Sedimentation and sustainability of western American reservoirs

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[1] Reservoirs are sustainable only as long as they offer sufficient water storage space to achieve their design objectives. Life expectancy related to sedimentation is a measure of reservoir sustainability. We used data from the Army Corps of Engineers, U.S. Bureau of Reclamation, and U.S. Geological Survey (Reservoir Sedimentation Survey Information System II (RESIS II)) to explore the sustainability of American reservoirs. Sustainability varied by region, with the longest life expectancies in New England and the Tennessee Valley and the shortest in the interior west. In the Missouri and Colorado River basins, sedimentation and rates of loss of reservoir storage capacity were highly variable in time and space. In the Missouri River Basin, the larger reservoirs had the longest life expectancies, with some exceeding 1000 years, while smaller reservoirs in the basin had the shortest life expectancies. In the Colorado River Basin at the site of Glen Canyon Dam, sediment inflow varied with time, declining by half beginning in 1942 because of hydroclimate and upstream geomorphic changes. Because of these changes, the estimated life expectancy of Lake Powell increased from 300 to 700 years. Future surprise changes in sedimentation delivery and reservoir filling area are expected. Even though large western reservoirs were built within a limited period, their demise will not be synchronous because of varying sedimentation rates. Popular literature has incorrectly emphasized the possibility of rapid, synchronous loss of reservoir storage capacity and underestimated the sustainability of the water control infrastructure.

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1. Introduction

[2] Reservoirs are sustainable only as long as they offer sufficient water storage space to achieve their design objectives. A major threat to reservoir sustainability is sedimentation that reduces storage capacity, so that life expectancy related to sedimentation is a measure of reservoir sustainability [Morris and Fan, 1998]. In the interior western United States, human use of water resources depends on an extensive system of dams and large reservoirs for water storage. John Wesley Powell [Powell, 1878] defined this area of the western United States west of the 100th meridian excluding the moist west coastal areas as the "arid lands" region. The twentieth century popular writer Marc Reisner [Reisner, 1986] dubbed the region the "Cadillac Desert" in recognition of the large investments in its water control infrastructure. The sustainability of these reservoirs has been a concern for water managers and planners from their inception, focusing largely on the continued availability of water during shorterterm droughts and longer-term climate changes. This paper

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explores an additional threat to sustainability of these western American reservoirs: sedimentation that reduces storage capacity, negatively impacts recreation, changes wildlife habitat, and blocks intake works for hydropower generation.

[3] The life expectancy of a reservoir is a useful parameter for assessing its sustainability as a useful component of a water resource system. The rate of sediment infilling directly translates to life expectancy of a reservoir, a measure that can be determined by repeated surveys of the capacity of the reservoir or by assessments of sediment flowing into the reservoir from contributing rivers. During the late 20th century two perspectives emerged concerning the sustainability of reservoirs. The first perspective was that sedimentation was a process entailing at least several hundred years, making reservoirs a sustainable part of the regional water control infrastructure on a human scale. Scientific research on sediment transport in interior western rivers was discontinuous in time and space, but its preliminary results suggested that reservoirs were likely to be viable for several centuries (reviewed by Schmidt and Wilcock [2008]).

[4] The second perception, common in literature readily accessible to the public and decision makers, was that the reservoirs of Powell's arid region and Reisner's Cadillac Desert were doomed to early senescence by sedimentation, with management problems becoming apparent within 50 years [*Reisner*, 1986, p. 492], a time period short enough to enter analyses of sustainability. In a prominent case that caused concern, investigators found that in its first 13 years, Lake Mead behind Hoover Dam had lost about 0.4% of its storage capacity, with a resulting life expectancy of about 250 years [*Smith et al.*, 1960]. Also, because most of the

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Figure 1. Map of the Missouri River Basin and Colorado River Basin showing the locations of large dams analyzed in this paper. GCD indicates Glen Canyon Dam; see Table 1 for serial numbers and corresponding names with data for the USACE dams in the Missouri River Basin. The larger map extends from longitude 89°W on the right to 115°W on the left and from latitude 28°N at the bottom to 49°N at the top.

very large reservoirs had been constructed during the same restricted period of the 1950s and 1960s, they might also have similar life expectancies and cease to be useful all at about the same time [*Powell*, 2009]. The importance of this perspective was highlighted by some well-known examples of sediment-related loss of reservoir function such as the complete filling and subsequent removal of Sweasy Dam on the Mad River of northern California [*Mount*, 1995].

[5] The resolution of the difference between these two perspectives was in the acquisition of additional data, but measures of reservoir sedimentation became increasingly scarce. The number of reservoir sedimentation surveys peaked in the 1960s and 1970s, and thereafter declined to negligible numbers by the 1990s [*Ackerman et al.*, 2009]. At the same time, federal agencies greatly reduced support for expensive sediment transport studies. When the hydropower industry conducted a survey of privately owned dams and their reservoirs licensed by the Federal Energy Regulatory Agency in the late 1990s, it found that only 25% of the respondents reported concerns about reservoir sedimentation, and only 6% reported continuing surveys [*Dixon*, 2000, pp. 2–3]. Possible reasons for the lack of surveys included cost, observed slow rates of sedimentation in some cases, and management time frames geared to licensing (about every 50 years or less) rather than longer time frames of centuries related to sedimentation. However, climatic extremes have potentially significant implications for sedimentation and reservoir storage. The prospect of warmer, drier climatic conditions for large sections of the interior western United States [*Overpeck and Udall*, 2010] gives renewed importance to the life expectancies of the region's reservoirs. Also, more data are available now than were available to researchers and commentators in the mid-20th century.

[6] In this paper we address three questions about sediment infilling in reservoirs of the United States: (1) Generally, how rapidly are American reservoirs filling with sediment and how do interior western reservoirs compare with those in other regions in the United States? (2) On the basis of recent information and longer records than were previously available, what are reasonable life expectancies specifically for reservoirs in the interior west? (3) What are the temporal and spatial variations in loss of storage capacity in western reservoirs, and what are the primary drivers of this variation? In addressing question 3 we focused on two primary examples from the interior west, the Missouri River and Colorado River basins (Figure 1). We examined only large Dams In RESISII Data Base



Figure 2. Distribution of reservoirs with sedimentation surveys in the RESIS II data series, shown with circles sized according to original reservoir capacity and mapped by HUC-2 units, with water resource regions broadly defined by large river basins. Data from the U.S. Geological Survey (see *Ackerman et al.* [2009] for a description of the data and *Gray* [2009] for a brief discussion).

dams and reservoirs because of their centrality in federal policy related to regional water resources and ecosystem health. In the following paragraphs, we use a newly available database that describes results from repeat sediment surveys to address regional rates of sedimentation. To assess geographic and historical variability of sedimentation rates in the Missouri and Colorado basins, we explore data collected by federal agencies. Finally, we close with a brief discussion of the perceptions of managers and the public about the sustainability of these reservoir-based water resources.

[7] In these discussions we note that there is substantial uncertainty associated with determinations of sediment transport in rivers [Gomez and Church, 1989] and of the volumes of sediment stored in reservoirs. Variation in field conditions, changing geomorphology at measurement sites, instrumentation changes, and choices of values for constants in estimating equations introduce uncertainty in sediment transport equations. Most sediment transport calculations are estimates of suspended load which depend on direct sampling in the field, while bed load is usually estimated rather than measured. Estimates of sediment transport for the same river and time period under the best conditions vary by more than 15% from each other [Topping et al., 2000; Grams and Schmidt, 2005]. Estimation of the amount of sediment stored in reservoirs is the product of complex bathymetry, uncertain knowledge of prereservoir topography, and uncertain estimates of the density of the stored sediments.

2. Western American Dams and Reservoirs in a National Context

[8] A recently completed U.S. Geological Survey project has produced a revised and updated Reservoir Sedimentation Survey Information System (RESIS II) [*Ackerman et al.*, 2009]. The agency continues to expand the database through

RESSED, a newly activated online database that accepts input from users [Gray, 2009]. The Web-accessible RESIS II database used in this paper contains 6617 sedimentation surveys at 1823 impoundments and provides a new view, albeit imperfect, of the loss of storage capacity in American reservoirs. The data in RESIS II are highly valuable in assessing the sedimentation in individual reservoirs, and useful long-term records are available for some cases. The data have limited utility for higher-order analysis or for a fine assessment of their geographic characteristics for at least three reasons. First, investigators conducted reservoir sedimentation surveys unevenly throughout the period of record from 1755 to 1993. The majority of surveys date from 1950 to 1980, with a dramatic decline in surveys after 1980. The representativeness of the data for other periods outside this narrow temporal window is suspect given known hydroclimate variation. Second, the database grew out of earlier work by the Soil Conservation Service (now the Natural Resource Conservation Service), an agency that focused on small dams. As a result, only a few of the reservoirs in the database have storage capacities of 123 million m³ (100,000 acre-feet (ac ft)) or more. Thus, the data mainly relate to upland cases rather than main stem rivers. Finally, the data represent reservoirs distributed unequally across the nation (Figure 2), with an emphasis on those regions where federal and state agencies were particularly interested in reservoir sedimentation because of soil erosion (as in the Great Plains) or in management of wetlands (as in Ohio).

[9] Although the RESIS II data have significant limitations for general analysis, they do suggest the importance of the interior west as a geographic singularity in the distribution of annual rates of loss for storage capacity in reservoirs. A distinct national pattern emerged from the RESIS II for the mean annual loss of reservoir capacity through sedimentation when we mapped the values according to the U.S. Geo-



Figure 3. Distribution of mean annual loss of reservoir capacity in the continental United States mapped by HUC-2 units, water resource regions broadly defined by large river basins. Data from U.S. Geological Survey, Data Series 434, Reservoir Sedimentation Information System II; see *Ackerman et al.* [2009] for a description of the data.

logical Survey's water resource regions (hydrologic unit codes at the two-digit level). Five of the six regions or basins with the highest annual loss of storage capacity are in the interior west: dryland portions of the Columbia River, Basin and Range, Lower Colorado River, Missouri River, and Rio Grande (Figure 3). This distribution suggests that *Reisner* [1986] and other popular writers were correct to point out that reservoir sedimentation is a national-scale issue that is most problematic in the Arid Region or Cadillac Desert. For the reservoirs in the RESIS II database (a group biased toward smaller reservoirs), the average life expectancy in much of the interior west was less than 100 years, while in some eastern regions the average life expectancy was more than 300 years.

3. Spatial Variation

3.1. General Regional Spatial Variation in Reservoir Sedimentation

[10] It is likely that life expectancies for reservoirs vary according to their locations because there is a common geography of sediment yield from watersheds. Upstream locations that are the outlets of small drainage basins have different sediment yields than downstream locations that are the outlets of large river basins. The sediment yield ratio connects drainage area with the sediment yield and addresses these scale-dependent aspects of the process. The sediment delivery ratio is the ratio between the amount of sediment produced from the surfaces in a basin and the amount yielded at its outflow point [*Neuendorf et al.*, 2005], and this delivery ratio becomes progressively smaller for increasingly large watersheds. Generally, with all other factors being equal, the larger the basin, the greater the internal storage of sediment. A standard relationship for the United States is

$$D_{\rm r} = k(A_{\rm d})^{-0.125},\tag{1}$$

where D_r is the sediment delivery ratio, k is a constant, and A_d is drainage basin area [American Society of Civil Engineers, 1975]. Many more sophisticated expressions of the relationship between sediment delivery ratios and other control variables have been established [Springer et al., 2001; Verstraeten et al., 2003; Lu et al., 2005], but contributing drainage area remains the most important variable. In aggregate, many evaluations of the constants in equation (1) have confirmed that the relationship is nonlinear and have shown that the exponent, connected to the rate of change, is different for different regions [Lu et al., 2005].

[11] The relationship in equation (1) has important implications for the geographic variability of reservoir sedimentation because it specifies the influence of scale in sediment yield, and thus, the sediment delivered to reservoirs at particular locations. The equation, with constants specified by empirical data, indicates that if all other influences are equal, downstream reservoirs receive proportionally less sediment with respect to their drainage areas. The larger downstream reservoirs are therefore likely to have the longest expected life spans, a situation observed on the Missouri River. This generalization does not hold true, however, if all other controls are not equal. For example, if major sedimentproducing areas with highly erodible geologic materials are located in midbasin areas, reservoirs in midbasin areas receive larger amounts of sediment and have correspondingly shorter life expectancies, a situation observed in the Colorado River system. Variability in sediment contributions to downstream reservoirs is likely to result from regional climatic change, internal basin changes that result in increased or decreased storage, floodplain management practices that result in erosion or sedimentation along the channel, and channel engineering works that alter the mobility of sediment.

[12] Because sediment delivery ratios decline in the downstream direction (with the noted exceptions), it is reasonable to expect that reservoir filling rates and the percentage of total storage area lost to sedimentation also decline in the down-

Dam Number and Reservoir	River Subbasin	Drainage Area Upstream ^b (km ²)	Total Storage Capacity ^c (km ³)	Year Closed	Year of Last Sedimentation Survey	Total Lost Capacity (%)	Mean Annual Capacity Loss (%)	Likely Life (years)	End Date
1. Gavins Point	main stem	723,825 (279,480)	0.6664 (576,036)	1955	2007	21.7	0.4	240	2195
2. Fort Randall	main stem	682,387 (263,480)	7.7742 (6,220,472)	1952	1996	1.27	0.3	346	2298
3. Big Bend	main stem	645,740 (249,330)	2.3446 (1989,011)	1963	1997	9.1	0.3	374	2337
4. Oahe	main stem	630,615 (243,490)	29.1224 (23,615,385)	1958	1989	2.6	0.1	1192	3150
5. Garrison	main stem	468,617 (180,940)	30.2330 (24,513,514)	1953	1988	3.7	0.1	946	2899
6. Fort Peck	main stem	149,502 (57,725)	23.5694 (19,535,714)	1937	2007	5.6	0.1	1250	3187
7. Perry	Kansas	2,893 (1,117)	0.8910 (135,100)	1969	2001	31.8	1.0	100	2069
8. Tuttle Creek	Kansas	24,936 (9,628)	2.6542 (366,017)	1962	2000	5.9	0.2	644	2606
9 Milford Lake	Kansas	9,831 (3,796)	1.3885 (173,098)	1967	1994	27.7	1.0	97	2064
10. Harlan County	Kansas	19,776 (7,636)	1.0046 (51,353)	1952	2000	15.4	0.3	311	2263
11. Wilson	Kansas	181 (70)	0.9421 (42,545)	1964	1995	35.5	1.1	87	2051
Kanopolis	Kansas	20,357 (7,860)	0.5517 418,387)	1948	1993	6.9	0.2	652	2600
13. Clinton	Kansas	950 (367)	0.4906 (28,838)	1977	1991	11.9	0.8	118	2095
14. Pomona	Osage	834 (322)	0.3053 (29,376)	1963	1989	24.0	0.9	108	2071
15. Melvern	Osage	904 (349)	0.4477 (25,814)	1972	1985	15.7	1.2	83	2055
16. Hillsdale	Osage	373 (144)	0.1972 (10,840)	1981	1993	17.8	1.5	67	2048
17. Stockton	Osage	3,004 (1,160)	2.0567 (22,659)	1969	1987	39.5	2.2	46	2015
18. Pomme de Terre	Osage	1,582 (611)	0.8005 (11,692)	1961	1974	37.3	2.9	35	1996
19. Harry S Truman	Osage	29,784 (11,500)	6.4283 (251,353)	1979	1992	8.9	0.7	146	2125
20. Long Branch	L. Chariton	282 (109)	0.0802 (3,999)	1978	1988	12.1	1.2	83	2061
21. Rathbun	Chariton	1,422 (549)	0.6807 (23,656)	1969	1999	ND	ND	100	2069
22. Smithville	L. Platte	552 (213)	0.3041 (52,240)	1979	1993	9.5	0.7	147	2126
23. Blue Springs	L. Blue	85 (33)	0.0328 (300)	1988	ND	ND	ND	100	2088
24. Longview	L. Blue	129 (50)	0.0579 (2,044)	1985	ND	ND	ND	100	2085

Table 1. USCOE Dams in the Missouri River Basin^a

^aND indicates no data. Serial numbers correspond to locations shown in Figure 1. Data are from U.S. Army Corps of Engineers [1996] and calculations are by authors.

^bValues in parentheses are in square miles.

^cValues in parentheses are in acre-feet.

stream direction. In such a case, reservoir sedimentation volumes would be negatively related to drainage area and would be best approximated by a power function because of the dimensions involved: filling rates are measured in volume (L^3) (they might also be measured as a percent of storage volume lost through sedimentation), while drainage basin sizes are measured in area (L^2) , resulting in an allometric or power function relationship [*Church and Mark*, 1980] such as

$$L_r = a(A_d)^{-b}, \tag{2}$$

where L_r is an annual rate of reservoir storage loss (or percent of total reservoir volume), *a* is a constant related to the scale of the system and is related to a minimum rate of storage loss (for a hypothetical drainage where $A_d = 1$), A_d is the drainage basin area upstream from the reservoir, and *b* is the relative rate of change between the two variables (any units of measure apply to the variables). When A_d and L_r are known from empirical data, standard regression techniques using the linear form of equation (2) can assess the strength of the statistical relationship between L_r and A_d and can estimate *a* and *b*:

$$\log(L_r) = \log(a) - b \log(A_d), \tag{3}$$

with symbols as in equation (2). Additional variables such as the number of large dams upstream (D_u) and a binary variable (T_r) to indicate if the reservoir has major tributaries in addition to the main stem river (=1) or not (=0) might strengthen the statistical explanation. The linear form for such a regression analysis might take several forms, including

$$\log(L_r) = \log(a) - b_1 \log(A_d) + b_2 D_u + b_3 T_r,$$
(4)

where $b_1...b_3$ are empirically defined coefficients, and other variables are as defined in equations (1) and (2). The expected life of a reservoir (E_l) is inversely related to its annual rate of its storage loss (L_r):

$$E_l = 100/L_r.$$
 (5)

3.2. Spatial Variation of Sedimentation in the Missouri River Basin

[13] Data for rates of sedimentation in reservoirs of the Missouri River system exemplify the influence of scale and location through the variable of drainage basin area and provide empirical definition of the value of the exponent b in equation (2) for a large interior western river basin and its major reservoirs. The Missouri River Basin is a useful exemplar because it has relatively high quality data on reservoir filling for a substantial number of reservoirs of across a wide range of reservoir sizes. The U.S. Army Corps of Engineers (USACE) has constructed 6 main stem reservoirs and 16 additional reservoirs on tributaries, with accurate sediment surveys to define annual rates of storage loss through sedimentation for all the reservoirs (Table 1). All of the reservoirs are located in the Great Plains and Central Lowland geomorphic provinces. The reservoirs range in capacity from 0.080 to 30.21 km^3 (65,000 to 24,500,000 ac ft) and have drainage areas from about 180 to 725,000 km² (70 to $280,000 \text{ mi}^2$). The completion of the major projects by the 1970s provided the Missouri River Basin with more storage than in any other major river basin in the country. The Missouri River Basin is rich in sediment transport studies that have focused on selected reaches or limited periods [e.g., Keown et al., 1981; Macek-Rowland, 2000;



Figure 4. Mean annual loss of capacity and life expectancies for 22 major U.S. Army Corps of Engineers dams in the Missouri River Basin. Data from U.S. Army Corps of Engineers.

Berkas, 1995; *Blevins*, 2006], but a basin-wide picture is only now coming into focus [*Meade and Moody*, 2010].

[14] For the purposes of this analysis, the annual percent capacity lost to sedimentation was

$$L_r = 100(V_i/C_0)/T_i),$$
 (6)

where L_r is the annual rate of storage loss expressed as percent of the total capacity lost per year, V_i is the most recently measured volume of sediment in the reservoir in year i, C₀ is the original storage capacity of the reservoir when its dam was closed, and T_i is the number of years between the closure of the dam and the date of the most recent measurement of sediment volume. In our analysis we used data reported by the USACE (K. Stark and D. Pridal, Missouri River sediment, public presentation to Missouri River Recovery and Sediment Management Committee, National Research Council, 22 January 2009, Omaha, Nebraska), but we imposed our own organization of the data and correlation analysis. In our approach, the volume available for sediment storage defined the capacity for each reservoir. The design of the dams determined this volume because if sediment accumulations rise to a level that interferes with the outlet works or with hydropower intakes, the dam loses functionality. For large structures, the storage capacity did not include the flood pool, a volume equal to the maximum volume behind the dam minus the volume reserved for all other purposes except flood mitigation. For these reasons, some of the USACE reservoir volumes are less than the storage capacity as indicated in the National Inventory of Dams [U.S. Army Corps of Engineers, 1996]. The calculations relied only on the most recent sediment survey in each case, producing a long-term average.

[15] While researchers, managers, and commentators are generally aware of the potentially damaging loss of storage capacity, the Missouri River Basin data showed that for that basin reasonable expectations for the useful lives of the basin's reservoirs range from ~100 to ~1000 years (Figure 4). Although these major dams in the Missouri River Basin were all constructed in the mid-20th century, the widely variable dates of the end of their useful lives showed that their demise will not be likely to be synchronous (applying equation (5); see last column of Table 1).

[16] There was a significant relationship between drainage area and annual loss of storage space for 21 major USACE reservoirs in the Missouri Basin (Table 2); two dams had incomplete data. Regression analysis of equations (3) and (4) showed that drainage area alone explained more than half of the variation in rates of storage loss. With the number of dams upstream and reservoir tributary data included in the analysis, it was possible to explain two thirds of the variation in storage loss rate. In larger data sets further explanation might be available through additional variables to describe geologic materials and climatic factors.

[17] Generally, small reservoirs had shorter expected lives than large ones, so that the exponent in equation (2) is negative. In the Missouri River system, the reservoirs with the shortest life expectancies are smaller ones on tributary streams, particularly in the Kansas and Osage River basins, where they receive runoff from drainage areas with high sediment yields. There are exceptions to this generalization, including the case of Lewis and Clark Lake (a large reservoir formed by the main stem Gavins Point Dam) which now has already lost more than 20% of its storage capacity to sedimentation. The lake is at the downstream end of a series of six large dams and reservoirs, so that it receives little sediment influx from the Missouri River, but its pri-

Component	Equation (3)	Equation (4)		
Dependent variable Independent variables	annual capacity loss (%) drainage area (km ²)	annual capacity loss (%) drainage area (km ²), number dams upstream, major reservoir tributaries (1 or 0)		
Number of cases	21	21		
Intercept or coefficient, $\log a$	-1.18	0.69		
Coefficient or exponent, b or b_1	-0.74	-1.20		
Coefficient b_2	NA ^a	0.52		
Coefficient b_3	NA	0.13		
Correlation coefficient, R	0.74	0.84		
Coefficient of determination, R^2	0.55	0.67		
F statistic	22.81	14.22		
Degrees of freedom	1,19	3,17		
Significance level, p	0.000131	0.000069		
Standard error of estimate, SEE	0.32	0.27		

^aNA means not applicable.

mary source of the sediment is the Niobrara River, a direct tributary of the lake. Another example is Elephant Butte reservoir on the Rio Grande in New Mexico. Although it is on the main stem river downstream from several other others, it has a very high sedimentation rate because it collects sediment from highly erodible basins drained by the Rio Puerco and Rio Salado [*Scurlock*, 1998].

4. Temporal Variation

4.1. General Temporal Variation in Reservoir Sedimentation

[18] The amount of sediment delivered to reservoirs responds to controlling factors that change over time as well as space. The primary controls on temporal change in reservoir sedimentation rates include climate, land use or land cover, geologic materials, internal fluvial system operation, and minor influences that may be locally or temporarily important. Climate variation (as opposed to longer-scale climate change) is especially important in the interior western United States. On the Great Plains, Tucker et al. [2006] demonstrated that the episodic timing of erosion and sediment yield were caused by climate oscillations between drought and copious convective rainfall. The 3,650 km² (1,410 mi²) Paria River Basin of southern Utah provides another example, where channels incised during 1883-1940 and then partially refilled 1940–1980. The incision was associated with higher flood peaks and the aggradation, with reduced flood peaks [*Hereford*, 1986; *Graf et al.*, 1991]. The larger 44,000 km² (17,000 mi²) Little Colorado River Basin of Arizona and New Mexico has a similar history [Hereford, 1984].

[19] Regardless of other controls such as land use or land cover and climatic variation, the internal operations of river basins cause variability in their delivery of sediment to reservoirs at rates that may change rapidly, within a few years [*Graf*, 1986; *Hereford*, 2002]. Gradual changes in hydroclimatic controls such as rainfall frequency and intensity may not produce substantial watershed responses until a major threshold of resistance is exceeded. As the resistance threshold is surpassed, a rapid response of the erosion and sedimentation processes occurs. Because of these complex responses and threshold-oriented behaviors, a step function often is the best description of the rate of sediment yield to a site [*Patton and Schumm*, 1975, 1981]. Because of complexities and thresholds of sediment delivery processes, reservoir sediment inputs may have periods of very different rates of delivery separated by short periods of rapid change.

4.2. Temporal Variation of Sedimentation in Lake Powell on the Colorado River

[20] The Colorado River Basin provides a useful test case for temporal variation in sedimentation because of its exceptionally long record of sediment transport describing sediment yields from all of its major subbasins. The earliest collections of suspended sediment on the Colorado River were in 1892 [Collingwood, 1892] and during the 1900-1904 period [Forbes, 1906] in the Colorado River at Yuma, Arizona. Investigators collected a series of limited samples from the river during the first decade of the 20th century, but the sampling and analysis techniques were not standardized [Howard, 1929]. The U.S. Bureau of Reclamation began continuous sampling at Yuma in 1909, and preliminary analysis of the record from 1912 to 1921 inaugurated attempts to understand sediment yields on monthly and yearly time scales [Rothery, 1923]. Thus, the early investigators of sediment flows in the Colorado River Basin produced shortterm and inconsistent records.

[21] An understanding of the sediment processes in the river system was important to planners of the Colorado River Storage Project because they envisioned a series of large dams in the basin. As a result from the 1920s to the closure of several large dams in the early 1960s, a few gage sites produced continuous records of sediment yield at various places in the basin. After the early 1960s, a unified systemwide picture of the temporal variation of sediment transport (and thus potential reservoir sedimentation) in the Colorado River system became impossible because the sediment flows were interrupted by unsurveyed reservoirs and water flows were highly regulated by the dams. Smith et al. [1960] compiled many of the predam records. In more recent investigations, substantial research has been accomplished on various segments and for some periods in the river system, exemplified by the work of Thompson [1982, 1984a, 1984b], Grams and Schmidt [2005], and Topping et al. [2000, 2003].

[22] One of the most instructive cases in the gaged sediment transport history of the Colorado River system is the

Statistic	Colorado River at Lee's Ferry, Arizona	Green River at Green River, Utah	Colorado River Near Cisco, Colorado	San Juan River at Bluff, Utah	Canyon-lands, Utah
Mean, 1930–1942 ^b (Mg/yr)	118,701 (130,846)	22,294 (24,575)	17482 (19,271)	42063 (46,366)	36,863 (40,634)
Mean, 1943–1959 ^b (Mg/yr)	62,660 (69,071)	15,005 (16,540)	8,998 (9,919)	16,796 (18,514)	24,054 (26,515)
<i>t</i> value mean	3.425	2.064	3.206	3.781	1.790
Degrees of freedom	29	28	28	28	28
p mean	0.002	0.048	0.003	0.001	0.084
Standard deviation, 1930–1942 ^b (Mg/yr)	60,093 (66,241)	12,291 (13,548)	9,518 (10,492)	25,268 (27,853)	26,243 (28,928)
Standard deviation, 1943–1960 ^b (Mg/yr)	29,967 (33,033)	6,890 (7,595)	4,728 (5,212)	9,838 (10,844)	11,977 (13,202)
F ratio variances	4.021	3.182	4.053	6.597	4.801
p variances	0.009	0.033	0.011	0.001	0.004

Table 3. Statistical Comparisons of Two Periods of Record for Mean Annual Sediment Discharge at Gage Stations Defining the Major Subbasins of the Colorado River Above Lee's Ferry and the Site of Glen Canyon Dam With Lake Powell^a

^aAll the subbasins have the same periods of record except for Colorado River at Lee's Ferry, Arizona, which has a second period extending to 1960. See Figure 5. Data are from *Oka* [1962], and calculations are by authors.

^bValues in parentheses are in 10⁶ t/yr.

set of records associated with sediment flows in the Upper Colorado River Basin. U.S. Geological Survey sediment discharge records for 1926 through 1960 are available from Lee's Ferry on the Colorado River, a short distance downstream from the site of Glen Canyon Dam and its reservoir, Lake Powell. Companion records for 1930 through 1959 are also available for the primary contributing areas upstream: the Green, Colorado, and San Juan rivers. The early date marked the beginning of coordinated and standardized data collection, and the ending date marked the closure of large dams upstream.

[23] This limited sediment record was the best basin-wide data available to planners in the 1960s, and it remains the best record of sediment transport in the system without the influence of large dams. Data collection sites included Colorado River at Lee's Ferry, a short distance downstream from the Glen Canyon Dam site, with data collection sites defining the four upstream contributing subbasins, all of roughly similar size. Green River at Green River, Colorado River at Cisco, and San Juan River at Bluff had direct sediment measurements during 1930–1959. Canyonlands, an ungaged Colorado Plateau region and the remaining upstream "interbasin" area not included in the other three subbasins, was an important contributor of sediment because of erodible geologic materials and a semiarid climate. Its contribution was calculated as the sediment yield measured at Colorado River at Lee's Ferry (the total from the Upper Basin) minus the yields from the other three subbasins.

[24] Published compilations of water and sediment data for the upper Colorado River Basin include work by *Iorns et al.* [1965], but an unpublished document stored in the files of the U.S. Bureau of Reclamation in Salt Lake City contains a highly consistent summary of sediment yield data from the upper basin, 1930–1959. In this set of working papers, Oka [1962] collated the sediment yield data that we then analyzed using a difference of means test and an analysis of variance (Table 3 and Figure 5). The sediment discharge records had two remarkably different periods, 1930–1942 and 1943–1959. Sediment discharge declined by about one half in the record at Lee's Ferry, with the largest decline in the contribution of the San Juan River [Graf, 1987]. The difference in sediment discharge annual means and variances between the two periods was statistically significant (p values in Table 3) at the 0.05 level or greater with only one exception, variance of the Canyonlands values. The decline in the later period of record occurred in all of the subbasins draining to Lee's Ferry and by extension to the site of Lake Powell. About 45% of the decline was due to the decline in the San Juan River contribution.

[25] After compiling a sediment discharge database in the early 1960s in his unpublished work, Oka [1962] pointed out that predicting the likely time to filling of Lake Powell with sediment was complicated by the nature of the sediment record at Lee's Ferry. Between 1926 and 1960, without the effects of large upstream dams, the sediment discharge record appeared to have three distinct periods: a high sediment discharge period from 1926 to 1929, an intermediate period between 1930 and 1942, and a low sediment discharge period between 1943 and the end of the record in 1960. Oka and his associates at the U.S. Bureau of Reclamation were faced with making future predictions based on the mean sediment discharge from the entire record or predictions based only on one or two periods in the record. They proposed two hypotheses as explanations for the fragmented record: changes in collecting the data and changes in upstream land use.

[26] Changes in sampling equipment and procedures for determining sediment concentrations in the Colorado River constituted a potentially reasonable explanation of the three distinct periods of sediment yield from the basin. Early investigators had used a variety of sediment samplers, including bottles and tubes that captured river water as it flowed through the length of the device [Fortier and Blaney, 1928]. By 1926 the U.S. Geological Survey standardized its equipment, settling on a design by Carl H. Au, a hydraulic engineer. The Au Sampler trapped water and sediment in a pint bottle when it was lowered into the water, and a movable knife punctured its paper cap (Figure 6, top left) [Howard, 1929, p. 18]. Data for calculating sediment concentrations came from three separate samples: one collected at the bottom of the stream with the sampler on the bed, a second sample collected by drawing the open bottle from the bed to the surface, and a third sample taking water only from near the surface. In 1930, the Colorado River Sampler entered use: a stopper attached to a control line replaced the paper cap and knife, and samples were collected by taking in water throughout the water column (Figure 6, top right) [Howard, 1947, p 4]. In 1940, the U.S. Geological Survey began collecting sediment samples from the Colorado River using a



Figure 5. Sediment yield record on the Colorado River at Lee's Ferry that was the basis for predicting the expected useful life of Glen Canyon Dam and Lake Powell. Vertical bars show suspended sediment discharge, and horizontal bars represent mean values for each of three time periods: 1926-1929 (Colorado River at Lee's Ferry only), 1930-1942, and 1943-1960. Records terminated when dam closures affected sediment discharges on major rivers upstream. Note the various scales for the *y* axes. For statistical analysis, see Table 3. Plots are based on U.S. Bureau of Reclamation data compiled by *Oka* [1962].

completely different design, the D-43 Sampler that was operated in a depth-integrating fashion (Figure 6, bottom) [*Edwards and Glysson*, 1982, pp. 6–7].

[27] Equipment and procedural changes were tempting explanations for the changes in the sediment discharge records because the dates of equipment and/or methods changes were close in time to the major changes in the record. For the early adjustment in the record, about 1930, the samplers seem highly similar, but the change in methods to a depthintegrating approach may explain the change to lower sediment discharges. In early years, taking a sample partly from the bottom of the channel may have included large amounts of saltating sediment near the bed that produced higher estimated concentrations. Although the D-43 sampler has a radically different appearance from its predecessors, subsequent paired, controlled evaluations showed no significant differences in results [*Oka*, 1962, p. 5]. Later, *Gellis et al.* [1991] explained the 1943 decline as a function of geomorphic and hydrologic factors rather than as an artifact of sampling. Thus, equipment and its use could explain the 1930





Post-1940

Figure 6. Sediment samplers used by the U.S. Geological Survey for the Colorado River during the period before the closure of Glen Canyon Dam in 1963.

decline in sediment discharge at the gage at Lee's Ferry but not the major change about 1943.

[28] During the 1930s the federal government instituted sweeping changes in the management of grazing on western lands, including those in the Colorado River Basin, perhaps providing some explanation for changes in sediment transport in the basin. The Tailor Grazing Act of 1934 and the creation of the Bureau of Land Management in 1947 brought about reductions in numbers of grazing animals in many basins, including in the Colorado River Basin. However, these dates were not coincidental with changes in sediment discharges in the river, and land use changes were gradual while changes in the sediment discharge record were abrupt [Oka, 1962, p. 5].

[29] Subsequent research has shown that the sharp decline in about 1942-1943 in the sediment discharge record of the Colorado River corresponds to the time when tributary processes changed from erosion to deposition [e.g., Hereford, 1984; Graf, 1987; Gellis et al., 1991]. Sediment eroded from upstream subbasins fueled the high sediment discharges observed prior to about 1943, but after that date many tributary streams began storing large amounts of sediment, building up their floodplains and filling their arroyo-bound channels, a common process in river systems [Schumm, 2005]. As shown in Figure 5, the post-1940 decline was accompanied by a similar decline in year-to-year variability, generally proportional to mean values in these data. There was remarkable consistency in sediment yield records from one subbasin to another: each one experienced declines in sediment yield after the early 1940s of 30%-50%. This widespread phenomenon suggests a large-scale driver such as climatic variation that affected the entire Upper Colorado River Basin.

[30] Although the exact climatic explanation for this process reversal in subbasins from generally erosive to generally depositional is not entirely clear, it apparently is partly related to changes in storm frequency and major atmospheric circulation patterns that drive the system, particularly since those changes occurred abruptly in the early 1940s [Reitan, 1979; Zishka and Smith, 1980]. Schumm [1998] reviewed this and other combinations of explanations for temporal variation of Upper Basin sediment yield as an exploration of the application of scientific methods in earth and water science. He pointed out that after several decades of research, no one single explanation is satisfactory. Our conclusions supported his perspective. It seemed logical that land use changes to improve management of grazing may have aided the long-term reduction of sediment yield, but the storage of sediment within tributary watersheds triggered by climatic changes was a primary explanation of the lower sediment yields in the post-1943 record.

5. Discussion and Conclusions

[31] Dealing with the sustainability of large reservoirs as measured by the length of their expected lifetimes is a difficult point of communication between scientists and popular writers who influence decision makers. Some popular writers have suggested that reservoirs in the Arid Region or Cadillac Desert would meet swift demises as a result of sedimentation. These authors used comments by researchers that (by one interpretation) cast doubt on the multicentury viability of the reservoirs. For example, Reisner [1986, p. 492] quoted Robert Strand, a U.S. Bureau of Reclamation researcher and administrator, as saying that the "payout lifetime" of the largest reservoirs was 50-100 years, after which sedimentation would begin to reduce financial returns from the structures. Popular writers changed this concept, however, so that Palmer [1986, p. 230] wrote that Lake Powell was likely to "fill up with sediment in a hundred years." Also, *Reisner* [1986] expressed concern that because many of the large reservoirs of the west were completed



Figure 7. Total reservoir storage capacity in the 21 largest dams of the Missouri River Basin calculated for each year from 1937 to 3159 under the following assumptions: no new dams will be built, presently known average rates of filling will continue, and there will be no efforts to flush sediments through or around existing structures. Year of maximum storage was 1979. The first reservoir, created by Fort Peck Dam, was the first large one in the system, and it will likely also be the last. Data are from U.S. Army Corps of Engineers, summarized in Table 1.

during a 10–20 year period in the mid-20th century, so (in his interpretation) many of the large reservoirs would encounter the ends of their useful lifetimes at roughly the same time. *Powell* [2009, p. 209] opined that many western reservoirs "are going to silt up within the same time period." These outcomes would be disastrous for a western American economic system dependent on large water projects, particularly in view of long-term population growth in a changing climate.

[32] The new data reviewed and analyzed in this paper do not support these concerns. Eventually, the reservoirs are likely to fill with sediment, and it is true that interior western reservoirs are losing capacity more rapidly than in other regions of the country. However, although some small reservoirs are likely to fill in the next century, most large reservoirs have life expectancies of 200-1000 years or more, and they appear to be sustainable parts of a regional water management system. Without further dam and reservoir construction, however, it is also clear that managers will be faced with a gradual long-term decline in total storage capacity, a metric of sustainability that has already passed its maximum (Figure 7). A very few reservoirs, such as Lewis and Clark Lake associated with Gavins Point Dam on the Missouri River, appear likely to become problem cases within a few decades. Our analysis showed that the rate of filling or capacity loss varied spatially, with the most long-lived reservoirs being those lowest in the basin, with some notable exceptions such as the Colorado River and Rio Grande. The rate of sedimentation and loss of capacity also varied with time, depending on controls that were partly external and partly internal to the drainage basins. Temporal changes have occurred abruptly, within a few years.

[33] In summary, the message that science should be sending to popular writers and managers is that the data indicate

that sustainability related to sedimentation is soon to be a problem for a readily identifiable subset of reservoirs that includes Gavins Point Dam on the Missouri River. The message should also be that for reservoirs in the interior western United States in general the end is not near, and when the end does arrive, it will not be at the same time throughout the region. Monitoring of sediment transport and reservoir sedimentation should continue because watershed processes may reverse themselves and change rates of reservoir sedimentation downstream, with the exact timing turning out to be a surprise. Surprises particularly may be in store for sedimentation rate in Lake Powell, since sudden changes in sediment yield have occurred there in the period of record. The rate might double if the present period of storage along streams in its subbasins ends in another process reversal with a period of renewed rapid erosion and high sediment yields similar to the 1930-1942 period. Whether or not similar reversals occur in the Missouri River Basin and streams on the Great Plains is little studied, but it seems reasonable to expect similar surprises there as well.

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