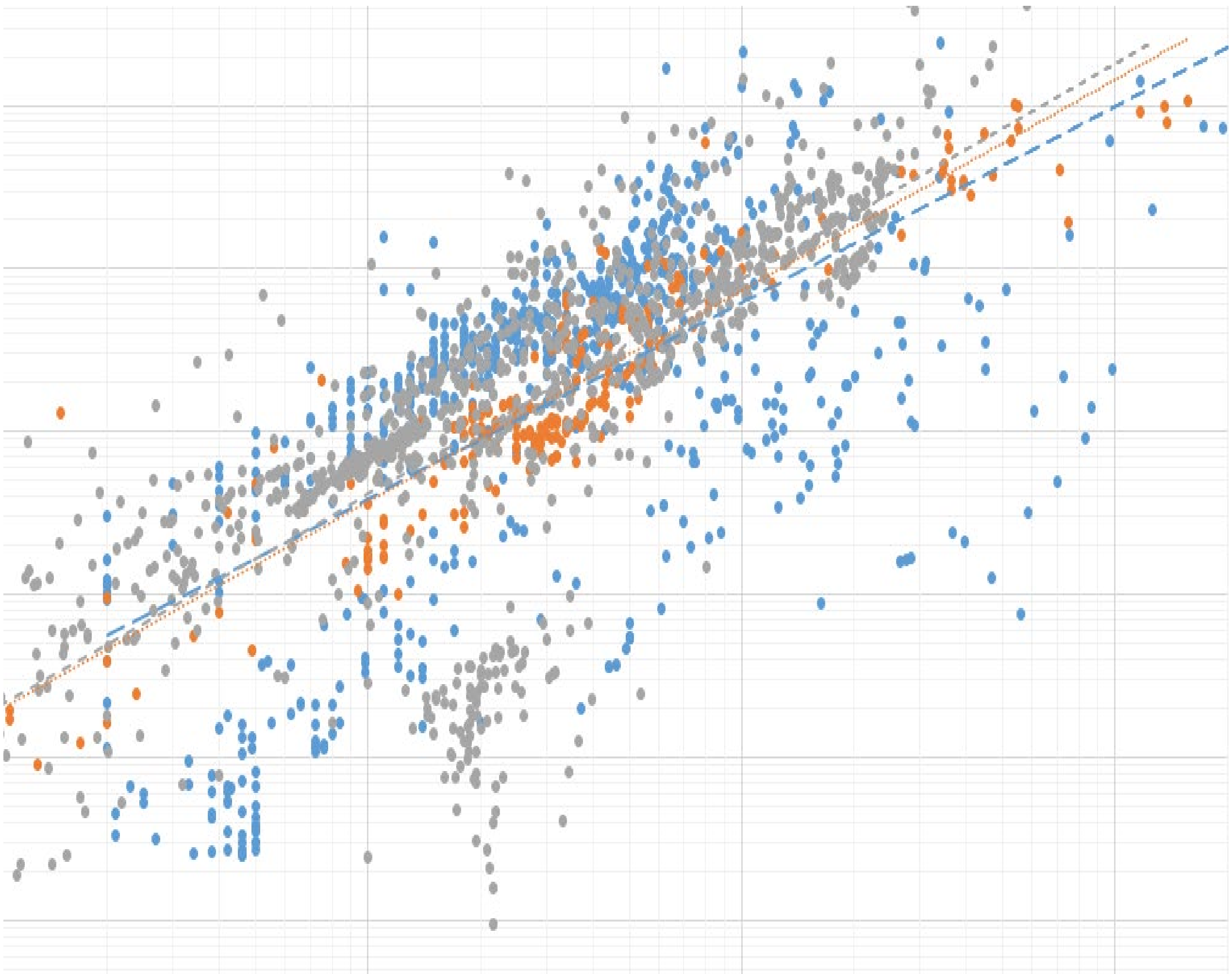
Jemez Reservoir Trap Efficiency Calculations

AUGUST 2020



US Army Corps of Engineers

US ARMY CORPS OF ENGINEERS
ALBUQUERQUE DISTRICT
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LIST OF ACRONYMS AND ABBREVIATIONS

Ac-ft	Acre-feet
C	Reservoir storage capacity
cfs	Cubic feet per second
cm^3	Cubic centimeters
EM	Engineer Manual
ft^3	Cubic feet
g	grams
I	Reservoir Inflow
L	Reservoir length
lb	pounds (weight)
LiDAR	Light Detection and Ranging
mg/L	Milligrams per Liter
NM	New Mexico
PE	Passing efficiency of the reservoir
ppm	Parts per million
S	Weight of sediment
SI	Sedimentation Index
TE	Trap efficiency
USACE	United States Army Corps of Engineers
USGS	United States Geological Survey
yr	year

1. EXECUTIVE SUMMARY

The United States Army Corps of Engineers (USACE), Albuquerque District requested an evaluation of the sediment transport of the Jemez River in 2018 from the U.S. Geological Survey (USGS), New Mexico Water Science Center. The specific focus area was sediment transport near the USACE Jemez Canyon Reservoir. The USGS evaluated historical accounts, aerial photography, reservoir capacity surveys, and USGS gage information collected for both surface water and suspended sediment. Currently the USGS is revising a draft report based on feedback from a USACE review. One of the USACE comments was a request for the USGS to update the trap efficiencies listed in a table in the report. The USGS explained that as they weren't the originator of this data (this was the USACE), that the USACE should provide any updates for utilization by the USGS in the final draft of the report. Trap efficiencies reported by the USGS in their draft report have been included in Jemez Canyon Reservoir Water Control Manuals (USACE 1994; USACE 2007). An environmental assessment (USACE 2000) conducted for the evacuation of the sediment pool, also included the trap efficiencies from the water control manuals, plus additional calculations from August 1959 and June 1998. None of these references recorded the analysis methodology used to assess the trap efficiency.

Since it was desirable to extend the estimation of trap efficiencies for the current reservoir surveys, an evaluation of trap efficiency methods was pursued for Jemez Canyon Dam reservoir. A total of five approaches were used to estimate the trap efficiency and compare with the previously reported values. Two of these used a mass balance approach, while three are empirical methods based on trap efficiency calculations from other reservoirs. The three empirical approaches report higher trap efficiencies than previously reported. This is to be expected, as the underlying methodology for these approaches assumes that the reservoir is wet all the time, which is not always true for Jemez Canyon Dam Reservoir. Of the other two methods, utilization of an annualized sediment yield for the Jemez River results in unrealistic trap efficiencies, likely because the delivery of sediment into the reservoir is episodic in nature and not uniformly consistent over time. The last method, utilizing existing data collected from the USGS downstream of the dam, resulted in trap efficiencies that were similar, but not exactly like the previously reported calculations. The trap efficiency calculations for the 1959 and 1983/1984 years were lower than the reported values, while those calculated for 1991 and 1998 were higher than the reported values. The trap efficiency calculations for the last year is negative because of Jemez River flows eroding deposited sediment in the reservoir pool that is now dry. The trap efficiency values estimated by using the USGS data are recommended for use in the future, as they provide a consistent, documented trap efficiency calculation approach.

2. INTRODUCTION

2.1 BACKGROUND

The United States Army Corps of Engineers (USACE), Albuquerque District requested an evaluation of the sediment transport of the Jemez River in 2018 from the U.S. Geological Survey (USGS), New Mexico Water Science Center. The specific focus area was sediment transport near the USACE Jemez Canyon Reservoir. The USGS evaluated historical accounts, aerial photography, reservoir capacity surveys, and USGS gage information collected for both surface water and suspended sediment. Currently the USGS is revising a draft report based on feedback from a USACE review. One of the USACE comments was a request for the USGS to update the trap efficiencies listed in a table in the report. The USGS explained that as they weren't the originator of this data (this was the USACE), that the USACE should provide any updates for utilization by the USGS in the final draft of the report. Trap efficiencies reported by the USGS in their draft report have been previously reported in the Jemez Canyon Reservoir Water Control Manuals (USACE 1994; USACE 2007). An environmental assessment (USACE 2000) conducted for the evacuation of the sediment pool, included the trap efficiencies from the water control manuals, plus additional calculations from August 1959 and June 1998. None of these references recorded the analysis methodology used to assess the trap efficiency.

2.2 STUDY LOCATION

Jemez Canyon Reservoir is located on the Pueblo of Santa Ana in Sandoval County, New Mexico. Construction of the dam was completed in 1953 and has been in operation since that time.

2.3 STUDY OBJECTIVES

The study objective for this work is to provide an update of the trap efficiency for Jemez Canyon Reservoir up to the 2016 reservoir rangeline survey.

2.4 DATA SOURCES

The previously cited water control manuals (USACE 1994; USACE 2007) listed the incremental and cumulative volume of sediment stored in the Jemez Canyon Reservoir, along with survey dates up to 1998. Information about the historical reservoir surveys is also provided through the Albuquerque District's webpage (USACE 2020), which provides incremental and cumulative sediment volumes, as well as intervening time periods between surveys (in years). The USGS has also intermittently collected both discharge and suspended sediment data from established gages on the Jemez River. Two USGS gages were used for this assessment. USGS gage # 08328950 (Jemez River outlet below Jemez Canyon Dam, NM) has been in operation since 8 October 2009. This gaging station records discharge values and both daily average and 15-minute discharge values were extracted from the collected data. Prior to 2009 another USGS gaging station (USGS gage # 08329000 – Jemez River below Jemez Canyon Dam, NM) collected discharge data between 1 April 1936 and 29 September 2009. Only daily average discharge was available for this dataset. Suspended sediment concentration has also been collected at the USGS gage # 08329000. This dataset was collected for the following time periods: 15 November 1955 through 30 September 1958, 1 October 1961 through 30 September 1962, and 30 July 2014 through 29 September 2018.

3. TRAP EFFICIENCY CALCULATIONS

3.1 TRADITIONAL RESERVOIR TRAP EFFICIENCY CALCULATIONS

The USACE's Engineer Manual (EM) 4000 for Sedimentation Investigations of Rivers and Reservoirs (USACE 1989) provides guidance on estimating trap efficiency in reservoirs. Three methods have been widely utilized for reservoirs with a permanent pool. These include the capacity-watershed method developed by Brown (Brown 1943; Brown 1950), the capacity-inflow method developed by Brune (Brune 1953) and subsequently modified by Dendy (Dendy 1974), and the sediment index method developed by Churchill (Churchill 1948).

These methods were utilized for the evaluation of trap efficiency at the Jemez Canyon Dam Reservoir and are described in the following sections.

A. BROWN

Brown (Brown 1943; Brown 1950) developed a curve of sediment trapped (percent) versus reservoir storage capacity. The reservoir storage capacity is based on the ratio of reservoir capacity and the watershed area. Brown developed both an upper and lower boundary curve, as well as a design curve (USACE 1989). The developed methodology assumes that there is a permanent reservoir pool, which is not the case for Jemez Canyon Dam Reservoir. The utilization of this method assumes that rainfall runoff occurs similarly on this watershed as the ones studied by Brown, which again is not necessarily the case for the arid southwest.

The USACE website for Jemez Canyon Dam Reservoir (USACE 2020) was used to extract the maximum pool capacity (257,276 Ac-ft) and the upstream drainage area (1,034 square miles). The cumulative sediment volume was subtracted from the maximum pool capacity to get a reservoir storage capacity at the time of the survey. The resulting ratio of reservoir capacity to watershed area varied between 249 and 230, which are represented by a relatively flat portion of Brown's curve. The sediment trapped efficiency is estimated to be about 99 percent. The specific calculation values are shown in Table 1.

Table 1. Brown trap efficiency calculations

Survey Year*[*]*	**Incremental Sediment Volume (Ac-ft)**[†]	**Cumulative Sediment Volume (Ac-ft)**[‡]	**Reservoir Capacity (Ac-ft)**	**Capacity/watershed area ratio**	**Trap Efficiency (%)**
October 1953	0	0	257,276	249	99
January 1958	1,392	1,392	255,884	247	99
September 1959	1,947	3,339	253,937	246	99
January 1966	1,065	4,404	252,872	245	99
February 1975	6,709	11,113	246,163	238	99
January 1984	3,388	14,501	242,775	235	99
July 1991	2,227	16,728	240,548	233	99
July 1998	3,060	19,788	237,488	230	99
December 2016	-1,909	17,879	239,397	232	99

Notes: * – Some of the month – year combinations are different than previously reported in the water control manuals (USACE 1994; USACE 2007). The website for Jemez Canyon Dam Reservoir (USACE 2020) was used to extract the intervening period of time (listed in years). Survey dates were adjusted in Excel so that the time frame between surveys matched the reported period years.

† – Data as reported from Jemez Canyon Dam Reservoir (USACE 2020).

‡ – estimated as the sum of the incremental sediment volumes up to a given period of time.

B. BRUNE

Brune (Brune 1953) developed a relationship to estimate long-term trap efficiency in reservoirs that are always wet. This is not a recommended method for dry reservoirs, which is how Jemez Canyon Dam Reservoir is currently operated. Brune developed a set of curves showing the sediment trapped (as a percentage) versus the capacity – inflow ratio. Dendy (Dendy 1974) added more reservoir data and developed an equation for a median curve on the developed Brune chart. This equation is shown in Equation 1

Equation 1. Median trap efficiency curve from Dendy (1974) as reported in (USACE 1989)

$$TE = 100\left(0.97^{0.19^{\log\left({C}/{I}\right)}}\right)$$

Where TE = trap efficiency (%), C = reservoir storage capacity (Ac-ft), and I = reservoir inflow (Ac-ft).

The reservoir capacity was calculated similarly to that described for Brown. The computed water inflow is based on the measured outflow discharge reported at USGS gages # 08329000 and 08328950 and modified to account for changes in storage and evaporation when there was a pool (Ball, R.J., written commun., 11 June 2020). The computed daily average discharge value was used for this calculation and converted to a value of Ac-ft by multiplying the number of seconds in a given day (86,400) and converting square feet to acres (43,560 square feet in one acre). The volume of water reported within a given time period (time between reservoir surveys) was summed and divided by the time period between surveys (in years). The assumption is that the computed inflow values are more representative of the actual inflow conditions. The reservoir storage and calculated reservoir inflow were utilized in Equation 1 to provide an estimate of the median trap efficiency as estimated from the Brune curves. Calculated values are shown in Table 2.

Table 2. Brune trap efficiency calculations

Survey Year***	**Reservoir Storage (Ac-ft)†**	**Computed Water inflow (Ac-ft)‡**	**Period between surveys (years)§**	**Mean Annual Water inflow (Ac-ft/yr)‖**	**Capacity/water inflow ratio**	**Trap Efficiency (%)**
October 1953¶	257,276	461,988	17.56	26,307	-	-
January 1958	255,884	129,095	4.25	30,380	8.42	99.3
September 1959	253,937	103,190	1.67	61,846	4.11	98.9
January 1966	252,872	179,692	6.33	28,381	8.91	99.4
February 1975	246,163	365,752	9.08	40,284	6.11	99.2
January 1984	242,775	541,257	8.92	60,675	4.00	98.9
July 1991	240,548	526,985	7.50	70,278	3.42	98.8
July 1998	237,488	481,295	7.00	68,756	3.45	98.8
December 2016	239,397	430,846	18.42	23,388	10.24	99.4

Notes: * – Some of the month – year combinations are different than previously reported in the water control manuals (USACE 1994; USACE 2007). The website for Jemez Canyon Dam Reservoir (USACE 2020) was used to extract the intervening period of time (listed in years). Survey dates were adjusted in Excel so that the time frame between surveys matched the reported period years.

† – Estimated similarly to Brown calculations (see Table 1)

‡ – estimated as the computed daily water inflow using measured USGS gages (# 08329000 and 08328950) and accounting for storage and evaporation when there is a reservoir pool. These values were provided by USACE Water Management (Ball, RJ, unpub data, 11 June 2020). The October 1953 estimate is based on just the USGS gage inflow since the start of the USGS record (1 April 1936) and was calculated as part of this work effort.

§ – time period between reservoir surveys.

‖ – water inflow in Ac-ft divided by the time period between surveys.

¶ – Null values are represented by a "-". The October 1953 represents the initial survey to build the dam, so no reservoir exists.

C. CHURCHILL

Churchill (Churchill 1948) developed a relationship between percent of sediment passing through a reservoir versus the sedimentation index. The relationship was developed for reservoirs within the Tennessee Valley Authority and thus is also applicable to reservoirs that continuously hold water. The sedimentation index is determined as the ratio of the reservoir's retention period and the mean flow velocity. Since these variables are not often known, the reservoir's retention period (estimated as the mean reservoir storage divided by the average reservoir inflow) and the reservoir's mean flow velocity (estimated as the average reservoir's inflow divided by the average reservoir cross section area) can be combined with an estimation of the average reservoir cross section area (median reservoir storage divided by reservoir length) to get the relationship shown in Equation 2 (USACE 1989).

Equation 2. Sedimentation index relationship (USACE 1989)

$$SI = \frac{\left(\frac{C}{I}\right)^2}{L}$$

Where SI = Sedimentation Index (seconds/foot), C = mean reservoir storage (cubic feet), I = reservoir daily inflow rate (cfs), and L = reservoir length (feet).

The mean reservoir storage was estimated based on daily observed storage at the Jemez Canyon Dam (Ball, R.J., unpub data, 11 June 2020). Jemez Canyon Dam is primarily a dry reservoir with periodic pools formed during high events. When the reservoir is dry or nearly dry the observed storage is listed as zero. To avoid numerical skewing due to use of an arithmetic average, the median reservoir storage area between the intervening survey periods was calculated (in acre-feet) and reported in Table 3. These values were converted to cubic feet. The reservoir annual inflow rate estimated for the Brune method was converted to the units of cfs for the Churchill method. The reservoir length (13,698 ft) was estimated in Google Earth for the pool shown in the 1996 imagery. The median reservoir storage for this time period (21,768 Ac-ft) was used to scale the reservoir length based on median reservoir storage. The sedimentation index was then calculated according to Equation 2. The percent of sediment passing through the reservoir (or passing efficiency) is given by Equation 3. The trap efficiency is then calculated as 100 minus the passing efficiency. Trap efficiency calculations are shown in Table 3.

Equation 3. Passing efficiency for local silt (USACE 1989)

$$PE = 800 * SI^{-0.2} - 12$$

Where PE = passing efficiency of the reservoir (or how much sediment passes through a reservoir (%) and SI = sedimentation index (seconds/foot).

Table 3. Churchill trap efficiency calculations

Survey Year*	**Median Reservoir Storage (Ac-ft) †**	**Median Reservoir Storage (ft^3)**	**Average daily inflow (cfs)‡**	**Sedimentation Index**	**Pass Efficiency (%) §**	**Trap Efficiency (%) §**
October 1953	0	0	36.3	0	-	-
January 1958	0	0	42.0	0	-	-
September 1959	0	0	85.4	0	-	-
January 1966	0	0	39.2	0	-	-
February 1975	0	0	55.6	0	-	-
January 1984	1,667	72,614,520	83.8	715,626,510	1.6	98.4
July 1991	26,727	1,164,228,120	97.1	8,552,472,396	-3.7	103.7
July 1998	21,768	948,214,080	95.0	7,277,230,846	-3.5	103.7
December 2016	0	0	32.3	0	-	-

Notes: * – Some of the month – year combinations are different than previously reported in the water control manuals (USACE 1994; USACE 2007). The website for Jemez Canyon Dam Reservoir (USACE 2020) was used to extract the intervening period of time (listed in years). Survey dates were adjusted in Excel so that the time frame between surveys matched the reported period years.

† – Median reservoir storage during the time period between surveys. These values were provided by USACE Water Management (Ball, RJ, unpub data, 11 June 2020).

‡ – Estimated similarly to Brune calculations, but with unit conversions (see Table 2)

§ – Null values are represented by a "-". The methodology assumes a constant reservoir pool, but the Jemez reservoir has operated without a pool for most of its operational life.

3.2 TRAP EFFICIENCY FROM MASS BALANCE APPROACH

The trap efficiency can also be estimated using a mass balance approach by using the relationship shown in Equation 4 and Equation 5.

Equation 4. Trap efficiency (USACE 1989)

$$TE = \frac{S_{in} - S_{out}}{S_{in}}$$

Where TE = trap efficiency (%), S_{in} = weight of sediment coming into the reservoir, and S_{out} = weight of sediment coming out of the reservoir.

Equation 5. Reservoir mass balance

$$S_{in} - S_{accum} = S_{out}$$

Where S_{in} = weight of sediment coming into the reservoir, S_{accum} = weight of sediment accumulated in the reservoir, and S_{out} = weight of sediment coming out of the reservoir.

For a constant unit weight of material (assumed to be true), similar void ratios in accumulated reservoir sediment and suspended sediment, and no hyperconcentrated flows, the above relationship can be utilized for performing a volumetric balance instead of a mass balance. The assumption of void ratio and hyperconcentrated flows is not always strictly applicable. It is likely that the void ratio of suspended sediments is larger than that of accumulated sediment in the reservoir. This is not known for this exercise, so for simplicity sake it was assumed to be constant. The relationship between volume and mass tends to deviate once suspended sediment concentrations get into the hyperconcentrated flow regime (> than about 100,000 mg/L) (Julien 2010). While there are some recorded suspended sediment concentrations that approach this value, most are below this, so again this assumption is made for simplicity.

The reservoir surveys record the volumetric change in the accumulated sediment within the reservoir pool. The methodology of the collected surveys changed after 1998 (move from rangeline surveys to LiDAR collections) so there may be apparent volume changes that are attributable to survey methods. This was not accounted for in the following described approaches as a comparison of the two methods from the same year was not readily available and beyond the scope of this analysis.

This results in essentially two unknowns, sediment flow into the reservoir and sediment flow out of the reservoir. Methods that assume one of these to estimate the other and then calculate the trap efficiency are provided in the following sections.

A. MASS IN FROM SEDIMENT YIELD APPROACH

The first approach assumes that the sediment flow into the reservoir is known. The basin sediment yield was previously estimated (Little 2007) as being 390,370 tons/year using the daily discharges between 1980 and 2000 and a bed material sediment rating curve estimated by Ayres and Associates. The sediment mass is converted to a volumetric inflow through unit conversions and the assumption of a unit weight of soil. The assumed unit weight of soil was 157.1 lbs/ft^3, based on an average of field collected data (Maynord et al. 2012). Maynord et al. (Maynord et al.

2012) collected bed material samples on the Jemez River upstream from the Jemez Canyon Dam Reservoir and evaluated the density of these samples. Two average sample densities were reported (2.51 and 2.52 g/cm^3). These were averaged and converted into English units to provide a soil unit weight of 157.1 lb/ft^3. This was assumed to be representative of all sediment (reservoir accumulations and suspended sediment). This provided an average annual sediment volume of 114.1 Ac-ft.

The assumption with this method is that sediment yield is assumed to be uniform over time. The reality is that sediment yield is likely variable with time and episodic, being timed with both snowmelt runoff and rainfall-runoff events. To account for this, the computed inflow to Jemez Reservoir ((Ball, R.J., unpub data, 11 June 2020) was used to generate an average annual water inflow volume (Ac-ft) for the period 1953 through 2018. This was done by converting the average daily computed inflows to a daily volume (multiplying by time and a unit's conversion, factor of 1.98) and generating a cumulative water inflow over the time period from 1953 to 2018. A lookup code in Excel was then utilized to extract the cumulative water volume at the end of each year (31 December) in the record. The difference between subsequent years is the water volume for that given year. The arithmetic average for each of these years was taken as the average annual water volume for this period. This was assumed to be correlated with the average annual sediment yield. To account, to some extent for the temporal variability of the flows, the ratio of any given year's water volume to the average annual water volume was used to adjust the annual sediment yield. In this manner a variable annual sediment loading was estimated, however, it does assume that the sediment yield itself was uniform over time. The calculated water and sediment inflows for each year are shown in Table 4.

The inflowing sediment for use in Equation 5 was estimated by summing the sediment volume for every given year between the reservoir surveys and then estimating the fraction of the sediment volume that occurred for the year the reservoir surveys occurred. The sediment volume fraction was determined by summing the volume of water that occurred up to the survey day and dividing by the water volume for the whole year. This fraction was then multiplied by the sediment volume for that year. Equation 5 was then used in conjunction with the known accumulated sediment volume over the same time period to estimate a sediment out flow. Knowing both the sediment inflow and outflow, a trap efficiency was calculated using Equation 4. Calculations are shown in Table 5.

Table 4. Annual Water and sediment inflow (the average water inflow is 43,236 Ac-ft and the annual sediment inflow is 114.1 Ac-ft). No values are given for 1953 as only a partial year existed for the computed inflows.

Calendar Year	**Water inflow (Ac-ft)**	**Ratio of water inflow to average water inflow**	**Estimated Sediment inflow (Ac-ft)**	**Calendar Year**	**Water inflow (Ac-ft)**	**Ratio of water inflow to average water inflow**	**Estimated Sediment inflow (Ac-ft)**
1953	-	-	-	1986	73,107	1.69	193
1954	22,472	0.52	59	1987	92,612	2.14	244
1955	29,604	0.68	78	1988	51,013	1.18	135
1956	11,124	0.26	29	1989	37,268	0.86	98
1957	63,554	1.47	168	1990	35,678	0.83	94
1958	89,830	2.08	237	1991	74,370	1.72	196
1959	15,127	0.35	40	1992	94,436	2.18	249
1960	43,744	1.01	115	1993	83,619	1.93	221
1961	43,997	1.02	116	1994	52,695	1.22	139
1962	36,751	0.85	97	1995	96,661	2.24	255
1963	11,735	0.27	31	1996	16,519	0.38	44
1964	10,195	0.24	27	1997	66,868	1.55	176
1965	32,514	0.75	86	1998	47,164	1.09	124
1966	19,446	0.45	51	1999	34,941	0.81	92
1967	20,712	0.48	55	2000	20,981	0.49	55
1968	41,386	0.96	109	2001	41,298	0.96	109
1969	66,775	1.54	176	2002	16,641	0.38	44
1970	36,460	0.84	96	2003	24,372	0.56	64
1971	18,824	0.44	50	2004	26,947	0.62	71
1972	28,838	0.67	76	2005	51,767	1.20	137
1973	109,568	2.53	289	2006	12,187	0.28	32
1974	22,118	0.51	58	2007	16,456	0.38	43
1975	82,460	1.91	218	2008	3,027	0.07	8
1976	19,051	0.44	50	2009	19,609	0.45	52
1977	25,935	0.60	68	2010	35,941	0.83	95
1978	49,539	1.15	131	2011	8,259	0.19	22
1979	112,863	2.61	298	2012	14,934	0.35	39
1980	69,362	1.60	183	2013	21,019	0.49	55
1981	23,193	0.54	61	2014	13,023	0.30	34
1982	51,818	1.20	137	2015	37,199	0.86	98
1983	107,931	2.50	285	2016	23,685	0.55	63
1984	61,525	1.42	162	2017	44,967	1.04	119
1985	134,904	3.12	356	2018	7,694	0.18	20

Table 5. Sediment yield trap efficiency calculations

Survey Year*	**S_{in} (Ac-ft) †**	**S_{accum} (Ac-ft)‡**	**S_{out} (Ac-ft)**	**Trap Efficiency (%)**
October 1953	-	0	-	-
January 1958	337	1,392	-1,055	413%
September 1959	272	1,947	-1,675	715%
January 1966	474	1,065	-591	225%
February 1975	965	6,709	-5,744	695%
January 1984	1,428	3,388	-1,960	237%
July 1991	1,391	2,227	-836	160%
July 1998	1,270	3,060	-1,790	241%
December 2016	1,137	-1,909	3,046	-168%

Notes: * – Some of the month – year combinations are different than previously reported in the water control manuals (USACE 1994; USACE 2007). The website for Jemez Canyon Dam Reservoir (USACE 2020) was used to extract the intervening period of time (listed in years). Survey dates were adjusted in Excel so that the time frame between surveys matched the reported period years.

† – Sediment yield inflow is based on annualized sediment load based on previous work (Little 2007; Maynord et al. 2012). The load is distributed temporally by using the computed water inflow provided by USACE Water Management (Ball, RJ, unpub data, 11 June 2020) to weight each year by the water volume in a given year compared to an average annual water volume.

‡ – Data as reported from Jemez Canyon Dam Reservoir (USACE 2020).

B. MASS OUT FROM USGS MEASUREMENTS

The second approach assumes that the sediment flow out of the reservoir is known. This approach uses the collected USGS data from USGS gage # 08329000 and # 08328950 to provide an estimate of the sediment outflow. The sediment record collected by the USGS is limited temporally and only measures the suspended fraction of the sediment load. To estimate a trap efficiency from the gathered data, two assumptions are needed. The first assumption is that discharge (for which there is a greater temporal resolution) can be related to the transported sediment. This is typically done by generating a sediment rating curve. The second assumption was that the suspended sediment data is representative of the total sediment load. This is likely not true, but this simplifying assumption was made to provide a trap efficiency calculation. A better estimation of the sediment outflow would be generated by developing a numerical sediment transport model and using the measured suspended sediment concentrations to calibrate the model. In this manner a more accurate representation of the sediment outflow could be made.

The generation of a sediment rating curve was done first by estimating daily suspended sediment loads and graphing these versus the average daily discharge. Daily suspended sediment loads were estimated by multiplying the measured suspended sediment concentration by the average daily flowrate and converting to units of short tons/day. Since the collected suspended sediment data was collected intermittently, power relationships were developed separately for data collected in the 1950s, 1960s, and 2010s. The resulting log-log graph and power regression relationships are shown in Figure 1. While some of the data has a fair correlated (1960s) the other data has a spread of 4 to 5 orders of magnitude. This was thought to be connected to the ephemeral quality of the Jemez River, especially during the rainfall-runoff season, when short duration, but high sediment load events can result in a low average daily discharge with a high suspended sediment load.

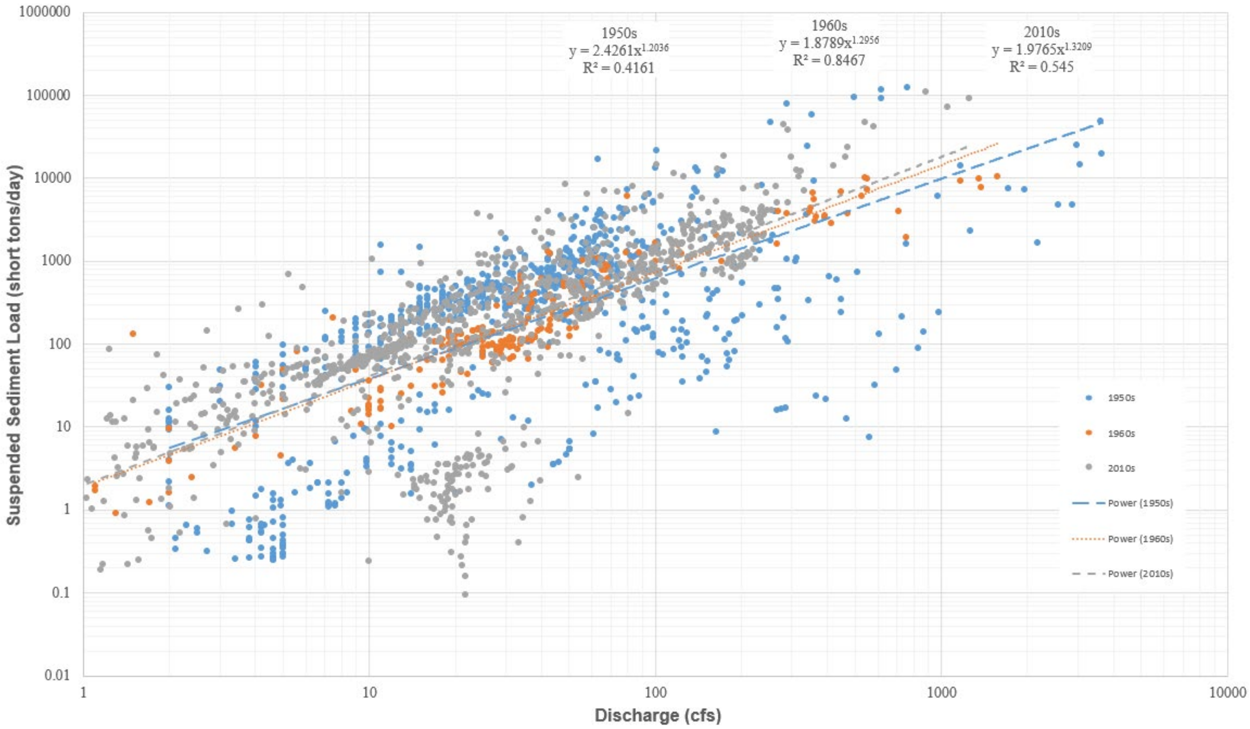

Figure 1. Suspended sediment rating curves for suspended sediment loads versus daily average discharge. Power regression equations are shown in the upper portion of the graph.

To eliminate some of the scatter caused by averaging a short duration discharge event over an entire day, instantaneous and 15-minute discharge data were utilized. The 15-minute daily discharge information is available after 2009 and the time stamp can be used to correlate measured suspended sediment concentrations. The USGS sometimes records instantaneous discharge measurements when they are at the sites collecting data. This is reported in the collected water quality data (parameter code 00061). For the USGS gage downstream of Jemez dam (gage # 08329000) instantaneous discharge paired with suspended sediment concentrations were reported between March 1974 and May 2020. In addition, historical USGS water supply papers were found to also provide pairs of instantaneous discharge and suspended sediment concentration. This information was found for water years 1951 (USGS 1955), 1952 (USGS 1956), 1953 (USGS 1958), 1954 (USGS 1959), and 1957 (USGS 1961). The reported suspended sediment concentrations in the water supply manuals were listed as parts per million (ppm). As some of the concentrations were greater than 50,000 ppm, the correction shown in Equation 6 was utilized to convert the listed values.

Equation 6. Conversion from concentration in ppm to mg/L (Julien 2010)

$$C_{mg/L} = \frac{GC_{ppm}}{G + (1 - G)10^{-6}C_{ppm}}$$

Where $C_{mg/L}$ is the suspended sediment concentration in mg/L, C_{ppm} is the concentration in ppm, and G is the specific gravity of sediment (taken as 2.518 based on the average density of sediment reported above and assuming a density of water of 62.4 lb/ft^3).

The instantaneous discharge and suspended sediment concentration pairs provided 63 data points pre-Jemez Dam installation, 47 data points during the 24 hour hold pool operations, 6 data points during the 20,000 Ac-ft permanent pool operations, and 1,181 data points during operation of the dry reservoir. Since the 15-minute data would just supplement available data during the last period, the data pairs for the instantaneous discharge measurements were used to develop regression curve relationships between discharge and sediment load (short tons/day). The instantaneous discharge value was multiplied by the reported suspended sediment measurement and a unit conversion to obtain a suspended sediment load in short tons/day. The correlation between the suspended sediment load and the instantaneous discharge, split by the various reservoir operation sequences was better, having a maximum scatter of only 3 orders of magnitude if some spurious outliers are eliminated.

Because the generation of statistical relationships in log-log space may underrepresent the actual sediment loads (Cohn et al. 1989), a nonparametric estimator, Duan smearing factor (Duan 1983), was employed to provide an unbiased sediment load estimate for four reservoir operation periods: pre-dam period (1 April 1943 to 30 September 1953), 24 hour hold pool period (1 October 1953 to 30 September 1979), 20,000 Ac-ft permanent pool period (1 October 1979 to 30 September 2001), and the dry reservoir period (1 October 2001 to 1 May 2020). The Jemez reservoir was only operated as a 2,000 Ac-ft permanent pool from 1979 to 1985, but there were no discharge suspended sediment information available for this period so it was assumed to function, with regard to sediment transport, similarly to the 20,000 Ac-ft permanent pool. The resulting log-log graph and power regression relationships, along with the unbiased sediment load relationship developed from estimating the Duan smearing factor, are shown in Figure 2, Figure 3, Figure 4, and Figure 5 for the pre-dam, 24-hour hold pool, 20,000 Ac-ft permanent pool, and dry reservoir periods, respectively.

The resulting power relationship between suspended sediment load and discharge, corrected to give an unbiased estimator was used to estimate a daily sediment load (short tons/day) for the entire range of daily discharge values, except for those after 30 July 2014. After this point the reported mean suspended sediment concentration and the mean discharge were used to estimate the suspended sediment load. The sediment load was then cumulatively summed for each day starting with the first recorded discharge value on 1 April 1943. A lookup chart was produced in Excel to correlate the cumulative sediment load value with the day of each survey. The difference between two surveys was the accumulated sediment difference in short tons observed between each survey as shown in Table 6.

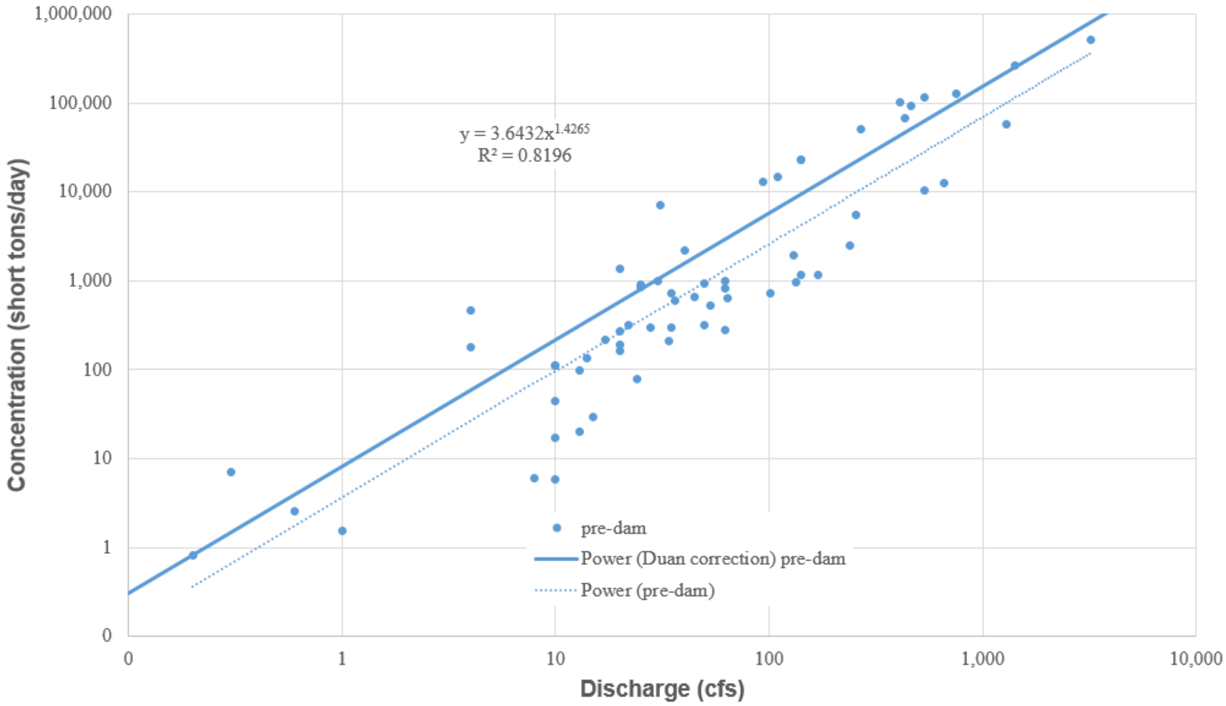

Figure 2. Suspended sediment rating curves for suspended sediment loads versus instantaneous discharge for the pre-dam period. Power regression equation is shown in the upper left portion of the graph. The unbiased estimator (2.22) is also shown in the graph.

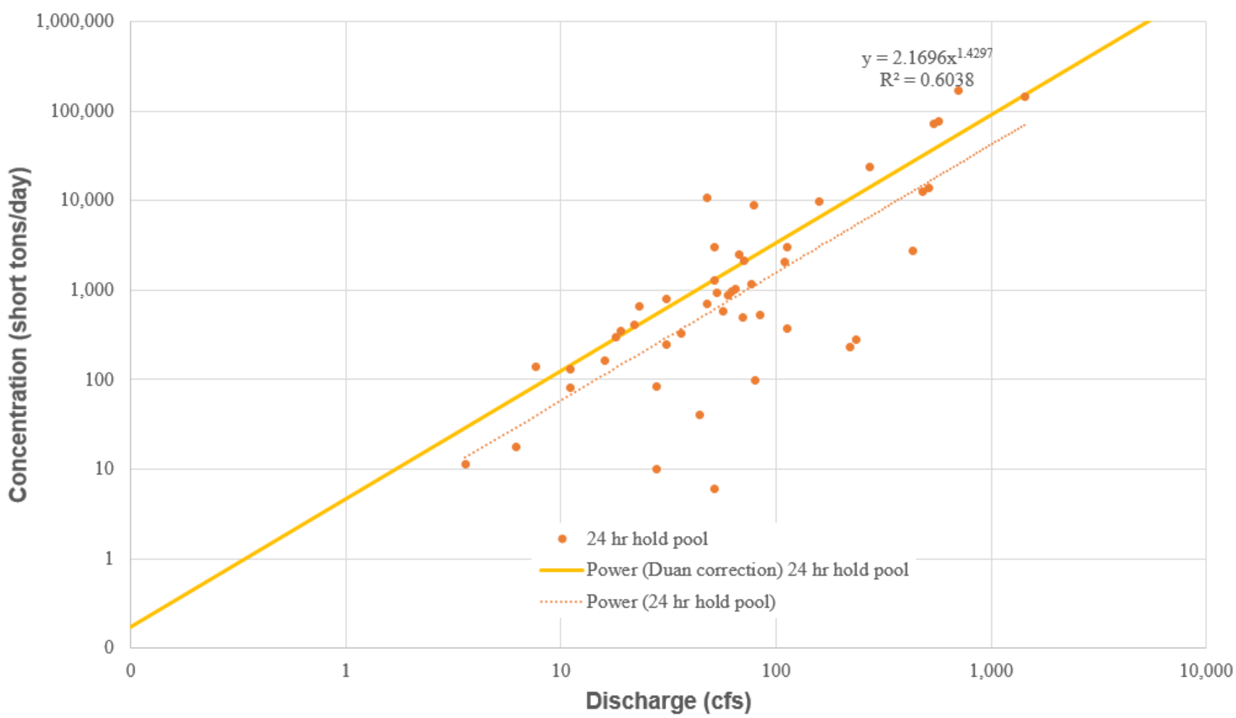

Figure 3. Suspended sediment rating curves for suspended sediment loads versus instantaneous discharge for the 24 hour hold pool period. Power regression equation is shown in the upper portion of the graph. The unbiased estimator (2.16) is also shown in the graph.

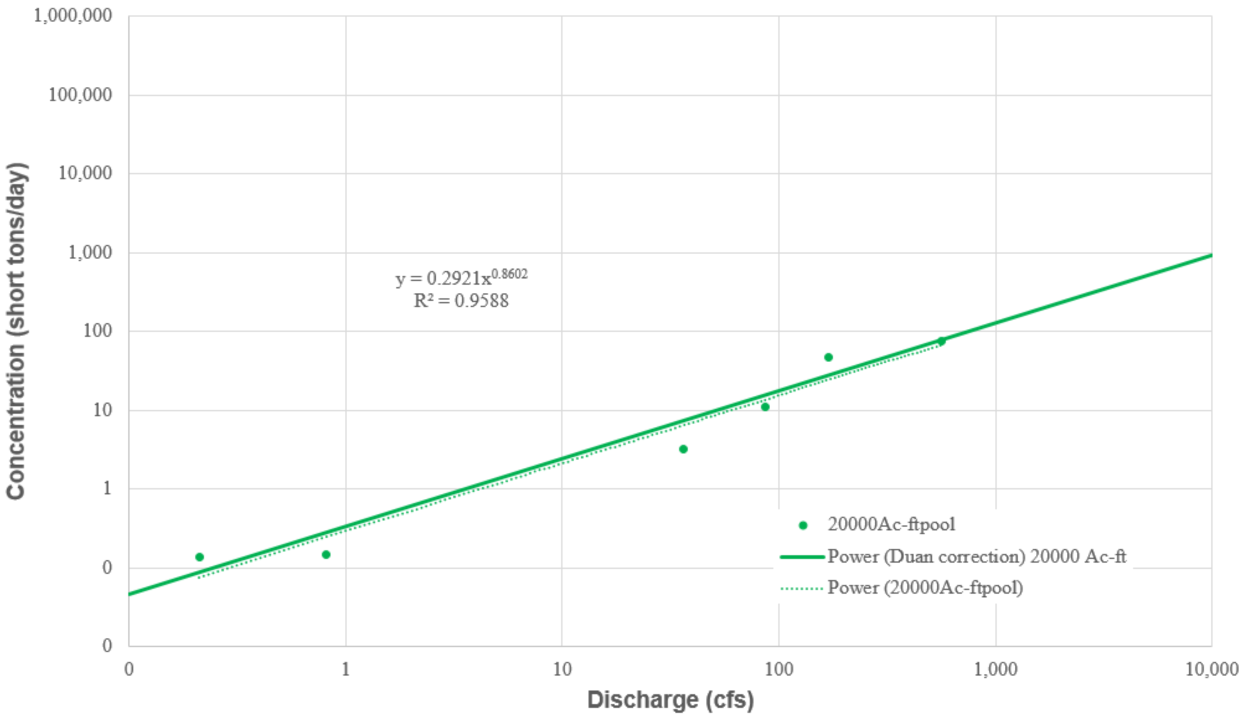

Figure 4. Suspended sediment rating curves for suspended sediment loads versus instantaneous discharge for the 20,000 Ac-ft permanent pool period. Power regression equation is shown in the upper left portion of the graph. The unbiased estimator (1.14) is also shown in the graph.

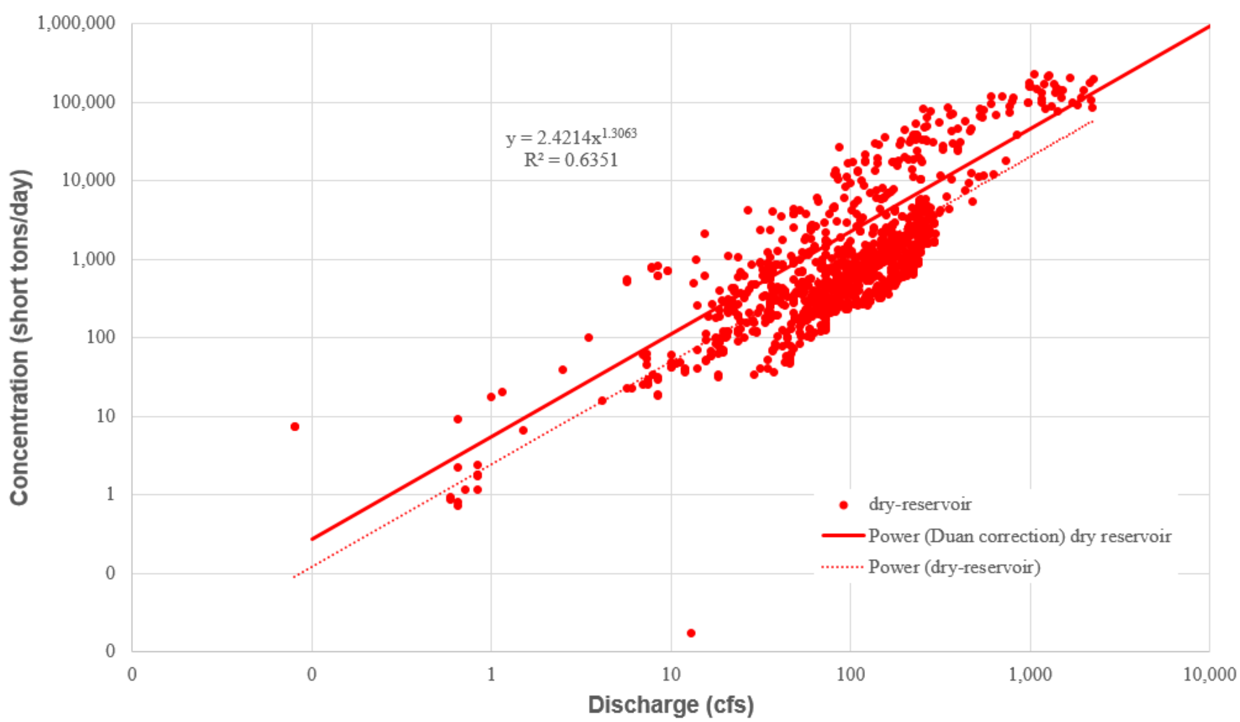

Figure 5. Suspended sediment rating curves for suspended sediment loads versus instantaneous discharge for the dry reservoir period. Power regression equation is shown in the upper left portion of the graph. The unbiased estimator (2.29) is also shown in the graph.

Table 6. Cumulative and incremental suspended sediment load (outflow from Jemez Canyon Dam Reservoir)

Survey Year*	**Cumulative sediment load (short tons)†**	**Incremental sediment load (short tons)**
October 1953	14,355,371	14,343,060
January 1958	16,850,964	2,495,593
September 1959	21,890,387	5,039,423
January 1966	27,140,358	5,249,971
February 1975	38,468,529	11,328,171
January 1984	45,824,390	7,355,861
July 1991	45,859,687	35,296
July 1998	45,892,293	32,606
December 2016	51,230,536	5,338,243

Notes: * – Some of the month – year combinations are different than previously reported in the water control manuals (USACE 1994; USACE 2007). The website for Jemez Canyon Dam Reservoir (USACE 2020) was used to extract the intervening period of time (listed in years). Survey dates were adjusted in Excel so that the time frame between surveys matched the reported period years.

† – mass reported for 1953 is the cumulative and incremental values reported since the start of a continuous USGS record (1 April 1943).

The inflowing sediment is determined by re-arranging Equation 5. The one exception was between 1998 and 2016 as the relationships break down due to erosion of deposited sediment in the reservoir pool. For 2016, the calculated incoming sediment volume from the mass in from sediment yield approach was used as the sediment in value. If sediment in was solved using Equation 5, the inflow of sediment would be negative and result in a trap efficiency of over -500%. With the assigned sediment incoming and outgoing loads then the trap efficiency is calculated using Equation 4. Calculated values are shown in Table 7.

Table 7. Measured suspended sediment trap efficiency calculations

Survey Year*	**S_{in} (Ac-ft)†**	**S_{accum} (Ac-ft)‡**	**S_{out} (Ac-ft)†**	**Trap Efficiency (%)**
October 1953	4,191	-	4,191	-
January 1958	2,121	1,392	729	65.6%
September 1959	3,419	1,947	1,472	56.9%
January 1966	2,599	1,065	1,534	41.0%
February 1975	10,019	6,709	3,310	67.0%
January 1984	5,537	3,388	2,149	61.2%§
July 1991	2,237	2,227	10	99.5%
July 1998	3,070	3,060	10	99.7%
December 2016	1,137	-1,909	1,560	-37.2%

Notes: * – Some of the month – year combinations are different than previously reported in the water control manuals (USACE 1994; USACE 2007). The website for Jemez Canyon Dam Reservoir (USACE 2020) was used to extract the intervening period of time (listed in years). Survey dates were adjusted in Excel so that the time frame between surveys matched the reported period years.

† – unit conversion of sediment loads in short tons/day by assuming a soil density of 157.1 lbs/ft^3.

‡ – Data as reported from Jemez Canyon Dam Reservoir (USACE 2020).

§ – The period between 1975 and 1984 includes a transition between the 24 hour hold pool and the 2,000 Ac-ft permanent pool. The daily sediment load estimations indicate 99.7% of the sediment reported in this period accumulated prior to this transition in 1979.

4. SUMMARY AND RECOMMENDATIONS

A total of five approaches were used to estimate the trap efficiency for the Jemez Canyon Dam Reservoir. Two of these used a mass balance approach, while three are empirical methods based on trap efficiency calculations from other reservoirs. The trap efficiencies for these five methods are summarized in Table 8. The previously reported trap efficiency values are shown in Table 9. The methodology used to estimate the previously reported trap efficiencies was not recorded, so an exact replication of the process could not be utilized to extend the trap efficiencies to the new survey dates. The three empirical approaches report higher trap efficiencies than previously reported. This is to be expected, as the underlying methodology for these approaches assumes that the reservoir is wet all the time, which is not always true for Jemez Canyon Dam Reservoir. Of the other two methods, utilization of an annualized sediment yield for the Jemez River results in unrealistic trap efficiencies. The Jemez River transfers the majority of the sediment during either the snowmelt or rainfall runoff. These runoff events are discrete and episodic and therefore may contribute more sediment in one year than the next. This biases an annualized sediment yield method, producing questionable results. The last method, utilizing existing data collected from the USGS downstream of the dam, resulted in trap efficiencies that were similar, but not exactly like the previously reported calculations. The trap efficiency calculations for the 1959 and 1983/1984 years were lower than the reported values, while those calculated for 1991, and 1998 were higher than the reported values. The trap efficiency calculations for the last year is negative because of Jemez River flows eroding deposited sediment in the reservoir pool that is now dry.

Table 8. Trap efficiency calculations

Survey Year*	**Trap Efficiency (%)**				
	Brown	**Brune**	**Churchill**	**Mass in from sediment yield**	**Mass out from USGS**
October 1953	99	99.4	-	-	-
January 1958	99	99.3	-	413	65.6%
September 1959	99	98.9	-	715	56.9%
January 1966	99	99.4	-	225	41.0%
February 1975	99	99.2	-	695	67.0%
January 1984	99	98.9	98.4	237	61.2%
July 1991	99	98.8	103.7	160	99.5%
July 1998	99	98.8	103.5	241	99.7%
December 2016	99	99.4	-	-168	-37.2%

Notes: * – Some of the month – year combinations are different than previously reported in the water control manuals (USACE 1994; USACE 2007). The website for Jemez Canyon Dam Reservoir (USACE 2020) was used to extract the intervening period of time (listed in years). Survey dates were adjusted in Excel so that the time frame between surveys matched the reported period years.

Table 9. Previous trap efficiency values

Survey Year	**Trap Efficiency (%)**		
	WCM 1994†	**WCM 2007‡**	**2000 EA§**
October 1953			
*January 1958**			
August 1959	65	65	65
December 1965	42	42	42
January 1975	68	68	68
December 1983	83	83	83
June 1991	90	90	90
July 1998			92
*January 2005**			
*October 2009**			
*December 2016**			

Notes: * – Some of the month – year combinations are different than previously reported in the water control manuals (USACE 1994; USACE 2007). The website for Jemez Canyon Dam Reservoir (USACE 2020) was used to extract the intervening period of time (listed in years). Survey dates were adjusted in Excel so that the time frame between surveys matched the reported period years.

† – 1994 Water Control Manual (USACE 1994)

‡ – 2007 Water Control Manual (USACE 2007)

§ – FONSI and EA for partial evacuation of the sediment pool at Jemez Canyon Reservoir (USACE 2000)

The USGS based mass balance trap efficiency values reported in Table 8 are recommended for use in evaluating trap efficiencies in the future, as they provide a consistent, documented trap efficiency calculation approach. This method is based on reliable sediment accumulation measurements in the reservoir pool and outflowing sediment measurements.

A higher level of accuracy may be achieved through development of a one-dimensional sediment transport model, calibrated to the observed suspended sediment observations of the USGS and recorded sediment volumes from the repeat reservoir surveys. This would provide the ability to estimate the outgoing bed load, which is currently unmeasured and provide a more realistic estimate of the incoming sediment load. This, coupled with operational rules for the reservoir, would provide a higher precision on the trap efficiency calculations than currently provided. Measurement of incoming sediment load, volumetric differences between the traditional reservoir survey volumetric calculations and the LiDAR volumetric calculations, void ratios of accumulated sediment in the reservoir, and grain size distribution of sediment in the reservoir would also be beneficial in better understanding the flux of sediment through the reservoir and thus in fine tuning the trap efficiency calculations.

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