Incorporating Nutrient and Heat Flow into River and Watershed Modeling to Better Predict Ecological Response across Large Scales

Next Generation Ecological Modeling Tools Seminar Series
February 14, 2024

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MOTIVATION AND BACKGROUND

Todd

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

Introduction: Nutrient Flow and Disturbances

- Human-caused disturbances are disrupting nutrient cycling
- This causes cascading effects on ecosystem health and functioning.
- The most common issue is nutrient excess:
  - Causes
    - Agricultural runoff
    - Urbanization (stormwater)
    - Industrial discharge
  - Effects
    - Rapid algae growth
    - Oxygen depletion
    - Harmful toxins

Introduction: Nutrient Flow and Invasive Species

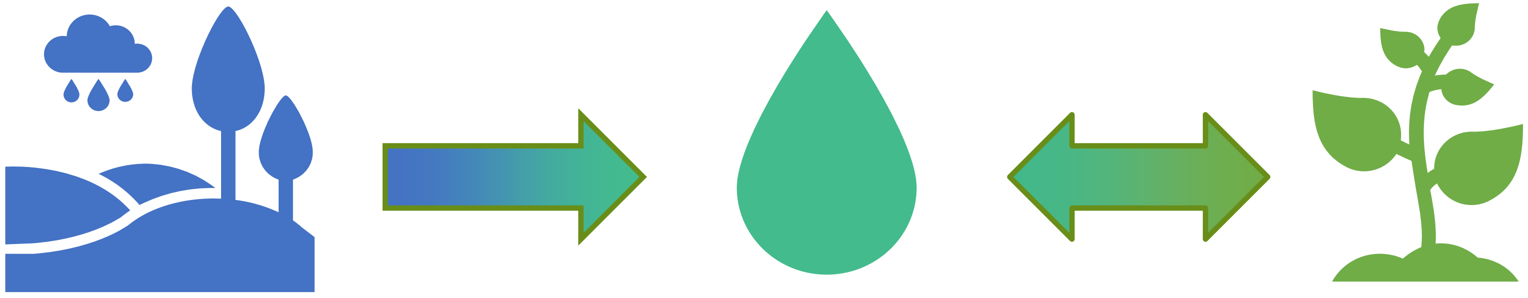
- Invasive species can take advantage of changes in nutrient dynamics
  - Nutrient-rich watersheds promote invasive aquatic plants, outcompeting native species.
  - Excess nutrients stimulate algal blooms, providing invasive species with abundant food sources.
  - Disrupted trophic interactions due to nutrient imbalances favor invasive predators over native prey.
  - Nutrient-enriched soils create favorable conditions for invasive plant colonization.

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: Project Objective

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



Water Resources Models

Water Quality Models (Nutrients & Temperature)

Ecological Models

ERDC Environmental Modeling Capabilities

- Linking environmental models with existing water resources models streamlines workflows and reduces costs. These simulate runoff, rivers, and reservoir hydraulics and hydrology
- Our team at USACE-ERDC has developed ClearWater (Corps Library for Environmental Analysis and Restoration of Watersheds).
- ClearWater provides environmental simulation capabilities with a suite of packages that are designed to leverage existing water resources models.
  - ClearWater *modules* simulate water quality constituent kinetics, and heat budget processes. Capabilities include:
    - Nutrients: Nitrogen, phosphorus, carbon, dissolved oxygen, algae, etc.
    - Temperature (heat budget)
    - General Constituents
  - ClearWater-Riverine computes transport (advection and diffusion) of heat and constituent mass using outputs from any 2D hydrologic or hydrodynamic model
  - Data visualization capabilities
  - Framework to couple multiple models
- Legacy Fortran modules integrated with HEC-RAS and HEC-ResSim
- New Python modules and were developed to support 2D river-floodplain modeling

Runoff

Reservoirs

Rivers

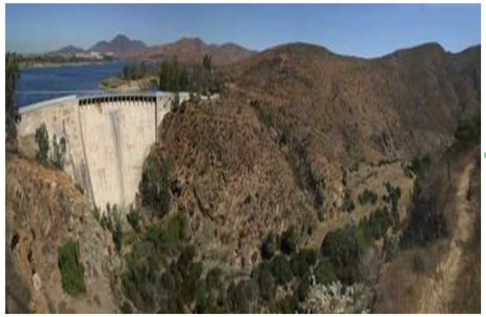
Water Quality and Environmental Systems Modeling

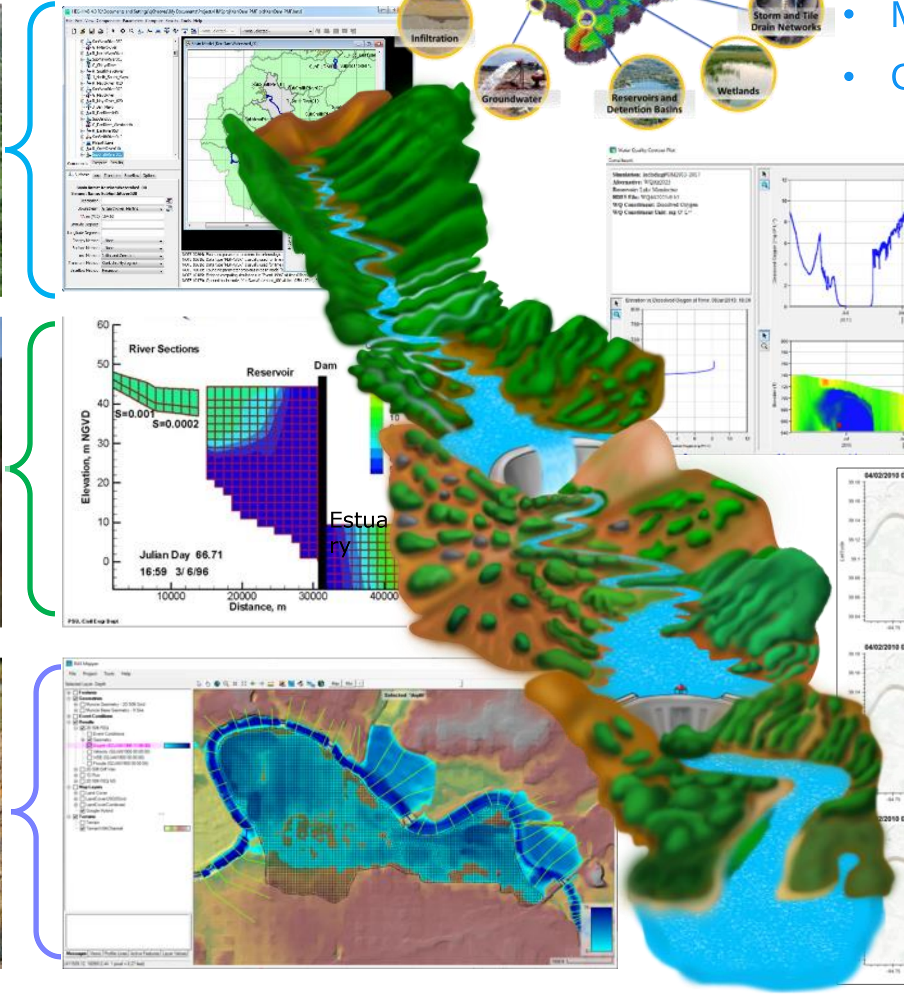
ERDC's Corps Library for Environmental Analysis and Restoration of Watersheds (ClearWater) provides environmental simulation capabilities that leverage existing hydrologic and hydraulic (H&H) models.

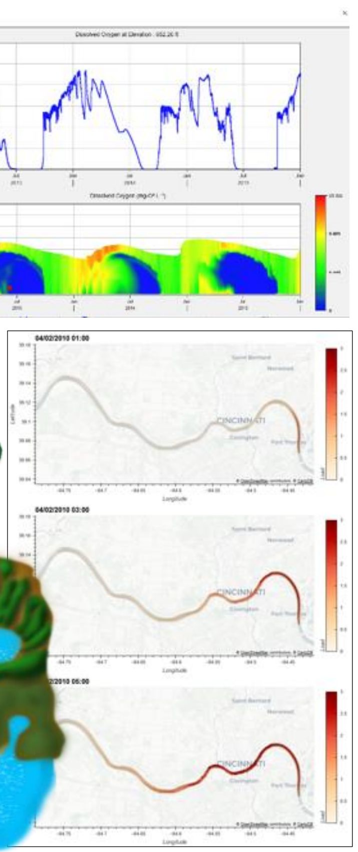
- Temperature
- Nutrients
- Dissolved Oxygen
- Algae
- Metals
- Contaminants

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



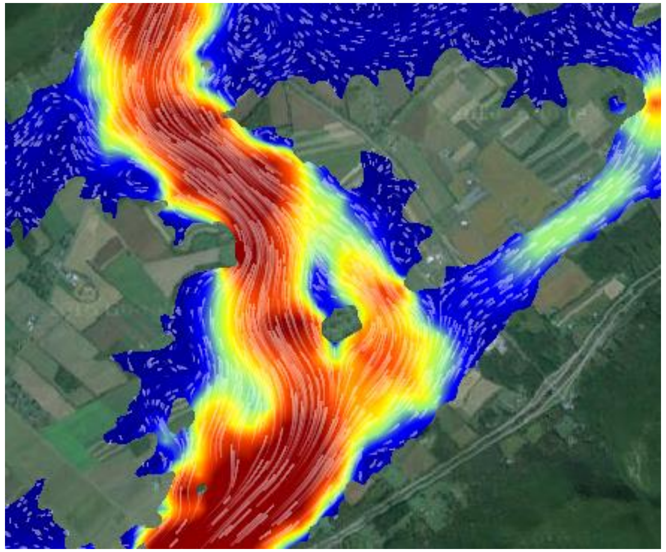


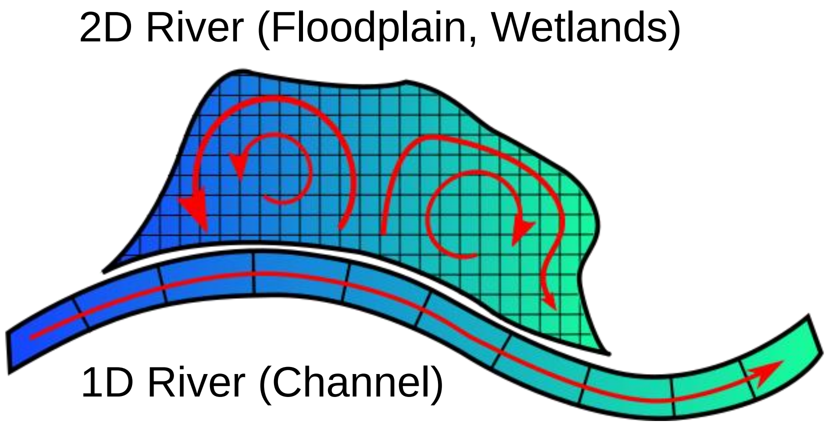


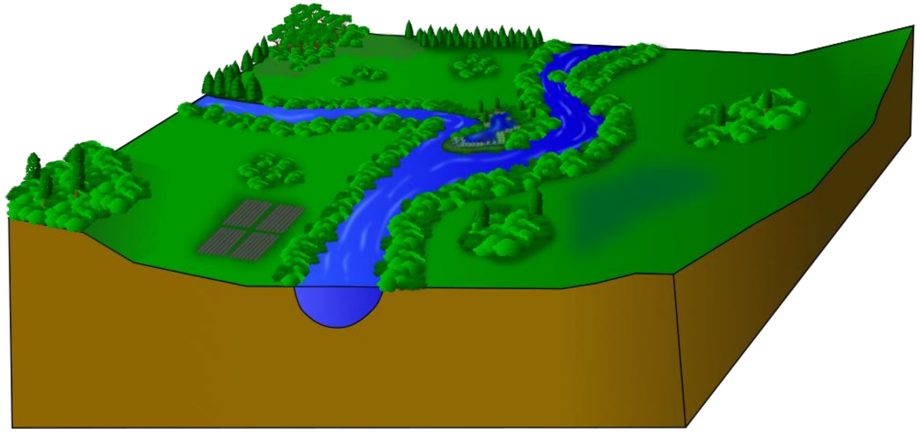
Key:
ERDC
HEC

Model Dimensions: River-Floodplain System

- Unstratified river channels are often modeled as one-dimensional (1D) water bodies, varying from upstream to downstream
- Hydrologic connectivity across the floodplain is important
- Floodplains need to be modeled as two-dimensional (2D) water bodies, varying in all directions across the landscape



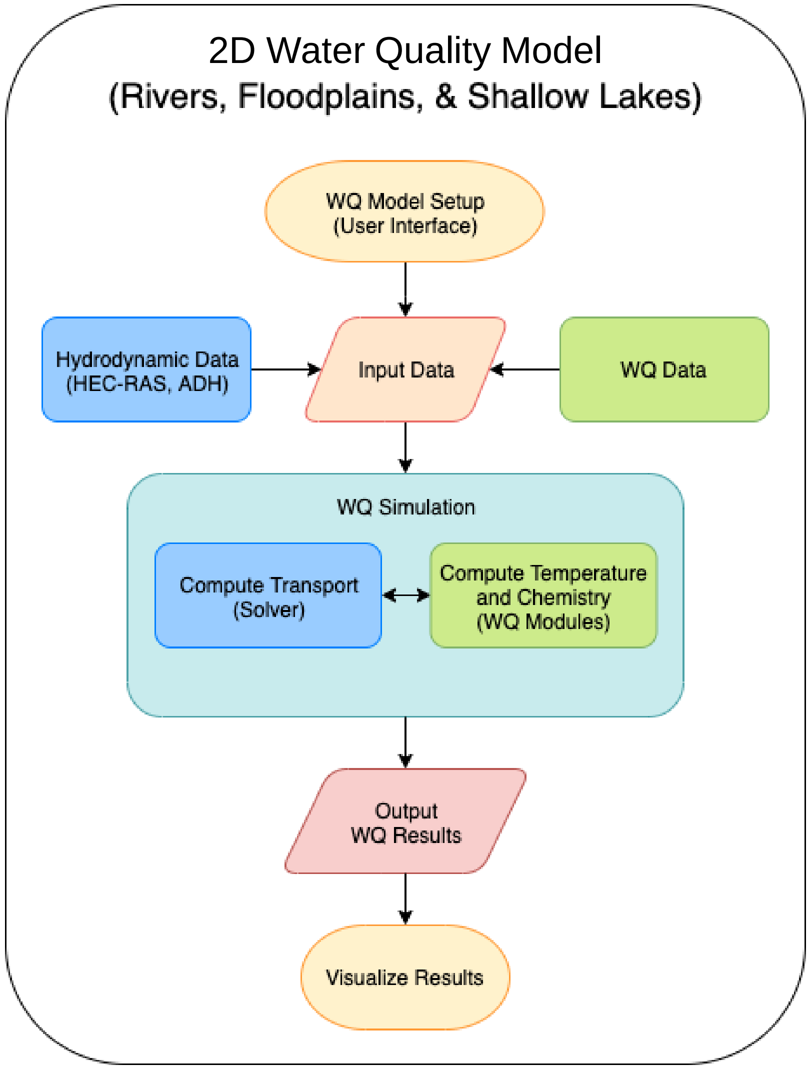




Graphics by Lauren Melendez

ClearWater-Riverine: 2D Water Quality Modeling with HEC-RAS and GSSHA

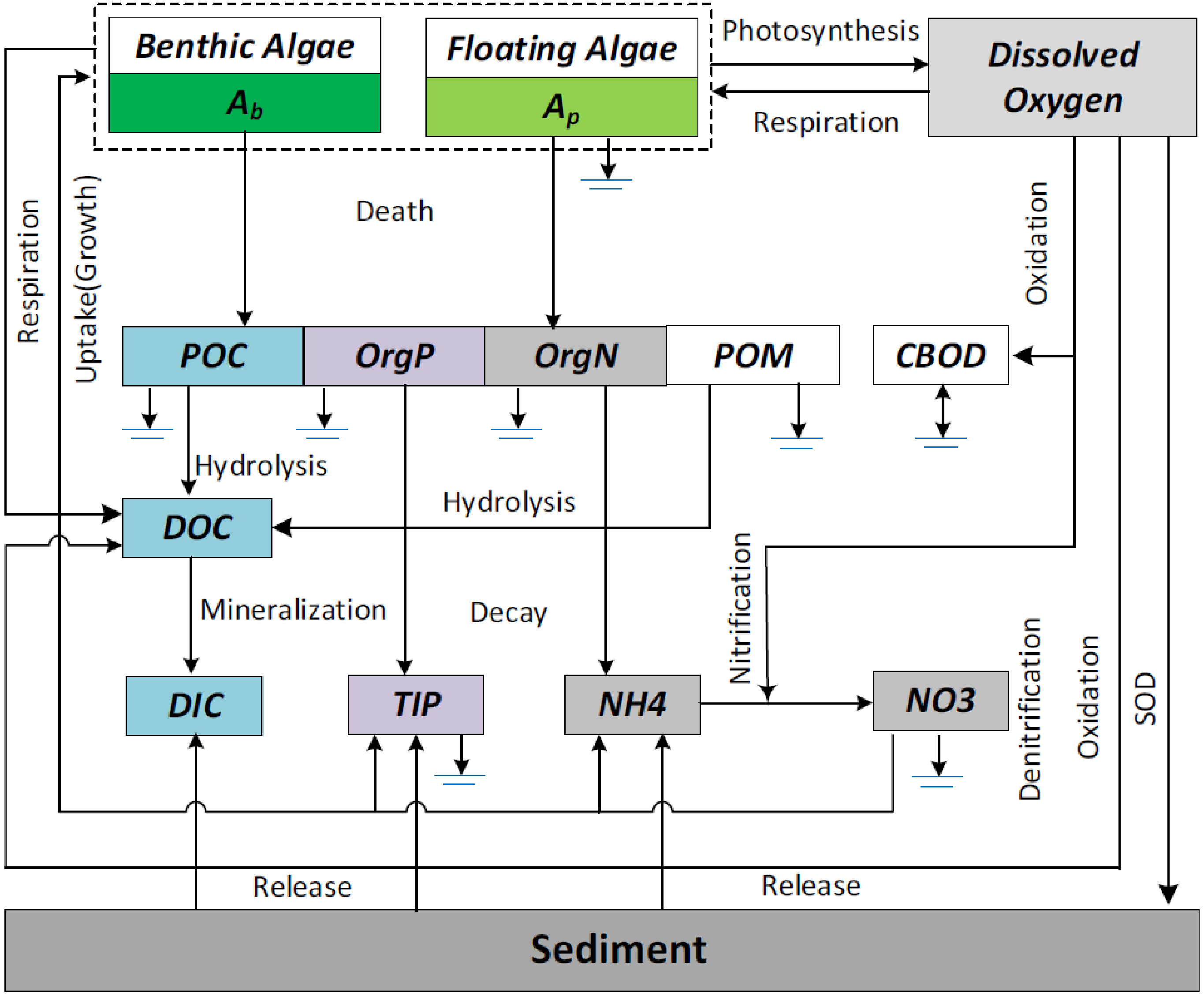
- ClearWater Modules:
  - Compute heat budget and constituent kinetics for a single cell
- ClearWater Engine:
  - Computes advection-diffusion across the model grid at each time step
- ClearWater Framework:
  - Links water quality and ecological models with water resources models
  - Controls
    - Model input and output
    - Time steps (computational, input, and output)
    - Simulation of transport across the model grid
  - Coordinates engine, modules, and data
- Inputs
  - Volumetric flows, velocities, depths
  - Model grid (bathymetry)
  - Observed meteorology and water quality time series
- Outputs
  - Time series of 2D water quality grids, one time series per variable
  - Time series of simulated hydrodynamic and water quality data at user-selected locations



DEVELOPING PYTHON VERSIONS OF TSM & NSM

Isaac and Kelsey

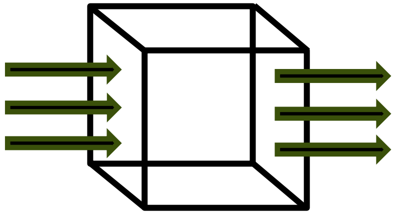
Nutrient Simulation Module (NSM) Processes

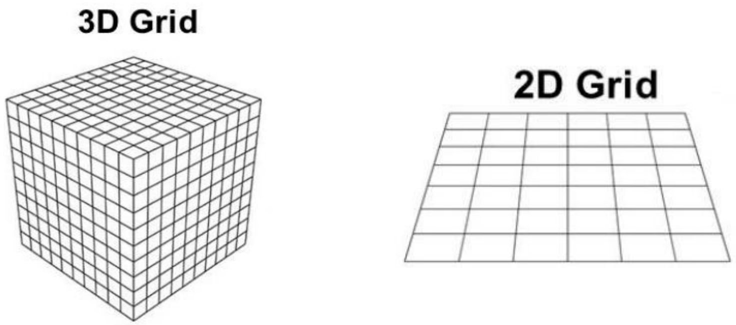


Zhang & Johnson, 2016

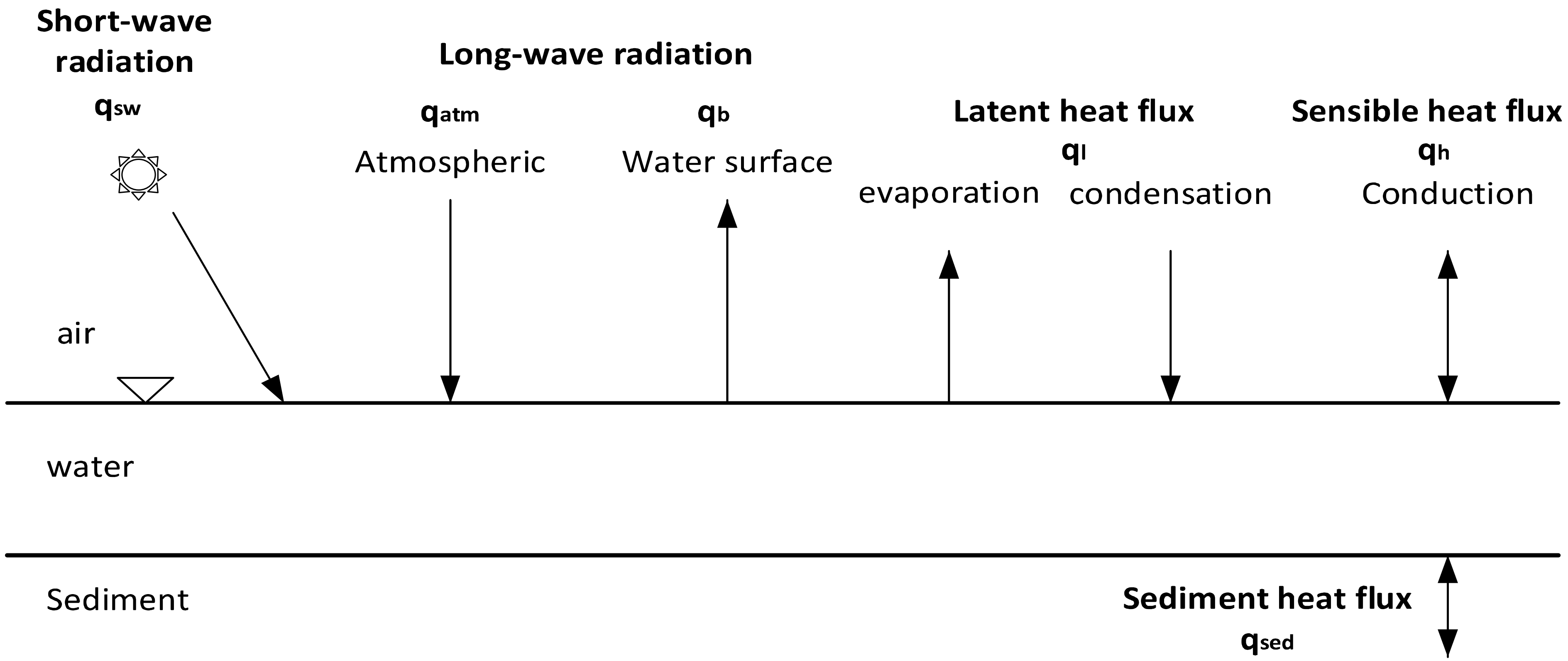
Developing new Python-based Modules

- Legacy NSM and TSM written in Fortran
- New versions of NSM and TSM written in Python
  - Single cell calculations
  - Python framework will iterate computations for multiple cells





Temperature Simulation Module (TSM) Processes



Zhang & Johnson, 2016

Testing TSM and Path Forward for NSM

- We tested the implementation of TSM by recreating the kinetic equations in Excel as well as comparing to the Fortran water quality modules developed by ERDC and HEC for HEC-RAS (1D).

Water Quality Model Configuration

Available Libraries | Dependent Variables | State Variables | Derived Variables | Parameters | Output Pathways | Explore Parameters

# of Days: 1 Δt: 86400 Region: Copy Paste Save State Compare to:

Name	Description	Source	Units	Value
State Variables - Initial Values:				
Water Temperature	Water Temper.	TemperatureEnergyBudget	°C	20
Sediment Temperature	Sediment Tem	TemperatureEnergyBudget	°C	5
Dependent Variable Values:				
Surface Area	Surface Area	TemperatureEnergyBudget	m^2	1
Volume	Volume	TemperatureEnergyBudget	m^3	1
Solar Radiation	Short Wave	TemperatureEnergyBudget	W/m^2	400
Wind Speed	Wind Speed	TemperatureEnergyBudget	m/s	3
Atmospheric Pressure	Atmospheric P	TemperatureEnergyBudget	mb	1013.25
Air Temperature	Air Temperatu	TemperatureEnergyBudget	°C	20
Cloud Cover	Cloud Cover	TemperatureEnergyBudget	fraction	0.1
Vapor Pressure	Vapor Pressur	TemperatureEnergyBudget	mb	1

Ordinate	Water Temperature Simulation (days)	Water Temperature (°C)
1	0.00000	20.000
2	1.00000	15.339

1	INPUT ARGS - BASELINE VARIABLES		TwaterK	293.16		SHORTWAVE RADIATION	
2	TwaterC	20	TairK	293.16		TOTAL	400
3	surface_area	1					
4	volume	1					
5	TairC	20					
6	TsedC	5					
7	q_solar	400					
8	wind_kh_kw	1					
9	eair_mb	1					
10	pressure_mb	1013					
11	cloudiness	0.1					
12	wind_speed	3					
13	wind_a	3.00E-07					
14	wind_b	1.50E-06					
15	wind_c	1					
16	use_SedTemp	TRUE					
17	num_iterations	10				q_net	-2.25E+02
18	tolerance	0.01				dTwaterCdt	-5.39E-05
19	time_step	86400				TwaterC	15.33893331

FRAMEWORK AND MODEL COUPLING

Anthony

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

OPEN CODE = BETTER SCIENCE

https://numfocus.org/sponsored-projects

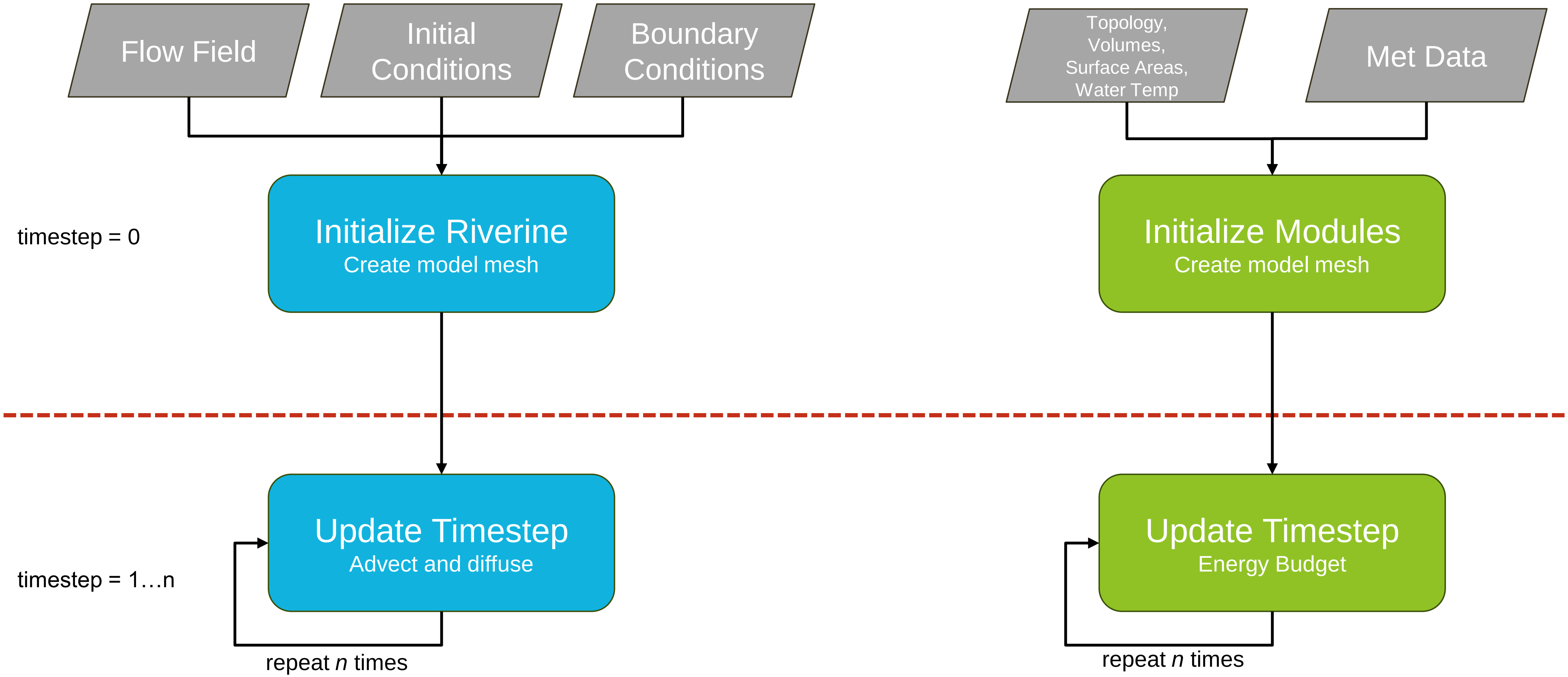
MODEL COUPLING

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

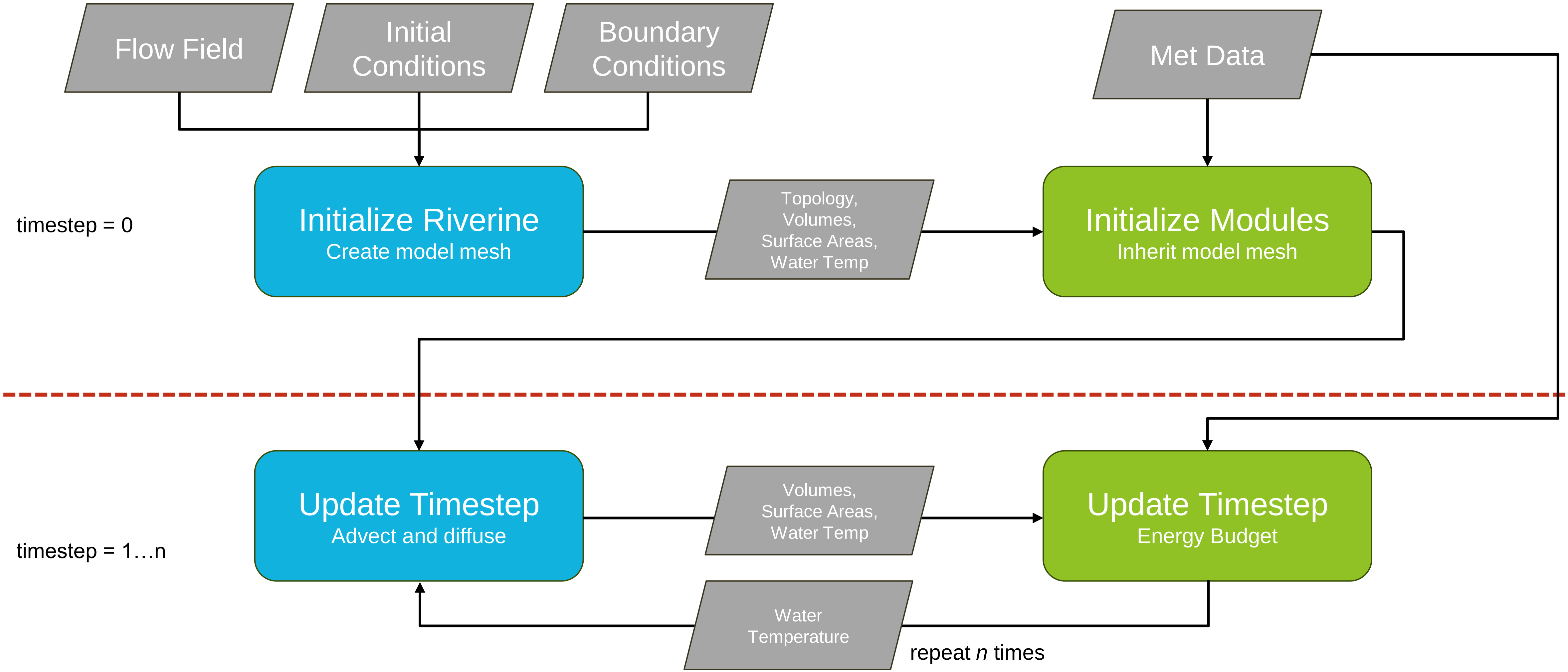
BMI 2.0 has become the standard for model coupling

- **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

Running Clearwater-Riverine and Clearwater-Modules Individually



Running Clearwater-Riverine and Clearwater-Modules as Linked Models

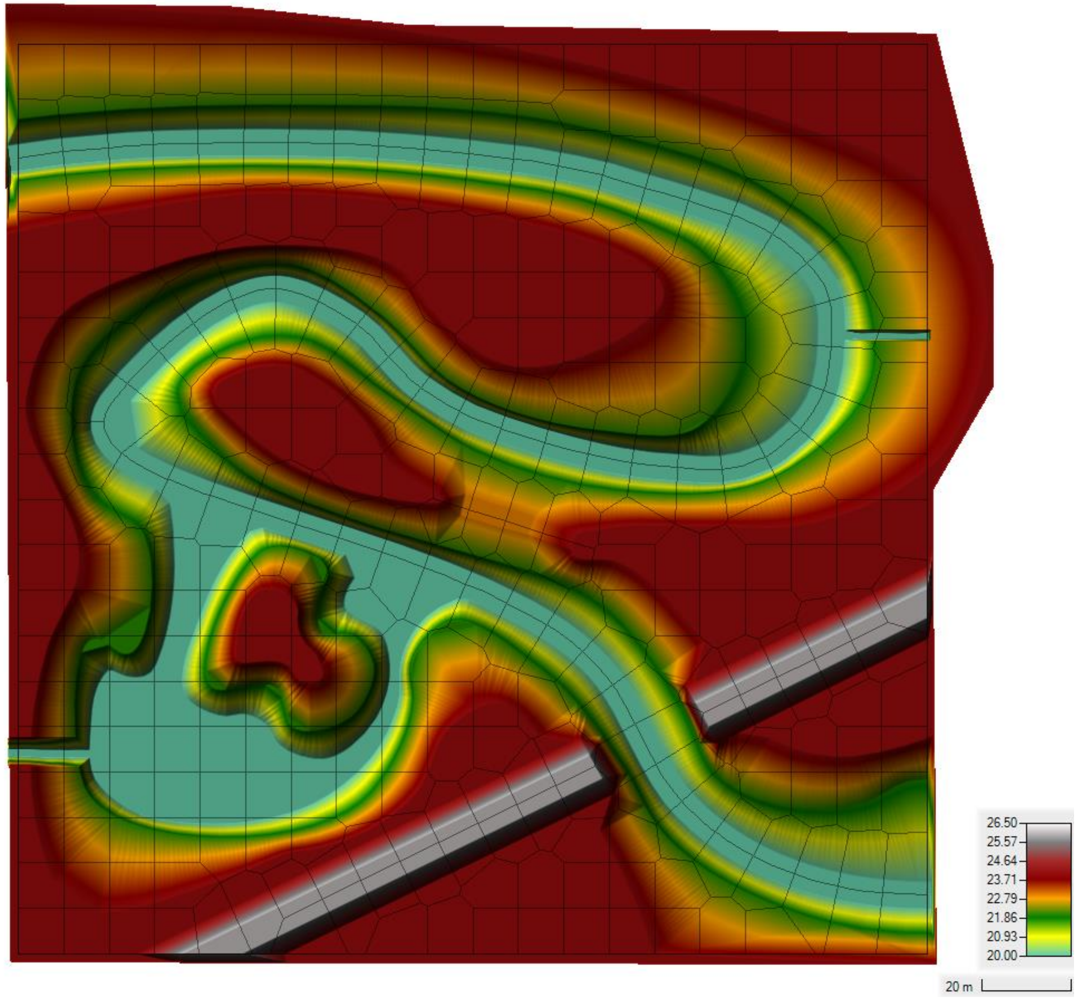


CLEARWATER DEMONSTRATION

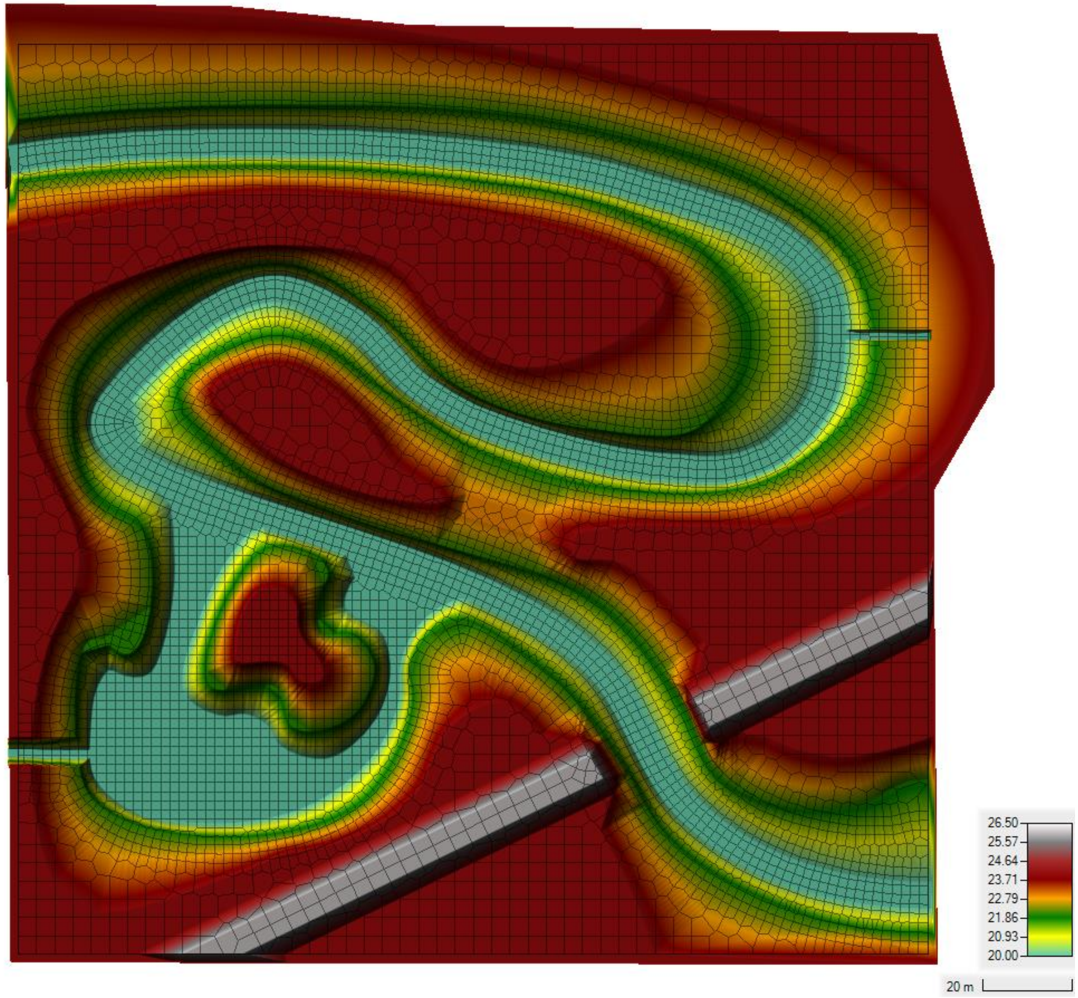
Sarah

Demo Case Study: Sumwere Creek — Domain & Mesh

Coarse Mesh

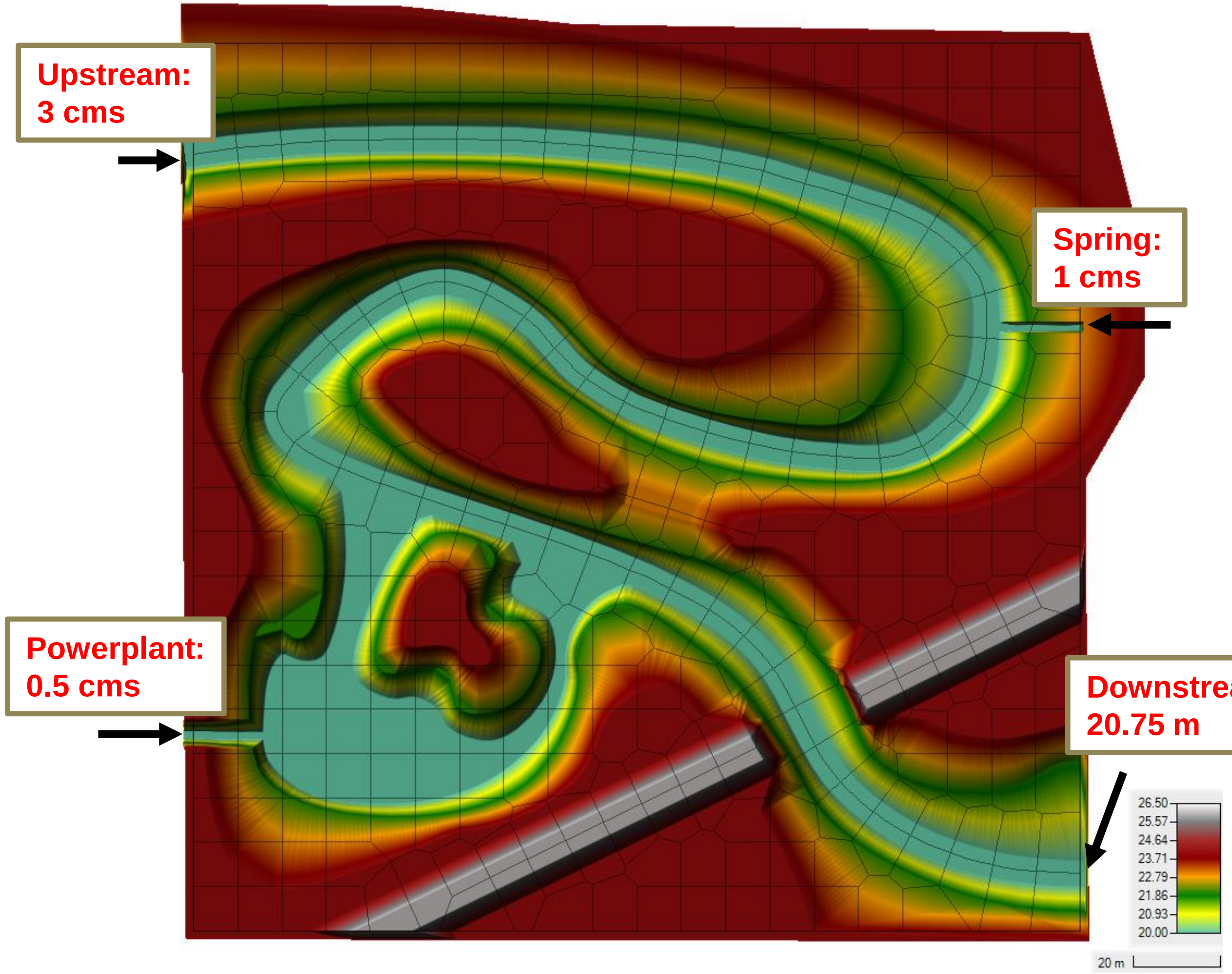


Fine Mesh



Demo Case Study: Sumwere Creek — Hydrodynamic Boundary Conditions

Coarse Mesh



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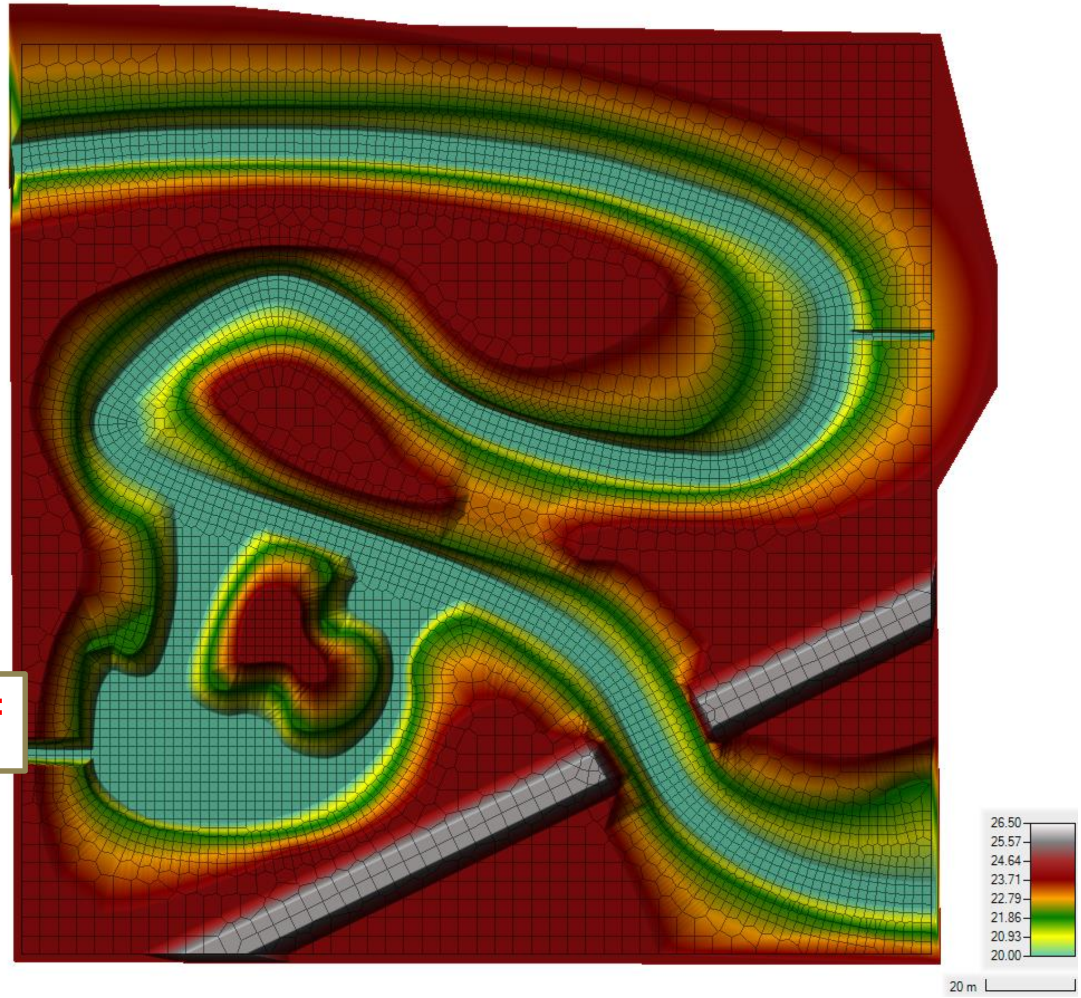
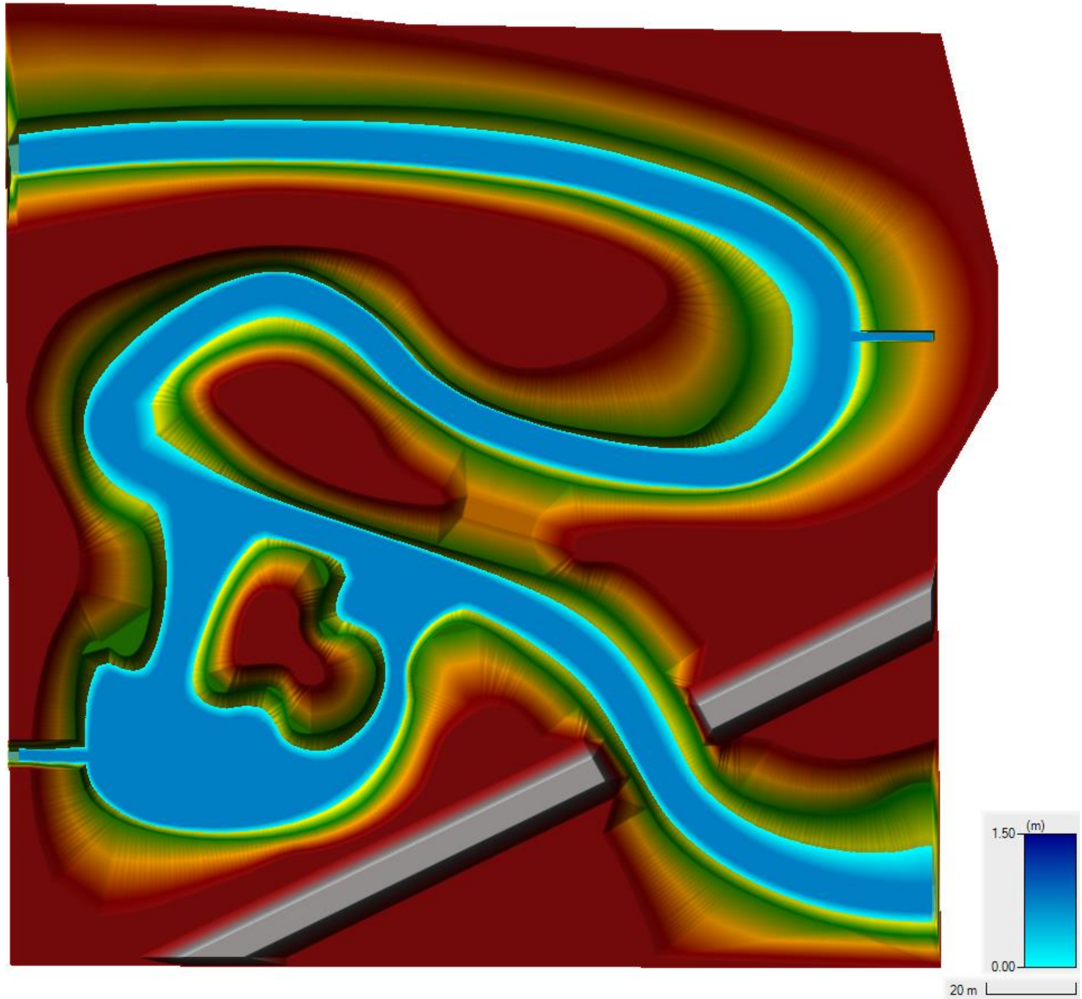


Demo Case Study: Sumwere Creek – Depth at Start of Simulation

Coarse Mesh



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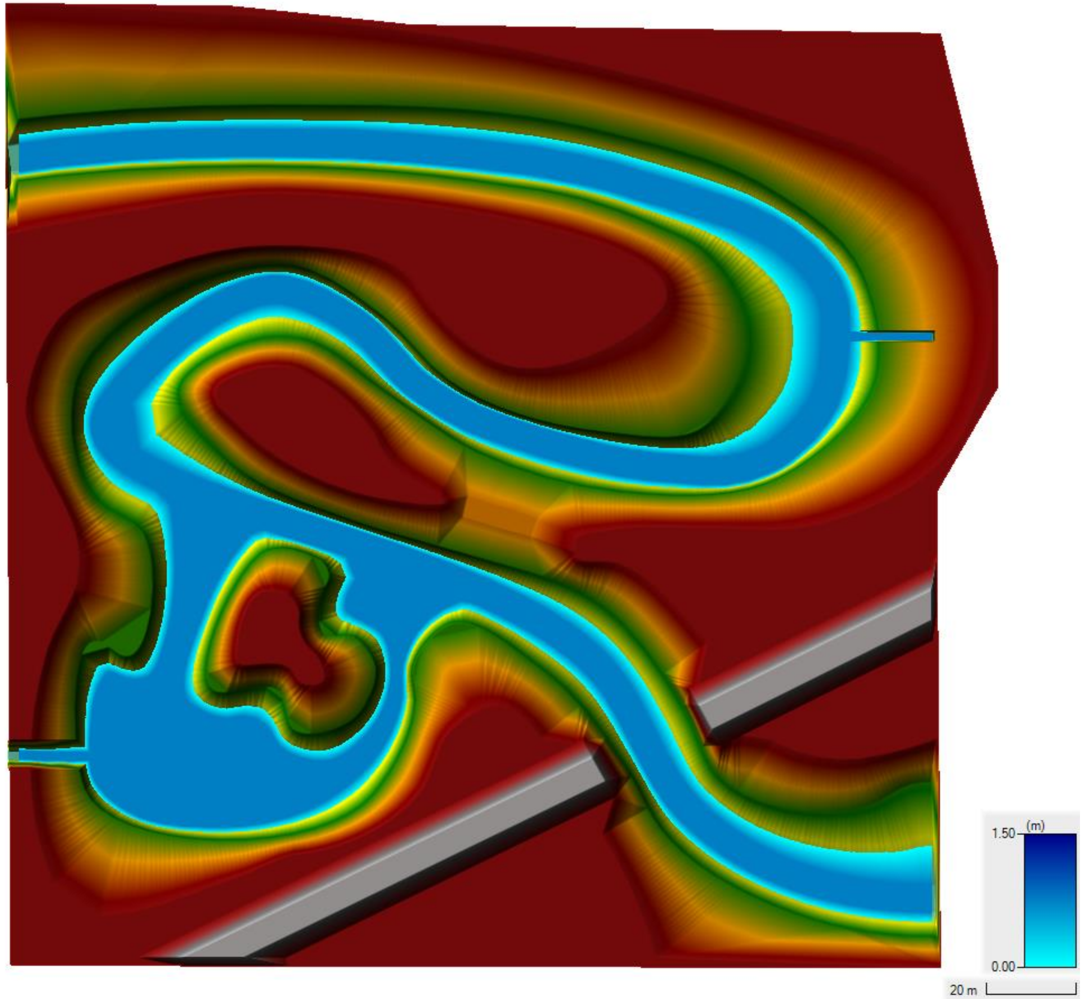
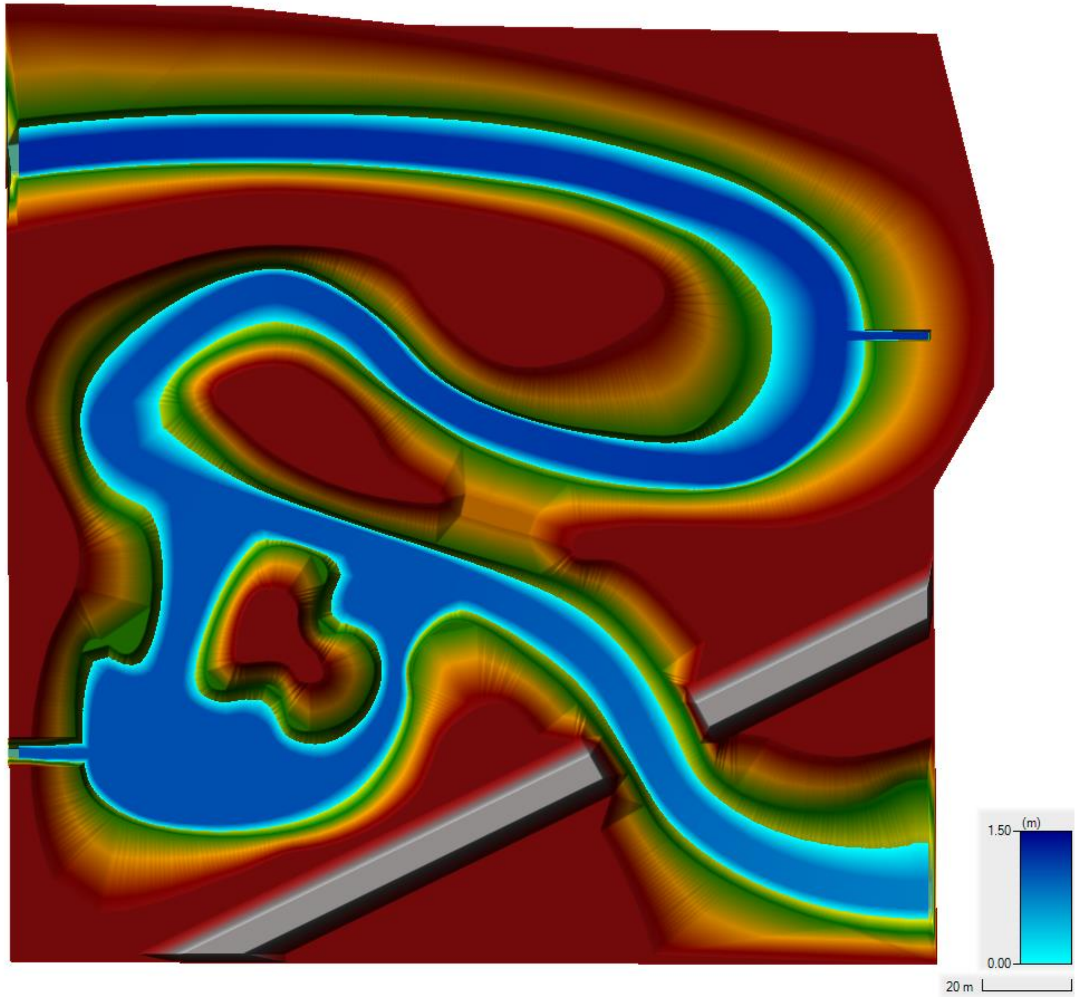
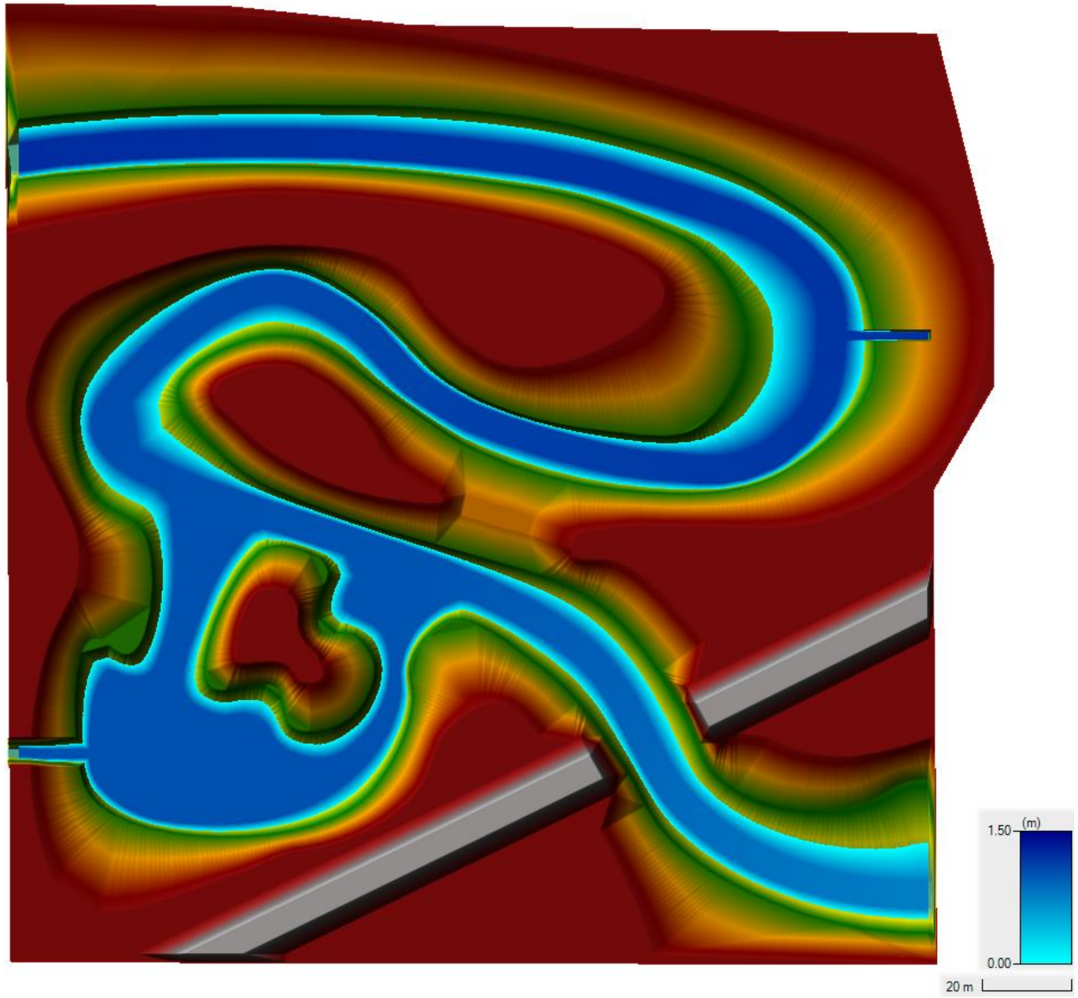


Demo Case Study: Sumwere Creek — Depth at End of Simulation

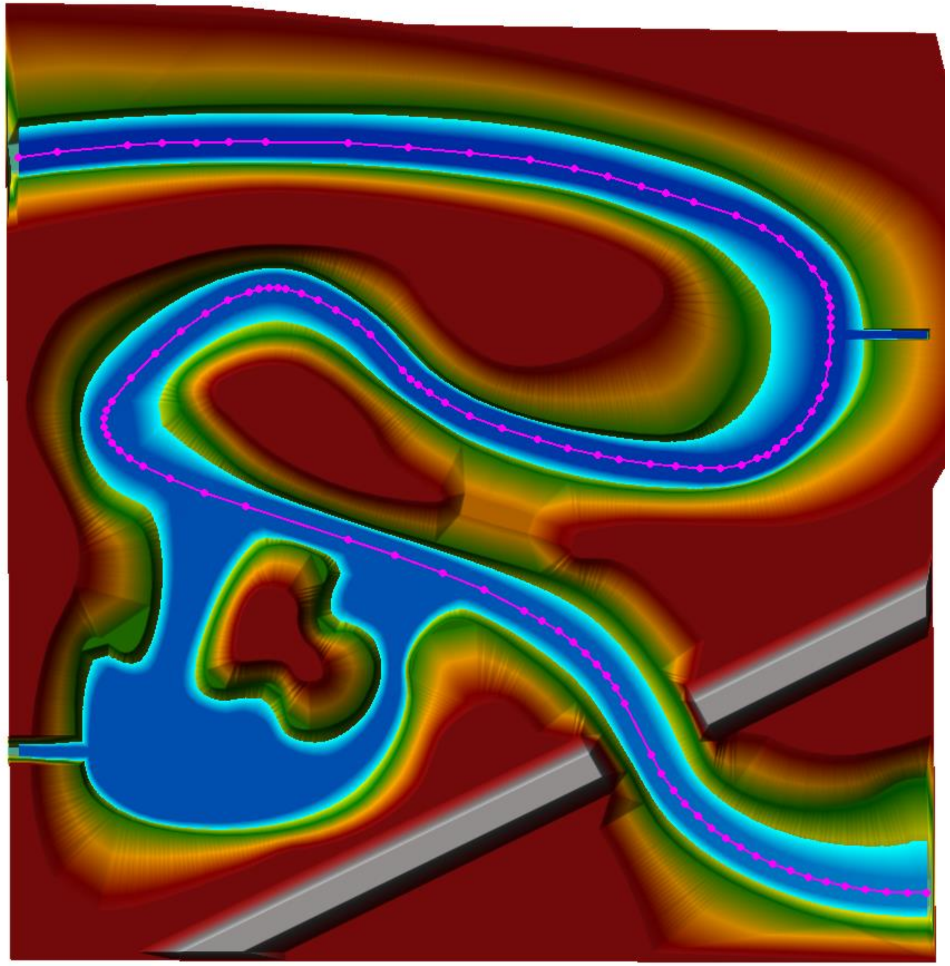
Coarse Mesh

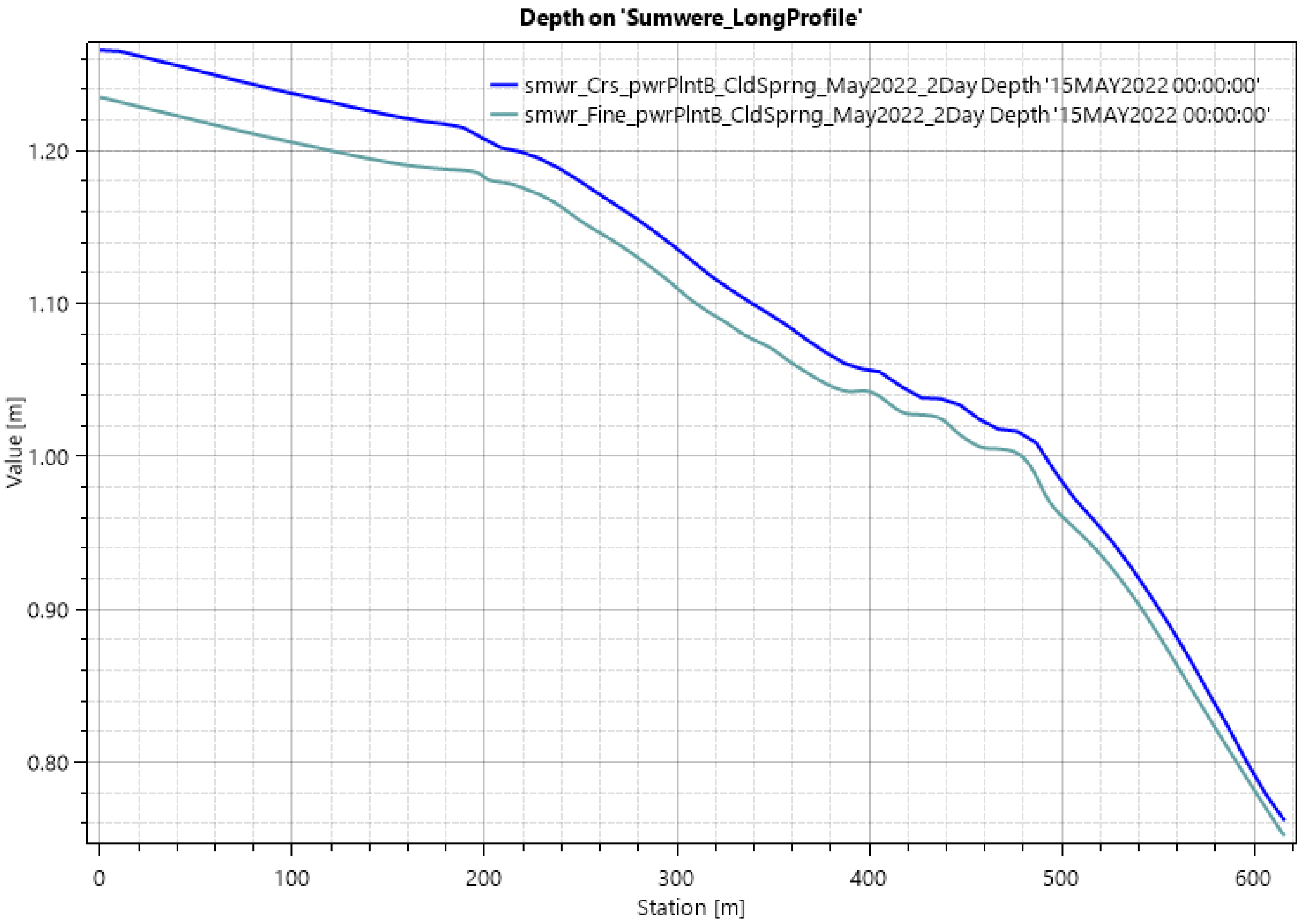


Fine Mesh



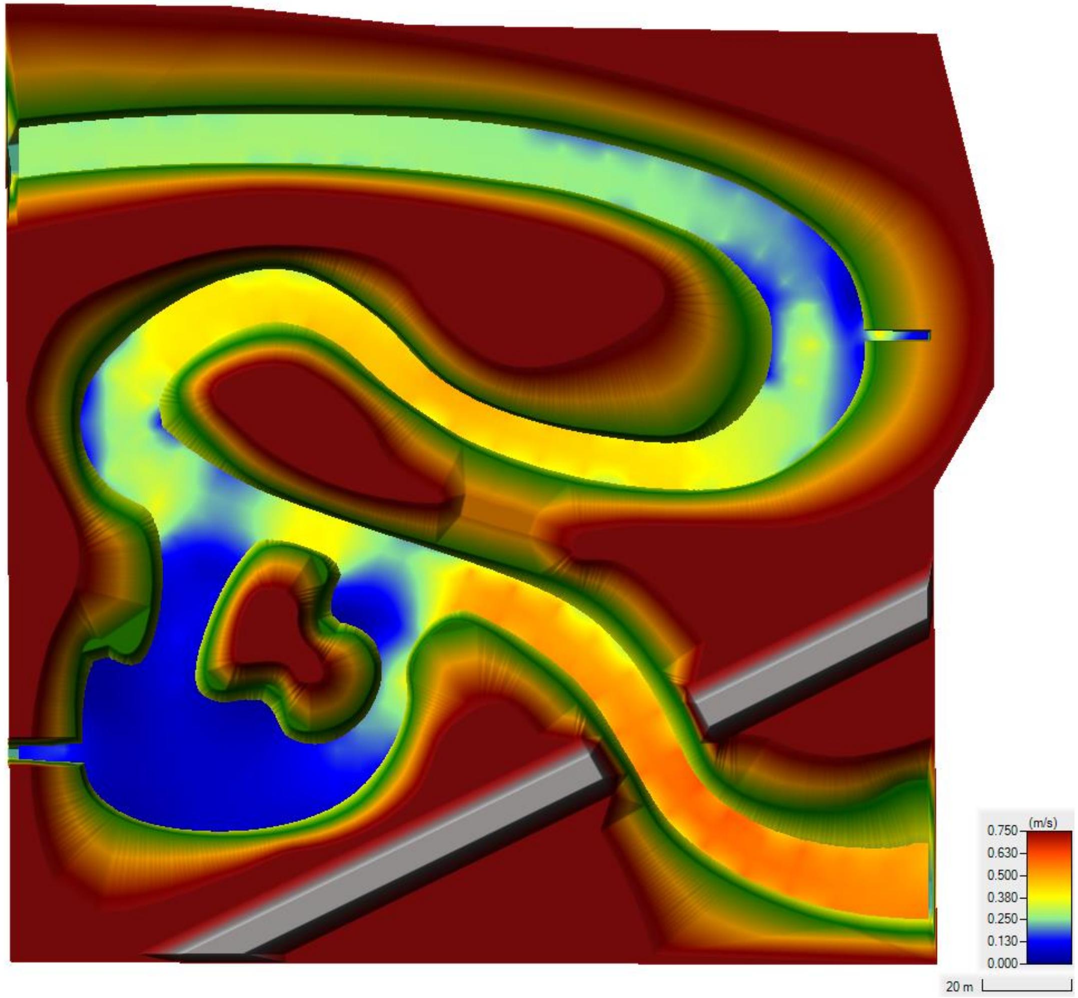
Demo Case Study: Sumwere Creek — Depth at End of Simulation



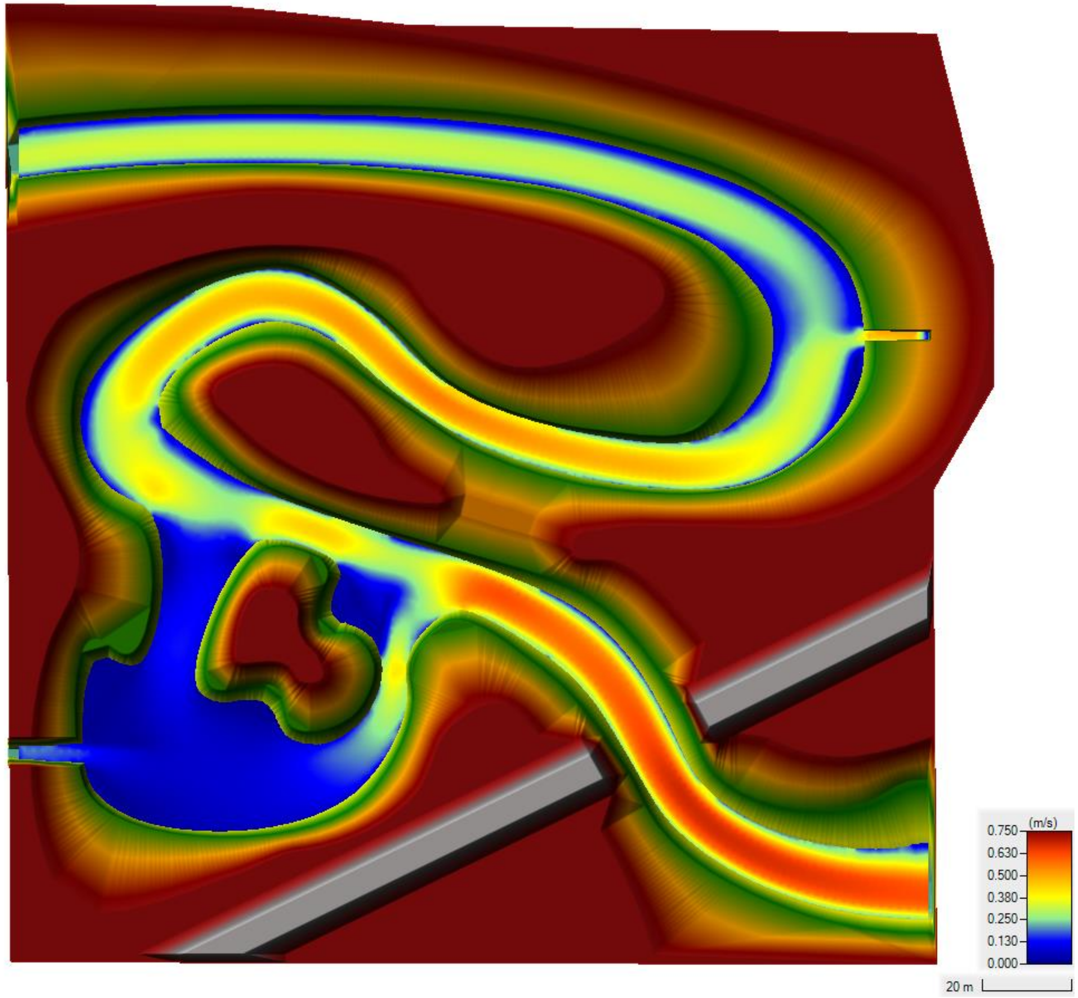


Demo Case Study: Sumwere Creek — Velocity at End of Simulation

Coarse Mesh

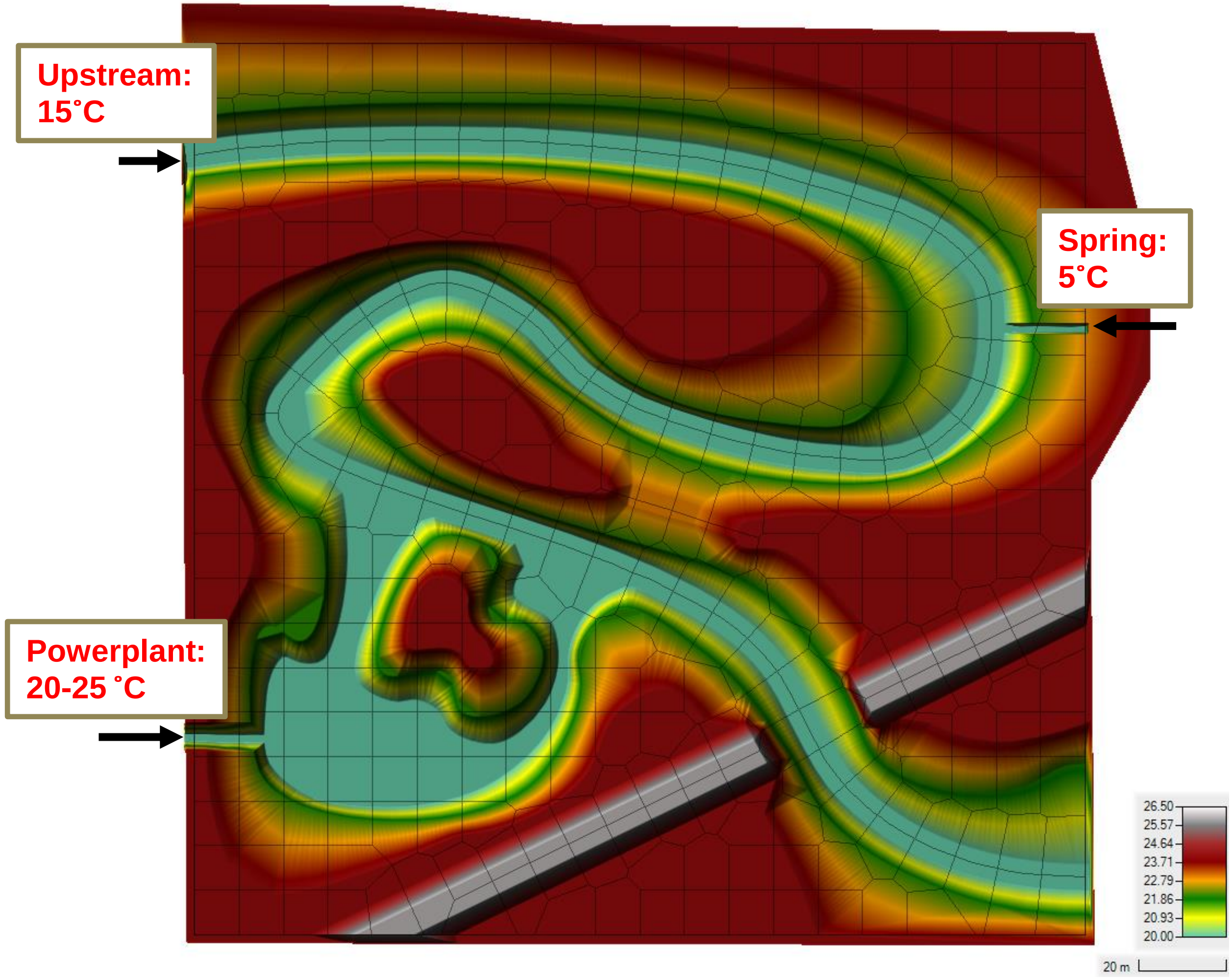


Fine Mesh

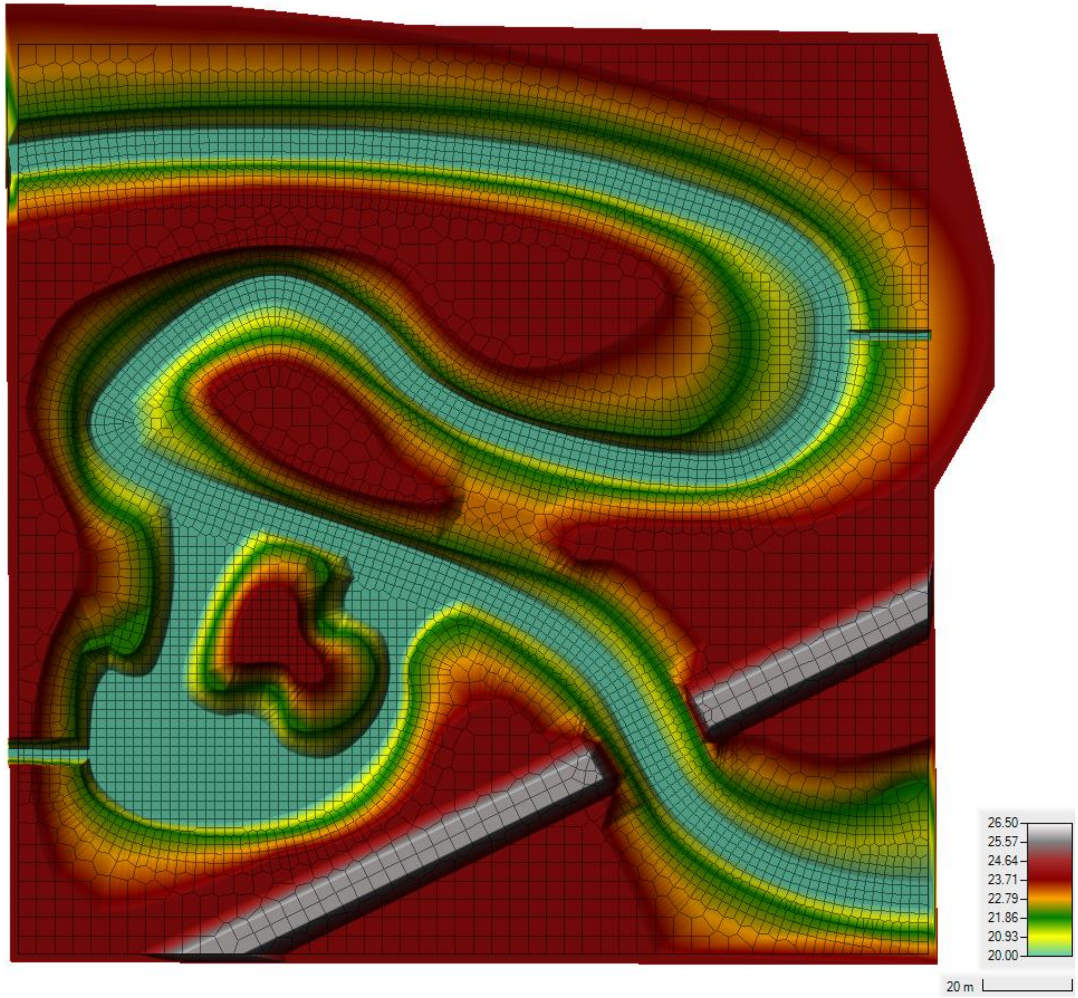


Demo Case Study: Sumwere Creek — TSM Temperature Boundary Conditions

Coarse Mesh

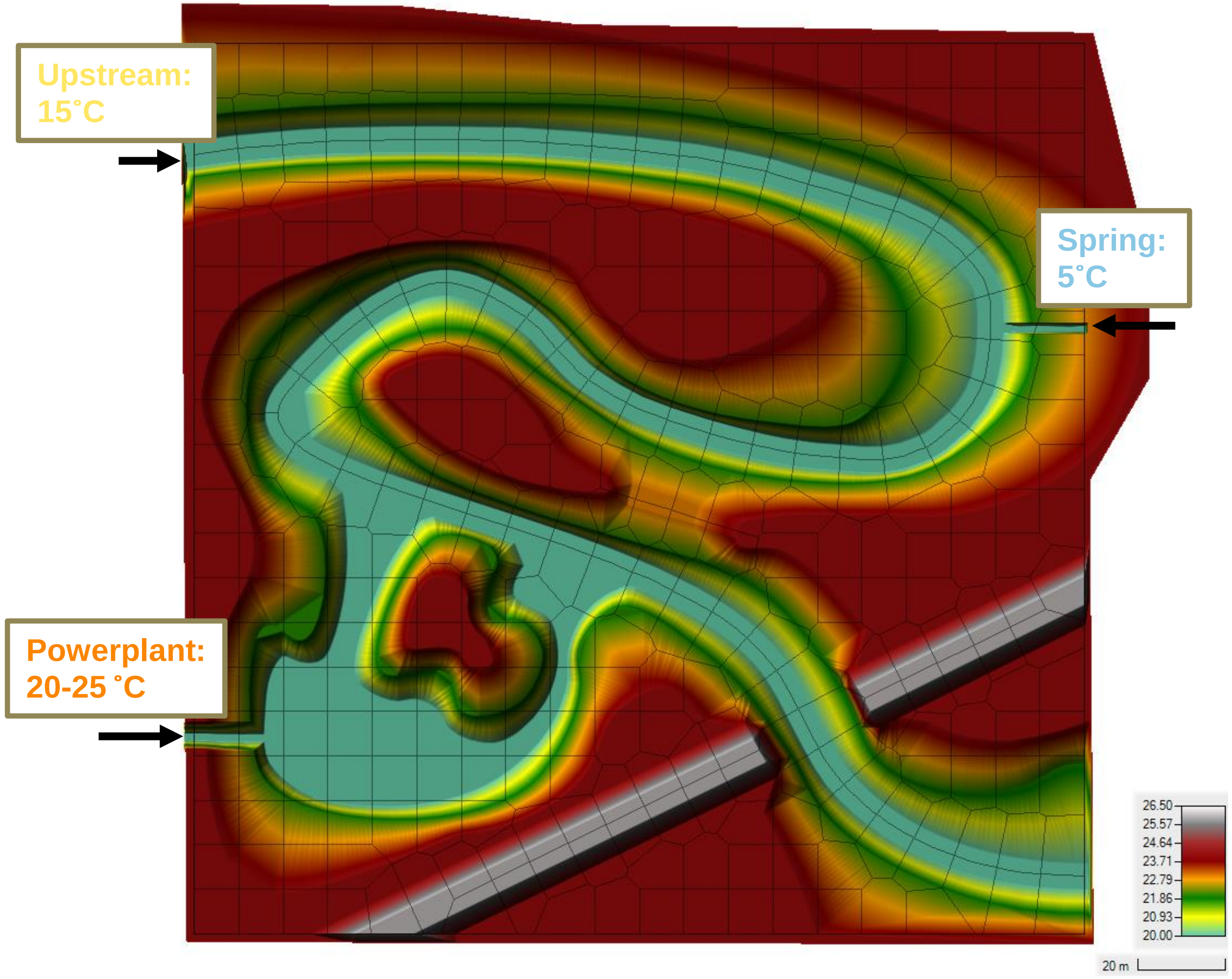


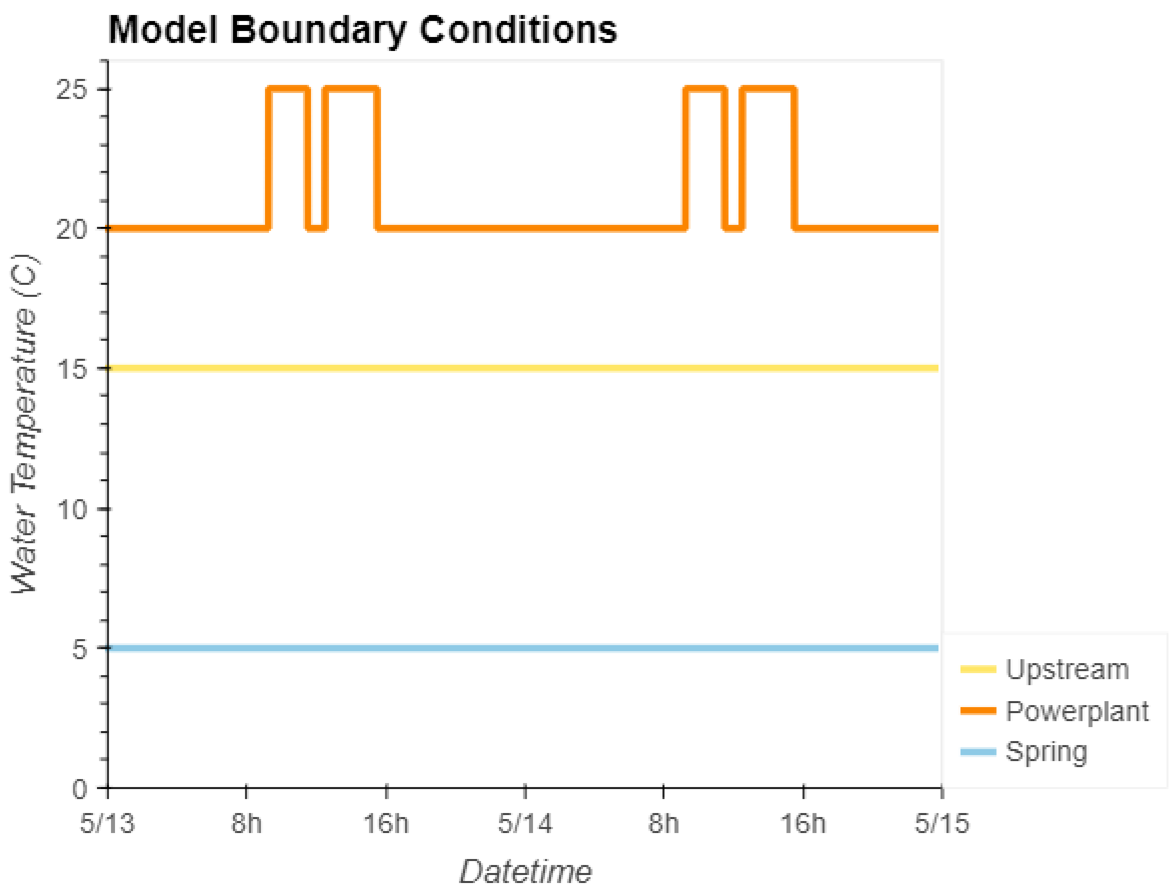
Fine Mesh



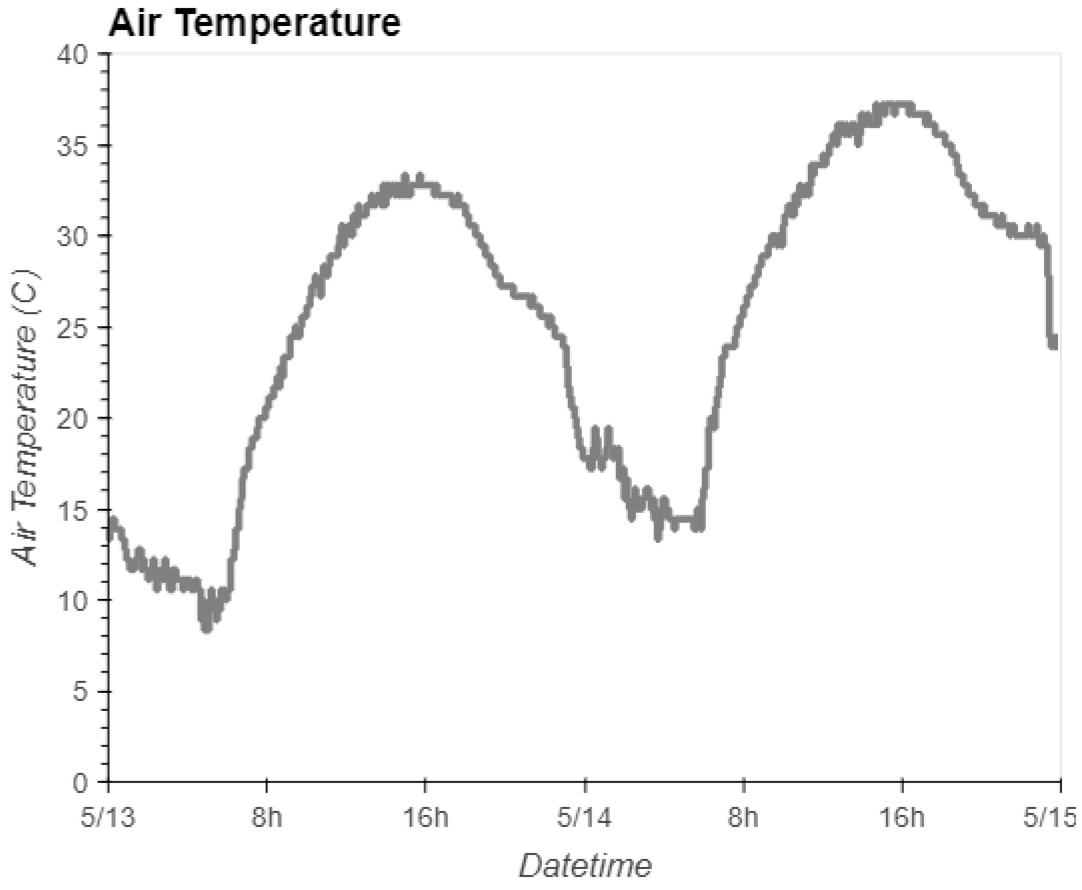
Demo Case Study: Sumwere Creek — TSM Temperature Boundary Timeseries

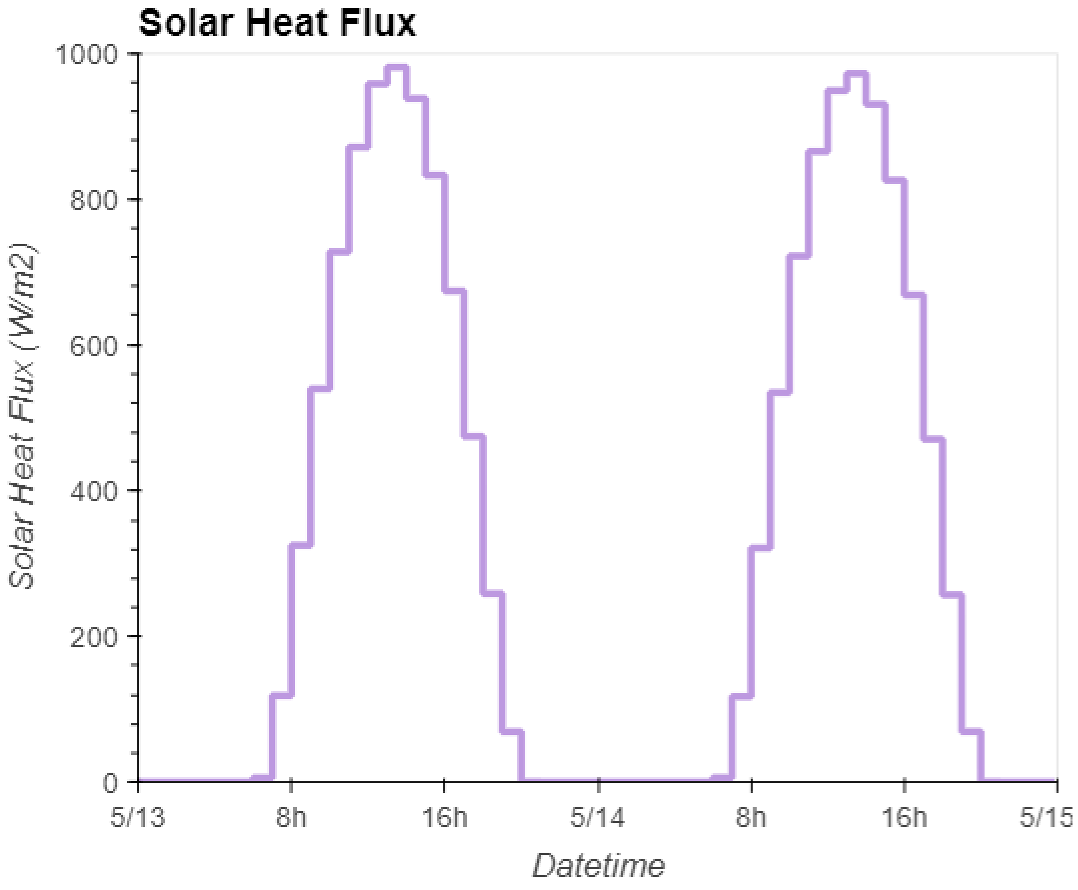
Coarse Mesh





Demo Case Study: Sumwere Creek — TSM Meteorological Timeseries

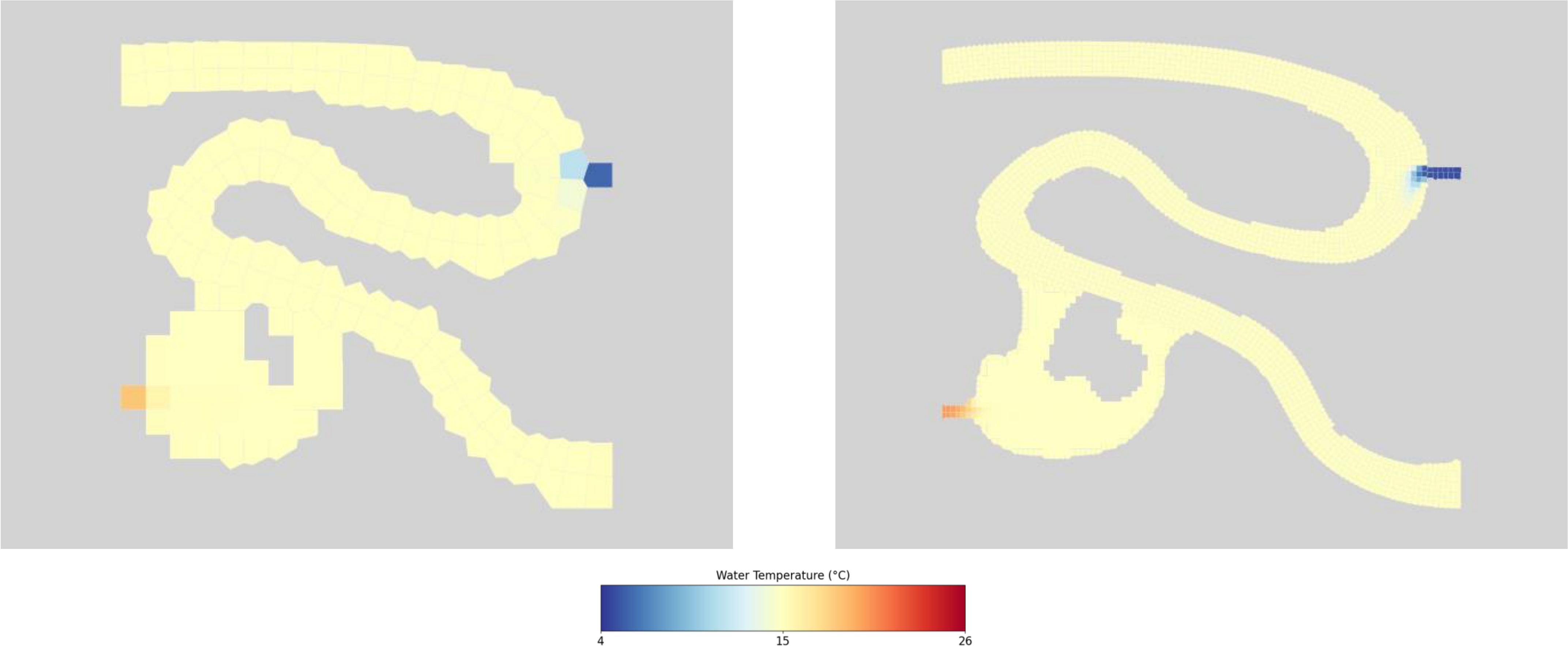




Results – Model Spin-Up

Coarse Mesh

Fine Mesh



Results – Model Spin-Up

Coarse Mesh

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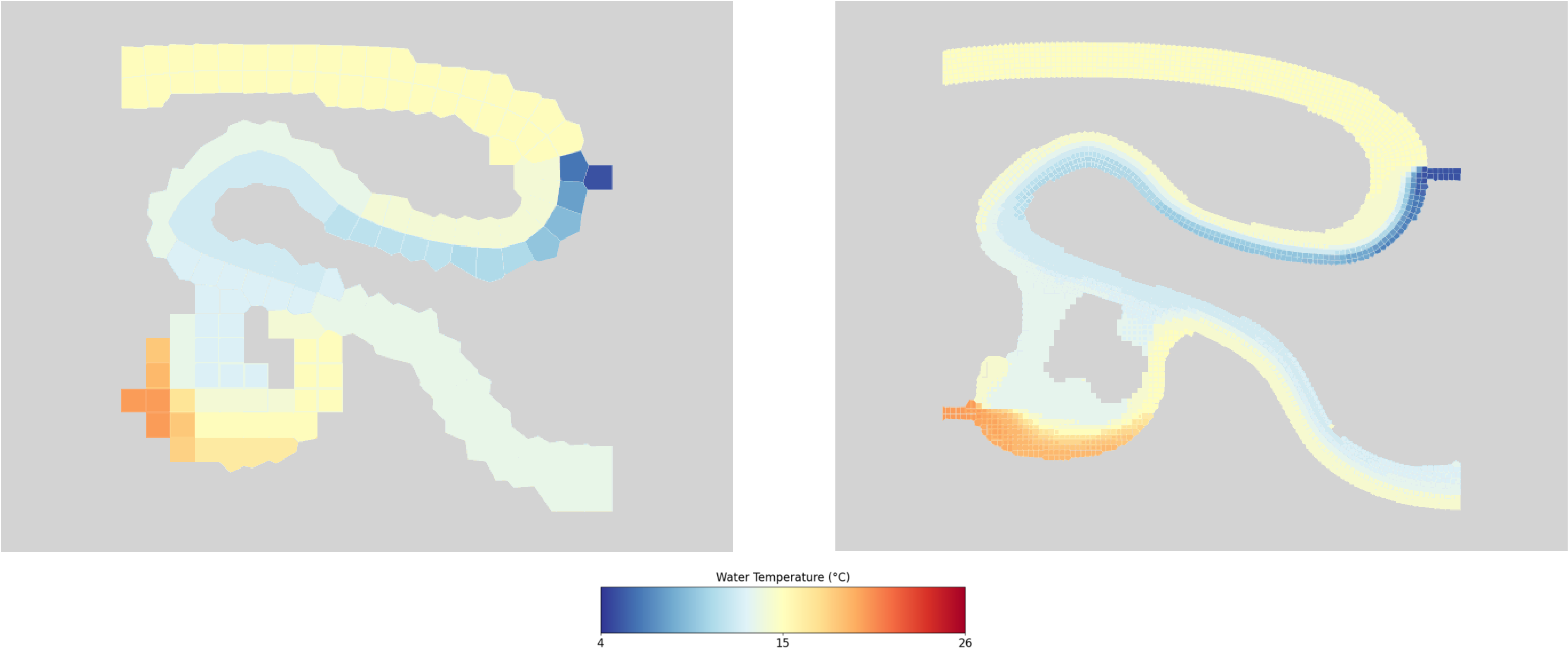
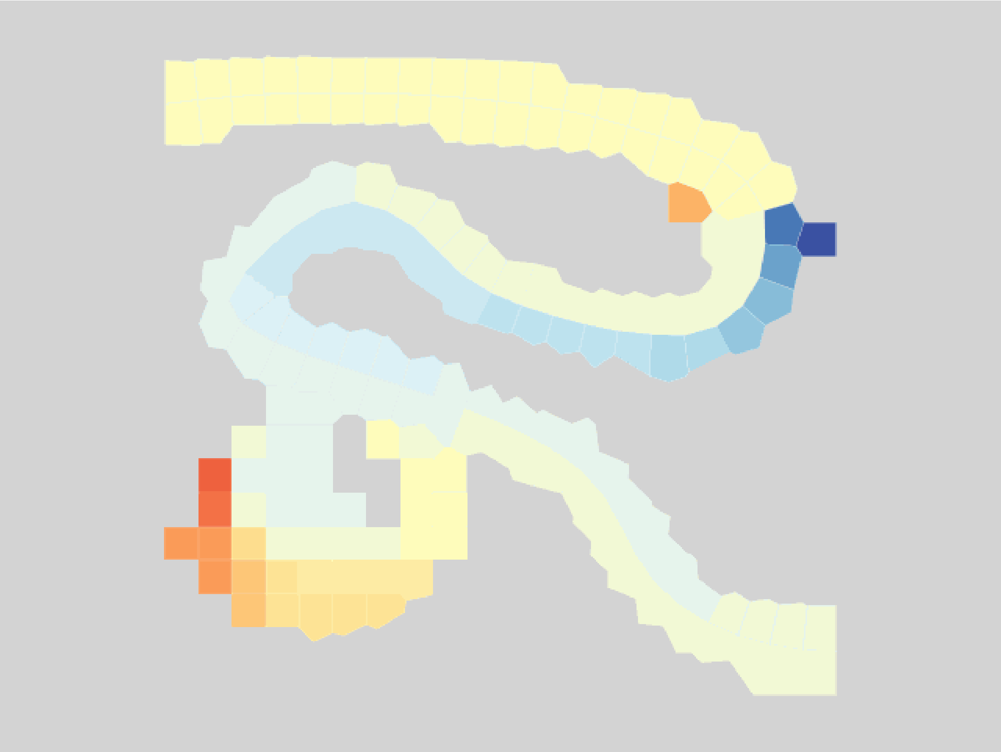
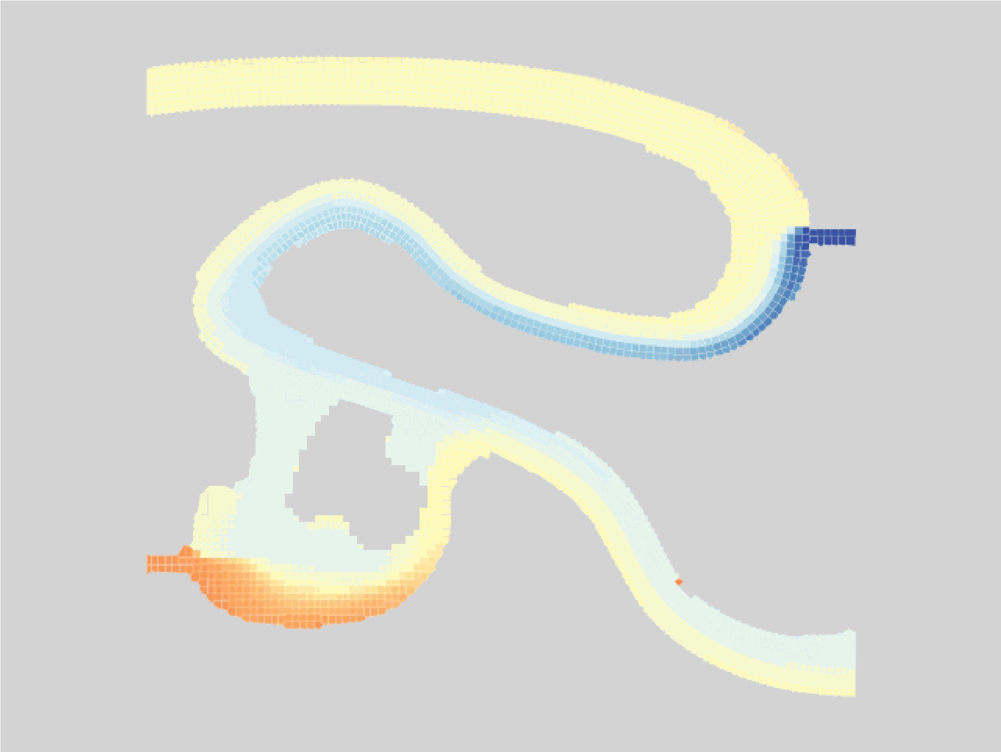


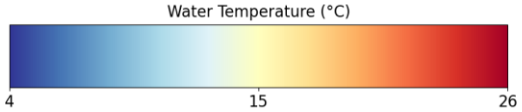
Results – Warm Powerplant Inflows

Coarse Mesh



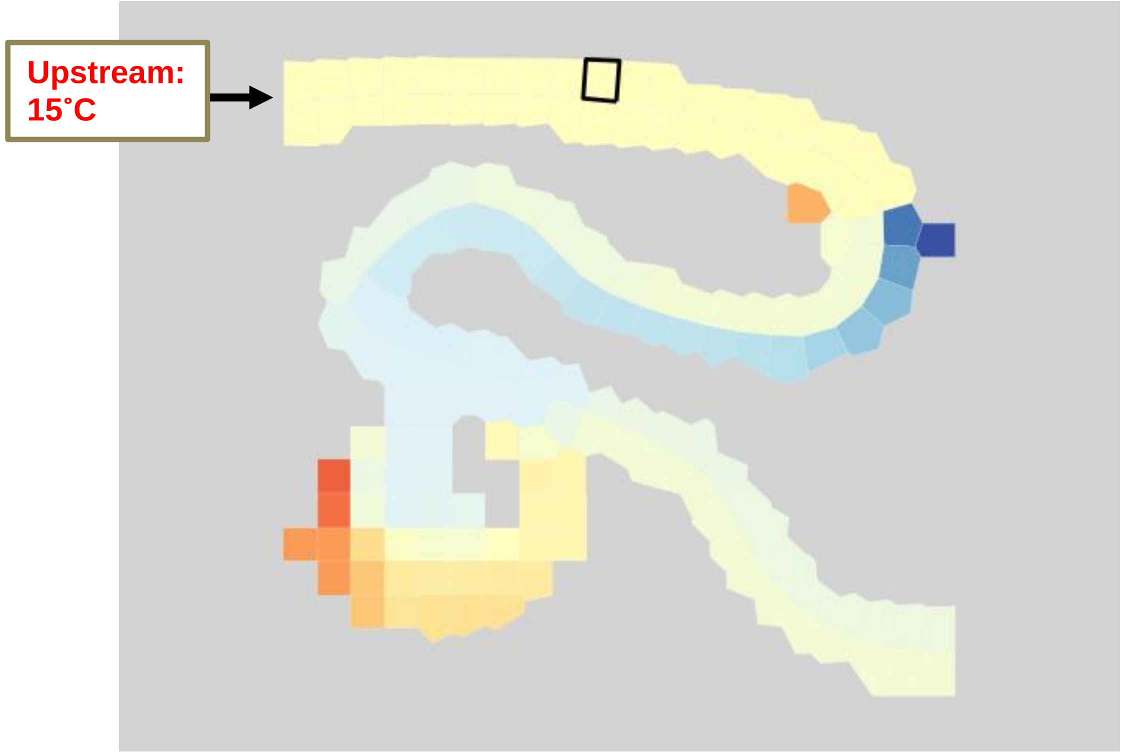
Fine Mesh



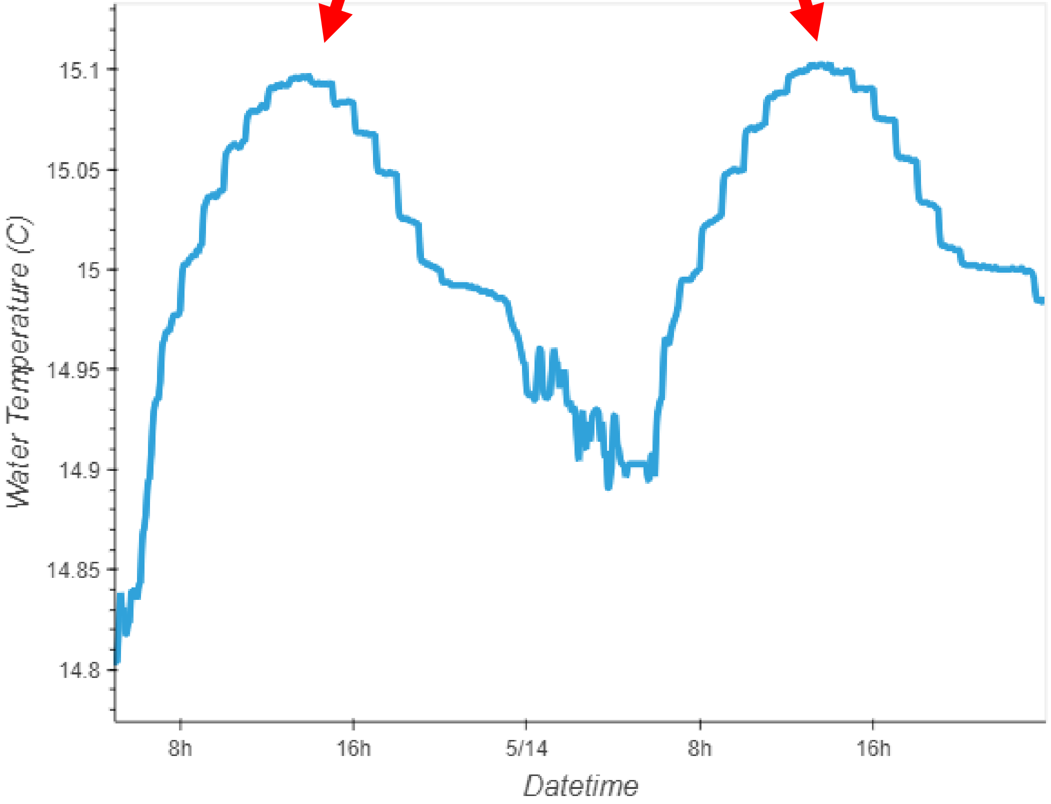


Results – Impact of TSM

Coarse Mesh



TSM: cyclical rise and fall of water temperature (solar heat flux, air temp)

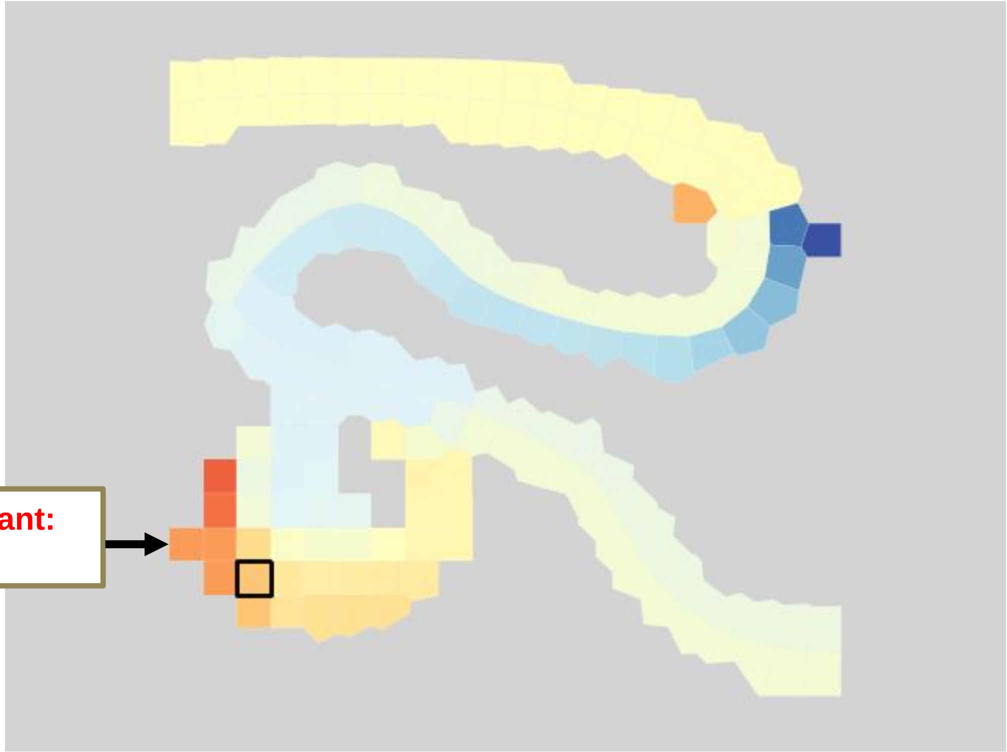


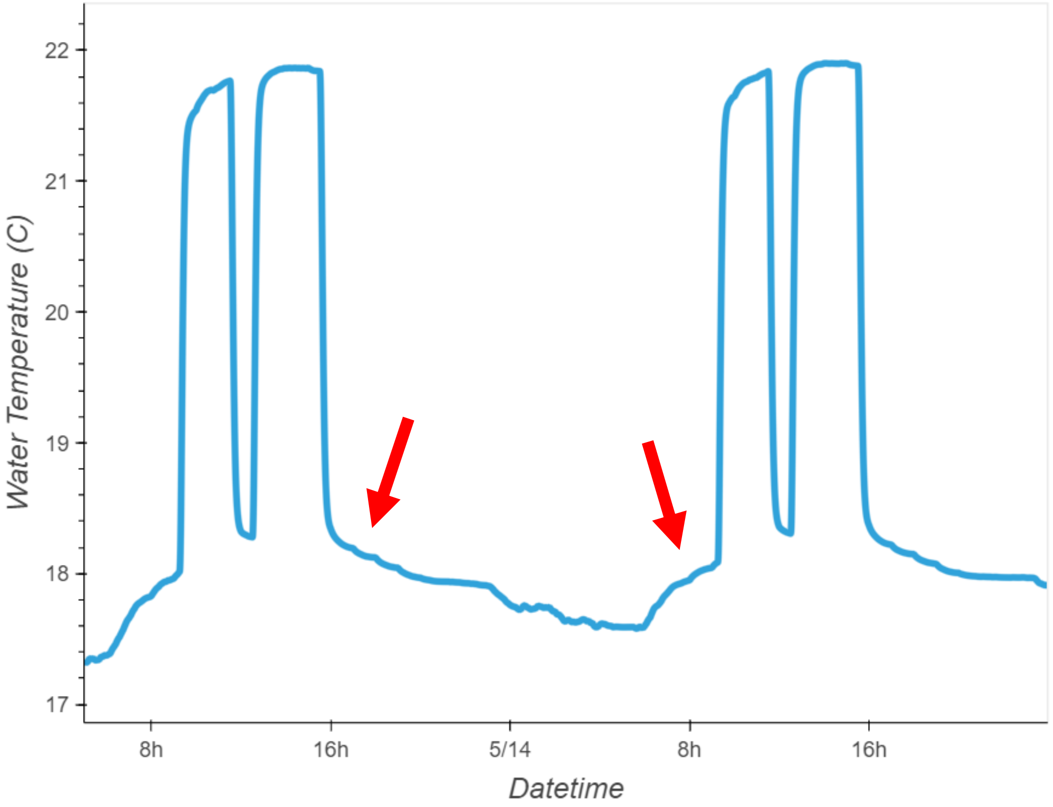
Results – Impact of TSM

TSM: impacts are still apparent in downstream mixing zones

Coarse Mesh

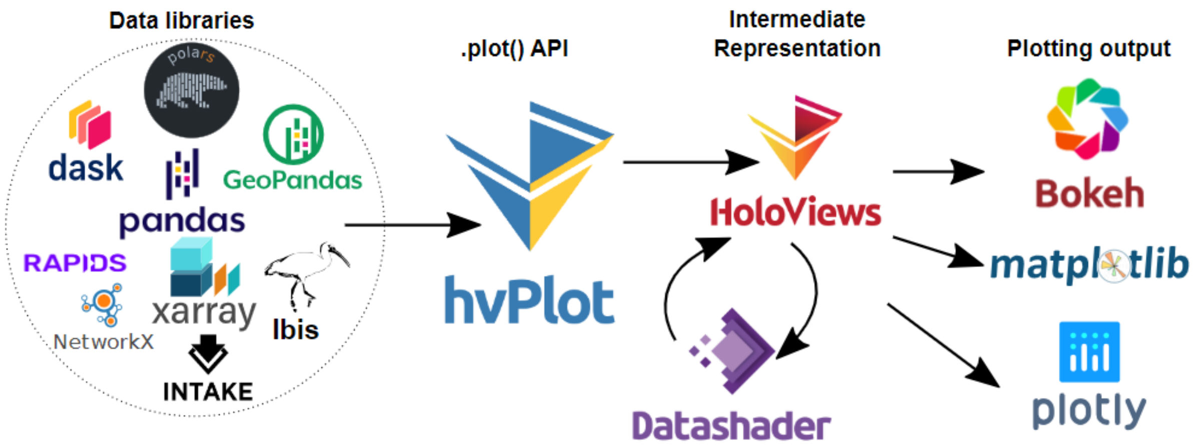
Powerplant: 20-25˚C





Results – Interactive Visualization

- Python 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



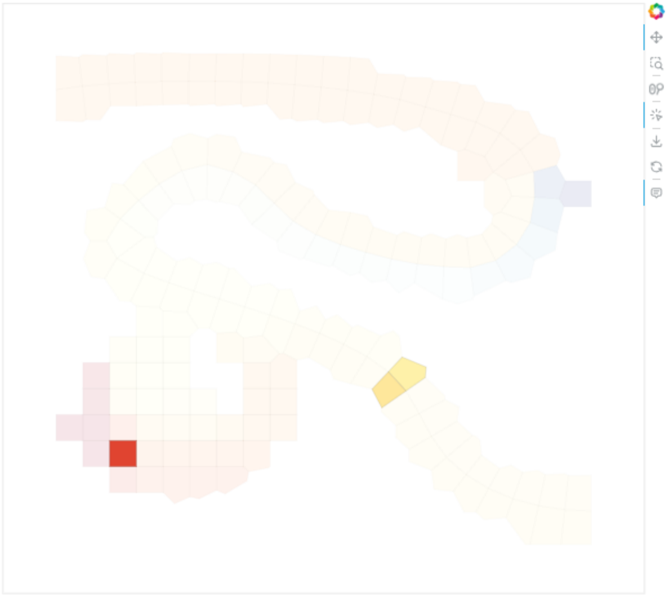
GeoViews

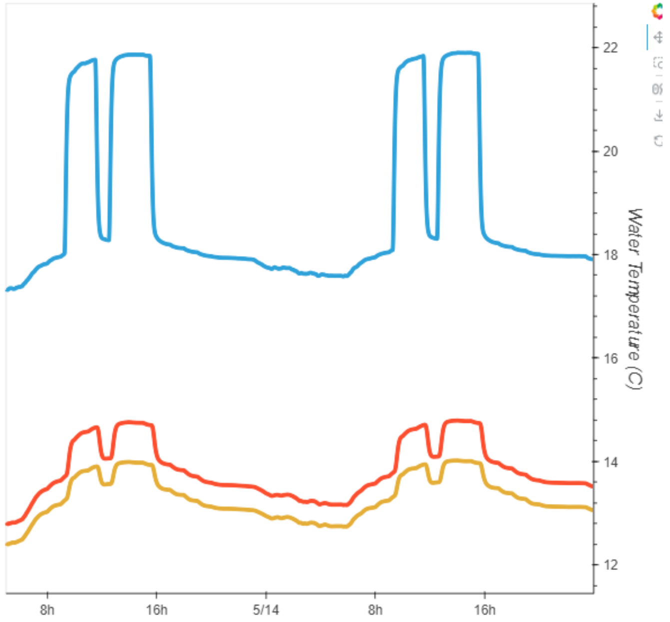
Panel

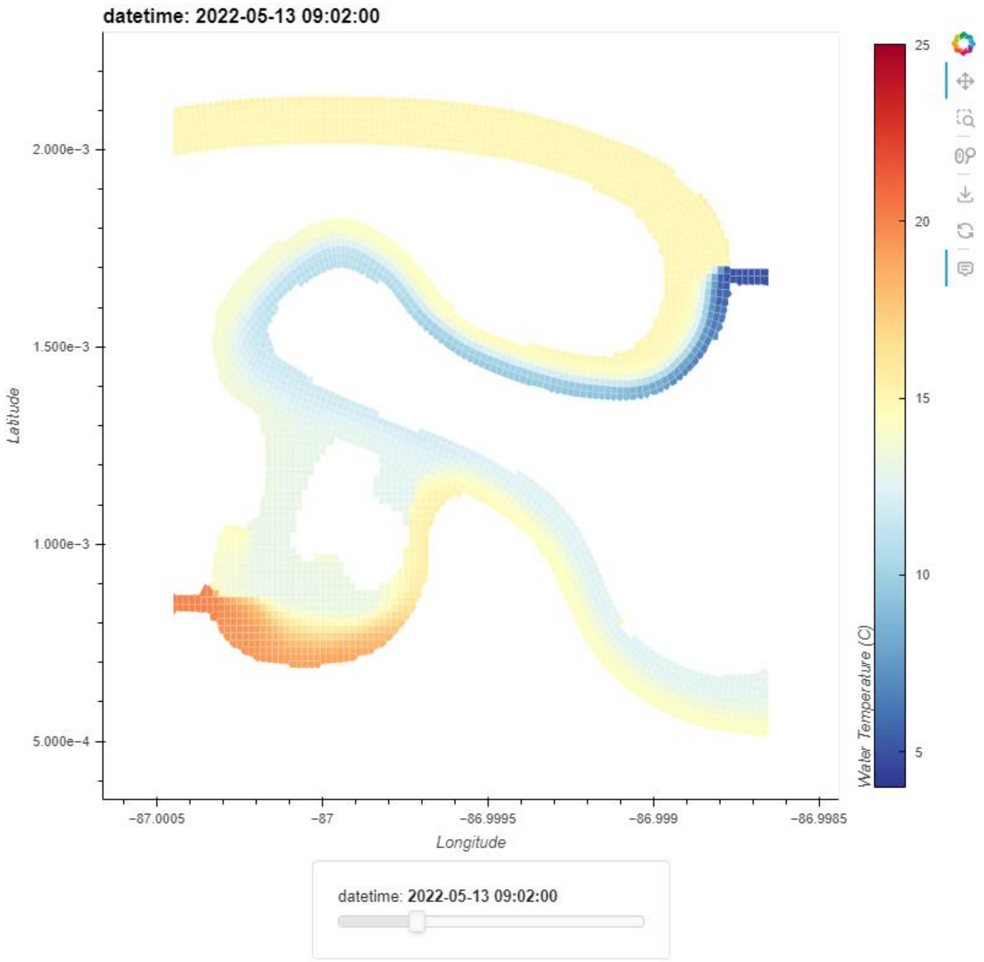
NUMFOCUS
OPEN CODE = BETTER SCIENCE

source

Results – Interactive Visualization Live Demo







Summary

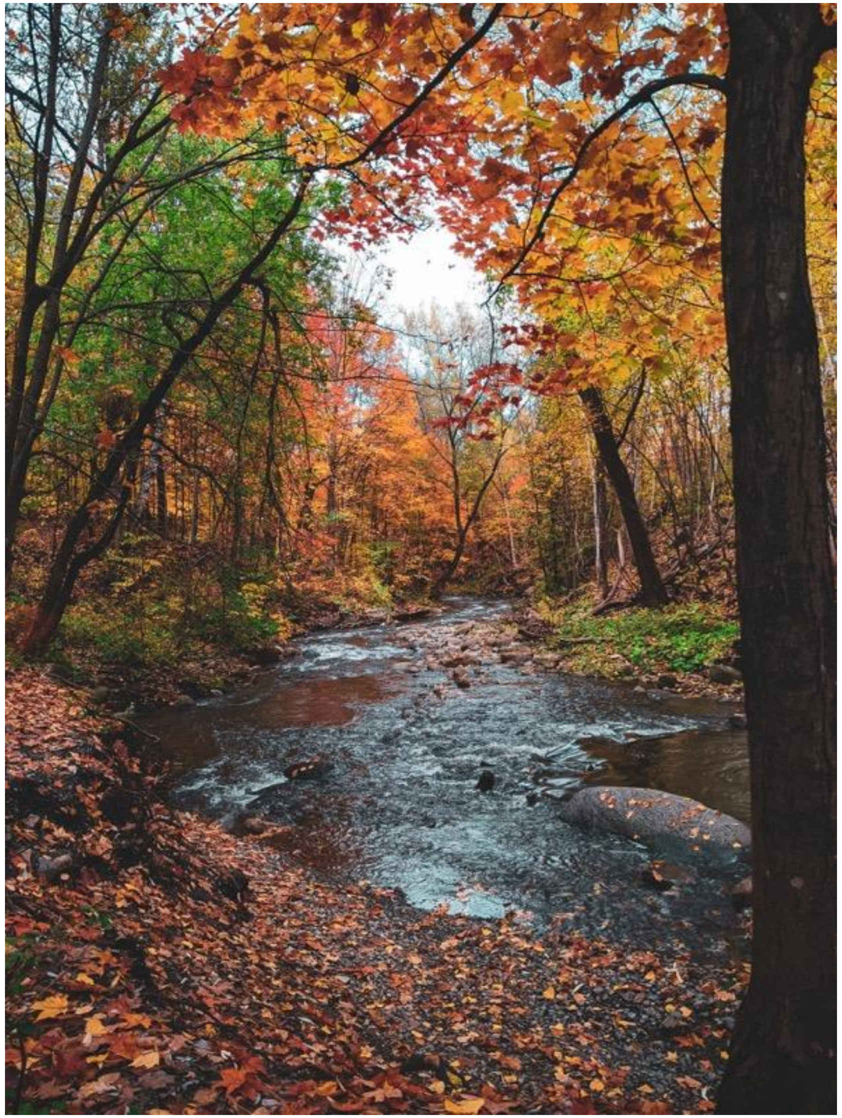
- ClearWater was expanded to simulate nutrient and temperature flow
- Flexible framework designed to link:
  - Water Quality models
  - Vegetation models
  - Water Resources models
    - HEC-RAS (2D)
    - GSSHA
- Demonstration showed simulation of heat transport in a complex riverine system

Benefits

- Improved understanding of how nutrient dynamics influence species distribution patterns
- Informs invasive species management
- Enhanced ability to predict and develop targeted ecosystem restoration strategies based on nutrient availability and species responses
- Better insights into the role of nutrient cycling in ecosystem functioning (e.g., primary productivity)
- Supports informed management decisions
- Improves prediction of carbon cycling (e.g., supports carbon sequestration analyses)

Implications for Next Generation Ecological Modeling

- 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




Questions?