Comparing Reservoir Sediment Yield, Depletion, and Sustainability within the Missouri River Basin

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Abstract

Repetitive reservoir storage capacity surveys are often thought to provide one of the most accurate methods to assess basin sediment yield. The Omaha District conducts a large scale sediment data collection and analysis program for six Missouri River mainstem and twenty-two tributary reservoirs. An analysis was conducted to compare the sediment yield, reservoir capacity, depletion trends, and comparison between projects for effects on project sustainability. Trend analysis is complicated by temporal variation in conservation practices that affect sediment yield, new reservoir survey techniques, and revised capacity computation methods. Results provide insight on the variation in basin sediment yield, reservoir depletion rates, variation due to a change in survey method, and impacts on long term reservoir sustainability.

Introduction

The U.S. Army Corps of Engineers (USACE), Omaha District conducts sediment monitoring and computational analyses within the upper Missouri River basin. The Missouri River basin has an area of 529,350 square miles covering parts of seven states which is over one-sixth of the United States drainage area. The Omaha District River and Reservoir Engineering Section conducts monitoring and analysis activities for federally constructed reservoirs on both the six Missouri River mainstem and twenty-two tributary streams.

The Missouri River mainstem reservoirs are comprised of six reservoirs that contain a total of about 73.4 million acre-feet of storage capacity, nearly three times the average annual flow of the Missouri River at Sioux City, Iowa. Authorized operating purposes for the system includes flood control, navigation, hydroelectric power, irrigation, water supply, water quality control, recreation, and fish and wildlife (USACE 2006). The mainstem dams are composed of six large earthen embankments which impound a series of reservoirs that extend upstream for 1,257 river miles from Gavin's Point Dam near Yankton, South Dakota to the head waters of Fort Peck Lake north of Lewiston, Montana. Fort Peck Dam, the oldest of the six dams, was closed and began storing water in 1937. Fort Randall Dam was closed in 1952, followed by Garrison Dam in 1953, Gavin's Point Dam in 1955, Oahe Dam in 1958, and Big Bend Dam in 1963.

The Missouri River dams intercept the sediment from one of the largest and highest sediment yielding regions in the continental United States. In its pre-dam state, the Missouri River transported an estimated total sediment load averaging 25 million tons per year in the vicinity of Fort Peck, Montana, 150 million tons per year at Yankton, South Dakota, 175 million tons per year at Omaha, Nebraska, and approximately 250 million tons per year at Hermann, Missouri near its confluence with the Mississippi River (USACE, 2006).

The twenty-two Missouri River tributary reservoirs were constructed primarily as local flood control projects with other authorized purposes including recreation and fish and wildlife. Fourteen reservoirs are located in Nebraska; three in South Dakota; three in Colorado; and two in North Dakota. Tributary reservoir projects were constructed primarily in the 1960's thru the early 1980's. The location of the mainstem and tributary reservoir projects within the Omaha District sediment monitoring program are shown in Figure 1. For purposes of figure clarity, the eight projects in the Lincoln, Nebraska vicinity are labeled as Salt Creek and the four projects in the Omaha, Nebraska vicinity are labeled as Papillion Creek.

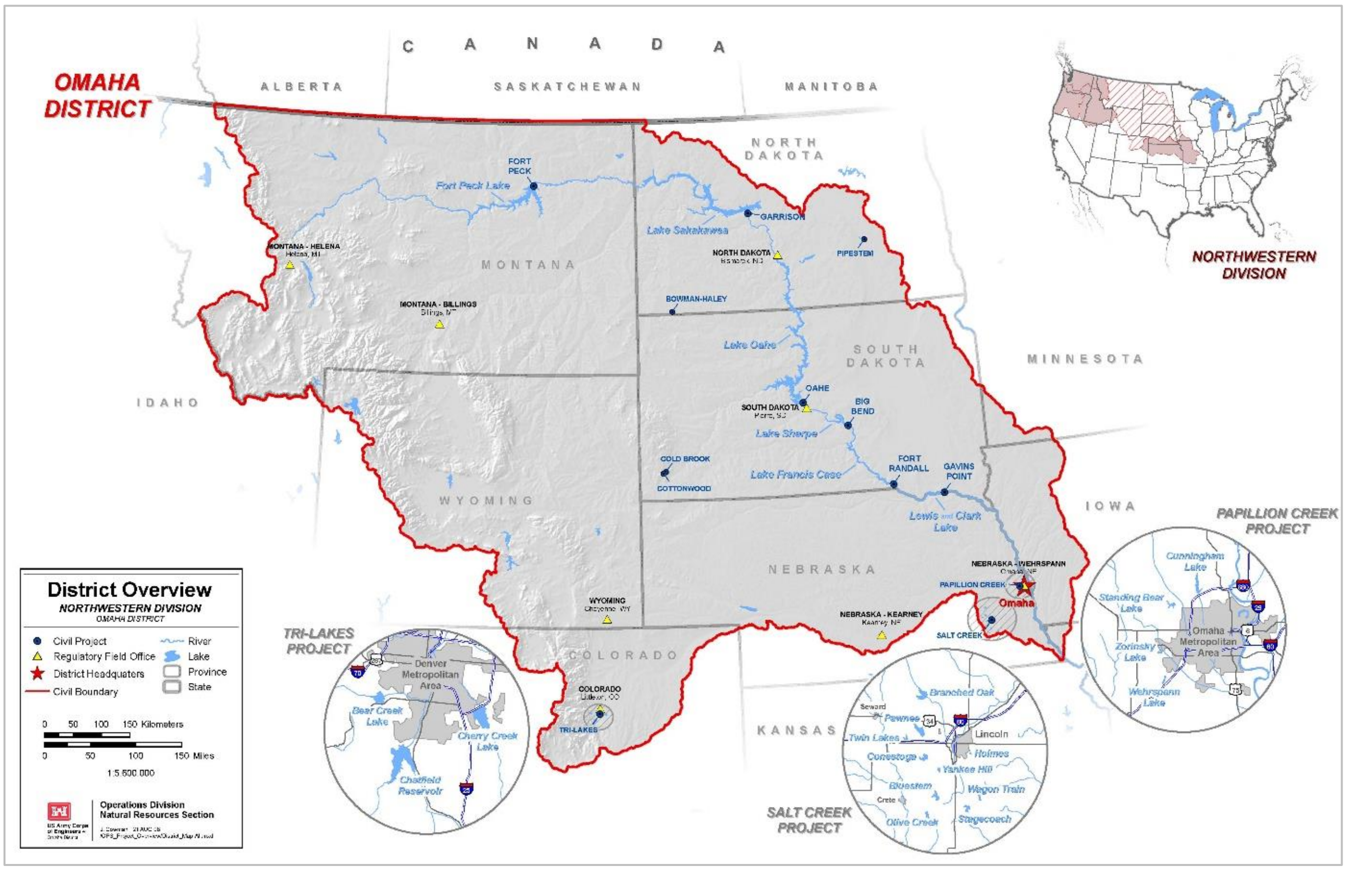

Figure 1. Omaha District - Reservoir Project Location Map

Reservoir Sedimentation

Processes

Reservoir sediment trapping has consequences that extend from the river channel above the reservoir pool, through the storage pool, and to the river reach below the dam. Missouri River sediment deposition has resulted in reservoir capacity depletion throughout the Omaha District. Sediment deposition observed from periodic surveys in the reservoir headwaters may increase river stages over time, block municipal water intakes, and restrict recreational use of the reservoir.

Trap Efficiency

Due to the large reservoir storage volumes on the Missouri, reservoir trap efficiency for the mainstem reservoirs is nearly 100% and water released from each dam contains virtually no sediment. The twenty-two tributary reservoirs also have trap efficiencies that are nearly 100%. Comparison between reservoir capacity depletion rates assumes that variation in trap efficiency between projects is insignificant.

Reservoir Storage Zones

Capacity at USACE reservoirs includes the total storage along with capacity within pool zones provided for various designated purposes. Terms used for the USACE pool zones vary by project and location. For the purposes of this analysis, storage depletion was evaluated for total storage (top of the exclusive \ flood control pool) and the sediment pool (top of the conservation, sediment, or inactive pool).

Omaha District Data Collection

Reservoir survey methods employed today have evolved significantly since the principal dam construction era from 1950 through 1980 within Omaha District. Survey technological advancements have generally increased data accuracy, precision, and data density and have provided variable cost savings dependent on many site-specific factors. Remote sensing capabilities continue to evolve with new techniques that may become standard in the future.

Early Methods

Each reservoir had a series of cross sections called sediment ranges that were monumented and surveyed using transit and plane table instruments to produce an original data set. Resurveys of these sediment ranges using these early methods continued within USACE into the 1980s followed by a transition to optical total station methods and then GPS technology in the 1990's. For most of the past century, aerial photogrammetry has been relied on for stereo-compilation of 2D planimetric maps and 3D topographic maps including contours (USACE 2007). For project bathymetry, USACE started to employ acoustic depth measurements (echo sounding) in the 1950s (USACE 2013). Omaha District collection methods followed the USACE national methods.

Current Methods

Surveys of the six mainstem reservoirs still rely on sediment range surveys using GPS survey methodology. These reservoirs are too large and remote to allow for economical high density topographic/bathymetric surveys. However, the twenty-two tributary reservoirs now use a combination of aerial LiDAR and either high-density single-beam or multibeam bathymetry. Sediment ranges are also frequently resurveyed as a check to verify the accuracy of LiDAR.

Omaha District Program

The Omaha District has conducted post-construction surveys since closure of each project at 10- to 20- year intervals as part of the data collection and analysis monitoring program. Analyses of the survey data have provided information on both the rate at which reservoir storage volume is being lost due to sedimentation and the location of these deposits both longitudinally and vertically within the reservoir pools.

Computation Methods

Original Storage Estimates

Original storage estimates for each Omaha District reservoir project were based on the best available information at the time of project construction. At most projects, this consisted of a pre-construction survey to the top of reservoir pool elevation. Contour maps were typically created from bathymetric surveys combined with field surveys or aerial photogrammetry. Storage volumes were derived from planimetered area on contour maps that were usually either a 5- or 10-foot intervals. Omaha District employed a modified average end area (MAEA) with ratio tables to replicate the contour area volume. This technique was used to allow for future repetitive surveys along the sediment ranges to compute reservoir capacity with increased accuracy compared to the simple average end area method (USACE 1984).

Current Computational Methods

This original MAEA technique is still used to compute storage capacity changes at the six Missouri River mainstem reservoirs because of survey limitations. The 22 tributary reservoir volume computations now use geographic information system (GIS) computation capabilities with digital elevation models (DEM) developed from the combined high-density data sources (LiDAR and dense hydrographic data). When sediment range surveys are available, capacity computations are also performed with the sediment range MAEA method to compare sediment depletion rates and inform on capacity variation due to the change in methodology.

Sediment Depletion

The reservoir storage capacity depletion rate is a useful metric that can be computed from capacity changes and indicates how quickly reservoir capacity is lost. Future reservoir operations and storage capacity rely on accurate estimates of the storage depletion rate. Variations in computed long-term reservoir depletion rates occur due to several factors.

a) Land Use and Natural Variability. Reservoir storage depletion will vary between survey periods due to man-made land use changes (site grading, environmental restoration projects, road construction, etc.) that affect sediment yield and natural factors (variability in annual runoff volume, precipitation intensity, etc.). Storage depletion rates are highly event driven and respond to extreme hydrologic events.
b) Future Variability. Future storage depletion rates may vary significantly from historical rates due to multiple factors that affect sediment yield such as land use, climate change, fire, and stream degradation.

c) Source Data Accuracy and Density. Data collection methods have evolved over time that has affected data accuracy due to changes in vertical point accuracy and point density. Collecting high density data is generally regarded as the best method to capture topography variation.
d) Methodology. When switching data collection and analysis methodologies, differences can occur due to the change in methodology (e.g. MAEA vs. GIS) rather than an actual variation in the storage depletion rate. Therefore, it is recommended to compute reservoir storage capacity with both methods when a methodology change is made to allow examination of any shift in capacity that may be associated with the change in methodology.
e) Sediment Range Localized Changes. The MAEA method assumes that elevation change on the bounding sediment ranges are representative of elevation change for the entire segment. Depletion for each segment occurs when the bounding sediment range average end area changes. Therefore, minor localized sediment range elevation changes have magnified impacts on capacity.

Capacity Comparison

Reservoir storage capacity at each reservoir was compiled from most recent reservoir surveys and capacity computation method as previously described. Figure *2* illustrates the storage capacity depletion that has been measured at all Omaha District reservoirs since project construction.

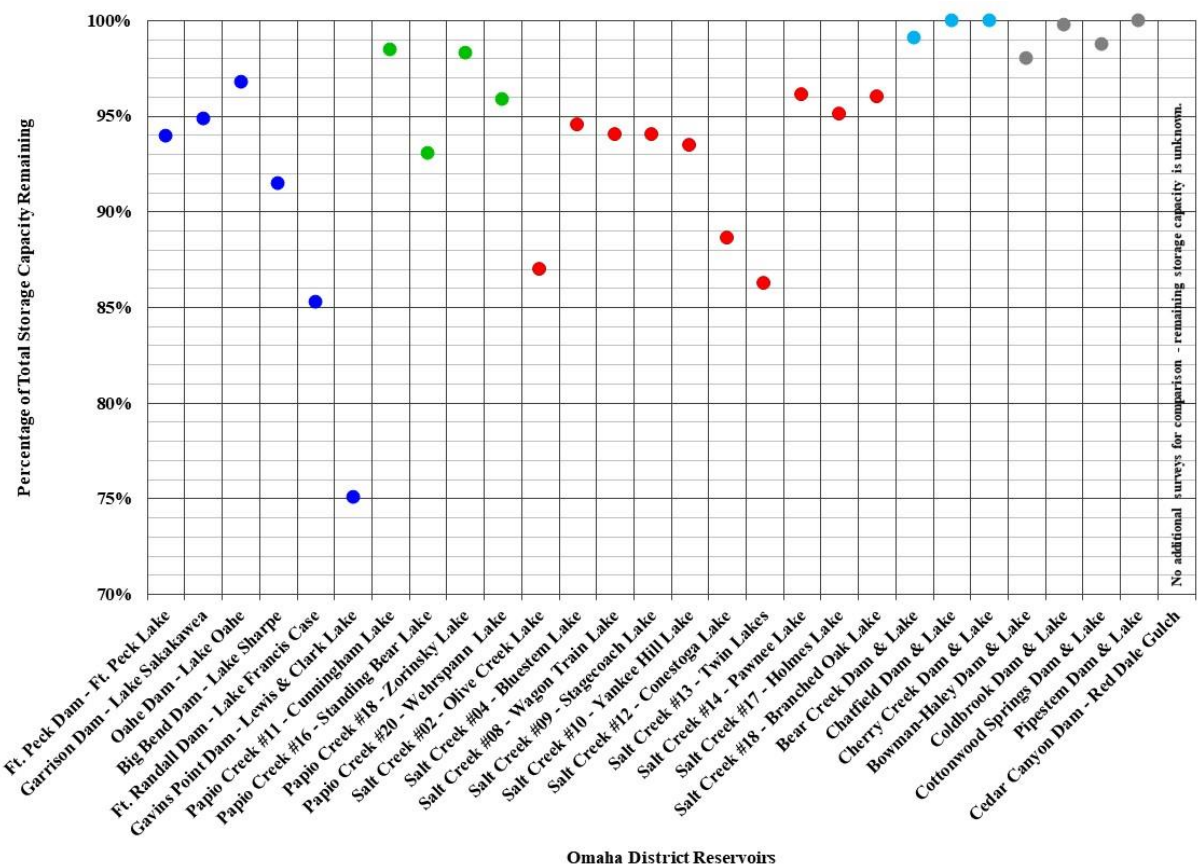

Figure 2. Omaha District Reservoirs – Percentage of Remaining Storage Capacity (Total Storage)

Reservoir storage capacity was normalized using the reservoir drainage area to allow comparison between projects as shown in Figure 3. A wide variation between depletion rates within the Omaha District is shown. The wide variation is not surprising given the large geographic area covered by the reservoirs (Figure 1) along with wide variability in watershed size, soil erodibility, precipitation, and similar factors that affect watershed sediment yield.

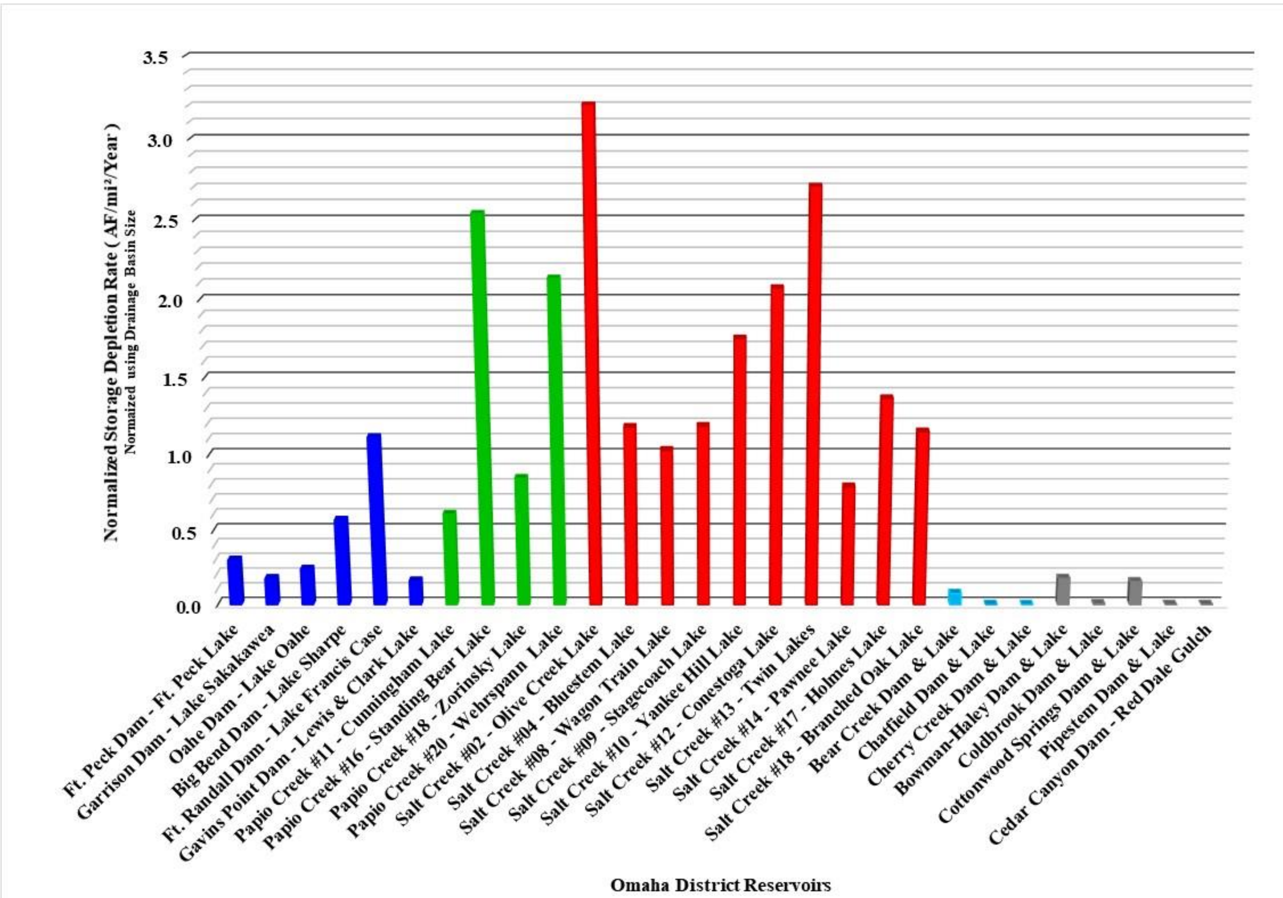

Figure 3. Omaha District Reservoirs – Normalized Storage Capacity Depletion (AF/mi²/Year)

Additional analysis was performed to compare reservoir depletion on similar size projects. Comparison of the Missouri River mainstem reservoirs is shown in Figure *4*. A comparison was performed between total reservoir storage and the sediment/inactive storage zone. A large variation between the two pool levels was not observed. Correlation of mainstem reservoir depletion between reservoir projects was poor.

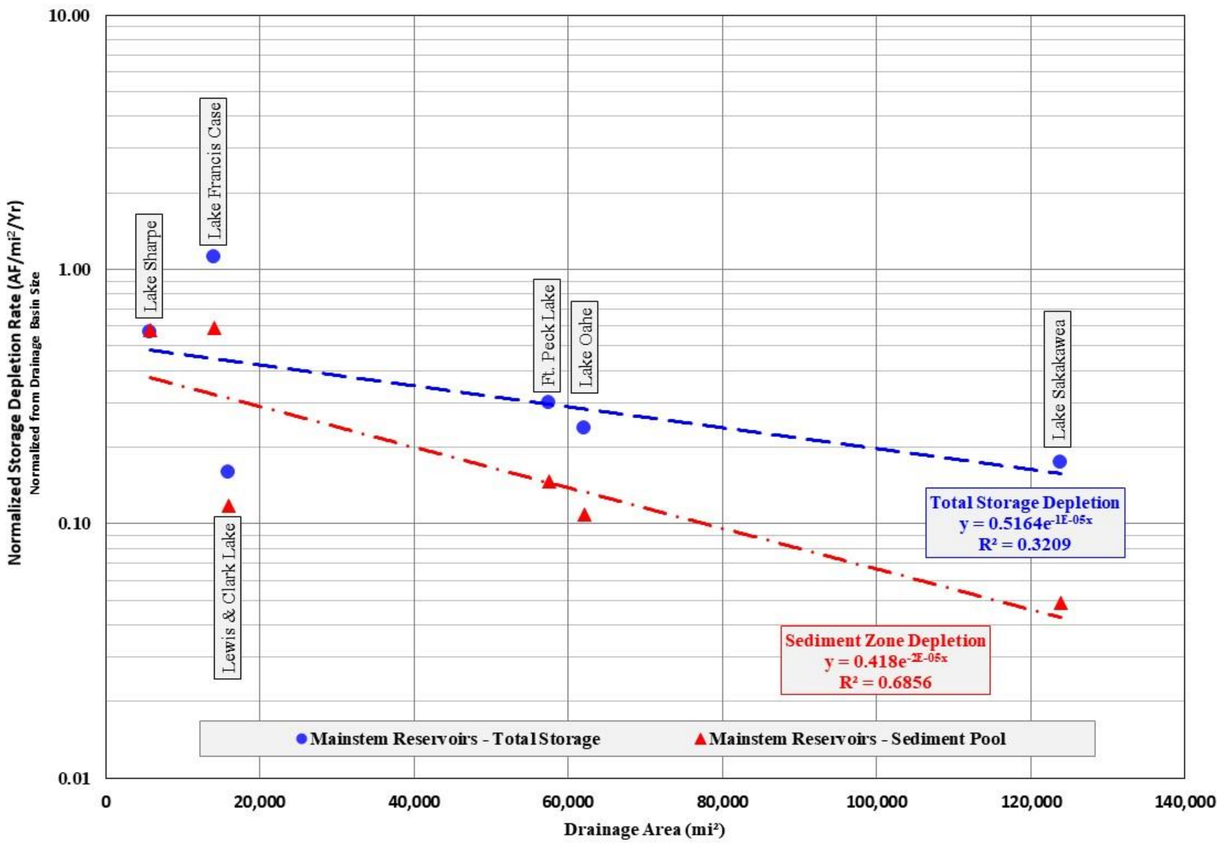

Figure 4. Missouri River Mainstem Reservoirs – Normalized Storage Capacity Depletion (AF/mi²/Year)

A comparison of the depletion at tributary reservoirs is shown in Figure 5. Comparison was performed for both the total storage and the sediment/inactive storage zone. Similar to the mainstem reservoirs, a large variation between the two pool levels was not observed. Tributary reservoirs were grouped by the two main areas, Salt Creek dam sites in the Lincoln, Nebraska vicinity, and the Papillion Creek reservoirs near Omaha, Nebraska. Correlation of depletion rates between the reservoir projects was significantly improved due to similar basin size, soil types, and land use compared to the mainstem dams.

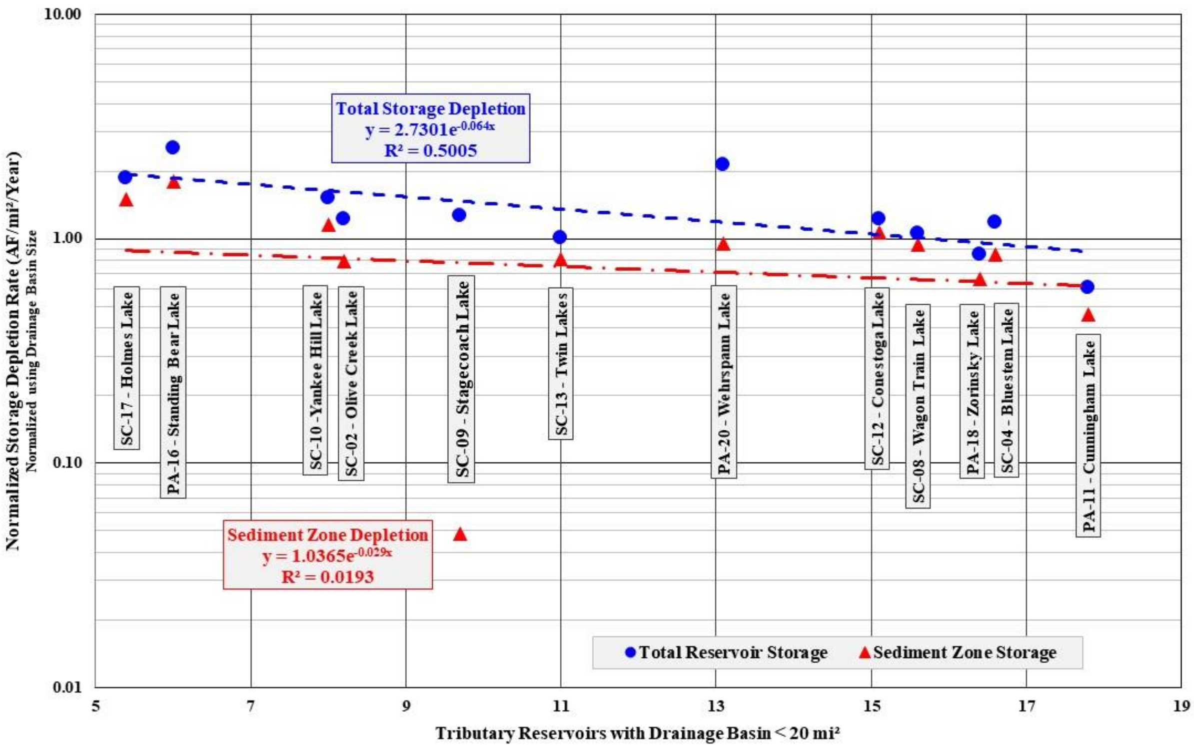

Figure 5. Tributary Reservoirs – Normalized Storage Capacity Depletion (AF/mi²/Year)

Comparison of depletion rates is recommended when conducting studies that require long term estimates of basin sediment yield. The variation and limited correlation can be due to a wide range of factors as previously discussed. However, using a single reservoir depletion rate based on historical surveys may not provide any indication of future rates. Development of an upper bound curve such as shown in Figure 5 based on multiple area reservoirs can improve estimates. This could be further enhanced with results from a basin sediment yield model.

Reservoir Sustainability

Sustainable reservoir sediment management seeks to achieve sediment transport equilibrium through the reservoir while still maintaining the storage capacity and beneficial uses. Limited sediment management may include slowing the deposition rate or may focus on minimizing impact to specific project benefits, such as removing sediment near water intakes, rather than overall sediment sustainability. USACE reservoirs within Omaha District were typically designed to trap and store incoming sediment in an area designated within the reservoir for sediment storage. The adequacy of this zone was usually evaluated based on an economic project life of 50 years. As reservoirs age, additional sediment accumulation displaces storage relied on for all project benefits. In addition, continued sediment trapping in reservoirs can cause upstream and downstream economic and environmental effects, including flooding, in-reservoir water quality impairment, recreational impacts, and downstream degradation and displacement of turbidity-dependent native species (USACE 2019).

For each reservoir, sustainability will have a different definition. That definition will be driven by the current and future operational goals of that reservoir. What should be common with all USACE reservoirs is a reservoir sustainability plan to assess the current and future sediment and water supply conditions at each reservoir (USACE 2019). Reservoir sustainability plans should consider future climate change (Pinson et al. 2016) and project resilience to those changes. Global changes facing USACE reservoirs include increasing water demand and the potential for increased sedimentation rates, both of which impact key reservoir functions including flood risk management, water supply, and recreation, among others.

Omaha District - Reservoir Life and Design Function Impacts

USACE reservoirs included sediment yield in project design and normally allowed a certain volume for sediment deposition over the project life. Morris and Fan (2008) point out that sediment deposition will seriously interfere with design function long before the entire storage volume is depleted and propose that a half-life metric is a more useful indicator of the period of effective reservoir operational life. This metric is defined as the period required to fill one-half of the original capacity using the estimated sediment load.

Reservoir life and design function impacts were qualitatively evaluated within Omaha District mainstem reservoirs. At Garrison Reservoir, Figure 2 illustrates that the remaining capacity is still about 95%. Sediment depletion at the historic rate since closure will result in the reservoir reaching 50% capacity in about 570 years from closure. However, significant sediment impacts have occurred in the reservoir delta zone. Over a 40 to 60 mile long river reach, observed river levels have increased by over 10 feet. In response, the Omaha District has purchased flowage easements, altered water intakes, encountered increased seepage rates and raised groundwater levels, and addressed.

At Gavin's Point Dam, Figure 2 illustrates that the remaining capacity is less than 75% of original. This reservoir has encountered many of the same issues that have occurred at Garrison Dam. USACE property purchases have been extensive. The large difference in capacity depletion between the two reservoirs has not resulted in a correlated difference in impacts. Therefore, caution should be applied when assuming that reservoirs with small capacity losses will have lower resource impacts than those with large capacity losses.

Sustainability Case Study – Climate Change

USACE has recognized the necessity of using the best current, actionable science on climate change impacts to water resources in evaluating reservoir sedimentation impacts, conducted numerous studies, and developed guidance (Pinson et al 2016).

Within the Omaha District, the Garrison Reservoir Climate Change Associated Sediment Yield Impact Study (USACE 2012) was undertaken to evaluate how climate change will affect the future basin runoff, sedimentation rates, and operations of Garrison Dam. This study was part of a larger inter-agency effort that included members of USACE, Reclamation, USGS, and NOAA. The study included both hydrologic and sediment aspects of climate change within the basin.

Two separate method were used to evaluate how hydrologic and sediment factors could affect sediment yield to Garrison Reservoir. First, Yellowstone River suspended sediment measurements were used to examine how altered seasonal runoff patterns could affect sedimentation rates. This analysis was performed to assess how a basin wide change in runoff could affect sediment yield. This analysis determined minor adjustment in future sedimentation rates due to seasonal affects but fairly large changes due to hydrologic effects.

Second, a SWAT model was used to evaluate hydrologic and seasonal changes on sediment yield for the Little Missouri River watershed. This small watershed (9,513 mi^2) analysis within the very large Garrison watershed (181,400 mi²) was performed to assess the impacts of climate change on sediment yield when the precipitation is not evenly distributed, and variables including soil type, land use, slope, and vegetation are considered. This analysis determined measurable impacts. Results from both methods were extrapolated to the entire Garrison Reservoir drainage basin. Results were applied with different climate project scenarios to determine impact on sedimentation rates as shown in Figure 6. Results show that even climate scenarios with less discharge can result in increased reservoir sedimentation inflows due to changes in timing. This finding was evident in the stream gage based analysis as well as in the results of the ArcSWAT model. Findings indicate that, when performing studies in which reservoir depletion rates are critical, assuming that future rates are the same as historic rates is likely non-conservative. Methods to assess climate change effect on sediment depletion may be warranted.

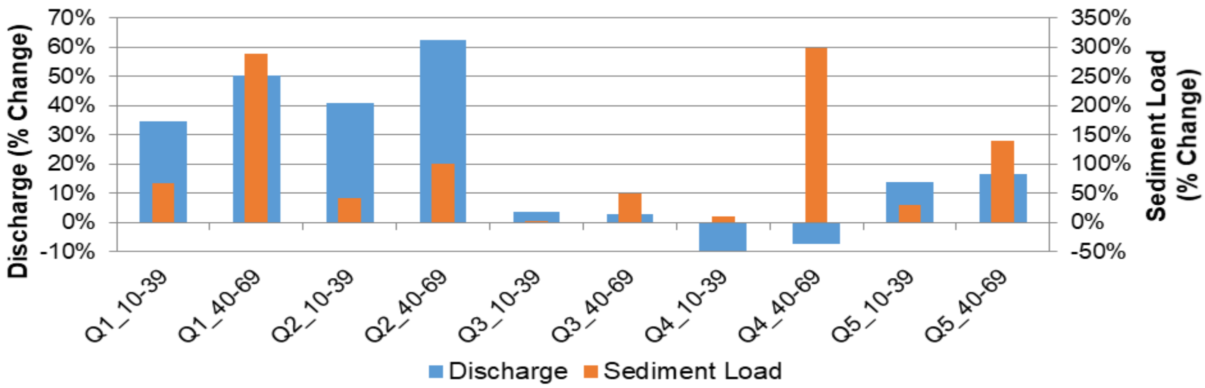

Figure 6. Climate Change Evaluation Comparing Discharge and Sediment Load Change at Garrison Reservoir

Summary and Recommendations

The Omaha District conducts a large-scale sediment data collection and analysis program for six Missouri River mainstem and twenty-two tributary reservoirs. Topographic and bathymetric data collection and computation methods have evolved since reservoir construction. Reservoir storage capacity depletion trends were compared between projects. Trend analysis is complicated by temporal variation in conservation practices that affect sediment yield, new reservoir survey techniques, and revised capacity computation methods. Reservoir sustainability was also evaluated for two specific instances.

Results provide insight on the variation in basin sediment yield, reservoir depletion rates, variation due to a change in survey method, and impacts on long term reservoir sustainability. Comparison of reservoir sediment depletion rates within similar watersheds indicated that developing an upper bound estimate from historic surveys is feasible. A climate change case study indicated that investigating how future sediment depletion rates may vary from historic is recommended. Combining results from the different methods, including an assessment of variation due to changes in data collection and computation methods, is recommended when developing long term estimates of future sediment depletion. These estimates, combined with observations regarding current reservoir capacity levels and impacts, are a critical factor in assessing long term sustainability at reservoirs within the Omaha District.

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