Development of an Eco-Hydrology Design Tool

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SWAT: JULY 2024

Introduction: Nutrient Flow through Ecosystems

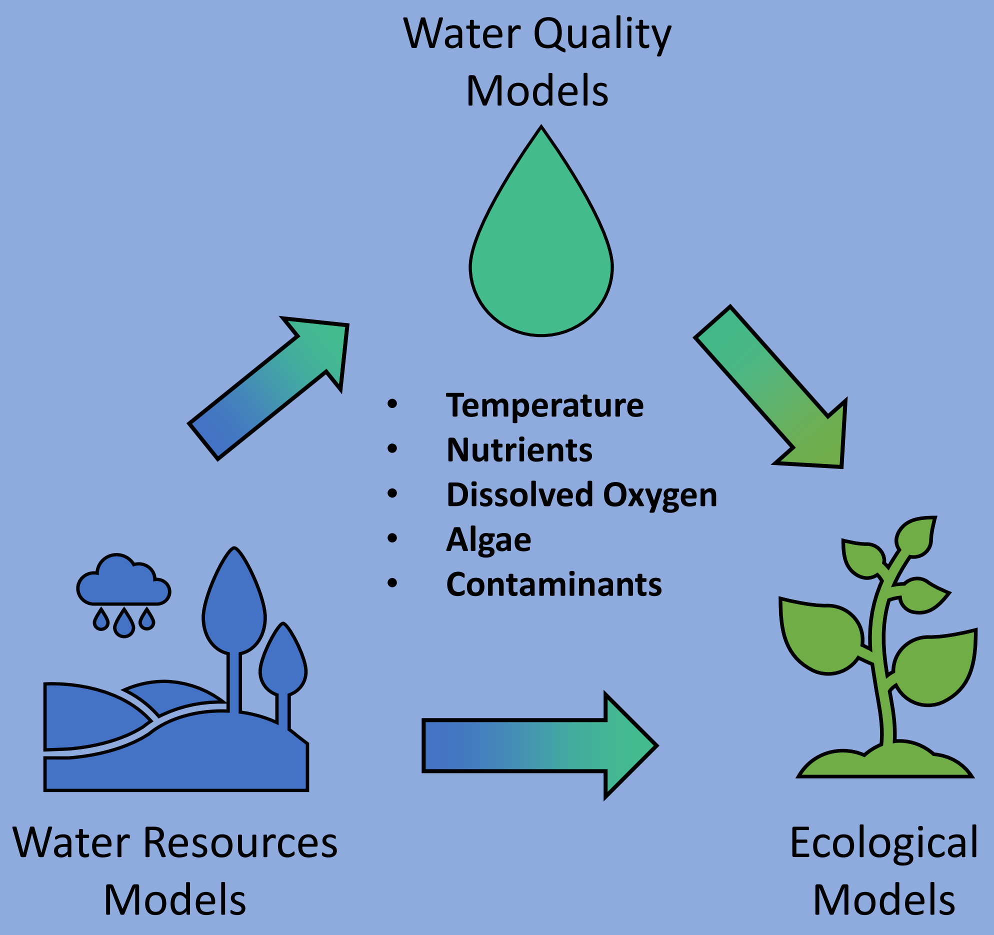
- Nutrient flow through ecosystems has a profound impact on how species utilize resources across watershed scales.
  - Primary production
  - Species distribution and abundance
  - Ecosystem productivity and stability
  - Community composition and diversity
  - Carbon sequestration
- Human-caused disturbances 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

Introduction: Objective

Develop an integrated ecohydrology modeling system that simulates heat and nutrient flow through ecosystems.

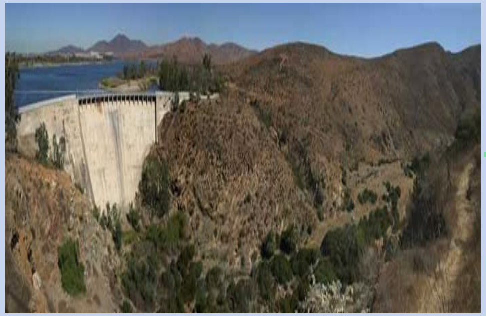


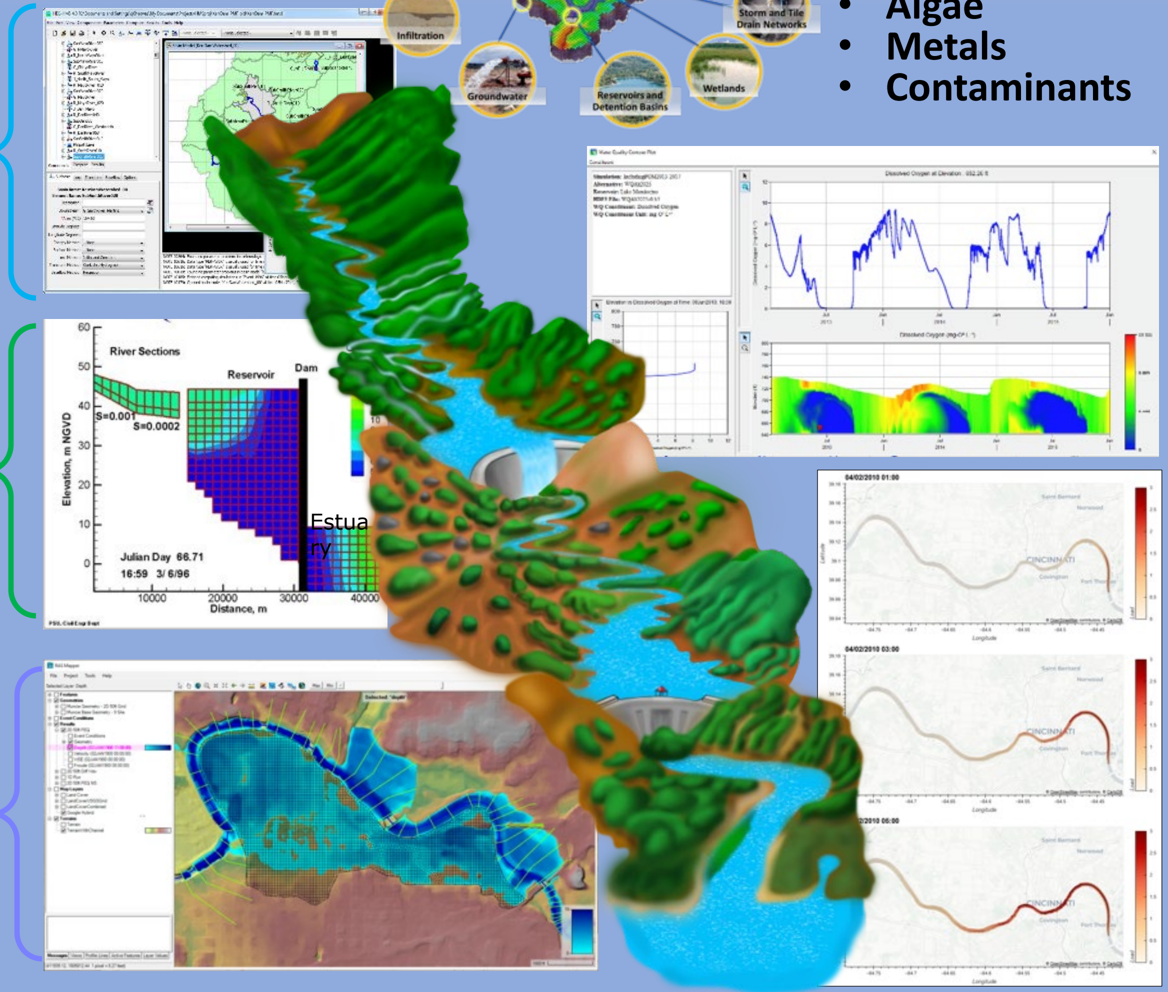
Water Quality and Environmental Systems Modeling

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

Water quality modeling tools:

- **Watershed Runoff:**
  - **GSSHA**: Surface and sub-surface water quality modeling
  - **SWAT**: Surface and sub-surface runoff and hydrological 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 – USDA/Texas A&M

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.

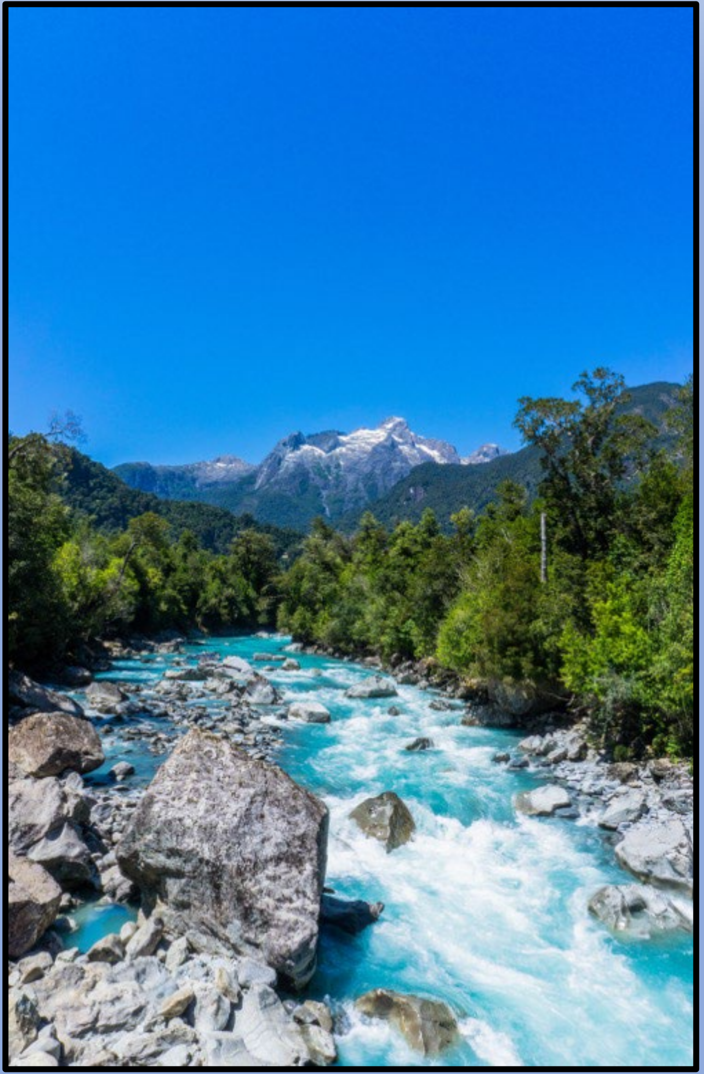
Runoff

Reservoirs

Rivers

ClearWater-Riverine

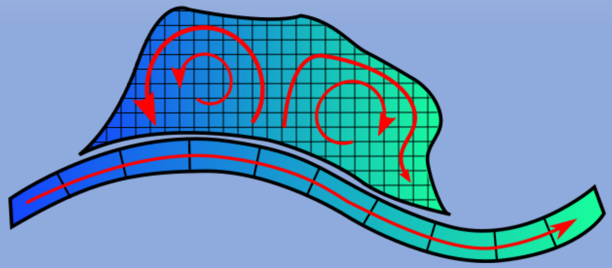
- Clearwater-Riverine simulates temperature and advanced nutrient cycling in branching river systems and floodplains, incorporating hydrodynamic, water quality, and meteorologic inputs from multiple data sources and models.
  - Flows: The model grid, volumetric flow, velocities, depths, diffusivity, 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.



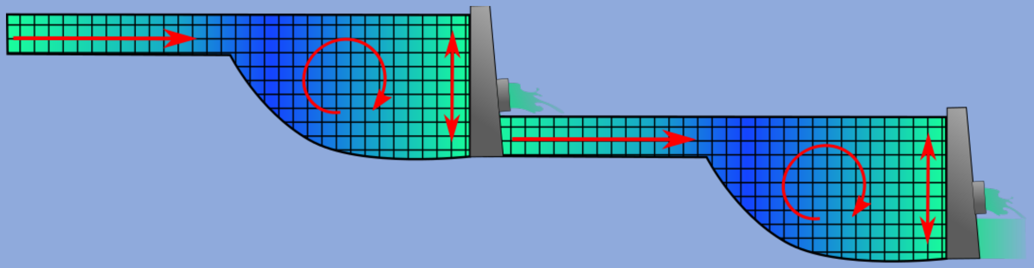
USACE Water Quality Model Benefits

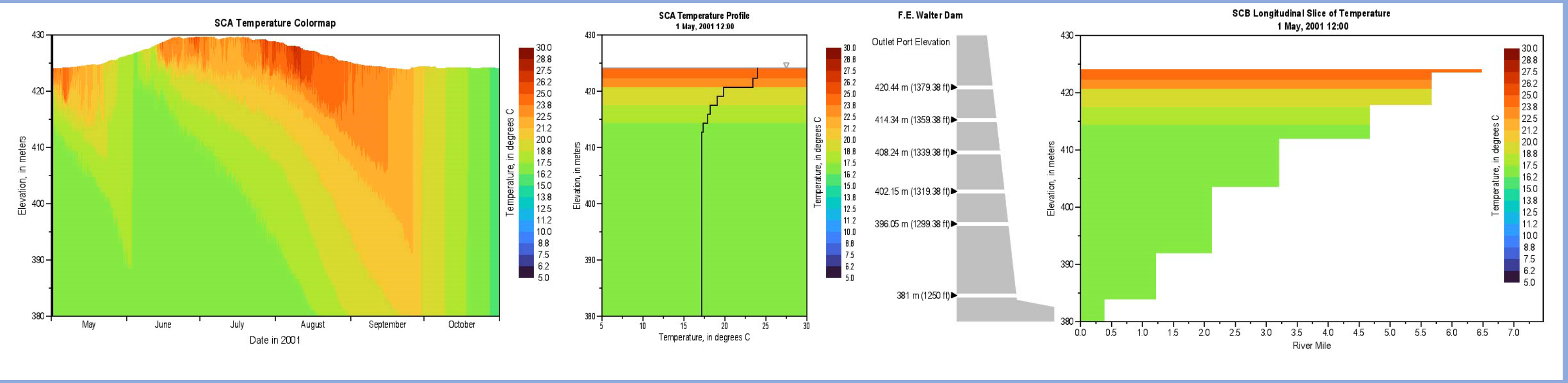
- Determine the spread and transformation of nutrients and contaminants in the watershed.
  - Nutrients and contaminants may spread through river, floodplain, and stormwater environments.
  - In reservoirs, the vertical location controls chemical reactions related to oxygen and temperature levels.
- 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:

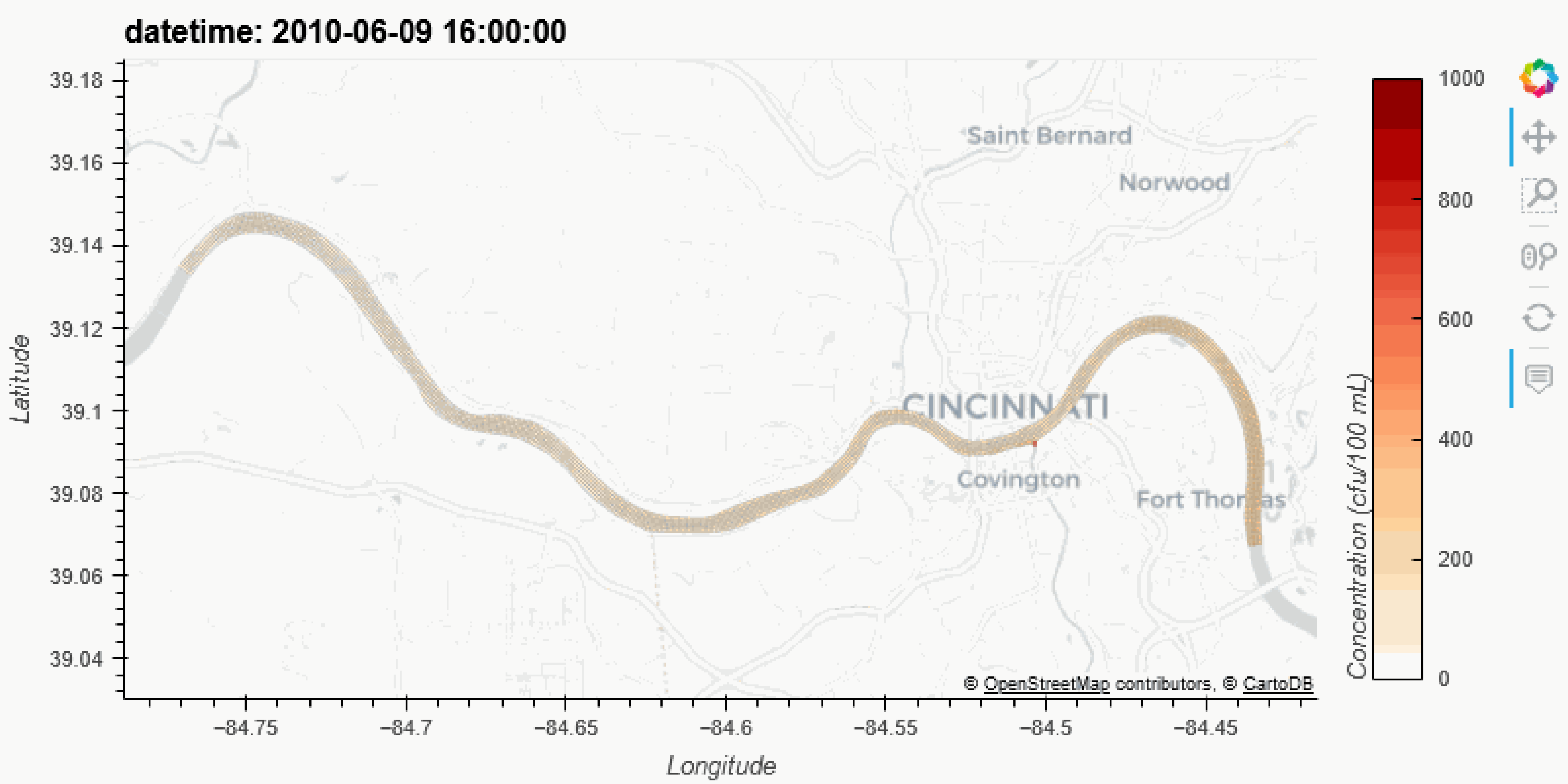


Reservoirs:

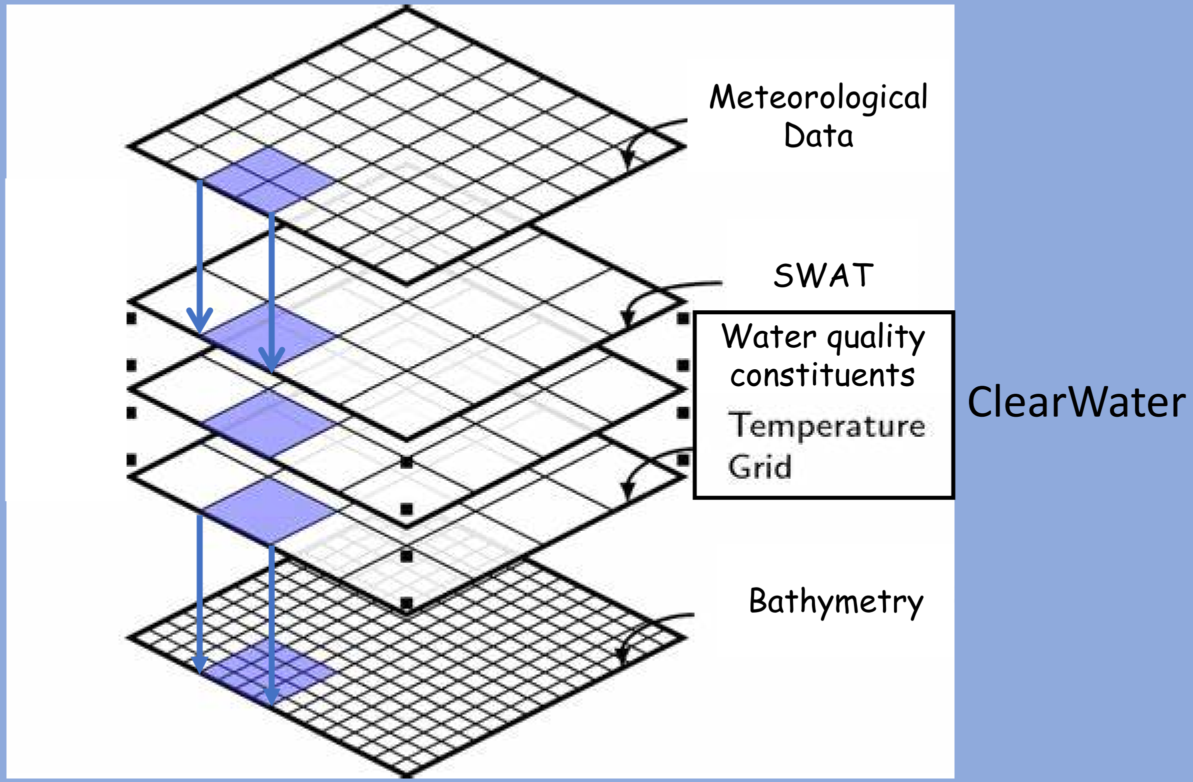




ClearWater-Riverine Example:
E. Coli Transport in the Ohio River



ClearWater
Water Temperature and Quality



Long term Goals: Nutrients and Plant Linkage

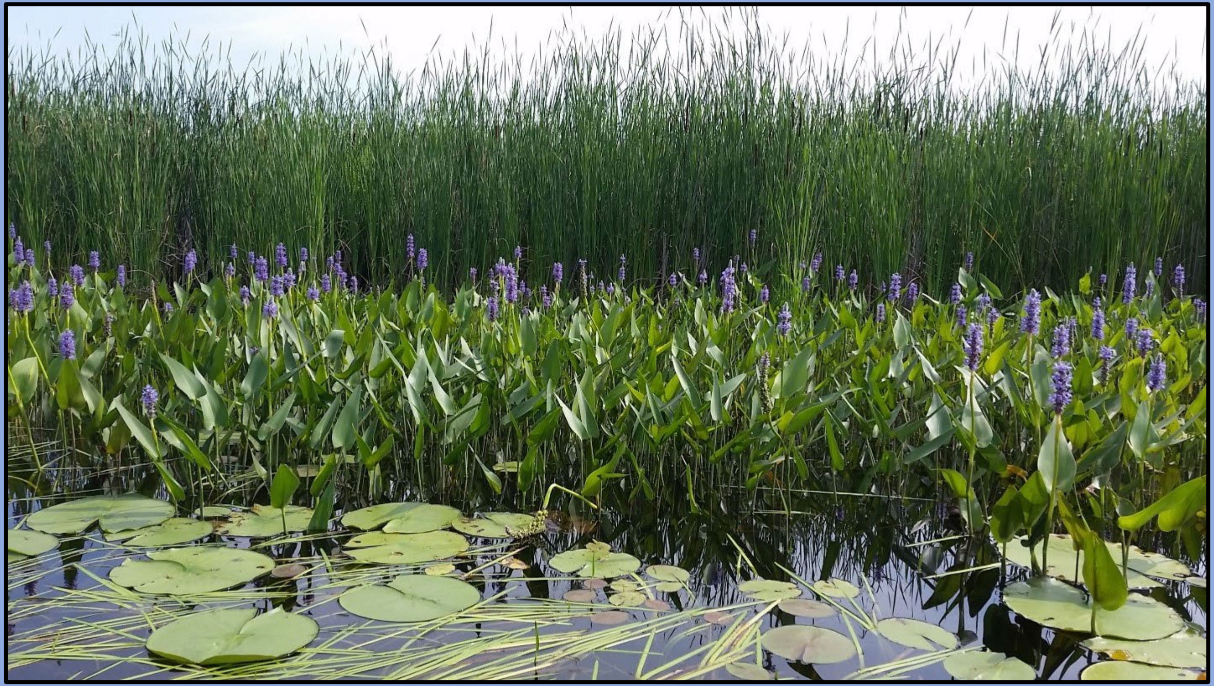
Nutrients

- Overland Kinetics
- Stream Kinetics
- Sub-surface Kinetics

ERDC Plant Modules

Time Series and 2D Gridded Maps

- Velocities
- Shear Stresses
- Sediment/Soil Erosion and Deposition
- Flow Depths
- Nutrient Concentrations
- Water Temperature
- Etc.



Long term Goals: Linking with SWAT

- Integration of watershed and riverine modeling
- Improved prediction of water quality
- Assessment of Management practices
- Scenario analysis and planning
- Data integration and calibration

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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

ERDC

MODEL COUPLING

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

BMI 2.0 has become the standard for model coupling

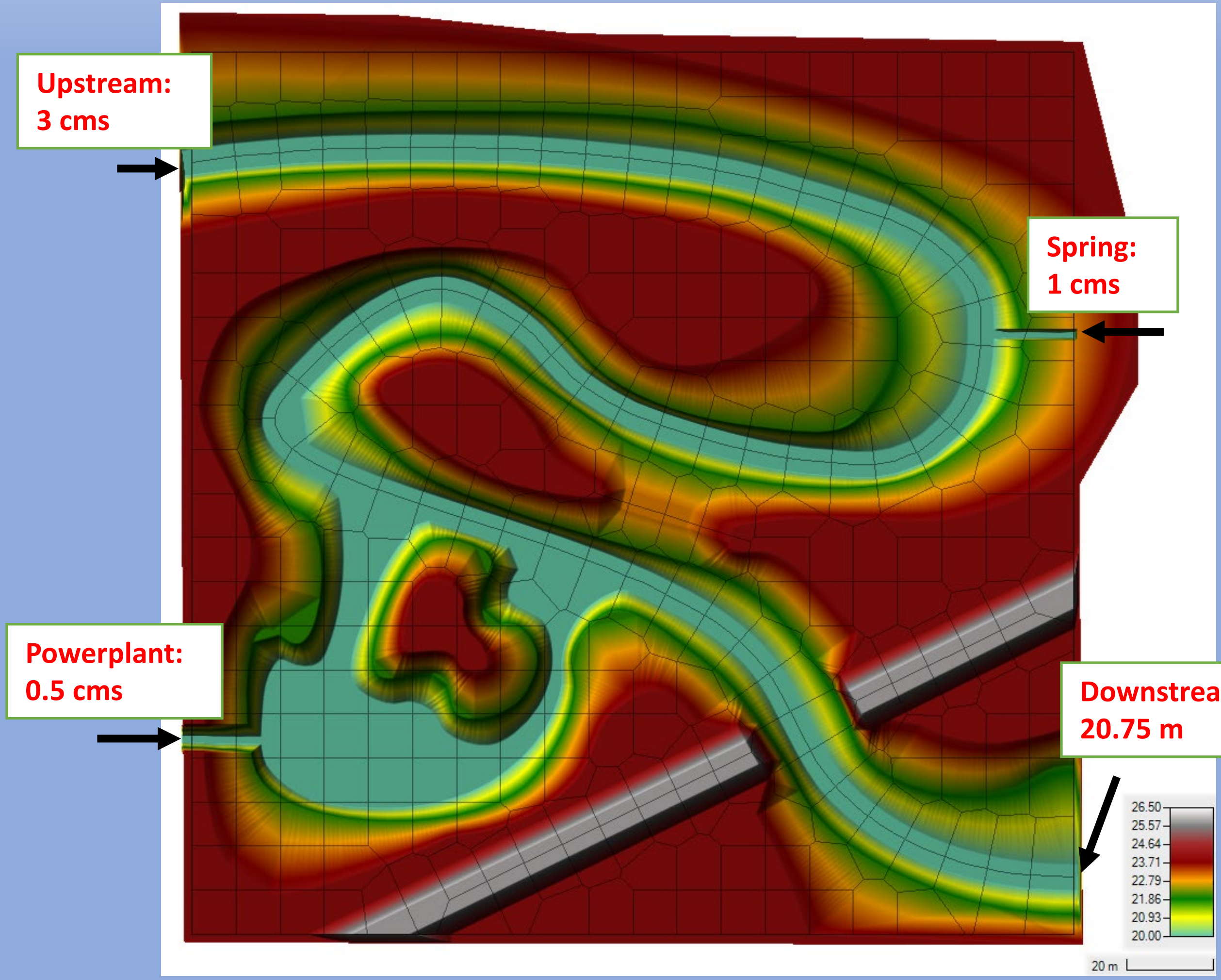
bmi

powered by csdms

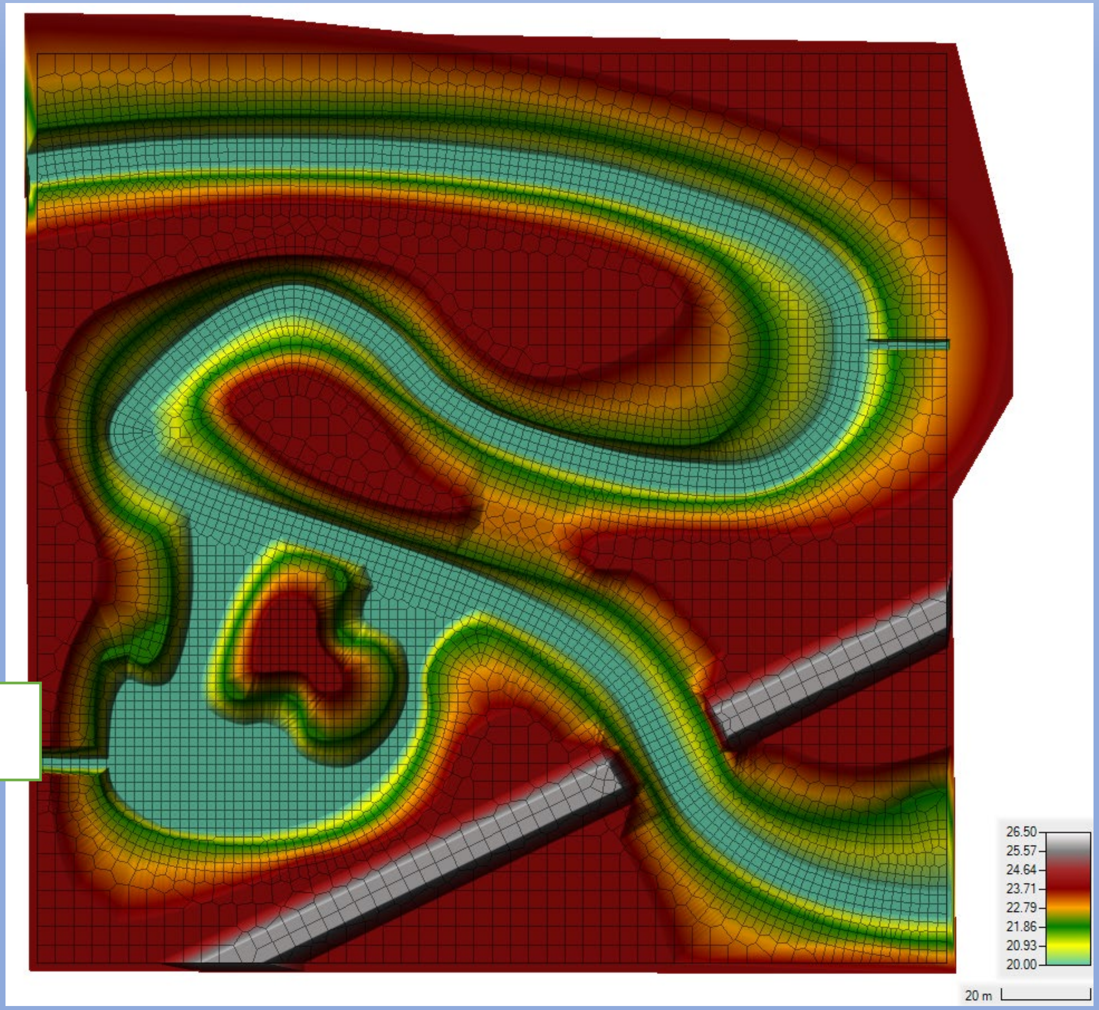
- Basic Model Interface (BMI)
  - Provides a common set of functions
    - To run models and exchange information and data on grids, variables, timesteps, etc.
  - Shares data among models using a zero-copy approach
    - Each model reads and writes to the same in-memory object using pointers
  - Supports 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

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

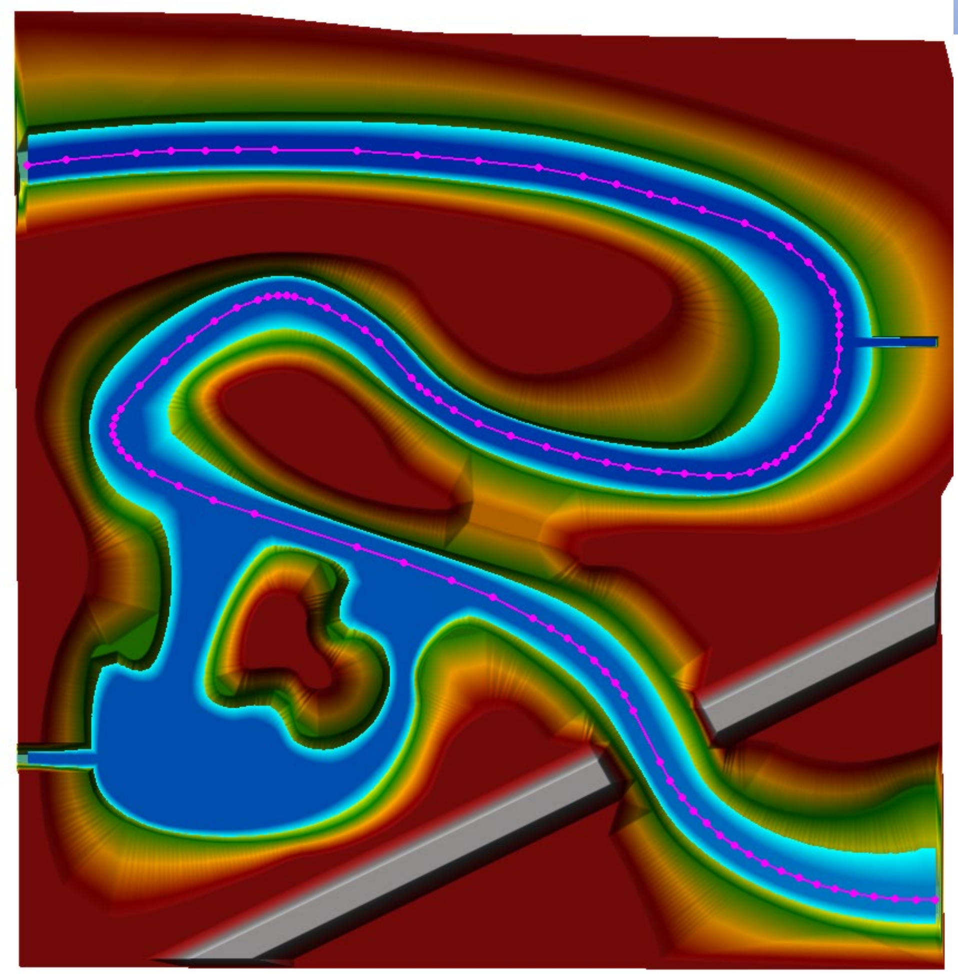
Coarse Mesh

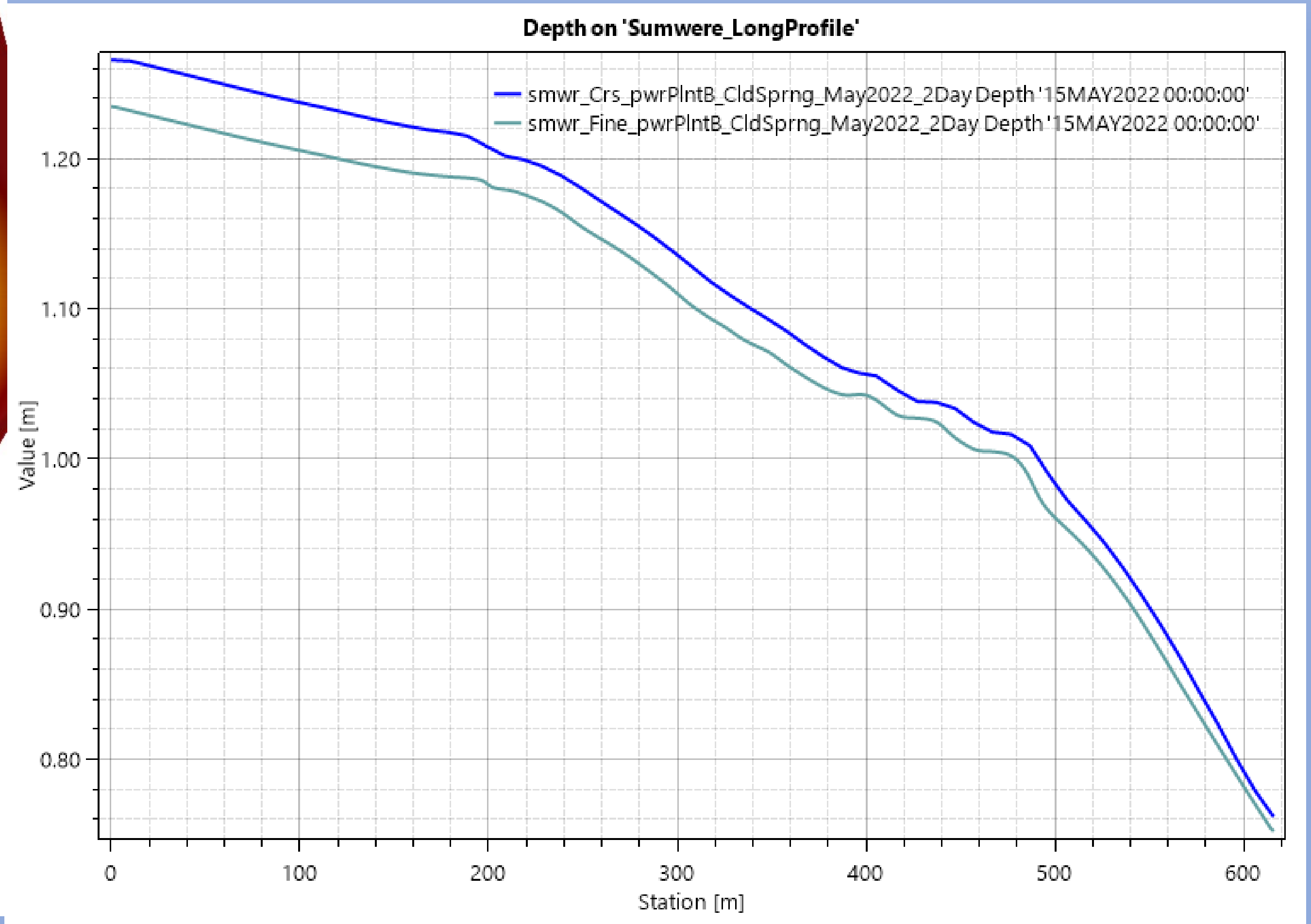


Fine Mesh



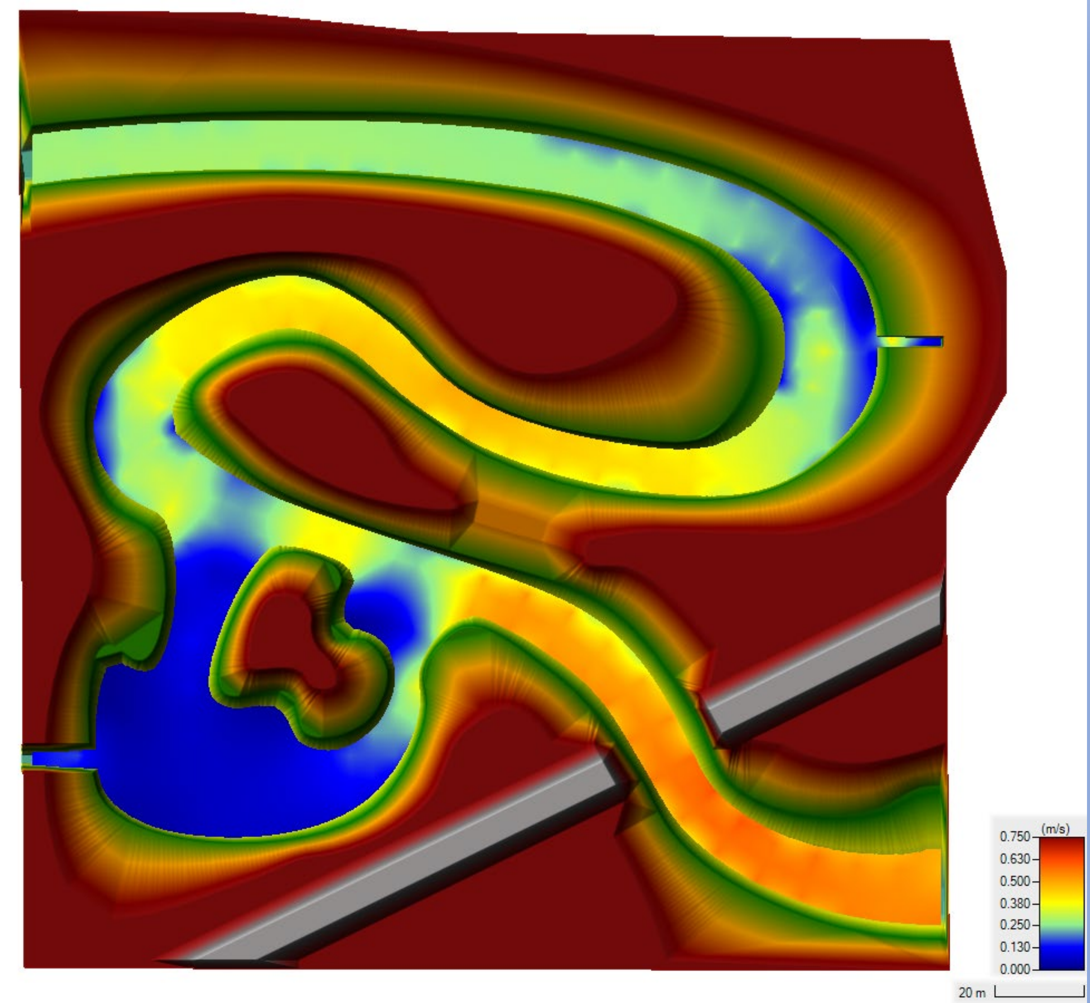
Demo Case Study: Sumwere Creek — Depth at End of Simulation



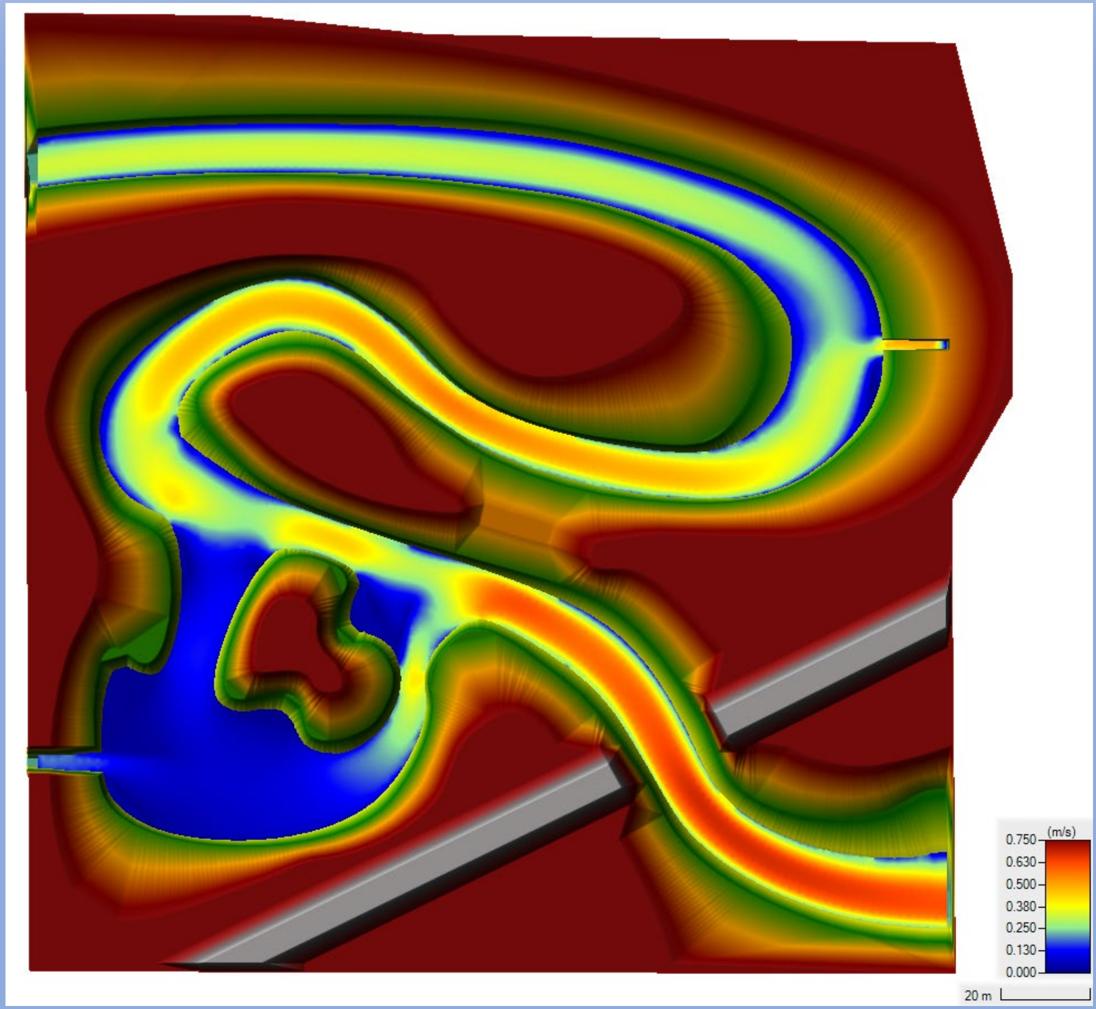


Demo Case Study: Sumwere Creek — Velocity at End of Simulation

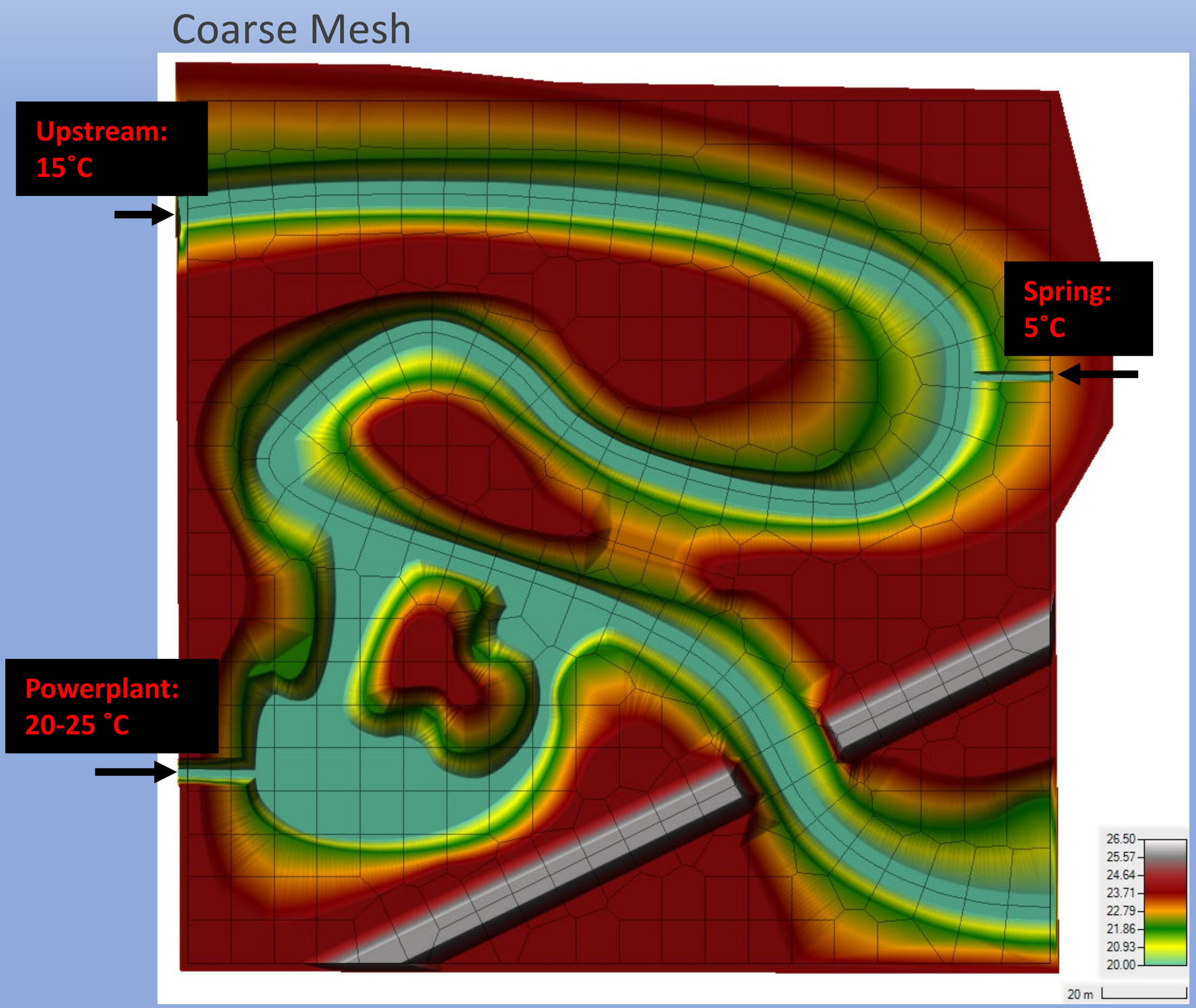
Coarse Mesh

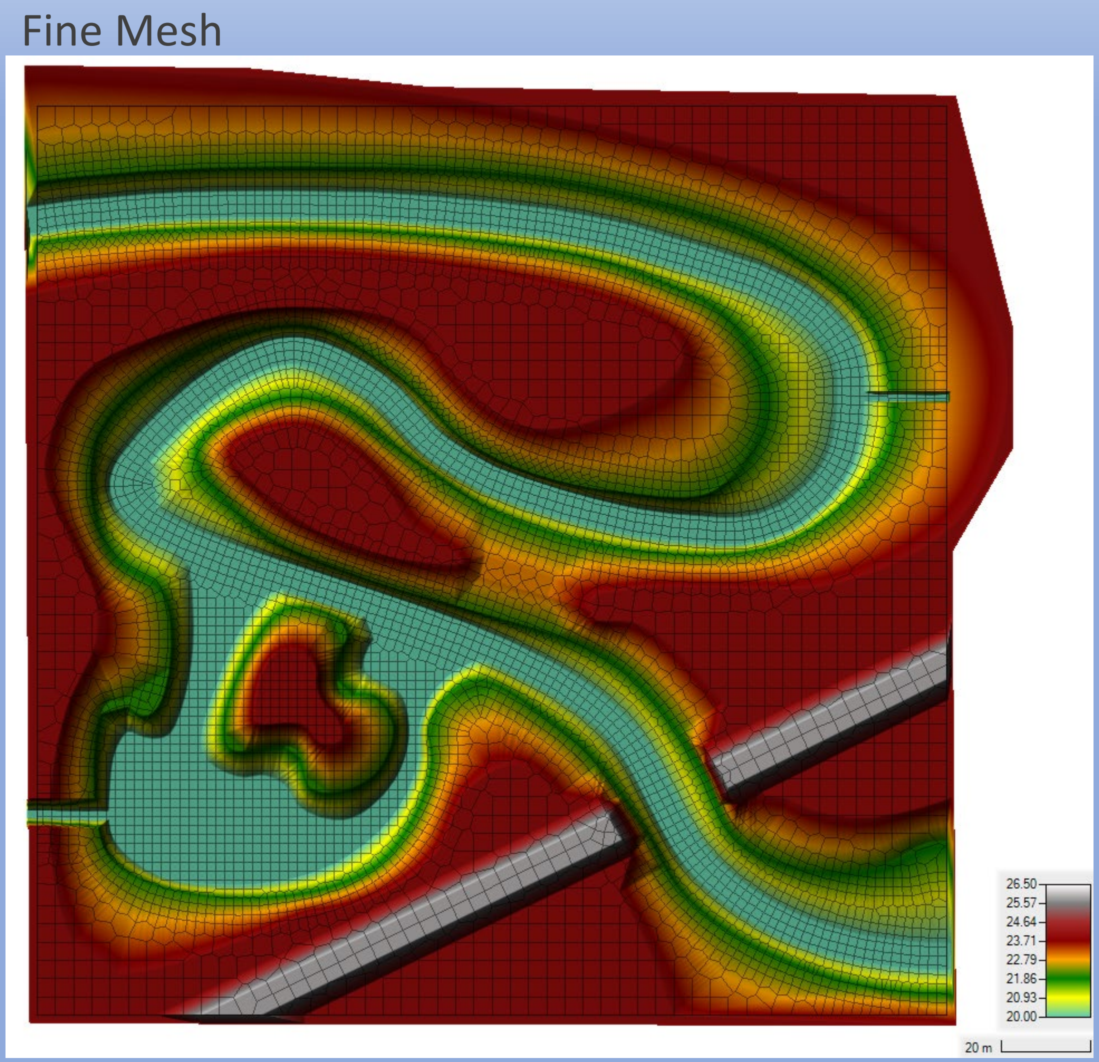


Fine Mesh



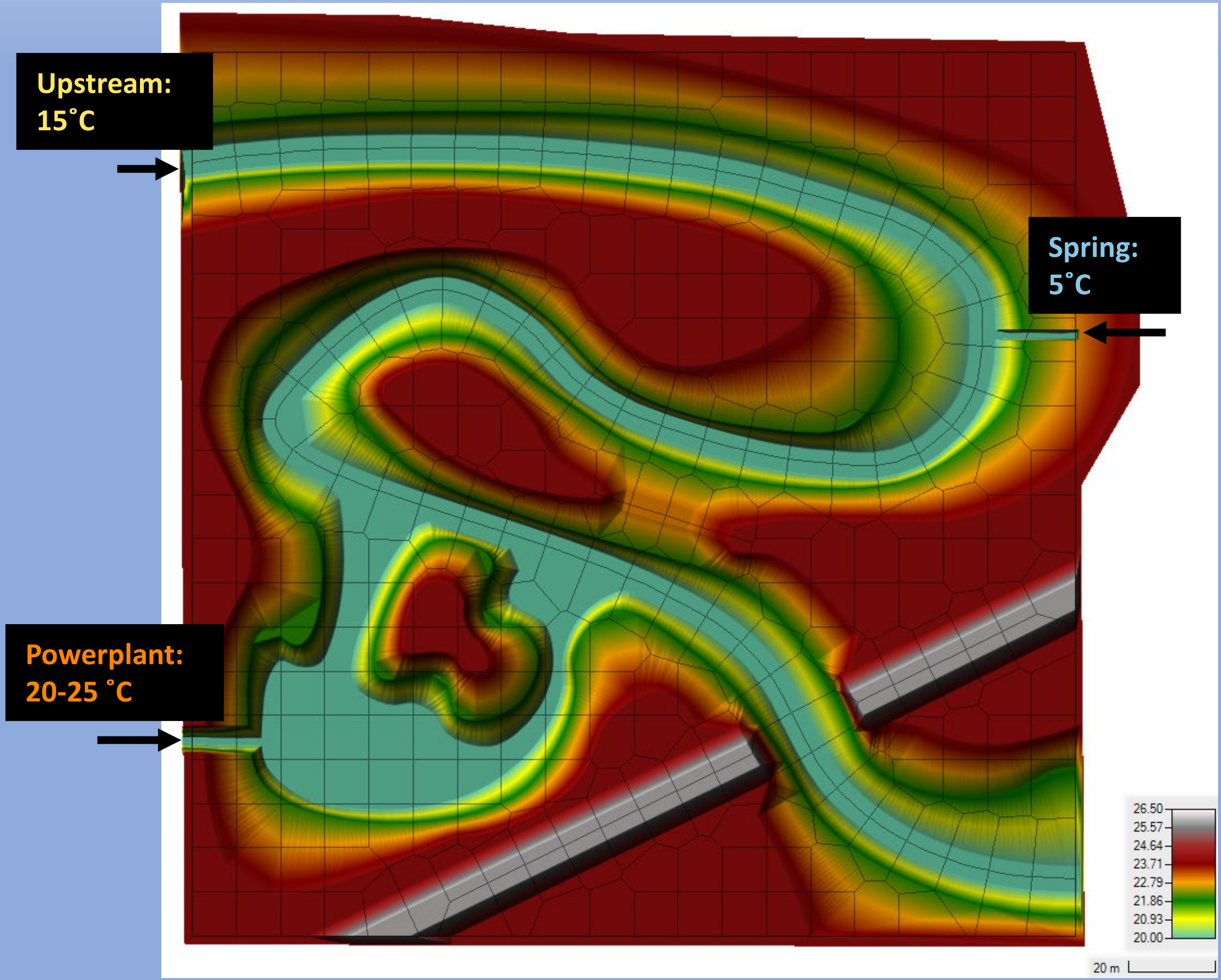
Demo Case Study: Sumwere Creek — Temperature Boundary Conditions

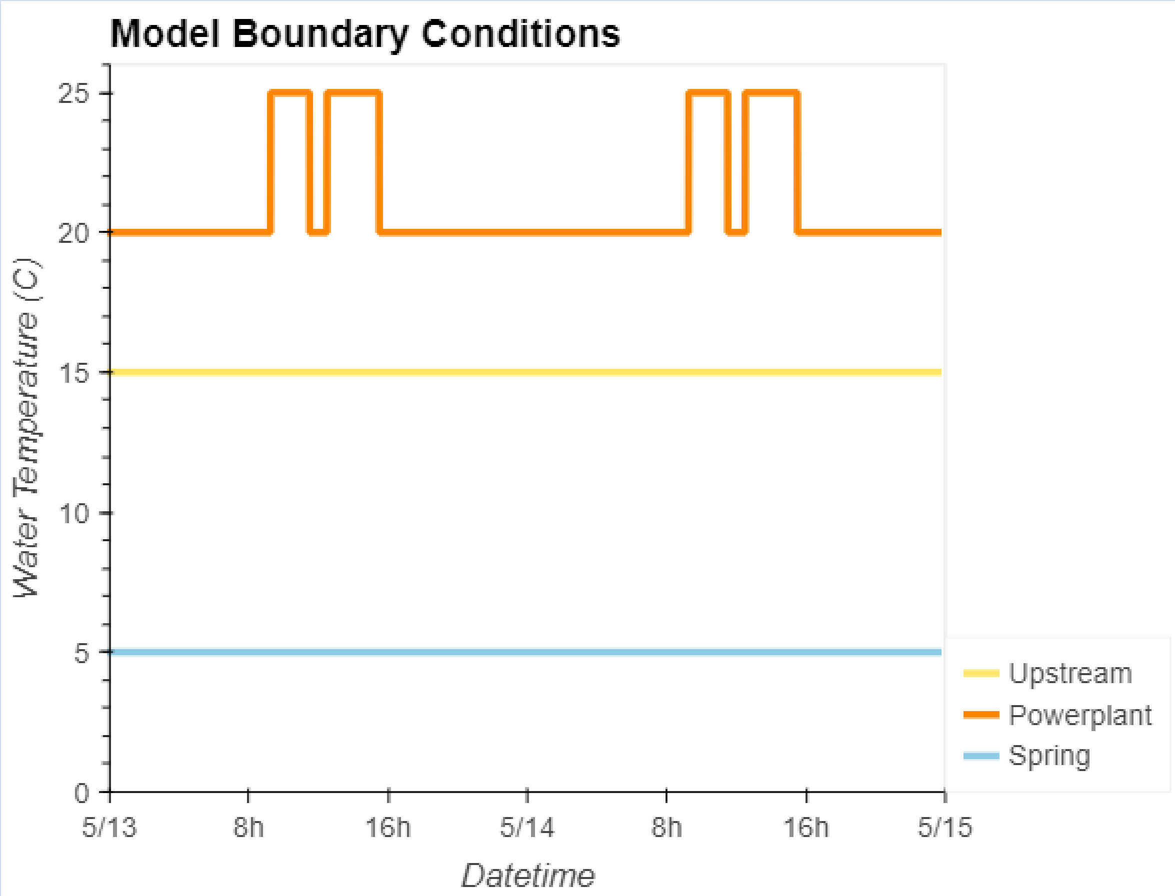




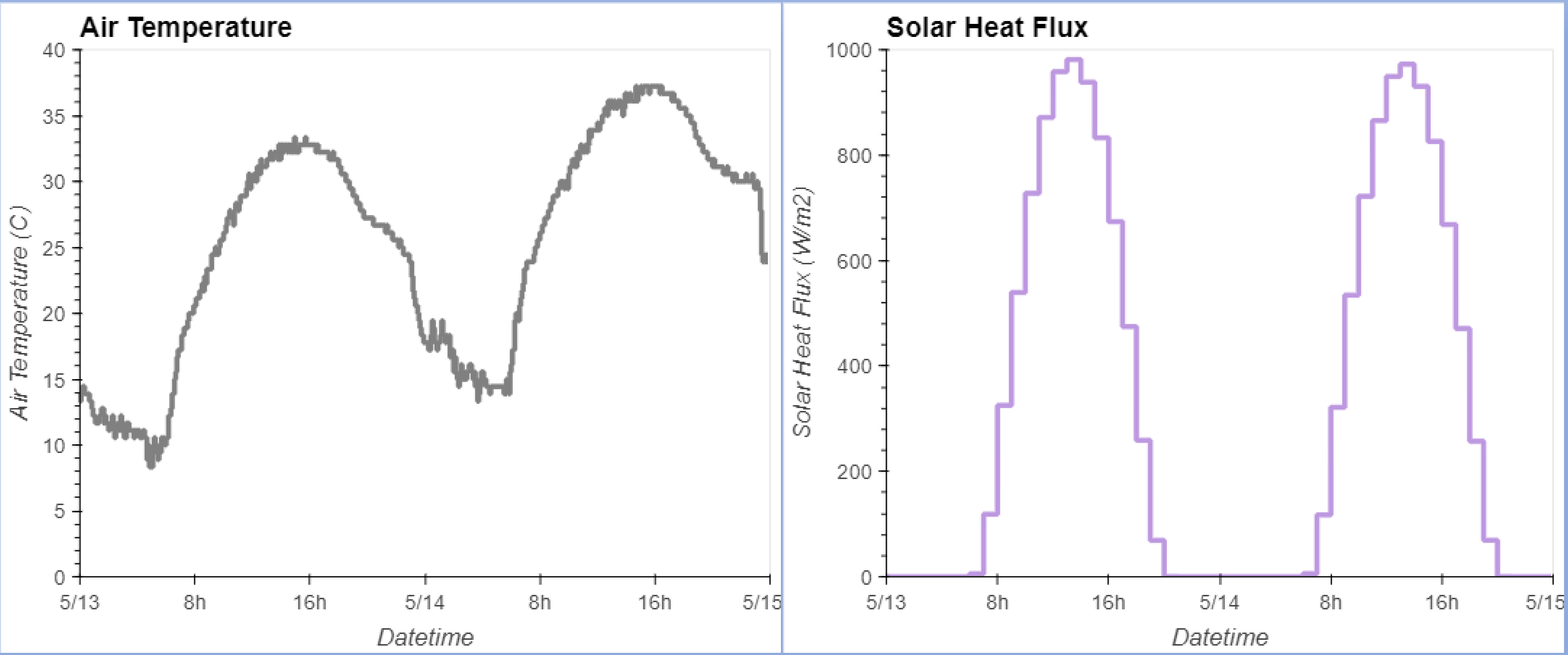
Demo Case Study: Sumwere Creek — Temperature Boundary Timeseries

Coarse Mesh



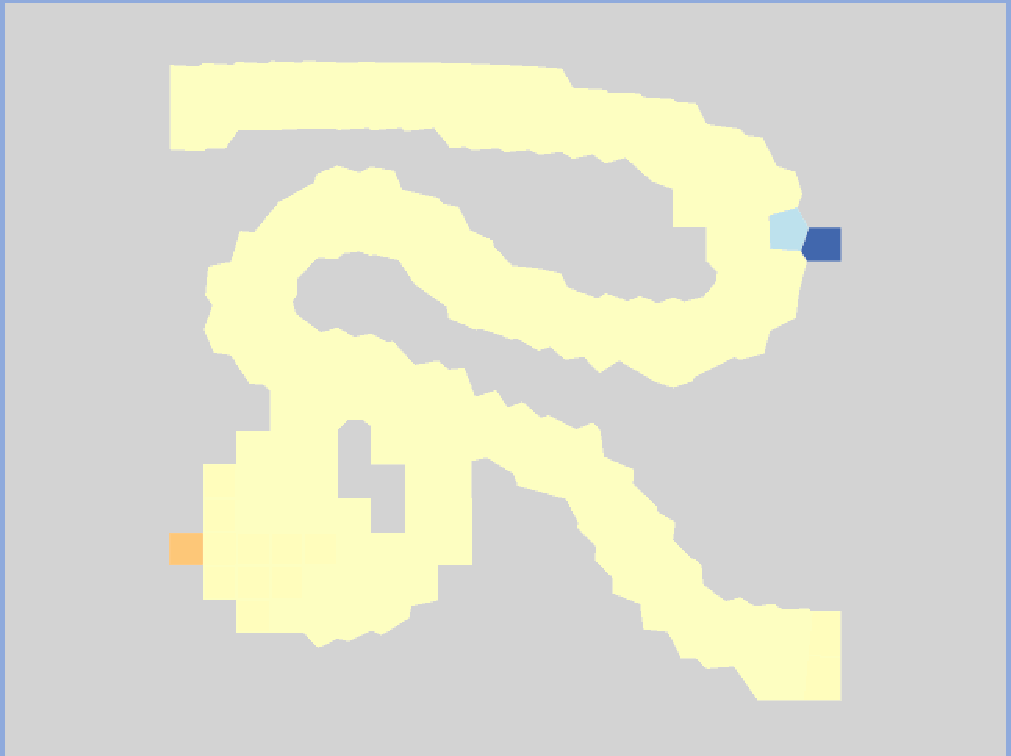


Demo Case Study: Sumwere Creek — Meteorological Timeseries

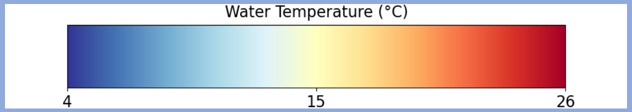


Results – Animation

Coarse Mesh



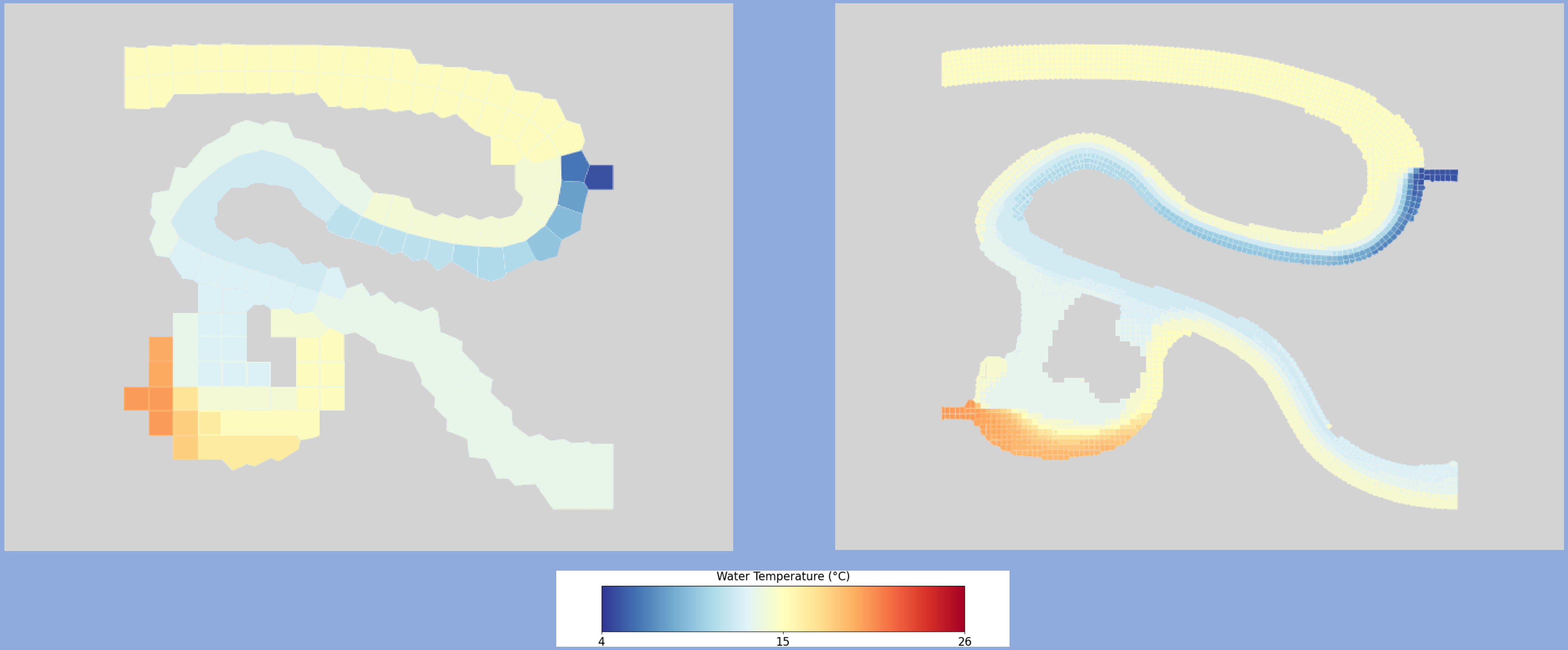
Fine Mesh



Results – Warm Powerplant Inflows

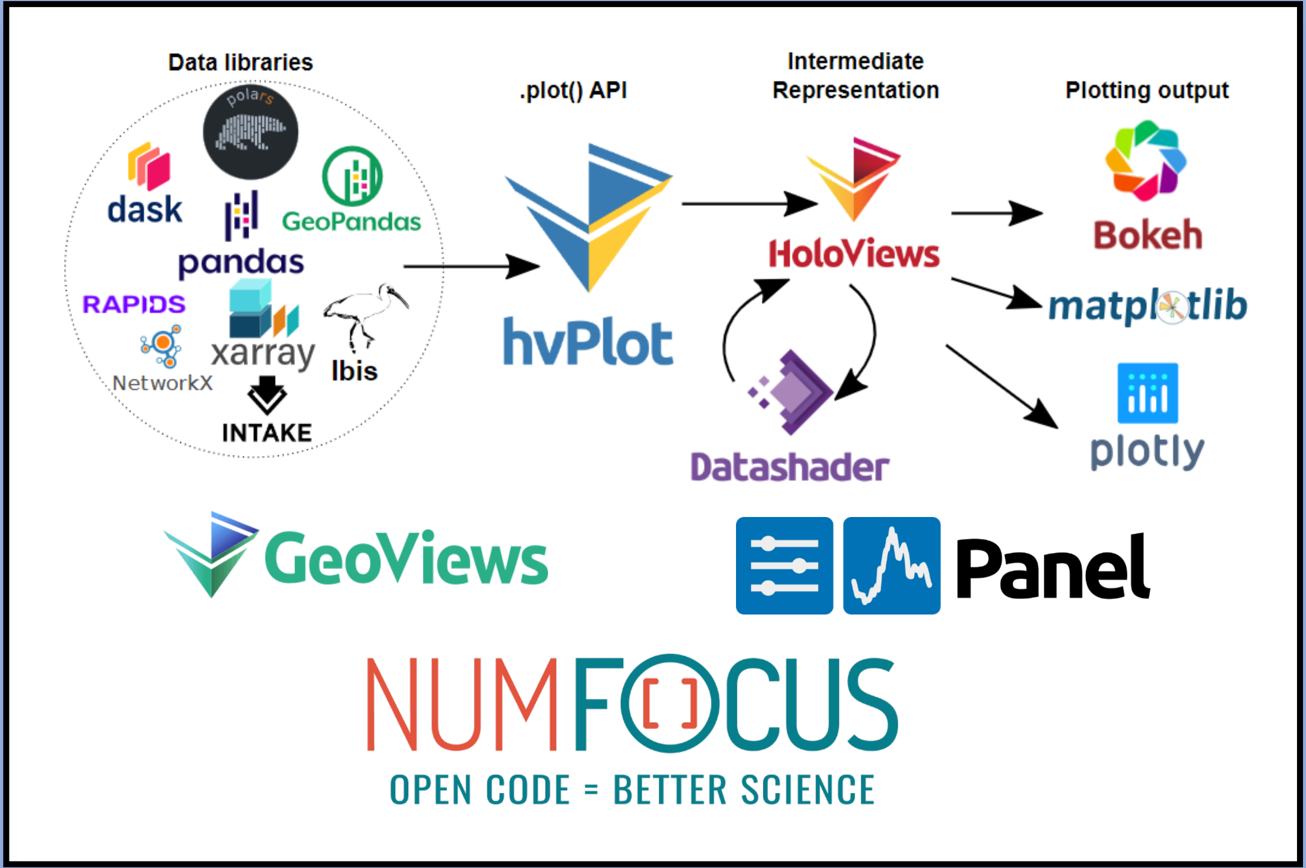
Coarse Mesh

Fine Mesh



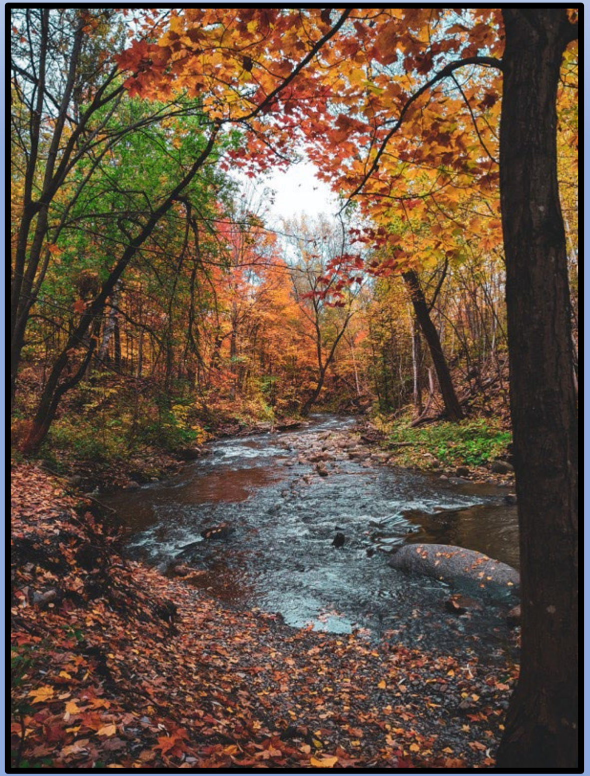
ClearWater Framework Summary

- 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



Benefits

- Model linking using BMI enables a seamless exchange of data and information between different components of the integrated modeling system.
- Facilitates data-driven decision-making
- Enhances collaboration between scientific disciplines
- Integrated models that simulate the interactions between heat, nutrients, water flow, and vegetation enable a comprehensive representation of ecosystem dynamics.
    - Accurate representation of real-world processes
- Enables assessment of the ecological responses to various environmental changes, such as land use modifications, climate change, or nature-based feature design and Best Management Practices (BMPs)
- Example applications:
    - Setting nutrient loading limits
    - Designing buffer zones
    - Implementing BMPs to restore aquatic ecosystems



Thank You

Questions?

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