

INTRODUCTION OF A NEW EMPIRICAL RESERVOIR SHAPE FUNCTION TO DEFINE SEDIMENT DISTRIBUTION PATTERN IN DAM RESERVOIRS*

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Abstract– Sedimentation is a very complex process of entrainment, transport and deposition of soil particles in the reservoir basin. Silting of reservoirs is influenced by many parameters, amongst which the reservoir shape is one of the most important. Till now, different empirical and semi empirical methods based on reservoir shape parameters have been presented to predict sediment distribution pattern. In an extended investigation over hydrographic maps of some Iranian dams, a strong relationship between the reservoir shape and sediment distribution pattern was found. So a new method for predicting sediment distribution through reservoirs was introduced. In this method, based on special definitions a new parameter which determines the reservoir shape was presented. It is suggested that this new technique, which accounts for distribution of sediment in a wide variety of reservoir configurations, can be used for preliminary design purposes.

Keywords– Empirical method, hydrography, Iranian reservoirs, reservoir shape, sediment distribution

1. INTRODUCTION

Silting process is inevitable and irreversible, and can have multiple effects in the reservoir basin. Prediction of sediment deposition pattern helps to prevent or to decrease some problems such as bed rising, increasing flood levels and sediment entry into the intake. Inflow characteristics, sediment transport capacity, either suspended load or bed load and reservoir geometry, are of the governing factors that affect sediment distribution in reservoirs [1]. Different numerical models as well as empirical and semi empirical methods have been developed to predict sediment distribution within dam reservoirs. Some of those empirical methods were represented by Cristofano (1953), Borland and Miller (1958), Lara (1962), Hobbs (1969), Borland (1970), Szechowycz and Qureshi (1973), Grade *et al.* (1978), Croley *et al.* (1978), Pemberton (1978), Chang (1979), Qian (1982), Rooseboom and Annandale (1983), Annandale (1984) and Mohammadzade and Heidarpour (2010) [2-14]. In this study the sedimentation pattern through some large Iranian reservoirs based on reservoir surveys was investigated and a new empirical method related to the shape of reservoirs for the description of sediment deposition model was presented. Reservoir's of Dez, Sefidrud, Droodzan, Jiroft, Minab, Karaj, Latian, Torogh and Kardeh dams with a total volume of 7365 mcm were investigated in this study. Around 25% of the total volume of large reservoirs in Iran belongs to these dams, which are located in different areas considering climate and geology. A new parameter, which shows how much the shape of a reservoir could be approximated by a pyramid, was defined in this paper. Next to it a new shape function in each depth was defined. It was shown that the new shape function could truly predict relative cumulative sediment deposition within all 9 investigated Iranian reservoirs. In this paper application of the new proposed function will be discussed for the studied reservoirs.

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2. STUDY AREA

Nowadays, more than 65 large dams, each having a capacity greater than 30 mcm and with a total volume of around 31000 mcm are in operation [15]. Studies on Iranian reservoirs showed that percentage of volume loss due to sedimentation is between 0.15% and 3.94% [16], while average annual sedimentation in reservoirs around the world is about 1% [17]. In this study on sedimentation behavior, 9 Iranian dams, the Latian, Dez, Sefidrud, Droodzan, Kardeh, Minab, Torogh, Jiroft and Karaj were investigated (Table 1).

Table 1. Characteristics of 9 Iranian dams investigated in our studies

Name of reservoir & starting year of operation	Initial capacity (mcm)	Mean annual sedimentation (mcm)	Reservoir length(m)	Normal water level (m.a.s.l)	Dam height (m)
Dez dam - 1962	3480	14.65	62,442	352.00	182.0
Sefidrud dam -1962	1749	45.81	28,000	271.81	81.0
Droodzan dam - 1973	993	3.31	16,100	1676.50	49.0
Jiroft dam- 1991	425	3.55	10,300	1184.00	129.0
Minab dam-1983	350	3.02	15,943	98.50	51.5
Karaj dam - 1961	205	0.51	14,000	1765.00	165.0
Latian dam - 1967	95	0.75	5177	1610.00	78.0
Torogh dam -1988	35	0.31	3474	1217.00	57.0
Kardeh dam - 1988	33	0.33	3039	1296.00	46.0
Total volume(mcm)	7365				

3. PREVIOUS IMPORTANT EMPIRICAL METHODS FOR PREDICTING SEDIMENT DISTRIBUTION IN RESERVOIRS

Sediment particles are carried by flows into a reservoir and distributed in the reservoir due to the increase of flow area, and thereby the reduction of flow velocity [18]. The empirical and semi-empirical methods aimed at evaluating sediment distribution within reservoirs have been mainly produced by the use of observations and field data collected at a large number of reservoirs from all over the world several decades ago. The methods of Cristofano (1953), Borland and Miller (1958), Borland (1970), Rooseboom and Mulke (1982), Rooseboom and Annandale (1983), and Annandale (1984, 1985, 1987, 1996) are of the methods which predict sediment distribution through the reservoirs based on their shape and are the most popular [19–24]. The Area-Increment Method has been developed by Cristofano [2] (Fig.1).

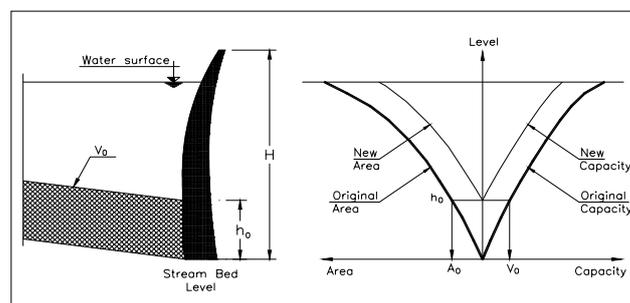


Fig. 1. Definition of parameters related to Area Increment method [21]

The Area Increment Method is very simple for evaluating the sediment distribution and is based on the following assumptions:

- The sediment deposition will take place in the dead storage of the reservoir.
- The sediment distribution can be approximated by reducing the reservoir area for each elevation by a fixed amount called an area correction factor.

The Borland and Miller method, also known as the Area-Reduction Method, was developed from resurvey data of 30 US reservoirs [23]. The data indicate that a definite relationship exists between the reservoir shape and the percentage of sediment accumulated in various depths throughout the reservoir (Fig.2). The shape of the reservoir is defined by the depth to capacity relationship.

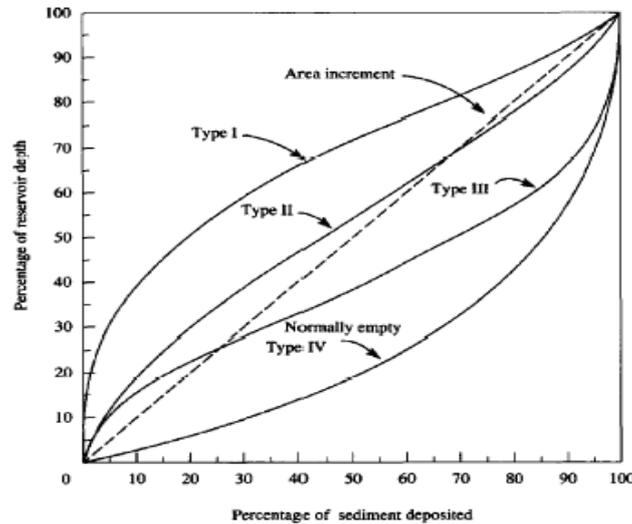


Fig. 2. Sediment distribution design curves (Area-Reduction Method) [22]

The Empirical Area-Reduction Method has been developed with revisions by Lara [4] and subsequent changes by Pemberton [10]. Rooseboom and Annandale [12] used field survey data for 11 large reservoirs in South Africa to compile a semi-empirical graph. Their new technique represents new empirical curves based on variation of wetted-perimeter through the reservoir length for predicting longitudinal sediment distribution pattern in reservoirs [22]. Among the scientists who implemented the Rooseboom and Annandale method, Michalec and Tarnawski [24] studied the possibility of application of this method. They showed that supplementary research works on additional parameters considering the reservoir shape is still required [24]. Also, Mohammadzadeh and Heidarpour introduced a new empirical method for prediction of sediment distribution in reservoirs based on original area-capacity and depth-capacity data of reservoirs [12].

4. METHOD OF STUDY

In order to study sedimentation behavior for the above-mentioned dams, each dam reservoir was divided by a different surface area along its depth on all available hydrographic maps. Surface area was measured for each depth and sedimentation between two subsequent elevations and was calculated using the real data during the years after operation. The relative cumulative sedimentation in each reservoir's depth was then studied. For better understanding of the influence of a reservoir's shape on sediment deposition pattern, extended studies were made over the shape of the mentioned Iranian reservoirs. Finally, a new function related to the shape of the reservoirs for description of sediment distribution in the depth of the reservoirs was proposed. In this study, surface-volume-depth curves of 42 large Iranian reservoirs were investigated. According to the studies, as can be seen in Fig. 3, the line of relative depth equal to relative volume can be considered as the lower limit of relative volume-depth curves of the studied reservoirs. It is found in Fig. 3 that variations of relative reservoir volume are smaller at lower levels and enhance as the water level increases. Through more investigations on the general configuration of 42 studied dams, the following is achieved, and the general reservoir shape and configuration of the 42 studied dams through the depth can be categorized in 3 groups.

Group 1: Reservoirs with such geometry that relative surface area at each level is smaller than the relative level.

$$\frac{A_i}{A_T} \leq \frac{h_i}{H} \tag{1}$$

H = normal height of reservoir, A_i = surface area of reservoir at level h_i , h_i = height of surface i , A_T = surface area of reservoir at normal level.

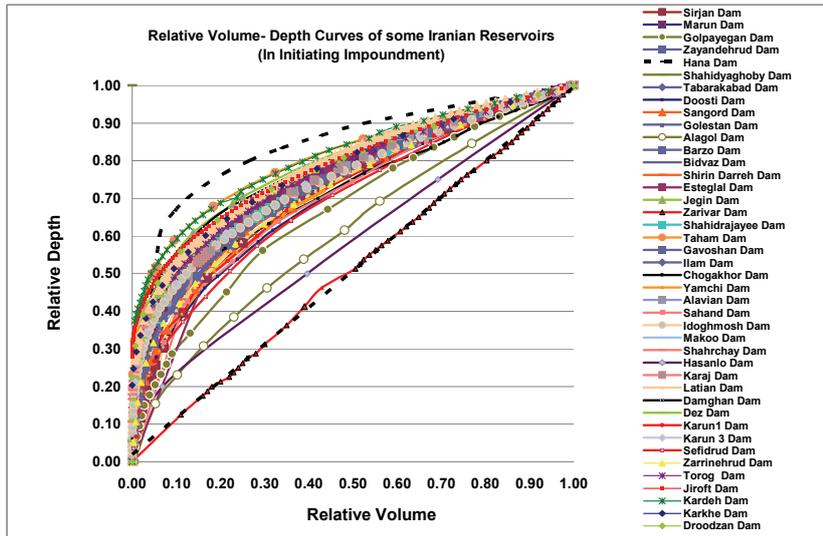


Fig. 3. Relative volume-depth curves of 42 investigated Iranian dams

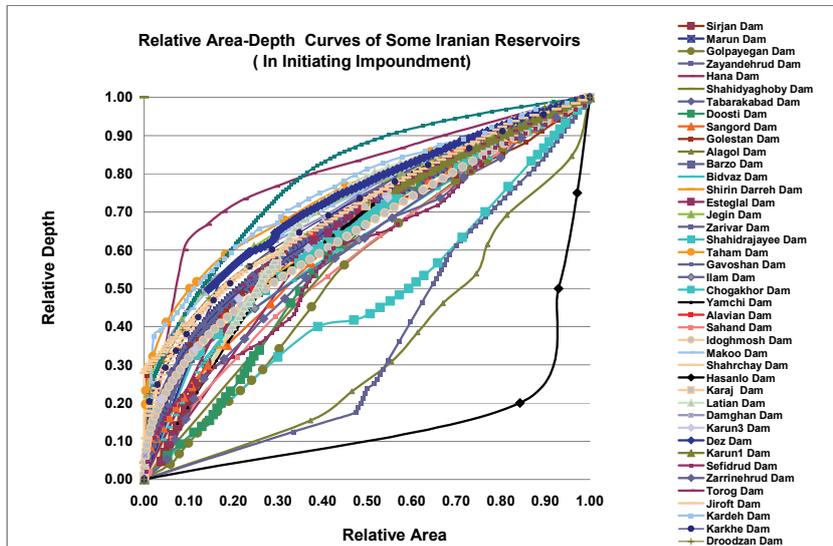


Fig. 4. Relative area-depth of 42 investigated Iranian dams

As can be seen in Fig. 4, 38 of the 42 investigated dams are included in group 1. Between these 38 dams, minimum and maximum heights of 17 and 182 m are related to the Golestan and Dez dams respectively.

Group 2: Reservoirs with such geometry in which the relative area of each surface is greater than relative level. Four dams of Zarivar, Hasanlo, Alagol and Chagakhor are grouped as 2 with normal heights between 4 to 10 meters.

$$\frac{A_i}{A_T} \geq \frac{h_i}{H} \tag{2}$$

Group 3: Reservoirs with such geometry in which the relative surface area is smaller than the relative level in some levels and greater than the relative level in others. None of 42 studied dams were included in this group. Generally speaking, it was concluded that, except those short dams with considerable volume, most reservoirs are categorized in group 1. This shows that in most of the studied reservoirs, the overall slope of the river bed near the end of reservoir's lake were very low, even zero, and have increased moving toward the dam body.

5. NEW CONCEPT OF RESERVOIR CONFIGURATION

According to the mentioned results and considering how much the shape of the reservoir deviates from pyramid shape, a new factor related to the depth of the reservoir was defined through the reservoir height.

6. INTRODUCTION OF A NEW CONCEPT OF RESERVOIR SHAPE (DEPTH FACTOR)

Following accomplished investigations over configuration of some Iranian reservoirs, a new parameter called Depth Factor (*DF*) was introduced. First, an equivalent pyramid in each reservoir elevation was defined with the area of reservoir surface (*A_i*) as its base and the depth of each surface from reservoir bed (*h_i*) as its height. Equivalent pyramid volume divided by actual reservoir volume at the same location was defined as Depth Factor. Thus Depth Factor shows how much the shape of a reservoir in depth could be approximated by a pyramid (Fig. 5, 6).

$$(DF)_i = \frac{VP_i}{V_i} = \frac{A_i \times h_i}{3 \times V_i} \tag{3}$$

(DF)_i = Depth factor at *h_i*, *h_i* = reservoir depth from stream – bed
VP_i = volume of equivalent pyramid from *h* = 0 to *h* = *h_i*, *A_i* = area of reservoir surface at *h_i*
V_i = volume of reservoir from *h* = 0 to *h* = *h_i*

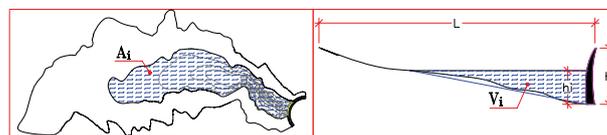


Fig. 5. Definition of parameters related to depth factor

Figure 6 illustrates schematic trend of depth factor variation in different levels of reservoir.

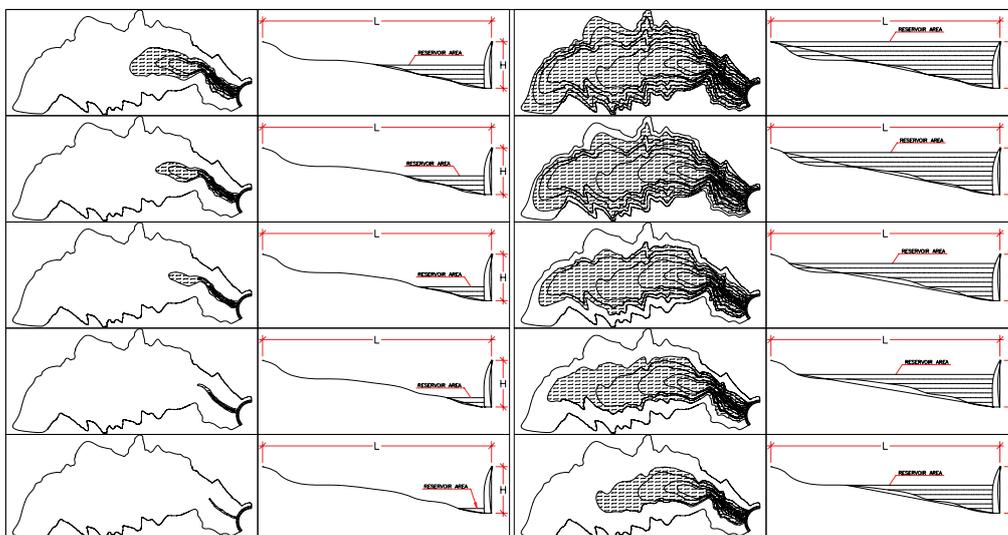


Fig.6. Schematic trend of variation of depth factor parameters at different levels of reservoir

Accordingly, the depth factor of each reservoir elevation can be separately calculated at different levels. For instance, the depth factor calculations of Golpayegan dam, included in the dams of group 1, are presented in Table 2 for the first year of operation (1956).

Table 2. Depth factor calculations of Golpayegan dam in different levels, based on the data related to the first year of operation

Elevation (m)	Volume (mcm)	Area (km ²)	Depth (m)	Relative depth	Relative volume	Relative area	DF
1884.55	0	0	0	0	0	0	*
1888	0.694	0.269	3.45	0.09	0.02	0.10	0.45
1890	1.144	0.376	5.45	0.15	0.03	0.14	0.6
1895	3.838	0.720	10.45	0.29	0.09	0.27	0.65
1905	12.528	1.214	20.45	0.56	0.3	0.45	0.66
1909	18.768	1.541	24.45	0.67	0.44	0.57	0.67
1913	25.008	1.886	28.45	0.78	0.59	0.70	0.72
1917	32.867	2.269	32.45	0.89	0.78	0.84	0.75
1919	37.607	2.485	34.45	0.95	0.89	0.92	0.76
1921	42.345	2.701	36.45	1	1	1	0.77

To calculate depth factor on a specific level, the reservoir surface area was multiplied by its depth and was then divided by 3 in that level as the first step. As a result, an equivalent pyramid volume of the mentioned level was obtained. Volume of the equivalent pyramid divided by the real reservoir volume of each level, gave the depth factor of that level. Investigation of the area-volume-depth curves of 38 studied dams related to group 1 showed that, depth factor varied between 0.77 and 1.65 considering total reservoir depth, respectively for the Golpayegan and Hana dams. Regarding 4 dams of group 2, the maximum values of depth factor were shown to be between 0.42 and 0.51. When the difference between reservoir volume and its equivalent pyramid volume were increased, the depth factor increased for group 1 reservoirs and decreased for group 2 reservoirs. Total depth factor varied between 0.42 and 1.65, considering all 42 studied Iranian dams. If the depth factor is greater than 1 it means that the real volume of the reservoir is surrounded by an equivalent pyramid volume. This new definition, when applied for different levels, can explain reservoir configuration in each favored level.

7. PRESENTATION OF A NEW RESERVOIR SHAPE FUNCTION (RDSF)

Investigations showed that sediment deposition between subsequent surfaces is considerably affected by the water volume surrounded by those surfaces. Therefore, water volumes surrounding the subsequent surfaces and thus the area of the surfaces are considered as important factors [25]. This means if the average surface area of a reservoir between subsequent surfaces increases, sediment deposition increases. Also, studies showed that a cumulative volume of sediment deposition was inversely related to variations of depth factor in height.

$$(\text{Cumulative sediment deposition from bed up to } h_i) \approx A_i \times \left(\frac{1}{DF_i}\right) \quad (4)$$

A = reservoir surface area at normal level , V = reservoir volume at normal level

To show these relations, two new empirical functions called Depth Shape Function (DSF) and Relative Depth Shape Function ($RDSF$) were introduced.

$$(DSF)_i = (A_i) \times \left(\frac{1}{DF_i}\right) = \left(\frac{3 \times V_i}{h_i}\right) \quad (5)$$

It can be understood that $(DSF)_i$ can explain cumulative sedimentation from bed up to h_i .

$$(RDSF)_i = \left(\frac{(DSF)_i}{(DSF)_{at \ normal \ level}} \right) = \left(\frac{3 * V_i}{h_i} \right) / \left(\frac{3 * V}{H} \right) = \left(\frac{V_i}{V} \right) * \left(\frac{H}{h_i} \right), \alpha_i = \left(\frac{h_i}{H} \right) \quad (6)$$

$$(RDSF)_i = \left(\frac{V_i}{V} \right) * \left(\frac{1}{\alpha_i} \right) \quad (7)$$

So, the mentioned function $(RDSF)$ can explain relative cumulative sediment deposition in different heights from the reservoir bed. It means that for a favored reservoir and regarding Eq. (7), predictions of the new method for definition of relative cumulative sediment distribution after different years of impounding could be obtained based on the relative initial depth-volume curve as shown in Fig. 7.

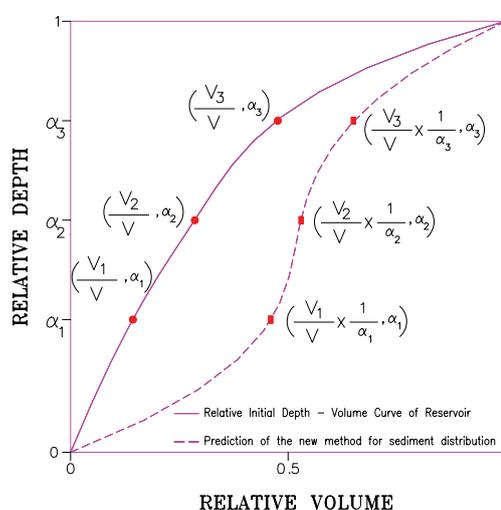


Fig. 7. The new concept prediction of relative cumulative sedimentation based on initial depth-volume curve of a reservoir

According to previously presented results, predictions of relative cumulative sedimentation in each reservoir includes the following steps, after long term operation:

1. Drawing of initial relative volume-depth curve of reservoir.
2. For a long duration operation, relative volume divided by relative level gives the relative cumulative sediment volume concept for each point on the relative curve of volume-depth.

Referring to the mentioned findings and relative volume-depth curves of 42 studied dams (Fig. 7), it can be concluded that the most significant amount of total sediments is deposited at lower levels when relative depth-volume curve of a reservoir gets close to the linear curve of relative volume equal to relative depth.

8. RESULTS AND DISCUSSION

As mentioned previously, hydrographic maps and hydrological data in different years of operation were studied to explain the sedimentation pattern in 9 Iranian reservoirs [26~41]. Investigation results of studies over reservoirs called Dez, Torogh, Jiroft, Minab, Droodzan, Latian, Karaj, Sefidrud and Kardeh are presented in this paper. Thus a new approach could appropriately predict sediment deposition pattern only based on the shape of studied reservoirs without employing any other dam characteristic. Application of the new concept for prediction of relative cumulative sedimentation for the 9 mentioned Iranian reservoirs

is discussed in this paper. Also, the new method is compared with previous empirical methods introduced in this paper in the next section.

9. NEW CONCEPT PREDICTIONS COMPARISON WITH RESULTS OF PREVIOUS METHODS

1. Latian dam

Referring to Fig. 8, for the Latian reservoir, a new method based on RDSF parameter and also Area Increment method have been shown to present minimum difference with the measured curve of relative cumulative sedimentation. Other methods like the Area Reduction methods of Borland and Miller and Lara for the prediction of sediment distribution of the Latian reservoir were not successful, especially at higher levels. However, regarding the Latian dam, all methods represent acceptable results for sediment distribution at lower levels, when compared to real data.

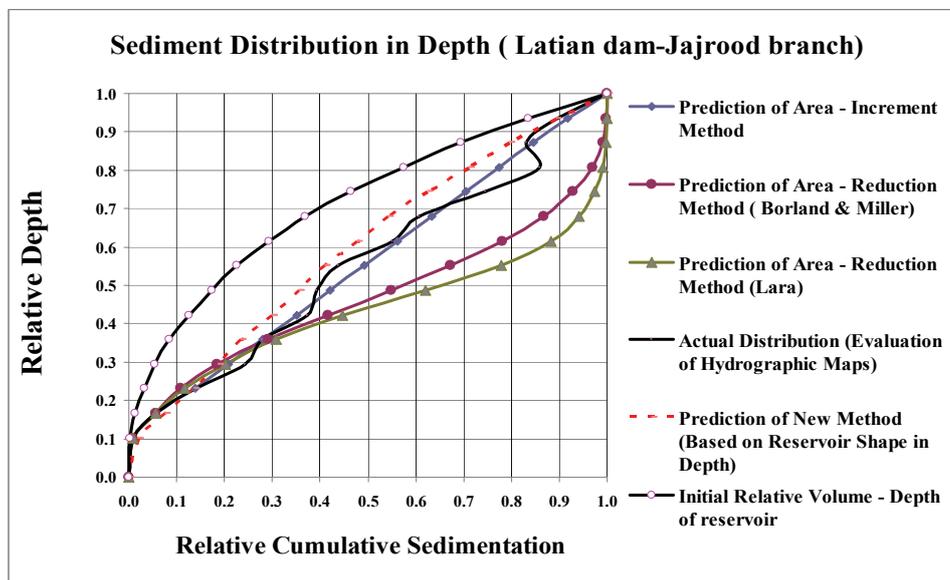


Fig. 8. Comparison of predictions of the new method (based on RDSF parameter) and other empirical and semi-empirical methods with real data regarding prediction of relative cumulative sediment distribution for Latian dam

2. Dez dam

Comparison of measured data of relative cumulative sedimentation through the depth of Dez reservoir with estimation of the new method and previous methods are available in Fig. 9. These comparisons are related to sediment distribution from 1962 to 2005. It is a great achievement, especially at lower levels which are the criteria for design and arrangement of dam accessory structures.

3. Sefidrud dam

The new method, based on *RDSF* parameter, also showed acceptable predictions for sediment distribution through the Sefidrud dam during the period 1963 to 1976 when compared to the other predicting methods. Prediction results from the Sefidrud dam are presented in Fig. 10. The last hydrography operation of the Sefidrud dam took place in 1976 before initial reservoir flushing.

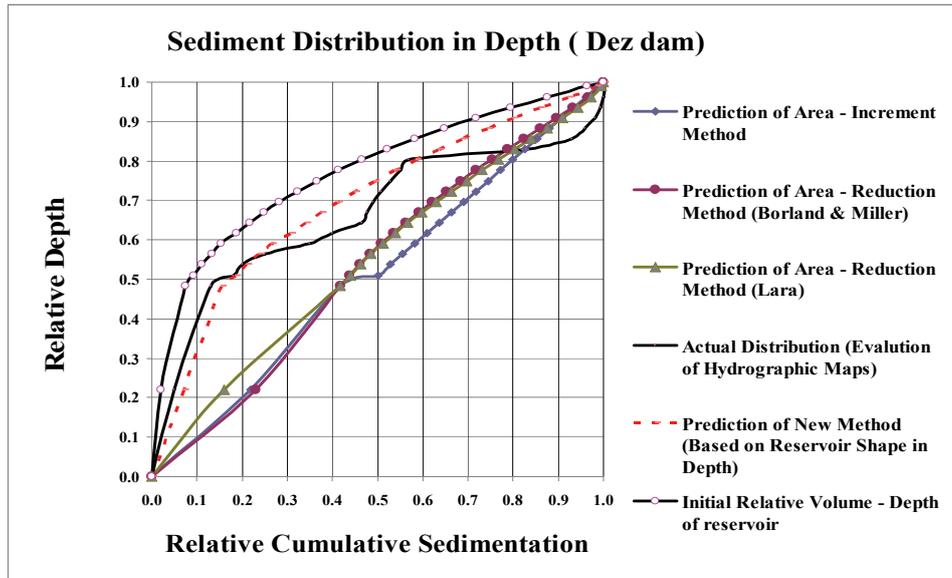


Fig. 9. Comparison of predictions of the new method (based on RDSF parameter) and other empirical and semi-empirical methods with real data regarding prediction of relative cumulative sediment distribution for Dez dam

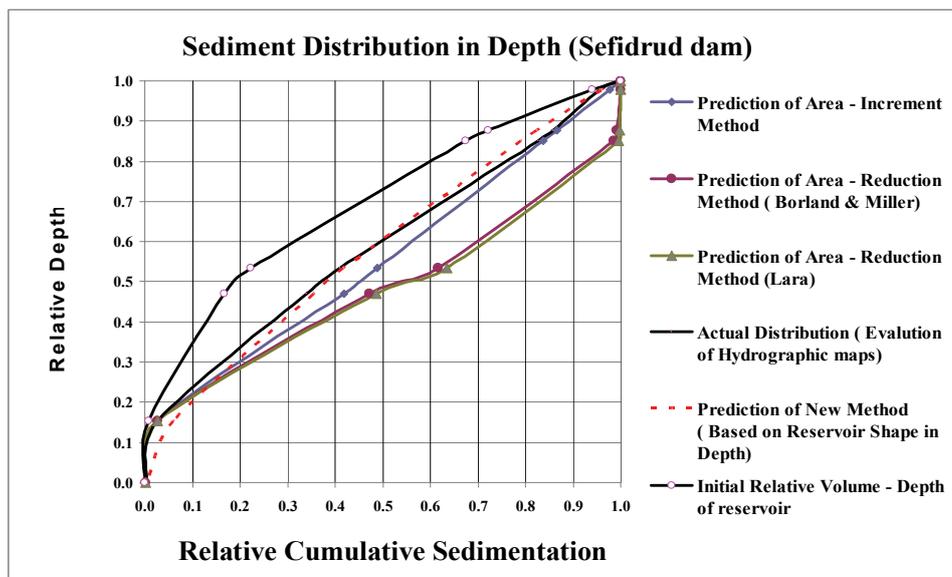


Fig. 10. Comparison of predictions of the new method (based on RDSF parameter) and other empirical and semi-empirical methods with real data regarding prediction of relative cumulative sediment distribution for Sefidrud dam

4. Kardeh dam

The Kardeh dam was the next reservoir to have its sediment distribution pattern investigated. Prediction results of the new method and previous methods are compared with measured sediment distribution in depth of the Kardeh dam in Fig. 11.

Referring to the data of the hydrography operation between 1988 and 2008, none of the applied methods, even the new method, could present an accurate estimation, especially at higher levels. However, the results of the new method have been more realistic.

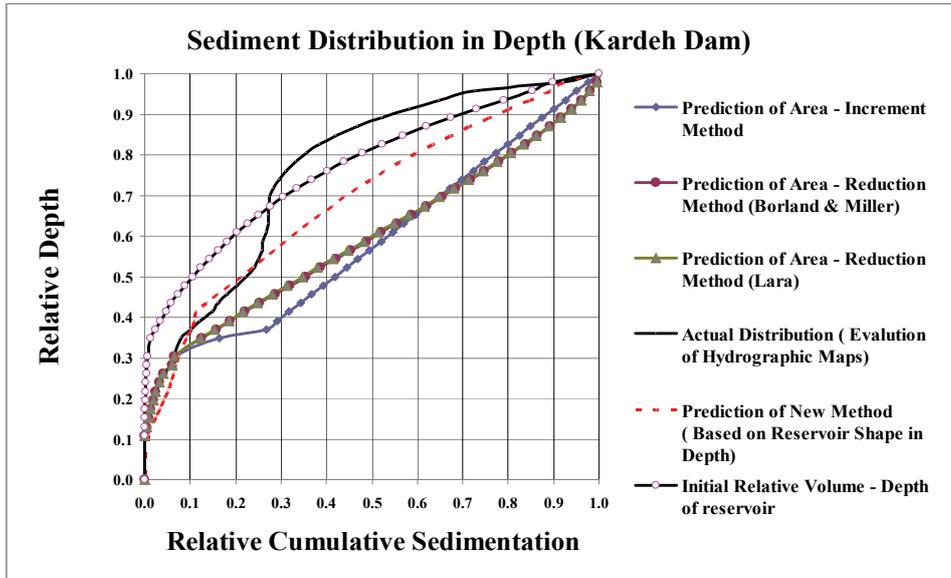


Fig. 11. Comparison of predictions of the new method (based on RDSF parameter) and other empirical and semi-empirical methods with real data regarding prediction of relative cumulative sediment distribution for Kardeh dam

5. Droodzan dam

In the case of cumulative sediment distribution pattern, regarding the Droodzan dam, comparisons are available in Fig. 12. Curves of the mentioned figure show that the relative cumulative sedimentation pattern in the depth of the Droodzan reservoir during the period 1984 to 2003 was very close to the initial relative depth-volume curve of this dam. But still, the prediction curve of the new method was closer to the real data gathered from hydrographic maps when compared to other previous prevalent methods. This considerable difference between predictions of the new method and others could be caused by specific configuration of this reservoir, as its width increases near the middle of the reservoir and reduces the chance of getting far away from the middle.

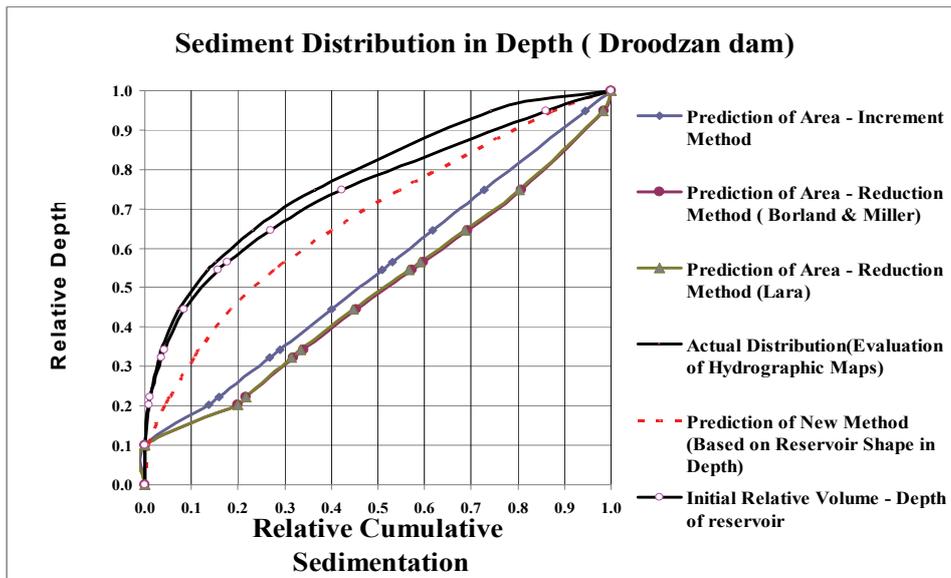


Fig. 12. Comparison of predictions of the new method (based on RDSF parameter) and other empirical and semi-empirical methods with real data regarding prediction of relative cumulative sediment distribution for Droodzan dam

6. Minab dam

Regarding the Minab dam, the results of the new method again showed relative success compared with other methods of sediment distribution definition. The curves in Fig. 13 are related to the Minab dam. Real data were produced by comparing the hydrographic maps of 1984 and 2005. Based on the Curves in Fig. 13, predictions of the new method for sediment distribution showed better agreement with the actual distribution compared to other previous methods. Prediction produced by the Area-Increment method were more reliable in most of the reservoir depths when compared with forecasts of the previous methods.

7. Jiroft dam

For the Jiroft Dam, relative cumulative sedimentation distribution in depth was determined on the basis of hydrographic maps of 1996 and 2005. Results of the prediction of other previous methods and their comparison with measured amounts, including the prediction of the new method, are shown in Fig. 14.

Comparing the results, it was perceived that up to the lower 20% depth, nearly all methods had successful predictions, but for depth greater than 55%, the new method has the best accordance with the measured amounts of the relative cumulative sedimentation in the depth. At the upper levels the area-reduction method was more successful. Although deviation of the new method's prediction from the measured reaches to 17% for the upper 45% of reservoir depth.

8. Torogh dam

Comparing the real data with the estimated data of the Torogh dam, it was concluded that the new method, based on the *RDSF* parameter, is more reliable than other methods except for higher levels, for which other methods gave more accurate predictions. Paying attention to the better prediction of this method for lower depths that are so important in the preliminary design stages, the efficiency of this new method is more obvious.

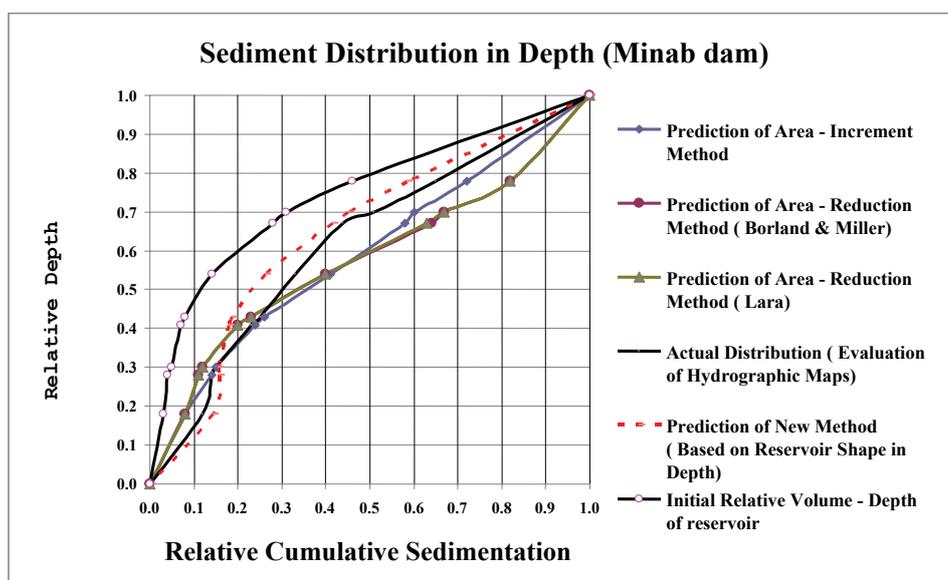


Fig. 13. Comparison of predictions of the new method (based on *RDSF* parameter) and other empirical and semi-empirical methods with real data regarding prediction of relative cumulative sediment distribution for Minab dam

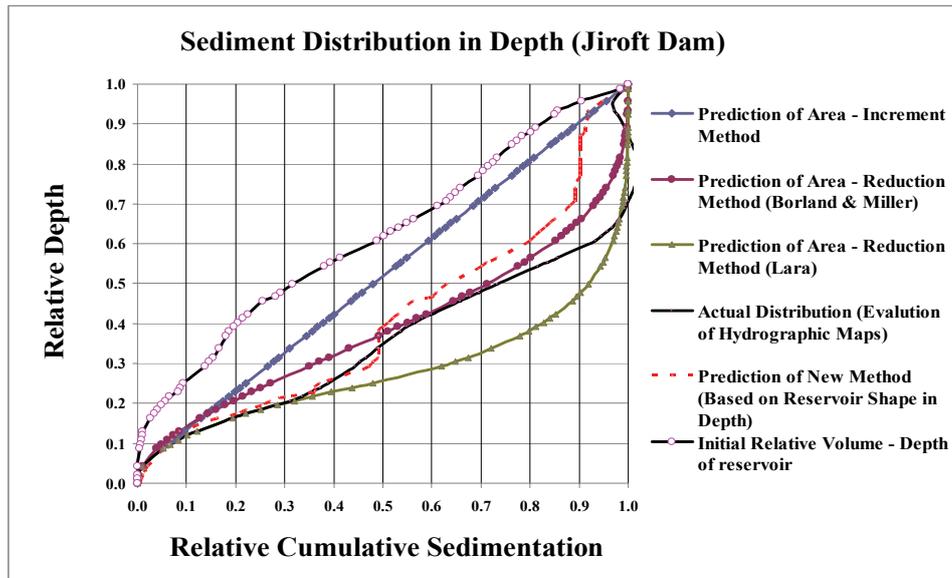


Fig. 14. Comparison of predictions of the new method (based on $RDSF$ parameter) and other empirical and semi-empirical methods with real data regarding prediction of relative cumulative sediment distribution for Jiroft dam

9. Karaj dam

The last dam that its relative cumulative sediment distribution in depth studied is the Karaj dam. After studying the hydrographic maps of 1971 and 2007, the measured distribution of relative cumulative sedimentation of this reservoir was drawn and compared with the prediction of the related prevalent methods and the new method. Also, regarding this reservoir, it was perceived that over a period of 37 years, the method based on the $RDSF$ parameter made a better prediction in comparison with other methods for determining relative cumulative sediment distribution.

Finally, prediction of the relative cumulative sediment distribution, based on the relative parameter correlated with the reservoir's shape which is known as the $RDSF$, was compared with the results of hydrographic maps, and also the prediction of other previous methods. Comparison indicated that the concept presented in this paper could be used as an efficient and reliable method. More accurate prediction produced by this method, especially at the lower levels that are very important in preliminary stages of design, is one of the reasons why this method is more efficient in comparison with other methods.

10. CONCLUSION

As mentioned, reservoir configuration has always been considered by engineers as one of the most important factors to affect the sedimentation pattern in reservoirs. Accordingly, referring to the hydrographic maps and hydraulic principles, sedimentation behavior in some Iranian reservoirs in different years of operation was studied. By estimation and comparison of the reservoir shape with its depth equivalent pyramid, a new empirical factor called Depth Factor was introduced. Combining the reservoir's Depth Factor in different levels by the relative surface area of the same levels, a new empirical function was defined as Depth Shape Function (DSF). Depth distribution of relative DSF and relative sedimentation patterns were compared for 9 Iranian dams. The results showed that $RDSF$ could successfully predict relative cumulative sediment deposition, as discussed and explained before for the 9 selected studied reservoirs. So the new function can predict sediment deposition pattern based only on the reservoir shape. The new method can be referred to determinate sediment deposition behavior in a wide

variety of reservoir geometries. Such estimates should be verified by analytical methods in the final design stages.

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