Evaluation and Modification of Some Empirical and Semi-empirical Approaches for Prediction of Area-Storage Capacity Curves in Reservoirs of Dams

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Evaluation and modification of some empirical and semi-empirical approaches for prediction of area-storage capacity curves in reservoirs of dams

Issa E. Issa\textsuperscript{1,2}, Nadhir Al-Ansari\textsuperscript{1}, Govand Sherwany\textsuperscript{3} and Sven Knutsson\textsuperscript{4}

\textbf{Abstract:} The storage capacity of reservoirs is gradually reduced due to sediment accumulation that causes changes in the area-storage capacity (ASC) curves. Establishing these curves and predicting their future change is an important issue for planners, designers and operators of dams. Many empirical and semi-empirical approaches have been suggested for establishing and predicting the future changes for these curves. In this study four empirical and semi-empirical methods were evaluated and three of them were modified to be used for the prediction of changes in the ASC curves due to sedimentation, based on the existing sedimentation survey data for 11 reservoirs in the USA. For evaluation, these approaches were reviewed and used to determine sedimentation depth and establishing the ASC curves for the Mosul dam reservoir (MDR), which is the biggest hydraulic structure on the River Tigris in northern Iraq. MDR started operating in 1986 with a storage capacity of 11.11 km\textsuperscript{3} and a water surface area 380 km\textsuperscript{2} at normal operation stage (330 m a.s.l.). The results obtained from these methods were
evaluated using observed bathymetric survey data that had been collected in 2011 after 25 years of the operation of the dam. The evaluation results showed three methodshad presented more accurate results for estimating water depth or sedimentation depth at dam site with percentage error about 1.06% to 3.30%. Whilst for establishing ASC curves, one method presented good agreement result with survey data. Furthermore, ASC and sedimentation depths at dam site of MDR for periods 50, 75, 100 and 125 years were estimated using the modified approaches and the area reduction method. The results of the modified methods provided reasonable agreement when compared with the area reduction method proposed by the U.S. Bureau of Reclamation and the agreement became better with an increase in time period.

**Keywords:** Area-capacity curves; Reservoir sedimentation; Area reduction method; Mosul dam.

1. Introduction

Construction of dams across rivers for the development and management of water resources causes changes in sediment transport regime that will lead to sediment accumulation in their reservoirs (Garde & Raju, 1985; Garde, 2006; Jain & Singh, 2003; Morris & Fan, 1998). Reservoir sedimentation is the main problem that directly affects the performance of dams due to the reduction in their storage capacity. The distribution of the sediment deposited in reservoirs mainly depends on several factors, but the most important are amount of sediment coming in, the grain size composition of the sediment inflow, the reservoir geometry and its age, the locations of the bottom outlets and the reservoir operation mode (Annandale, 1987; Garde, 2006; Morris & Fan, 1998). The deposition of sediment in a reservoir causes changes in its ASC curves (or stage-area curve and stage-storage capacity curve) (Mohammadzadeh-Habili et al., 2009; Morris & Fan, 1998; U.S. Bureau of Reclamation, 1987). These curves are very important for planners, designers and operators of dams and are regarded as one of the most important physical characteristics of dams and their reservoirs. The ASC curves are commonly used to determine the storage capacity and water surface area of the
reservoir at a given water elevation as well as to support flood routing, reservoir classification and operation (Borland & Miller, 1958; Morris & Fan, 1998; Strand & Pemberton, 1982). Determination and future prediction of these curves is an important issue for:

- Estimating the sedimentation depth at a dam site.
- Determining the useful life of the dam (reservoir active storage capacity).
- Designing the elevation of the bottom outlet.
- Determining the effect of backwater conditions on the flood level upstream of the reservoir.
- Assessing changes in the reservoir storage capacity with time of dam operation.

The complexity of sediment transport and the deposition of sediment in a reservoir has led to the development of numerous techniques to predict sediment distribution in the reservoirs. These techniques can be classified as theoretical and empirical or semi-empirical approaches. Theoretical or analytical methods are based on numerical solution of water and sediment continuity equations and momentum or stream power and sediment transport equations using computer packages such as HEC-6 (U.S. Army Corps of Engineers, 1993) and Gstars3 (Yang & Simões, 2002). Empirical and semi-empirical methods have been developed using the sedimentation survey data collected for reservoirs. The most commonly used empirical methods are the area reduction and the area increment methods that were developed by the U.S. Bureau of Reclamation using resurvey data for 30 reservoirs in the United States (Morris & Fan, 1998). The latter techniques are the most widely applied, because they are relatively easy and quick to use and they require limited data. But their limitations include their inability to identify the depth and location of the sedimentation (Annandale, 1984; Morris & Fan, 1998) whilst, the theoretical models require calibration and large quantities of input data which are costly to obtain.

In this study four different empirical and semi-empirical methods were evaluated. These methods are; the area reduction method proposed by Borland and Miller (1958) that has been adopted by the U.S. Bureau of Reclamation and the methods reported by Mohammadzadeh-Habili et al. (2009), Mohammadzadeh-Habili and Heidarpour (2010) and Kaveh et al. (2013). The methods were reviewed and applied to determine the ASC curves and maximum water depth or depth of sediment at dam site for the MDR. The results provided by these methods were compared with bathymetric survey data.
that were collected in 2011 after 25 year of operating MDR (Issa et al., 2013). Furthermore, the last three methods that were mentioned before were modified to predict future changes in ASC curves due to sedimentation, based on the existing survey data for 11 reservoirs in the USA. Thus, the main objectives of this study were: evaluating these methods with reference to the bathymetric survey for determining ASC curves and maximum sediment depth at dam site. In addition, the last three methods were modified and applied to predict future changes in ASC curves for MDR for periods 50, 75, 100, 125 years and were compared with area reduction method. The evaluation and modifications of these methods can help decision makers, planners and designers, to use these methods to determine the ASC curves for reservoirs that were used to estimate their useful life. Moreover, this help to put prudent strategies for Iraqi water resources problems because Iraq is facing serious water shortage now due to climate changes and increasing demand (Al-Ansari, 2013; Droogers et al., 2012; Issa et al., 2014) and MDR is the biggest and the most important strategic project in Iraq. Therefore, it is very important to know which technique is suitable to adopt for MDR in the future.

2. The Mosul dam and available data

The MDR is one of the most important strategic projects in Iraq for the management of its water resources. The project was constructed on the Tigris River in the north of Iraq, located 60 km north west of Mosul city at latitude 36°37'44"N and longitude 42°49'23"E (Iraqi Ministry of Water Resources, 2012) (Fig. 1). The dam is a multipurpose project and it started operating on July 7th, 1986 to provide water for three irrigation projects, flood control and hydropower generation. One of its functions is to provide water for an irrigation project known as “North Al-Jazira Irrigation project” that covers an area of 625 km². The pumping station for this project is located in the upper zone of Mosul dam reservoir. In 1991 and 2005, the station stopped for several days due to sediment accumulation at its inlets (Iraqi Ministry of Water Resources, 2012).

Fig. 1. The location of the Mosul dam.

The dam is an earth filled dam, 113 m high and 3650 m long including its spillway. The maximum, normal and dead storage levels of the reservoir are 335, 330 and 300 m a.s.l respectively. The dam was designed to impound 11.11 km³ of water at normal operation level, including 8.16 and 2.95 km³ of live
storage and dead storage respectively. The shape of the reservoir is elongated where the River Tigris enters the upper zone and broadens close to the dam site. Its length is about 45 km, with width ranging from 2 to 14 km at the normal level and a water surface area of 380 km² (Iraqi Ministry of Water Resources, 2012) (Fig. 1). The River Tigris provides the main source of the water and sediment entering the reservoir. The catchment area of the River Tigris above the Mosul dam site is about 56,275 km² shared by Turkey, Syria and Iraq (Saleh, 2010; Swiss Consultants, 1979). A bathymetric survey of the MDR was conducted in May 2011 after 25 years of dam operation using an echo sounder sonar viewer system (Issa et al., 2013). The survey was conducted according to U.S. Army Corps of Engineers standards for the distances between transverse sections, boat type and calibration methods (U.S. Army Corps of Engineers, 2004). The error values of water depth measurements were ±4 cm depending on the water depth within the reservoir. The final bathymetric survey data was about 84,684 points within the reservoir area. The survey results showed that 1.143 km³ of sediment had accumulated over the period 1986-2011. This represents an annual sediment deposition rate of 45.72 × 10⁶ m³ yr⁻¹. As a result, the reservoir lost 10.29% of its storage capacity during this period (Issa et al., 2013). The survey results were also used to construct ASC capacity curves (Fig. 2). The results indicated that the water depth below the normal operation level at the dam site was 83 m in 1986 and with sedimentation it became about 80 m in 2011. This suggests 3.0 m of sediment accumulated near the dam during the operational period of the project (Issa et al., 2013). These data were used for evaluating the results of the used techniques.

**Fig. 2.** Area-storage capacity curves for the MDR.

**3. Techniques and methods used**

Empirical and semi-empirical techniques are used to determine the amount of sediment deposited in a reservoir as a function of water depth or stage (or to determine ASC curves). These methods are widely used for engineering purposes. Consequently, large numbers of empirical methods have been reported (e.g. Annandale, 1984; Borland & Miller, 1958; Borland, 1970; Chien, 1982; Croley et al., 1978; Garde et al., 1978; Rahmanian & Banihashemi, 2011; Szechowycz & Qureshi, 1973), but the most commonly used is the area reduction method that was developed and adopted by the U.S. Bureau
of Reclamation (Morris & Fan, 1998). The first empirical method was developed by Borland and Miller (1958) referred to as the area increment method. This method assumed that the reduction on water surface area at any depth above the new zero depth is constant, meaning that an equal amount of sediment will be deposited in each depth increment of the reservoir (Borland & Miller, 1958; Strand & Pemberton, 1982). The following methods were used in this study:

3.1 The area reduction method

The area reduction method is the most commonly used method for predicting the impact of sediment deposition in a reservoir or the change in the ASC curves with reservoir sedimentation. The method was proposed by Borland and Miller (1958) based on an analysis of sedimentation data for 30 reservoirs in the USA. This technique is based on the adjustment of the water surface area above zero depth to a new area due to sedimentation that reflects the relationship between reduction in water surface area and sedimentation rate and reservoir characteristics. Reservoirs are classified into four categories based on the shape factor of the reservoir “M” (Table 1). The shape factor “M” represents the reciprocal slope of the straight line that can be calculated from plotting the relationship of water depth at the dam site as the Y-axis against the storage capacity as the X-axis on a logarithmic scale plot (Borland & Miller, 1958; Kaveh et al., 2013; Mohammadzadeh-Habili et al., 2009; Mohammadzadeh-Habili & Heidarpour, 2010).

Table 1. Reservoirs classification according shape factor “M” (Borland & Miller, 1958).

The area reduction method involves four different sedimentation pattern curves that were developed from the resurvey data assembled for 30 reservoirs (Fig. 3). These curves are dimensionless and are used to determine the change in the ASC curves due to sedimentation. This technique is usually used when the sedimentation rate and characteristics of the reservoir are available (for more details see Strand & Pemberton, 1982, 1987).

Fig. 3. Type curves of reservoirs for area reduction method (modified Strand & Pemberton, 1987).

3.2 The Mohammadzadeh-Habili semi-empirical method

Mohammadzadeh-Habili et al. (2009) proposed a dimensionless equation for the relationship between water depth and storage capacity using the similarity between the natural logarithmic function curve
and the stage-storage capacity curve. This equation depends on only one unknown dimensionless parameter called the reservoir coefficient “N” as follows:

\[ V_y = V_m \left[ e^{\ln 2 \left( \frac{y}{y_m} \right) - 1} \right]^N \]  \hspace{1cm} (1)

where \( V_y \) is reservoir capacity at depth \( y \), \( V_m \) is reservoir capacity at maximum pool level, \( y \) is the water depth above the streambed at the dam site and \( y_m \) is the maximum water depth at the dam site. The water surface area and reservoir coefficient equations were derived from equation (1) as follows:

\[ A_y = \frac{v_m \times (\ln 2)}{N + y_m} \left[ e^{\ln 2 \left( \frac{y}{y_m} \right) - 1} \right]^N \]  \hspace{1cm} (2)

\[ N = 2 \ln 2 \frac{v_m}{A_m + y_m} \] \hspace{1cm} (3)

where \( A_y \) is reservoir water surface area at depth \( y \), and \( A_m \) is the water surface area of reservoir at maximum pool level.

The equations obtained were compared with the resurvey data for 16 reservoirs. The comparison of the results demonstrated good agreement, especially with reservoirs that had smoothed stage-storage capacity curves (Mohammadzadeh-Habili et al., 2009). Furthermore, the results were used to develop an empirical relationship between the reservoir shape factor “M” and its coefficient (Eq. 4).

\[ N = 1.075M^{-0.9063} \] \hspace{1cm} (4)

In 2010 Mohammadzadeh-Habili and Heidarpour modified the reservoir coefficient equation (Eq. 3) based on the original and secondary ASC curves of 40 resurveyed reservoirs in the United States as:

\[ N_m = 2 \ln 2 \frac{N_{SSE}(\text{Minimization of SSE})}{A_m + y_m} \frac{V_m}{N} \] \hspace{1cm} (5)

where \( N_m \) is the modified reservoir coefficient and \( N_{SSE} \) is the reservoir coefficient obtained using minimization of the sum of squares of the errors (SSE) of the original normalized water depth-capacity curve and the curve from equation (3).

### 3.3 The Kaveh et al. (2013) method

A parabolic equation is used to represent the general form of the relationship between storage capacity and depth which can be expressed as follows:

\[ V_y = a + b \times y + c \times y^2 \]  \hspace{1cm} (6)
where \(a, b, c\) are the coefficients that are usually computed using the ACAP computer program adopted by the U.S. Bureau of Reclamation (Ferrari & Collins, 2006; U.S. Bureau of Reclamation, 1985). Kaveh et al. (2013) differentiated the simple dimensionless capacity equation using a parabolic equation for reservoir capacity. Kaveh’s equation depends on one reservoir coefficient parameter as:

\[
V_y = V_m \left( \frac{y}{y_m} \right)^{2N_r} \tag{7}
\]

where \(N_r\) is the reservoir coefficient proposed by Kaveh et al. (2013).

The water surface area equation for a reservoir at different elevations and the reservoir coefficient equation were obtained as a derivative of the above equation (7) as follows:

\[
A_y = \frac{2V_m}{N_r \gamma} \left( \frac{y}{y_m} \right)^{\frac{2}{N_r}} \tag{8}
\]

\[
N_r = \frac{2V_m}{y_m \gamma_m} \tag{9}
\]

In addition, Kaveh et al. (2013) derived a relationship between the reservoir coefficient and the shape factor based on the above equations, which is:

\[
N_r = \frac{2}{\gamma_m} \tag{10}
\]

It should be noted here, the three approaches suggested by Mohammadzadeh-Habili et al. (2009), Mohammadzadeh-Habili and Heidarpour (2010) and Kaveh et al. (2013) that are described above mainly depend on the dimensionless parameters \((N\) or \(N_r\)) in their calculation which are called reservoir coefficients. These coefficients depend on the dimensionless relationship between the ratio of volume \((V/V_m)\) and ratio of water depth at dam site \((y/y_m)\) as stated in equations 1 and 7 for \(N\) and \(N_r\) respectively. These coefficients depend on the sedimentation condition. Therefore, the reservoir coefficient value changes with time depending on these conditions too. It should be mentioned however, that last three mentioned methods did not take into consideration future variation in this relationship or reservoir coefficient in response to sedimentation.

### 3.4 Methodology

All the methods employed assumed that the river behavior and the reservoir’s sedimentation characteristics will remain constant in the future i.e. no change in the operation mode and sedimentation conditions with time (Mohammadzadeh-Habili & Heidarpour, 2010; Morris & Fan, 1998). Therefore
the average sedimentation rate for MDR ($45.72 \times 10^6 \text{ m}^3\text{yr}^{-1}$ during the past 25 years) was assumed to be constant in the future and it was used to calculate the amount of sediment deposited in 50, 75, 100, and 125 years. Furthermore, the banks of the reservoir at maximum elevation were assumed to be stable (no sliding and wave erosion) and that the water stage in the reservoir does not exceed the maximum operation level so that the water surface area at this level will be constant with time (Mohammadzadeh-Habili & Heidarpour, 2010).

The four methods described above were firstly applied for the MDR to generate ASC curves for the reservoir after 25 years of dam operation. To apply the area reduction method, the first step necessitated selecting the type of reservoir or type of sediment deposition pattern. This process depends on the shape factor, the mode of operating the reservoir and the predominant grain size of the sediment deposited (Morris & Fan, 1998). This information was used to select the appropriate empirical curve that was used to predict the sediment distribution within the reservoir. The data for MDR showed that the shape factor was 2.77, based on the slope of the original depth-capacity curve plotted on log-log paper. Its mode of operation is classified as moderate drawdown and the predominant grain sizes of the sediment deposited were mainly silt, sand and clay (Al-Ansari et al., 2013). According to these data, the MDR can be designated as type II, which represents the Flood plain–foothill reservoir type (Table 1). To confirm the type of curve, the existing depth-capacity curves produced for two previous surveys were plotted on the curves that were proposed by Borland and Miller (1958) for the empirical area reduction method (Fig. 3). The empirical curve type II was used to develop a stage-capacity curve and stage-area curve for 25 years (Figs. 4 and 5). Also the area reduction method was applied to predict the variation in those curves with sedimentation over 50, 75, 100, and 125 years of dam operation (Figs. 6 and 7). The method was also used to estimate the maximum water depth at dam site for the same periods (Table 2).

**Fig. 4.** Stage-storage capacity curves for the MDR for 25 year of dam operation. (Habili et al. is Mohammadzadeh-Habili et al. and Habili and Heidarpour is Mohammadzadeh-Habili and Heidarpour)

**Fig. 5.** Stage-area curves for the MDR for 25 year of dam operation. (Habili et al. is Mohammadzadeh-Habili et al. and Habili and Heidarpour is Mohammadzadeh-Habili and Heidarpour)
In addition to the above, the methods proposed by Mohammadzadeh-Habili et al. (2009), Mohammadzadeh-Habili and Heidarpour (2010) and Kaveh et al. (2013) were used to determine ASC curves and maximum water depth at the dam site using the sedimentation survey data for MDR as follow:

- The dimensionless relationship of depth-capacity curve of MDR for 1986 and 2011 surveys were used to calculate its reservoir coefficients ($N$, $N_m$ and $N_v$) that were employed by Mohammadzadeh-Habili et al. (2009), Mohammadzadeh-Habili and Heidarpour (2010) and Kaveh et al. (2013) respectively (Table 2).

- The storage capacity for different elevations for MDR were computed using equations 1 and 7 based on its reservoir coefficients that were computed from the dimensionless relationship of its original depth-storage capacity curve.

- Equations 2 and 8 were used to compute the water surface area for the same elevations using the same reservoir coefficients.

- These results obtained from the above steps were used to construct the stage-storage capacity (Fig. 4) and stage-area curves (Fig. 5).

- Equations 3, 5 and 9 were used to determine water depth at the dam site for the methods of Mohammadzadeh-Habili et al. (2009), Mohammadzadeh-Habili and Heidarpour (2010) and Kaveh et al. (2013) respectively (Table 2).

**Table 2.** Variation of maximum water depth at dam site with sedimentation.

The last three methods suggested by Mohammadzadeh-Habili et al. (2009), Mohammadzadeh-Habili and Heidarpour (2010) and Kaveh et al. (2013) as mentioned in the previous section depend mainly on reservoir coefficients in their calculations. The methods did not take into consideration future variation of this coefficient with sedimentation during the determination of the ASC curves. Therefore, the
methods were modified in this study to predict the future changes in ASC curves using the original and secondary survey data for 11 reservoirs in the USA. The details and the characteristics of these reservoirs are tabulated in Table 3. The dams of these reservoirs are classified as “large dam” according to the International Committee on Large Dams (ICOLD) classification (Morris & Fan, 1998). Accordingly, MDR falls within the same category. The data in Table 3 for the original and secondary surveys were used to compute the reservoir coefficients $N$ and $N_s$ using equations 3 and 9 that were proposed by Mohammadzadeh-Habili et al. (2009), and Kaveh et al. (2013) respectively.

The results of field data surveys for the selected reservoirs (Table 3) indicated that there is small variation of their reservoir coefficients ($N$ and $N_s$) with time in general. This implies that there is a small change in the conditions of the reservoir sedimentation with time. In addition, it was also noticed that the Angostura and Nambe Falls dams had big differences between the initial and subsequent estimates of the reservoir coefficients. This might be due to the nature of sedimentation, the shape of these reservoirs and their operation conditions. The reservoir coefficient might increase or decrease depending on the changes of sedimentation conditions. Furthermore, the result showed that there is a linear relationship between the reservoir coefficient (both $N$ or $N_s$) and time with the correlation coefficients $R^2$ ranging from 0.65 to 0.995 (Figs. 8 and 9).

**Table 3.** Original and secondary characteristics of the studied reservoirs.

**Fig. 8.** Variation coefficient of reservoir $N$ with time according to Mohammadzadeh-Habili et al. (2009).

**Fig. 9.** Variation coefficient of reservoir $N_s$ with time according to Kaveh et al. (2010).

The calculated coefficients for MDR for the last surveys (1986 and 2011) were extrapolated to compute their future values of $N$, $N_m$, and $N_s$ for 50, 75, 100, 125 years based on the linear relationship of reservoir coefficients variation with time that was obtained from the resurveys data from 11 existing reservoirs (Table 2). These coefficients were used to compute the maximum water depth at the dam site by applying equations 3, 5, 9 for the methods of Mohammadzadeh-Habili et al. (2009), Mohammadzadeh-Habili and Heidarpour (2010) and Kaveh et al. (2013) respectively (Table 2). In addition, equations 1 and 7 were used to compute the storage capacity for different elevations using these coefficients. Equations 2 and 8 were used to compute the water surface area for the same
elevations and same coefficients. These results were used to construct the stage-storage capacity and stage-area curves for sedimentation periods of different lengths (Figs. 6 and 7).

4. Evaluation and comparison of the techniques used

The four methods described in the previous sections were evaluated by testing them against the bathymetric survey data for the MDR obtained by a bathymetric survey conducted in 2011. The percentage errors for the maximum water depth at the dam site for all methods based on the bathymetric survey results are tabulated in Table 2. For estimating maximum water depth at the dam site, the last three methods gave good results with errors ranging between 1.06 to 3.30% but that of Mohammadzadeh-Habili and Heidapour (2010) method gave very close results to those obtained by the bathymetric survey. The other methods, however, predicted water depth less than that provided by the bathymetric survey. This implies that the deposition depth predicted by these methods is greater than that represented by the actual sedimentation rate at the dam site. This might be due to the fact that most of the sediment was deposited within the upper part of the reservoir because the MDR has an elongated shape and the river Tigris enters the reservoir in its upper part. This is very normal in reservoirs (Vanoniet al., 2006).

The stage-storage capacity curves for 25 year (Fig. 4) show that the Kaveh et al. (2013) method provided results that were in close agreement with the actual survey data, when compared to other methods. The results showed that all methods converge and produce good agreement with the survey data at elevations up to 318 m a.s.l (Fig. 4). Also, the results provided by the Kaveh et al. (2013) method were the closest to the 2011 survey for the stage-water surface area curve (Fig. 5).

The results of the ASC curves for 50, 75, 100 and 125 years (Figs. 6 and 7) showed that the modified methods using a linear relationship principle to determine the reservoir coefficient produced results in close agreement with those provided by the method adopted by the U.S. Bureau of Reclamation (U.S. Bureau of Reclamation, 1987) (area reduction method) and the agreement became even better when time increased. The average results for years mentioned above showed that the percentage errors for sedimentation depths at dam site were ranging from 1.4 to 3.75 for the last three methods while for the area reduction method it was 24.63% (Table 2). The modified approach can be used if
thesedimentation conditions and reservoir operation mode remain constant. The changing reservoir coefficient with time reflects the variations of the conditions of reservoir sedimentation. The survey data for 11 reservoirs indicated that the change of reservoir coefficient with time will be very small if the variation of reservoir sedimentation conditions is small and in such a case, the average value could be used for this purpose.

The reservoir shape factor changes with time due to the change in the stage-capacity curve caused by sedimentation. This factor was computed via the slope of the depth-capacity curve for the surveys of 1986 and 2011 according to the method proposed by Borland and Miller (1958) (Table 4). It was also computed using the relationships proposed by Mohammadzadeh-Habili et al. (2009), Mohammadzadeh-Habili and Heidarpour (2010), and Kaveh et al. (2013) using equations 4 and 10 respectively (Table 4). The results of these three methods showed that Kaveh et al. (2013) method gave convergent results with percentage errors of 1.08% and 5.24% for the 1986 and 2011 surveys respectively (Table 4). According to the above results the method proposed by Kaveh et al. (2013) is considered a good approach for computing and predicting the ASC curves due to its accurate results and its ease of use.

Table 4. Shape factor variation with sedimentation for different methods

5. Conclusions

ASC curves are very important characteristics of reservoirs. Four empirical and semi-empirical methods for deriving these curves were reviewed and applied to the MDR. These methods include the area reduction method (Borland & Miller, 1958) and those proposed by Mohammadzadeh-Habili et al. (2009), Mohammadzadeh-Habili and Heidarpour (2010) and Kaveh et al. (2013). The results were compared with those obtained using the bathymetric survey conducted in 2011 after 25 years of operating MDR. The comparison of the results for establishing the ASC curves showed that the method proposed by Kaveh et al. (2013) gave good agreement with bathymetric results. For maximum water depth at the dam site or sedimentation depth the Mohammadzadeh-Habili and Heidarpour (2010) and Kaveh et al. (2010) methods were more accurate for determining sedimentation depth at the dam.
Sitewith apercentage errorsof 1.06% and 2.12% respectively. TheKaveh et al. method also gave a good result for computing shape factor $M$ of reservoir that was adopted in the area reduction method.

The last three methods (Kaveh et al., 2013; Mohammadzadeh-Habili et al., 2009; Mohammadzadeh-Habili & Heidarpour, 2010) had been proposed for determining the ASC curves. In this study these methods were modified to enable them to be used for predicting the changes in the ASC curves, based on data from the original and secondary surveys of 11 reservoirs in the USA. The results of the reservoirs used showed that reservoir coefficients suggested by Mohammadzadeh-Habili et al. (2009) and Kaveh et al. (2013) depends on the conditions of reservoir sedimentation. They change linearly and slightly (increase or decrease) with time if the conditions of reservoir sedimentation are steady. Therefore, this principle was applied to the MDR to predict the future ASC curves for 50, 75, 100 and 125 years. The curves predicted by these modified methods showed that there is good agreement with the method adopted by the U.S. Bureau of Reclamation (area reduction method). It should be mentioned however, that the differences in results between all methods decreased as the period of sedimentation increased. Furthermore, the modification methods showed good results for sedimentation depth at dam site relative to with the results obtained by the area reduction method. Therefore, the principle of linear changed for reservoir coefficient can be used for the prediction changing on the ASC curves using the last three methods. In case there are more survey data for large reservoirs available in future, this will definitely improve this work. The study confirms the possibility to rely on the empirical technique in estimating the sedimentation characteristics within reservoirs; this will help in prudent operation of reservoirs. Finally, it is recommend that reservoir surveys should be conducted more frequently on existing reservoirs so that more data will be available to reach better and more precise predictions.

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**References**


Table 1: Reservoirs classification according shape factor “M”. Source: (Borland and Miller, 1958).

<table>
<thead>
<tr>
<th>Type of reservoir</th>
<th>Classification</th>
<th>Shape factor $M$</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>Lake</td>
<td>3.5 – 4.5</td>
</tr>
<tr>
<td>II</td>
<td>Flood Plain–Foot hill</td>
<td>2.5 – 3.5</td>
</tr>
<tr>
<td>III</td>
<td>Hill</td>
<td>1.5 – 2.5</td>
</tr>
<tr>
<td>IV</td>
<td>Gorge or normally empty</td>
<td>1.0 – 1.5</td>
</tr>
</tbody>
</table>

Table 2: Variation of maximum water depth at dam site with sedimentation.
Table 3: Original and secondary characteristics of the studied reservoirs.

<table>
<thead>
<tr>
<th>Dam</th>
<th>Year of survey</th>
<th>Year of survey</th>
<th>A_m (10^6 m^2)</th>
<th>C_m (10^3 m^3)</th>
<th>N</th>
<th>N_a</th>
<th>R^2</th>
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### Table 4: Shape factor variation with sedimentation for different methods.

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Figure 5
Figure 7