Developing an Automated Method to Estimate Reservoir Sedimentation at ~30,000 Reservoirs Across the United States

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Extended Abstract

Water-storage reservoirs are one of the United States' most important assets. However, we do not know the present-day capacity of our water-storage reservoirs due to reservoir sedimentation. Once a storage dam is complete, reservoirs begin trapping sediment and debris. The volume of sediment and debris reduces the reservoir's storage capacity. The World Bank identified reservoir sedimentation as a major risk to global water supply (e.g., Mahmood, 1987) and a recent study indicates that the world's largest dams could lose a quarter of their capacity by 2050 (Perera et al., 2022). The risk of capacity loss in the United States is high, as many large reservoirs often have a 100-year design life for sedimentation (e.g., Strand and Pemberton, 1982) and the peak dam-building era of the United States (US) was in the mid-20th century (e.g., Billington et al., 2005). For the 7,469 US dams included in the Perrara et al. study (2023), they estimate a 34% storage-capacity loss by 2050.

Topobathymetric surveys typically provide the best estimate of sedimentation and storage loss at a moment in time. Researchers commonly calculate an annual loss rate from repeat surveys to project capacity loss into the future (e.g., Wisser et al., 2013). However, many projections likely overestimate sedimentation because they do not incorporate sediment trapping at upstream dams and reservoirs. In addition, the sedimentation rate likely slows through time as the dam's efficiency in trapping sediment and debris decreases (trap efficiency). Very few studies project storage capacity loss with respect to upstream dams and trap efficiency (e.g., Minear and Kondolf, 2009).

Our study seeks to quantify storage loss at sites with repeat reservoir surveys and to project future sedimentation at these sites and their associated upstream dams, following the methods of Minear and Kondolf (2009). Thus far, we acquired data from 535 sites across the United States with repeat surveys from: (1) the Reservoir Sedimentation Information (RSI) database (US Army Corps of Engineers private database, accessed 2020), (2) US Bureau of Reclamation (Reclamation) survey reports, (3) Reservoir Sedimentation database (RESIS-II, 2020), (4) Texas Water Board data (TWDB, 2020), and (5) Minear and Kondolf source data (2009). We only collected data from sites with repeat surveys at least 10 years apart. We also used only the first and last survey, to minimize the effect that changing methods has on quantifying capacity loss between surveys. In addition, a related study is utilizing these data to detect regional trends and potential environmental parameters that influence sedimentation rates (Eckland et al., 2023). Therefore, we did not want to bias the sedimentation trends by giving equal significance to multiple surveys from a single geographic location.

We created a semi-automated workflow to identify dams upstream from our sites and order them from upstream to downstream. We downloaded datasets from (1) the National Inventory of Dams (NID) database (NID, 2020), containing approximately 91,000 dams within the United States; (2) the Global Reservoir and Dam database (GRanD, 2021), containing 6,862 global dams from NASA imagery, focused on dams with greater than 0.1 km^2 of surface area; and (3) the National Hydrography Dataset (NHD) Plus High-Resolution Version 2.0 (NHD, 2021). We manually checked the location of our 535 sites, individually snapped them to NHD flowlines, created unique numerical short IDs for referencing, and then cross-referenced our sites with both the NID and GRanD dam datasets.

The NID database is the most comprehensive list of dams in the United States but it contains several errors. Of the approximately 30,000 NID-registered dams we initially identified within or nearby our sites' delineated drainage basins, we found that many of the sites were incorrectly located or lacked storage data. Where possible, we snapped them to the GRanD site location and substituted GRanD data for missing NID storage data. The NID database also contains duplicate storage listings at some sites for the main dam and associated dikes, forebays, and/or afterbays. Therefore, we conducted thorough filtering of the dataset to remove suspect data as well as water storage facilities that are not on a natural river (Table 1). Following our initial filtering, we used Python to snap the NID dams to the closest NHD flowline within 500 m that was categorized as a NHD-reservoir flowline; through trial and error we found that this distance best snapped larger reservoirs to the correct flowline without moving points to other drainage systems. However, approximately 5,000 NID dams did not snap to reservoir flowlines and are likely too small for the NHD dataset to identify them as reservoir. Therefore, we snapped these remaining NID dams to the closest flowline within 50 m. Following this step, we eliminated 2,977 dams from the study that did not snap to any flowline (Table 1).

Table 1. Search queries used in Python to eliminate suspect data from the approximately 30,000 NID dams identified within or close to delineated drainage basins for our 535 sites.

Filter query	Eliminated Dams
Name contains "saddle"	36
Name contains "dike"	89
Name contains "afterbay"	6
Name contains "spillway"	14
Name contains "levee"	22
Name contains "forebay"	4
Name contains "evap"	20
River listed as "offstream"	253
Duplicate NID identification number	20
Storage = 0, no GRanD data to substitute	70
Dam did not snap to a flowline	2,977
Dam did not link to a downstream site	2,155

Using the filtered-NID dams, we created a Python code to search downstream along NHD flowlines and to link every dam to the next downstream dam until reaching the terminal dam, defined as our most-downstream site on a drainage system. We then imported the dam-linkage file into Matlab for additional filtering and to order dams from upstream to downstream. We removed another 2,155 dams that did not link with a downstream site (Table 1), resulting in a final number of 25,077 filtered-NID dams located above our sites. In addition, there were another 2,367 dams lacking a dam completion date, which we need to constrain how the timing of dam emplacement affects the sediment-contributing drainage area above sites. Rather than eliminate these dams, which would break the chain of dam linkages, we set the completion year to 2200, effectively removing them from the analysis for the time being. Our Matlab code then steps through time from 1850 through 2050 to calculate how upstream dams reduce the sediment-contributing drainage area at our sites. The sediment contributing drainage area is the portion of the upstream watershed that contributes sediment to a reservoir, reduced by the drainage area and trapping efficiency of upstream dams, such that:

$$DA_{sed_{a,t}} = TE_{a,t}\left[DA_{tot_a} - \left[TE_b\left(DA_{tot_b}\right) + TE_c\left(DA_{tot_c}\right) + \cdots\right]\right] \quad (1)$$

where DA_{sed} is the sediment-contributing drainage area to site *a*, DA_{tot} is the total drainage area, *TE* is trap efficiency, *b* and *c* are identifiers for individual upstream reservoirs, and *t* represents a particular timestep (Minear and Kondolf, 2009). In this example, reservoir *a* is one of our 535 study sites and reservoirs *b* and *c* are upstream, headwater reservoirs, meaning that other dams do not exist upstream from them. If reservoirs *b* and *c* also had upstream dams, we would need to calculate their DA_{sed} first, and substitute DA_{sed} at *b* and *c* for DA_{tot} at *b* and *c* in Eqn. 1. Thus far, we have kept the trap efficiency of upstream reservoirs static with time and only changed the trap efficiency at our 535 sites through time; we intend to incorporate changing trap efficiency at upstream sites next.

We use the Brown equation for trap efficiency, where:

$$TE_{a,t} = 100\left[1 - \frac{1}{1 + D\dfrac{C_{a,t}}{DA_{tot}}}\right] \quad (2)$$

where $TE_{a,t}$ is the trap efficiency for reservoir *a* at timestep *t*, *D* is a factor determined by detention time and sediment particle size (Brown, 1944), *C* is the storage capacity (m^3), and DA_{tot} is the total drainage area (km^2). We assumed a *D* value of 1 for coarse sediment; finer sediment has lower values of *D*, which will result in lower trap efficiencies especially at lower drainage areas. The strength of the Brown equation is that it allows us to calculate trap efficiency without inflow data, and we plan to update this equation with *D* values more representative of D_{50} values in reservoirs. However, we are also currently working to get estimates of inflow, which will allow us to switch to the more accurate Brune equation for trap efficiency (Brune, 1953).

After calculating the sediment-contributing drainage at our sites through time, we can calculate the time-averaged sediment yield rate:

$$SY_{a,\bar{t}} = \frac{SV}{\sum_{t_1}^{t_2} DA_{sed_{a,t}}} \quad (3)$$

where $SY_{a,\bar{t}}$ is the volume of sediment produced by the sediment-contributing watershed in cubic meters per square kilometer per year ($m^3km^{-2}yr^{-1}$). SV is the sediment volume in m^3, t_1 is survey year 1 and t_2 is survey year 2. The volume of sediment delivered to reservoir a is higher than the sediment yield, as the trap efficiency dictates how much sediment is retained, such that:

$$SD_{a,\bar{t}} = \frac{SV}{\sum_{t_1}^{t_2}\left[\left(DA_{sed_{a,t}}\right)/\left(TE_{a,t}\right)\right]} \quad (3)$$

where $SD_{a,\bar{t}}$ is the time-weighted volume of sediment delivered to reservoir a in cubic meters per square kilometer per year ($m^3km^{-2}yr^{-1}$). This value is more representative of the upstream basin's physical processes, as it better quantifies the rate at which sediment is produced by the upstream basin and delivered to a study reservoir. At our sites, we use the sediment delivery (*SD*) rate at t_2 to project sediment delivery at our sites into the future, up to year 2050. We continue to recalculate DA_{sed} and *TE* based on each site's storage capacity loss due to sediment accumulation (Figure 1). We expect that our estimates are currently over-predictions, since we have not yet incorporated changing trap efficiency at upstream dams. However, our estimate of capacity loss for our 535 study sites is approximately 13% by 2050, much lower than the 34% average estimate from the Perrara et al. study, which included a larger number of study sites but did not account for upstream dams and repeat survey data (Perrara et al., 2023).

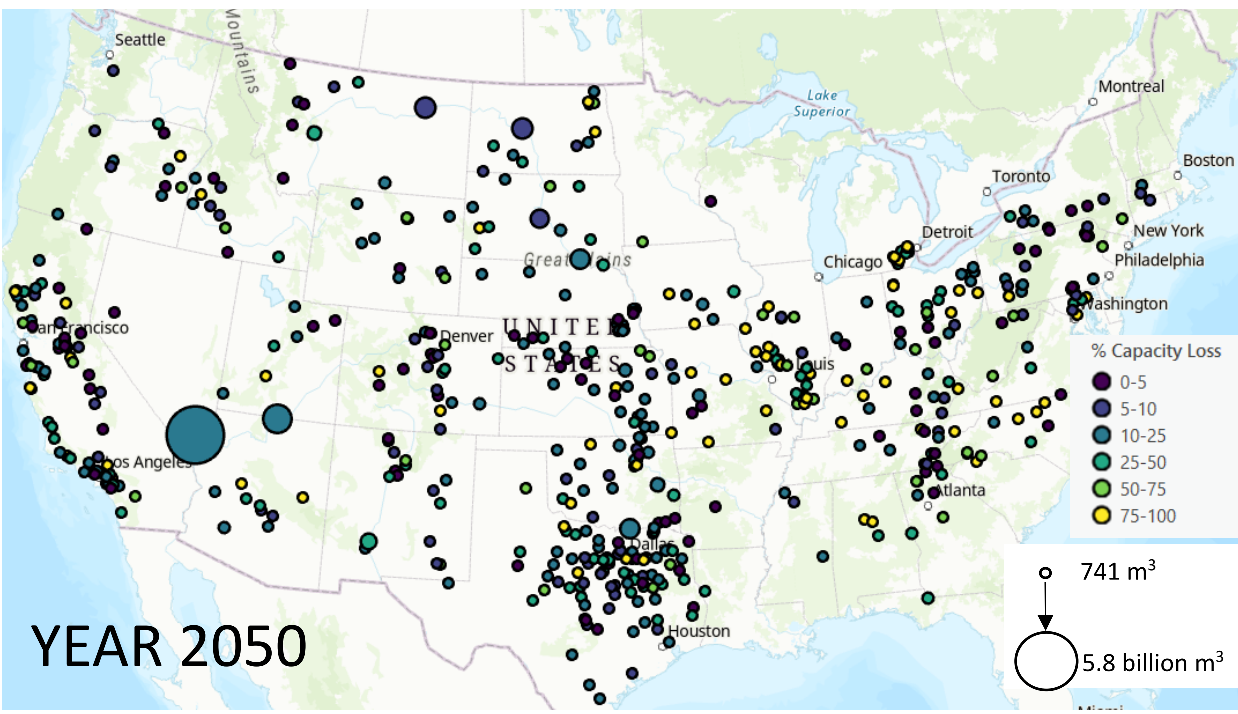

Figure 1. Projected capacity loss at sites by year 2050.

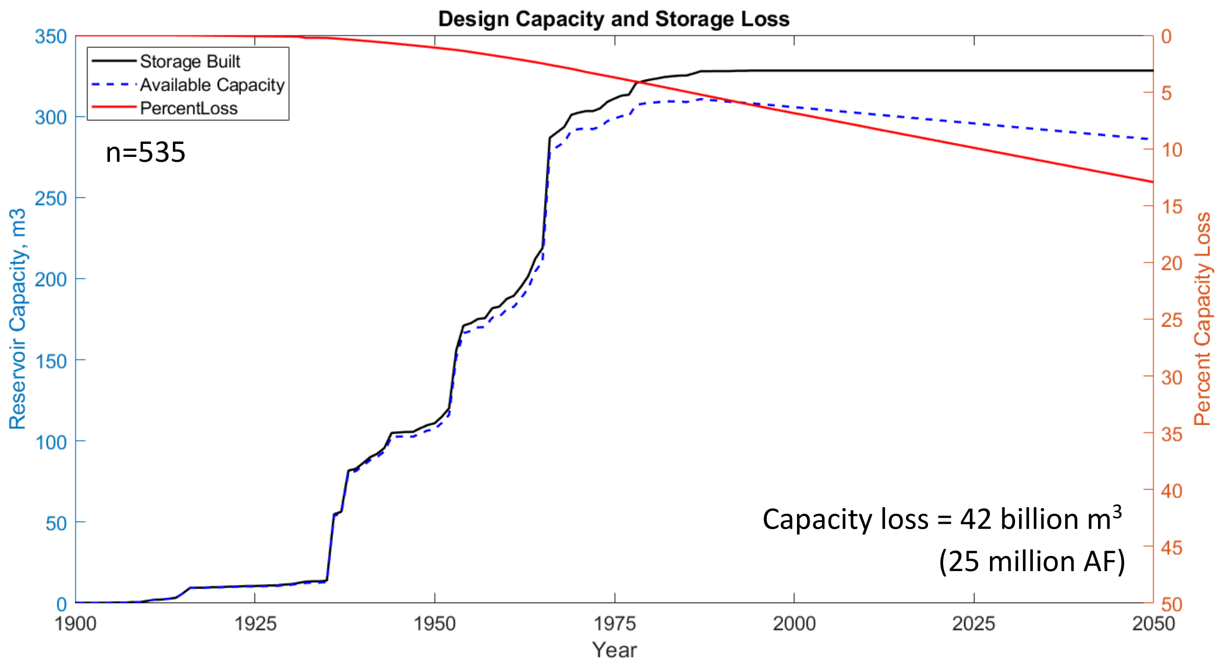

Figure 2. Storage capacity growth and decline for our 535 study sites.

Our next step in this project is to incorporate additional site data that we gathered in the last three years. We are easily able to incorporate these data, since we recently completed dam linkages and ordering for the entire NID-dam network in the continental United States. We will then add capacity loss and trap efficiency changes to upstream dams, which will yield an estimate of reservoir sedimentation at approximately one-third of all reservoirs in the United States. As a comparison, we also intend to complete the study using only the GRanD dams. The GRanD dataset includes a smaller number of reservoirs from NASA's remote sensing database and therefore avoids many of the location and data entry errors that plague the NID dataset. Finally, we intend to convert the dam ordering Matlab code to Python, so that we may make this automation process open-source and publicly available.

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