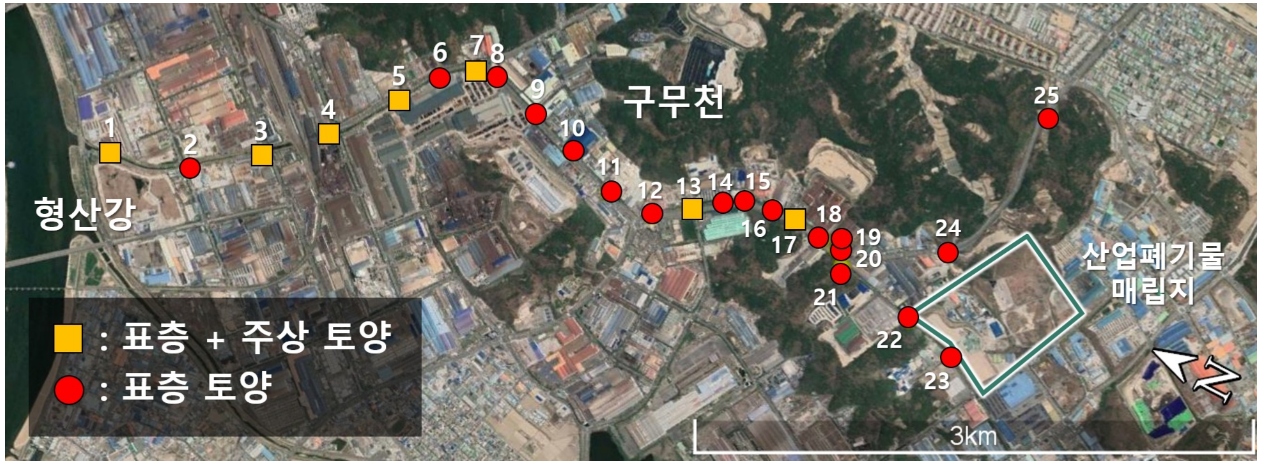
- 2016 report noted that high concentrations of mercury were detected in marine products collected from the Hyeongsan River.
- High concentrations of mercury and other heavy metals were found in the river sediments.

# Backgrounds | 2021/2022 Study on Mercury Contamination in Gumu Creek



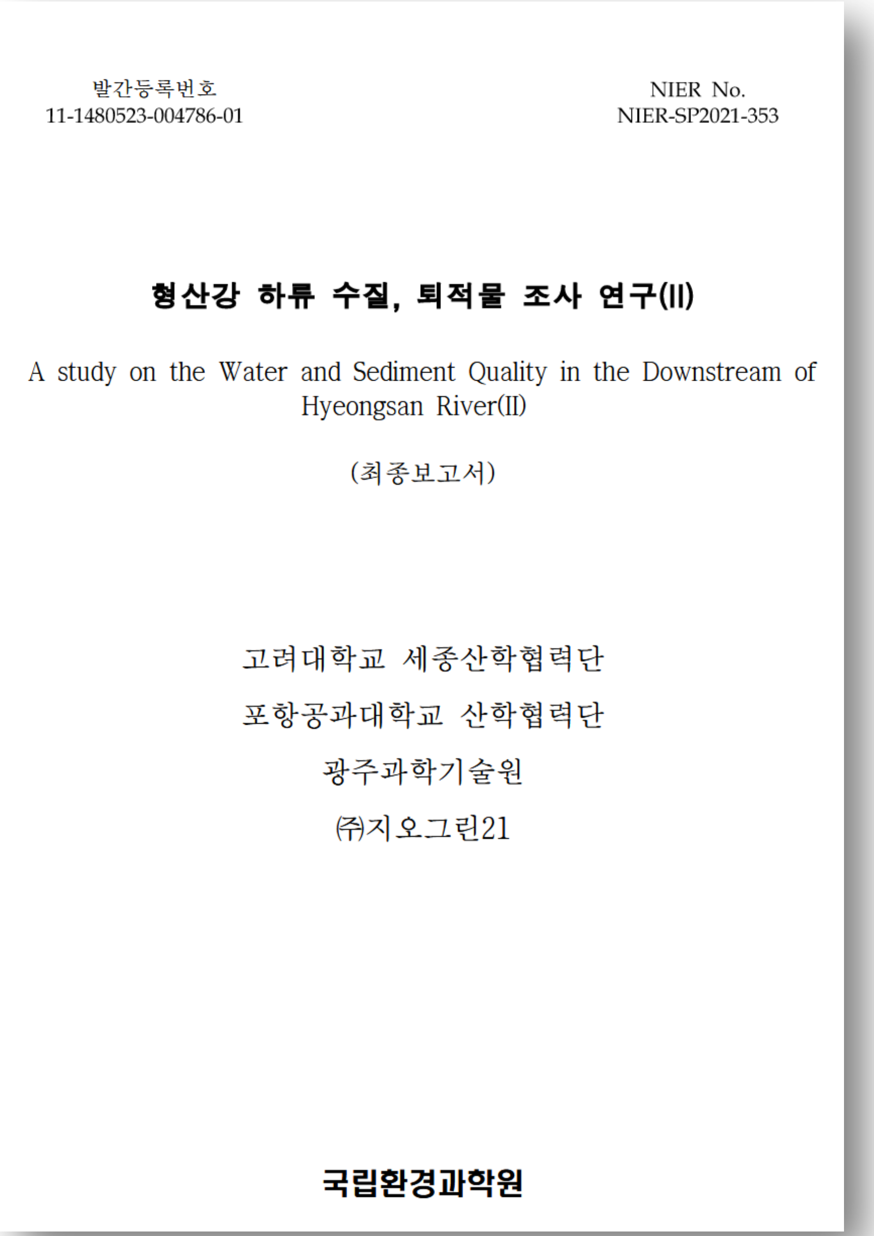
- 2021.07.26. ~ 2022.07.21.






# Backgrounds | 2021/2022 Study on Mercury Contamination in Gumu Creek





발간등록번호
11-1480523-004786-01

NIER No.
NIER-SP2021-353

**형산강 하류 수질, 퇴적물 조사 연구(II)**

A study on the Water and Sediment Quality in the Downstream of Hyeongsan River(II)

(최종보고서)

고려대학교 세종산학협력단
포항공과대학교 산학협력단
광주과학기술원
㈜지오그린21

**국립환경과학원**

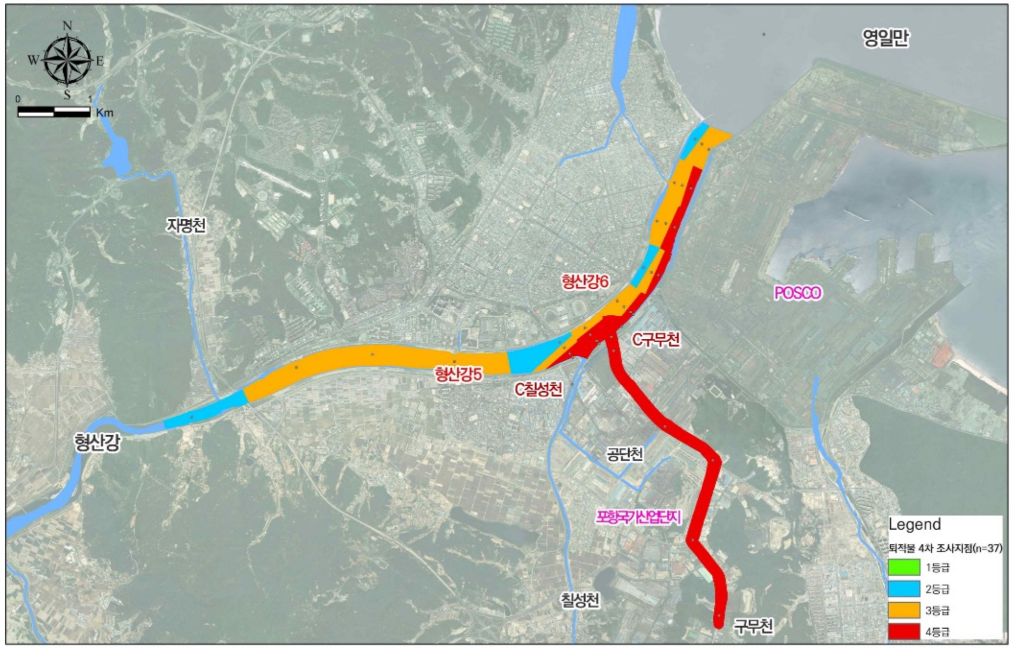



**Fig. 3-54. 2022년 2월 표층퇴적물 수은 오염 등급도(Hg_Interpolation_IDW)**

- In Gumu Creek, mercury load is generally in particulate form, with particulate mercury load (10,707 ~ 184,803 g/yr) being 4.2 to 386 times higher than dissolved mercury load (266 ~ 10,105 g/yr).
- Mercury deposited at the confluence of Gumu Creek and the mainstream contribute to the mercury load in the mainstream of Hyeongsan river through the process of sediment resuspension.

# Model Enhancement | SWAT-Hg



Environmental Modelling and Software 126 (2020) 104644

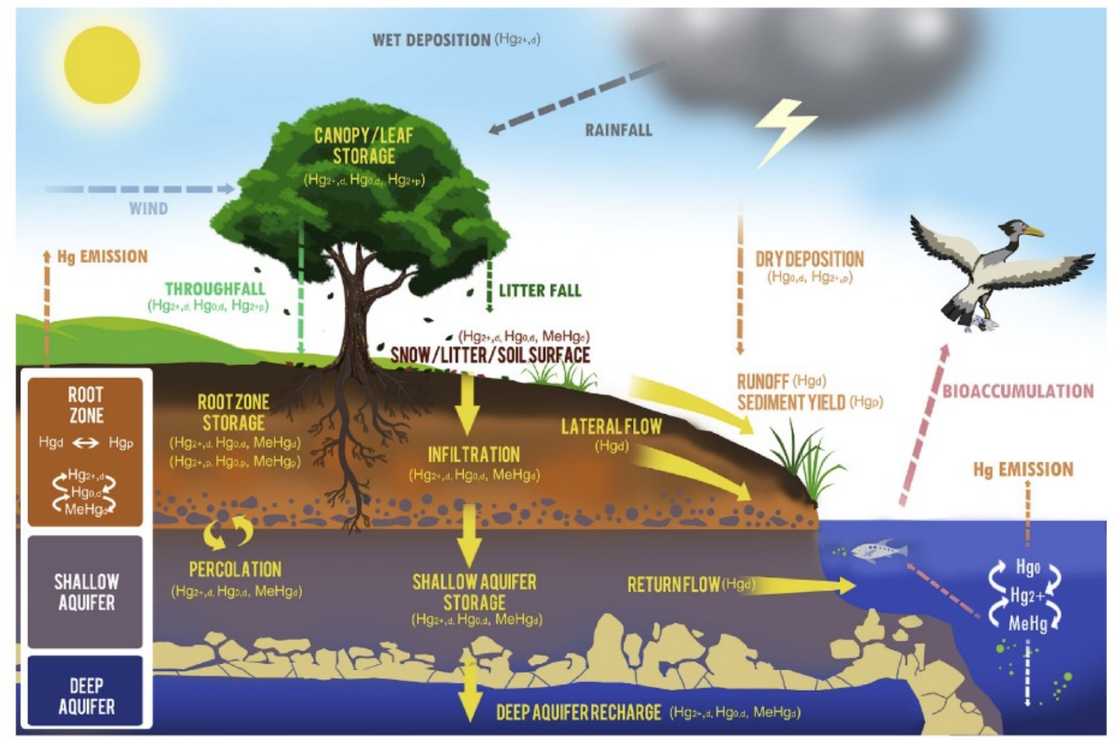
Contents lists available at ScienceDirect

Environmental Modelling and Software

journal homepage: http://www.elsevier.com/locate/envsoft

Assessment of coupled hydrologic and biogeochemical Hg cycles in a temperate forestry watershed using SWAT-Hg

Jaehak Jeong [a], Jisook Yang [b], Seunghee Han [b], Yong-Seok Seo [c], Yongseok Hong [d,*]




- Atmospheric Hg deposition model
- Fate and transport of Hg in soils
- Characterizing tree growth and leaffall
- Hg evaporation from surficial soil
- Mercury process in water and sediment
- Hg bioaccumulation and biomagnification

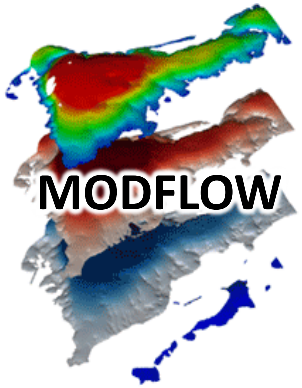
# Model Enhancement | SWAT-MODFLOW-Hg



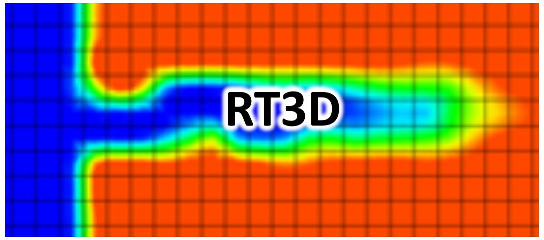
Hg inputs:

- Hg in Atmosphere
- Hg in soils (Subarea scale)
- Hg in Point sources (Reach)

Soil & Water Assessment Tool SWAT +




\+




Mercury Module: Divalent mercury ($Hg^{2+}$), methylmercury ($CH_3Hg^+$) and elemental mercury ($Hg^0$),

Hg:

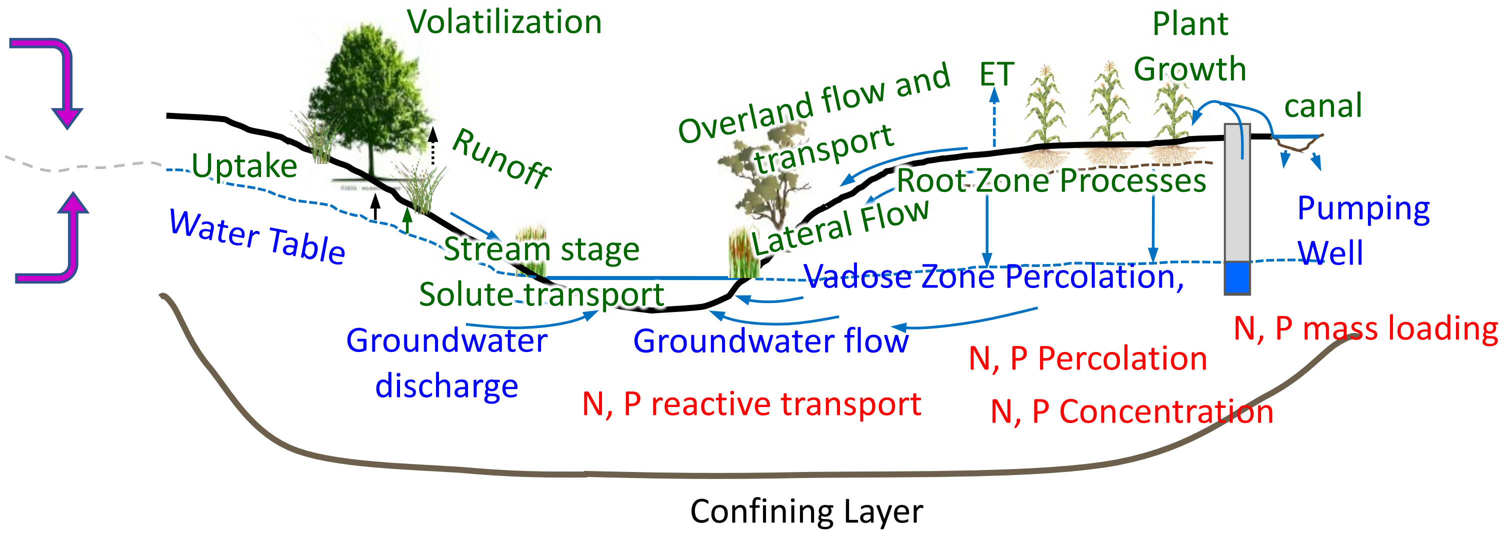
- Dissolved

Surface

Subsurface

Hg:

- Hg mass loading
- Hg transport
- Hg Concentration

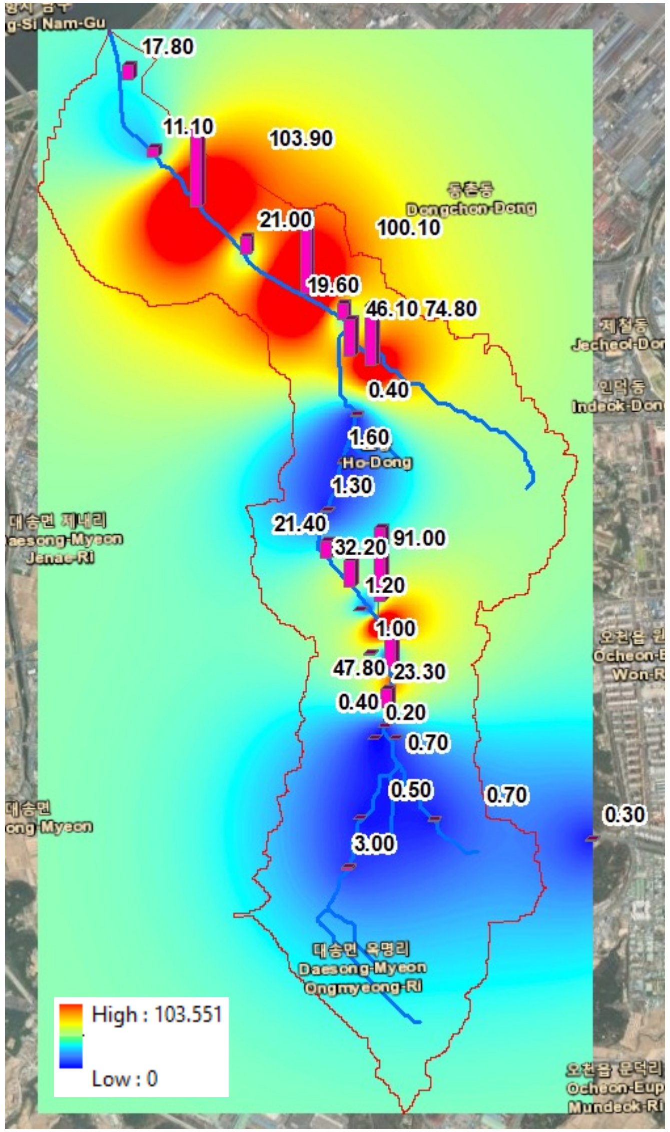



**SWAT**
**MODFLOW**
**RT3D**

# Model Construction | Gumu Creek Watershed



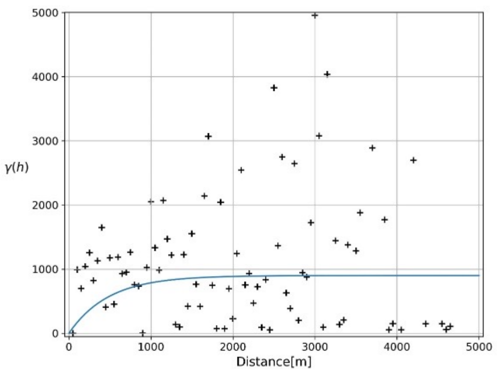
- Interpolated Hg (ppm) in Soil




Omni Directional Semi-variogram

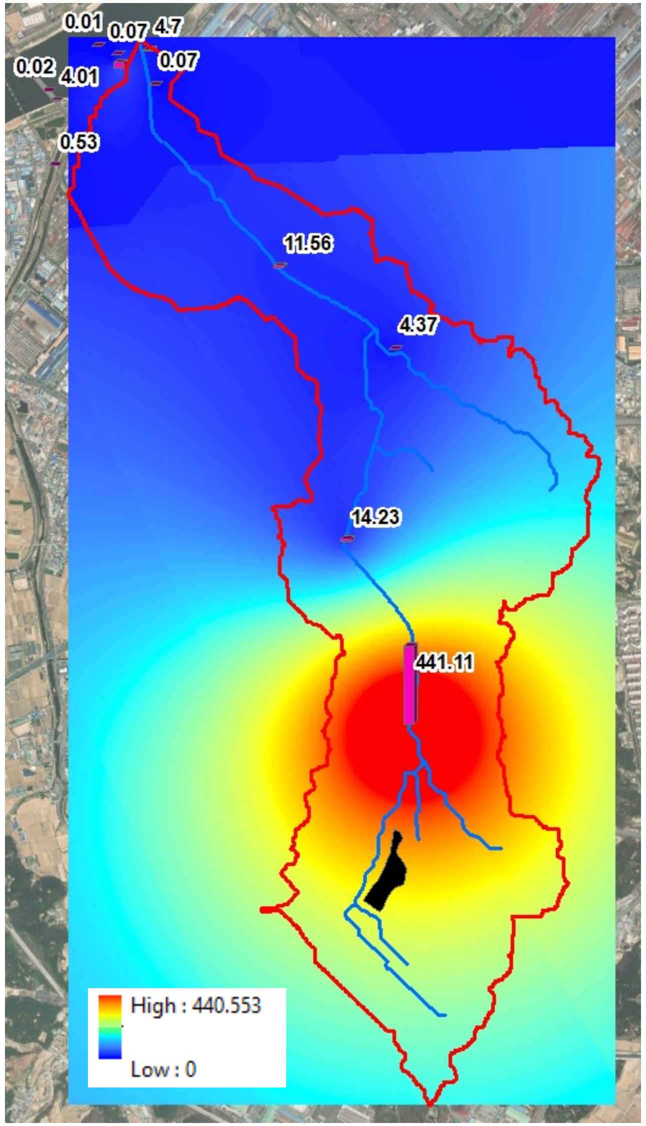
Sill: 900

Range: 1450



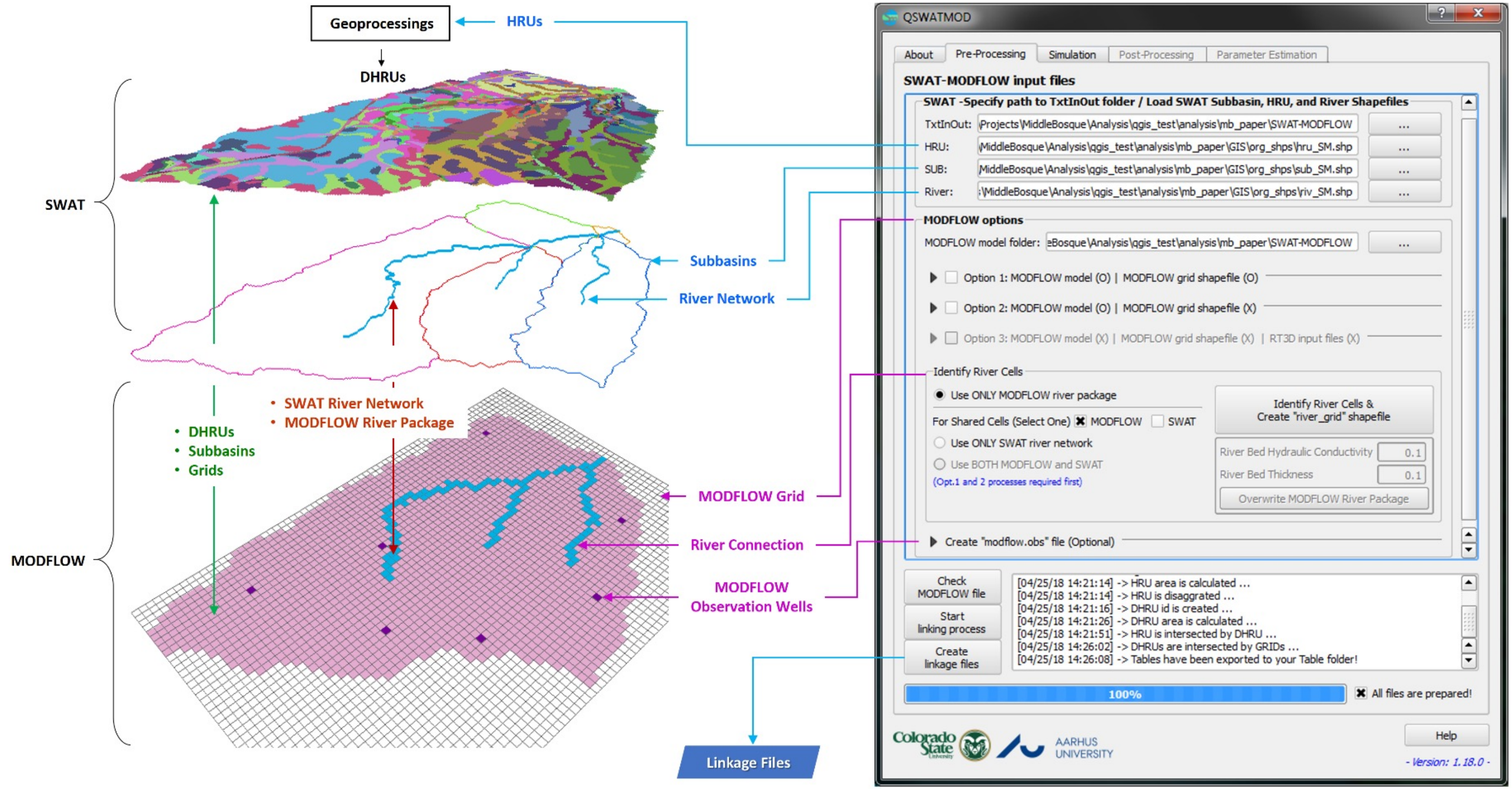

- Number of lags: 100
- Lag separation: 50 m
- Lag tolerance: 25 m
- Tolerance: Omni-director
- Bandwidth: 25 m

- Interpolated Hg (ppm) in Sediment



# Model Construction | Gumu Creek Watershed

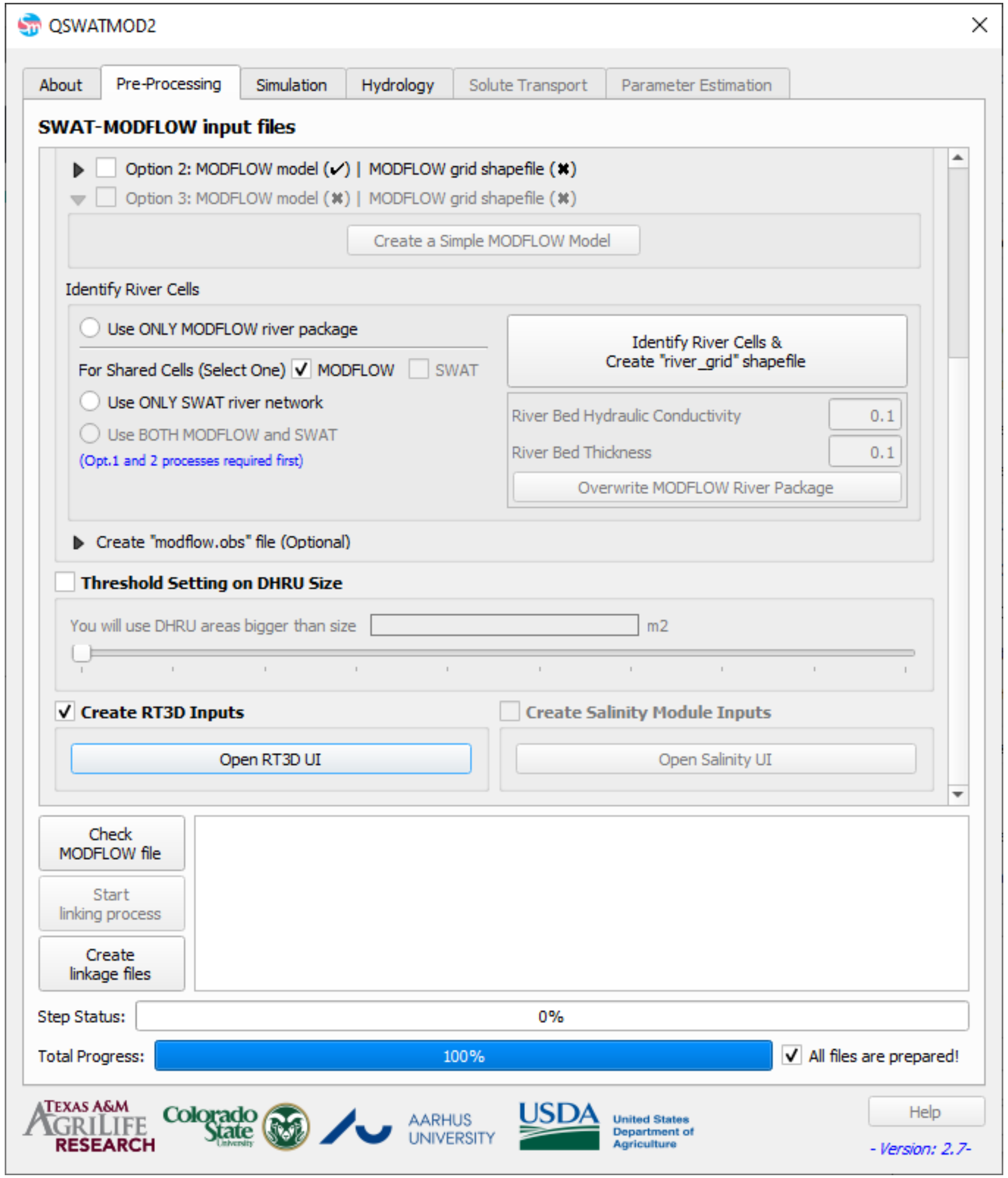


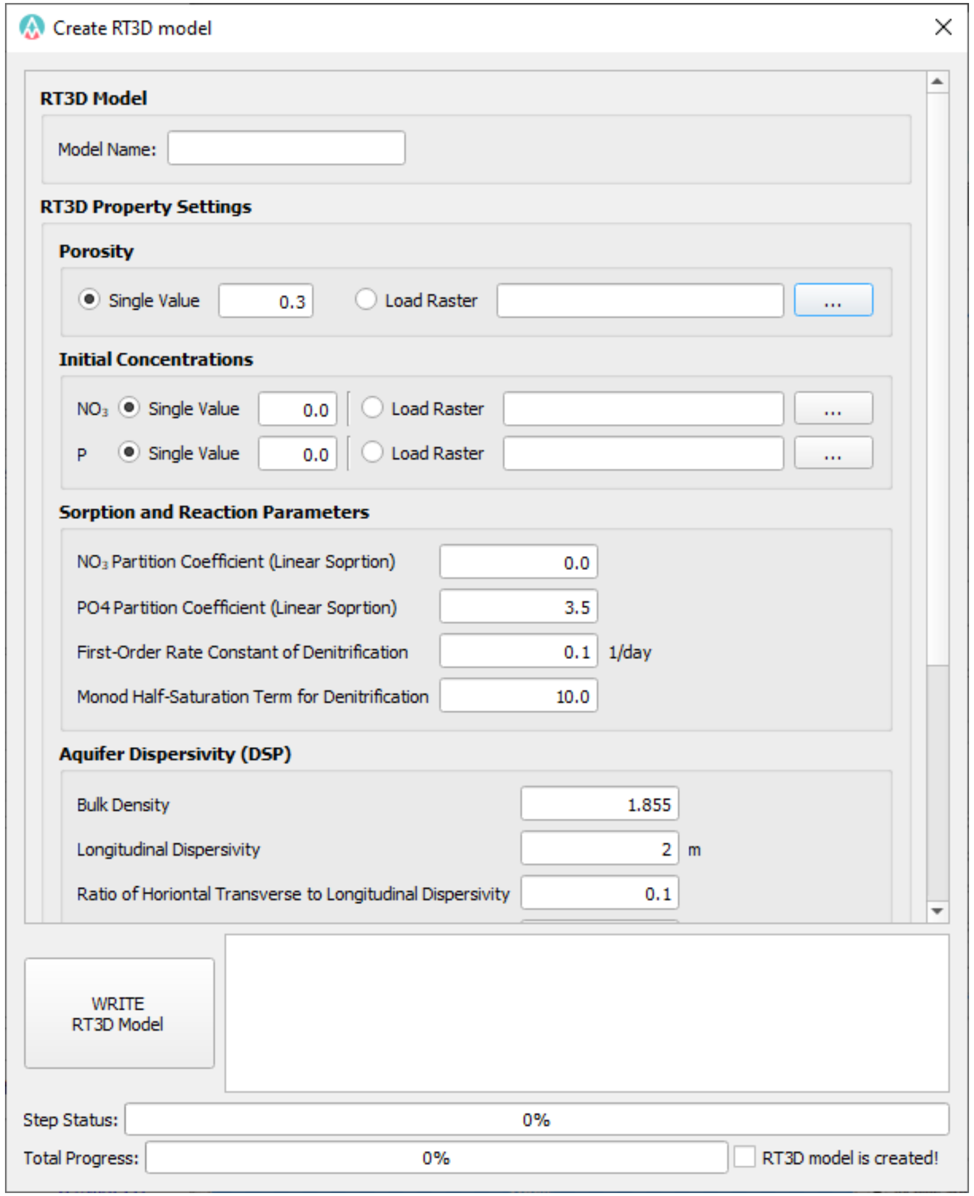



*Source: (Park et al., 2019)*

# Model Construction | Gumu Creek Watershed





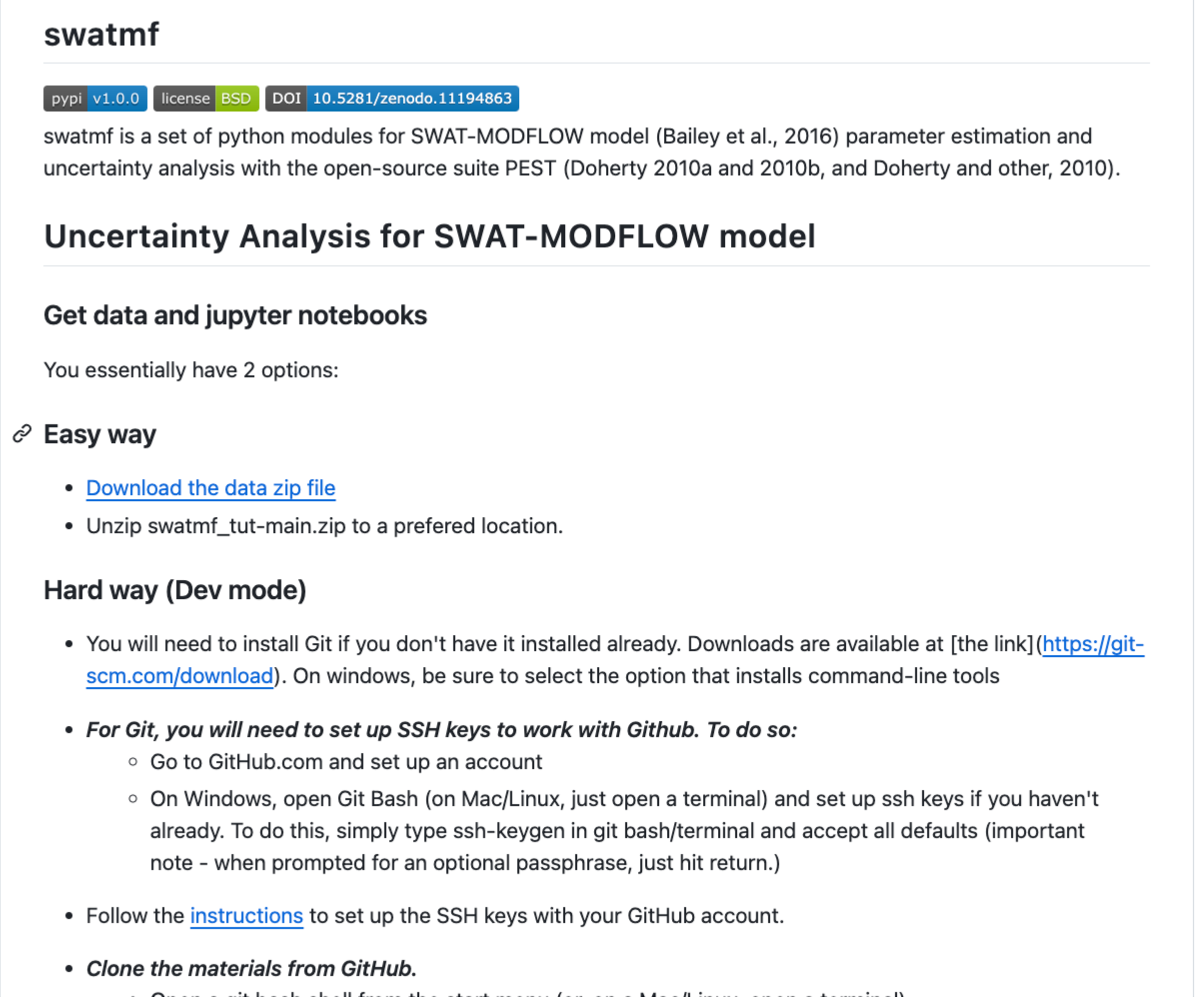

*Source: (Park et al., 2019 & https://github.com/spark-brc/QSWATMOD2-plugin)*

# Model Optimization | Soft calibration (Groundwater levels)



https://github.com/spark-brc/swatmf_wf

- 28 pilot points for HK, SS, SY (84)
- 6 zones for River Conductance and Bottom Thickness (12)
- SWAT parameters (15)
- Total 111
- Number of observations (3,887)



## swatmf

pypi v1.0.0 license BSD DOI 10.5281/zenodo.11194863

swatmf is a set of python modules for SWAT-MODFLOW model (Bailey et al., 2016) parameter estimation and uncertainty analysis with the open-source suite PEST (Doherty 2010a and 2010b, and Doherty and other, 2010).

## Uncertainty Analysis for SWAT-MODFLOW model

### Get data and jupyter notebooks

You essentially have 2 options:

### Easy way

- Download the data zip file
- Unzip swatmf_tut-main.zip to a prefered location.

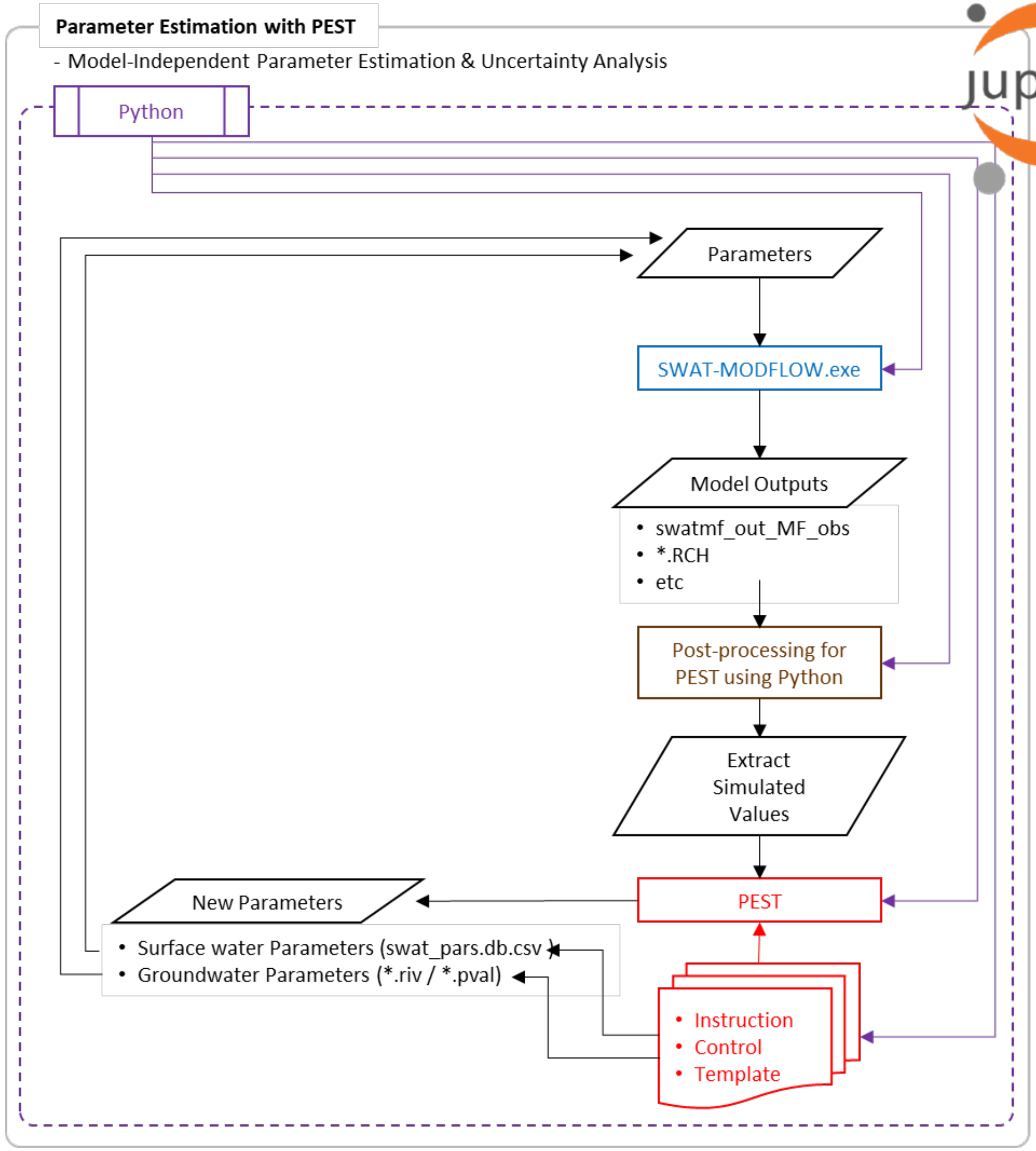
### Hard way (Dev mode)

- You will need to install Git if you don't have it installed already. Downloads are available at [the link](https://git-scm.com/download). On windows, be sure to select the option that installs command-line tools
- ***For Git, you will need to set up SSH keys to work with Github. To do so:***
  - Go to GitHub.com and set up an account
  - On Windows, open Git Bash (on Mac/Linux, just open a terminal) and set up ssh keys if you haven't already. To do this, simply type ssh-keygen in git bash/terminal and accept all defaults (important note - when prompted for an optional passphrase, just hit return.)
- Follow the instructions to set up the SSH keys with your GitHub account.
- ***Clone the materials from GitHub.***

# Model Optimization | Soft calibration (Groundwater levels)



https://github.com/spark-brc/swatmf_wf





- work with the latest version of swatmf

```
swatmf.__version__
```

```
from swatmf import swatmf_pst_utils
```

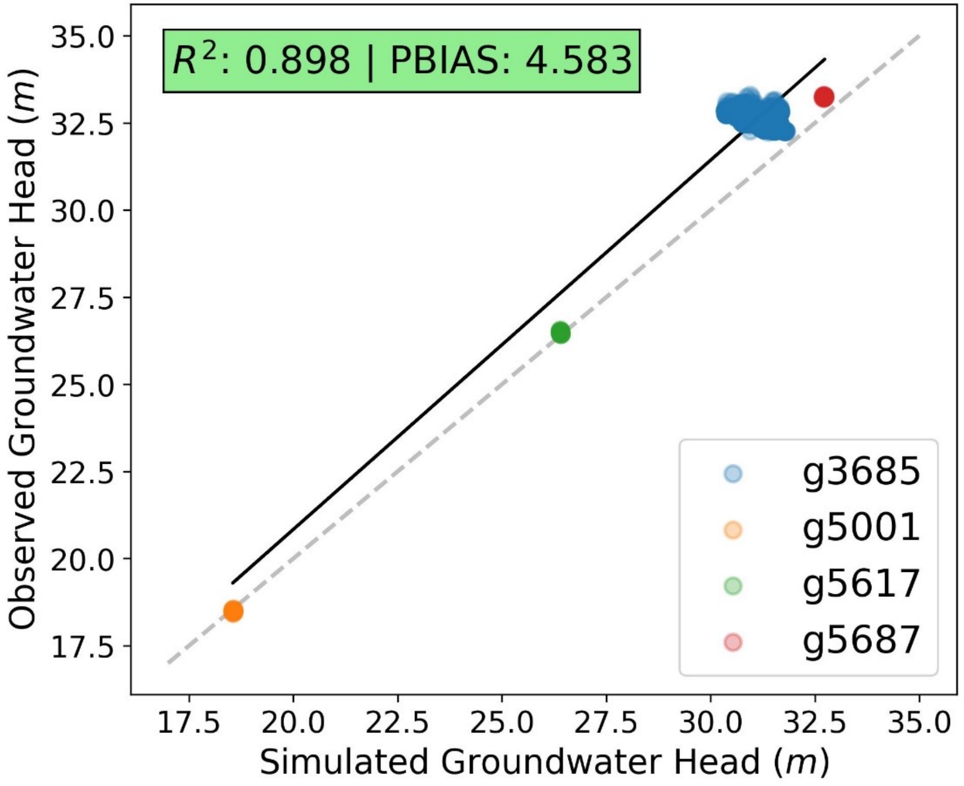
## 02. write swatmf.con file and initial setup

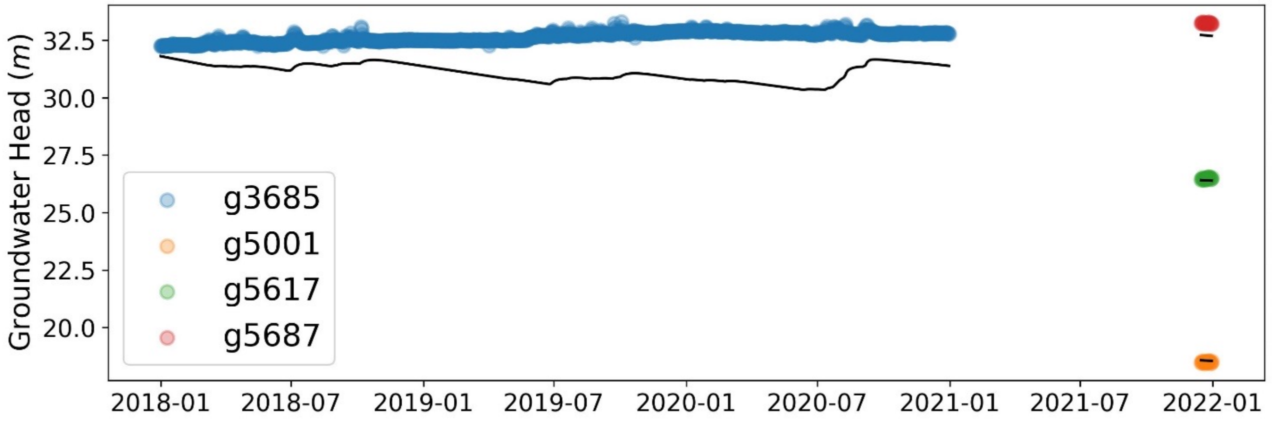
```
swatmf_pst_utils.create_swatmf_con?
```

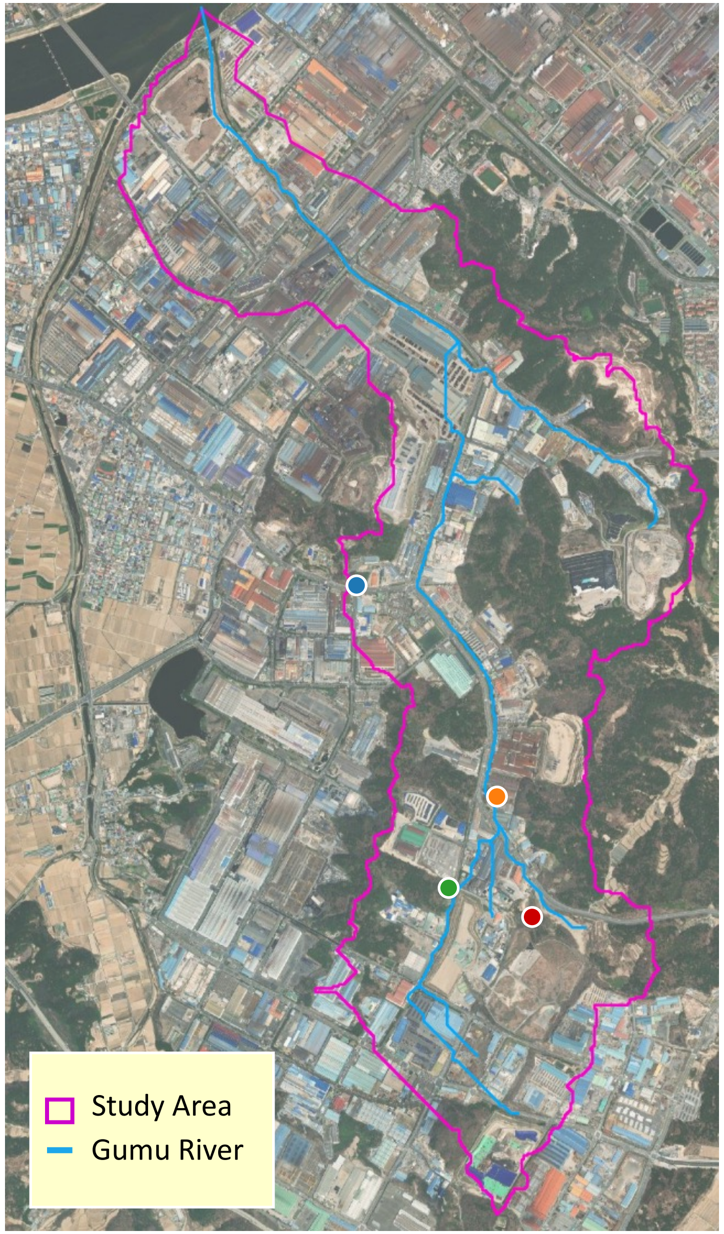
```
# working directory
prj_dir = "D:/test"
swatmf_model = "D:/spark-brc_gits/swatmf_wf/models/middle_bosque_1000/SWAT-MODFLOW"
swat_model = "D:/spark-brc_gits/swatmf_wf/models/middle_bosque_1000/SWAT"
```

```
# calibration period
sim_start = '1/1/1985'
warmup = 0
cal_start = '1/1/1985'
```

# Preliminary Results | Model Performance – Groundwater Levels

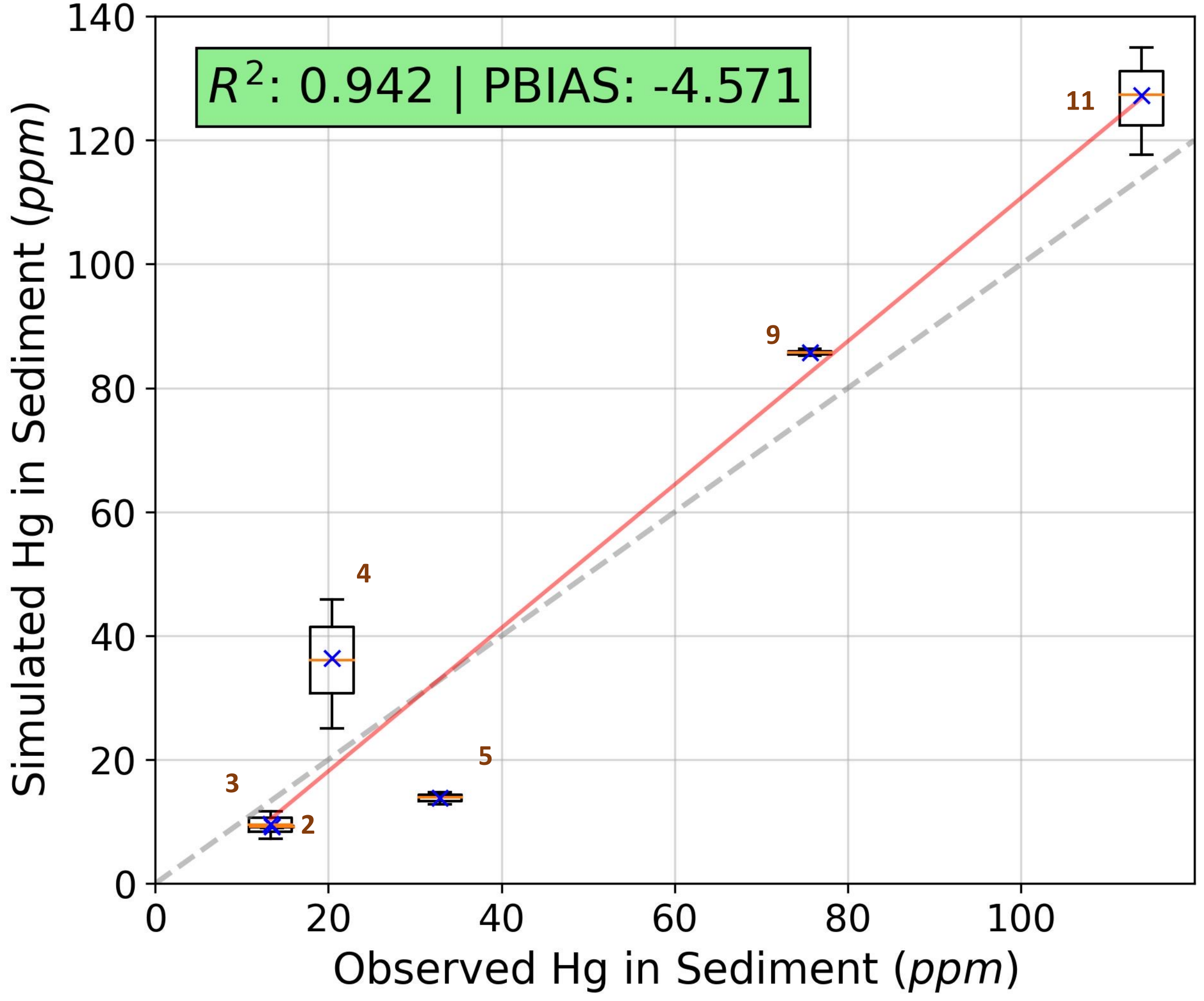


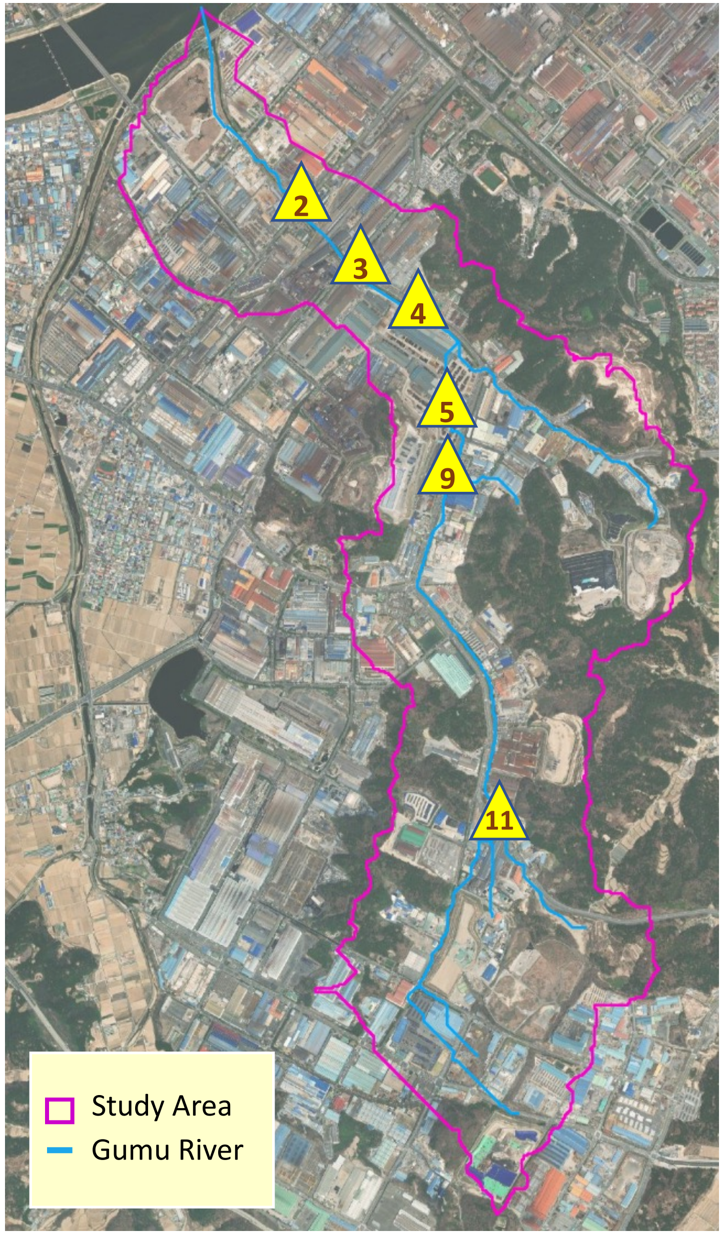



# Preliminary Results | Hg Concentrations in Sediment

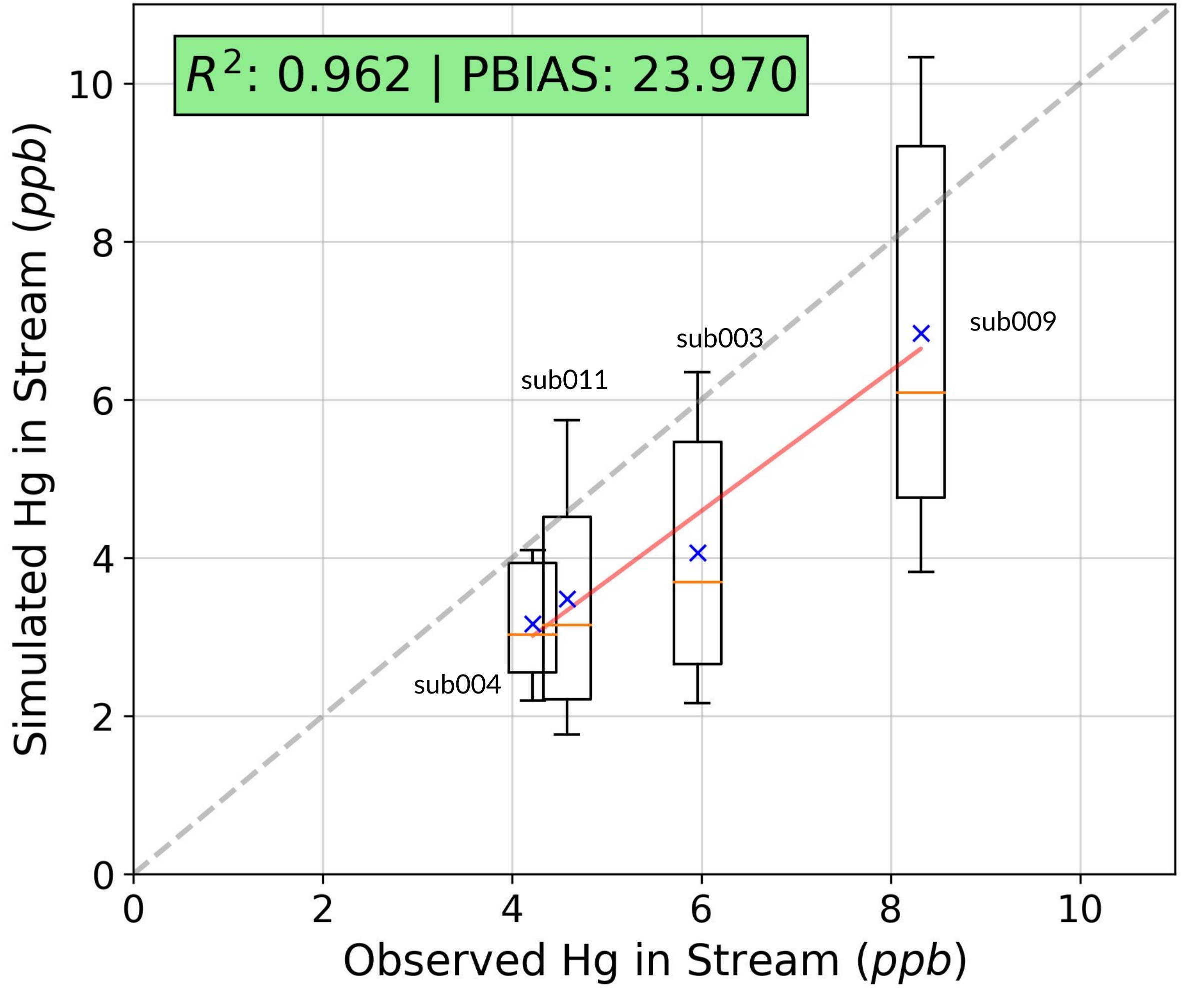


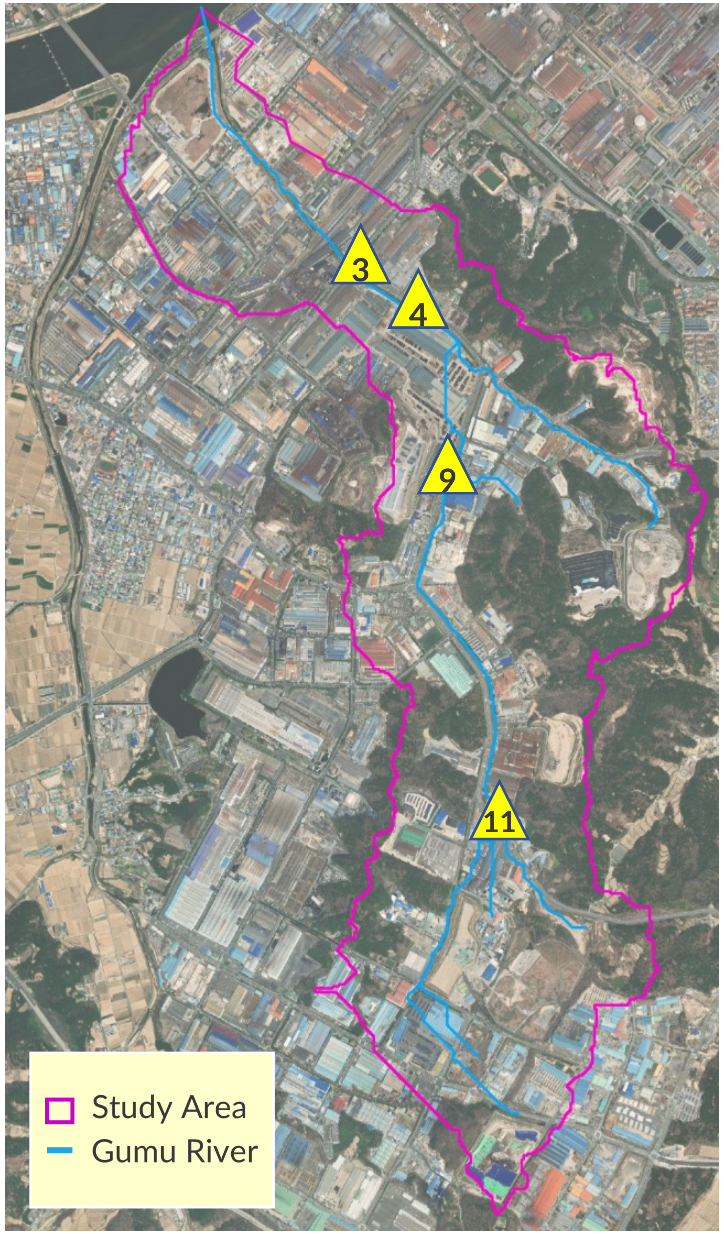


# Preliminary Results | Hg Concentrations in Stream



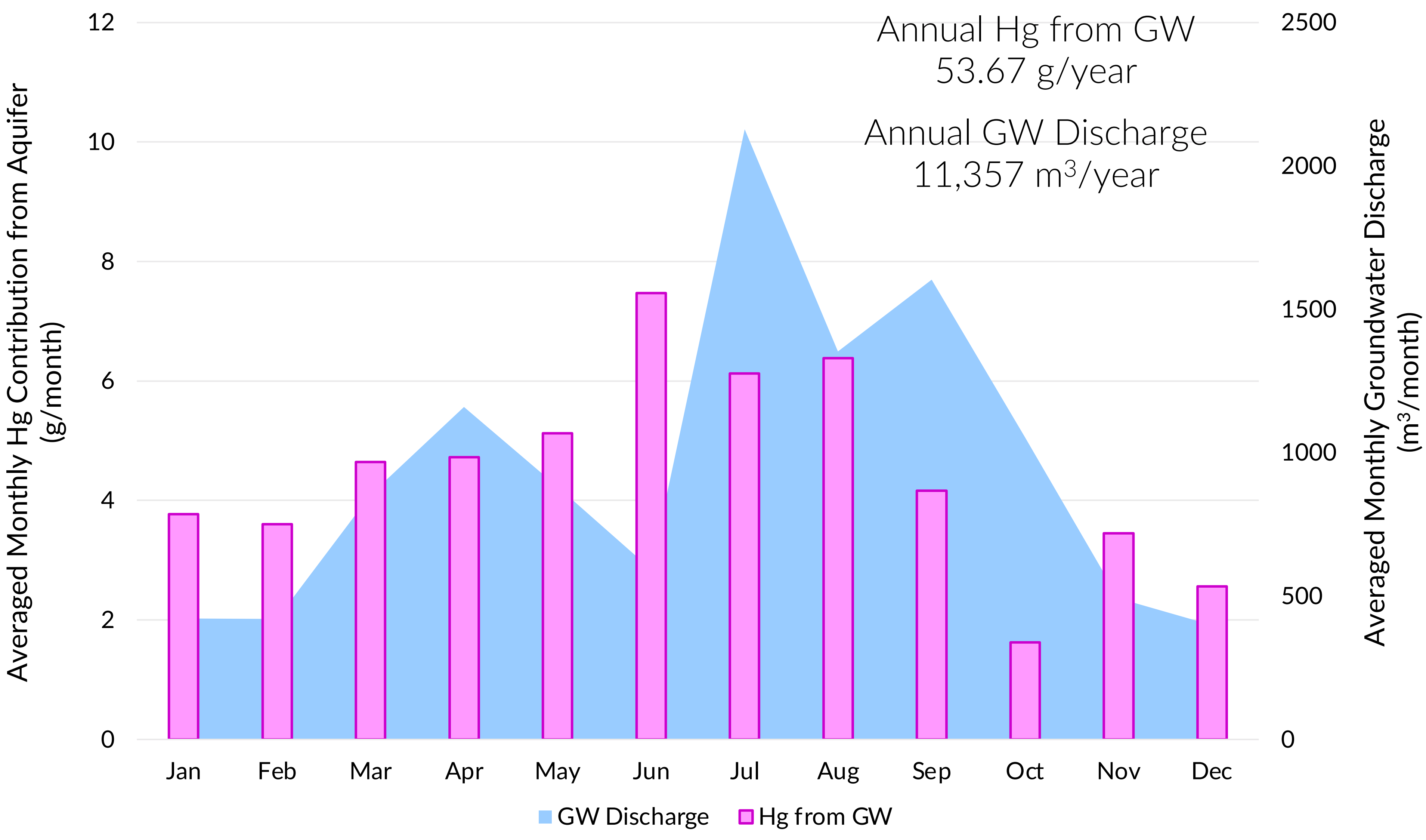



- Forecast predictive uncertainty is required for Mercury point source.

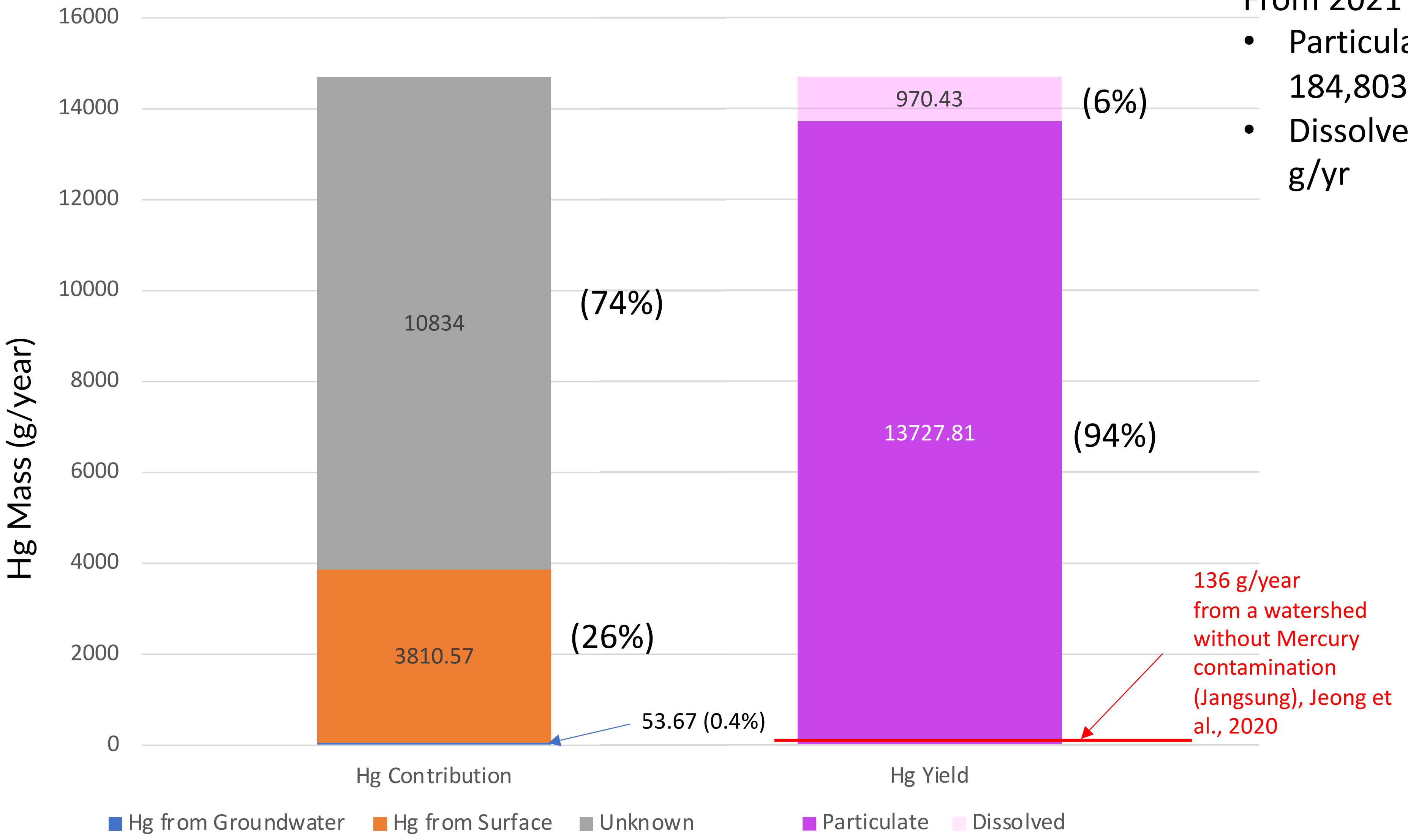
# Preliminary Results | Hg from GW and GW Discharge (2015 – 2021)





# Preliminary Results | Hg Contributions & Yield

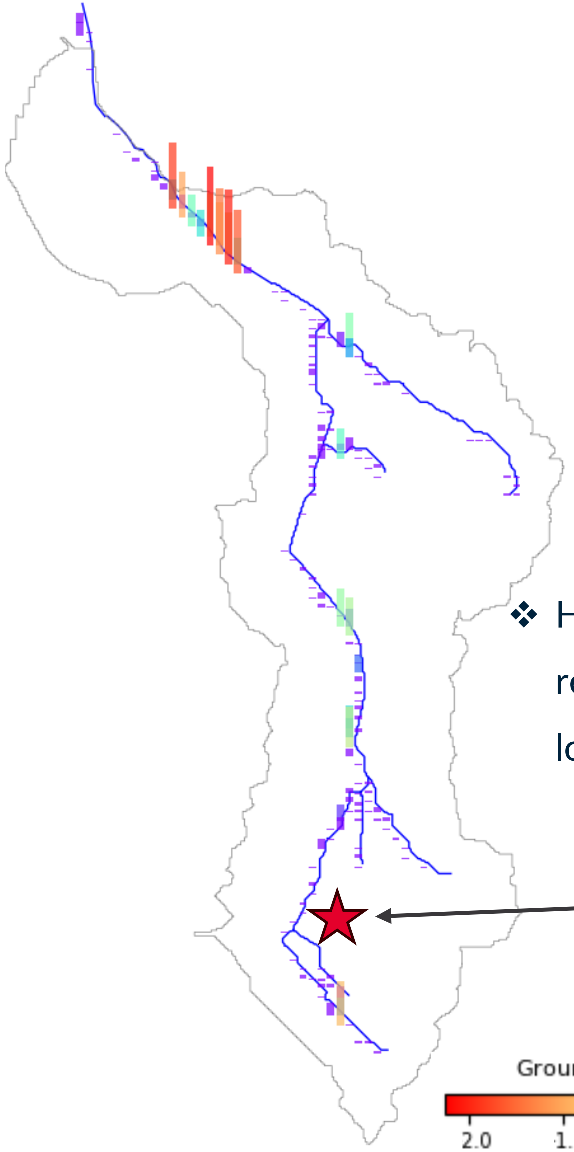


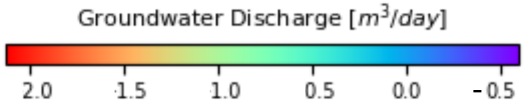



From 2021 report
- Particulate: 10,707 ~ 184,803 g/yr
- Dissolved: 266 ~ 10,105 g/yr

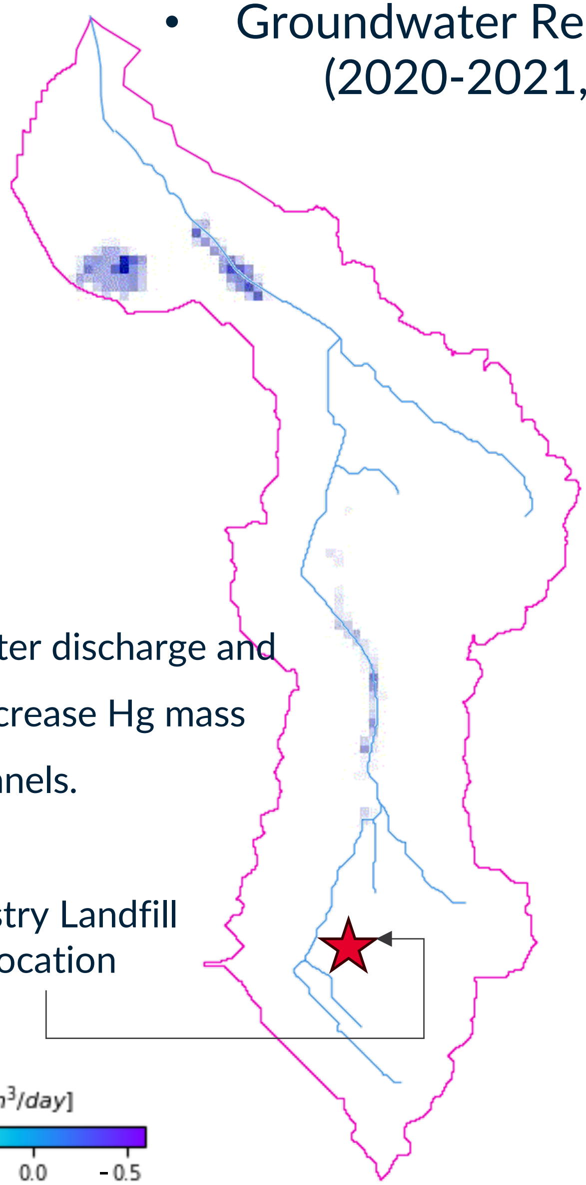
# Preliminary Results | GW/SW, Recharge, Hg Concentration

- GWSW interaction in 2021

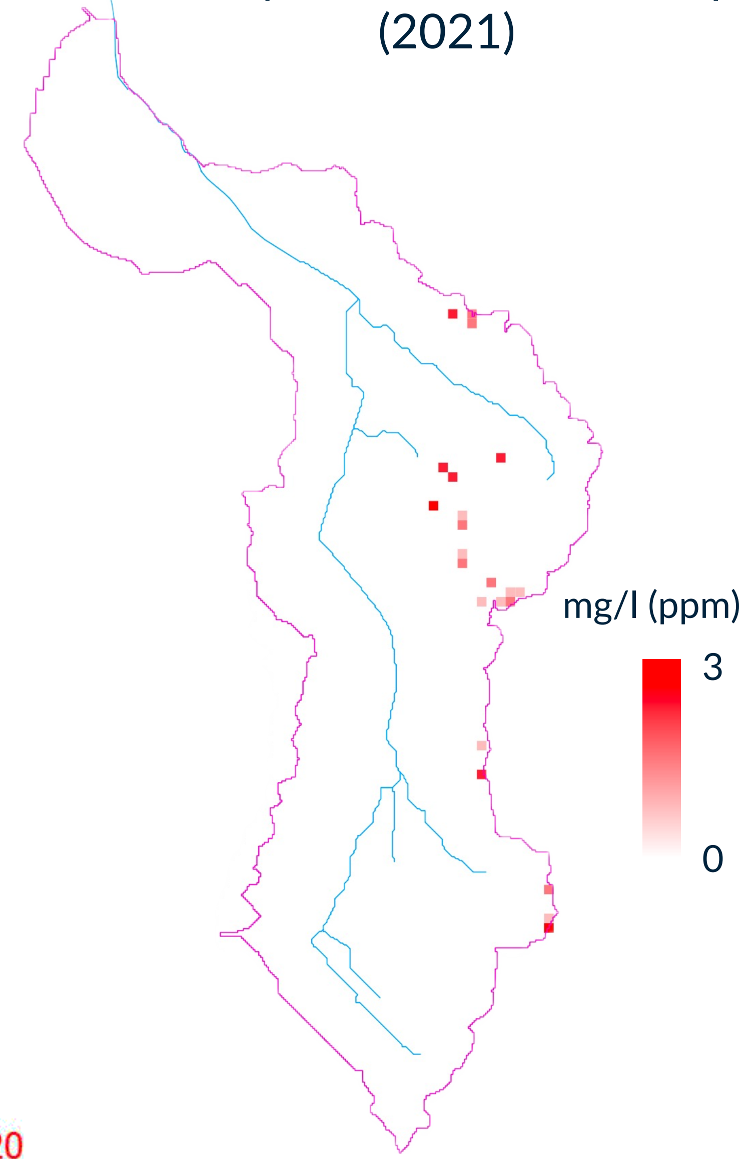





- Groundwater Recharge (2020-2021, m3/day)



- Mercury Concentration in Aquifer (2021)



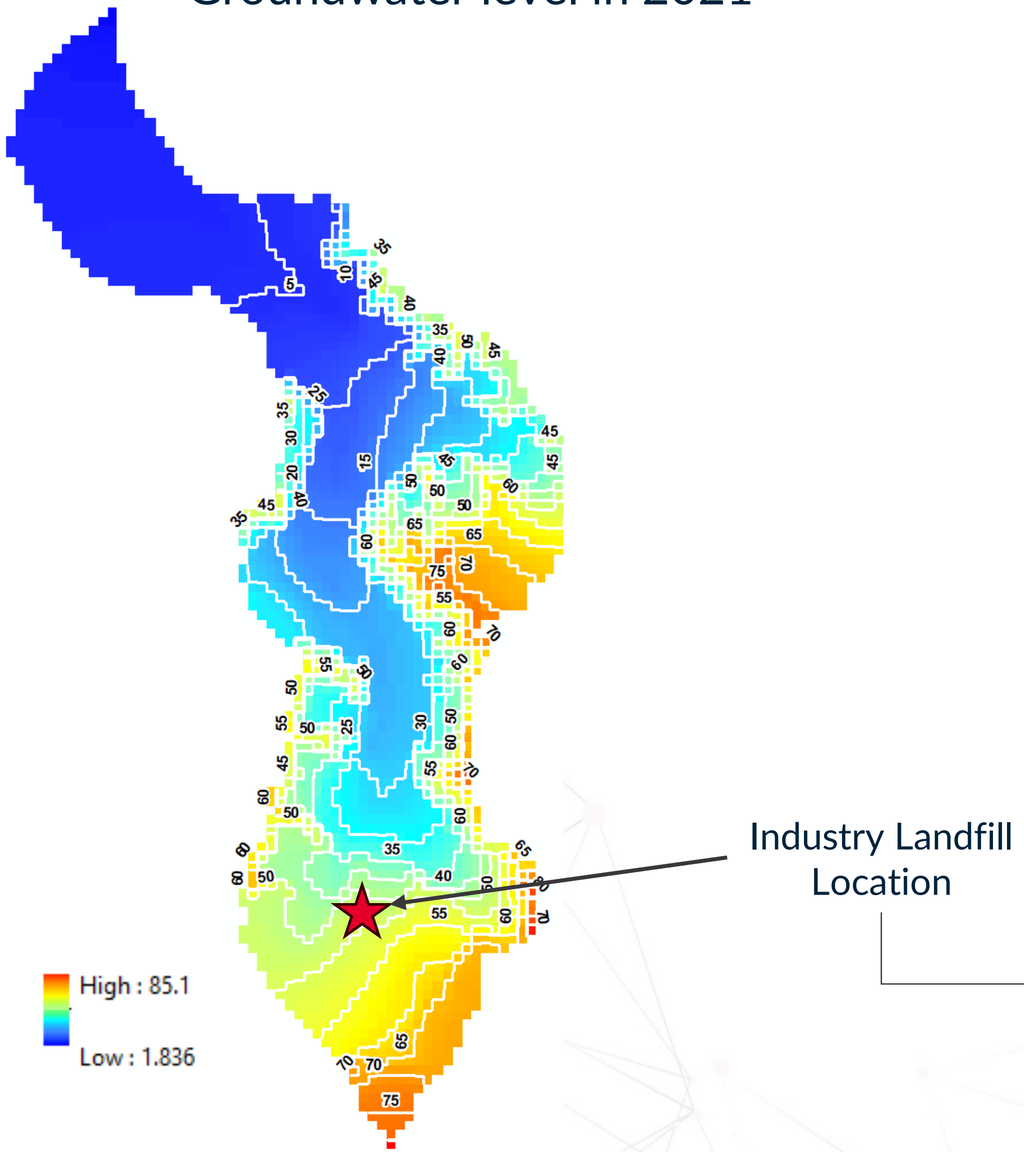

❖ High groundwater discharge and recharge can increase Hg mass loadings in channels.

Industry Landfill Location

Jan-2020

# Preliminary Results | Water table and Depth to water

- Groundwater level in 2021



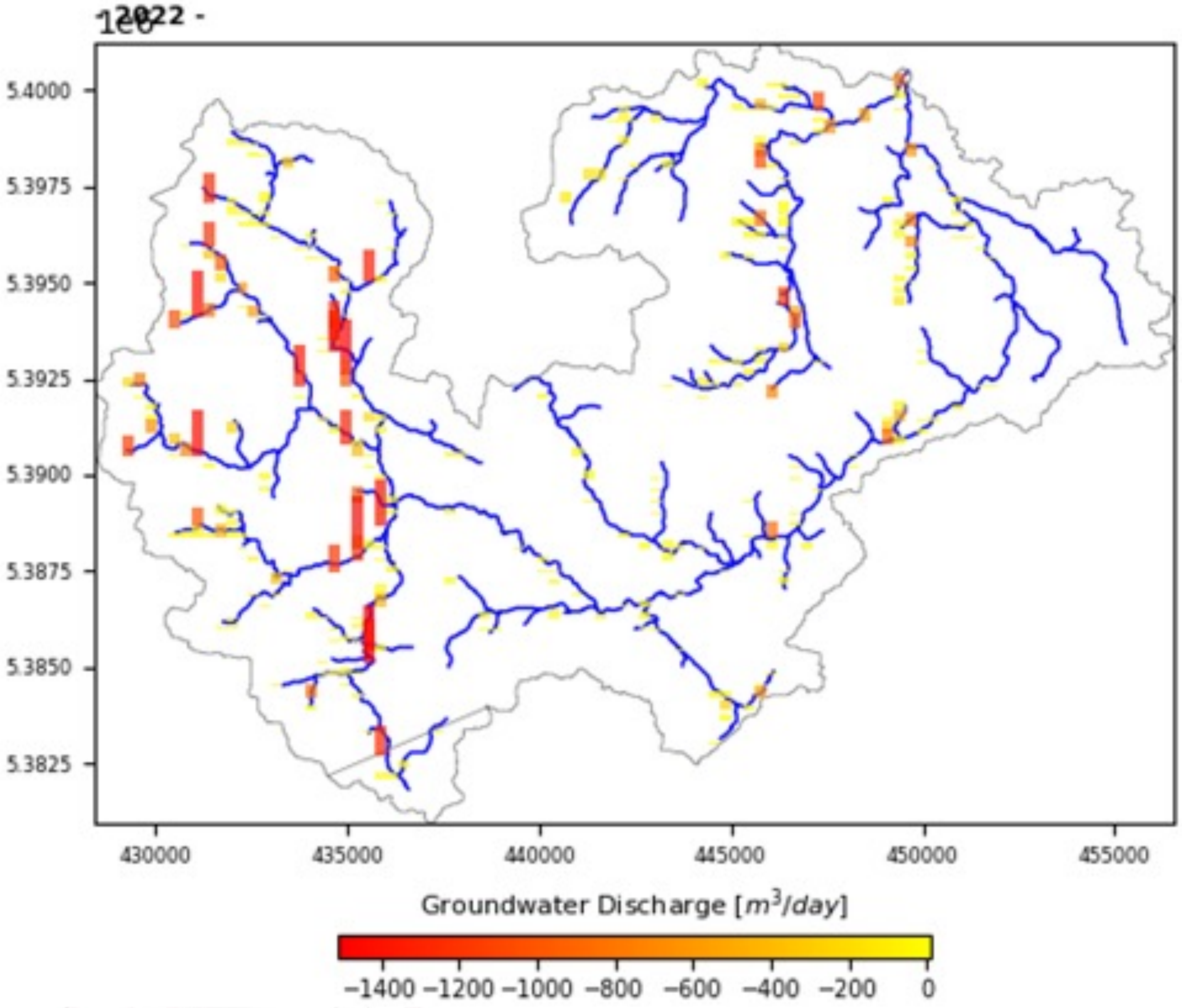

- Depth to water in 2021


❖ Areas with high groundwater level can increase Hg mass loadings in channels.

# Ongoing and Future tasks



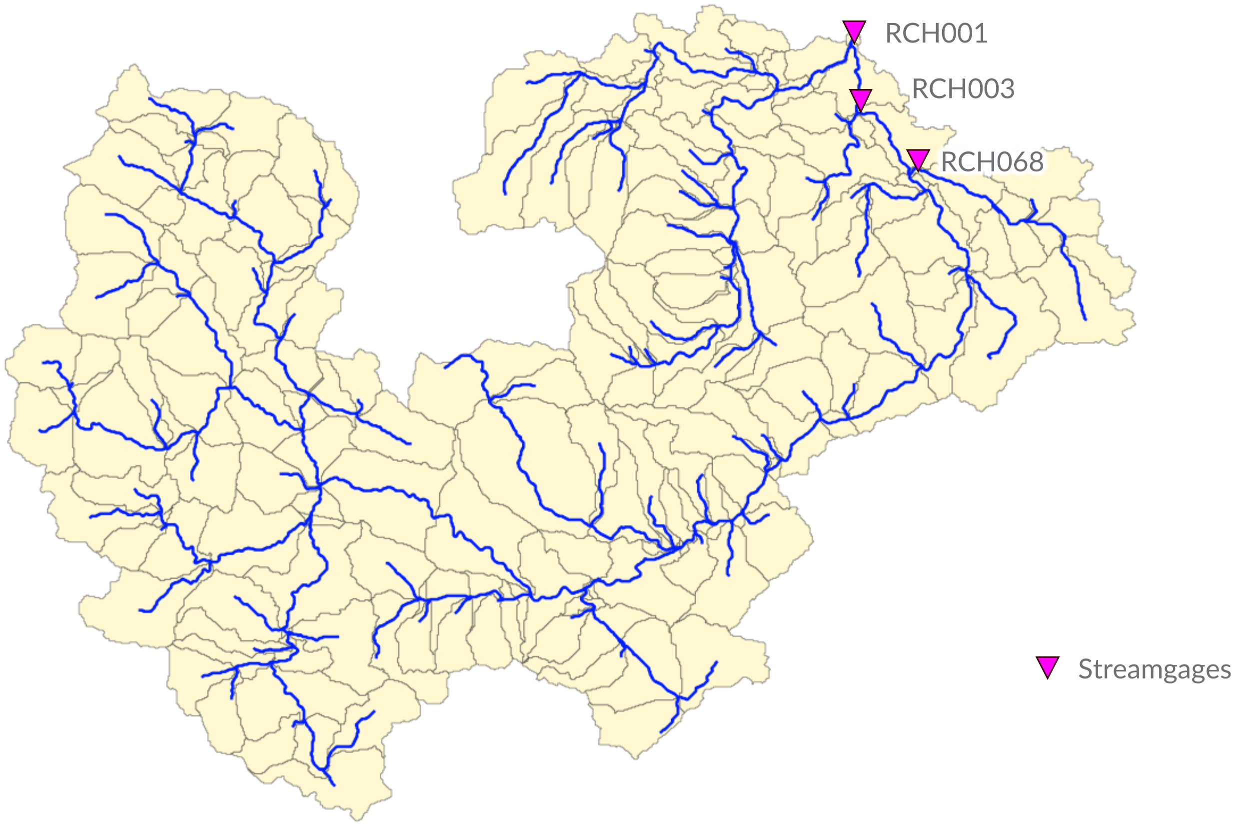
- Forecast Predictive Uncertainty f
    - Hg initial concentration in S
- What if scenarios
    - Sediment detention pond im
    - Contaminated sediment rem



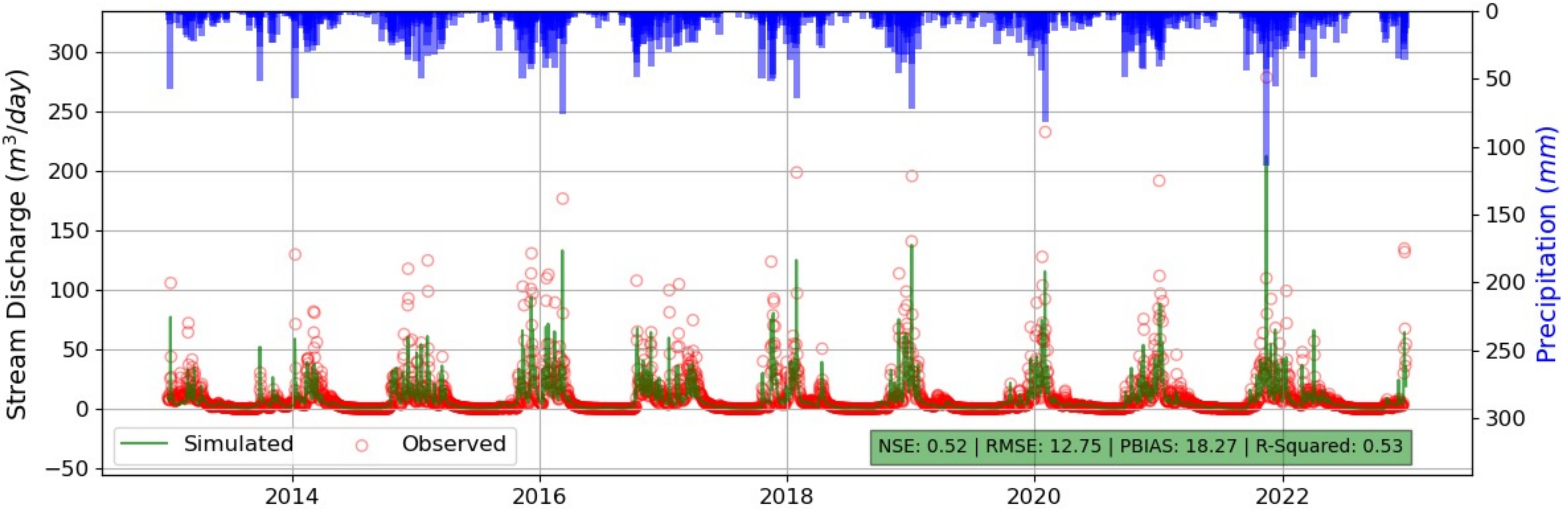
# CASE IV

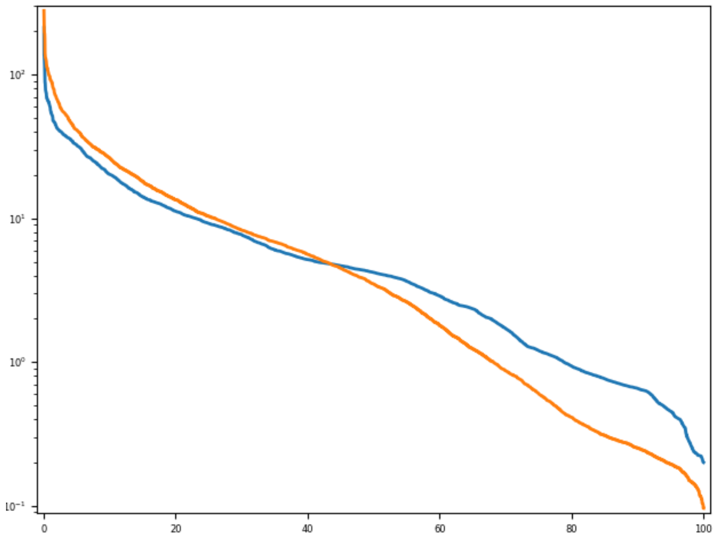
# Kokshila Watershed

# (University of Victoria, Canada)

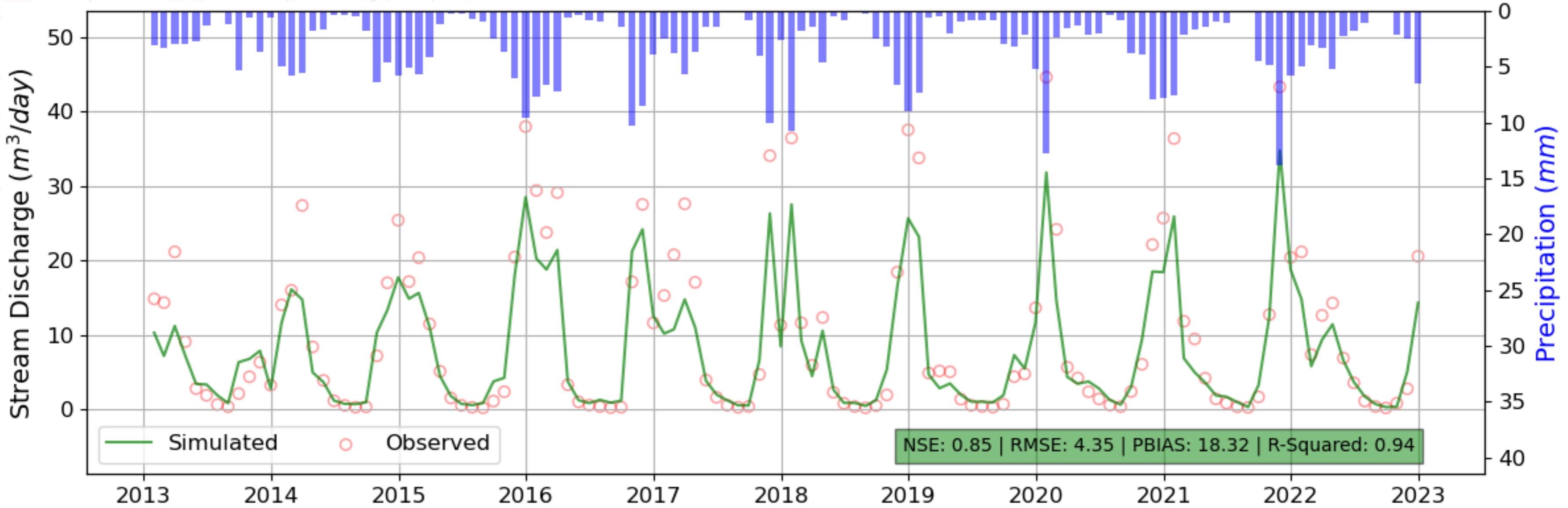

RCH001
RCH003
RCH068
Streamgages

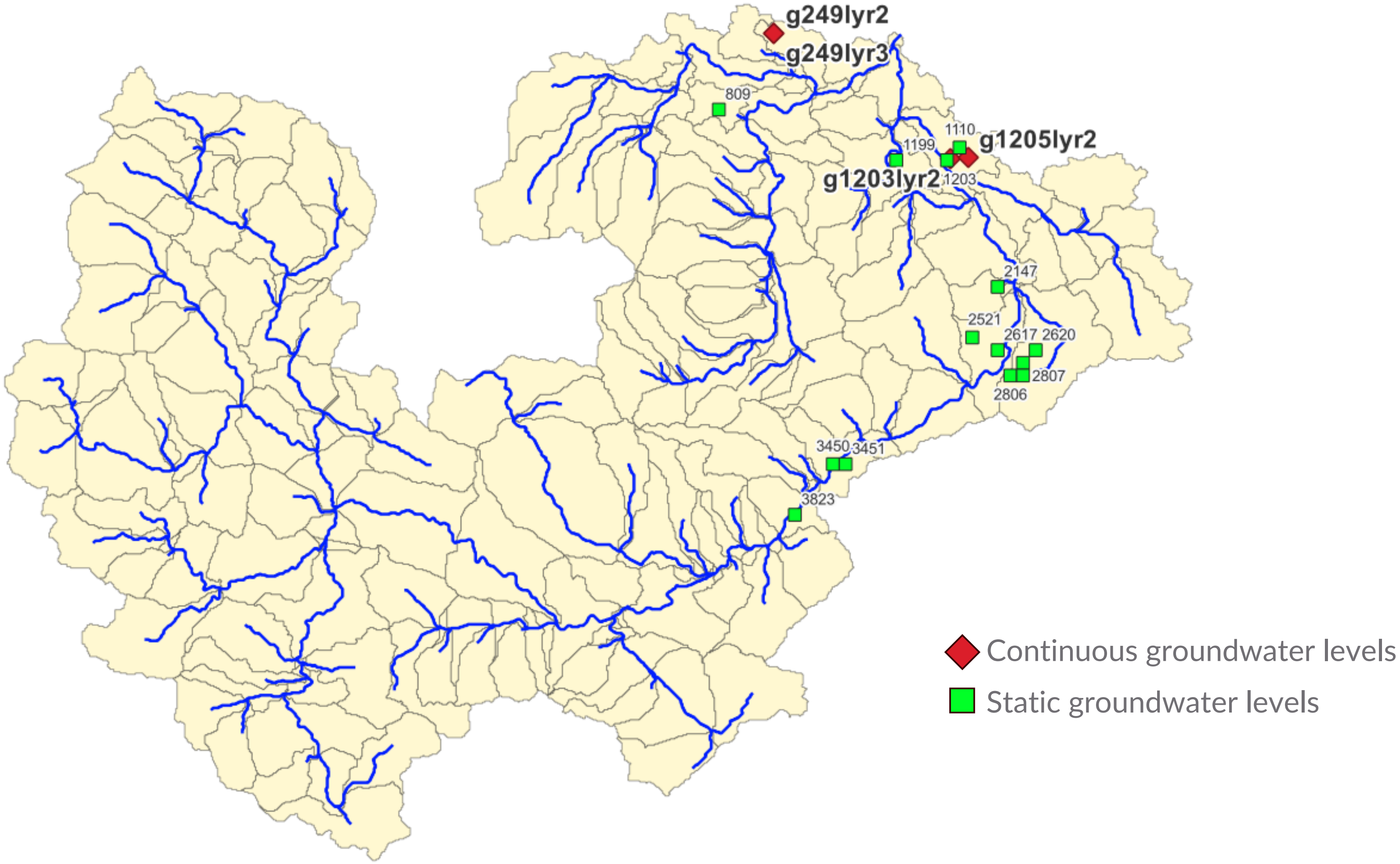
## Daily streamflow discharge at RCH003



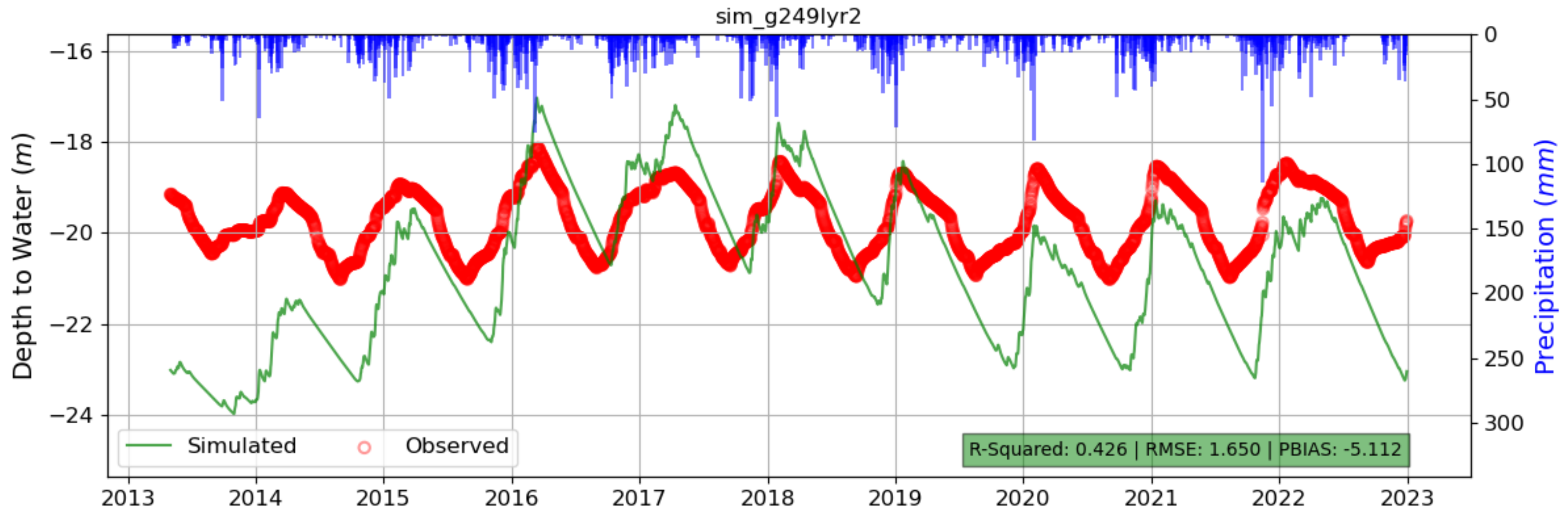
## Monthly average streamflow discharge at RCH003



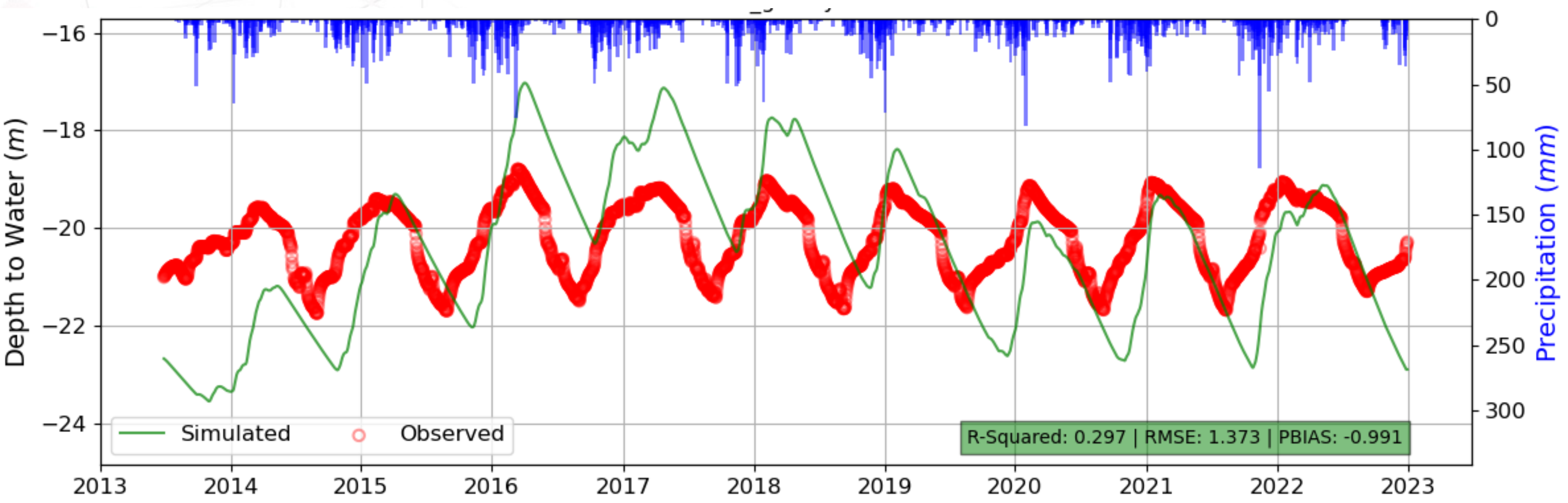


g249lyr2
g249lyr3
809
1110
g1205lyr2
1199
g1203lyr2
1203
2147
2521
2617
2620
2807
2806
3450
3451
3823
Continuous groundwater levels
Static groundwater levels

## Groundwater levels at Grid id 249 in 2nd layer

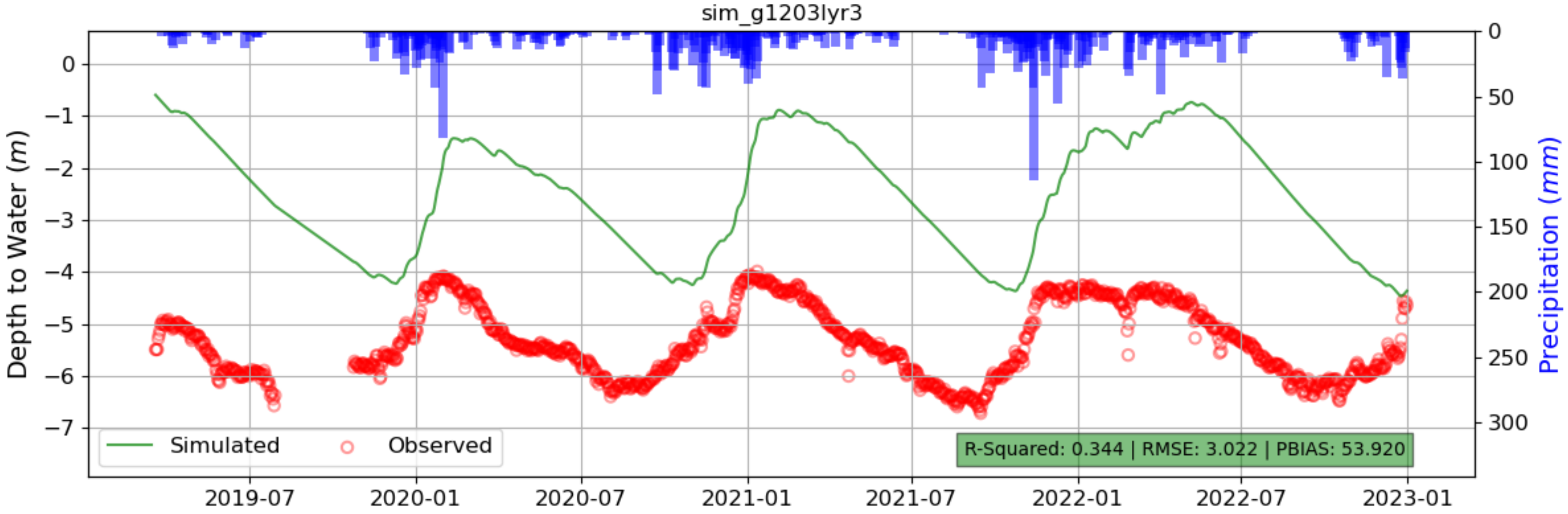



## Groundwater levels at Grid id 249 in 3rd layer

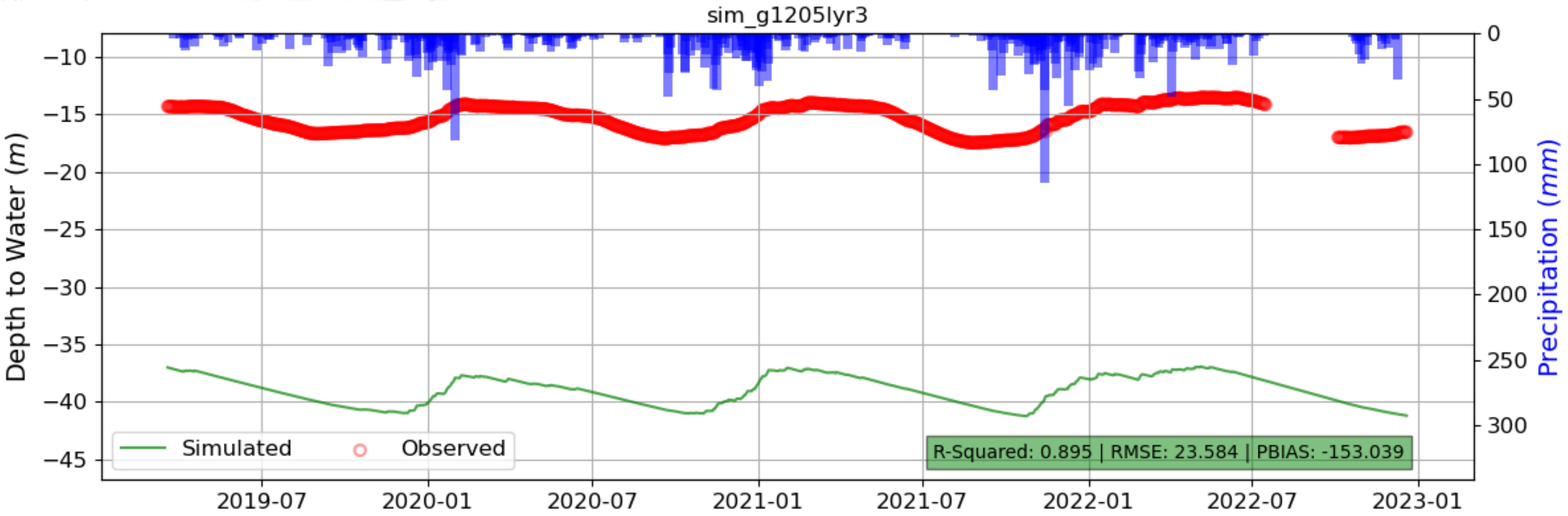



TEXAS A&M AGRILIFE RESEARCH

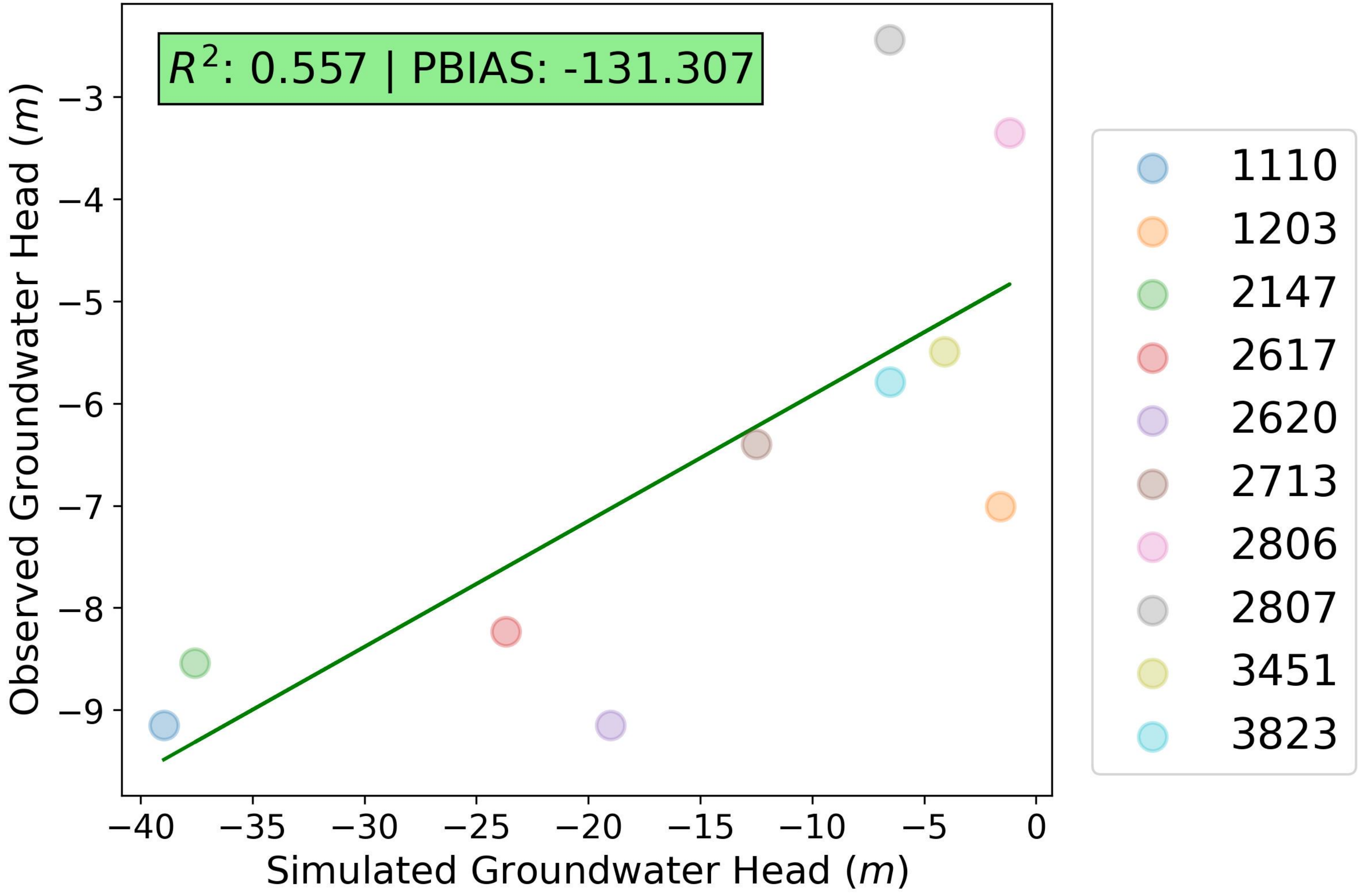
# Groundwater levels at Grid id 1203 in 3rd layer




# Groundwater levels at Grid id 1205 in 3rd layer

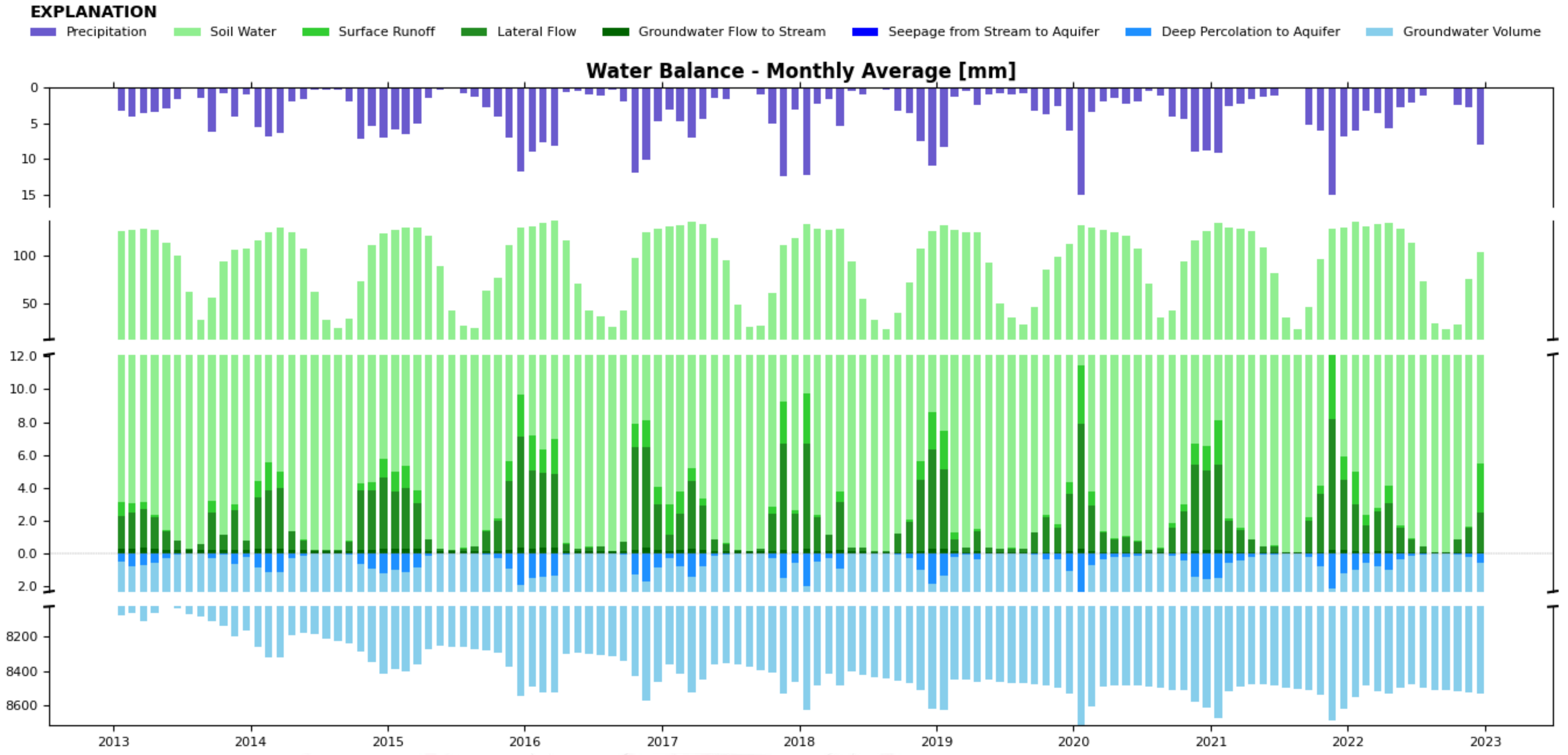


## Static groundwater levels

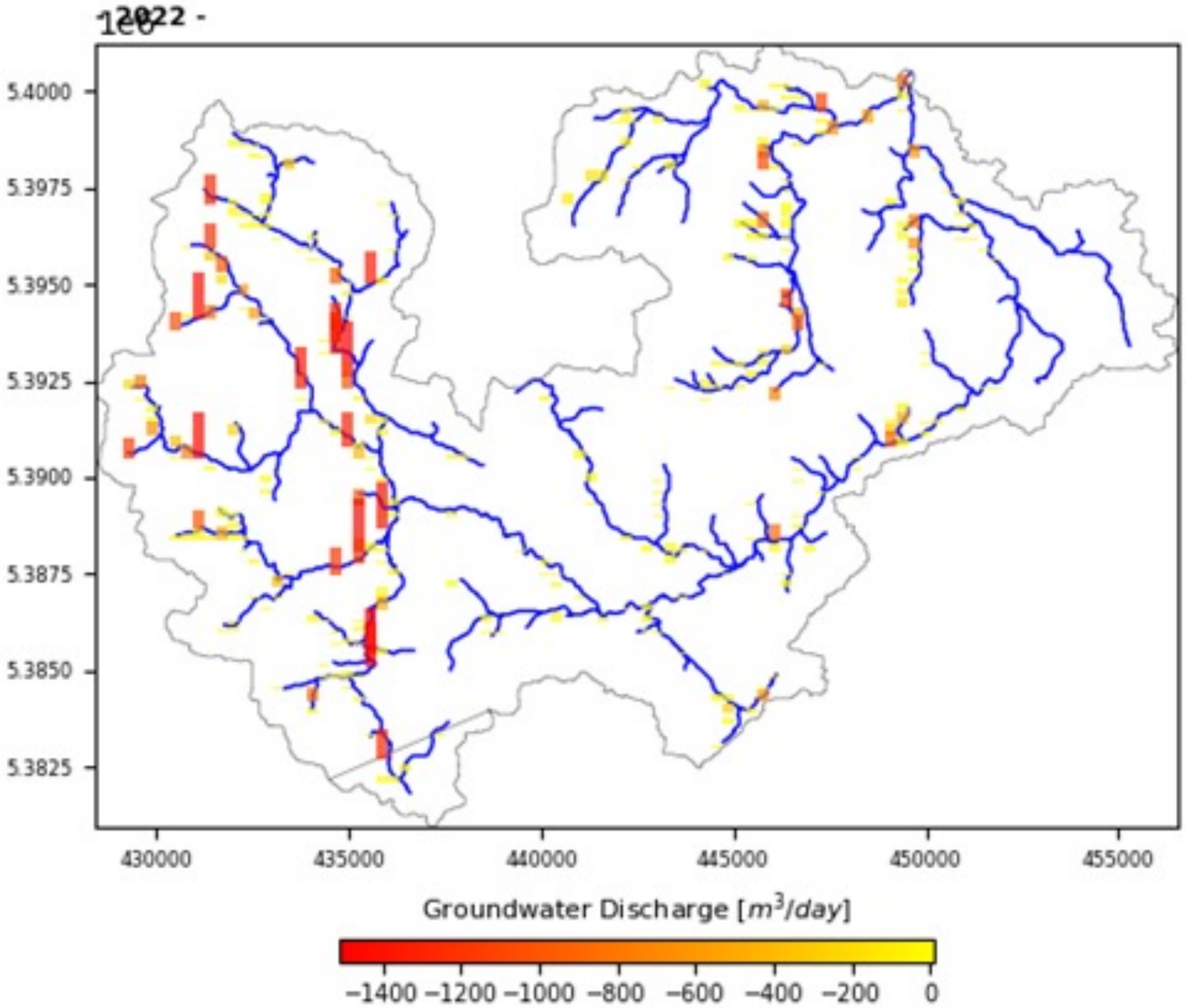



| grid_id | layer | date | obd | sim |
|---|---|---|---|---|
| [redacted] | | | | |
| 1110 | 3 | 3/1/2015 | -9.15E+00 | -3.90E+01 |
| [redacted] | | | | |
| 1203 | 1 | 3/4/2020 | -7.01E+00 | -1.59E+00 |
| 2147 | 3 | 7/13/2016 | -8.54E+00 | -3.76E+01 |
| [redacted] | | | | |
| 2617 | 3 | 1/13/2017 | -8.23E+00 | -2.37E+01 |
| 2620 | 1 | 1/31/2013 | -9.15E+00 | -1.90E+01 |
| 2713 | 1 | 8/15/2013 | -6.40E+00 | -1.25E+01 |
| 2806 | 1 | 4/12/2013 | -3.35E+00 | -1.18E+00 |
| 2807 | 1 | 4/14/2016 | -2.44E+00 | -6.54E+00 |
| [redacted] | | | | |
| 3451 | 2 | 9/23/2014 | -5.49E+00 | -4.09E+00 |
| 3823 | 2 | 5/19/2016 | -5.79E+00 | -6.53E+00 |

# Water balance – Monthly Average (mm)

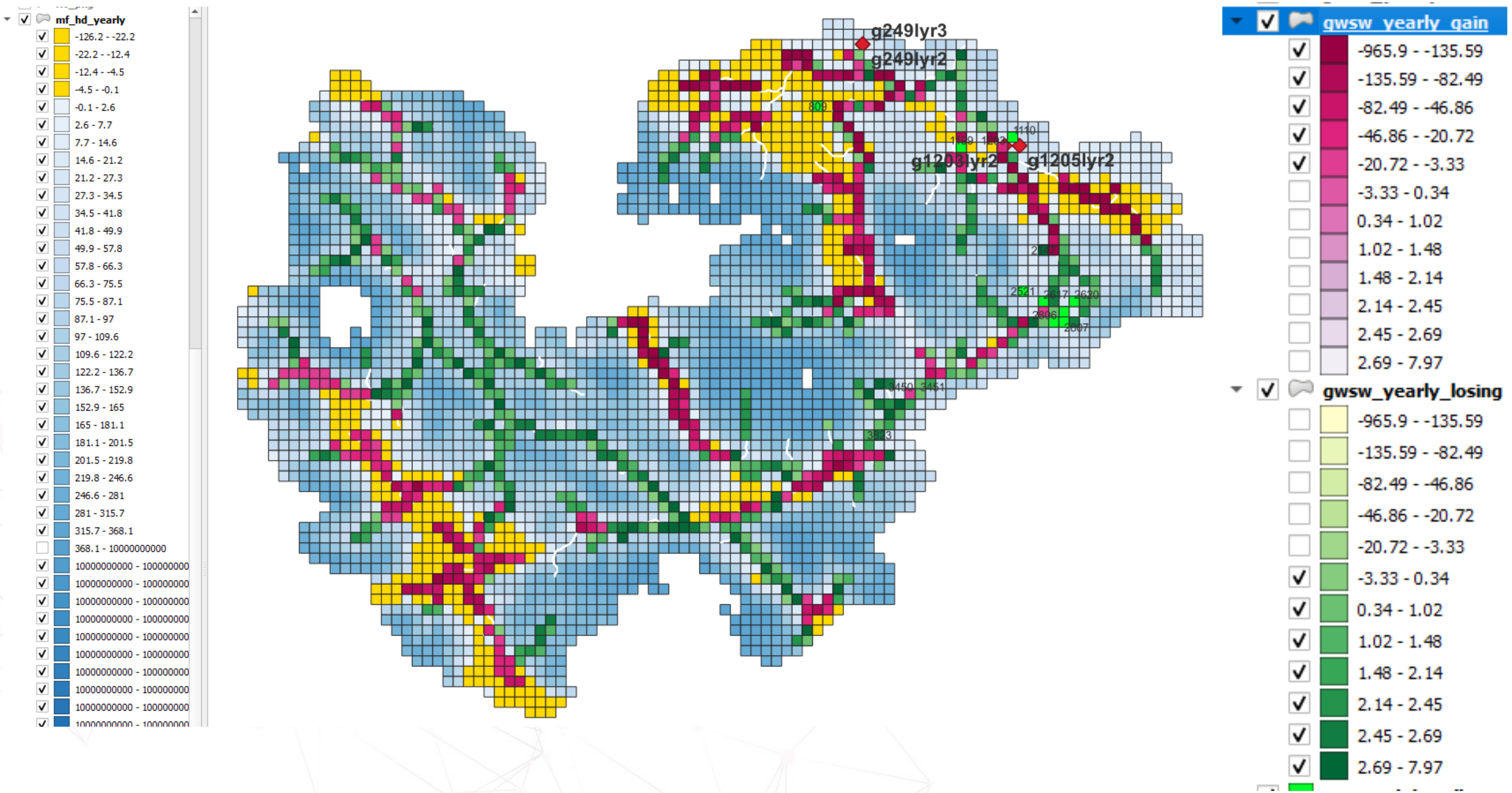


# Groundwater/Surface water interactions (m³/day)



Depth to water (m) (Yellow color can be considered shallow water tables) in 2022

Yearly averaged Groundwater/Surface water interaction $m^3/day$ (2022)



# DISCUSSION