ClearWater-Riverine:

An Integrated Water Quality Modeling Framework for Riparian and Floodplain Ecosystems

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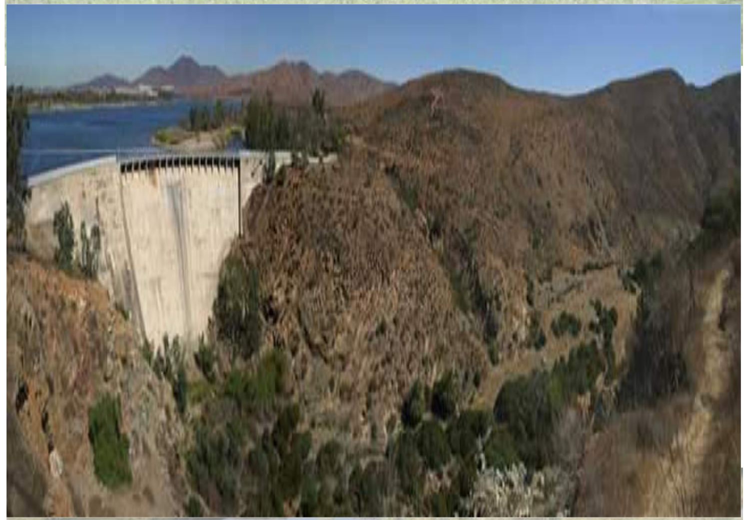
Introduction

Watersheds comprise a complex web of interactions as water, heat, nutrients, and contaminants flow in varying frequency and quantities through riverine ecosystems. Integrated process-based riverine water quality models are needed to incorporate these processes and interactions in river channels, riparian buffers, and floodplain ecosystems. These models will reliably predict changes to watersheds due to stressors, e.g., land use and climate change, as well as alterations associated with beneficial actions, such as ecosystem restoration.

ClearWater:

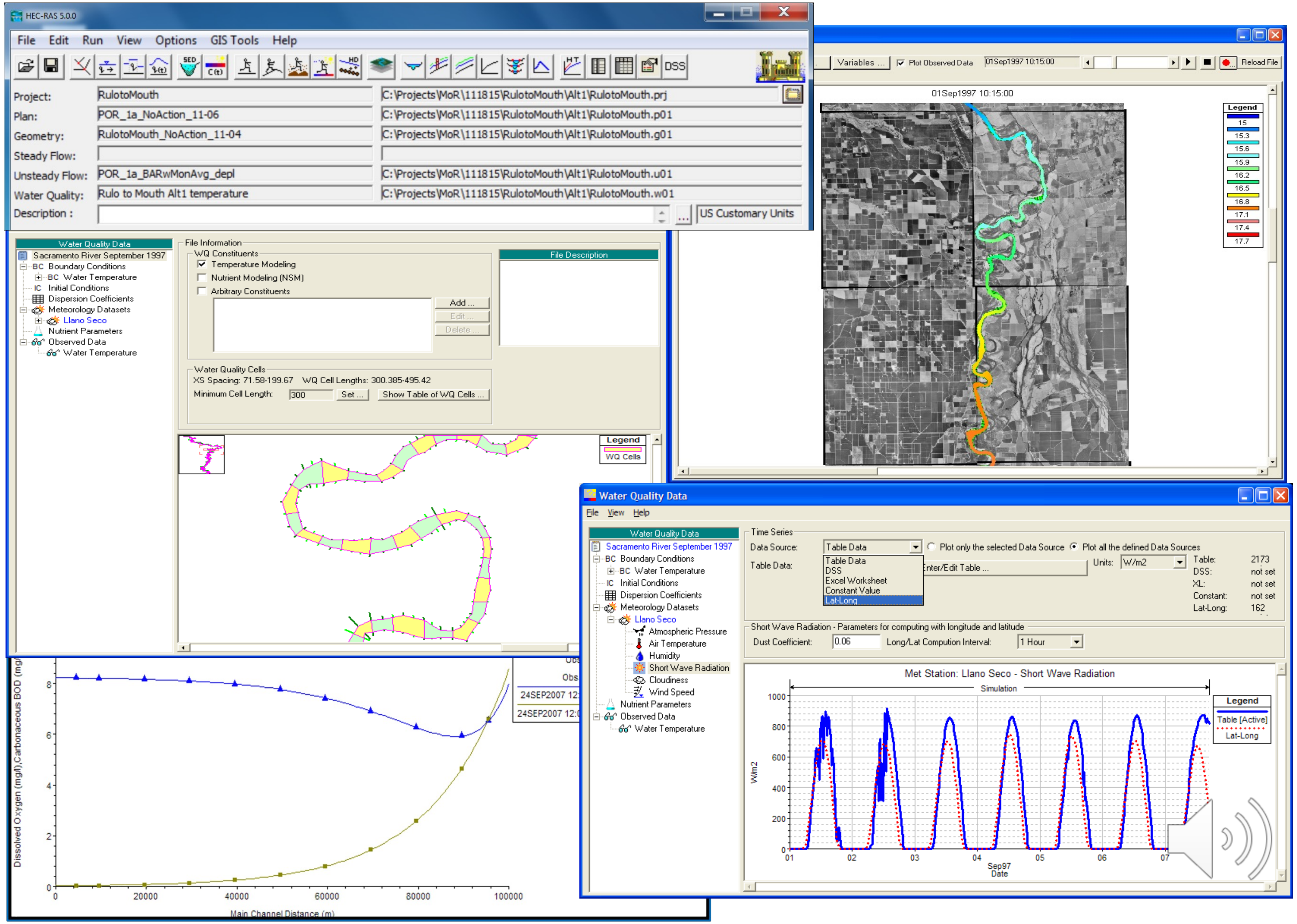
Corps Library for Environmental Analysis and Restoration of Watersheds

- The Environmental Systems Modeling team of the U.S. Army Corps of Engineers (USACE) has developed a modular library of environmental modeling capabilities, ClearWater, which provides environmental simulation capabilities that leverage existing hydrologic and hydraulic (H&H) models.
- The Environmental Laboratory of the USACE Engineer Research and Development Center (ERDC) is leading this effort, in collaboration with the USACE Hydrologic Engineering Center (HEC).
- Water quality kinetics and vegetation simulation modules include the following:
  - NSM: Nutrient Simulation Module (NSM-I and NSM-II)
  - TSM: Temperature Simulation Module
  - GCSM: General Constituent Simulation Module
  - CSM: Contaminant Simulation Module
  - MSM: Mercury Simulation Module
  - SSM: Solids Simulation Module
  - RVSM: Riparian Vegetation Simulation Module
- Water quality engine computes transport (advection and diffusion) of heat and mass across the watershed.
- Integration of water quality with HEC-ResSim, HEC-RAS, and HEC-HMS enable
  - Efficient development and application of new capabilities and
  - Linking water quality data with existing visualization and reporting capabilities.



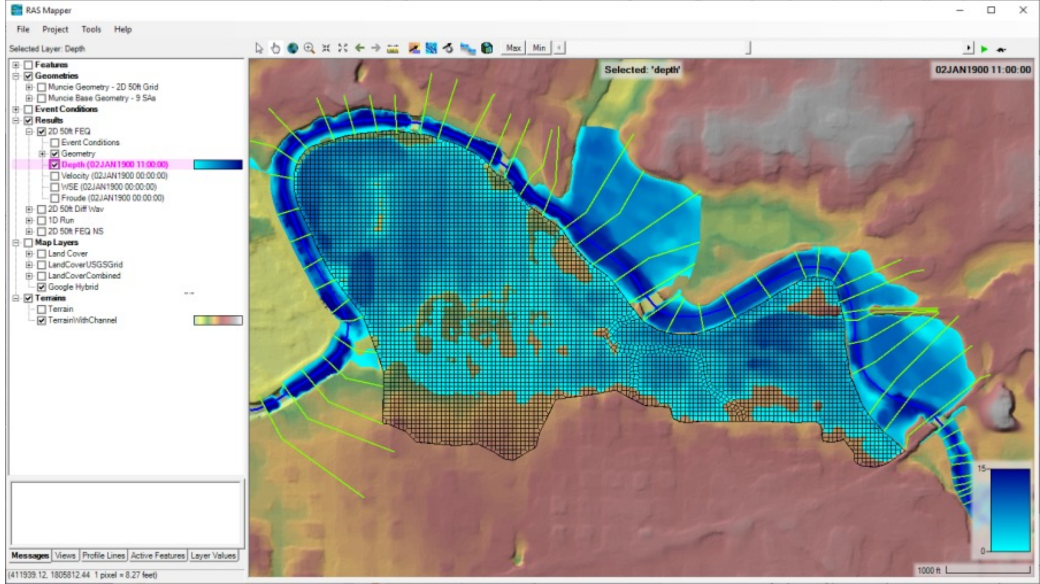
HEC-RAS River Water Quality (1D)

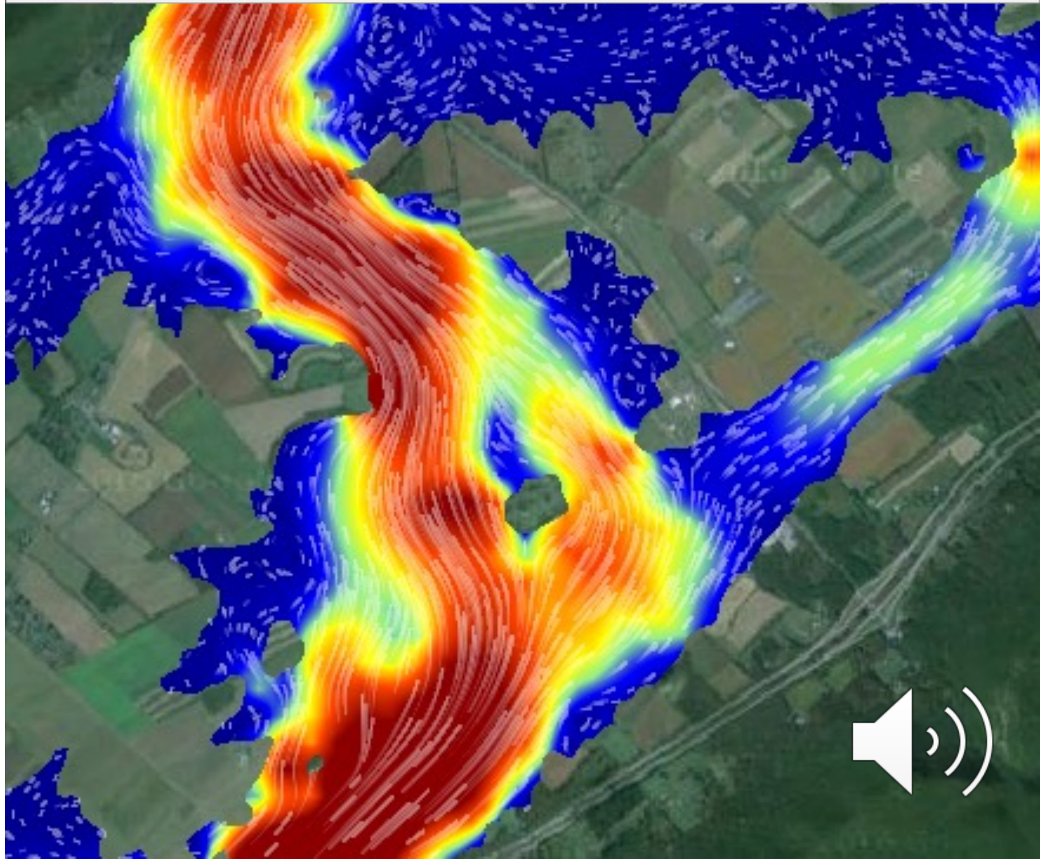
- The USACE Hydrologic Engineering Center's River Analysis System (HEC-RAS) simulates one- and two-dimensional (1D and 2D) river hydraulics:
  - Computes river velocities, stages, profiles, and inundated areas (with RAS Mapper) given stream flow and geometry
  - Industry standard hydraulic tool used worldwide
  - 100,000 worldwide downloads per year
  - One-dimensional (1D) water quality capabilities allow environmental impacts assessments in rivers and streams



HEC-RAS-2D: Hydrodynamic Simulations

- HEC-RAS can perform two-dimensional (2D) hydrodynamic routing within the unsteady flow analysis portion of the program.
- 2D flow areas in HEC-RAS can be used in several ways. The following are examples of how 2D flow areas can be used to support modeling with HEC-RAS:
    - Detailed 2D channel modeling
    - Detailed 2D channel and floodplain modeling
    - Multiple 2D flow areas in the same geometry
    - Directly connect multiple 2D flow areas with hydraulic structures
    - Mixed flow regime. The 2D capability (as well as the 1D) can handle supercritical and subcritical flow, as well as the flow transitions from subcritical to super critical and super critical to subcritical (hydraulic jumps).
- 2D flow modeling is accomplished by adding 2D flow area elements into the HEC-RAS model in the same manner as adding a storage area.
- A 2D flow area is added by following these steps:
    - Drawing a 2D flow area polygon
    - Developing the 2D computational mesh
    - Linking the 2D flow areas to 1D model elements and/or directly connecting boundary conditions to the 2D areas.





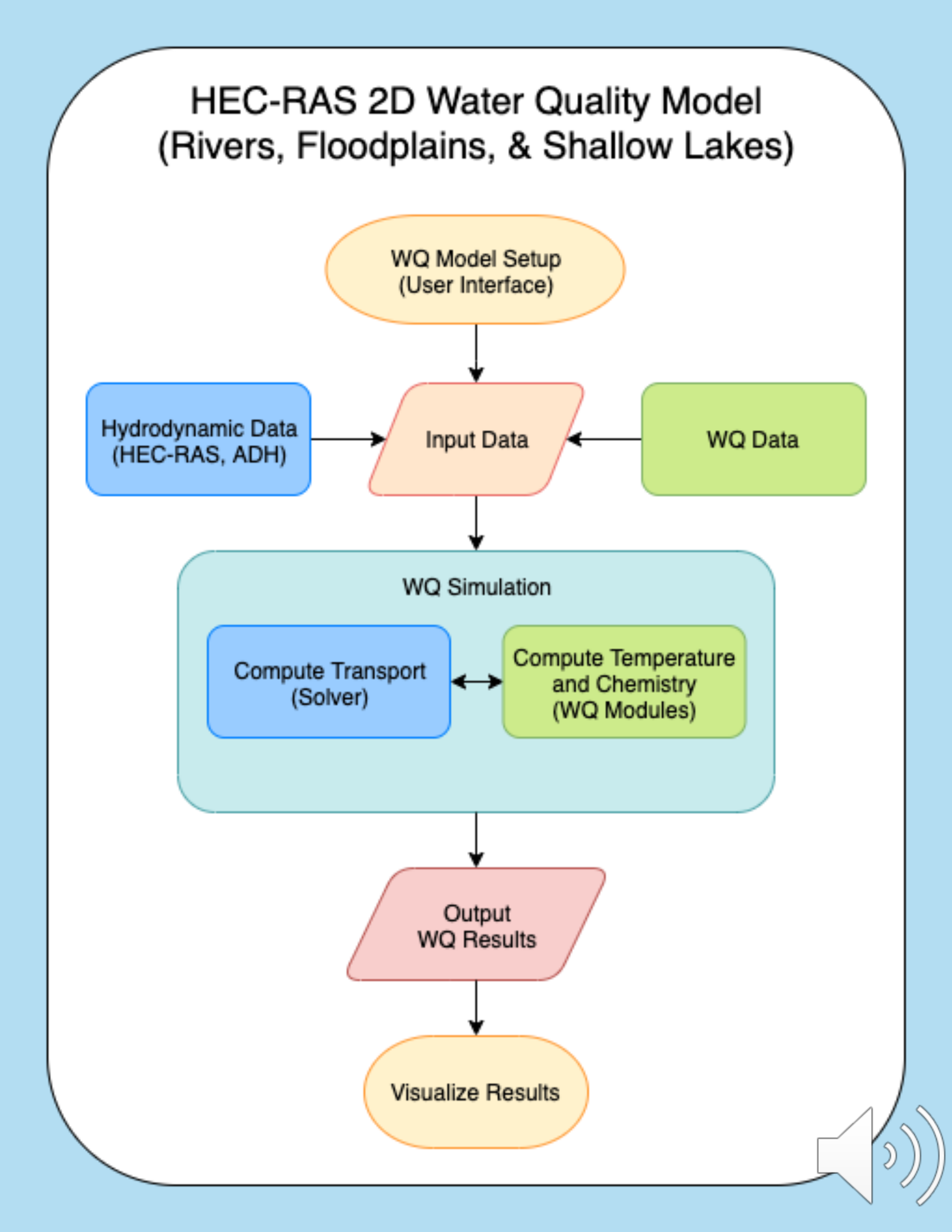
ClearWater-Riverine

- The ERDC Environmental Laboratory (ERDC-EL) is developing a state-of-the-art water quality modeling system, Clearwater-Riverine, that 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.
- ClearWater-Riverine will enable the evaluation of system vulnerabilities and identification of adaptation pathways to improve the resilience of floodplain ecosystems to environmental stresses, which include increasing frequency and intensity of extreme precipitation events and decreasing freshwater flows.
- Water quality kinetics, heat budget, and transport simulation capabilities in ClearWater-Riverine are furnished by ERDC's ClearWater modules.
- The ClearWater-Riverine framework links the capabilities provided by the ClearWater modules and advection-diffusion engine with the two-dimensional (2D) HEC-RAS model.
- HEC-RAS models have been developed for most of the watersheds around the world. By leveraging these existing models, ClearWater-Riverine provides a cost-effective, data-driven tool for impact assessment, planning studies, and the restoration and management of aquatic ecosystems.

ClearWater-Riverine

2D Water Quality Modeling with HEC-RAS

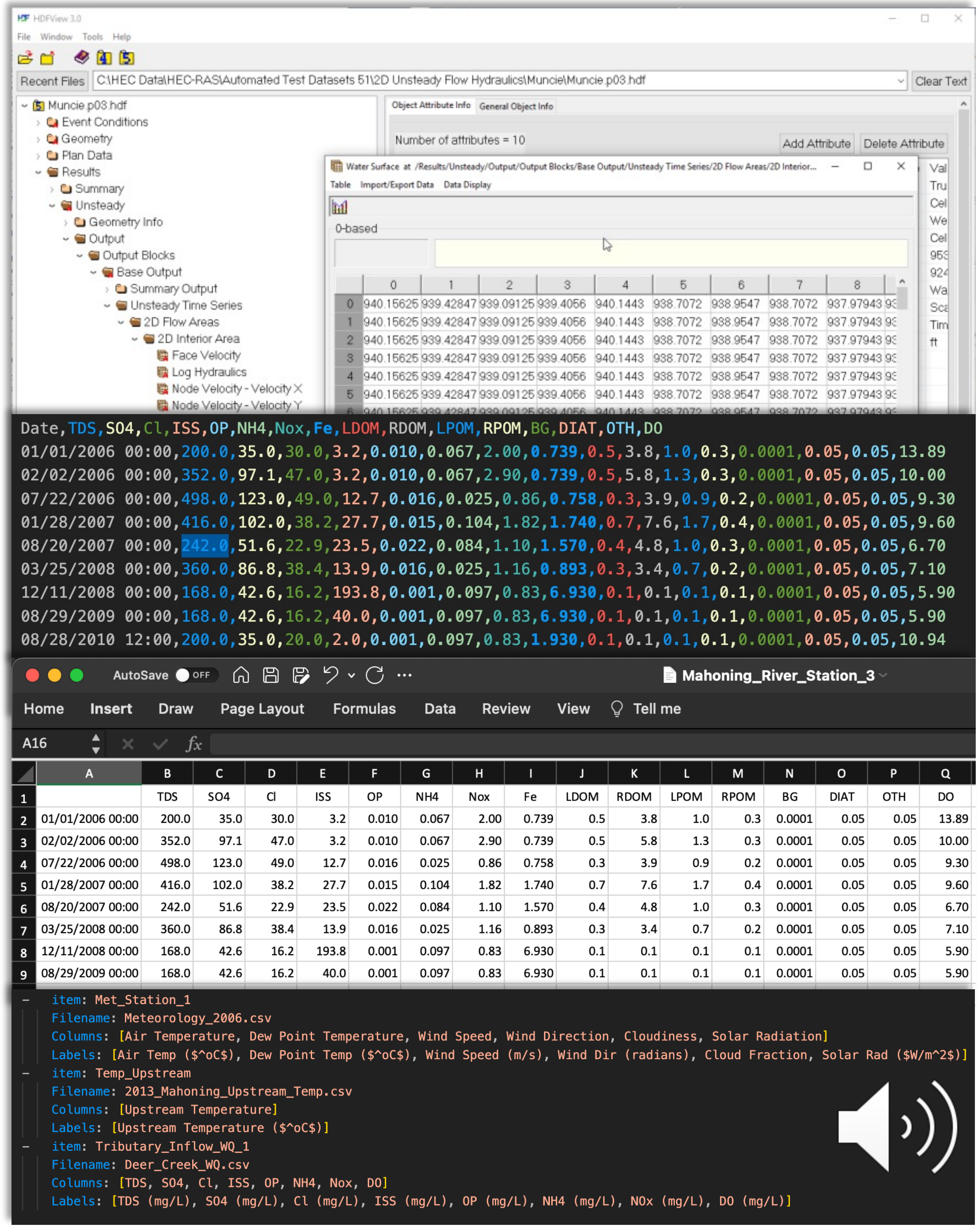
- Inputs
  - HEC-RAS-2D Model Data
    - Volumetric flows, velocities, depths
    - Model grid (bathymetry)
  - Observed meteorology and water quality time series
- ClearWater water quality modules
  - Compute heat budget and constituent kinetics for each cell
- Water Quality Engine
  - Computes advection-diffusion across the model grid at each time step
- 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
- Framework
  - Controls model input and output
  - Controls the computational, input, and output time steps
  - Controls simulation across the model grid
  - Coordinates engine, modules, and data



Data Storage and Exchange

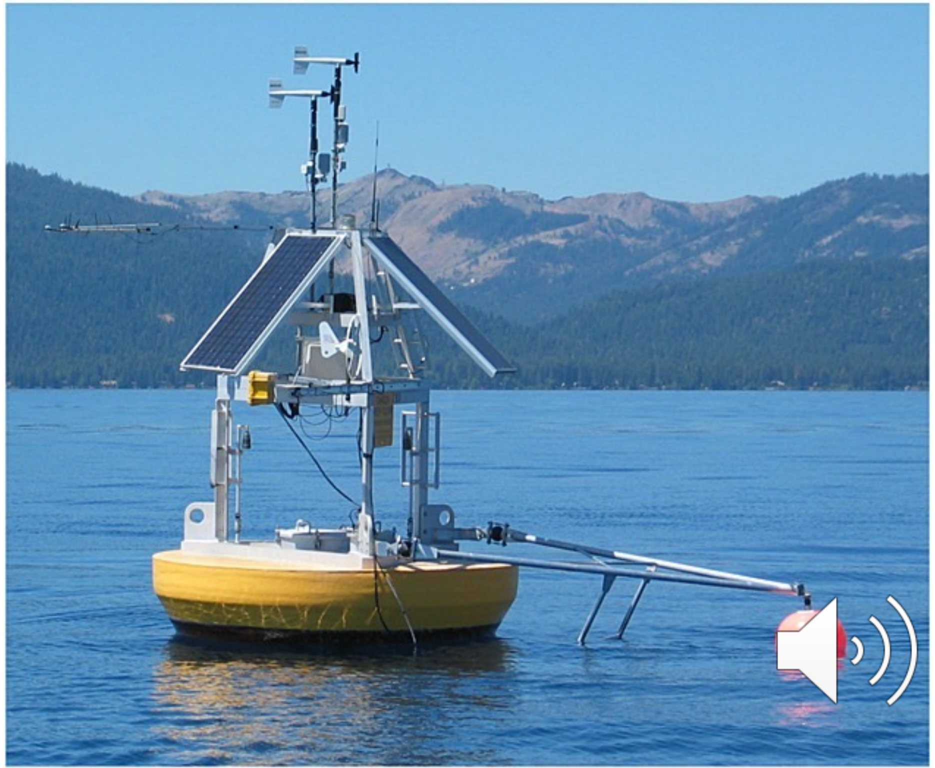
The following file formats support data input and output (I/O):

- HDF5: Hierarchical Data Format, Version 5
  - Open standard format developed by the National Center for Supercomputing Applications. Supported by the HDF Group.
  - Purpose: Store data along with associated metadata in a hierarchical structure analogous to files (datasets) and folders (groups)
  - Python data structure: xarray
  - Python library: h5py
- CSV: Comma-Separated Values
  - Python data structure: data frames
  - Python library: pandas
- Microsoft Excel
  - Python data structure: data frames
  - Python library: pandas
- SQLite
  - Python data structure: data frames
  - Python library: pandas
- YAML:
  - User-friendly superset of JSON
  - Used for configuration files



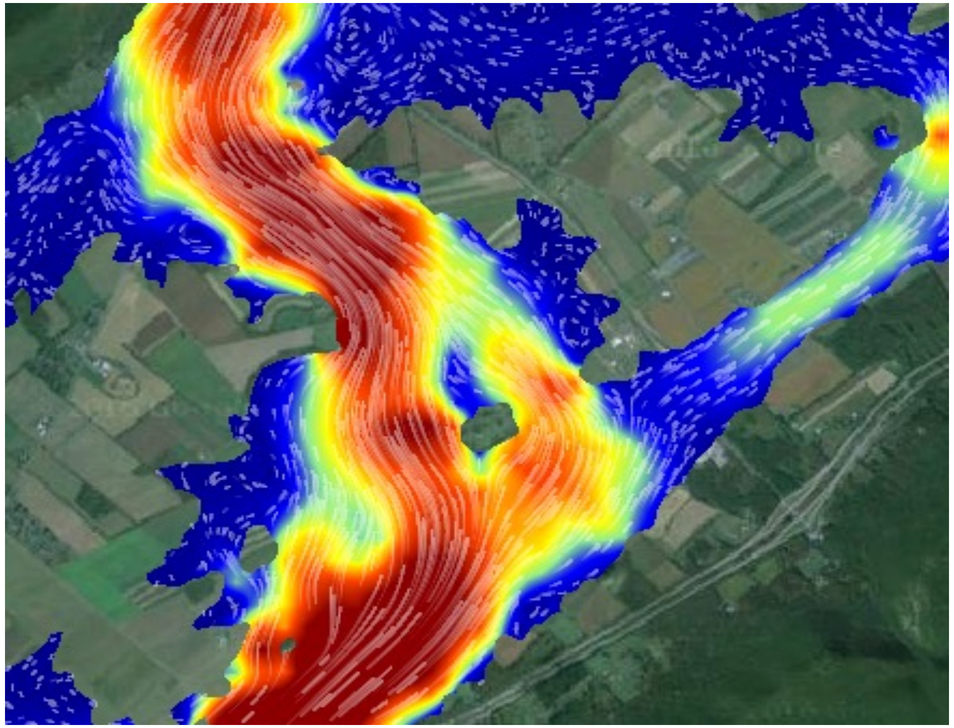
Input Data

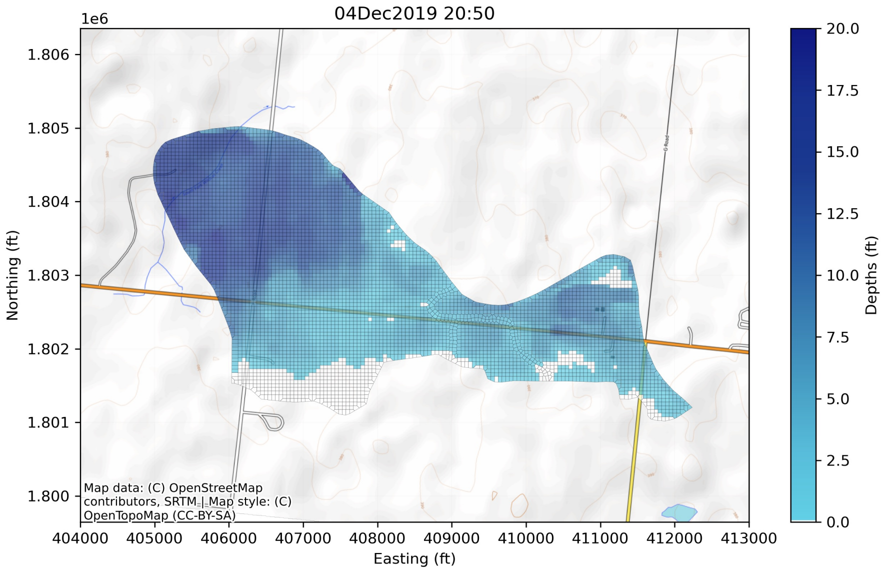
- Categories
  - Boundary Conditions
    - Time series of meteorological forcing
    - Time series of inflows of heat and mass at important tributary locations
  - Initial Conditions
    - Initial values at upstream boundaries
    - Initial values of water surface elevation, temperature, and constituent concentrations throughout the model grid
- Variables
  - Hydrology & Hydraulics
    - Velocity, depth, volumetric flow
  - Meteorology
    - Shortwave radiation, air temperature, wind speed & direction, relative humidity, air pressure, cloudiness
  - Water Temperature (and heat budget components)
  - Water Quality Constituents
    - DO, nutrients, chlorophyll-a, contaminants, etc.

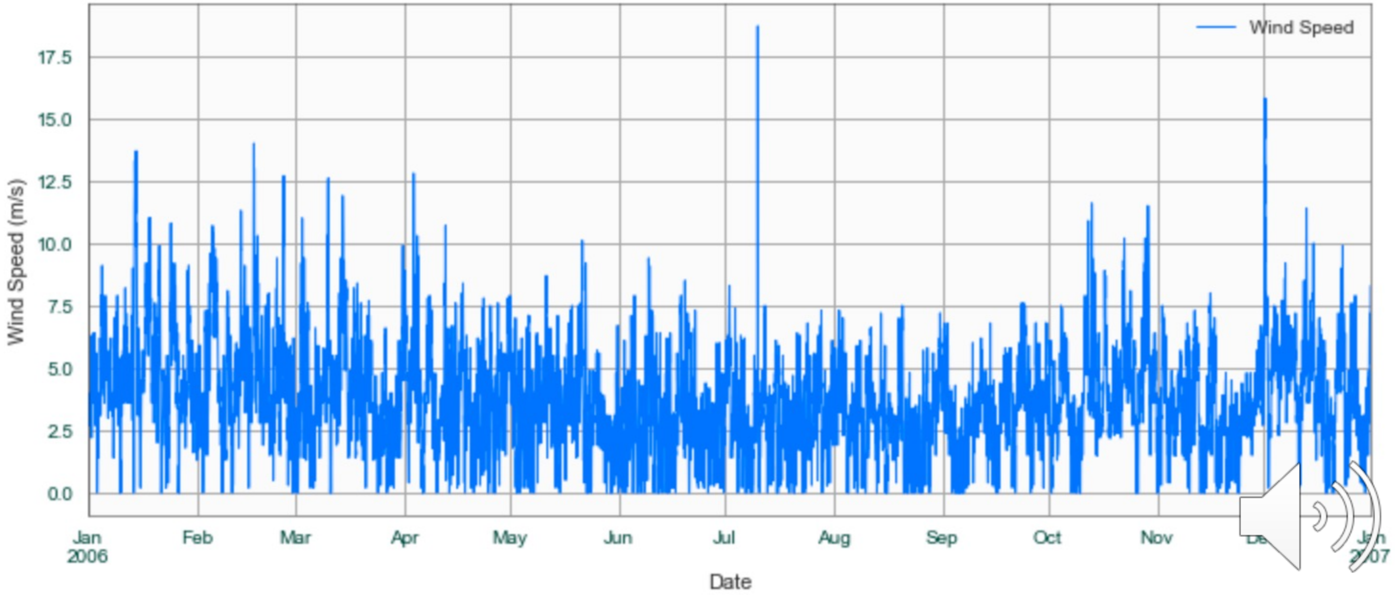


Output Data and Visualization

- 2D: Time series of model grids
  - Water Temperature (and heat budget components)
  - Water Quality Constituents
    - DO, nutrients, chlorophyll-a, contaminants, etc.
- 1D: Time series at user-specified locations
  - Water Temperature (and heat budget components)
  - Water Quality Constituents
    - DO, nutrients, chlorophyll-a, contaminants, etc.
  - Hydrodynamics







File Formats

Input Data	HDF5	CSV	Excel	SQLite
Model grid	✅			
2D hydrodynamic time series	✅			
1D water quality time series	☑️	✅	✅	☑️
1D meteorology time series	☑️	✅	✅	☑️

Output Data	HDF5	CSV	Excel	SQLite
2D water quality time series	✅			
1D water quality time series	✅	✅	☑️	☑️
1D hydrodynamics time series	✅	✅	☑️	☑️

✅ Primary or preferred format
☑️ Supported format

Data Processing and Exchange: Input Data

- Station Class
  - Handles meteorology and water quality inputs
  - Handles water quality outputs
  - Easily inputs time series from Excel, CSV, and HDF5
  - Supports temporal interpolation at any model time step and irregular input time series data
  - Supports creating constant-value time series for any variable
  - Plot function allows the generation of period-of-record time series for each variable that has been added to the station

Framework: Input Data

- Meteorology Stations
  - Support standard meteorological measurements and data, such as wind coefficients
  - Correct for wind sensor height
  - Estimate atmospheric pressure from station elevation and air temperature
  - Estimate solar radiation from station geolocation and cloudiness
  - Handle spatial interpolation between stations
- Water Quality Stations
  - Support input of WQ time series
  - Allow input of observed data and other time series data to drive or calibrate & validate the model

Framework: Output Data

- Output Stations
  - Support water quality and hydraulic outputs
  - 2D time series are output to HDF5
  - Time series output supported for specified grid cells or regions
  - Allow specifying a radius. A time series of the average of all cells falling within that radius of the station will be output to either CSV or HDF5

Benefits

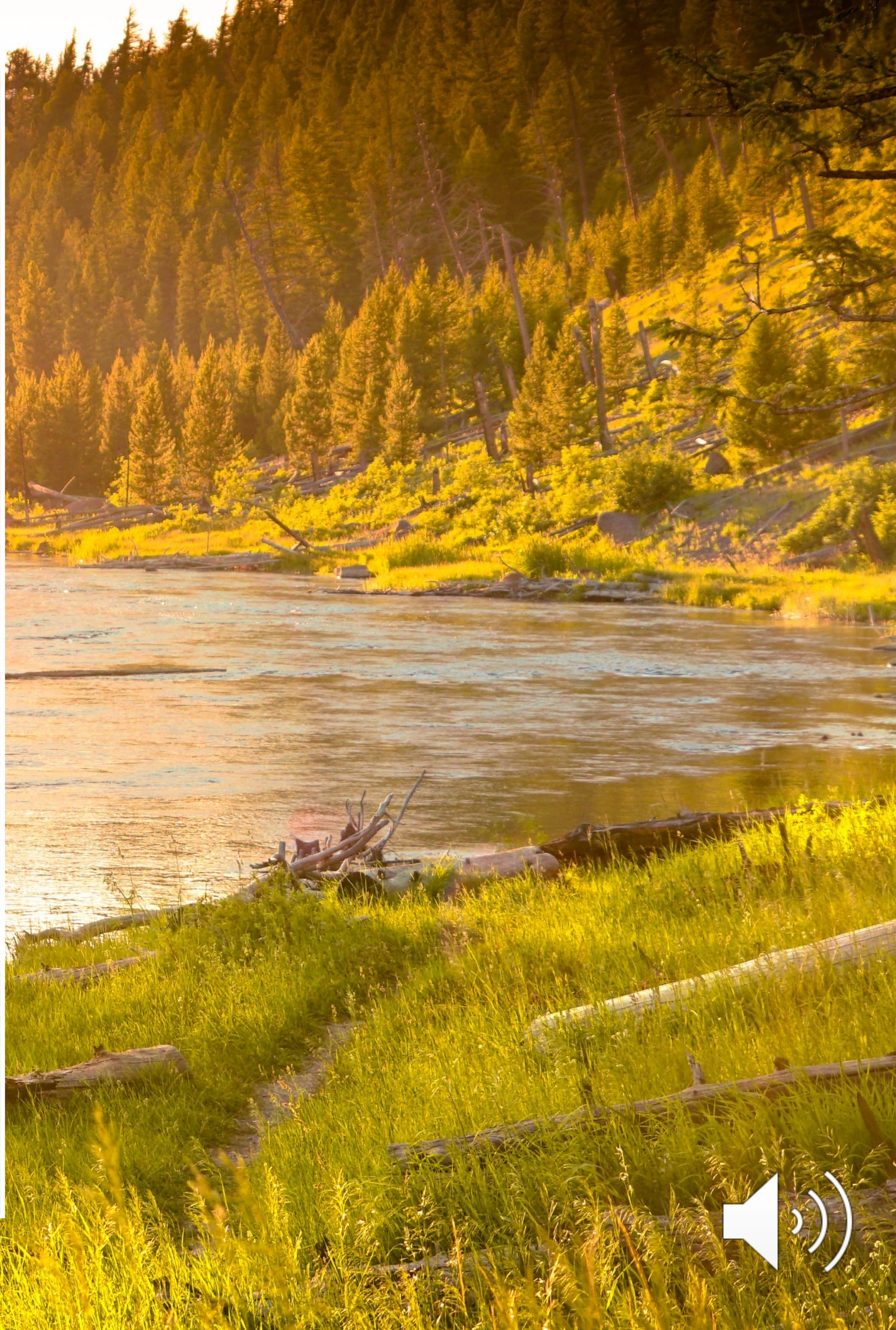
- Improves decision-making capabilities and reduces operations and maintenance costs
- HEC-RAS models provide detailed river hydraulics data and maps (flow, velocity, and water levels). Integrating water quality capabilities leverages these capabilities and existing models to provide detailed hydraulics and water quality information for riverine systems (rivers, streams, floodplains, etc.).
- HEC-RAS is already widely deployed for ecosystem restoration projects – as a *hydraulic* model. Water quality capabilities provide critical short-term and long-term information about dynamic river systems. This provides important information for designing restoration projects that are stable and functional, while also reducing operations and maintenance costs.
- Leverages existing models and expertise, reducing costs. HEC-RAS is widely deployed (100,000 downloads per year), with calibrated hydraulic models already applied to almost all rivers and streams in the U.S., thus significantly reducing the modeling effort and project costs relative to developing separate water quality models.

Summary

- ClearWater-Riverine will provide a state-of-the-art riverine water quality modeling system to simulate water temperature and water quality in branching river systems and floodplains, incorporating hydrodynamic, water quality, and meteorologic inputs from multiple sources, including hydrologic, hydraulic, and non-point models, climate models, and observed data.
- ERDC's ClearWater modules and engine provide water quality kinetics, heat budget, and transport simulation capabilities in ClearWater-Riverine.
- The ClearWater modules were developed to extend state-of-the-art hydrologic and hydraulic (H&H) modeling tools and has linked or integrated with several widely used USACE H&H models to simulate water quality in rivers, reservoirs, and watershed runoff.

Summary, Continued

- ClearWater-Riverine leverages two-dimensional HEC-RAS river-and-floodplain models to enable cost-effective, data-driven impact assessments, planning studies, and aquatic ecosystem restoration and management.
- To efficiently transfer data between models, ClearWater-Riverine uses open-source file formats that support large, complex, and heterogeneous data and metadata.
- ClearWater-Riverine’s modeling framework links hydrologic, hydraulic, hydrodynamic, and water quality models while providing data visualization and analysis capabilities.
- The integrated modeling system enables identification of system vulnerabilities as well as adaptation pathways that improve ecosystem resilience to environmental stresses, which are predicted to increase due to frequent and intense extreme precipitation events and diminishing freshwater flows.



Acknowledgements

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