RECLAMATION

Managing Water in the West

Reservoir Sediment Prediction over the Western United States

Research and Development Office
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Final Report ST-2017-1752-1

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Mission Statements

Protecting America's Great Outdoors and Powering Our Future

The Department of the Interior protects and manages the Nation's natural resources and cultural heritage; provides scientific and other information about those resources; and honors its trust responsibilities or special commitments to American Indians, Alaska Natives, and affiliated island communities.

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Reservoir Sediment Prediction over the Western United States

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Executive Summary

Sedimentation can reduce reservoir storage, decrease water quality, and impact reservoir operations. The actual rate of sedimentation remains largely uncertain due to both practical and logistical challenges in sediment monitoring. Existing sediment models have largely been limited to disparate applications at the hill-slope scale with few exceptions. Despite advances in hydrologic modeling techniques and climate research, comparatively little has been done to integrate these advancements into sediment modeling and provide commensurate improvements in prediction to the reservoir and water-treatment communities. This report summarizes a scope of work to develop improved estimates of reservoir sedimentation

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Introduction

Water resource management in the western U.S. is reliant upon aging reservoirs for critical storage and flood mitigation. One impending concern is the impacts of reservoir sedimentation on these reservoirs. Sedimentation can reduce reservoir storage, decrease water quality, and impact reservoir operations. The actual rate of sedimentation remains largely uncertain due to both practical and logistical challenges in sediment monitoring. Existing sediment models have largely been limited to disparate applications at the hill-slope scale with few exceptions. Despite advances in hydrologic modeling techniques and climate research, comparatively little has been done to integrate these advancements into sediment modeling and provide commensurate improvements in prediction to the reservoir and water-treatment communities.

The location of all Reclamation and US Army Corp of Engineers reservoirs with two or more surveys is shown in Figure 1. The locations of other Reclamation reservoirs with one or no survey are also shown in the figure. Only approximately 1/3 of Reclamation reservoirs have 2 or more surveys that could be used to compute sedimentation rates. Figure 2 shows the age distribution of Reclamation reservoirs. The “sediment design life” (time to fill the storage space allocated to sedimentation) was typically set at 100 years; a significant number of Reclamation reservoirs are now over 100 years old or rapidly approaching that age. Furthermore, the predicted rates of sedimentation were often made with limited data and knowledge and had significant uncertainty associated with them.

This report documents the results of a scoping level research project performed in FY2017, which developed a more detailed scope of work to improve the prediction of sedimentation at Reclamation Dams.

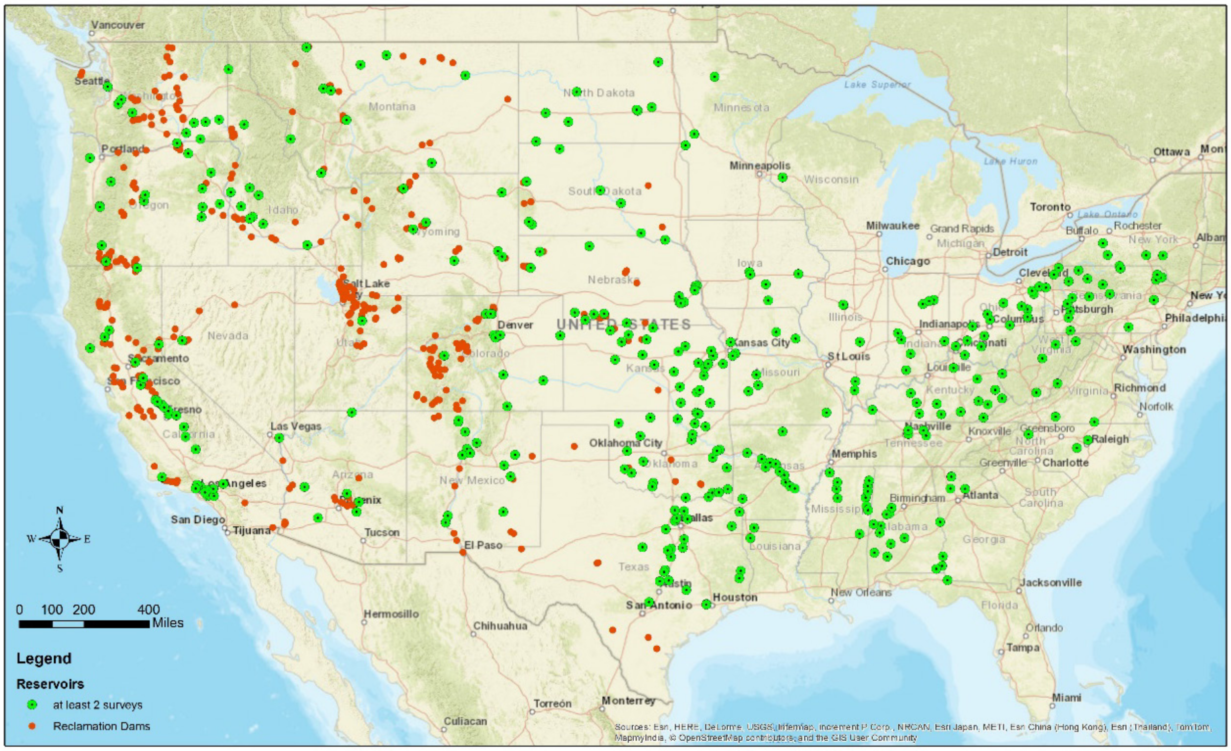

Figure 1. Map showing dams with at least 2 surveys (green) and locations of other Reclamation dams with 1 or no surveys (red).

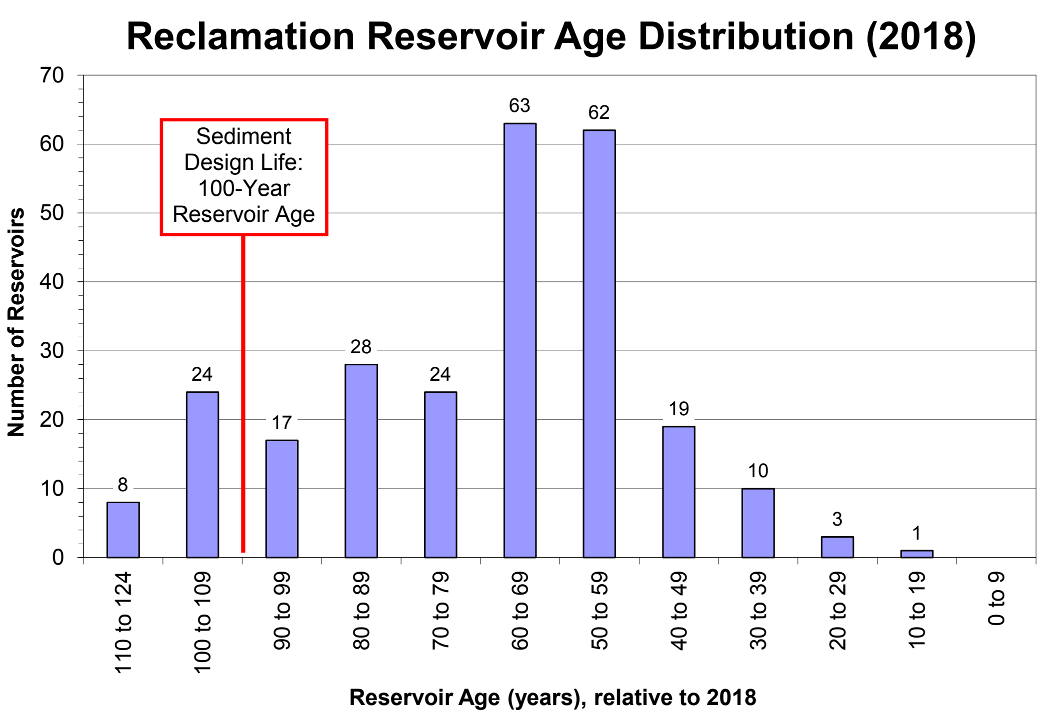

Figure 2. Age distribution of Reclamation Reservoirs.

Proposal for work

This work aims to comprehensively estimate historical, current, and projected future sediment loading along with attendant uncertainties through the coordinated application of multiple sediment modeling approaches over the western U.S. at both US Bureau of Reclamation (Reclamation) and US Army Corps of Engineers (USACE). This framework will integrate 4 model structures: empirical, statistical, conceptual and physically-based across a broad range of on-stream Reclamation and USACE reservoirs using the overarching 1/16° Variable Infiltration Capacity (VIC) model structure developed for Reclamation by Livneh et al. (2015). This effort aims to obviate the need for multiple, potentially incongruous modeling studies and help estimate sedimentation rates in un-surveyed reservoirs.

A key output will be novel and robust estimates of reservoir sedimentation that include structural uncertainties from a diverse set of sediment algorithms. Major outcomes will include an improved understanding of sedimentation processes and an estimate of historical and future uncertainties. This framework will then be applied to un-surveyed or not recently surveyed reservoirs, enabling estimates of sedimentation and probabilistic estimates of sedimentation rates. Overall, this effort can be used to identify areas of greatest risk for sedimentation and inform mitigation strategies. Partners include Reclamation and USACE.

This work will leverage EPA-funded model development efforts at CU-Boulder, as well as scoping funds from Reclamation from FY17 that have facilitated preliminary testing of some of the proposed methods. The merits of four general categories of models will be evaluated in the context of sediment prediction: empirical (monovariate rating curve, Glysson, 1986; Universal Soil Loss Equation, Williams and Berndt, 1977), stochastic (USGS LOAD ESTimator, Runkel et al., 2004; statistical regression), conceptual (Hydrologic Simulation Program-Fortran, HSPF, Bicknell et al., 1996), and a process-based model (Distributed Soil Hydrology Vegetation Model, DHSVM, Doten et al., 2006).

Although the latter models reconcile processes explicitly, the complexity of required inputs often exceed available data. These practical limitations need to be weighed against computational expense and model performance. To date, rigorous sediment model inter-comparisons have been lacking over large and diverse regions with few exceptions, generally over small, European watersheds (Jetten et al., 1999; De Vente et al., 2008, 2013). Furthermore, the use of dynamic Land Surface Model (LSM) physics on daily time steps will enable capturing the large episodic sediment events that are impossible to infer from annual or decadal frequency reservoir surveys (Minear and Kondolf, 2009; Graf et al., 2010).

The following steps will be carried out to achieve the research goals. The steps outline a multi-year effort to capture achieve the major goals of the project.

1. Domain definition: Define reservoirs of interest based on reservoir sedimentation database developed by Reclamation including data from USCOE reservoirs. The database may be supplemented by USGS sediment measurement sites or state reservoir sedimentation databases if certain regions are not well represented. Identify the contributing areas; i.e., watersheds that drain into these basins.

2. Data collection and literature review: Collect descriptive landscape data and hydrologic information on the selected watersheds. Conduct a literature review to outline knowledge gaps, existing methodological tools, and identify realistic ranges for parameters and model inputs.
3. Incorporation of upstream dams and operations. The effect of upstream dams on the sediment regimes will be assessed using empirical models of reservoir trap efficiency.
4. Model uniqueness: Outline the theoretical underpinnings from the empirical and process-based models used. The models will include regional regression based approaches that will include physiographic input variables such as drainage area, geographic region, soil texture, land-cover, annual flow, etc... similar to those performed by Renwick (1996) and Gartner et al (2009). In addition, the incremental value of process-based models, such as SWAT, HSPF, DHSVM will be evaluated. We will identify the practical limitations (data requirements, computational expense) of each model and important input model parameters. The degree to which the sediment modules and respective physics are truly independent from one another will also be identified.
5. Uncoupling of sediment modules and re-coupling to VIC: Assess how strongly the sediment prediction modules are coupled with their respective overarching model structure, and test running the sediment schemes in a standalone mode. Encapsulate each of the module structures within the existing VIC model framework (Livneh et al., 2015) to enable for consistent application and testing of each model.
6. Parameter estimation: Calibrate and validate sediment model parameters together and separately from VIC calibration parameters using a multi-objective optimization scheme seeking to optimize simulated discharge and sediment with observations. Evaluate the performance of each model locally and on a regional basis, seek to highlight trends in performance and inter-model agreement. Identify important performance signatures (peak flow, low flow, annual versus event-based sediment loading, etc..) based on discussions with partners. Explore issues of model scale and time-step on performance.
7. Comparison with regional regression and long-term (millennia-scale) denudation rates being developed by Dr. Foster research funded by Reclamation Science and Technology.
8. Historical and current sediment loading: Construct an estimate of historical and current sediment loading based on the evaluation of local and regional model performance, focusing on inter-model agreement, spread, and regions of greatest uncertainty
9. Future sedimentation and uncertainty: Use results from downscaled Global Climate Models (GCM) to force future sediment loadings and likely reservoir sediment design life. Use inter-model spread to provide estimates of uncertainty for streamflow rates and sediment loading, take into account available reservoir storage.

Input and feedback from collaborators at Reclamation and USACE will help guide the proposed scope and analysis. Interim meetings and progress reports will facilitate co-development of research with these partners. This first-of-its-kind study is expected to provide valuable insights into the feasibility of different modeling approaches, estimates of uncertainty, and climate-sediment sensitivities.

Benefits:

The benefits from this work include:

- estimates of sedimentation for reservoirs without recent surveys;
- analysis of existing sedimentation rates with respect to physiographic basin characteristics
- projections of future loadings and sediment-design life;
- Use of GCM data to address potential impacts of climate change
- improved understanding of sedimentation drivers, including an assessment of the important physics (models) necessary for making skillful sediment predictions.
- an unique estimate of uncertainty associated with sediment prediction, enabling an exploration of inter-model agreement and model spread.

Urgency

As time passes more sediment accumulates within our nation's reservoirs at relatively unknown rates. Knowledge of rates and ensuing risks for operational issues is critical to inform mitigation strategies. This work represents an important first step towards this end.

Quality Control

Reclamation developed a cooperative agreement with University of Colorado (CU), where CU is responsible for the majority of the quality control tasks. There will be quarterly meetings between the Reclamation PI and CU to discuss progress and review products in terms of: data quality, scientific analysis, and public communication. There will also be semi-annual meetings with USACE, Reclamation, and CU to review project progress.

Risk Management

There is a risk that the uncertainty associated with the sediment predictions, whether they be regression models or process-based models, is unacceptably high. This will be determined through critical, quantitative evaluation between predicted and observed sediment rates and variability.

Previous Work

High resolution meteorology and hydrologic modeling framework:

In previous work with Reclamation, Prof. Livneh developed a data set of observed daily precipitation, maximum and minimum temperature, gridded to a 1/16° (~6km) resolution spanning the entire country of Mexico, the conterminous U.S. (CONUS), and regions of Canada south of 53º N for the period 1950-2013 (Livneh et al. 2015). The data set was used as the training data for a newly developed downscaling method for global climate models, called localized constructed analogs (LOCA; Pierce et al 2014). A set of simulated hydrological variables were derived with the Variable Infiltration Capacity (VIC) model. This dataset is suitable for downscaling climate change projections, for water balance studies and for driving land surface models.

Proof-of-concept of sediment model coupling:

More recently, as a proof-of-concept, Livneh's research group (Stewart et al., 2017) implemented 5 different types of sediment models within the aforementioned VIC dataset for an intermediate size (~1000 sq. km) watershed on the Colorado Front Range. Relevant outcomes included multi-objective calibration and validation of both streamflow and sediment parameter sets, finding important tradeoffs between sediment and streamflow performance, as well as their respective parameters. Of note, slightly better performance was achieved for the process-based sediment modules, when transferring parameters to a neighboring watershed. Important developments in pre-processing GIS data, linking model-physics, and overall data quality control procedures were developed that will be foundational to the proposed research.

Other model development and large-sample watershed calibration:

Other relevant work from Livneh includes the development of a new land surface model (the Unified Land Model, Livneh et al., 2011) that involved intensive integration of multiple physics components and a calibration of the model over 250 catchments across the U.S.. Lastly, the calibrated model parameters were `regionalized', whereby model parameters were regressed -- using principle components regression --upon land-cover and soil features, so as to predict parameters over ungauged basins (Livneh and Lettenmaier, 2012, 2013).

Constraining long-term basin-averaged denudation rates in basins where reservoir surveys exist:

Dr. Foster is conducting a Reclamation Science and Technology project funded starting in FY17 and ending in FY19 to compare long-term (millennia-scale) denudation rates with modern rates of reservoir sedimentation. For this study, basin-averaged denudation rates will be constrained using ^{10}Be within river sands (for methods, see Brown et al., 1995 and Granger and Schaller, 2014). This is a relatively inexpensive technique that could provide a baseline for sediment production in basins. Basin-averaged erosion rates represent the long-term surface lowering for the entire basin upstream from the measurement point. This work tests the hypothesis that trends exist between basin-averaged erosion and rates of reservoir sedimentation, which may allow the ^{10}Be-derived measurements of basin-averaged erosion to be used as a proxy for reservoir sedimentation.

Relevant large-sample reservoir sedimentation database:

Reclamation and USACE are also in process of completing the Reservoir Sedimentation Information (RSI) data base. The database contains all the reservoirs within the USACE and Reclamation that have been re-surveyed and contains valuable information on the sediment yield from watersheds. This reservoir database will be used as the basis for this project.

Task Completed

Using FY2017 Science and Technology funds, the following tasks have been completed:

1. Data and domain definition: Transfer of reservoir sedimentation data to CU- Boulder for 9 reservoirs was coordinated by Reclamation. A single reservoir was selected for preliminary testing, the Prineville reservoir in OR. For this reservoir, two sediment observations from the

RSI were obtained. The drainage area was delineated and hydrologic layers relevant for routing were constructed, including flow-direction and flow accumulation files.

2. Reservoir descriptors: Physiographic variables such as land-cover, soil texture, topography, and meteorology were identified for the Prineville reservoir.

3. Model development and implementation: Grid cells from the Variable Infiltration Capacity (VIC) model were overlaid atop the watershed delineation based on the Livneh et al. (2015) 1/16 (~6 km) set up. This was done in preparation for dynamic simulations that would include estimates from at least three sediment transport routines coupled with VIC, with the goal of assessing key sensitivities and uncertainties in both model predictions and data.

Completion of future tasks is dependent upon additional funding from Science and Technology program.

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