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Managing Water in the West

Time-Based Estimation of Reservoir Sedimentation Impacts

Research and Development Office
Science and Technology Program
(Final Report) ST-2017-9072
Report SRH-2017-37

U.S. Department of the Interior
Bureau of Reclamation
Research and Development Office

September 2017

Mission Statements

Protecting America's Great Outdoors and Powering Our Future

The Department of the Interior protects and manages the Nation's natural resources and cultural heritage; provides scientific and other information about those resources; and honors its trust responsibilities or special commitments to American Indians, Alaska Natives, and affiliated island communities.

REPORT DOCUMENTATION PAGE		*Form Approved* *OMB No. 0704-0188*
T1. REPORT DATE: SEPTEMBER 2017	**T2. REPORT TYPE:** RESEARCH	**T3. DATES COVERED**
T4. TITLE AND SUBTITLE Time-Based Estimation of Reservoir Sedimentation Impacts – Conducting Report		**5a. CONTRACT NUMBER**
		5b. GRANT NUMBER
		5c. PROGRAM ELEMENT NUMBER 1541 (S&T)
6. AUTHOR(S) Jianchun "Victor" Huang Sean Kimbrel		**5d. PROJECT NUMBER** ST-2016-9072
		5e. TASK NUMBER
		5f. WORK UNIT NUMBER 85-824000
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Sedimentation and River Hydraulics Group, Technical Service Center Bureau of Reclamation Denver Federal Center, Bldg. 67 PO Box 25007 (85-824000) Denver, CO 80225		**8. PERFORMING ORGANIZATION REPORT NUMBER** Report SRH-2017-37
9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES) Research and Development Office U.S. Department of the Interior, Bureau of Reclamation, PO Box 25007, Denver CO 80225-0007		**10. SPONSOR/MONITOR'S ACRONYM(S)** **R&D:** Research and Development Office **BOR/USBR:** Bureau of Reclamation DOI: Department of the Interior
		11. SPONSOR/MONITOR'S REPORT NUMBER(S) ST-2016-9072
12. DISTRIBUTION / AVAILABILITY STATEMENT Final report can be downloaded from Reclamation's website: https://www.usbr.gov/research/		
13. SUPPLEMENTARY NOTES		
14. ABSTRACT *(Maximum 200 words)* The objective of this research study is to investigate for any improvements and updates to empirical reservoir sedimentation distribution methods such as Reclamation (1962) for use in future vulnerability assessments and water resource planning at both publicly and privately owned dams/reservoirs.		
15. SUBJECT TERMS Reservoir Sediment Distribution, Sedimentation, Reservoirs		

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT** U	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON** Victor Huang
a. REPORT U	**b. ABSTRACT** U	**c. THIS PAGE** U			**19b. TELEPHONE NUMBER** 303-445-2158

S Standard Form 298 (Rev. 8/98)
P Prescribed by ANSI Std. 239-18

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Research and Development Office
Science and Technology Program

Sedimentation and River Hydraulics Group, Water, Environmental and Ecosystems Division, Technical Service Center, 85-824000

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Time-Based Estimation of Reservoir Sedimentation Impacts

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Executive Summary

The objective of this research study is to investigate for any improvements and updates to empirical reservoir sedimentation distribution methods such as Reclamation (1962) for use in future vulnerability assessments and water resource planning at both publicly and privately owned dams/reservoirs. While storing water for municipal and agriculture uses, reservoirs increase the water surface level, reduce the flow velocity, and introduce undesired reservoir sedimentation. Removal of sediments from reservoirs can be cost prohibitive. Better methods to predict the sediment distribution in a reservoir helps to better understand the coming impacts to near-water infrastructure (boat ramps, marinas, water intakes, penstocks, etc.) and the life span of a reservoir in order to plan and prepare for measures and actions to be taken. The first phase of this study was to perform a literature review regarding any existing reservoir sediment distribution prediction methods. The next phase in this study was to use Bureau of Reclamation reservoir survey data to examine the applicability of existing methods. Finally, attempts were made to investigate the link between reservoir sediment distribution patterns and reservoir operations.

The literature review is performed in this report for empirical reservoir sediment distribution methods in both the vertical direction and in the longitudinal direction. To describe the reservoir sediment distribution in the vertical direction, one usually presents the original capacity and reservoir surface as a function of the water depth from its original elevation at the dam, and predicts the secondary capacity and reservoir surface in the same form. To describe reservoir sediment distribution in the longitudinal direction, the sediment deposition is usually presented as a function of the distance from the dam.

72 Reclamation reservoir survey datasets were available for testing of existing reservoir sediment distribution methods. However, at the time of the research effort, only 32 Reclamation reservoir survey datasets had more than one set of elevation-area-capacity survey data. The initial and final reservoir depth and capacity relations were used to check the accuracy of the existing methods.

It was found that the existing methods were based mainly on the current reservoir shape. For example, a gorge-shaped reservoir would bring more sedimentation near the dam; conversely, a lake-shaped reservoir would build sedimentation near the entry of the reservoir. It might be expected that reservoir operation would also play a role in the reservoir sediment distribution.

Several reservoir operation parameters are presented in an attempt to relate sediment distribution with reservoir operations. Initial results show that sediment distribution is more complex than what simple parameters can present. Reservoir shape, defined as slope of the depth-capacity curve on log-log coordinates, presents the best correlation with the sediment distribution. Poor correlations between proposed reservoir operation parameters and sediment distribution were found.

It is recommended to use sediment deposition curve index *ID* to calculate future sediment distribution. The index ID can be calculated to match historical sediment distribution, or calculated by regression equation with slope of the depth versus capacity in logarithmic space.

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Tables

1 Introduction

The objective of this research study is to improve and update empirical reservoir sedimentation distribution methods such as Reclamation (1962) for use in future vulnerability assessments and water resource planning at both publicly and privately owned dams/reservoirs. Improved empirical methods will be useful in the rapid evaluation of reservoir sedimentation that occur at all facilities that store water on rivers. Better methods to predict the sediment distribution in a reservoir helps to better understand the coming impacts to near-water infrastructure (boat ramps, marinas, water intakes, penstocks, etc.) and the life span of a reservoir in order to plan and prepare for measures and actions to be taken. The first phase of this study was to perform a literature review regarding any existing reservoir sediment distribution prediction methods. The next phase in this study was to use Bureau of Reclamation reservoir survey data to examine the applicability of existing methods. Finally, attempts were made to investigate the link between reservoir sediment distribution patterns and reservoir operations.

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It was found that the existing methods were based mainly on the current reservoir shape. For example, a gorge-shaped reservoir would bring more sedimentation near the dam; conversely, a lake-shaped reservoir would build sedimentation near the entry of the reservoir. It might be expected that reservoir operation would also play a role in the reservoir sediment distribution. For example, a run-of-river dam/reservoir would result in sedimentation primarily near the dam. Is there a simple correlation between the reservoir operation and reservoir sediment distribution? This study is an initial attempt to answer this question.

2 Literature Review of Reservoir Sediment Distribution in the Vertical Direction

This section details the literature review of four different reservoir sediment distribution procedures in the vertical direction, which are the 1) Area Increment Method, 2) the Area Reduction Method, 3) the Modified Area Reduction Method, and 4) the Empirical Reservoir Shape Function.

2.1 Area Increment Method (AIM)

The Area Increment Method (AIM) is a very simple empirical method developed by Cristofano (1953). AIM is based on two assumptions that 1) the sediment will deposit in the "dead storage" of a reservoir defined as the space below new bed elevation at the dam (y_0) and 2) above the new bed elevation at the dam (y_0), the sediment will take an equal area, which is equal to the original reservoir area A_0 at elevation y_0. The method can be expressed as

$$V_y = A_0(y - y_0) + V_0 \qquad \textbf{(2.1)}$$

where:

V_y = sediment volume (acre-ft) to be deposited in the reservoir below the elevation y,

y = the elevation below which the sediment is deposited,

A_0 = the original reservoir area at the new bed elevation at the dam (y_0),

V_0 = the original reservoir storage under elevation y_0, and

y_0 = the new bed elevation at the dam.

When y reaches the reservoir depth (H), measured from the original stream bed to the normal water surface, V_y equals the total sediment to be deposited in the reservoir (V_s) and Eq. (2.1) can be expressed as

$$V_s = A_0(H - h_0) + V_0 \qquad \textbf{(2.2)}$$

where

V_s = total sediment volume (acre-ft) to be deposited in the reservoir,

H = reservoir depth at the dam (ft), from the original stream bed to the maximum normal water surface (maximum water elevation under normal operation conditions).

h_0 = the new bed depth (ft) at the dam to the original bed elevation at the dam.

Equation (2.2) states that the total sediment volume, V_s, consists of the partition of original reservoir below the new elevation, plus the uniform disposition over the height H-h_0 with equal area A_0.

An example for the Alamogordo Reservoir (now known as Sumner Lake) was obtained in the 1944 re-survey, as given in Borland and Miller (1958). The basic information for reservoir is shown in Table 2.1 and the original area and capacity curves are shown in Figure 2-1.

Table 2.1 Basic information for Alamogordo Reservoir

Stream-bed elevation at dam	4,150 ft
Maximum water surface elevation	4,275 ft
Spillway crest elevation	4,275 ft
Original reservoir depth at dam	125 ft
Original capacity at elevation 4275 ft	156,750 acre-ft
Annual sediment inflow	3,600 acre-ft
Period of sedimentation	6.8 years
Sediment accumulation	24,580 acre-ft
Elevation of Sediment at dam	4,190 ft (approximately)
Capacity after sedimentation	132,170 acre-feet

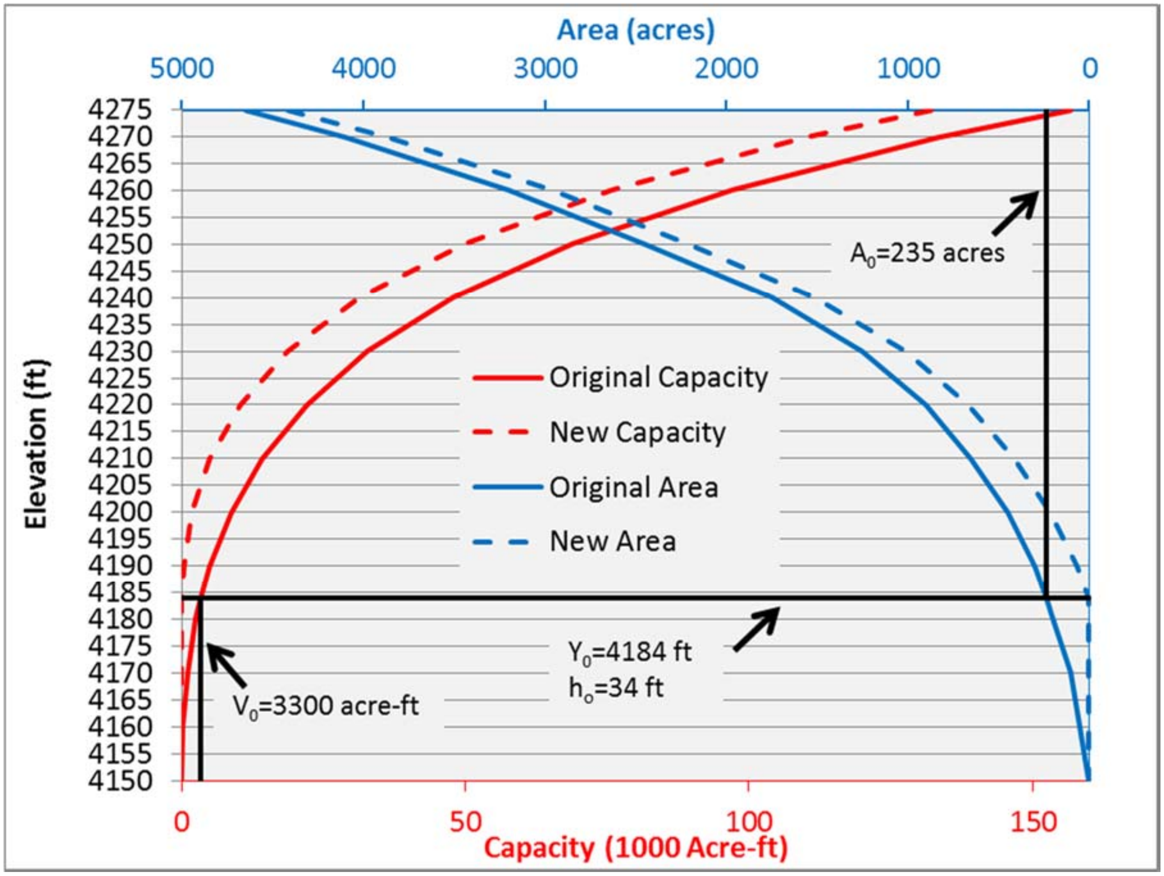

Figure 2-1 Area-Capacity Curves for the Alamogordo Reservoir AIM Example

The procedure for AIM is given as:

Step 1: Given the total sedimentation volume V_s = 24,580 acre-ft and the normal water depth H = 4,275 - 4,150 =125 ft, the new bed depth (ft) at the dam h_0 can be obtained by trial and error with Eq. (2.2).

First trial: assuming h_0 = 25 ft and y_0 = 4,150 ft + 25 ft = 4,175 ft, then A_0 = 150 acres, V_0 = 1,600 acre-ft, and

$$V_s = 150 \times (125 - 25) + 1{,}600 = 16{,}000 < 24{,}580 \text{ too small}$$

Second trial: assuming h_0 = 34 ft and y_0 = 4,150 + 34 = 4,184 ft, then A_0 = 235 acres, V_0 = 3,300 acre-ft, and

$$V_s = 235 \times (125 - 34) + 3{,}300 = 24{,}680 \approx 24{,}580$$

The new sediment elevation at the dam is y_0 = 4,184 ft, and the sedimentation area is the original area at that elevation, A_0 = 235 acres at y_0.

In Table 2.2, column 1 contains the elevation (y), and Column 2 and Column 3 contain the original area and capacity. Column 4 contains the correction area A_0, which is the original reservoir area at y_0 = 4,184 ft. If the elevation y is above y_0, the correction area equals original reservoir area at y_0 (column 2, Row 11), if the elevation y is below y_0, then the correction area equals original area (Column 2).

Step 2: Compute the accumulative sediment volume (Column 5) by Eq. (2.1). For example, when y = 4270 ft (Column 1, Row 2), $V_y = 235 \times (4{,}270 - 4{,}184) + 3{,}300 = 23{,}510$ acre-ft, which is the sediment volume at y = 4270 ft.

Step 3: Reduce the original areas (Column 2) at each increment by the area correction A_0 (Column 4) to give the revised area in Column 6 = (Column 2 - Column 4).

Step 4: Reduce the original capacity (Column 3) at each increment by the sediment volume (Column 6) to give the revised capacity in Column 7 = (Column 3 - Column 5).

Table 2.2 Sediment Distribution Computation by AIM

	Elevation (ft)	Original area (acres)	Original capacity (acre-ft)	Ao (acres)	Sediment volume (acre-ft)	Area (acres)	Capacity (acre-ft)
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
(1)	4275	4650	156,750	235	24,680	4415	132,070
(2)	4270	4100	133,500	235	23,510	3865	109,990
(3)	4260	3200	97,000	235	21,160	2965	75,840
(4)	4250	2450	68,750	235	18,810	2215	49,940
(5)	4240	1750	47,750	235	16,460	1515	31,290
(6)	4230	1250	32,750	235	14,110	1015	18,640
(7)	4220	900	22,000	235	11,760	665	10,240
(8)	4210	650	14,250	235	9,410	415	4,840
(9)	4200	450	8,750	235	7,060	215	1,690
(10)	4190	300	5,000	235	4,710	65	290
(11)	4184	235	3,300	235	3,300	0	0
(12)	4180	200	2,500	200	2,500	0	0
(13)	4170	100	1,000	100	1,000	0	0
(14)	4160	50	250	50	250	0	0
(15)	4150	0	0	0	0	0	0

The results of modified area and capacity curves are also shown in Figure 2-1.

2.2 Area Reduction Method (ARM)

The area reduction method (ARM) was developed by Borland and Miller (1958), which was then revised by Moody (1962) and Reclamation (1962). The method was developed based on reservoir surveys of 30 reservoirs in the United States. In ARM, reservoir type is obtained by plotting depth versus initial reservoir capacity on log-log coordinates as shown in Figure 2-2. The slope of the line defines the reservoir into four types: Type I (lake), Type II (flood plain-foothill), Type III (hill), and Type IV (gorge). Other conditions such as anticipated reservoir operation (e.g. lake to normally empty) or size of the inflowing sediments (e.g. clay, silt, sand, gravel) may override the reservoir classification based on shape (Borland, 1970). For example, a hill type reservoir (Type III) classification based on reservoir shape will demonstrate a gorge type (Type IV) sediment distribution if the reservoir is operated under substantially drawn-down conditions or if the inflowing sediments are predominantly of the clay size. The reason of the type change is because majority of the sediment would deposit near the reservoir bottom.

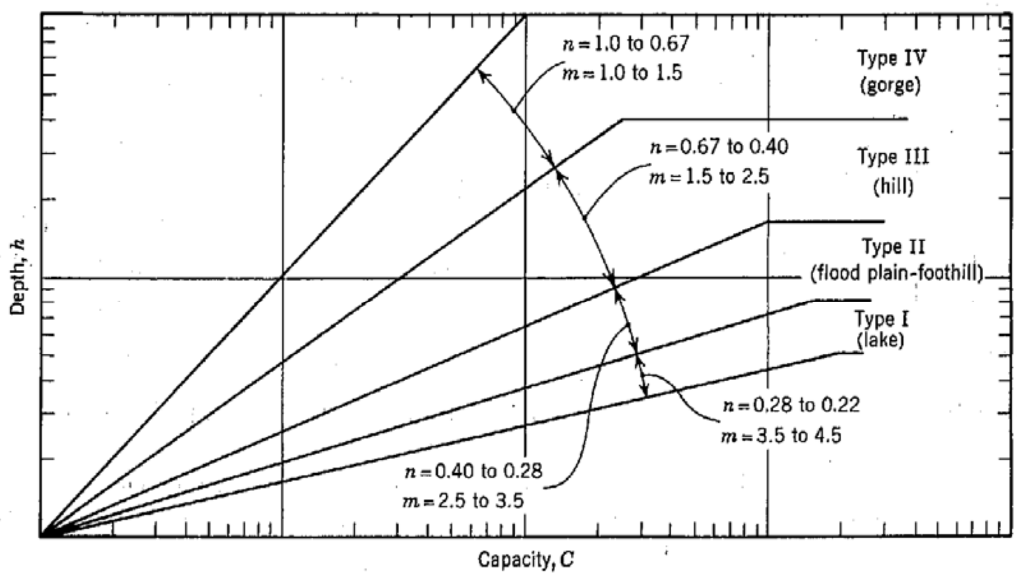

Figure 2-2 Classification of Reservoirs by the Depth versus Capacity Relationship (source: Borland and Miller, 1958). The variable *n* is the slope of the depth versus capacity in logarithmic space and *m* is 1/*n*.

The ARM assumes the sediment will take an area that will be a function of the relative depth and reservoir type expressed as

$$a(p) = Cp^m(1-p)^n \quad \textbf{(2.3)}$$

where:

a is the relative sediment area,

p=*h*/*H* is the relative depth of the reservoir,

h= the calculated depth of reservoir measure from the bottom, and

H = the maximum reservoir depth at the dam wall.

The dimensionless coefficient C, m, and n for the four standard reservoir types are given in Table 2.3.

The relative sediment volume (v) below a particular relative depth (p) is an integration of Eq. (2.3), written as

$$v(p) = \int_0^p Cz^m(1-z)^n dz \quad \textbf{(2.4)}$$

Table 2.3. Coefficients in Relative Area Equation by Reservoir Type.

	Reservoir Sedimentation Type			
Parameter	**I**	**II**	**III**	**IV**
C	5.074	2.487	16.967	1.486
m	1.85	0.57	1.15	-0.25
n	0.35	0.41	2.32	1.34

At $p = 1$ the relative sediment volume v should be equal one, thus C is a function of m and n expressed as

$$C = \frac{1}{\int_0^1 z^m(1-z)^n dz} \quad \textbf{(2.5)}$$

$$A(p) = Ka(p) \quad \textbf{(2.6)}$$

where K is the reference area, calculated with

$$A_0 = Ka(p_0) \quad \textbf{(2.7)}$$

where A_0 is the original reservoir area at new reservoir elevation y_0, and at the relative depth of the new reservoir elevation.

ARM is based on two assumptions that 1) the sediment will deposit on a “dead storage” of a reservoir defined as the space below new bed elevation at the dam (y_0), and 2) above the new bed elevation at the dam (y_0), the sediment will take an area that will be changed according the reservoir type expressed as $a(p)$ in Eq. (2.3).

The actual sediment volume in the reservoir may not follow the idealized distribution because it will be limited by the available storage volume below the depth of sediment at the dam. The volume of sediment within the actual reservoir can be computed as

$$V_s = V_0 + K \int_{p_0}^{p} a(z)dz \qquad \textbf{(2.8)}$$

which can be integrated to give:

$$V_s = V_0 + KH[v(p) - v(p_0)] \qquad \textbf{(2.9)}$$

where:

V_0 = volume of sediment below zero storage,

p_0 = relative depth of sediment at dam,

K = reference area for converting relative area to actual area = A_0/a_0,

A_0 = area of sediment at depth of sediment at dam, and

a_0 = relative area of sediment at relative depth of sediment at dam.

When $p = 1$, the relative volume of sediment $v(p) = 1$, and the total sediment volume $V_s = S$, and Eq. (2.9) can be expressed as

$$S = V_0 + \frac{A_0}{a_0} H[1 - v(p_0)] \qquad \textbf{(2.10)}$$

The relative depth of sediment at the dam, p_0, satisfies the following equation (Reclamation, 1962)

$$\frac{S - V(p_0 H)}{HA(p_0 H)} = \frac{1 - v(p_0)}{a(p_0)} \qquad \textbf{(2.11)}$$

where:

S = total sediment deposition;

$V(p_0 H)$ = measured reservoir capacity at a given depth $p_0 H$, same as V_0 in Eq. (2.10);

$A(p_0 H)$ = measured reservoir area at a given depth $p_0 H$, same as A_0 in Eq. (2.10);

$v(p_0)$ = dimensionless sediment volume at p_0,

$a(p_0)$ = dimensionless reservoir area at p_0, same as a_0 in Eq. (2.10).

This equation can also be written as

$$F'(p_0) = F(p_0) \qquad \textbf{(2.12)}$$

Where the functions F' and F are defined as:

$$F'(p) = \frac{S - V(pH)}{HA(pH)} \qquad \textbf{(2.13)}$$

$$F(p) = \frac{1 - v(p)}{a(p)} \qquad \textbf{(2.14)}$$

$F'(p)$ = a function of a particular reservoir and its anticipated sediment storage, and

$F(p)$ = a function of one of four types of theoretical design curves.

The equation can be solved by interpolating a value of p_0 at the point where $F' = F$.

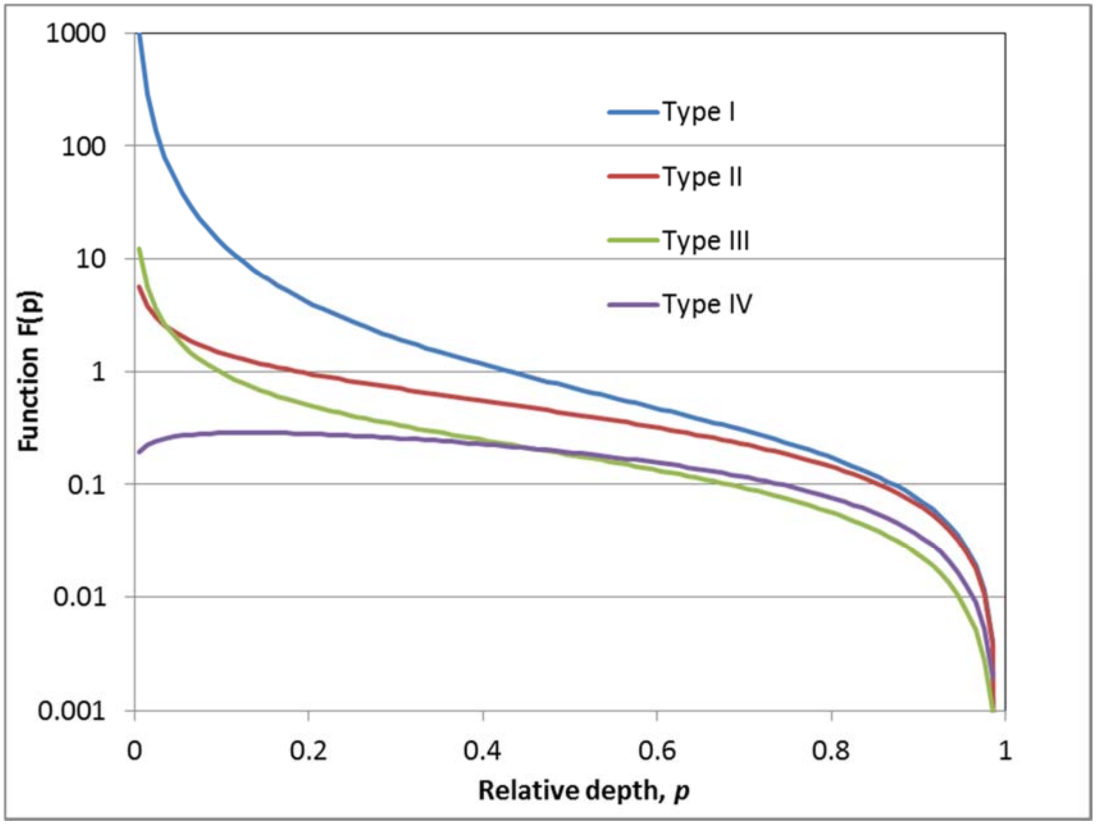

Figure 2-3 Theoretical Design Function *F*(*p*) for each of the Four Types of Reservoirs

The ARM procedure for the Alamogordo Reservoir is given as an example below to calculate the sediment distribution of a deposition volume *S* = 24,680 acre-ft, summarized as:

Step 1: Plotting the depth-capacity curve (as in Figure 2-2), the reservoir type was classified as Type II.

Step 2. Calculate function *F*'(*p*) in Eq. (2.13) according to the initial area and storage curves, as shown in Table 2.4. In the table, Column 1 is the reservoir elevation where the original area and capacity is given. The reservoir normal depth is *H* = 4,275-4,150 = 125 ft, where the normal reservoir water surface elevation is 4,275 ft and the initial bed elevation at dam is 4,150 ft. Column 2 is the relative depth. For example, at elevation 4,250 ft, the depth is 100 ft, giving a relative depth of 100 ft/125 ft = 0.80. Columns 3 and 4 are original reservoir area and capacity from initial reservoir survey. Column 5 is calculated from deposition volume *S* = 24,680 acre-ft minus *V*(*pH*) as in Column 4. Column 6 is calculated from with depth *H* = 125 ft and area *A* from Column 3. Column 7 is calculated with Eq. (2.13) and values from Columns 5 and 6.

Table 2.4 Calculation of F' in ARM

	Elevation	Relative Depth, *p*	Original Area A(pH)	Original Capacity V(pH)	S-V(pH)	HA	F'(p)
	(ft)	(-)	(acres)	(acre-ft)	(acre-ft)	(acre-ft)	(-)
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
(1)	4275	1.00	4650	156,750	-132,070	581250	-0.227
(2)	4270	0.96	4100	133,500	-108,820	512500	-0.212
(3)	4260	0.88	3200	97,000	-72,320	400000	-0.181
(4)	4250	0.80	2450	68,750	-44,070	306250	-0.144
(5)	4240	0.72	1750	47,750	-23,070	218750	-0.105
(6)	4230	0.64	1250	32,750	-8,070	156250	-0.052
(7)	4220	0.56	900	22,000	2,680	112500	0.024
(8)	4210	0.48	650	14,250	10,430	81250	0.128
(9)	4200	0.40	450	8,750	15,930	56250	0.283
(10)	4190	0.32	300	5,000	19,680	37500	0.525
(11)	4180	0.24	200	2,500	22,180	25000	0.887
(12)	4170	0.16	100	1,000	23,680	12500	1.894
(13)	4160	0.08	50	250	24,430	6250	3.909
(14)	4150	0.00	0	0	24,680	0	-

Step 3. Plot the function $F'(p)$ of Alamogordo Reservoir in Table 1.2 and Column 2 and Column 7 superposed on the design curve $F(p)$ of type II reservoir expressed in Eq. (2.14) and Figure 2-3, as shown in Figure 2-4. The intersection point of these curves is at p_0=0.25.

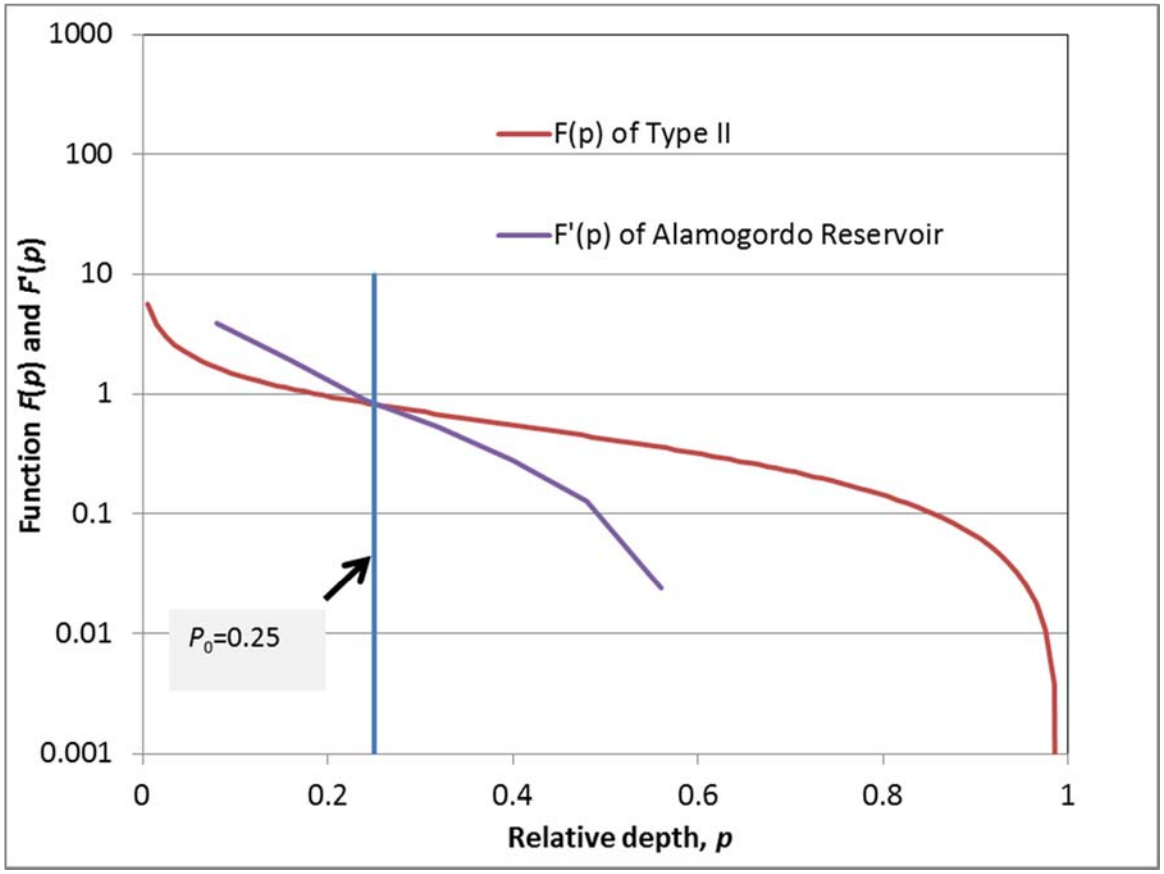

Figure 2-4 Comparison of Theoretical Design Function *F*(*p*) for Reservoir Type II and Sediment Storage Function *F'*(*p*) of the Alamogordo Reservoir

Step 4. Fill in the supplement information in

Table 2.5. p_0 is the relative depth obtained in Step 3. H is the reservoir normal depth H = 4,275 - 4,150 = 125 ft, where normal reservoir water surface elevation is 4,275 ft and the initial bed elevation at dam is 4,150 ft. p_0H = 0.25*125 = 31.3 ft which added to the bottom elevation of 4,150 ft gives the elevation of sediment deposited at the dam equal to 4181.3 ft. The original reservoir area at 4,181.3 ft gives A_0 = 213 acres. The relative area at p_0 is calculated by Eq. (2.3) as $a_0 = Cp_0^m(1-p_0)^n = 2.443 \times 0.25^{0.57} \times (1-0.25)^{0.41} = 1.00$. Finally, the reference deposition area is calculated as $K = \frac{A_0}{a_0} = \frac{213}{1.0} = 213$ acres.

Table 2.5 Supplement Information in ARM

p_0	0.25	(-)
H	125	(ft)
p_0H	31.3	(ft)
Bottom elevation	4150	(ft)
Elevation of sediment deposited at dam (y_0)	4181.3	(ft)
Original reservoir area A0 at h0	213	(acres)
$a(p_0)$	1.00	(-)
K	213	(acres)

Step 5. Fill in sediment deposition data in Table 2.6. Column 1, Column 2, Column 3, Column 4 are the original area and capacity from initial reservoir.

- Column 5 is the relative area, calculated from Eq. (2.3), with value p from Column 4 and coefficients C, m, and n from reservoir type II.

Column 6 is the sediment volume. When the elevation is above elevation of sediment deposited at dam, y_0, it is calculated as $A(p) = Ka(p)$, where K is the reference area calculated in

- Table 2.5 and *a(p)* in Column 5. When the elevation is below y_0, it is the same as original area in Column 2.
- Column 7 is the sediment volume calculated as $0.5\,(y^i - y^{i+1}) \times (A^i + A^{i+1})$ where elevation *y* is from Column 1 and sediment area A is from Column 6. For example, the sediment volume between elevation 4,275 ft and 4,270 ft is calculated as $0.5\ \times (4275 - 4270) \times (0 + 136) = 346$ acre-ft.
- Column 8 is the accumulated sediment volume, calculated from Column 7. For example, the accumulated sediment volume at elevation 4275 ft is calculated as 24,640 = 346 + 24,294 acre-ft.
- Column 9 is the revised area calculated as Column 2 minus Column 6.
- Column 10 is the revise capacity calculated as Column 3 minus Column 8.

Table 2.6 Sediment Deposition Computations in ARM

	Elevation	Original area A(pH)	Original capacity V(pH)	Relative depth p	a(p) Type II	Sediment Area	Sediment Volumn	Accumulated Sediment Volume	Revised Area	Revise Capacity
	(ft)	(acre-ft)	(acre-ft)	(-)	(-)	(acres)	(acre-ft)	(acre-ft)	(acres)	(acre-ft)
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
(1)	4275	4650	156,750	1.00	0.000	0	346	24,640	4650	132,110
(2)	4270	4100	133,500	0.96	0.650	138	1,726	24,294	3962	109,206
(3)	4260	3200	97,000	0.88	0.970	207	2,240	22,569	2993	74,431
(4)	4250	2450	68,750	0.80	1.133	241	2,512	20,328	2209	48,422
(5)	4240	1750	47,750	0.72	1.225	261	2,657	17,816	1489	29,934
(6)	4230	1250	32,750	0.64	1.270	270	2,713	15,159	980	17,591
(7)	4220	900	22,000	0.56	1.278	272	2,695	12,446	628	9,554
(8)	4210	650	14,250	0.48	1.253	267	2,610	9,751	383	4,499
(9)	4200	450	8,750	0.40	1.198	255	2,458	7,140	195	1,610
(10)	4190	300	5,000	0.32	1.110	236	2,182	4,682	64	318
(11)	4180	200	2,500	0.24	0.986	200	1,500	2,500	0	0
(12)	4170	100	1,000	0.16	0.816	100	750	1,000	0	0
(13)	4160	50	250	0.08	0.570	50	250	250	0	0
(14)	4150	0	0	0.00	0.000	0	0	0	0	0

Step 6. Update the new area and capacity curves, as shown in Figure 2-5 with Column 1, Column 9 and Column 10 in Table 2.6.

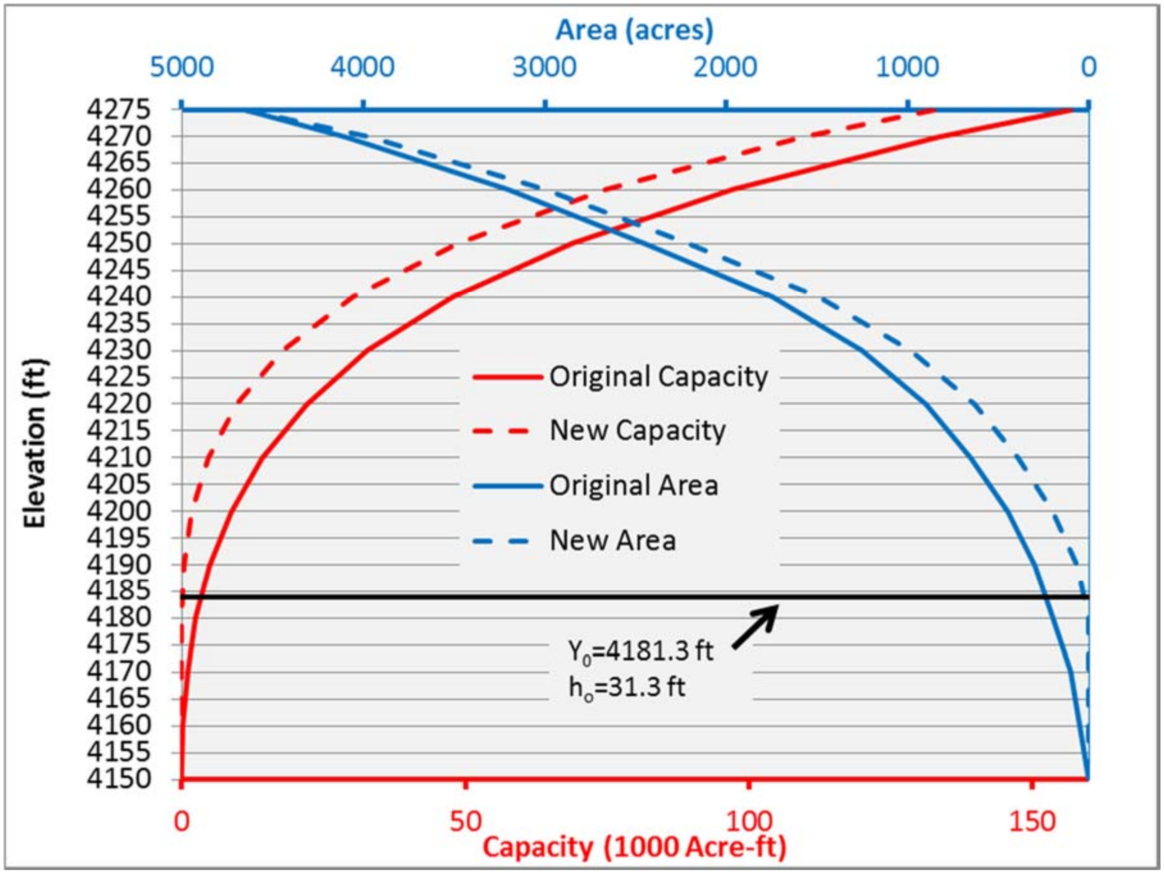

Figure 2-5 Area-Capacity Curves for Alamogordo Reservoir Calculated with ARM

2.3 Modified Area Reduction Method (MARM)

The ARM of Borland and Miller (1958) was modified by Mohammadzadeh-Habili J. et al. (2009) to represent the reservoir deposition volume as a logarithmic function similar to the reservoir capacity curve. Mohammadzadeh-Habili J. et al. (2009) argued that the reservoir capacity curve is similar to the natural logarithmic function curve, and the dimensionless reservoir deposition volume also can be represented as a logarithmic function. After some derivations, the following functions were used for relative reservoir deposition volume and area:

$$a(p) = \frac{1}{2} e^{p \ln 2} \left(e^{p \ln 2} - 1\right)^{(1-N)/N} \quad \textbf{(2.15)}$$

$$v(p) = \frac{1}{2} \left(e^{p \ln 2} - 1\right)^{1/N} \quad \textbf{(2.16)}$$

where a is the relative sediment area, $p=h/H$ is the relative depth of the reservoir, h= the calculated depth of reservoir measure from the bottom, H = the maximum reservoir depth at the dam wall, and N is the “reservoir coefficient”, which can be calculated as

$$N = 1.0751\ M^{-0.9063} \quad \textbf{(2.17)}$$

Where *M* is the slope of the log-log curve of relative capacity *v* and relative depth *p*, defined in Figure 2-6.

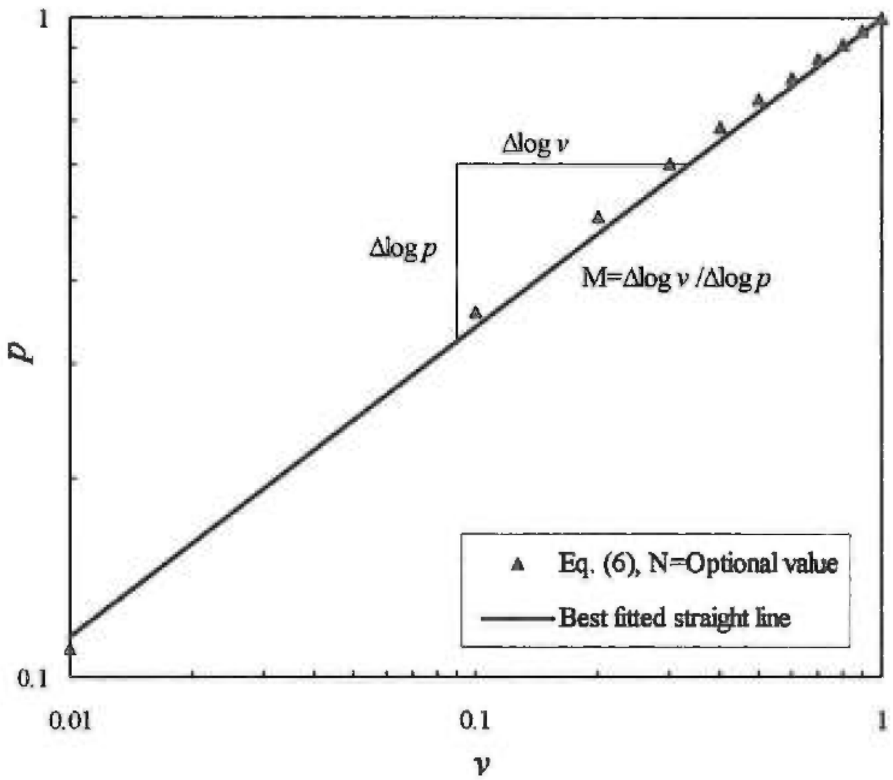

Figure 2-6 Obtaining the relationship between N and M

Later, Mohammadzadeh-Habili and Heidarpour (2010) presented another empirical method to calculate "reservoir coefficient", *N*. The method is based on the original and secondary area-capacity data of 40 reservoirs in the United States. Two assumptions (or observations) were made:

- The reservoir surface area at maximum water level remains roughly unchanged.
- The relationship between the area above the depth capacity curve and the sediment volume follows the power function as follows:

$$\frac{A_{(d-c)s}}{A_{(d-c)o}} = \left(\frac{V_s}{V_o}\right)^{2.05} \quad \textbf{(2.18)}$$

where $A_{(d-c)o}$ and $A_{(d-c)s}$ are areas above the original and secondary (after years of deposition) reservoir depth-capacity curves, as shown by Keene Creek reservoir in 1959 and 1999 in Figure 2-6, V_o is the original reservoir volume at maximum water level, and V_s (=V_o-S) is the secondary reservoir volume at maximum water level.

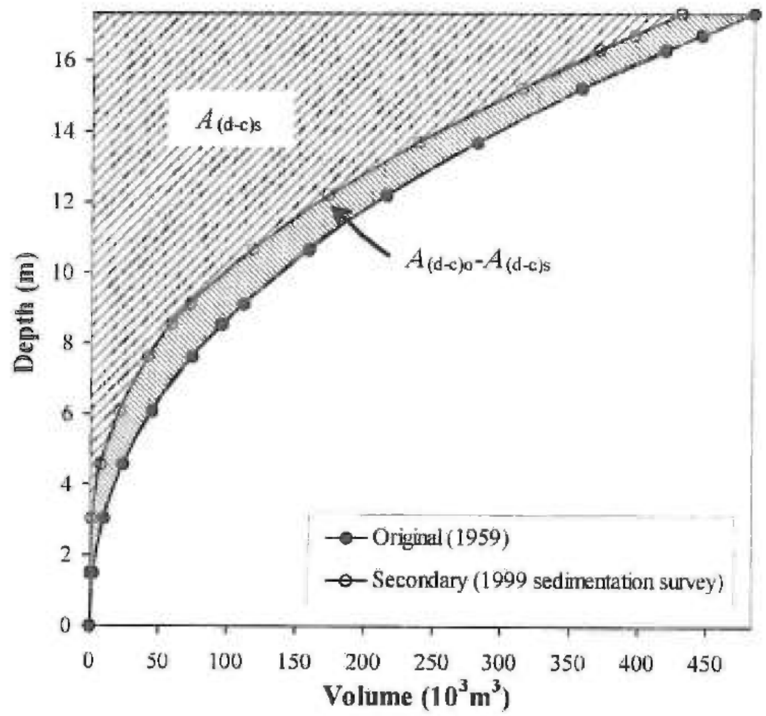

Figure 2-7 Area Above the Original and Secondary Depth-Capacity Curves of a Reservoir (Source: Mohammadzadeh-Habili and Heidarpour, 2010)

The following definitions or equations were derived and used in Mohammadzadeh-Habili and Heidarpour's method (2010).

The "reservoir coefficient" can be calculated by an equation, defined as $N_{o,Eq}$ and calculated as

$$N_{o,Eq} = 2\ln(2)\frac{V_m}{A_m H} \tag{2.19}$$

where A_m and V_m are the reservoir surface area and volume at maximum water level, H is the reservoir capacity at maximum depth.

The "reservoir coefficient" can be obtained by minimization of the sum of squared errors (SSE) between the original normalized depth-capacity curve and the curve of Eq. (2.15), defined as $N_{o,SSE}$.

The normal depth-capacity curve can be expressed as

$$a_{d-c} = 1 - \int_0^1 \frac{1}{ln2}(v^N + 1)\mathrm{d}v \tag{2.20}$$

Table 2.7 Calculated Values of a_{d-c} and $a_{d-c/N}$ for the Various Values of N (Source: Mohammadzadeh-Habili and Heidarpour, 2010)

N	a_{d-c}	a_{d-c}/N
0.25	0.1584	0.6337
0.30	0.1852	0.6173
0.35	0.2105	0.6015
0.40	0.2345	0.5862
0.45	0.2571	0.5715
0.50	0.2786	0.5573
0.55	0.2990	0.5437
0.60	0.3183	0.5305
0.65	0.3367	0.5180
0.70	0.3541	0.5059
0.75	0.3696	0.4928

The new reservoir maximum depth, H_s, can be expressed as

$$H_s = 2\ln(2)\frac{N_{o,SSE}}{N_{o,Eq}}\frac{V_s}{A_o N_s} \quad \textbf{(2.21)}$$

and

$$\frac{a_{(d-c)s}}{N_s} = \frac{A_{(d-c)s} A_o N_{o,Eq}}{1.4177 V_s^2 N_{o,SSE}} \quad \textbf{(2.22)}$$

The following steps were used to update the reservoir capacity and depth curve:

Step 1. Using Eq. (2.19) to calculate the "reservoir coefficient", $N_{o,Eq}$.

Step 2. Using minimization of SSE between the original relative reservoir area and Eq. (2.15) to calculate $N_{o,SSE}$.

Step 3. Using the original depth-capacity curves to calculate the area, above the curve as shown in Figure 2-72.182.22$\frac{a_{(d-c)s}}{N_s}$.

Step 5. Using Figure 2-7 and values $\frac{a_{(d-c)s}}{N_s}$, calculated from Step 5 to interpolate N_s.

Step 6. Using Eq. (2.21) to calculate the new reservoir maximum depth, H_s.

Step 7. Using Eq. (2.16) and calculated N=N_s (from step 6) to calculate the new reservoir volume with each elevation is above the new reservoir depth.

2.4 Empirical Reservoir Shape Function Method by Rahmanian and Banihashemi

Rahmanian and Banihashemi (2012) introduced the Relative Depth Shape Function (RDSF) to explain relative cumulative sediment deposition in different heights from the reservoir bed. The RDSF was introduced as

$$(RDSF)_i = \frac{V_i}{Vp_i} \qquad \textbf{(2.23)}$$

where V is the reservoir volume at normal level, V_i is reservoir volume from h=0 to h=h_i, h_i is the reservoir depth from stream bed, p_i is the relative reservoir depth (=h_i/H), and H is the normal height of reservoir.

Rahmanian and Banihashemi (2012) assumed that after deposition, the RDSF of the reservoir keeps the same shape. The RDSF method was applied on nine Iranian dams and the results showed it could predict sediment deposition pattern based only on the reservoir shape.

No details were given how to use the method, it seems that after a period of reservoir deposition, the new reservoir volume V can be obtained, and the V_i at each depth can be calculated from Eq. (2.23), and the reservoir area at each depth can be calculated from the original area A_i and the difference between the original V_i and the new calculated V_i.

3 Literature Review of Reservoir Sediment Distribution in the Longitudinal Direction

This section details the literature review of two different reservoir sediment distribution procedures in the longitudinal direction, which are the: 1) the Longitudinal Distribution Estimated from the Area Increment Method, and 2) Sediment Distribution as a Change Rate of the Wetted Perimeter.

3.1 Longitudinal Distribution Estimated from AIM

After estimating the new elevation-capacity and surface by ARM, as discussed in Section 2.2, Borland (1970) estimated reservoir sediment distribution in the longitudinal direction. First, the original surface areas at each contour interval are plotted. Second, the surface areas are reduced according to the results from the sediment distribution computations discussed in Section 2.2. The procedure for this is illustrated by the cross hatching in Figure 3-3. In creating the new contours, the new contour line will cross the streambed profile about normal to it and closer to the dam. The methodology to plot the new contours is not clear, however, it appears that the new contours are graphically similar to the old. Finally, the new contour crossing locations are used to obtain a revised streambed profile, as shown in Figure 3-4. The revised profile converges with the original one at the point where the top water surface profile and the original channel profile interest, shown as point “L” in the figure.

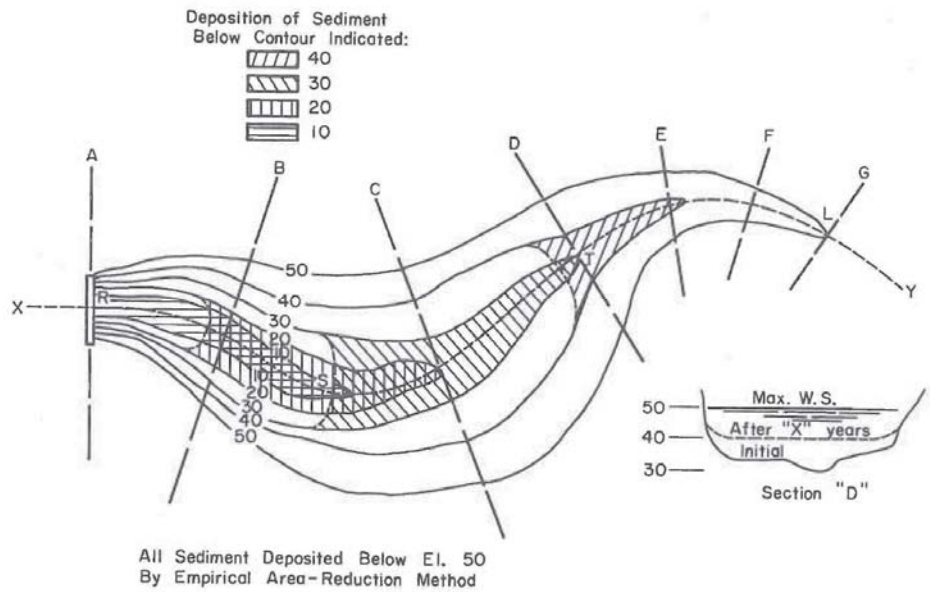

Figure 3-1 Reservoir Plan Paper Showing Sediment Inundated Areas by Cross-hatching (Source: Borland, 1970)

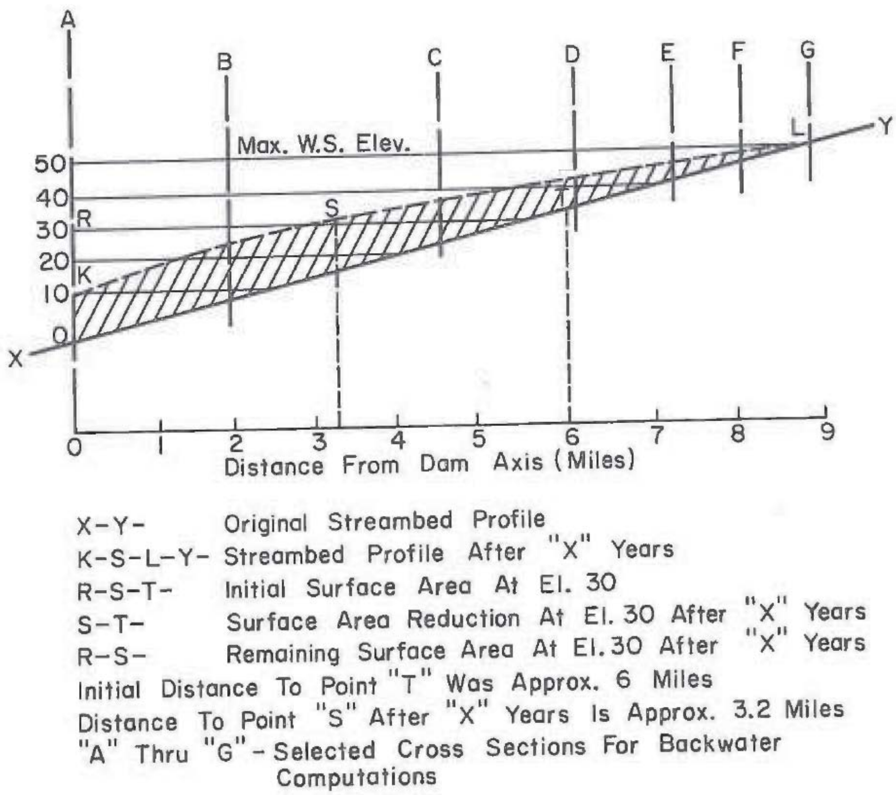

Figure 3-2 Theoretically Determined Reservoir Sediment Depositional Profile (Source: Borland, 1970)

3.2 Sediment Distribution as a Change Rate of Wetted Perimeter

Annandale (1984) introduced an approach to forecasting the distribution of the reservoir sedimentation in longitudinal direction. This method is based on the principle of minimum stream power. The method allows distribution of reservoir sediment as a function of distance from the dam wall for various rates of change in reservoir width with distance. The relation can be described as

$$\sum \frac{V}{V_{FSL}} = f\left(\frac{L}{L_{FSL}}, \frac{\mathrm{d}P}{\mathrm{d}x}\right) \tag{3.1}$$

where V is the volume of deposited sediment, V_{FSL} is the total volume of sediment at full supply level (FSL); L is the distance from the dam's wall (same as x), L_{FSL} is the total length of a reservoir at FSL, P is the wetted perimeter, and x is the distance from the dam's wall. $\sum \frac{V}{V_{FSL}}$ is the dimensionless cumulative sediment volume.

The equation can also be illustrated in Figure 3-3, where the values from 0.02 to 1.20 on solid lines represent longitudinal gradient $\mathrm{d}P/\mathrm{d}x$. Michalec (2014) showed how to obtain the longitudinal gradient $\mathrm{d}P/\mathrm{d}x$ as illustrated in Figure 3-4, which shows the relationship between the wetted perimeter (P) and the distance from the dam for the Krempna-2 Reservoir in Poland. A linear regression relationship was identified for specific wetted perimeters (P) and distances from the dam's wall (x) of each cross-section of the reservoir, and the longitudinal gradient $\mathrm{d}P/\mathrm{d}x$ is obtained as 0.264.

Annandale (1984) found that the higher the longitudinal gradient ($\mathrm{d}P/\mathrm{d}x$), the more sediment distribution is near the dam wall. Annandale's method was based on silting measurements of 11 reservoirs whose length was from a few to several dozen kilometers.

In the study of small reservoirs of Upper Vistula in Poland, Michalec (2014) found opposite result. The lower the longitudinal gradient ($\mathrm{d}P/\mathrm{d}x$), the more sediment distribution is near the dam wall. Michalec (2014) concluded that Annandale's method cannot be applied to small reservoir with a capacity less than 5 million m^3.

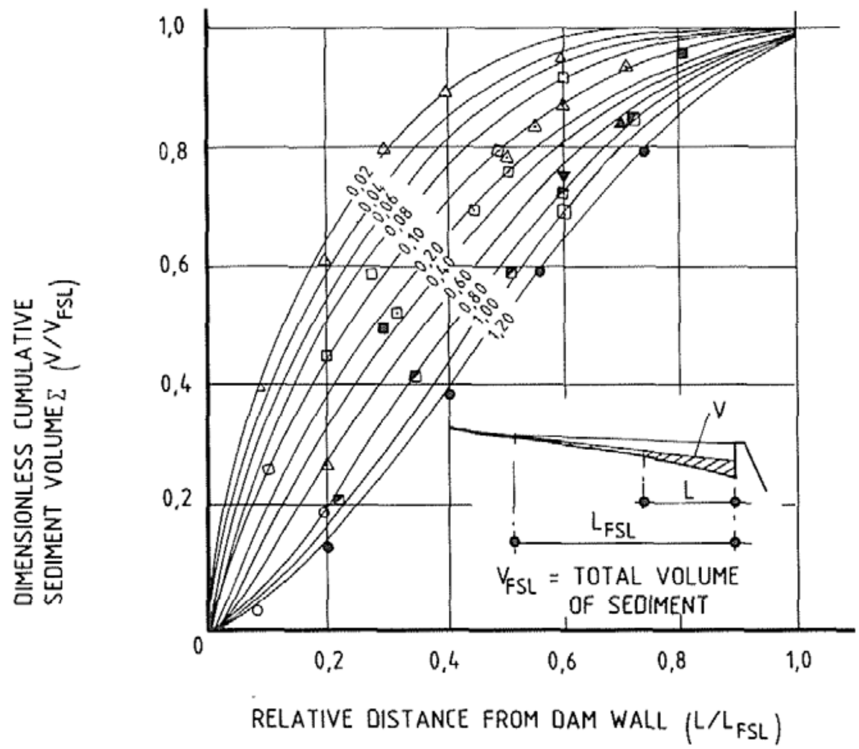

Figure 3-3 Dimensionless Cumulative Mass Curves Explaining Sediment Distribution as a Function of $\mathrm{d}P/\mathrm{d}x$ (Source: Annandale, 1984)

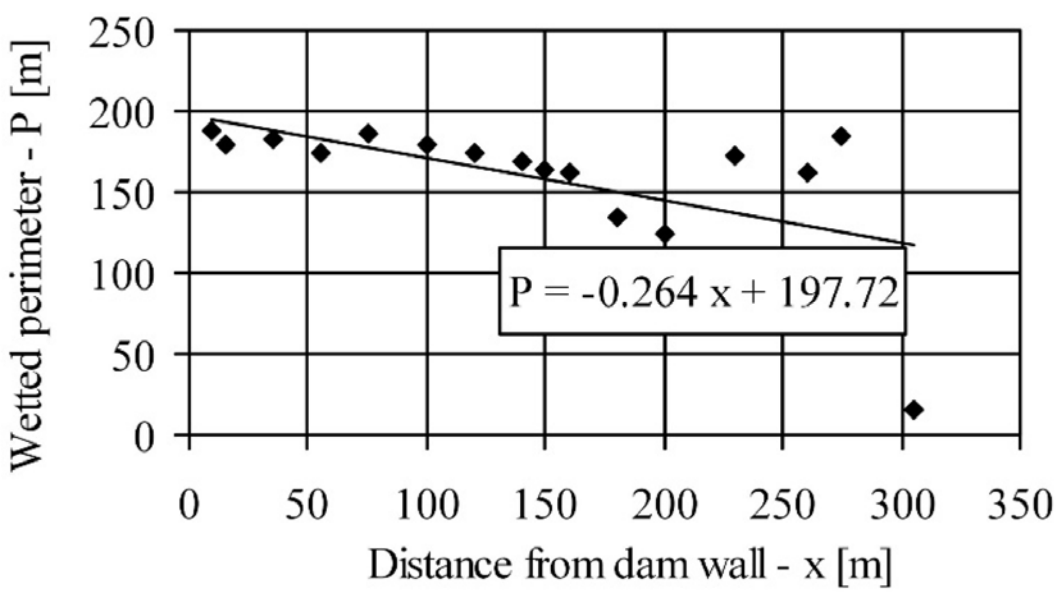

Figure 3-4 Example Calculation of d*P*/d*x* with Krempna-2 Reservoir in Poland (Source: Michalec, 2014)

4 Examination of Existing Methods

Existing methods are examined with repeat reservoir survey data to check the accuracy of each method. For this purpose, a database of multiple Bureau of Reclamation reservoir surveys was used. The original data were available in the form of Microsoft Access. Visual Basic (VBA) subroutines were developed to read the reservoir survey data into Microsoft Excel format, which include Year-of-Survey/Elevation/Area/Capacity table for each reservoir. Data were then arranged in a separate Excel worksheet for each reservoir whose name was set as the dam's National Inventory of Dams (NID) number. A summary worksheet was used to record the general dam information which include reservoir NID, reservoir Name, Area Office, Regional Office, Stream Name, Watershed Name, etc.

Survey data of 72 reservoirs were used to compare existing reservoir sediment distribution methods. Reservoirs with at least two surveys can be used to check the sediment distribution between the two surveys. Of the reservoirs available in the database, only 32 of the reservoirs were surveyed more than once, as listed in Table 4.1. The sedimentation volumes computed from the initial reservoir survey to the most recent reservoir survey are presented in the table as *S*. The sedimentation volumes of four reservoirs, shown in blue color, are presented as negative implying a net sediment erosion from the reservoir, likely due to the improvement in reservoir survey technologies since the initial survey. These four reservoirs are not used in the study. The sedimentation volumes of five reservoirs, shown in red color, are less the one percent of the original reservoir capacity. Due to relative high uncertainties, these five reservoirs are also not included in the study; therefore, a total of 23 reservoirs were used to examine the reservoir distribution methods.

Table 4.1 General Information of the Studied Reservoirs

NID Number	Reservoir Name	Number of Surveys	1st Year	Last Year	Normal Depth (ft)	Normal Area (acre)	Normal Capacity (acre-ft)	Bottom Elevation (ft)	S (acre-ft)
AZ10307	LAKE POWELL	2	1963	1986	574	169027	28735325	3136	871406
AZ10317	THEODORE ROO	3	1981	2013	170	17337	1336734	1966	3030.8
CA10141	CLEAR LAKE	2	1910	2007	33	25760	518510	4510	11258
CO00299	PUEBLO	2	1993	2012	172.2	8027	527626	4752.8	11565
CO01654	FLATIRON	2	1954	2012	50.6	57.3	1136	5429.45	42
CO01663	PINEWOOD	2	1954	2012	78.5	124	3180	6500	85
ID00285	MANN CREEK	2	1967	1992	137.1	313	15502	2760	547
MT00570	FRESNO	3	1978	2013	75	9527	248447	2520	44437
MT00571	GIBSON	2	1996	2009	0	0	0	0	-2513
MT00576	BIGHORN LAKE	3	1965	2007	494	17958	1435186	3166	103461
ND00148	EDWARD ARTH	3	1951	2013	48	2092	27205	2382	2018
ND00149	LAKE TSCHIDA	3	1949	2013	110	11344	451972	2010	11218
ND00151	JAMESTOWN	2	1954	2009	72.4	17435	381105	1390	1198
NE01078	SWANSON LAK	3	1953	2011	0	0	0	0	-352018
NM00122	HERON LAKE	3	1970	2010	227.8	6148	430507	6955.2	2152
NM00129	ELEPHANT BUT	5	1915	2007	200	41283	2756600	4210	622293
NM00130	LAKE SUMNER	2	2001	2013	101.7	7615	226796	4207	386
NM00131	CABALLO	3	1938	2007	77	11532	346736	4105	21802
NM00412	NAMBE FALLS	3	1976	2013	173	74.4	2913	6667	297
NM00500	BRANTLEY	2	2001	2013	68	13587	169066	3204	10674
NM10008	EL VADO	2	1984	2007	0	0	0	0	-4568
NV10122	LAKE MEAD	2	1935	2001	580	163224	32544690	650	2402790
OK02500	LAKE ALTUS	3	1940	2007	67.3	7705	192842	1496.7	30316
OK02502	FORT COBB	2	1959	1993	96	9546	297123	1279	13044
OK02503	FOSS	2	1961	2009	119	21909	881137	1563	9263
OK20502	TOM STEED	2	1975	2009	51	9478	197363	1364	16
OR00098	OCHOCO	2	1920	1990	118.2	1180	54000	3017.7	3181
OR00592	THIEF VALLEY	2	1932	1992	50	763	19310	3085	4598
OR00593	UNITY	2	1938	1991	77.3	1100	34453	3750	1536
SD01099	ANGOSTURA	4	1949	2004	133.1	5797	217700	3065	37344
WA00263	BUMPING LAKE	2	1910	1990	0	0	0	0	-1691
WY01291	GLENDO	3	1957	2003	145	17986	797018	4508	33709

The mean square error of the capacity (MSE) is defined as

$$MSE = \frac{\sqrt{\sum_1^n (V_i - VF_i)^2}}{n\,S} \tag{4.1}$$

where n is the number of values in the reservoir capacity versus depth table of the initial survey or final survey (if n is not the same in the two surveys, final capacity at the same depth of the initial survey is interpolated); V_i is the reservoir capacity from final survey at depth d_i; VF_i is the calculated reservoir capacity at depth d_i; S is the total reservoir sediment deposition at between initial and final surveys.

First, the ARM method is compared with MARM to see if MARM improved the accuracy of the prediction. Example reservoir area and capacity curves of Lake Powell calculated with ARM and MARM methods, along with initial and final curves from the reservoir surveys, are presented in Figure 4-1 and Figure 4-2. The defined mean square errors for all 23 Reclamation reservoirs are listed in Table 4.2. Observations show that ARM predicts better sediment distribution than MARM.

Table 4.2 Comparison of MSE for ARM and MARM for all 28 Reservoir Locations

	MSE
ARM	0.14
MARM	1.39

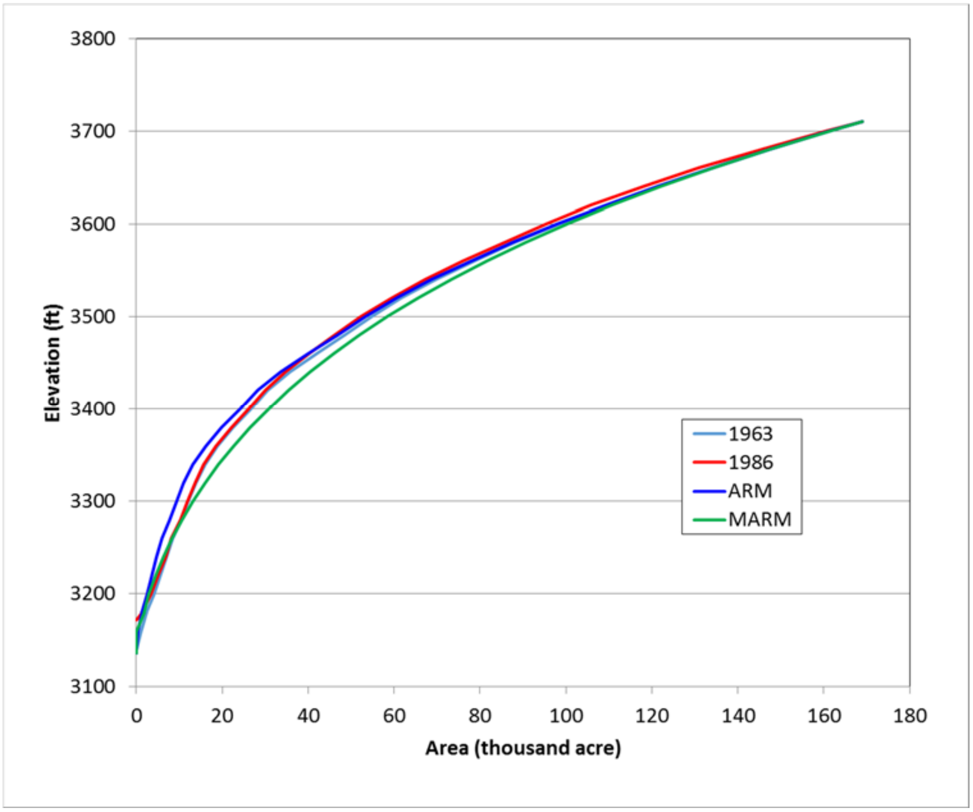

Figure 4-1 Reservoir Area and Elevation Curve Comparison of Lake Powell

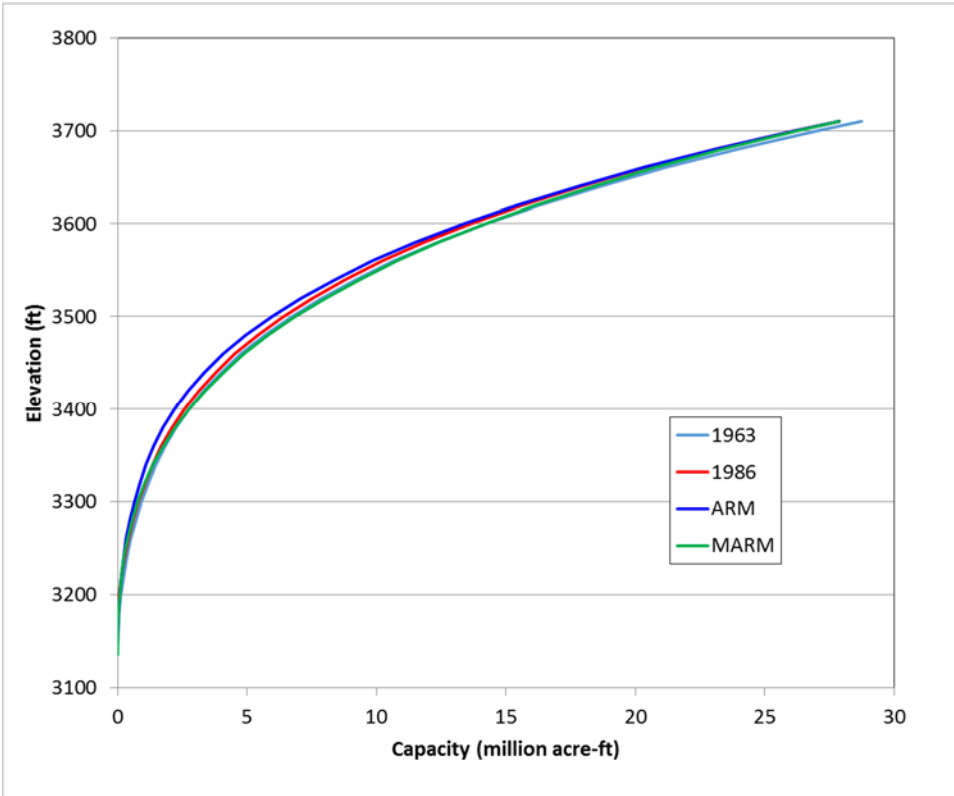

Figure 4-2 Reservoir Capacity and Elevation Curve Comparison of Lake Powell

The ARM method is further investigated to see if the classification of reservoirs (listed as Types I, II, III, and IV in Figure 2-2) by the depth versus capacity relationship can best represent the sediment distribution. In the ARM method, the reservoir classification is linked directly to the reservoir shape, obtained by the slope of the depth-capacity curve on log-log coordinates. A smaller slope represents Type I sedimentation distributions (lake) and a larger slope Type IV (gorge). In this step, sediment distributions in all four reservoir types are used to find a type that minimized the *MSE* of the calculated distribution.

Table 4.3 shows the comparison of original reservoir types obtained from reservoir shape with calculated reservoir types that best fit the survey data. Results show that reservoir shape should not be the only factor in classification of a reservoir; of the 23 reservoirs, only six fit the original reservoir types by minimizing the *MSE* between reservoir survey and calculated sediment distribution.

Table 4.3 Comparison of Original Reservoir Types Obtained from Reservoir Shape with Calculated Reservoir Types that best Fit the Survey Data

Original Reservoir Type	Reservoir Type with Best Fit			
	I	II	III	IV
I	Flatiron			
II			Fresno	
III	Lake Powell Bighorn Lake Elephant Butte Brantley Lake Mead	Pueblo Lake Altus Fort Cobb Angostura Glendo	Mann Creek Edward Arthur Patterson Nambe Falls Unity	Clear Lake Caballo
IV		Ochoco	Pinewood Lake Tschida Thief Valley	Foss

5 Reservoir Operation Effects on Reservoir Sediment Distribution

5.1 Selection of Reservoir Sediment Distribution Curves

To find the relationship between reservoir operation and reservoir sediment distribution, the sediment deposit curve of Moody (1962) is used and written as

$$= c\, p^{m}(1-p)^{n} \qquad (5.1)$$

where A_p represents a dimensionless relative area at a relative distance p above the reservoir bed, and c, m, and n are dimensionless constants. The selections of m and n are purely mathematical as long as the location of the maximum relative sediment area covers a whole range from high relative depth near 1.0 to lower relative depth near 0. With m and n defined, c is calculated to make the area under the curve equal unity.

Two sets of parameters are proposed in this study with up to 19 sediment deposit curves in each set. More curves would provide a finer linkage between the reservoir operation and sediment distribution, if this linkage exists. In the first set (Set One) curves, m increases monotonically from 0.05 to 2.75, and n in reverse order. As m increases, the reservoir type changes from a lake type, to flood plain-foothill, to hill, and finally to gorge, and sediment deposition moves from reservoir entry to near the dam. In the second set (Set Two) curves, m and n are interpolated from original four reservoir types of Borland and Miller (1958), in which m does not increases monotonically from one type to the next as sediment moves from reservoir entry to dam. In Table 5.1, the red color represents constants of Borland and Miller . In the analysis of Set Two sediment distributions, another index (*ID*) is used which increases as sediment distribution moves from reservoir entry to dam.

Table 5.1 Characteristic constants in the dimensionless relative area formula

Set One			Set Two			
m	*n*	*c*	*m*	*n*	*c*	*ID*
0.05	2.75	4.206	1.5	0.2	3.433	*1*
0.10	2.50	4.280	1.3	0.26	3.378	*2*
0.15	2.25	4.296	1.1	0.32	3.260	*3*
0.20	2.00	4.249	0.9	0.38	3.080	*4*
0.25	1.75	4.133	0.7	0.44	2.841	*5*
0.30	1.50	3.946	0.5	0.5	2.549	*6*
0.35	1.25	3.689	0.62	0.86	3.827	*7*
0.40	1.00	3.365	0.74	1.22	5.590	*8*
0.45	0.75	2.981	0.86	1.58	8.014	*9*
0.50	0.50	2.549	0.98	1.94	11.339	*10*
0.75	0.45	2.981	1.10	2.3	15.882	*11*
1.00	0.40	3.365	0.90	2.3	12.626	*12*
1.25	0.35	3.689	0.70	2.3	9.849	*13*
1.50	0.30	3.946	0.50	2.3	7.512	*14*
1.75	0.25	4.133	0.30	2.3	5.579	*15*
2.00	0.20	4.249	0.1	2.3	4.012	*16*
2.25	0.15	4.296				
2.50	0.10	4.280				
2.75	0.05	4.206				

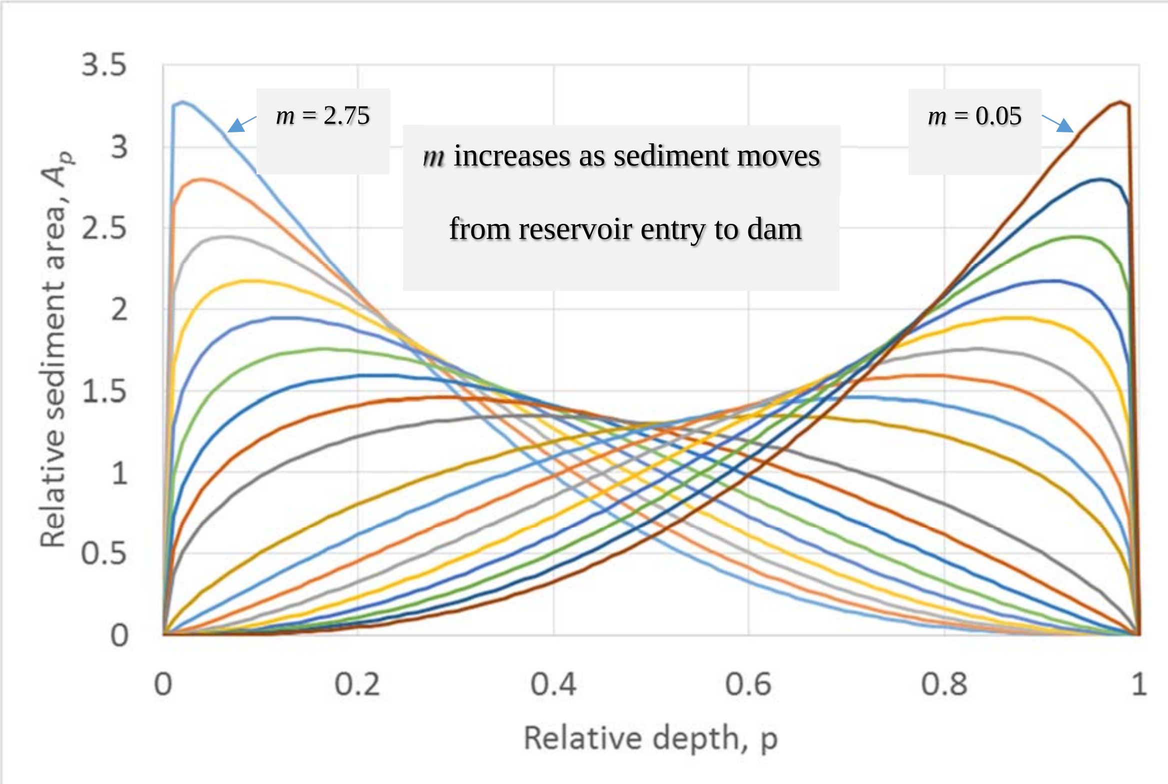

Figure 5-1 Area Design Curves of Set One with Increasing *m*

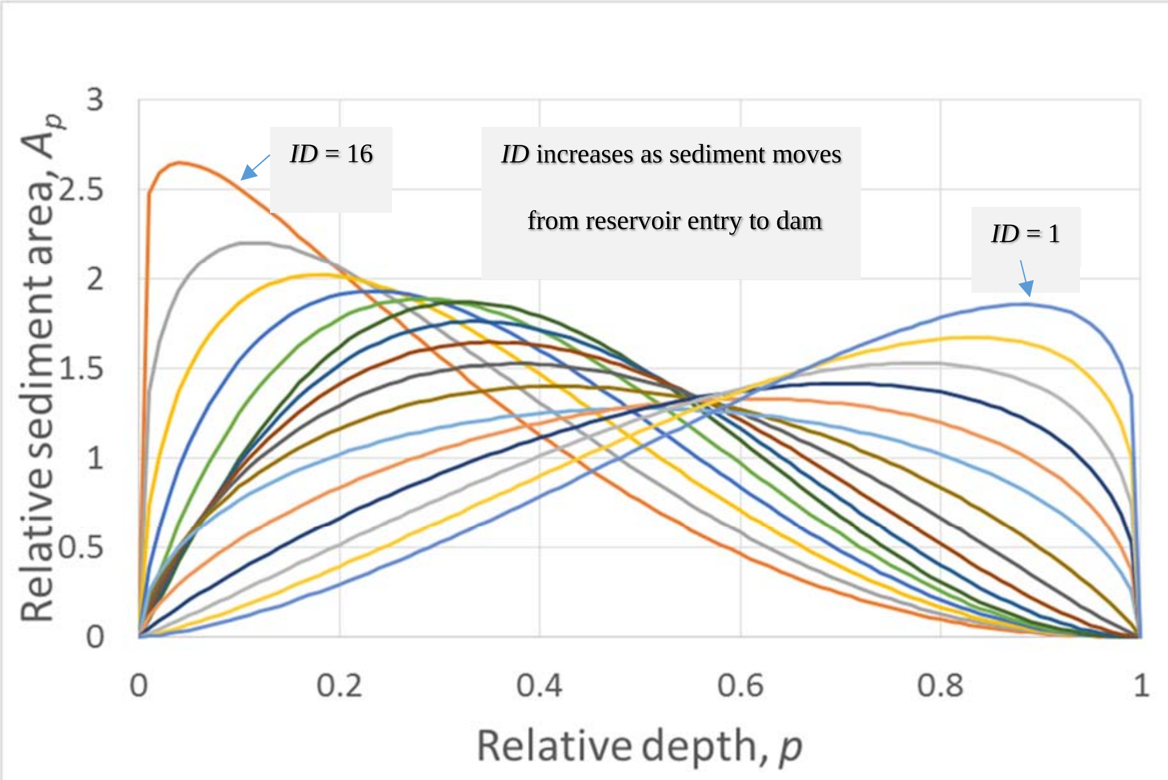

Figure 5-2 Area Design Curves of Set Two with Increasing *ID*

5.2 Reservoir Operation Parameters

There are limited data available that can be used to represent reservoir operations, which are defined in this section.

- Maximum Pool Elevation (Z_{max}): maximum historical pool elevation (ft).
- Minimum Pool Elevation (Z_{min}): minimum historical pool elevation (ft).
- Average Maximum Pool Elevation (A_{max}): average of annual maximum pool elevation (ft).
- Average Minimum Pool Elevation (A_{min}): average of annual minimum pool elevation (ft).
- Average Middle Pool Elevation (A_{ave}): average of A_{max} and A_{min} (ft).
- Normal Depth (H_m): difference between max pool elevation and min pool elevation (Z_{max} - Z_{min})
- Average Pool Range (Δd): depth of average middle pool elevation relative to minimum historical pool elevation (A_{ave} - Z_{min}).
- Pool Range Ratio (Rd): The ratio of average pool range and normal depth ($\Delta d/H_m$).

- Maximum Pool Depth Ratio (R_{max}): The ratio of maximum pool depth and normal depth ((A_{max} - Z_{min})/ H_m).
- Average Pool Depth Ratio (R_{avg}): The ratio of average pool depth and normal depth ((A_{ave} - Z_{min})/ H_m).
- Minimum Pool Depth Ratio (R_{min}): The ratio of minimum pool depth and normal depth ((A_{min} - Z_{min})/ H_m).

5.3 Correlation between Reservoir Operation Information and Parameter *m* in Set One Area Design Curves

Correlation between defined reservoir operation parameters and parameter *m* in Set One area design curves are presented from Figure 5-3 through Figure 5-7. All trendline options are tested, and the trendline with the maximum correlation (as shown with R-squared value in the figures) is selected in each figure. For comparison, the correlation between the depth-capacity log slope (defined in Figure 2-2) and parameter *m* is also presented here in Figure 5-3. Significant correlations between reservoir shape and parameter *m* are found. Poor correlations between reservoir operation parameters and parameter *m*, however, are found, indicating that the relationship between reservoir sediment distribution and reservoir operation is more complex than simple parameters can present.

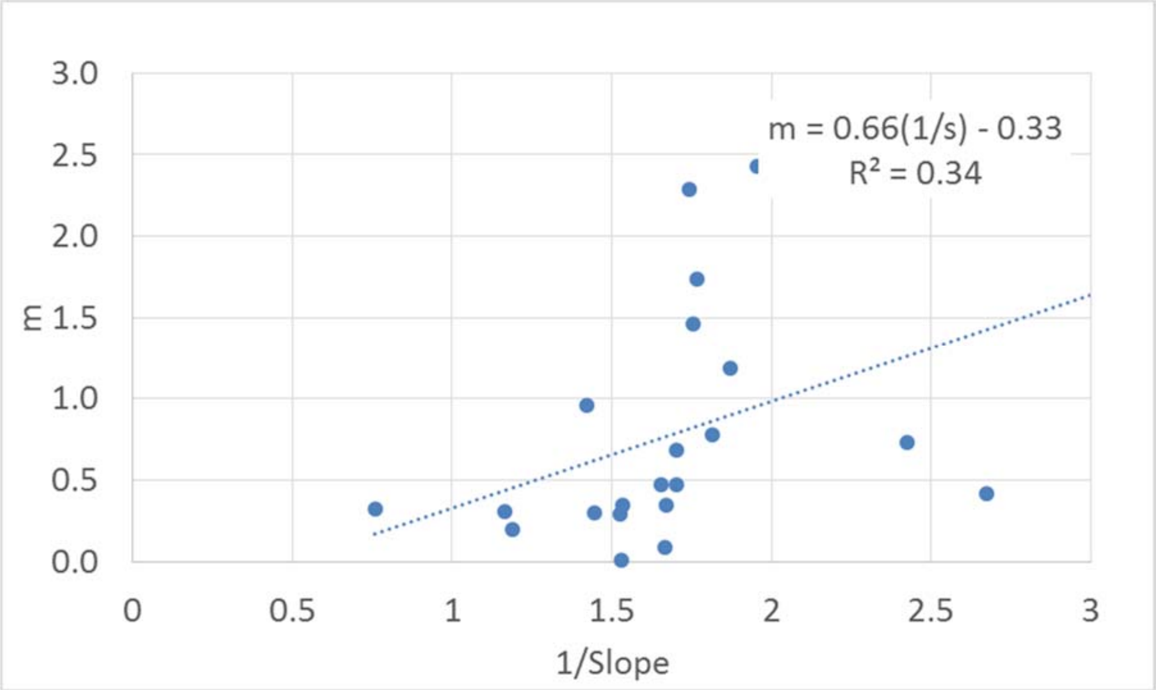

Figure 5-3 Relationship between Depth-Capacity Log Slope and Parameter *m* in Set One Area Design Curves.

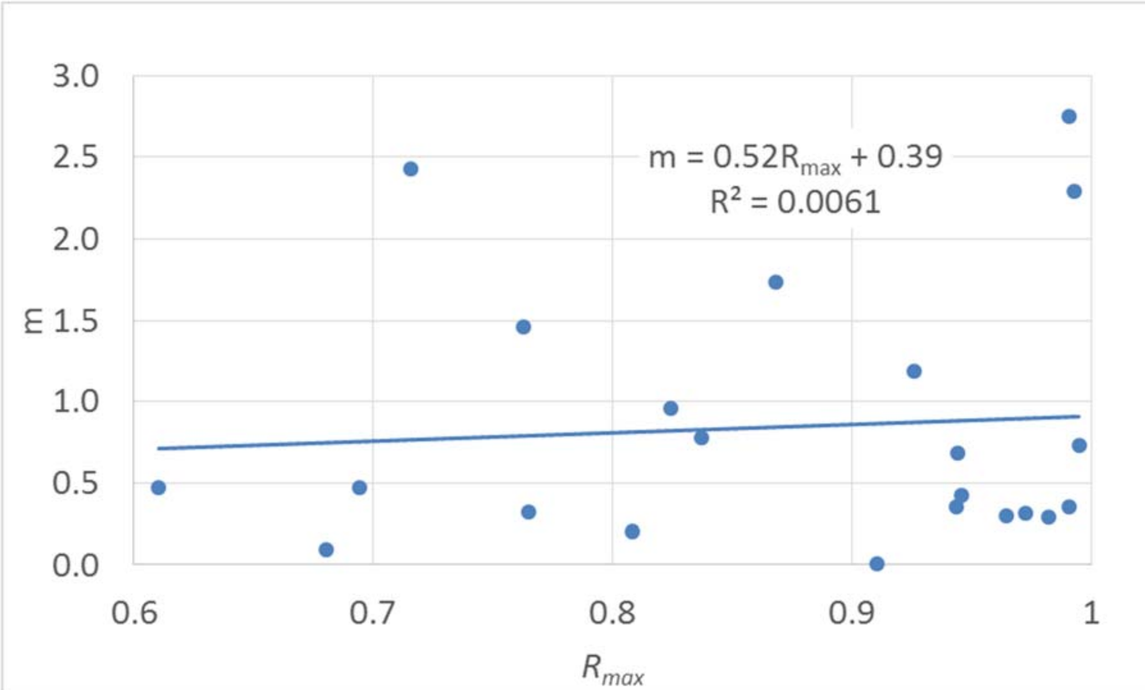

Figure 5-4 Relationship between Maximum Pool Ratio (R_{max}) and Parameter *m* in Set One Area Design Curves

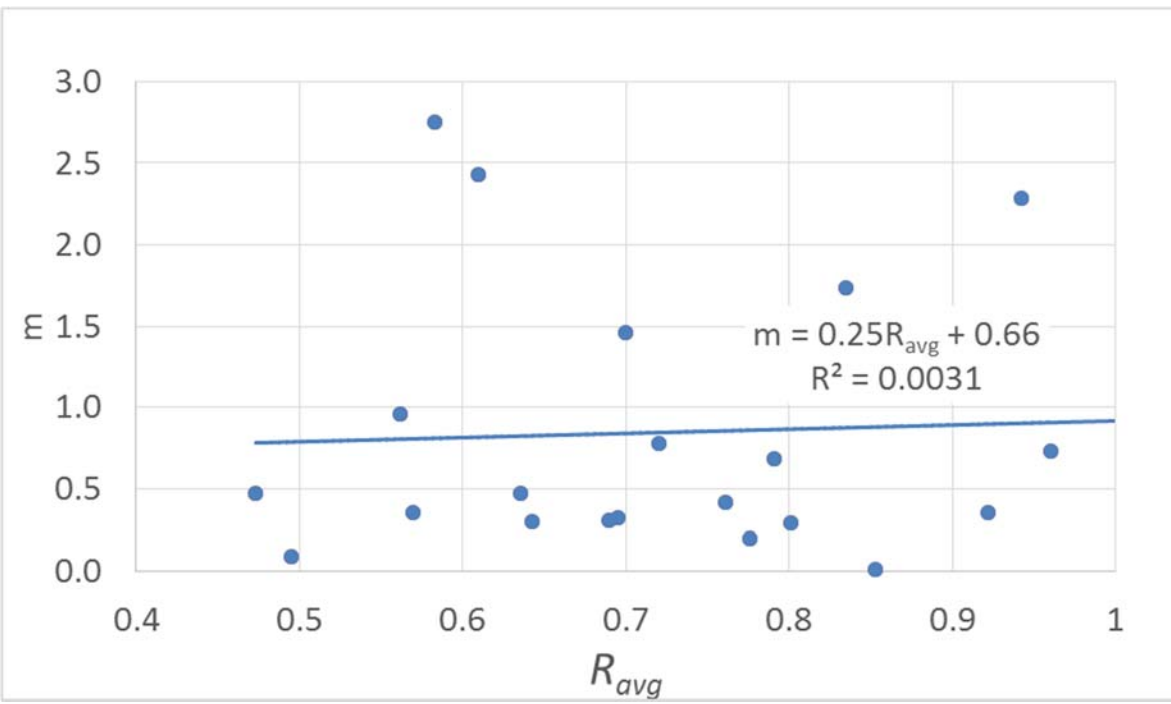

Figure 5-5 Relationship between Average Pool Ratio (R_{avg}) and Parameter *m* in Set One Area Design Curves.

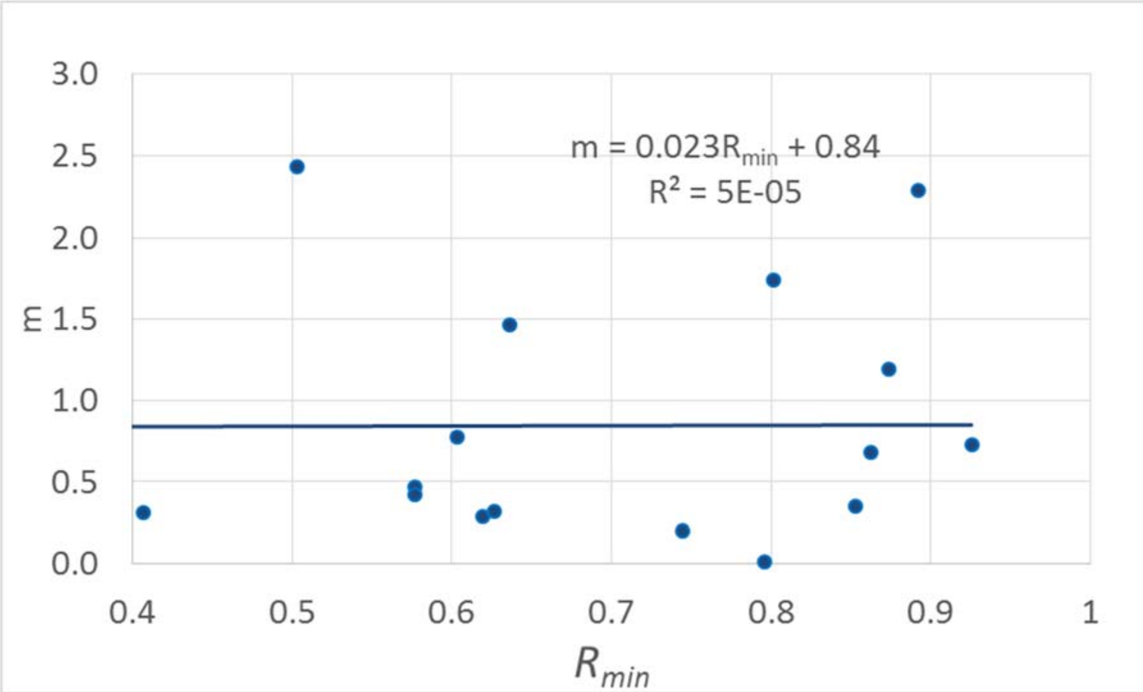

Figure 5-6 Relationship between Minimum Pool Ratio (R_{min}) and Parameter *m* in Set One Area Design Curves

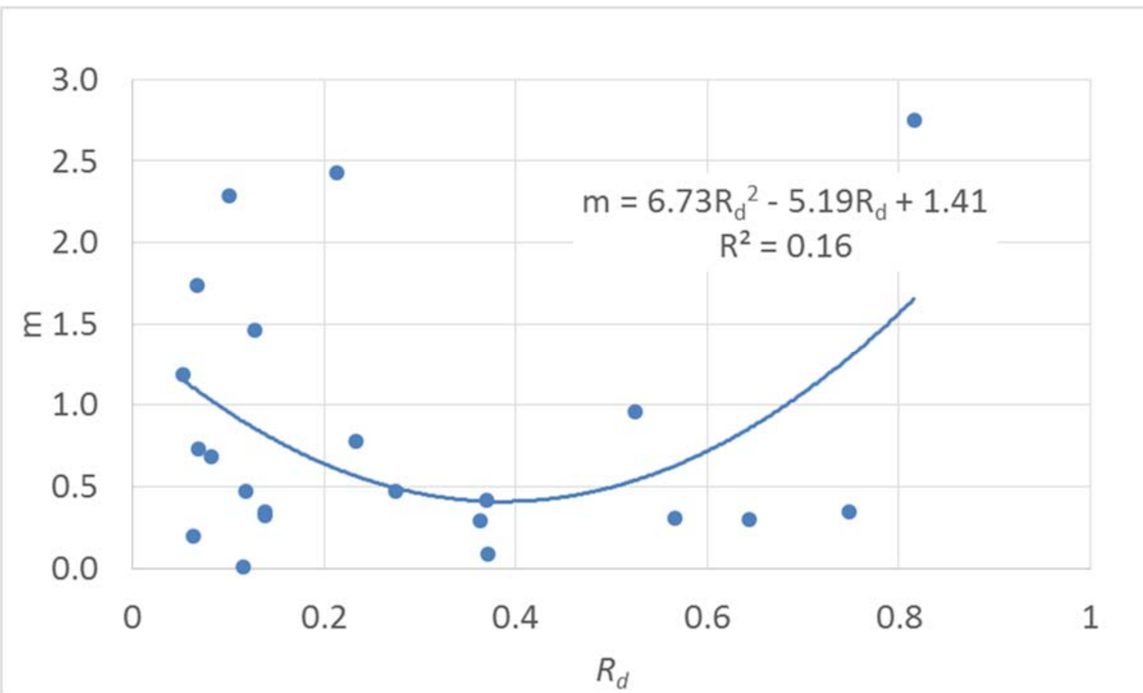

Figure 5-7 Relationship between Pool Range Ratio (Rd) and Parameter *m* in Set One Area Design Curves

5.4 Correlation between Reservoir Operation Information and Parameter *ID* in Set Two Area Design Curves

Correlation between defined reservoir operations parameters and parameter *ID* in Set Two area design curves are presented from Figure 5-9 through Figure 5-12. All trendline options are tested, and the trendline with the maximum correlation (as shown with *R*-squared value in the figures) is selected in each figure. For comparison, the correlation between the depth-capacity log slope and parameter *ID* is also presented here in Figure 5-8. Overall, slope (presented as 1/slope) vs *m* bears the significant correlation (shown as R-squared value in the figures). Poor correlation between reservoir operation parameters and parameter *ID* is observed, indicating that the relationship between reservoir sediment distribution and reservoir operation is more complex than simple parameters can present.

Multiple regressions were attempted that used two explanatory variables, reservoir shape (defined as 1/slope) and pool range ratio (Rd), and a response variable as parameter *ID*. Results show that multiple regression does not predict a more accurate parameter *ID* that reduces the mean square error of the predict capacity table, when compared with simple regression with reservoir shape.

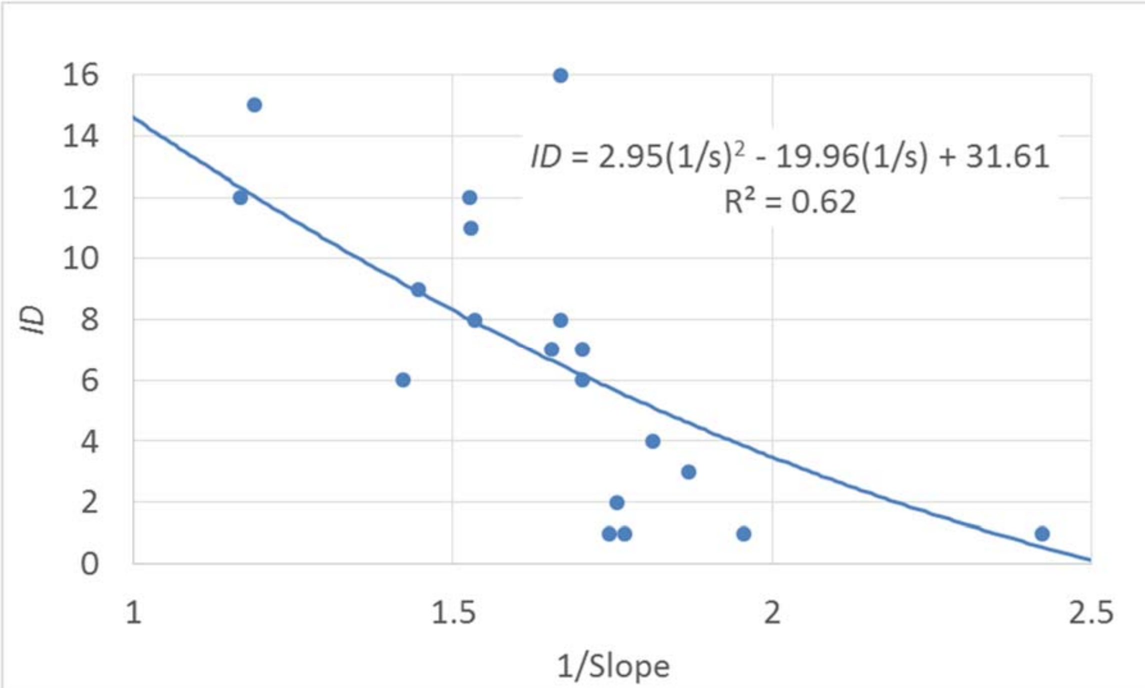

Figure 5-8 Relationship between Depth-Capacity Log Slope and Parameter *ID* and in Set Two Area Design Curves.

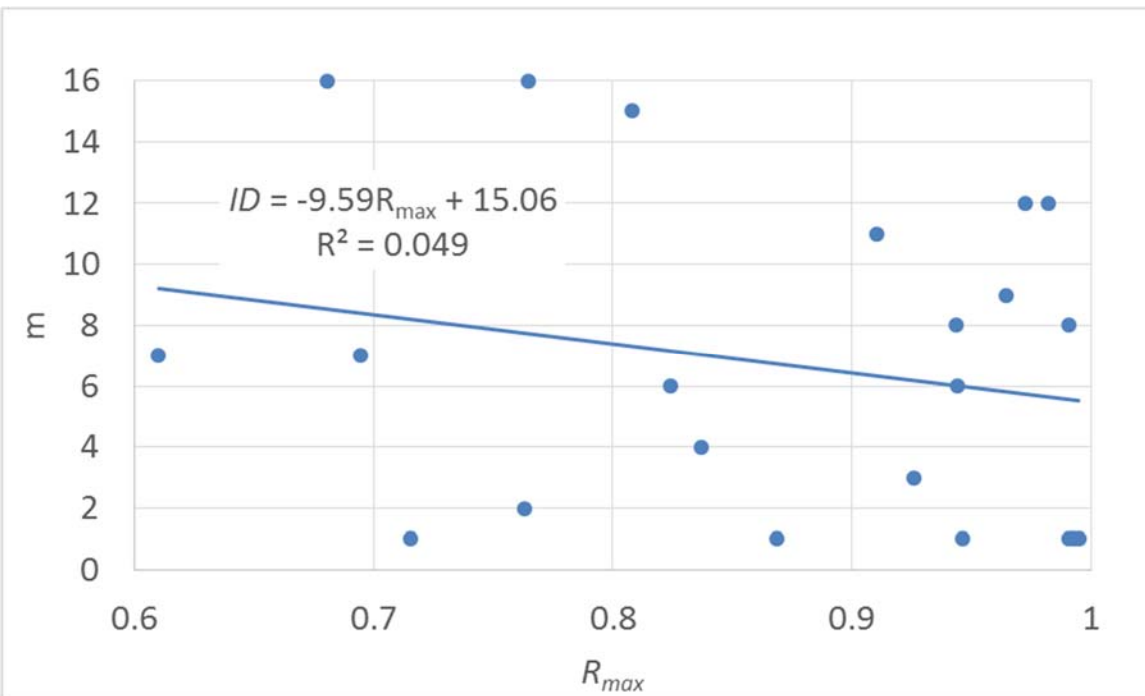

Figure 5-9 Relationship between Maximum Pool Ratio (R_{max}) and Parameter *ID* and in Set Two Area Design Curves

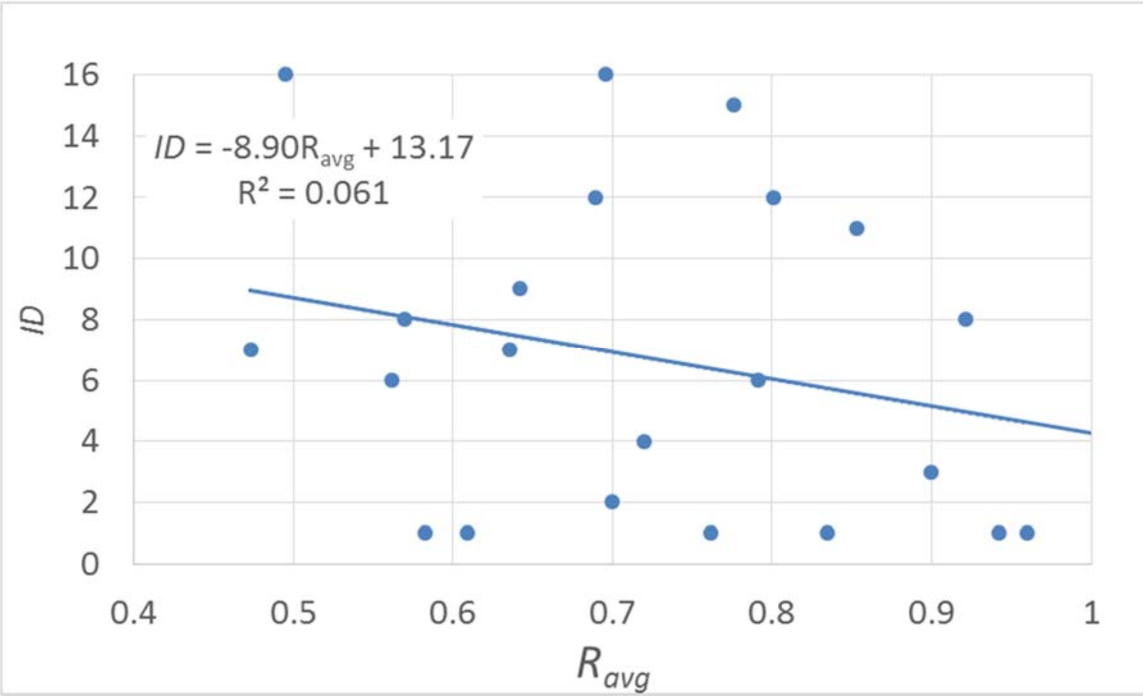

Figure 5-10 Relationship between Average Pool Ratio (R_{avg}) and Parameter *ID* and in Set Two Area Design Curves.

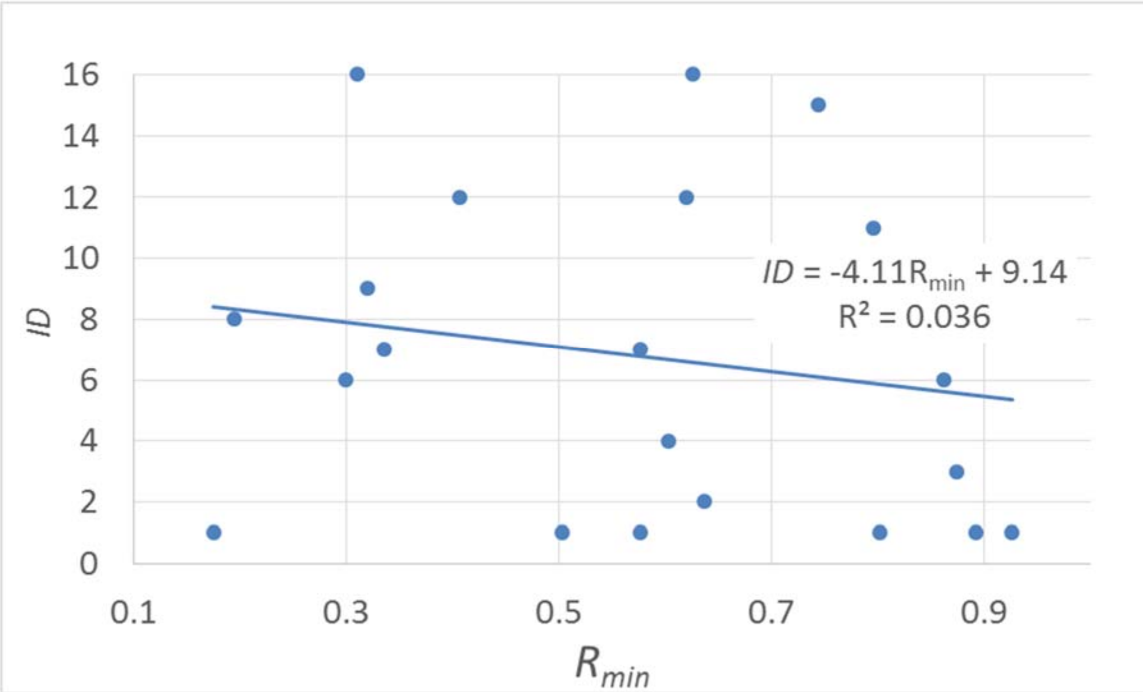

Figure 5-11 Relationship between Minimum Pool Ratio (*R_{min}*) and Parameter *ID* and in Set Two Area Design Curves.

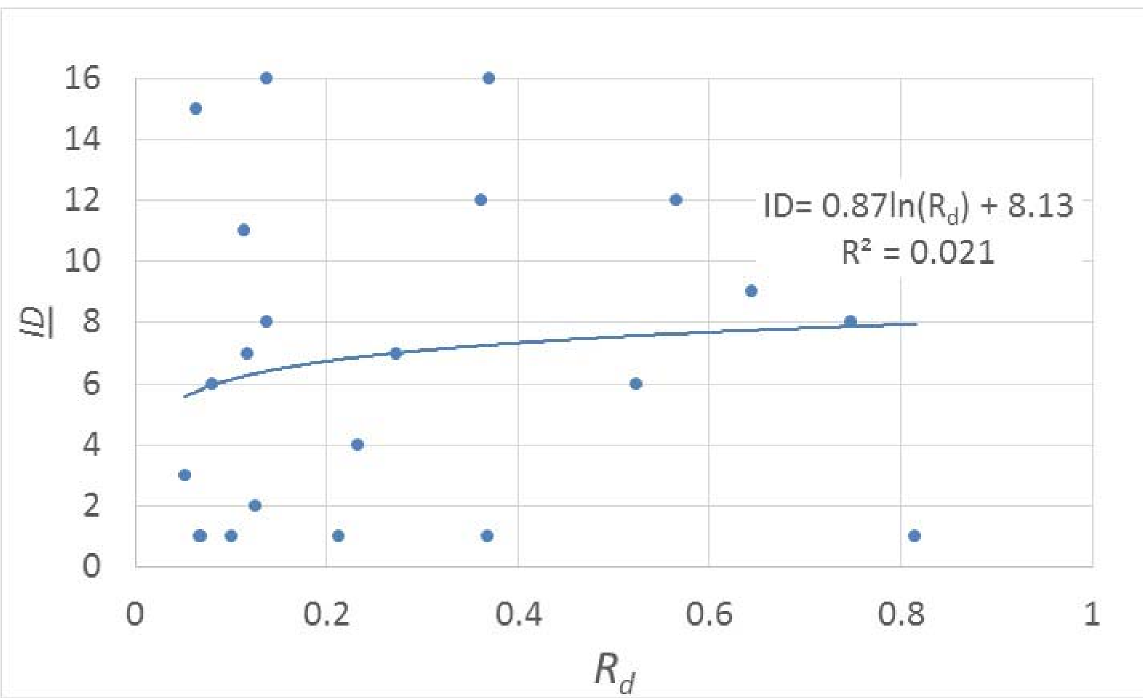

Figure 5-12 Relation between Pool Range Ratio (*Rd*) and Parameter *ID* and in Set Two Area Design Curves.

Finally set two area design curves were chosen with the index *ID* calculated by the regression equation (Eq. 5.2), which is obtained in Figure 5-8.

$$ID = 2.95\left(\frac{1}{s}\right)^2 - \frac{19.96}{s} + 31.61 \qquad \textbf{(5.2)}$$

where *ID* is index that is used to define the sediment deposit curve as shown in Table 5.1, *s* is slope of the depth versus capacity in logarithmic space. Result shows that the new method predicts better sediment distribution than original ARM method, as shown in Table 5.2.

Table 5.2 Comparison of *MSE* for New Method with Calculated ID and Original ARM and MARM

	MSE
ARM	0.14
MARM	1.39
ARM_ID	0.09

If historical reservoir sediment distribution is known, it is recommended to use the sediment deposition curve (Eq. 5.2) with coefficient *m*, *n*, and *c* in set two of Table 5.1 that minimizes the mean square error between field measurement and calculation. If that information is not available, Eq. 5.2 should be used to pick a set of coefficient to calculate the sediment distribution.

6 Summary

To better understand how to estimate the time-related impacts of reservoir sedimentation, two phases of research were performed. First, literature reviews were performed regarding methods to predict sediment distribution in reservoirs in the vertical and longitudinal directions. Second, with available reservoir survey data from 72 reservoirs owned by the Bureau of Reclamation, 23 with at least one resurvey were used to examine the existing sediment distribution methods. This study finds that the Area Reduction Method (ARM) produces the best results with existing Bureau of Reclamation data. Further examinations show that the reservoir type determined from the reservoir shape usually does not produce the best sediment distribution fitting compared to reservoir survey data. Reservoir sedimentation pattern depends not only on the reservoir shape, but also on reservoir operation rules, water surface levels, and sediment size distribution.

Several reservoir operation parameters are presented in an attempt to relate sediment distribution with reservoir operations. Initial results show that sediment distribution is more complex than what simple parameters can present. Reservoir shape, defined as slope of the depth-capacity curve on log-log coordinates, presents the best correlation with the sediment distribution. Poor corrections between proposed reservoir operation parameters and sediment distribution were found.

It is recommended to use sediment deposition curve index *ID* to calculate future sediment distribution. The index *ID* can be calculated to match historical sediment distribution, or calculated by regression equation with slope of the depth versus capacity in logarithmic space.

To better predict the reservoir sediment distribution, including the capacity and surface curves and bed depth near the dam for Reclamation reservoirs, further research is recommended to study the reservoir operation effects on reservoir distribution. Incoming sediment size fraction of reservoir sediment deposits is data that was not used or is currently not available, and it is speculated by the researchers that this physical parameter should play a major role in the reservoir sediment distribution. One-dimensional or two-dimensional sediment transport models can also be used to perform a sensitivity analysis regarding individual parameters to provide more of a general guideline for analyzing the reservoir sedimentation pattern.

7 References

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