Sediment and Eco-Hydraulics Modeling Roadmap

Research and Development Office
Science and Technology Program
Final Report EN-2019-8240-01

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Reclamation is responsible for large water resource infrastructure in the Western United States and a critical component to managing the water is managing the sediment that it carries. These large dams and diversions dramatically alter the routing of sediment and interrupt natural processes causing both positive and negative impacts. Because of this, Reclamation has a long history in the development of sediment analysis numerical models, tools and methods. This report details a Sediment and Eco-hydraulics Modeling Roadmap for Reclamation’s Science and Technology Program that can be used to assist in the development and evaluation of future research proposals.</td></tr>
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Sediment and Eco-Hydraulics Modeling Roadmap

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Reclamation S&T Sediment and Eco-Hydraulics Modeling Roadmap

Reclamation is responsible for large water resource infrastructure in the Western United States. A critical component to managing the water is managing the sediment that it carries and mitigating for impacts to endangered species habitat. Large dams and diversions dramatically alter the natural environment, affect the routing of sediment and interrupt natural processes causing both positive and negative impacts. Because of this, Reclamation has a long history in the development of sediment and eco-hydraulic numerical models, tools and data post-processing methods. This report details a Sediment and Eco-hydraulics Modeling Roadmap for Reclamation's Science and Technology Program that can be used to assist in the development and evaluation of future research proposals. Within Reclamation, the intended audience is researchers along with resource managers to facilitate knowledge transfer of existing research efforts and potential collaborations for research needs. The audience is also intended to be partner agencies and academic institutions to further broaden partnership opportunities and additional knowledge sharing among environmental research sediment and eco-hydraulics modeling topics. Feedback on research needs was solicited within Reclamation's Technical Service Center along with regional and area offices through the Science and Technology Regional Coordinators. We received additional helpful ideas on research needs from colleagues at the U.S. Army Corps of Engineers, U.S. Geological Survey, and Bonneville Power Administration.

Eco-hydraulics is a field concerned with the interactions between fluids and the biota that live in them. Some of the more common examples where sediment and eco-hydraulic analysis is necessary to inform water resource and management decisions are listed below and shown in Figure 1.

1. ***Reservoir Sediment Management***. Sediment and debris accumulate in all reservoirs on natural watercourses. For example, sediment and debris have filled in almost 20% of the Paonia Reservoir in Colorado, significantly reducing the ability to make downstream water deliveries. In fall of 2014, sediment and debris plugged the intake trash rack and now requires continual cleaning, and the minimum pool evaluation was raised to prevent future plugging. The raise in the minimum pool further reduces the volume of water available for delivery. Sediment analysis models help predict future sedimentation rates and evaluate sediment management alternatives.

2. ***Stream Restoration and Habitat Assessment***: Reclamation performs large scale stream modifications to improve fish habitat to meet environmental compliance requirements and recovery program goals on the Trinity River, San Joaquin River, and Rio Grande River and in several watersheds within the Columbia Basin. Eco-hydraulic assessments are critical to quantifying the benefit of these projects. In addition, in many cases, it is necessary to estimate future channel evolution resulting from proposed restoration features, particularly when changes occur to the river and floodplain connectivity or hydrologic regime.

3. ***Sedimentation at Diversions***: Reclamation has built and operates many diversions in rivers with large sediment loads. The sediment in the diverted water can plug fish screens, reduce conveyance in canals, and increase water treatment costs. It is often necessary to design sediment management programs and facilities so that diversions can proceed uninterrupted. Some examples where Reclamation is currently assisting on the design of sediment management programs at diversion include: Isleta Diversion on the Rio Grande, Robles Diversion on the Ventura River, the proposed Delevan diversion on the Sacramento River, and the planned diversion on the San Juan River.

4. ***Scour near Facilities***: Rivers can naturally scour their bed and banks. Because Reclamation facilities are constructed along the beds and banks of rivers, this infrastructure needs to be protected from scour. Some examples include the protection of bridge piers and abutments or the protection from scour at pipeline crossings.

5. ***Gravel Augmentation***: Gravel augmentation downstream of dams has been a central restoration strategy to improve salmon spawning success. Sediment transport analysis tools assist in the prediction of the location, timing and amount of gravel necessary to meet sediment composition goals. Gravel augmentation is being performed on many rivers including the Trinity, Sacramento, Stanislaus, and American Rivers.

6. ***Reservoir operations***: An operational understanding of the effects of our projects on water quality parameters such as temperature is critical for meeting environmental targets. For example, temperature targets exist on the Trinity, Sacramento, Columbia Rivers and those targets can require alteration of reservoir operations, particularly during drought years.

There are many different types of sediment and eco-hydraulics analysis that can be performed. Generally, the types of analysis can be categorized into empirical methods, physical models, and then one-dimensional (1D), two-dimensional (2D), and three-dimensional (3D) models. Empirical methods include simple direct relationships between variables. For example, empirical relations can estimate the amount of scour in a river bed given a certain flow and river bed material. The relations are useful but will be limited by the range of available data that was used to develop them. Physical models are scaled representations of the real system where the physical features and water flow are essentially miniaturized to fit inside laboratories. The scaling is performed so that the essential physics of the system are retained. 1D models compute cross section averaged properties to estimate erosion and deposition volumes within cross sections. They are most appropriate for simple geometric systems where we need to estimate reach-averaged results. 2D models average properties over the river depth and are useful for more complex problems, such as diversion design and complex river restoration design. 3D models are useful when significant changes in the vertical direction need to be resolved, such as flushing of sediment through low level gates in a full reservoir and scour around in-stream structures. The data input and computational resource needs escalates from the progression of 1D to 2D and 3D models. Research to improve efficiency of pre- and post-processing tools is an important component as technical advances are made in predictive capabilities.

This roadmap focuses on research needs for numerical models and tools for use in eco-hydraulic and sediment analysis. A numerical model's life-cycle follows the general procedure listed below:

1. **Conceptualization**: The development of a conceptual model will start with a literature review and overview of existing models. Then a conceptual model will be described that incorporates the processes relevant to the system one is analyzing. This step may include identification of a mathematical construct of the conceptual model.

2. **Codification**: The model will be codified into a computer language.

3. **Verification**: The model will be tested to ensure that gives the intended answers. the associated data accurately represent the conceptual model and underlying mathematical construct. Verification data includes information to compare at intervals within the model code to ensure the output is reproducing expected values, or if not debug to address.

4. **Calibration**: The model parameters will be adjusted using available experimental data to improve agreement.

5. **Validation**: The model will be tested against other data from laboratory and field cases and evaluated for how well the model can represent real world systems for the intended application. This step will include uncertainty analysis of model results.

6. **Application**: The model will be applied to its intended purposes.

The model development process may not be entirely linear, and some iteration is expected as new information or problems arise. Research proposals typically accomplish only a portion of the model life-cycle, and they should explicitly define which parts of the cycle they will address. In the next section, research needs are highlighted relative to sediment and eco-hydraulics modeling tools.

Sediment and Eco-Hydraulics Modeling Roadmap

The roadmap was developed and based on over twenty years of model development and application experience by the Sedimentation and River Hydraulics Group at the Technical Service Center of Reclamation. The SRH Roadmap falls within and serves as a supplement to the broader category Environmental Research roadmap produced in 2018. Project application and management questions helped inform the types of tools highlighted and research needs where more advancement is needed to improve model capability, accuracy, or efficiency. The SRH Roadmap focuses on reservoir and river sediment and eco-hydraulics modeling and does not address reservoir operations explicitly. The SRH Roadmap is organized into three application areas: River Restoration, Infrastructure Sustainability/Resiliency, and Water Quality. River restoration is central to Reclamation's mission of providing water and power in an environmentally sound manner. Because our infrastructure is essentially irreplaceable, the need for the sustainability and resiliency of our infrastructure is a continued challenge that requires multi-year to decadal predictions. The need to understand and predict water quality is important to meet water quality targets within reservoirs or downstream of Reclamation's dams for environmental compliance.

A description of the specific research needs within each category follows.

River Restoration to Meet Environmental Compliance Requirements

- **Aquatic habitat assessment –** River restoration projects have a basic need to quantify the habitat generated by their projects. In general, these assessments are in the application phase, but as the fish science evolves in time, there is a need to adapt hydraulic models and the processing of their results to better reflect the latest science in fish biology and habitat assessment. These updated methods would be implemented into 2D and 3D models. Further development of both 2D and 3D models, however, is needed to increase the assessment area and reduce the computation speed. Habitat assessments can also be used to capture changing interaction between a species and its habitats across different life cycle stages. Results from research in this category could provide input data for life cycle models or influence the choice of locations and goals for habitat restoration.

- **Fish passage and fish barrier –** There are many methods to improve fish passage around structures and numerical models are necessary to design and evaluate these facilities. There is also a need to develop structures and non-structural and non-structural methods to exclude fish from areas we do not want them to go to (fish barrier). This has been an extremely active area of research, but most of the design and analysis are empirical in nature. The current trend is to resort to numerical fish models that may predict fish movement behaviors in response to various eco-hydraulic changes. Recent research needs have arisen in specific areas, such as non-structural approaches to fish barrier and the attraction of juvenile fishes to fish collection facilities in large reservoirs.

- **Assessment and design of river restoration projects –** River restoration design is a rapidly evolving field and requires complex modeling tools to predict how the flow and sediment will respond to designs.

    - **Representation of river restoration structures and features –** Restoration design often includes the addition of significant amounts of woody material. There is lack of knowledge regarding how large wood features can and should be represented by numerical models. Both field data and testing of model formulations are necessary to develop technical guidance on best practices for analysis. Guidance may include topographic data or grid resolution, documentation of calibration data, flood risk analyses, and other important analyses steps in large wood design.

    - **Interactions between surface water and groundwater –** Groundwater is critical to the survival of riparian plant species and interactions between surface water and groundwater can be important in the regulation of water quality and temperature. There are currently no models available that can represent the detailed interactions in complex restoration projects.

- **Evolution of river restoration projects**

    - **Interaction of vegetation, hydraulics, and sediment –** A critical component in a heathy river system is the establishment and continual renewal of the riparian plant community. Current hydraulic and sediment models typically do not explicitly represent the plant community and how it interacts with flow and sediment processes. Conceptual models have been proposed in the literature, but further development of conceptual models, mathematical construct, field data collection, and model testing all need to be performed to better understand the interactions between vegetation, hydraulics, and sediment.

    - **Sediment transport and channel evolution in complex planforms –** Most sediment transport model testing and data collection has been in simple single-thread channels. There is a growing recognition that such river forms are not ideal for aquatic habitat and that multi-channel complex planform offer significantly more habitat value. There is a need to understand and codify the best methods to evaluate and predict the behavior of sediment and river geometry under complex river planforms.

<u>Infrastructure Sustainability/Resiliency</u>

- **Reservoir sediment sustainability and sluicing –** The sustainability of water supply in the Western United States will be related to our ability to manage the sediment in our reservoirs. The typical design methodology was to design the reservoir so that it would meet proposed project objectives with 100 years of sedimentation (Reclamation, 1982, Design of Small Dams). There was typically no plan in place about what to do after 100 years. We have already passed 100 years at many of our facilities and are rapidly approaching that age at several others.

    - **Prediction of sediment delivery to rivers and reservoirs –** Surveys of reservoir sedimentation exist only at approximately 30% of our reservoirs. There is a need to conduct more surveys and supplement them with hydrological models to better predict sedimentation rates. There are existing empirical models available from many decades ago, but those models could be drastically improved by using a larger and more current dataset and adopting/developing more advanced watershed models. Wildfires can increase sediment delivery to reservoirs. Predictions are needed to understand the impact to storage capacity and long-term sustainability of operations.

    - **Prediction of reservoir sedimentation patterns –** Once the amount of sediment is understood, it is necessary to estimate where in the reservoir it will be deposited. Current empirical methods exist to perform this, but more recent and comprehensive data could be used to improve the methods.

    - **Prediction of reservoir erosion, removal, and exclusion for sediment management –**Often the most efficient and economical approach to reservoir sedimentation is to drawdown the reservoir and allow natural erosion processes to move sediment from the reservoir to the downstream reach. There has been some testing of 1D models against field data at Paonia Reservoir. There is a need to improve and test 2D and 3D models for more complex situations. Additionally, more test cases with monitoring data are needed to better understand model performance and effectiveness with evaluating reservoir removal and exclusion alternatives relative to storage capacity.

- **Water diversion design and maintenance**

    - **Exclusion of sediment –** Sediment diverted into canals creates large and long-term sediment management costs that can be challenging to accomplish and pose impacts to threatened and endangered species. Research is needed to improve operation or infrastructure modification options to exclude sediment at water diversions, Sediment processes near diversion intakes are complex and cause operation and maintenance issues. Existing models cannot fully capture the complexities at these structures when modifications or replacement alternatives are being analyzed to reduce sediment impacts. Site specific sediment problems are common and it is often necessary to extend current sediment modeling capabilities to address such concerns.

<u>**Water Quality to Meet Environmental Compliance Requirements**</u>

- **Contaminant risk due to heavy metals in reservoir deltas –**Reservoir deltas can accumulate heavy metals such as mercury that were mobilized during past mining or other industrial practices and are attached to the sediment. These reservoir deposits can be unintentionally mobilized as the reservoir elevation fluctuates during normal reservoir operations or intentionally mobilized during reservoir sediment management activities. Sedimentation and erosion models need to be coupled to models of the speciation of heavy metals to understand the fate and transport of these contaminants. There are no known models available that can simultaneously predict the complex sedimentation and chemical processes that occur, and therefore model development will be necessary.

- **Sediment modeling in the context of wildfires –** Wildfires can increase sediment loads from contributing basins to reservoirs. Modeling is needed to understand potential for sediment mobilization to ensure that water quality meets established standards. Additionally, sediment disturbed in wildfires may contain contaminants that are washed into reservoirs in subsequent rains. Modeling is needed to understand the risk of sediment mobilization and fate of the transported sediment.

- **Temperature and other water quality parameters in rivers and reservoirs –** A natural temperature regime is critical to the survival of aquatic species. Temperature models of the reservoir and river are used in planning of reservoir operations. Other water quality parameters may also be of concern for endangered species habitat maintenance in wetlands, side channels, or other aquatic areas. Continued support and improvement of models is necessary as water demand and scarcity rise in the Western United States. Tools are needed to better assess dissolved oxygen as it relates to sediment and biological oxygen demand post sediment transport events.

- **Benthic and macroinvertebrates after disturbances –**Tools are needed to estimate the reestablishment of benthics and macroinvertebrates after a disturbance such as dam removal, wildfires, or reservoir sediment sluicing to inform management decisions and mitigation related to threatened and endangered species.

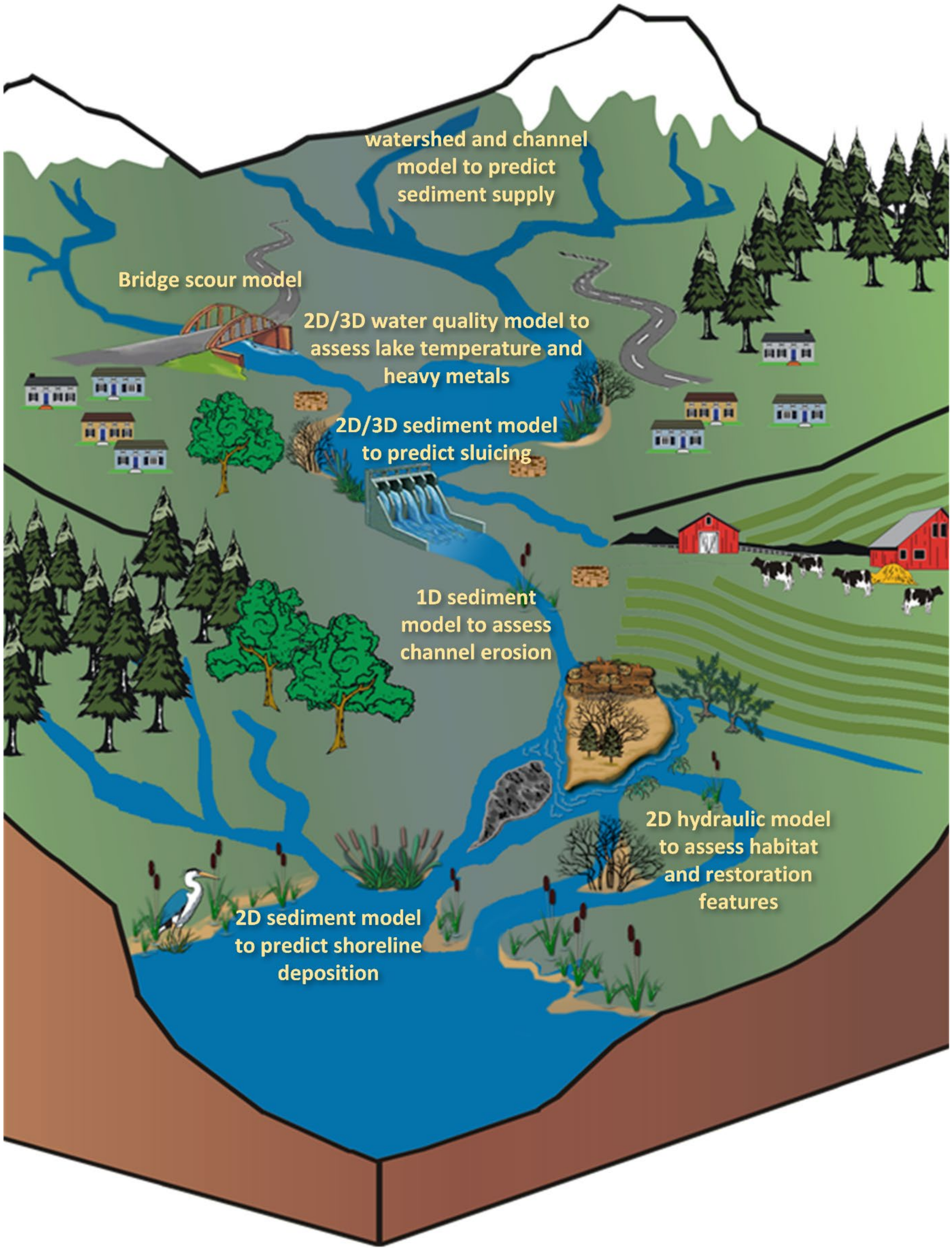

Figure 1.—Overview of model types that can be used to address variable spatial scales within a watershed related eco-hydraulics and sediment processes.

Active Research in FY19 and FY20 Addressing SRH Roadmap Topics

The following environmental (EN) research projects were actively funded by the Science and Technology Office in fiscal years 2019 or 2020 and represent progress already being made on the SRH modeling roadmap topics identified in sediment and eco-hydraulics and where there are gaps. Collaboration opportunities and active research at other federal agencies is also noted for information shared during the external peer review of this roadmap.

General Modeling Tools to Improve Efficiency and Save Costs

- EN1724: Development of a new 2D structured and unstructured mesh generator for flow, sediment, temperature, groundwater, and vegetation modeling

River Restoration to Meet Environmental Compliance Requirements

- **Aquatic habitat assessment**
  - EN1867: Seasonal/Temporary Wetland/Floodplain Delineation using Remote Sensing and Deep Learning
  - EN19239: Technology Transfer: Developing Tools for Efficient Handling of Data for Hydraulic Modeling and Habitat Analysis
  - EN20052: Quantifying the Development and Dynamics of Reservoir Delta and Related Backwater Vegetation in the Context of Physical Drivers
  - U.S. Army Corps of Engineers is developing a set of habitat assessment tools for habitat quality and quantity (Engineering Research Development Center, Vicksburg, MS)

- **Fish passage and fish barrier**
  - EN19105: Fish Passage at River Diversion Juncture: A Science-Based Approach
  - U.S. Army Corps of Engineers technical report on fish passage in final stages of review (Engineering Research Development Center, Vicksburg, MS)

- **Assessment and design of river restoration projects**

  - **Representation of river restoration structures and features**

    - EN1726: Design of Low-Flow Ecosystem Features for Urban Flood Control Structures

    - EN1734: Robust Eco-Hydraulic 3D Modeling Tools for Rivers with Complex In-Stream Structures

    - EN1756: Representation of Large Wood Structures Using a Two-Dimensional Model

    - EN1798: River Restoration Freeboard Design Requirements

- **Interactions between surface and groundwater**
  - EN3226: Coupling Reclamation's Surface Water Model to a Groundwater Model
  - EN19212: The potential for restoring thermal refugia for cold-water fishes

- **Evolution of river restoration projects**
  - **Interaction of vegetation, hydraulics, and sediment**
    - EN1781: Improvement in the accuracy and speed of riparian vegetation simulation
    - EN19290: Improving predictions of scour in the vicinity of vegetation in habitat rehabilitation areas
  - **Sediment transport and channel evolution in complex planforms**
    - EN1778: Modeling of complex sediment processes using experimental data and laboratory measurements
    - EN19266: Side channel evolution and design: achieving sustainable habitat for aquatic species recovery
    - EN19306: Side channel evolution, geomorphic diversity, and sediment transport on the Bighorn River following larger dam releases between 2008 and 2018

<u>Infrastructure Sustainability/Resiliency</u>

- **Reservoir sediment sustainability and sluicing**
  - **Prediction of sediment delivery to rivers and reservoirs**
    - No active research
  - **Prediction of reservoir sedimentation patterns**
    - No active research
  - **Prediction of reservoir erosion, removal, and exclusion for sediment management**
    - EN1754: Prediction of Reservoir Sediment Pressure Flushing
    - EN8235: Pilot Studies of Reservoir Sustainability Options - Flushing and Sluicing
    - Phase 1 prize competition completed in FY2019 to develop white papers of innovative solutions with 6 winners awarded monetary prizes; technology search and Phase 2 competition to test innovative ideas planned for FY2020

- U.S. Army Corps of Engineers recently completed research related to estimating sediment stored behind dams and the geomorphic implications of removal (Engineering Research Development Center, Vicksburg, MS)

- **Water diversion design and maintenance**
  - **Exclusion of sediment**
    - No active research

<u>Water Quality to Meet Environmental Compliance Requirements</u>

- **Contaminant risk due to heavy metals in reservoir deltas**
  - EN1809: Mercury Loading to Streams and Reservoirs: A Process-Based Approach
- **Sediment modeling in the context of wildfires**
  - **No active research**
- **Temperature or other water quality parameters in rivers and reservoirs**
  - EN1859: The Implementation of Flow-Temperature Artificial Neural Network Regression into Operations Planning Models
  - EN1883: Development of a GPU Accelerated Salinity Module for the SRH-2D Platform