COLLECTION AND INTERPRETATION OF RESERVOIR DATA TO SUPPORT SUSTAINABLE USE

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Abstract. Sustainable reservoir management seeks to retard sedimentation and reduce its adverse impacts, ultimately achieving an equilibrium between sediment inflow and outflow while sustaining storage capacity to maximize project benefits.

Sedimentation data has traditionally been collected with the objective of simply documenting the timewise decline in reservoir capacity and computation of reservoir "useful life". However, if the decision is made to manage the reservoir in a sustainable manner the available data needs to be analyzed differently, and additional data will be required to better understand sedimentation processes and develop management alternatives. This paper outlines some of the shortcomings of existing datasets and identifies data interpretation strategies and additional data types that can support sustainable reservoir management.

INTRODUCTION

Data on reservoir sedimentation has traditionally been collected with the objective of documenting the decline in storage capacity over time and accounting for its impact on the various reservoir pools. Most sedimentation datasets consist of periodic bathymetric surveys, presenting survey results as a change in volume over time, updating the elevation-volume curve and perhaps plotting representative cross-sections. Many reservoirs have never been surveyed at all.

When the decision is made to manage a reservoir for sustainable use instead of simply documenting its demise, it becomes necessary to: (1) re-process existing data to extract additional information, and (2) obtain additional and different types of data needed to better understand the sedimentation process, how it is changing over time, and to assess strategies for sustainable management. Sustainable management strategies are described by Morris and Fan (1997) and have been categorized in Figure 1.

RESERVOIR BATHYMETRIC DATA

Limitations of Bathymetric Datasets

Bathymetric data are used to document the change in reservoir volume over time, which is essential information for extrapolating future reservoir volume, discerning changes in sediment yield with time, and calibrating sediment transport models used to evaluate management alternatives. It is necessary to understand the limitations and potential problems with these datasets to interpret them properly and to plan a data collection program that supports sustainable management.

Bathymetric data are, for the most part, assumed to be accurate. However, many US and international datasets reveal significant error. When there are very few survey data, errors may go unrecognized. Consider, for example, reservoir volume data shown in Table 1.

Data from 5 of the 13 reservoirs are highlighted in bold red because they show that either total reservoir volume or the conservation pool volume has increased since reservoir construction. This is obviously an impossible result and therefore the affected data are deemed in error. However, the data for all the reservoirs are affected by error, but the potential for error is not noticed in the other reservoirs because the error is not as large or occurs in the opposite direction, thereby indicating an erroneously high rate of volume loss instead of a volume increase. However, because data for the other reservoirs have passed the "test of impossible results" they are tacitly accepted as accurate.

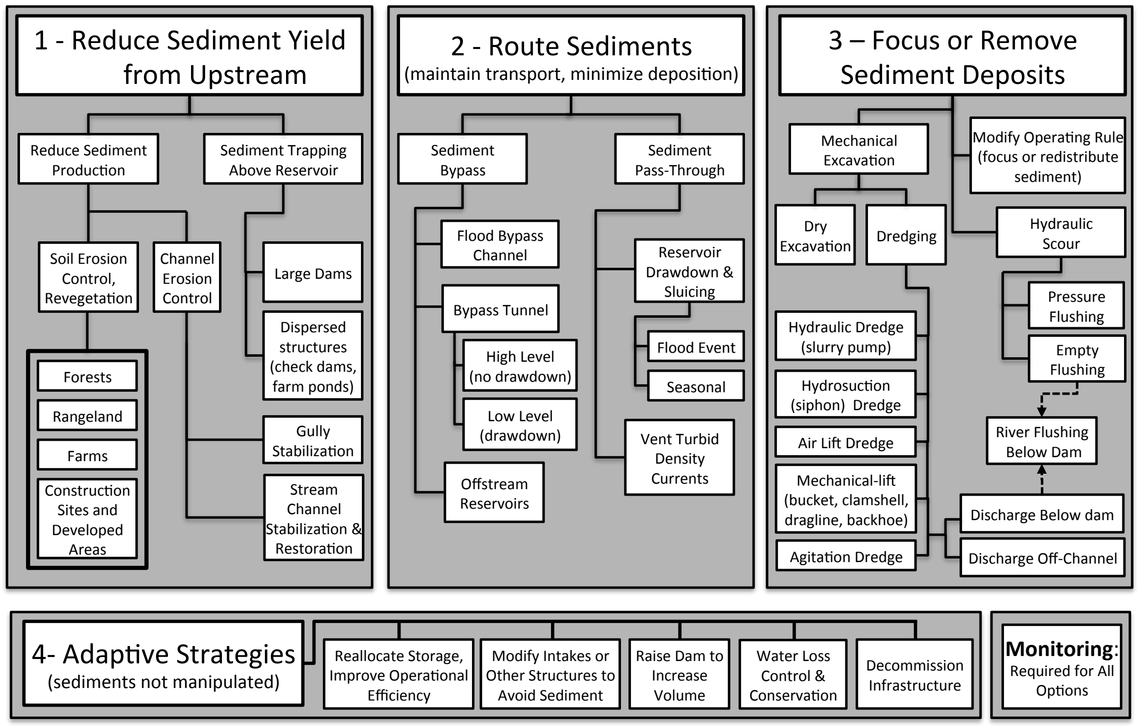

Figure 1 Strategies for sustainable reservoir management (after Morris, 2014).

Bathymetric errors can originate from a variety of sources. The original pre-impoundment reservoir volume is often not of high accuracy. It may have been determined by conventional ground survey, by photogrammetric methods, or computed from published topographic mapping. Post-impoundment volume surveys necessarily use different techniques. The *range-line* method has been used conventionally, but since the 1990s the *contour method* has come into widespread use. A contour survey collects a high-density of position and depth data points measured by GPS and sonar, from which the sediment surface is mapped and the volume computed by mapping or survey software. Survey methodologies are summarized by Ferrari and Collins (2009) and Ferrari (2006a).

All surveys incorporate errors, and these errors are not necessarily easy to detect since the bathymetric data collection process is typically open-ended without the check that occurs, for example, in a conventional topographic survey which may close back to the point of origin. As an example, consider the reservoir survey data presented in Figure 2. The data were collected on different days with the boat running track lines oriented perpendicular to each other on each day. The resulting checkerboard pattern, with both high and low survey lines, was the result of not having the bathymetric equipment properly calibrated; different days produced track lines having different elevations for the same area. Because bathymetric track paths are typically parallel and do not repeat the same area, this type of error would not normally be detected.

Table 1 Reservoir Capacities for Corps of Engineer Reservoirs, Baltimore District.

Basin and Reservoir	Watershed (km^2)	Dam Closure Year	Last Survey Year	Storage Loss (%)	
				Below Top of Conservation Pool	Below Top of Flood Pool
North Branch Potomac River Basin					
Jennings Randolph	681	1981	1997	-6.8	-6.3
Savage	272	1952	1996	-3.3	-3.0
East Sidney	264	1950	2000	-15.2	-2.4
Whitney Point	660	1942	1997	-6.5	-2.6
Almond	145	1949	1997	-48.8	-8.5
Tioga	725	1978	1999	**+4.7**	**+0.5**
Hammond	316	1978	1999	-2.5	**+0.8**
Cowanesque	772	1980	1997	-7.8	-4.6
Bush	585	1962	1999	**+7.1**	-0.1
Sayers	878	1969	1997	-1.4	**+1.5**
Curwensville	945	1965	1997	-19.9	-3.7
Main Stem Susquehanna River Basin					
Stillwater	96	1960	2000	-28.0	-3.7
Aylesworth	16	1970	2000	-3.1	**+4.4**

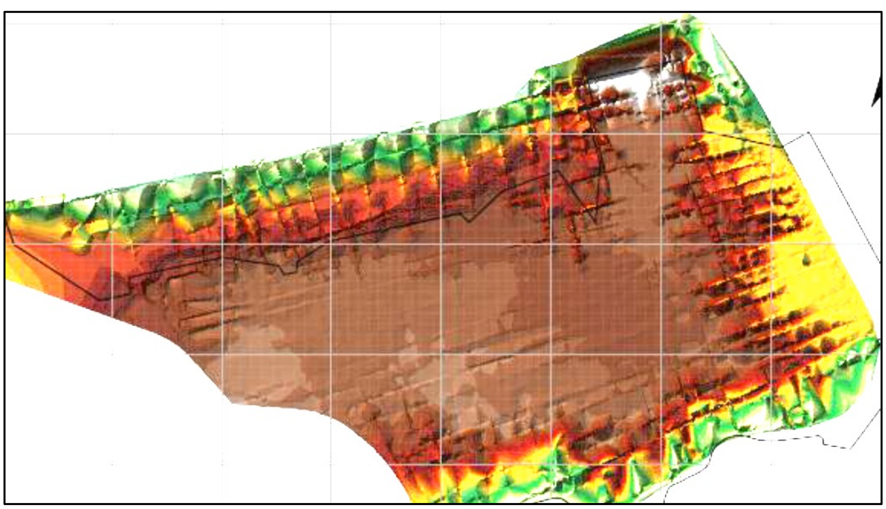

Figure 2: Bathymetric survey showing irregular gridded lines in the reservoir.

A potentially large source of error is associated with changes in methodology, such as changing from pre-impoundment to post-impoundment surveys, or from range-line to contour surveys. Given the differences in field measurement methods, together with the variety of computational techniques available for making volume computations, a change in methodology can generate a significant change in the measured volume, independent of sedimentation. Even contour survey computational algorithms represent a potential source of error of some significance. For example, Ortt et al. (2000) analyzed digital datasets from Loch Raven and Prettyboy reservoirs in Maryland using two different software algorithms, resulting in volume differences of 1.4% and 2.2% respectively due to software differences alone.

Consider the data for John Redmond Reservoir in Figure 4, showing a recent increase in reservoir volume. The last survey was performed by the contour method, the prior surveys by range-line. The volume shift coinciding with the changed methodology makes the sedimentation trend unclear.

For sustainable management, the principal objective of repeated surveys is to calculate the rate of sedimentation, and not to simply achieve a more accurate measure of the current reservoir volume. For this reason, when changing survey methodologies it is always appropriate to compute the new volume measurement by both the old and the new methodologies. To support this dual-computation, the new survey track lines should be planned to insure that each of the original range lines is replicated to provide the necessary data needed for volume computation by the old method. By comparing the survey volume by the two methods, the difference in apparent volume due to the changed methodology may be separated from the physical volume change due to sedimentation.

Changing Sedimentation Rate

Data from U.S. reservoirs frequently show that the rate of volume loss is not constant, but tends to decline over time (see Figure 3 and Figure 4). The most important factors that probably contribute to this result are: (1) sediment compaction, and (2) declining sediment yield due to erosion control or upstream dams. Reduced trap efficiency due to volume loss is probably not an important consideration in reservoirs which still retain much of their original volume (Brune, 1953). Changes in measurement methodology would probably not introduce a uni-directional bias, and at many sites the measurement methodology is unchanged.

A timewise change in sedimentation rate will not be observable absent data from multiple surveys. Drawing a trend line from the pre-impoundment volume through a single bathymetric survey data point 20 or 30 years following impoundment may provide a poor estimate of the long-term sedimentation rate. For example, if only the pre-impoundment (1949) and the 1981 survey data were available for Harry Strunk Reservoir, the projection of capacity loss based on these two data points alone would be remarkably different from the situation revealed with more complete data, as illustrated by the difference in the trend lines drawn in Figure 3.

For many federal reservoirs the datasets needed to detect changing in rates of volume loss do not exist. For example, 70% of the Bureau of Reclamation’s 400+ storage facilities have not been surveyed since initial impounding, and another 20% have only been surveyed once (Ferrari and Collins 2006).

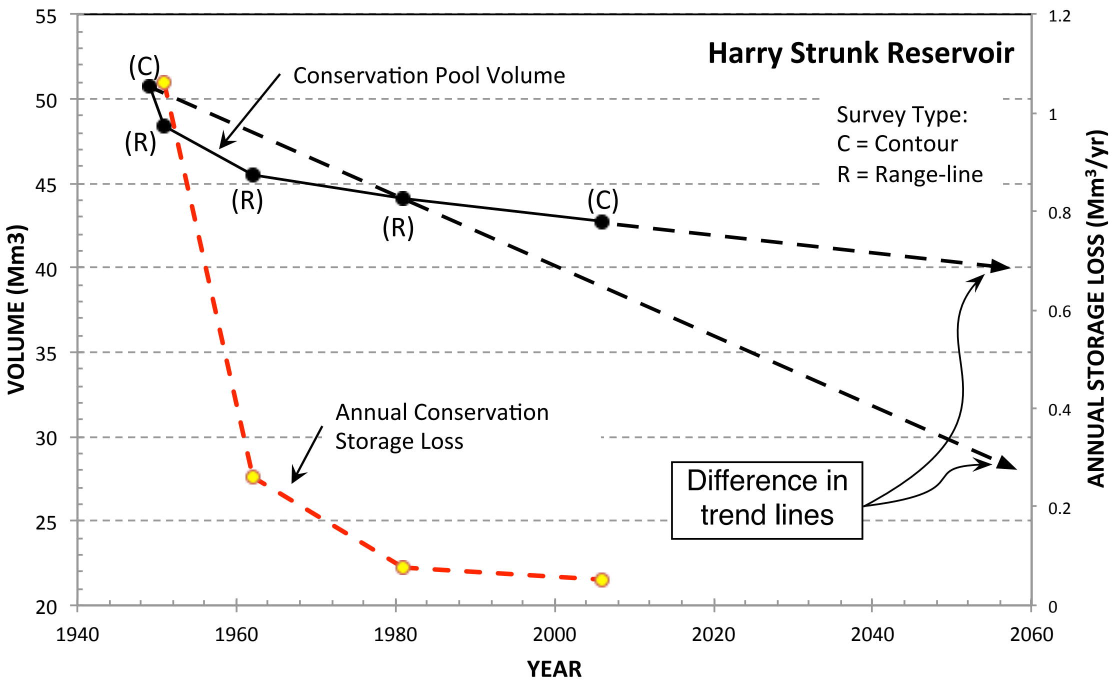

Figure 3 Timewise decline in reservoir volume and rate of storage loss at the Bureau of Reclamation's Harry Strunk Reservoir with trend lines superimposed (historical data from Ferrari 2006b).

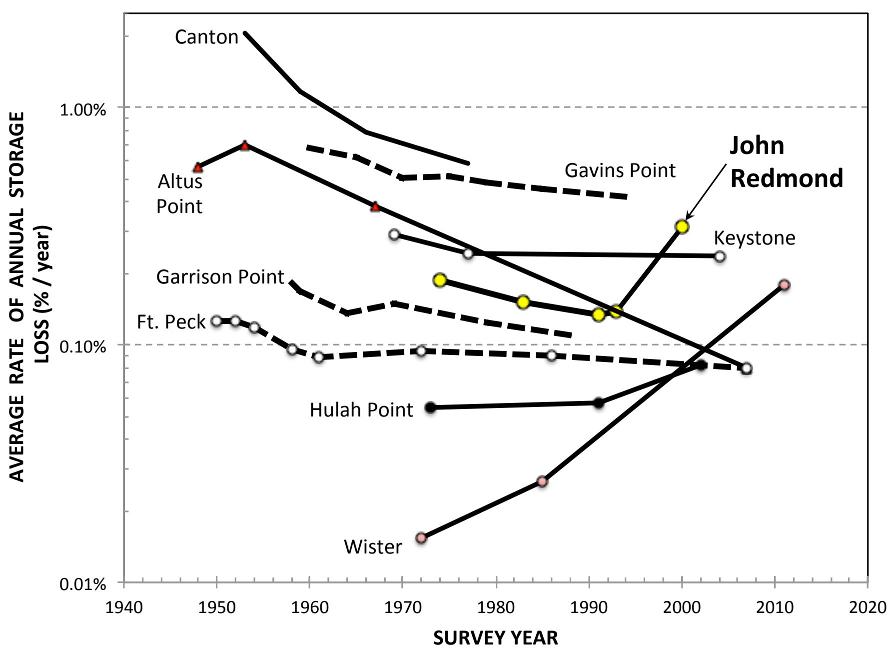

Figure 4 Change in rate of storage loss at several Corps of Engineers reservoirs in the Tulsa and Omaha districts.

Longitudinal Reservoir Profiles

Insight into the sedimentation process can be gained by plotting the timewise change in the reservoir's longitudinal bottom profiles. Profiles revealing horizontally-bedded sediment at the dam indicate that turbid density currents are transporting significant volumes of sediment to the dam which is not being released (Figure 5). Longitudinal profiles can also be used to monitor the pattern of delta advance (

Figure 6) as influenced by the reservoir operational levels. It is quite difficult to deduce these patterns by examining changes in the elevation-volume curves over time (Figure 7). Although simple to construct and highly instructive of the sedimentation process, longitudinal profiles are not normally plotted in sedimentation studies. It can also be useful to prepare a graph showing a longitudinal plot of cumulative sediment volume. Existing datasets may be reprocessed to display this information.

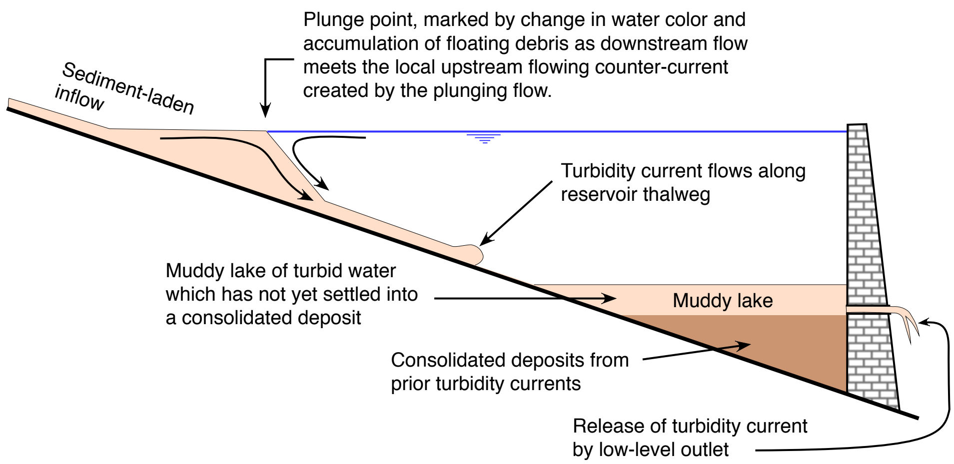

Figure 5 Longitudinal profiles can reveal the presence of turbidity current deposits at the dam.

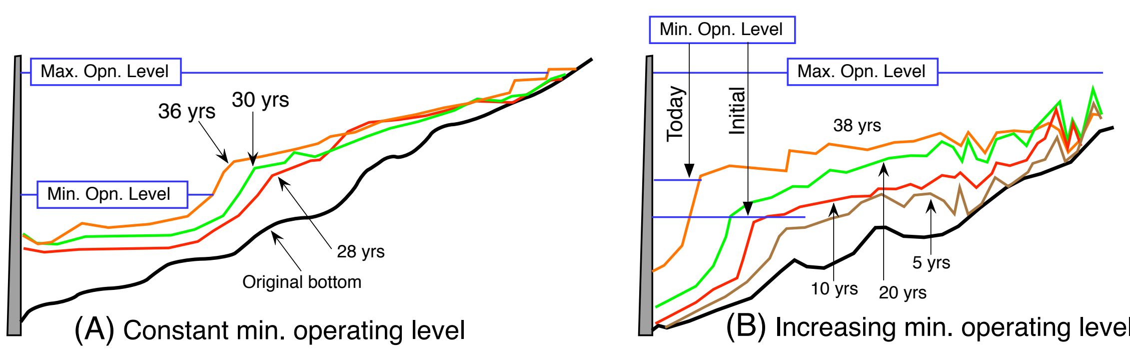

Figure 6 Longitudinal profiles showing different patterns of delta advance.

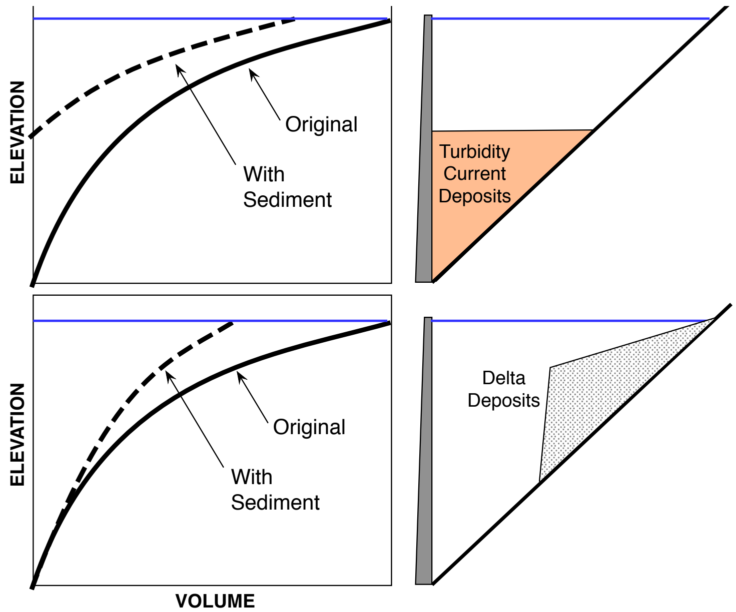

Figure 7 Change in shape of elevation-volume curve over time as influenced by the predominant pattern of sediment deposition in a reservoir.

SEDIMENT CORES

Sediment cores may be obtained from the bottom of a reservoir by conventional geotechnical boring equipment working from a floating platform. For example, at Tarbela Reservoir, Pakistan, ten cores penetrating up to 60 m of sediment thickness to reach the original reservoir bottom, were obtained operating from a barge during 56 working days. This did not include time consumed by weather delay when the water was too rough to work (SMS Consultants, 2013). This is a costly and time-consuming sampling alternative. In contrast, for core lengths not exceeding about 3 to 4 m, low-cost vibracore equipment may be used for rapidly sampling multiple locations each day. Vibracore sampling and analysis protocols are described by Bennett et al. (2013). Portable vibracore equipment used to sample in water up to 60 m deep in a hydropower reservoir in Colombia is illustrated in Figure 8. The objective was to obtain bulk samples to determine how far sand was being transported in the direction of the power intake during reservoir drawdown, when the sandy delta is subject to scour and sediment remobilization.

Sediment cores are not routinely collected in reservoirs but can be important aids in understanding and managing the sedimentation processes. Because sediments deposit in an episodic nature, the sediments in a reservoir will be layered, and samples from the top of the deposits will not provide representative information. Sample cores are required to obtain a more representative characterization of the deposit characteristics for determining representative values for parameters such as grain size, bulk density, organic content, and sediment chemistry. Because sandy delta sediments will advance and prograde over previously deposited fines, the composition of the top part of the bed may be different from the bottom. Depending on the management strategy, the composition of the deeper sediment may or may not be a concern.

Figure 8 Battery operated vibracore used for sampling sand concentration near a hydropower intake.

Computing Sedimentation Rate

When the original volume of a reservoir is unavailable or uncertain, fully penetrating cores in combination with a dual-frequency bathymetric survey (sub-bottom profiler) can map both the top and bottom of sediment deposits. Cores are useful to confirm the bulk density of the deposits and to confirm the depth to original ground (sediment thickness) as identified by the sonar data. This approach will not work if reservoir sediments contain methane gas from organic decomposition, since the sonar signal is strongly reflected by the air-water interface created by bubbles in the sediment.

If there is a datable stratigraphic horizon within the sediment that can be identified in the cores, this can also provide additional information on relative rates of sedimentation on either side of the event horizon. Horizons may be created by a large wildfire, volcanic eruption, contaminant discharge, and the cesium-137 layers from atmospheric testing of thermonuclear weapons that started in 1952 and peaked in 1963 (Cox et al., 2002).

Determining Bulk Density

To determine sediment yield from sediment volume requires knowledge of the dry bulk density of the sediment deposits. Bulk density varies with sediment grain size, and generally decreases moving downstream in a reservoir. Higher bulk densities occur in coarse delta sediment and lower bulk densities in fine grained sediments near the dam. The bulk density of fine sediment is not static but increases over time (and with depth) due to the weight of overlying sediment. Because sediment is not uniformly deposited, in some areas of the reservoir (and particularly near the delta face), bulk density will also vary with depth due to sediment layers of different grain sizes. Sediment cores can provide direct measurements of bulk density. Juracek (2006) provides information on sampling strategies for bulk density determinations.

Sediment Characteristics

Particle-size distribution data for different areas of the reservoir can provide useful information for calibrating sediment transport models. In hydropower plants, sand more than about 0.2 mm in diameter is generally considered to be highly abrasive, making it essential that is be excluded from the power intake. Sediment cores extending upstream from the intake can provide information on the grain size and percentage of sand, and can monitor its rate of advance toward the power intake. Knowledge of organic content, potential contaminants, and other parameters may be needed prior to excavating and discharging sediment, and samples required for this analysis are also normally obtained by cores.

DAILY SEDIMENT BALANCE

Sediment routing strategies (Figure 1) are based on the tendency for sediment discharge to be highly concentrated in time. Routing techniques reduce the rate of sediment accumulation by maintaining sediment-laden flood flows in motion, either passing them around the storage zone (sediment bypass) using offstream reservoirs or sediment bypass tunnels, or by passing sediment-laden flow though the storage zone with the minimum detention time or by releasing submerged turbid density currents. Given the episodic nature of sediment inflow events, daily discharge and concentration datasets are required to analyze these strategies, and depending on the site continuous (e.g. 15 minute) data may be required for refinement of the analysis and for subsequent operational purposes.

Aside from the difficulty and cost of acquiring reliable suspended sediment data, a significant disadvantage lies in the potentially high variability of sediment yield over time, particularly in mountainous watersheds. Large floods will frequently deliver sediment volumes that exceed several years of "normal" hydrology. Capturing data from these events, which may have a large impact on long-term sediment yield and the degree of success of a sediment routing strategy, requires a data collection platform that can withstand extreme floods and hurricanes, plus the good fortune to have the gage's funding period coincide with an extreme event.

CONCLUSIONS

Today's inventory of reservoirs cannot be managed in a sustainable manner without substantially expanded data collection and improved data analysis. The most critical issue at this point is to survey reservoirs at regular intervals to better determine the long term rates of storage loss, and document the timewise variability in these rates. These data can help identify reservoirs with the highest priority for management.

Many reservoirs in which capacity was previously determined by the range-line method will next be surveyed by the contour method. When changing methodologies it is essential to perform the new survey using both the old and the new methodologies, so that the volume change attributable to the change in methodology can be differentiated from the actual change in reservoir volume due to sedimentation.

While gage stations and daily data collection are essential for understanding sediment transport dynamics and developing workable management strategies, they do not substitute for good bathymetric datasets.

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