# Interdisciplinary Environmental Models: Water Quality, Hydrology, Hydraulics

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# Introduction: Nutrient Flow through Ecosystems

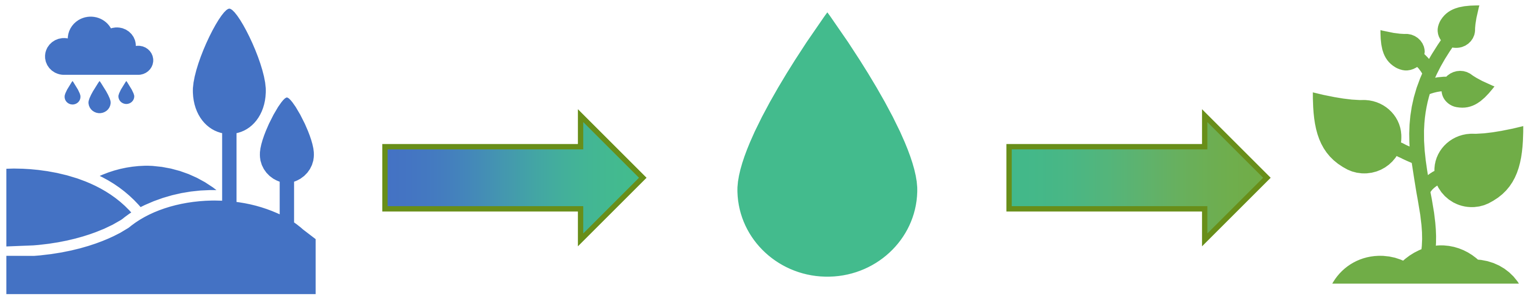
- Nutrient flow through ecosystems has a profound impact on how species utilize resources across watershed scales.
  - Primary production
  - Species distribution and abundance
  - Ecosystem productivity and stability
  - Community composition and diversity
  - Carbon sequestration
- Human-caused disturbances are disrupting nutrient cycling, destabilizing ecosystem health and functioning.



# Introduction: Simulation of Nutrient Flow at Watershed Scales

- Nutrient flow through ecosystems was not being simulated across watershed scales using a flexible integrated modeling system.
- This hindered our ability to:
  - Assess ecosystem risk analysis
  - Predict morbidity and mortality of key species
  - Predict spatial distribution of species across landscapes in response to changing conditions
  - Identify effective ecosystem restoration strategies and management interventions
  - Design measures to control the spread of invasive species

# Integrated Environmental Modeling



Water Resources Models

Water Quality Models

- Nutrients
- Temperature
- Dissolved Oxygen
- Algae
- Contaminants

Ecological Models

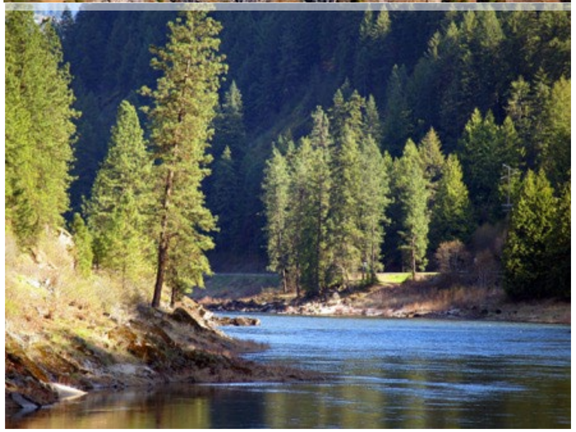
# ClearWater: Next Generation Integrated Water Quality Modeling

- ClearWater: Corps Library for Environmental Analysis and Restoration of Watersheds
- Purpose: Link environmental models with existing water resources models that simulate runoff, rivers, and reservoir hydraulics and hydrology
- ClearWater provides environmental simulation capabilities that are designed to leverage existing water resources models.
    - The ClearWater water quality modules simulate constituent kinetics, heat budget processes, and vegetation growth cycles. Capabilities include:
        - NSM: Nitrogen, phosphorus, and carbon cycling; dissolved oxygen, algae, etc.
        - TSM: Temperature (heat budget)
        - GSM: General Constituents
        - CSM: Organic and inorganic contaminants
        - MSM: Mercury
- ClearWater contains legacy modules written in Fortran and C++ and next-generation modules written in Python (NSM and TSM)
    - Engine computes the transport (advection and diffusion) of heat and constituent mass across the watershed
    - Data visualization capabilities
    - Framework to integrate multiple models.

Runoff

Reservoirs

Rivers



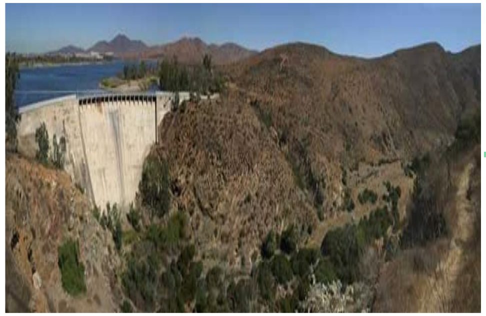
# Water Quality and Environmental Systems Modeling

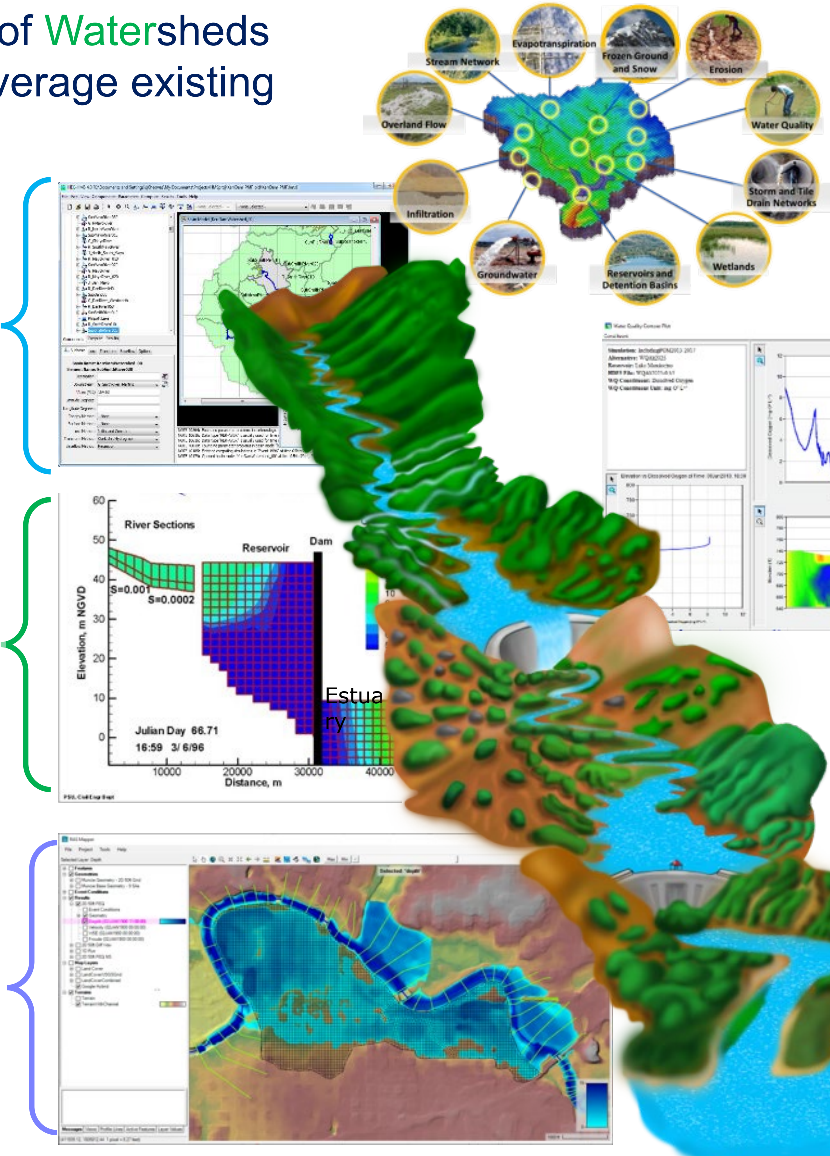
ERDC's Corps Library for Environmental Analysis and Restoration of Watersheds (ClearWater) provides environmental simulation capabilities that leverage existing hydrologic and hydraulic (H&H) models.

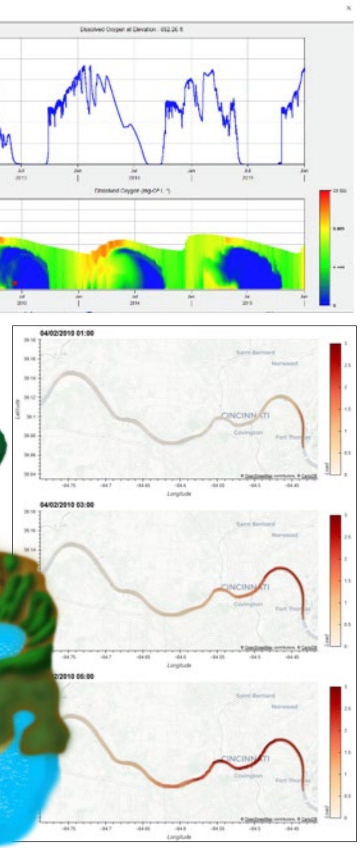
Water quality modeling tools:

- Watershed Runoff:
  - ▸GSSHA: Surface and sub-surface water quality modeling
  - ▸HEC-HMS: Surface runoff temperature modeling
- Reservoirs:
  - ▸CE-QUAL-W2: 2D reservoir-river hydrodynamics and water quality modeling
  - ▸HEC-ResSim: Reservoir operations and water quality modeling
- Rivers and Floodplains:
  - ▸ HEC-RAS: 1D River hydraulics and water quality & vegetation modeling
  - ▸ ClearWater-Riverine: 2D River-floodplain hydraulics and water quality modeling with HEC-RAS-2D

Key: ERDC-EL – ERDC-CHL – HEC





- Temperature
- Nutrients
- Dissolved Oxygen
- Algae
- Metals
- Contaminants

# MODERN SCIENTIFIC PYTHON

Built using the cloud-native geospatial Python stack being widely adopted by NOAA, USGS, NASA, etc.

An object-oriented architecture inspired by xarray-simlab / fastscape and CSDMS LandLab

Automated unit testing

python™

SciPy

xarray

dask

NumPy

pandas

NUMFOCUS

OPEN CODE = BETTER SCIENCE

https://numfocus.org/sponsored-projects

# MODEL COUPLING

**Modeling community moving toward systems of coupled models from modular model components.**

**BMI 2.0 has become the standard for model coupling**

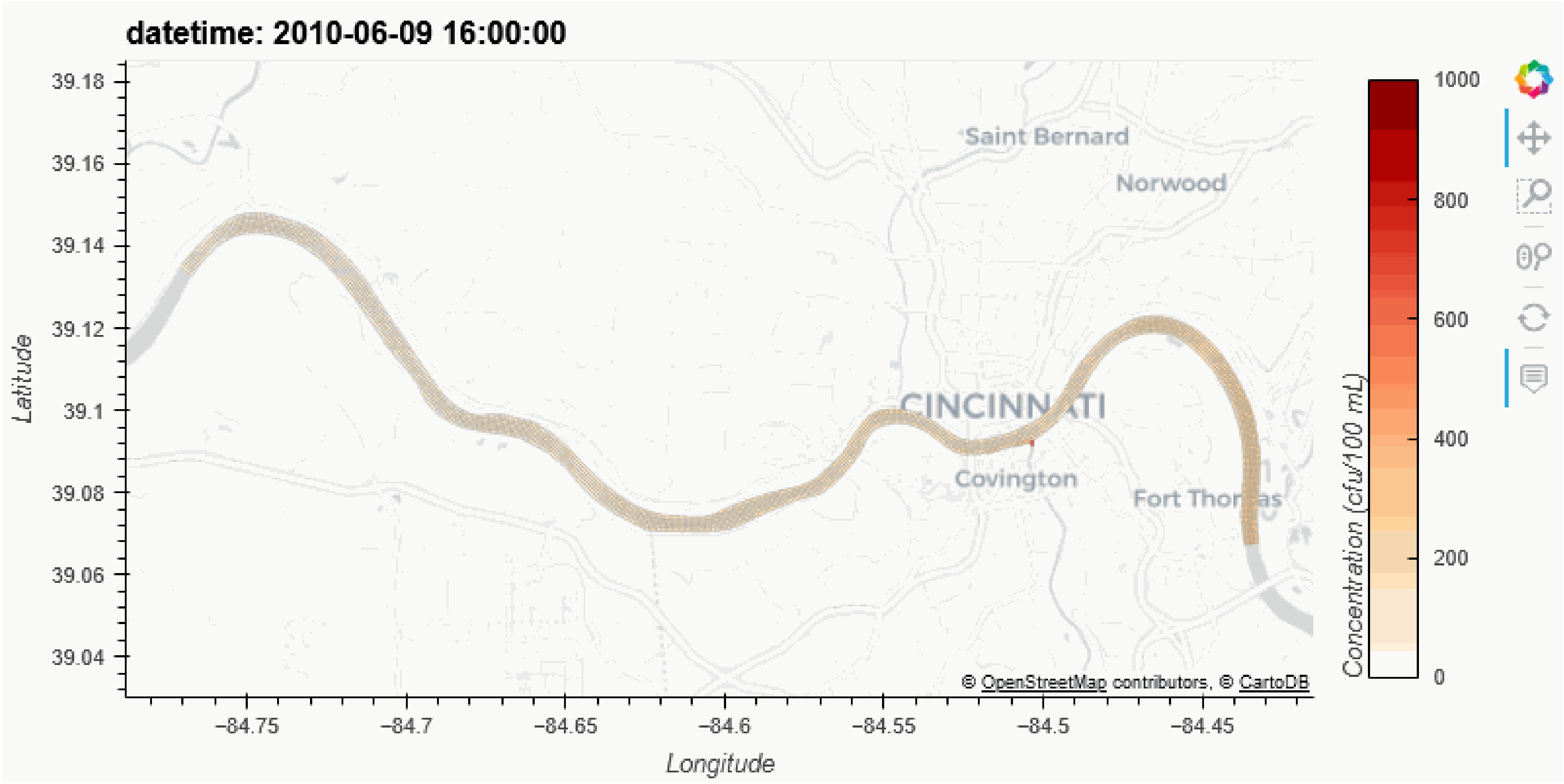
- **Basic Model Interface (BMI)**
  - Provides a common set of functions
    - To run models and exchange information and data on grids, variables, timesteps, etc.
  - Shares data among models using a zero-copy approach
    - Each model reads and writes to the same in-memory object using pointers
  - Supports models written in C, C++, Fortran, Java, Python, Javascript, Julia
    - NOTE: BMI must be implemented in the source code of a model before it can be used to couple that model to other BMI-compliant models
  - Learn more: https://bmi.readthedocs.io

# ClearWater-Riverine

- Clearwater-Riverine simulates temperature and advanced nutrient cycling in branching river systems and floodplains, incorporating hydrodynamic, water quality, and meteorologic inputs from multiple data sources and models.
  - Flows: The model grid, volumetric flow, velocities, depths, diffusivity, etc. are provided by existing 2D water resources models.
    - HEC-RAS (2D)
    - GSSHA (in progress)
  - Modules: Water quality kinetics and heat budget simulation capabilities in ClearWater-Riverine are furnished by ERDC's ClearWater modules (e.g., NSM).
  - Transport: The ClearWater transport engine computes advection-diffusion of heat and mass through the model network.
  - Framework: The ClearWater framework links all the components together and performs the water quality compute sequence.
- Currently design is based on *decoupled* modeling, i.e., the flows are pre-computed by the hydro models.

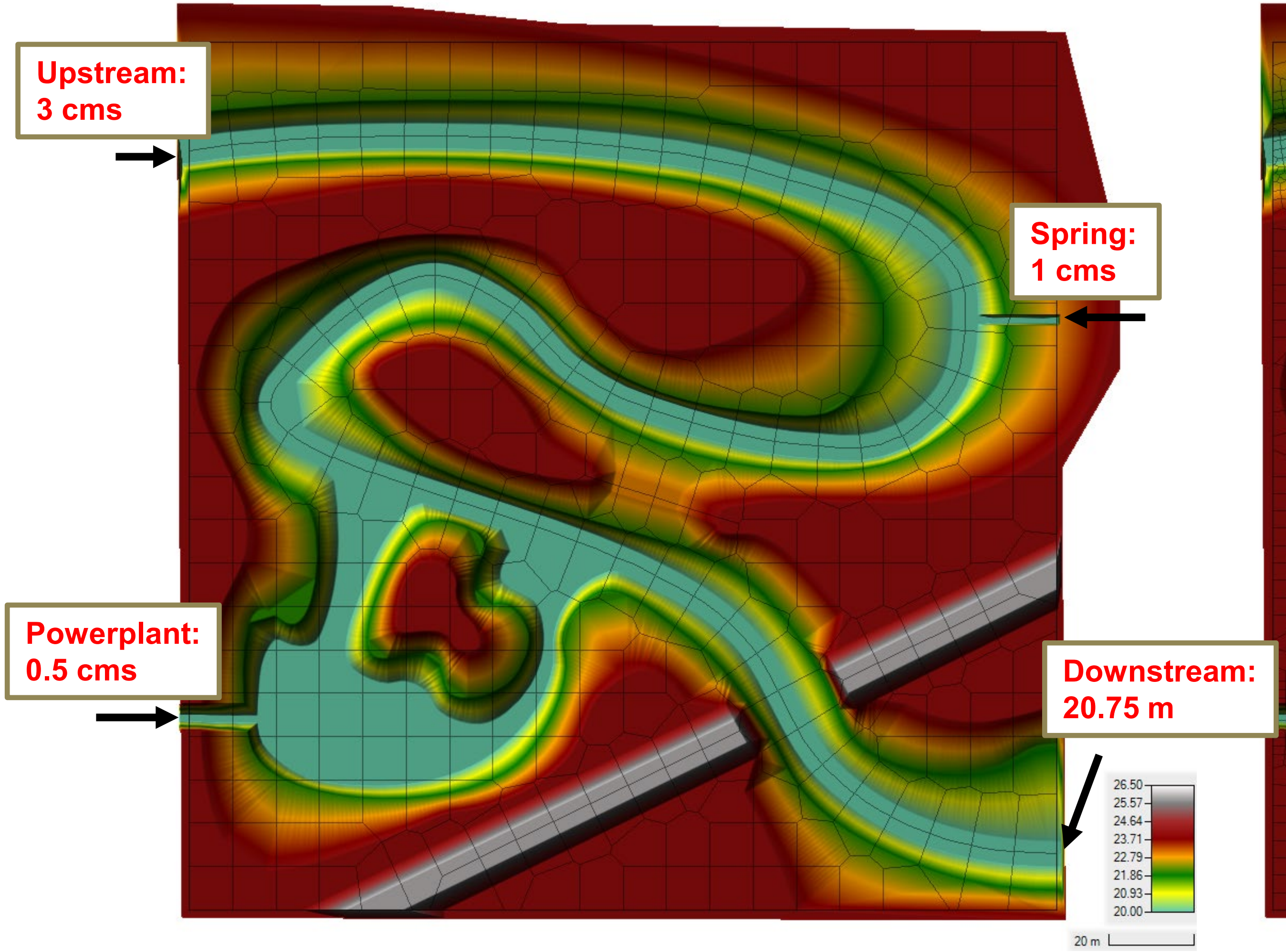
# ClearWater-Riverine Example:

## E. Coli Transport in the Ohio River

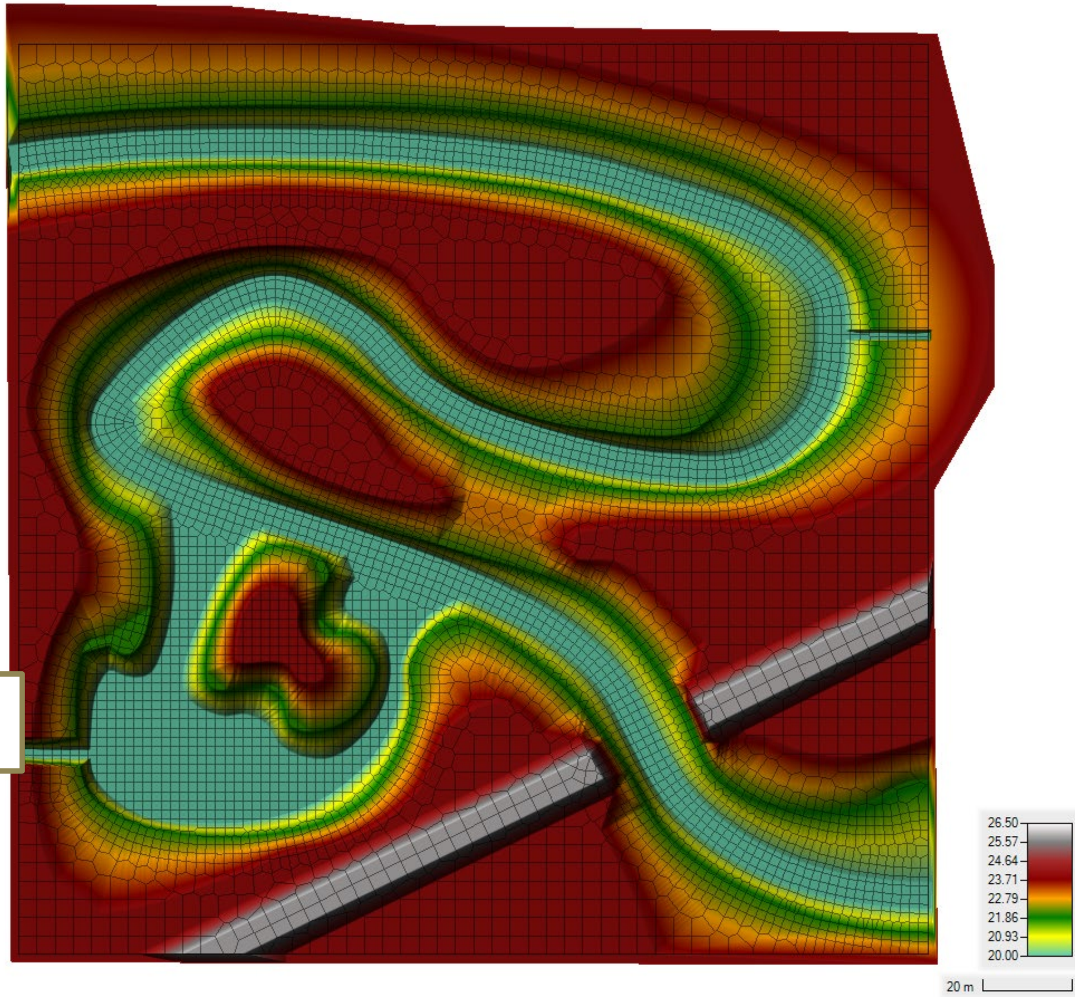


# Demo Case Study: Sumwere Creek — Domain, Mesh, and Hydrodynamic Boundary Conditions

Coarse Mesh

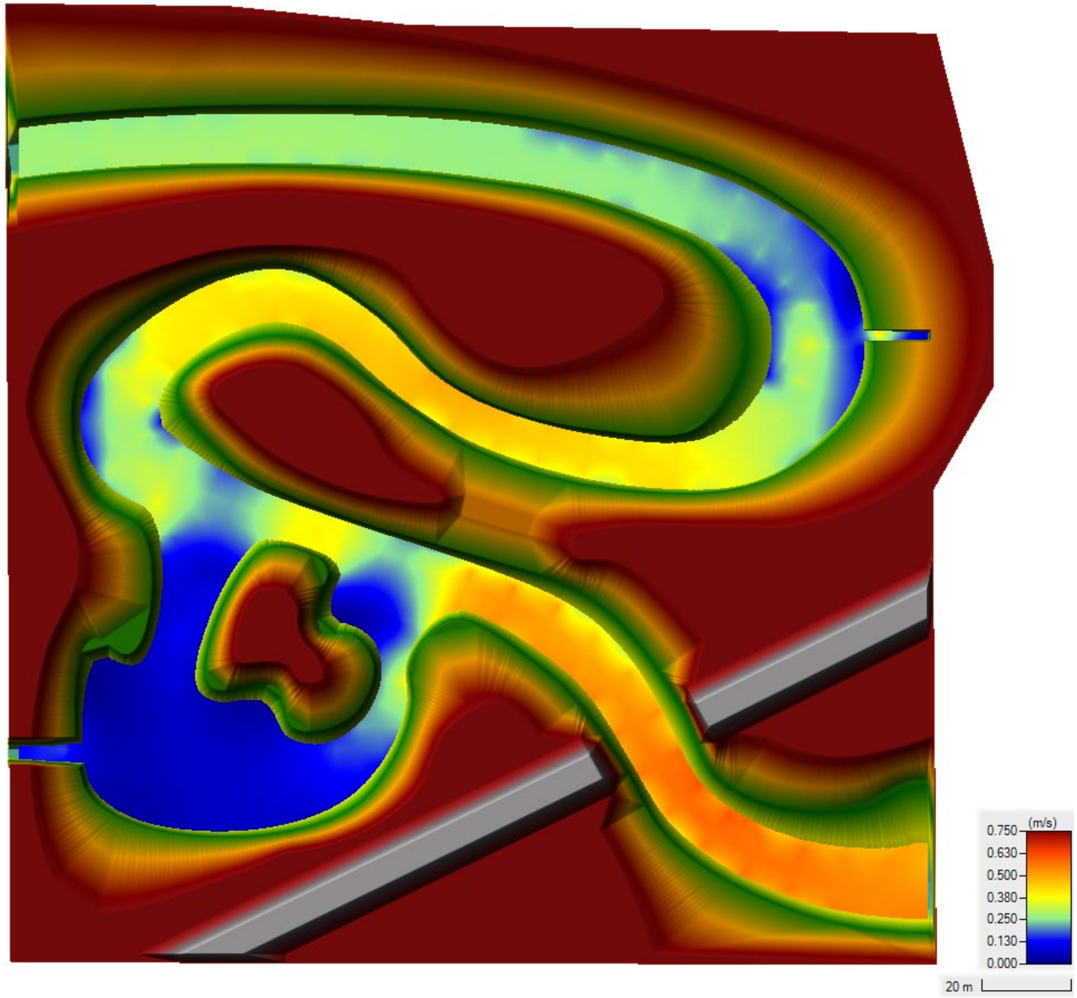



Fine Mesh

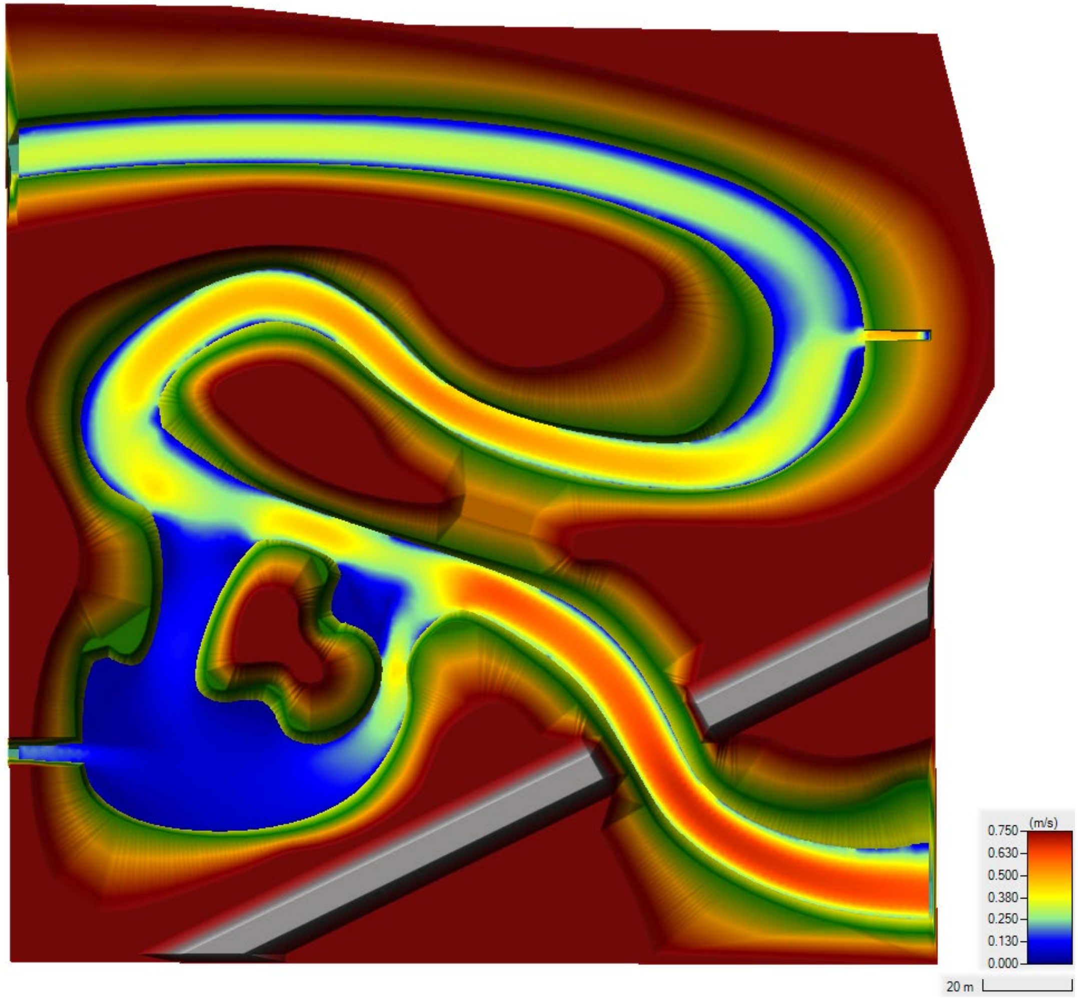


# Demo Case Study: Sumwere Creek — Velocity at End of Simulation

Coarse Mesh

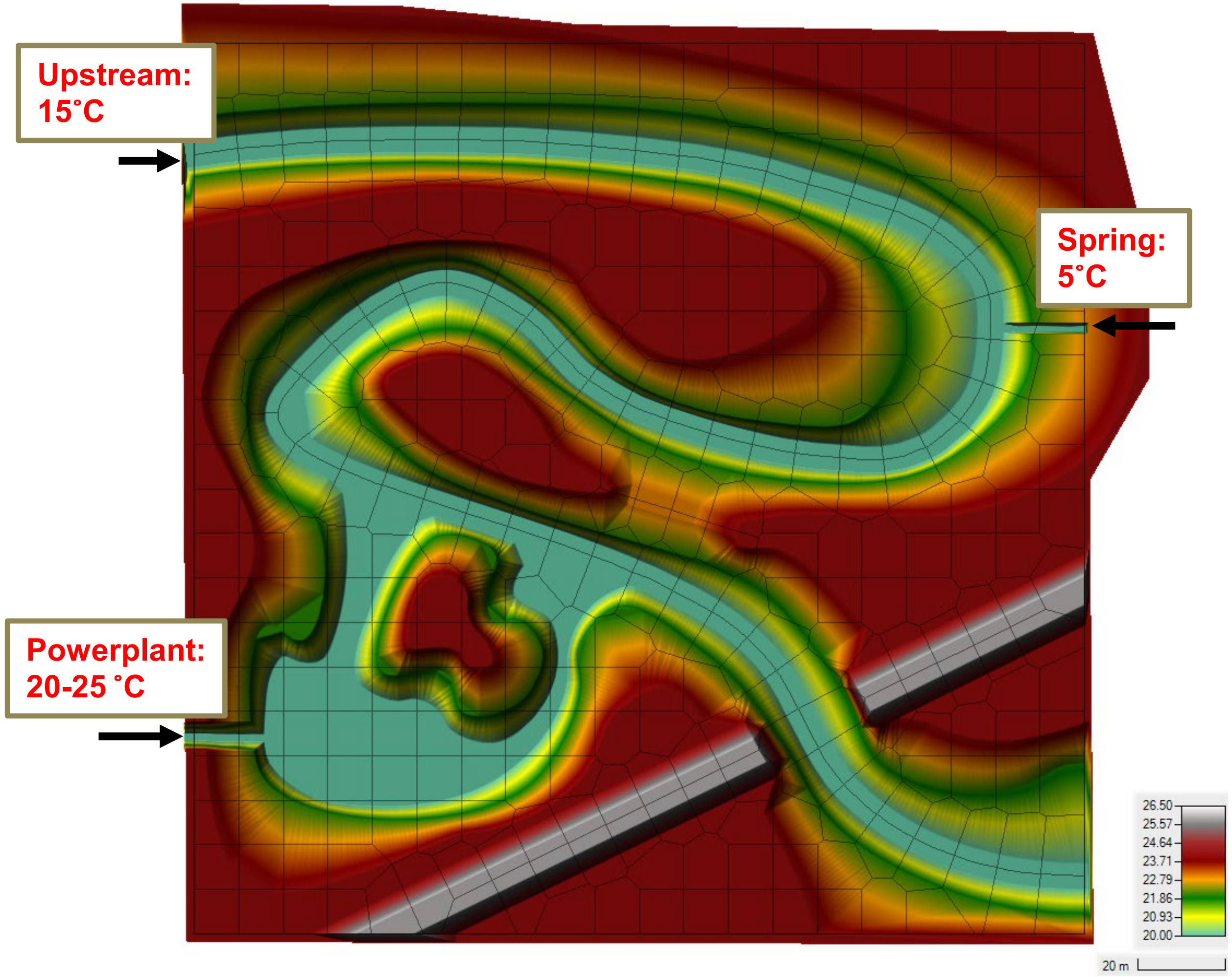



Fine Mesh

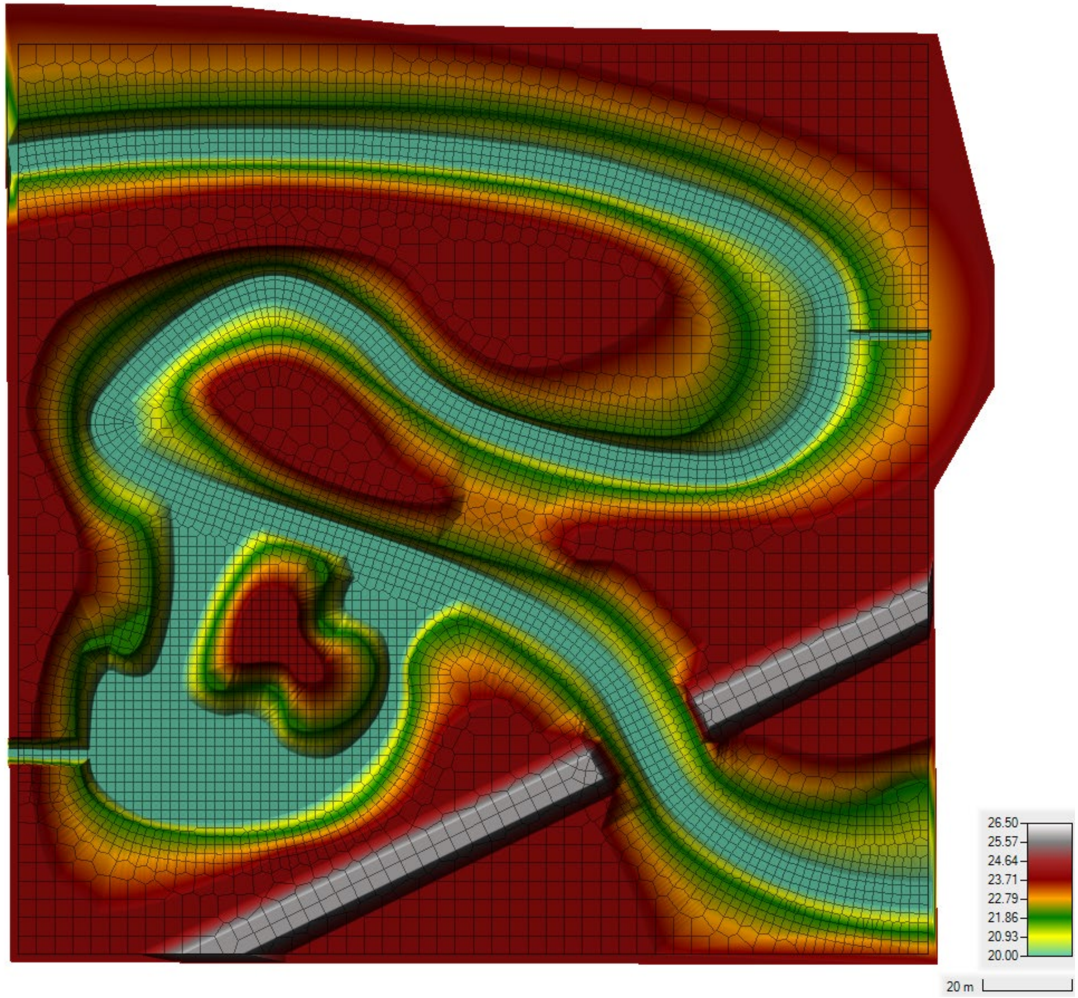


# Demo Case Study: Sumwere Creek — Temperature Boundary Conditions

Coarse Mesh

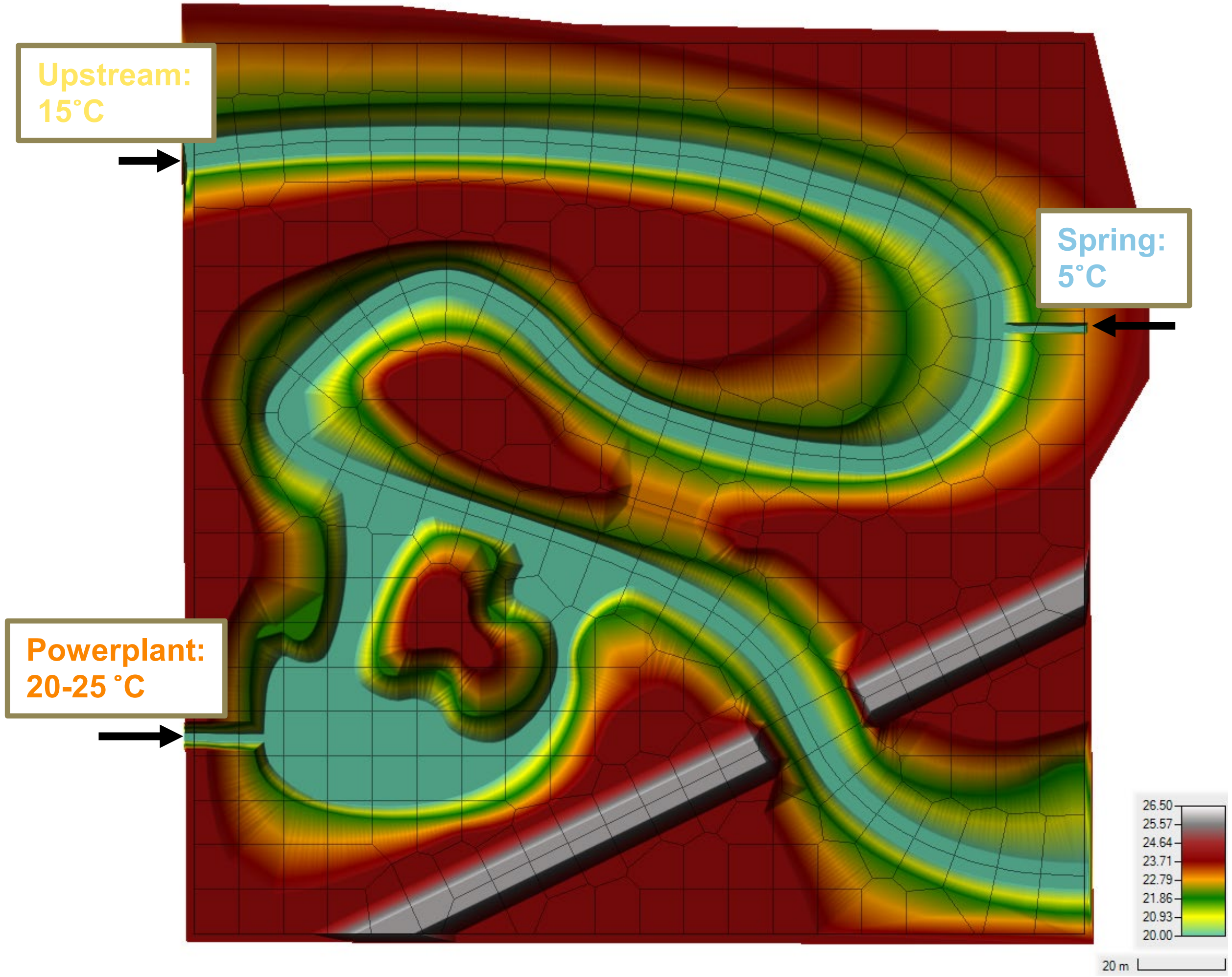


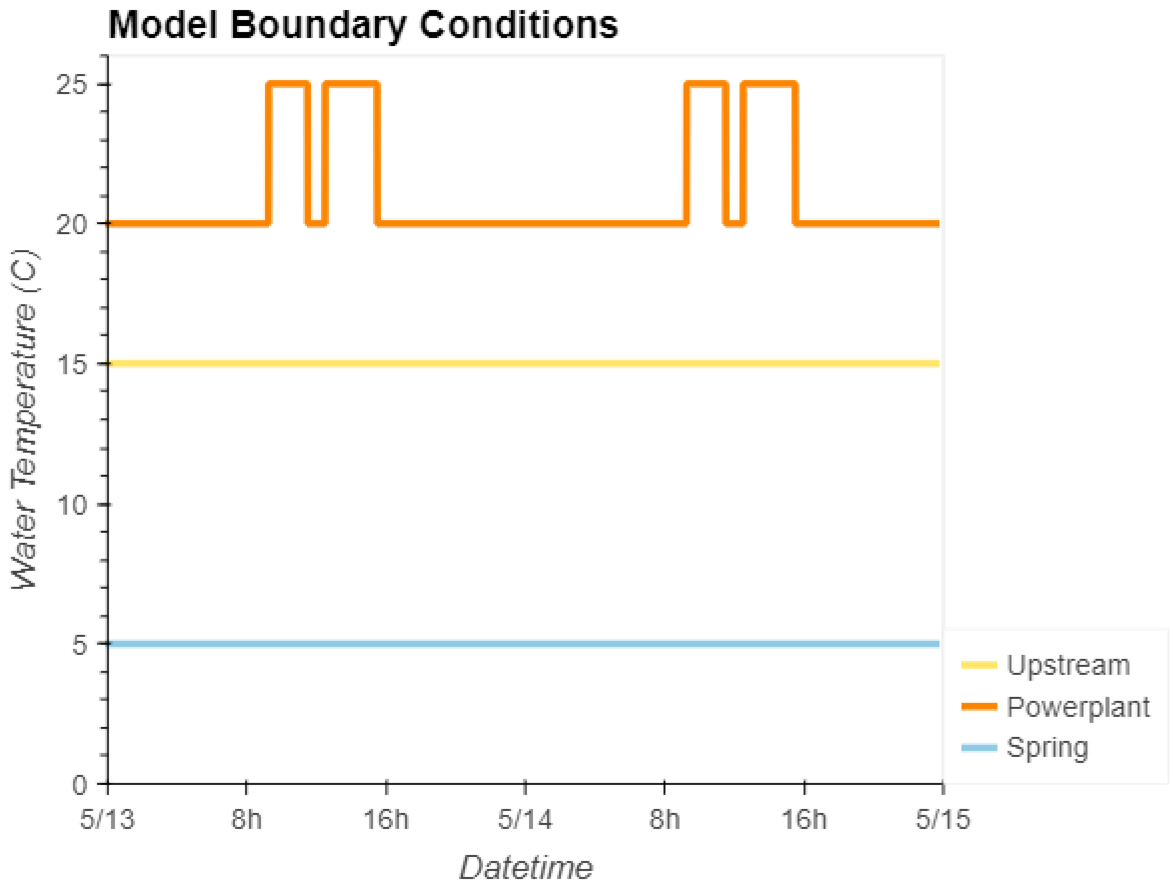

Fine Mesh



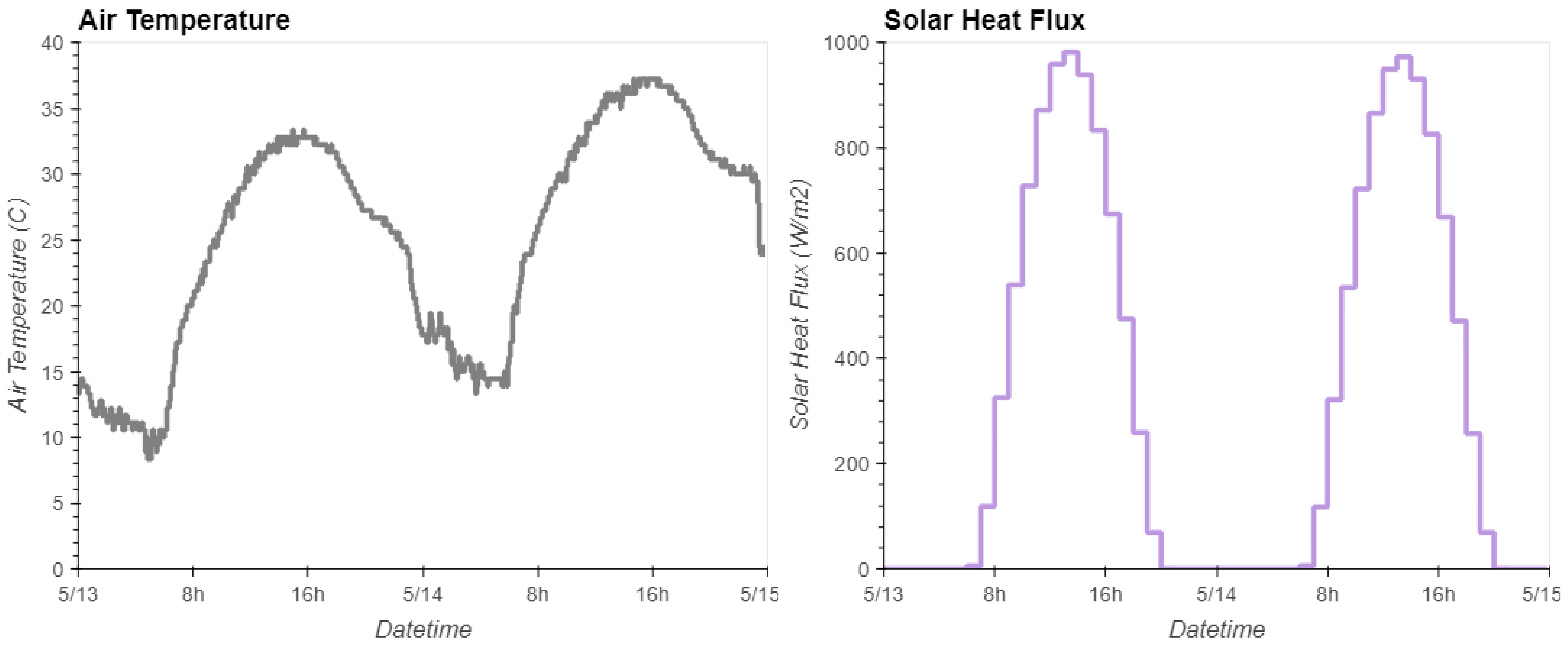
# Demo Case Study: Sumwere Creek — Temperature Boundary Timeseries

Coarse Mesh



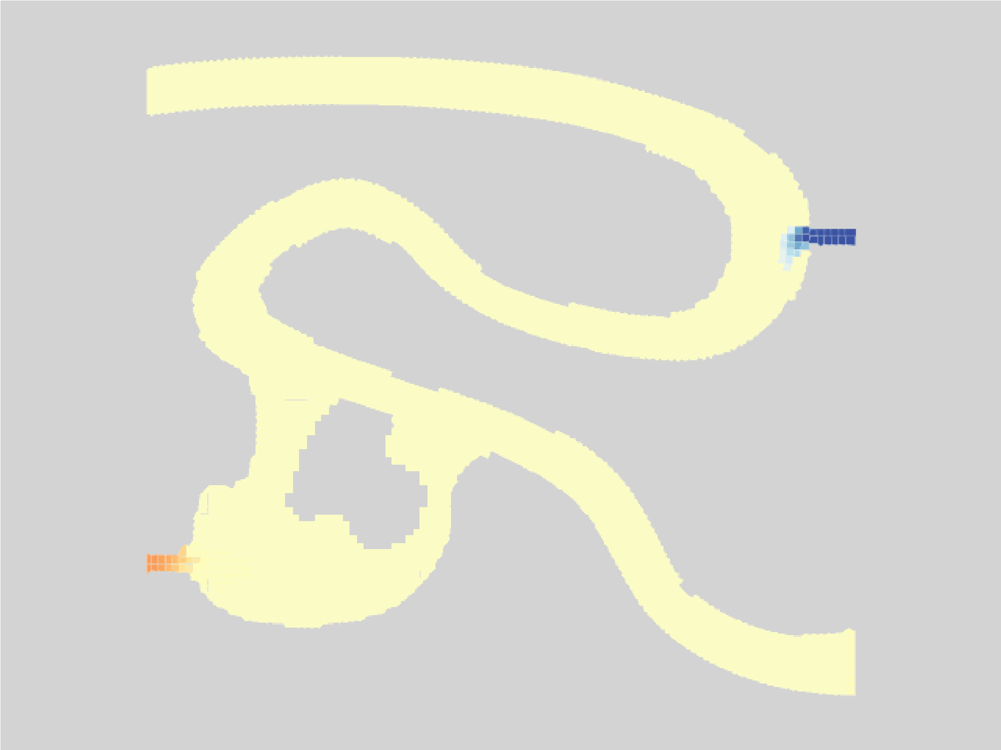
# Demo Case Study: Sumwere Creek — Meteorological Timeseries

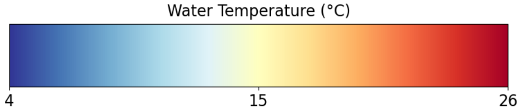


# Results – Animation

Coarse Mesh

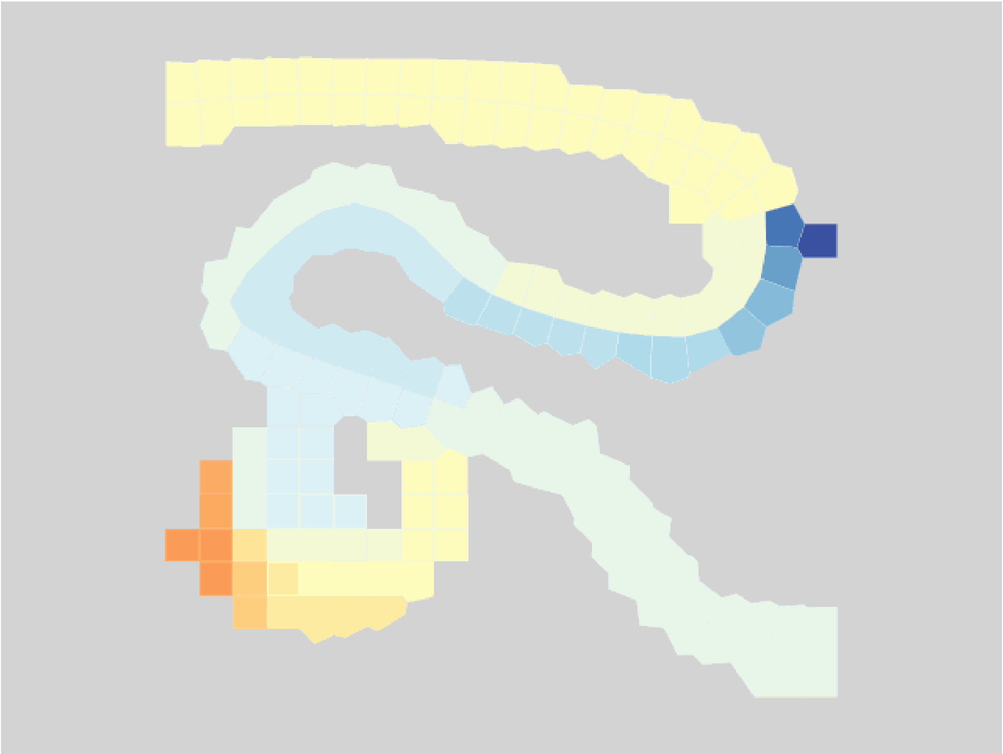
Fine Mesh



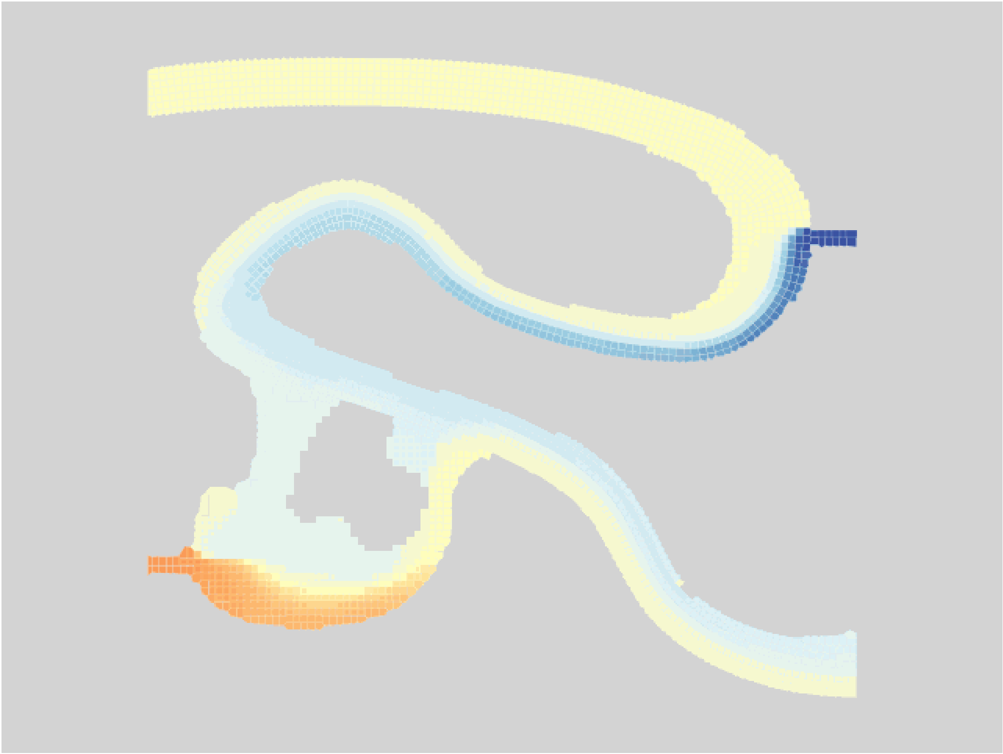


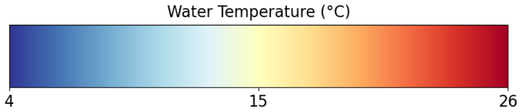
# Results – Warm Powerplant Inflows

Coarse Mesh



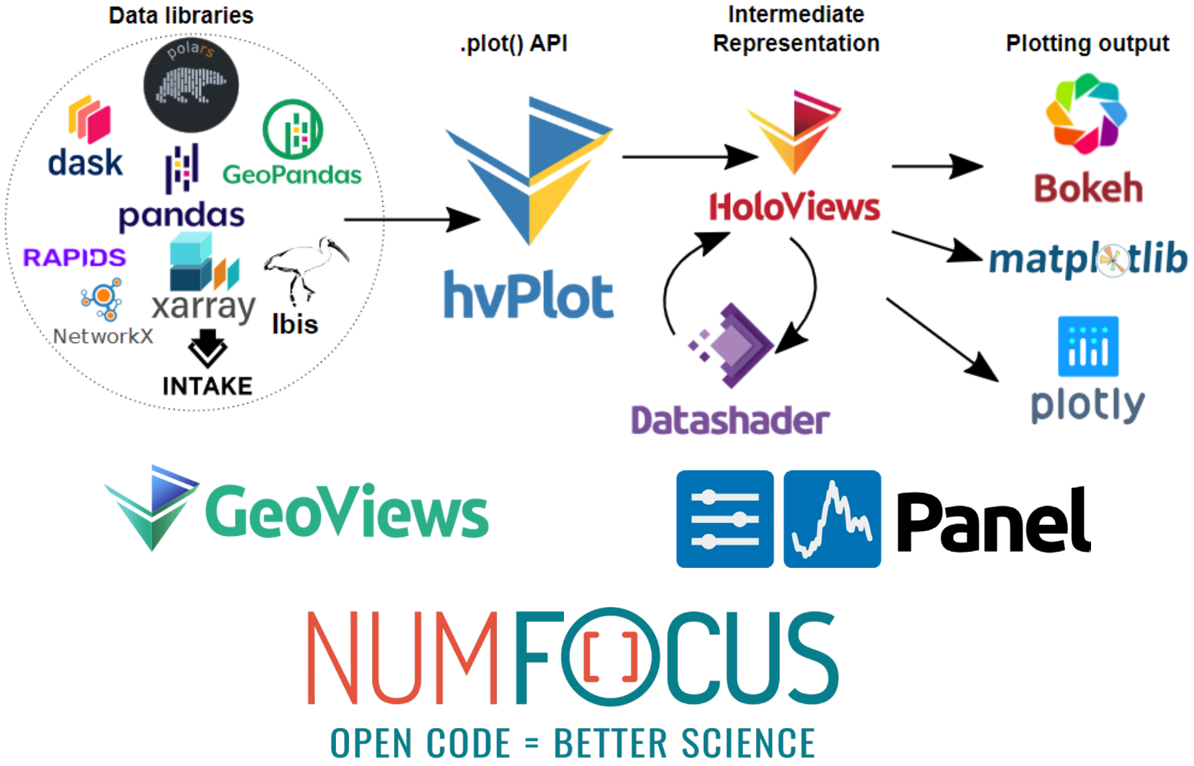
Fine Mesh





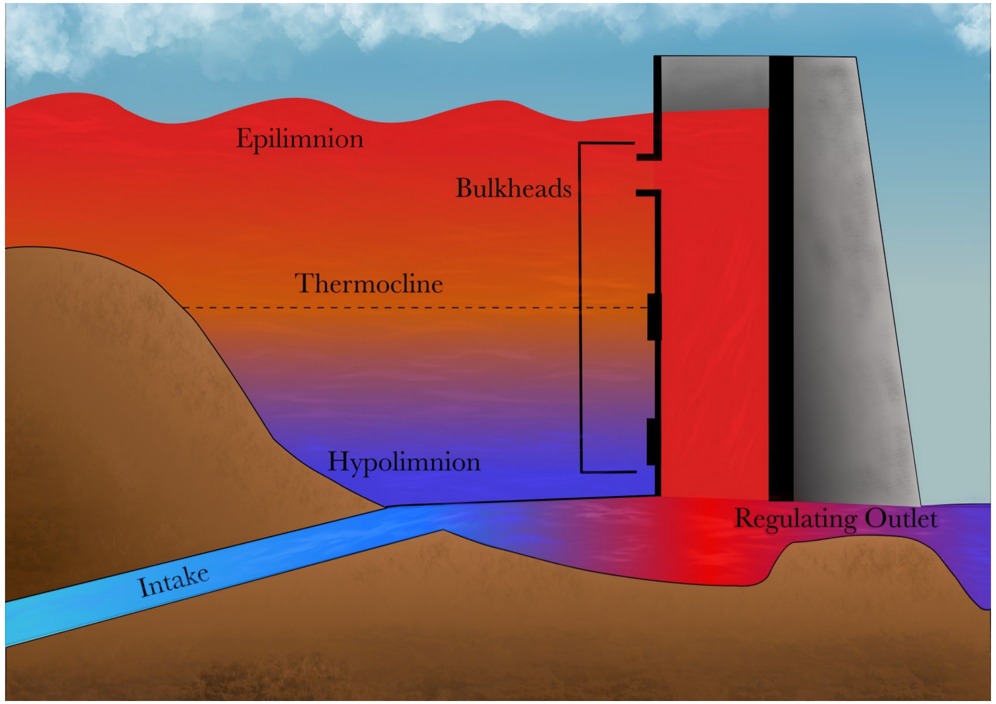
# ClearWater Framework Summary

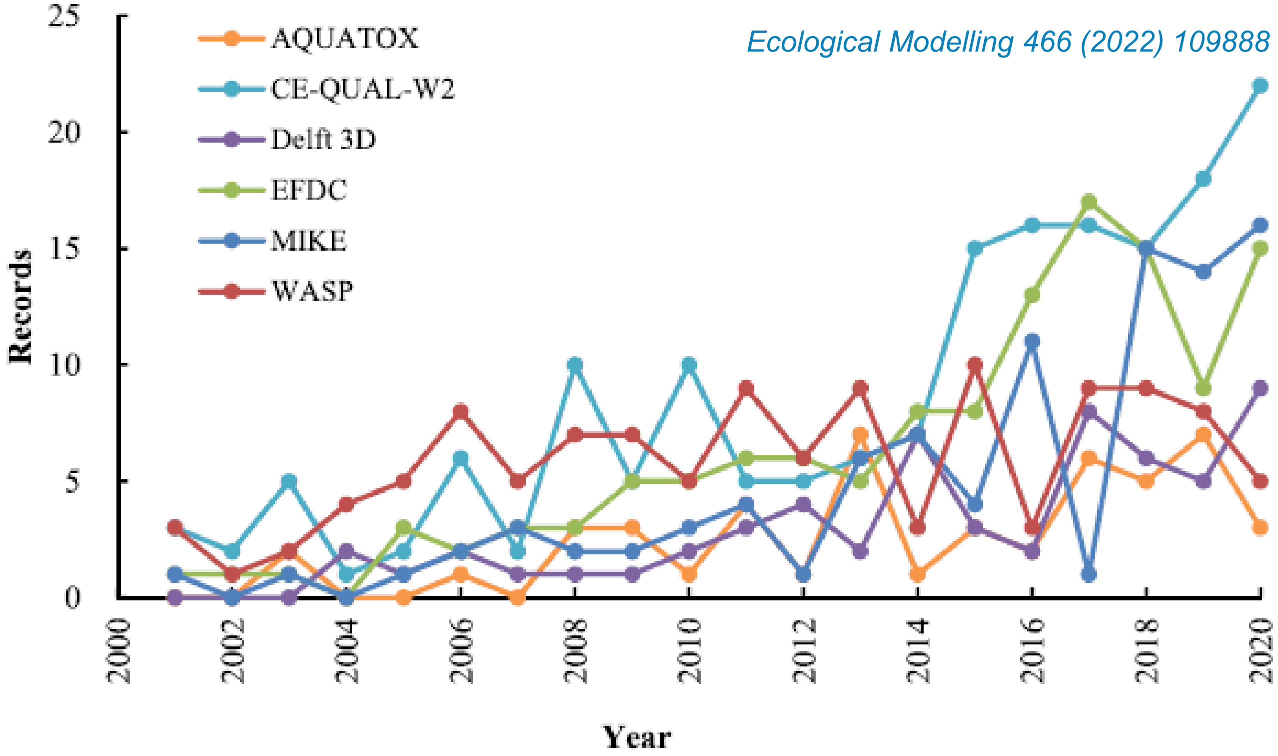
- ClearWater's Python-based framework allows easy integration with powerful interactive visualization packages
  - ***Enhanced understanding*** of complex environmental/ecological outcomes
  - ***Iterative analysis*** and scenario discovery
  - ***Multidimensional exploration*** across time and space
  - ***Effective communication*** of results across teams and stakeholders



# CE-QUAL-W2

- CE-QUAL-W2 is a two-dimensional (2D), longitudinal/vertical, hydrodynamics and water quality model that enables characterization of vertical and longitudinal changes in reservoirs.
- The model assumes reservoirs are *well mixed* laterally, with no variation from one channel side to the other in a layer (vertical) and segment (longitudinal).
- CE-QUAL-W2 has been applied to rivers, lakes, reservoirs, and estuaries.

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# CE-QUAL-W2 Capabilities

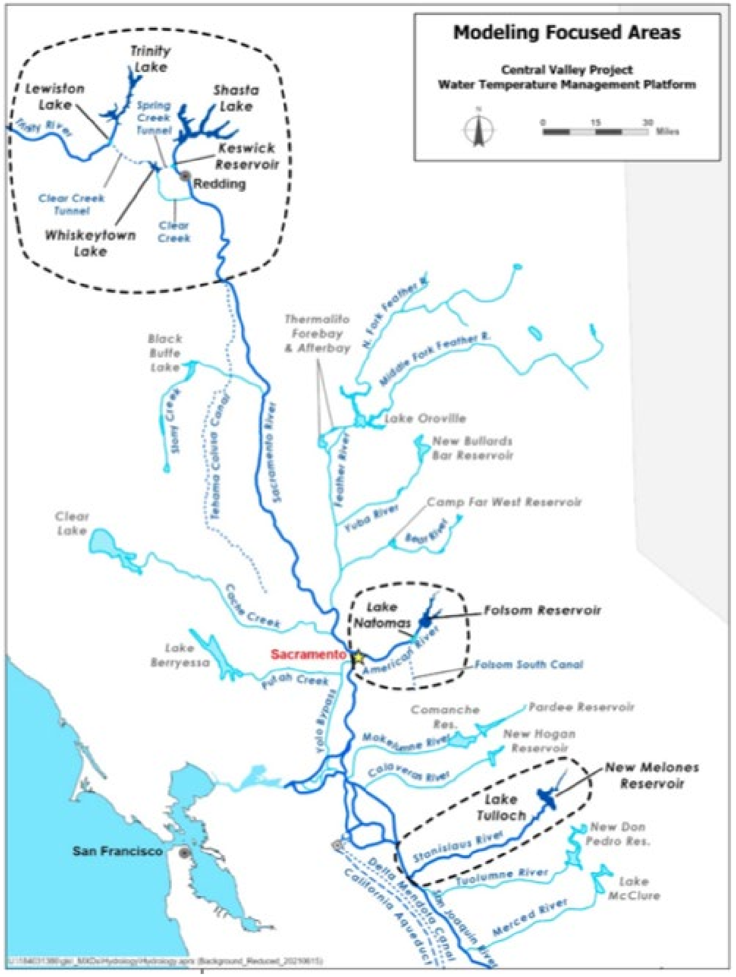
- Longitudinal-vertical hydrodynamics and water quality in stratified and non-stratified systems
- Nutrients-dissolved oxygen-organic matter interactions
- Fish habitat
- Selective withdrawal from stratified reservoir outlets
- Hypolimnetic aeration
- Multiple algae, epiphyton/periphyton, zooplankton, and macrophytes
- CBOD
- Sediment diagenesis model
- Generic water quality groups
- Internal dynamic pipe/culvert model
- Hydraulic structures (weirs, spillways) algorithms, including a dynamic shading algorithm based on topographic and vegetative cover.
- Water age – Useful for forensic analyses

# Past and Current Applications of CE-QUAL-W2

- CE-QUAL-W2 is widely used by USACE and other federal, state, and local agencies for environmental impact assessments, planning studies, etc. Agencies that use CE-QUAL-W2 as their standard reservoir water quality model include:
    - U.S. Geological Survey (USGS)
    - U.S. Bureau of Reclamation
    - U.S. Environmental Protection Agency (EPA)
    - State of California
- More than 1,100 model applications have been developed worldwide for reservoirs, rivers, estuaries, and other water bodies since CE-QUAL-W2 was released in 1986.
- CE-QUAL-W2 is also used as a research tool by researchers at universities and other organizations.
- At least 1,500 publications utilized or cited CE-QUAL-W2 in the year 2022 alone.

Recent Studies:

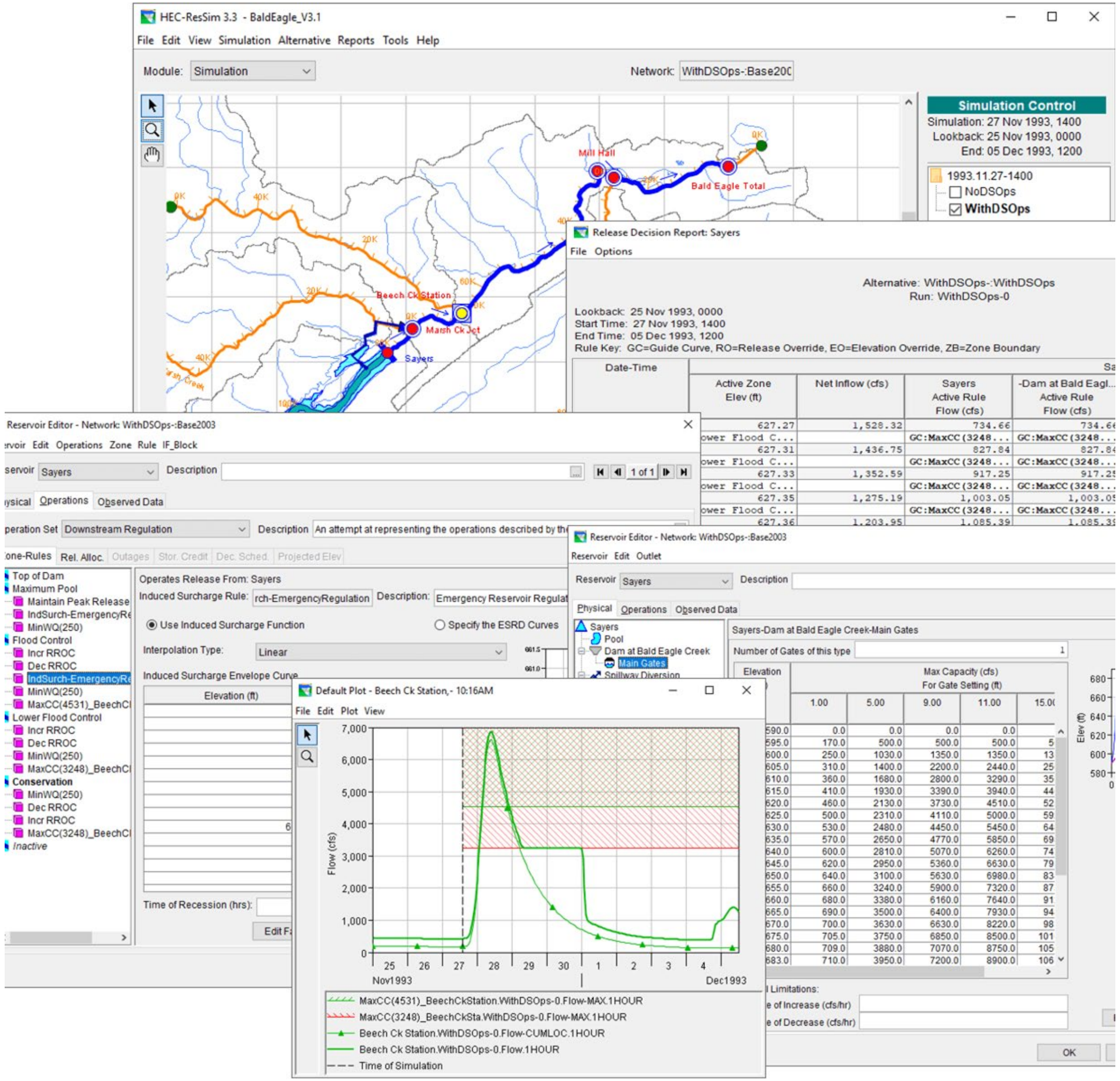
- Water Temperature Modeling Platform, California Central Valley Project (USBR and State of California): This platform applies CE-QUAL-W2 for ongoing and future operations decision-making
- USACE Northwest Division, Columbia and Snake River Watershed
    - ▸ Columbia System Reservoir Operation (CRSO) Project
    - ▸ Columbia River Treaty (CRT) Project
- Philadelphia District, Lehigh River Water Quality Modeling




Region of Application:
Water Temperature Modeling Platform
California Central Valley Project

# HEC-ResSim Water Quality Model: Reservoir Operations

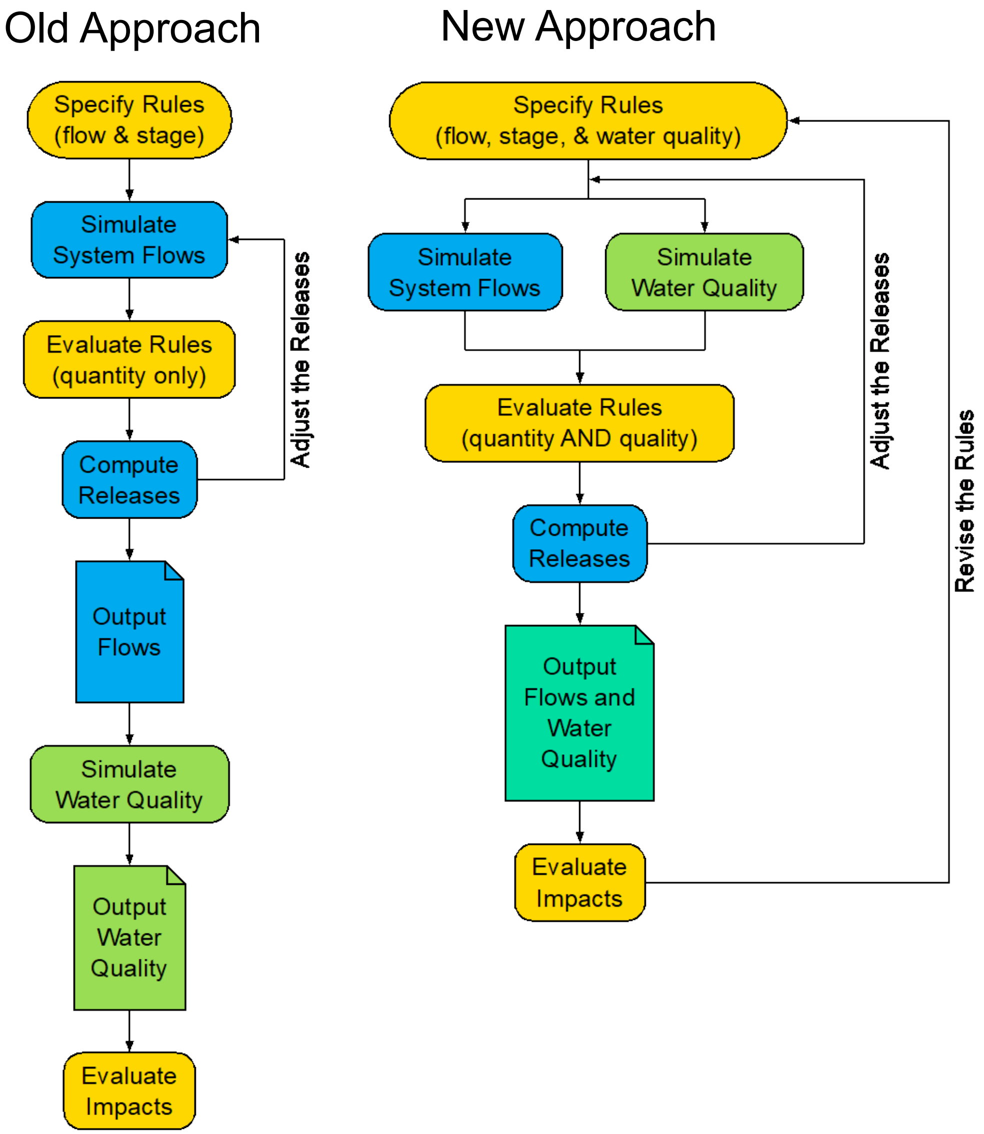
- Develop fully integrated water quality capabilities into HEC-ResSim (Reservoir System Simulation)
- HEC-ResSim simulates reservoir operations at one or more reservoirs for:
  - Flood management
  - Low flow augmentation
  - Water supply
- Applications:
  - Planning studies
  - Detailed reservoir regulation plan investigations
  - Real-time decision support



# Integrating Water Quality in Reservoir Release Decision-Making

Old Approach:

- WQ was simulated after computing the hydrology and release decisions.
- WQ operation rules were specified indirectly (using stage and flow) to meet environmental objectives.
- Environmental objectives were often combined with other objectives, like navigation, flood control, or hydropower.
- If the desired environmental benefits of an alternative are not achieved, new guesses need to be made, and the simulation recomputed. This stage has often been neglected.

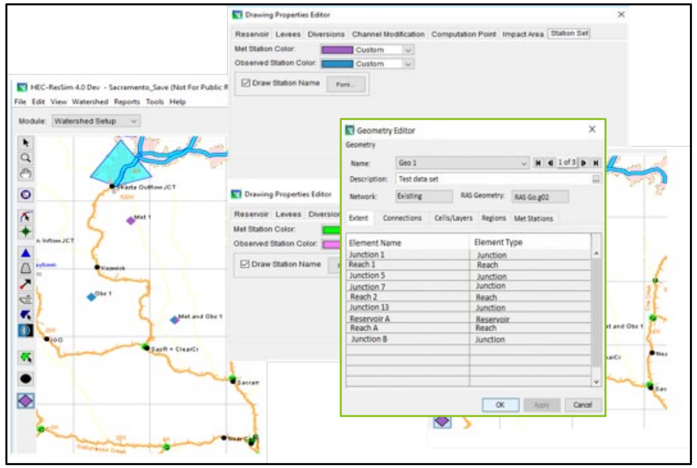



**New Approach:**

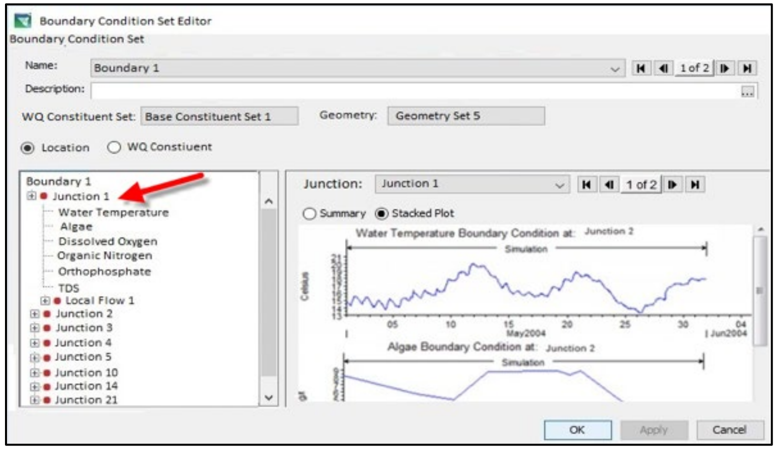
- WQ is simulated in parallel with the hydrology and release decisions.
- WQ operation rules can be specified directly (temperature, concentration, or load) to meet environmental objectives.
- Environmental objectives can be specified and managed independently of other objectives, clarifying the environmental impacts of operation decisions.

# HEC-ResSim Water Quality Modeling User Interface

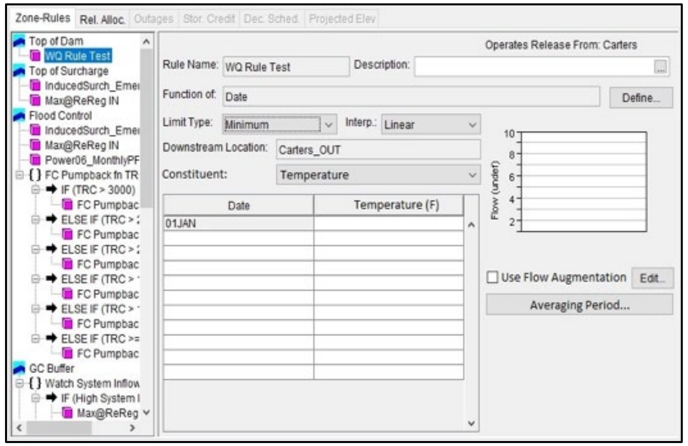
## Model Geometry



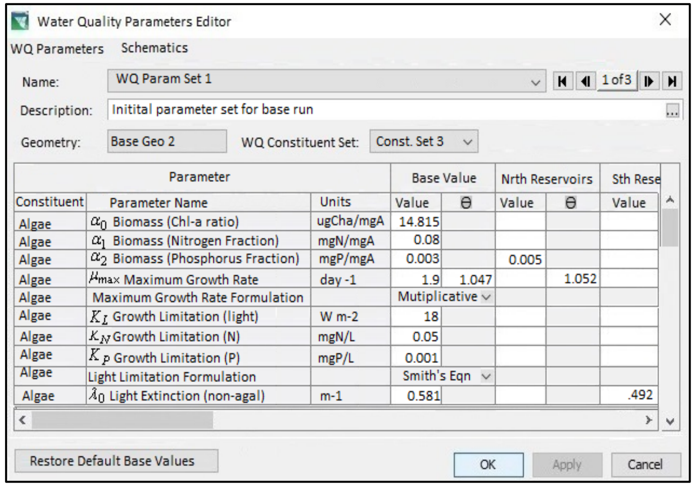

## Specifying Boundary Conditions



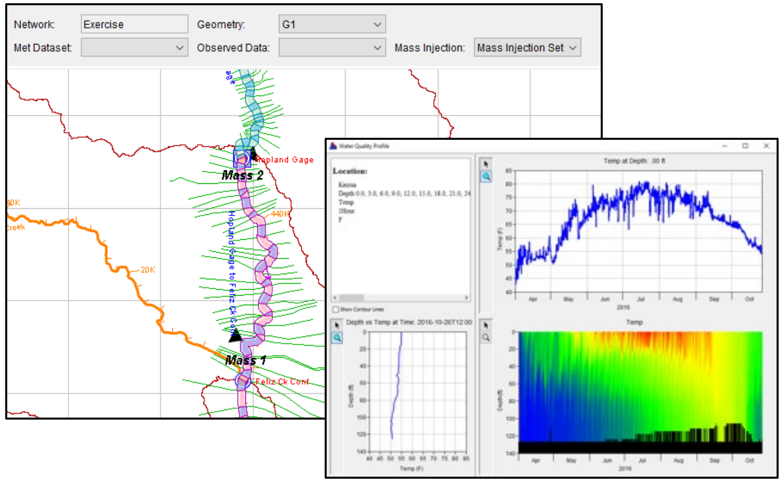

## Operating Rule Priorities



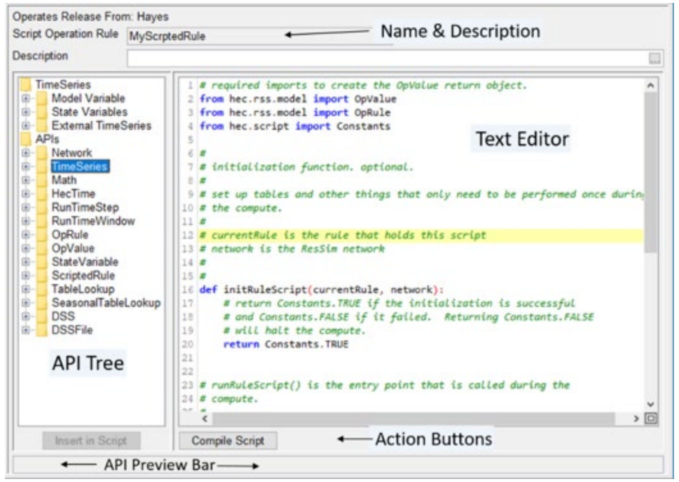

## Constituent Relation Parameters




## Visualization




## Scripted Rules and State Variables



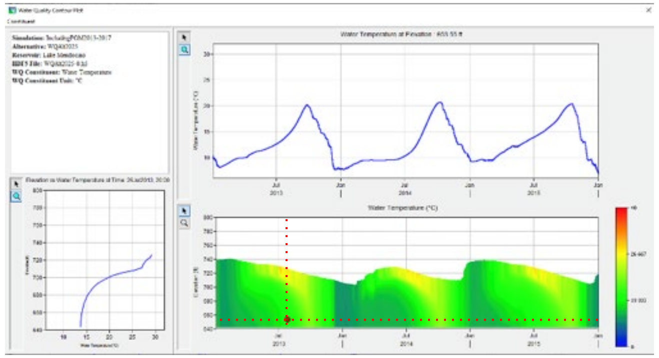
# Temperature and Dissolved Oxygen Simulation with HEC-ResSim

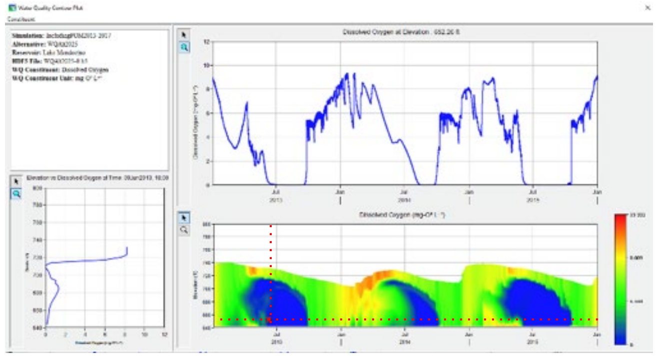
## Russian River, California

## Prepared by RMA for the Sonoma County Water Agency

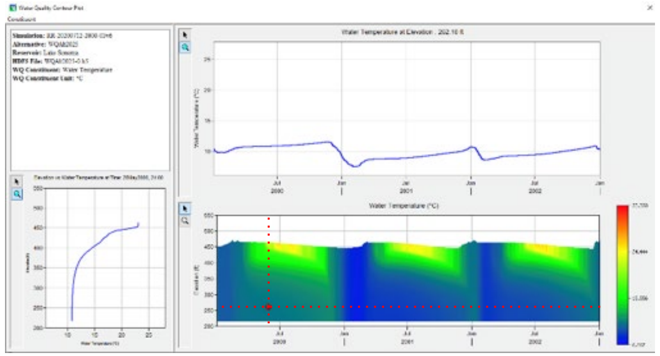
Temperature | Dissolved Oxygen

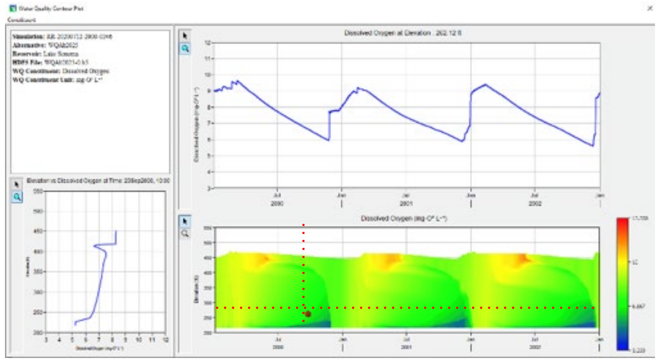
Lake Mendocino

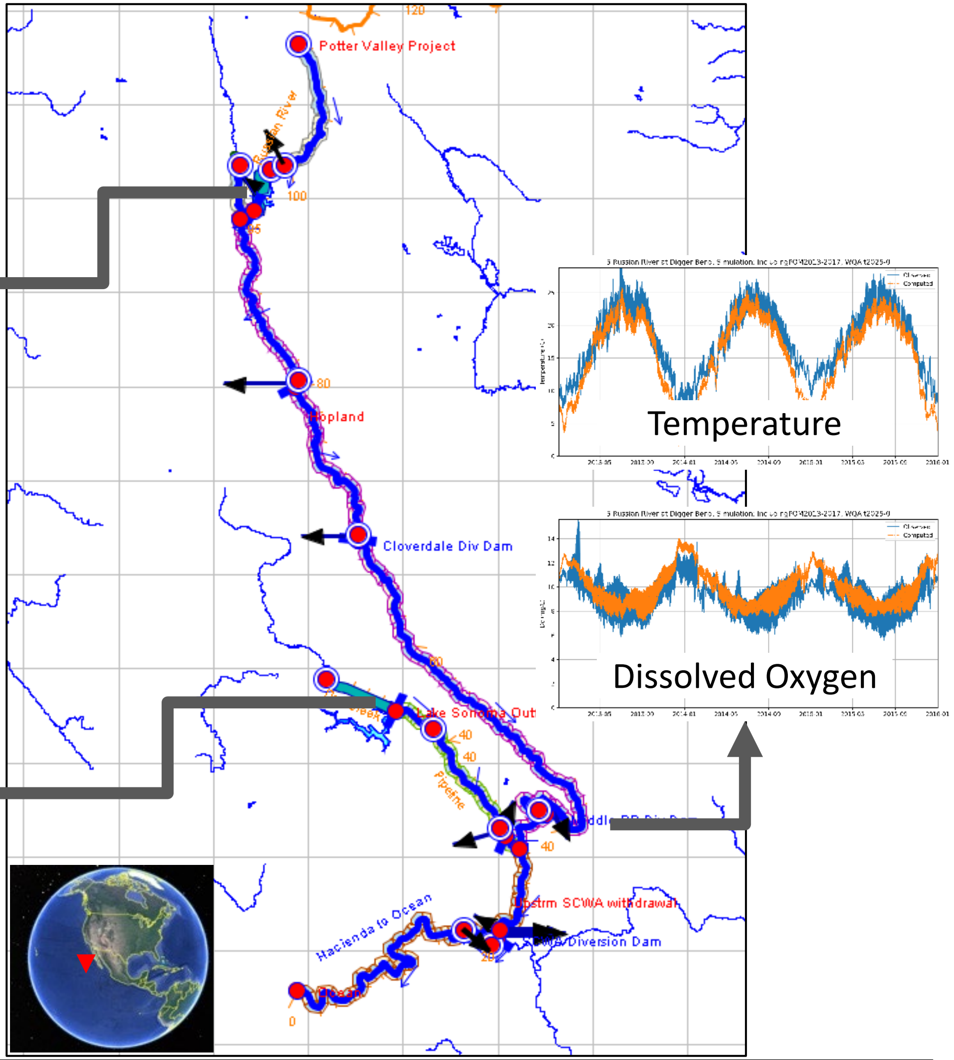




Lake Sonoma



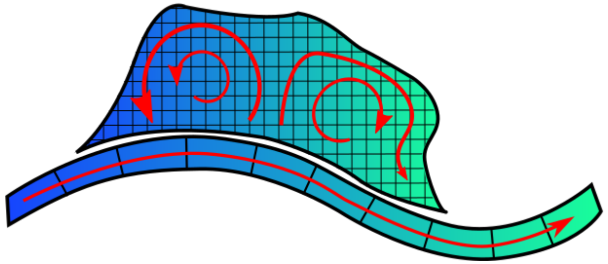


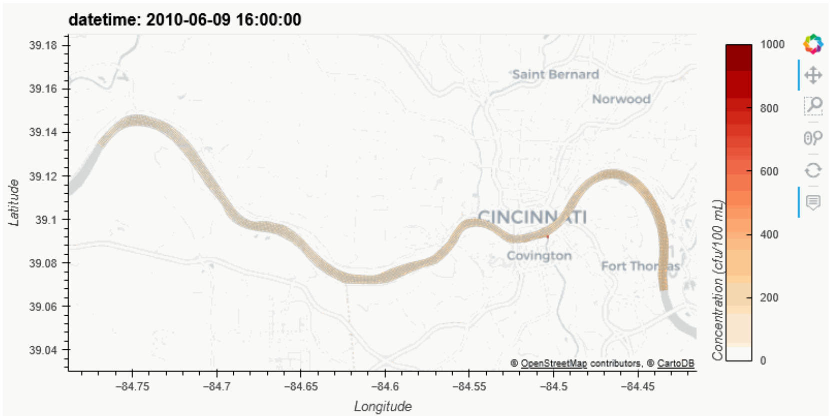


# Benefits

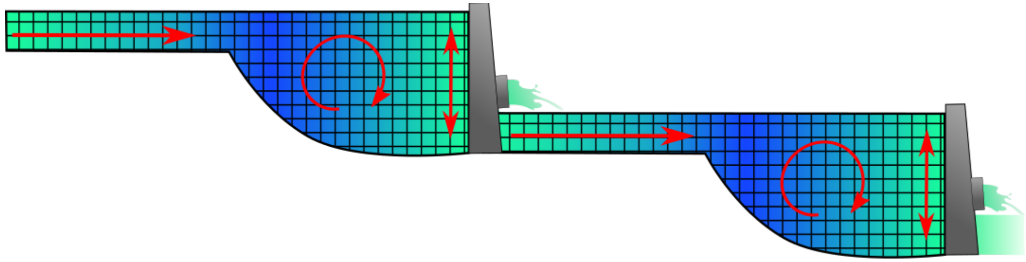
- Determine the spread and transformation of nutrients and contaminants in the watershed.
  - Nutrients and contaminants may spread through river, floodplain, and stormwater environments.
  - In reservoirs, the vertical location controls chemical reactions related to oxygen and temperature levels.
- Understand the timeline of pollution events and ecosystem processes through animations of water quality simulations.
- Evaluate ecosystem impacts
- Evaluate restoration projects, adaptive management plans, and Nature-based feature designs

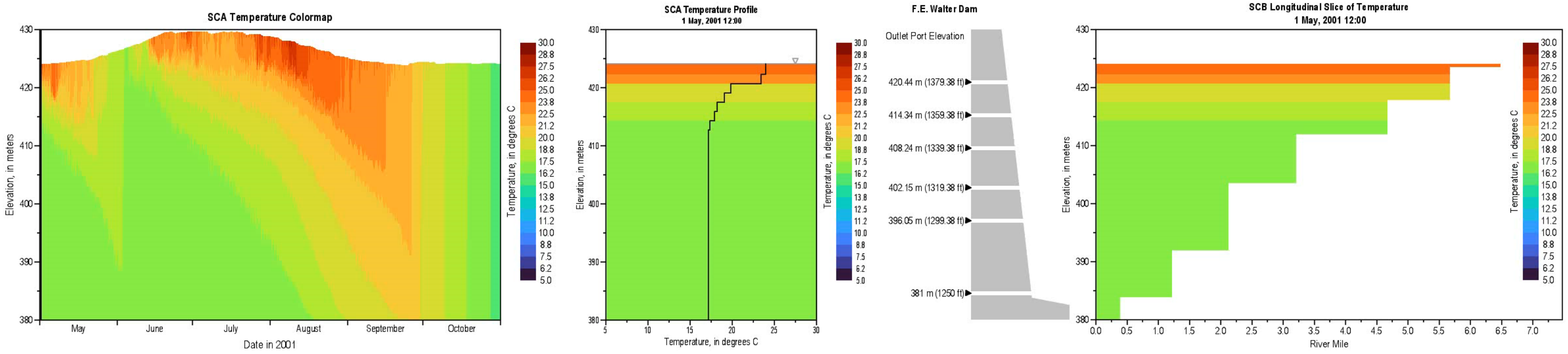
Rivers, floodplains, stormwater systems:






Reservoirs:






Questions?