Area-Storage Capacity curves for Mosul Dam, Iraq Using Empirical and Semi-Empirical Approaches

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ABSTRACT:
The storage capacity of reservoirs is gradually depleted due to sediment accumulation that causes changes in the area-storage capacity curves (ASC). These curves are important for planners, designers and operators of dams. Many empirical and semi-empirical approaches have been suggested for establishing and predicting these curves. In this study four empirical and semi-empirical methods were evaluated and used to determine the ASC curves for 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 km³ and a water surface area 380 km² 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 methods presented more accurate results for estimating water depth or sedimentation depth at dam site with percentage error about 1.06% to 3.295%.

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 and Raju, 1985; Morris and Fan, 1998; Jain and Singh, 2003; Garde, 2006). Reservoir sedimentation is the main problem that directly affects the performance of dams due to the reduction in their storage capacity. The distribution of sediment deposited in reservoirs mainly depends on several factors, but the most important are the properties of sediment, amount of sediment coming, the characteristics of reservoir and its age and the reservoir operation mode (Annandale, 1987; Morris and Fan, 1998; Garde, 2006). Accumulation of sediment in the reservoirs causes changes in their ASC curves (or stage-area curve and stage-storage capacity curve) (U.S. Bureau of Reclamation, 1987; Morris and Fan, 1998; Mohammadzadeh-Habili et al., 2009). ASC curves are regarded as one of the most important physical characteristics of the dams and their reservoirs. Therefore establishing these curves and predicting their future change is an important issue for planners, designers and operators of dams. 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 mode (Borland and Miller, 1958; Strand and Pemberton, 1982). Determination these curves is an important issue for; determining the sedimentation depth at dam site, estimating the useful life of the dam, designing the bottom outlet elevation, determining the effect of backwater conditions on the flood level upstream of a reservoir and assessing changes in the reservoir storage capacity with time of dam operation. 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 because they are relatively easy and quick to use and they require limited data. Consequently, large numbers of empirical methods have been reported (e.g. Borland and Miller, 1958; Borland, 1970; Szechowycz and Qureshi, 1973; Croley et al., 1978; Garde et al., 1978; Chien, 1982; Annandale 1984; Rahmanian and Banhashemi, 2011). 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 based on resurvey data for 30 reservoirs in the United States (Morris and Fan, 1998).

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...
The methods were reviewed and applied to determine the ASC curves and maximum water depth or sediment deposited depth 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). 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. This can help decision makers, planners and designers, to use these methods to determine the ASC curves for reservoirs that used to estimate their useful life. Moreover, to put prudent planning for Iraqi water resources problems because Iraq is facing serious water shortage problems now due to climate changes and increasing demand (Droogers et al. 2012; Al-Ansari, 2013; 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 EMPIRICAL AND SEMI-EMPIRICAL METHODS EMPLOYED IN THE STUDY

The first empirical methods were developed by Borland and Miller (1958) referred to as “area increment method” and “area reduction method”. The first one 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 within the each depth increment of the reservoir (Borland and Miller, 1958; Strand and Pemberton, 1982). 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 based on analysis of sedimentation data for 30 reservoirs in the USA and adopted by the U.S. Bureau of Reclamation (Morris and Fan, 1998). 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, sedimentation rate and reservoir characteristics. In this method the reservoirs are classified into four categories based on the shape factor of the reservoir “M” (table 1). The shape factor represents the reciprocal slope of the straight line for the relationship of reservoir depth at the dam site as the Y-axis against the storage capacity as the X-axis presented as a logarithmic scale plot (Borland and Miller, 1958; Mohammadzadeh-Habili et al., 2009; Mohammadzadeh-Habili and Heidarpour, 2010; Kaveh et al. 2013). The shape factor of a reservoir does not change linearly with time and depends on many factors including the characteristics, age and operation mode of the reservoir (Borland and Miller, 1958; Morris and Fan, 1998).

Table 1: Reservoirs classification according shape factor “M” (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>

The area reduction method involves four different sedimentation pattern curves that were developed from the resurvey data assembled for 30 reservoirs (Fig. 1). These curves are dimensionless and are used to determine the changes 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 and Pemberton, 1982; 1987).
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 dimensionless curve. This equation depends on only one unknown dimensionless parameter called the reservoir coefficient “$N$” as follows:

$$C_y = C_m \left[ e^{\ln(2) \frac{y}{y_m}} - 1 \right]^\frac{1}{N}$$

where $C_y$ is reservoir capacity at depth $y$, $C_m$ 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 result obtained when plotting this equation on log-log paper is approximately a straight line for any $N$ value and the slope of this line represents the shape factor of the reservoir as proposed by Borland and Miller (1958). While, the water surface area and reservoir coefficient equations were derived from equation (1) as follow:

$$A_y = C_m \frac{2 \ln(2) \frac{y}{y_m}}{N \cdot y_m} \left[ e^{\ln(2) \frac{y}{y_m}} - 1 \right]^\frac{1}{N}$$

$$N = 2 \ln 2 \frac{C_m}{A_m \cdot y_m}$$

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 curve (Mohammadzadeh-Habili et al., 2009). Furthermore, the results used to develop an empirical relationship between the reservoir shape factor “$M$” and its coefficient (Eq. 4).

$$N = 1.075 M^{-0.9063}$$

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 USA as:

$$N_m = 2 \ln 2 \frac{N_{SSE}(\text{Minimization of SSE})}{N} \frac{C_m}{A_m \cdot y_m}$$

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 curve from equation (3).
In 2013 Kaveh et al., differentiated a simple dimensionless capacity equation using a parabolic equation that used for reservoir capacity. The parabolic equation is used to represent the general form of the relationship between storage capacity and water depth which can be expressed as follows:

\[ C_y = a + b \cdot y + c \cdot y^2 \]  \hspace{1cm} \text{(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 (U.S. Bureau of Reclamation, 1985; Ferrari, and Collins, 2006). Kaveh’s equation depends on one reservoir coefficient parameter as:

\[ C_y = C_m \left( \frac{y}{y_m} \right)^{2/N} \] \hspace{1cm} \text{(7)}

where \(N\) 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:

\[ A_y = 2 \cdot C_m \left( \frac{y}{y_m} \right)^{2/N} \] \hspace{1cm} \text{(8)}

\[ N = \frac{2 \cdot C_m}{y_m \cdot A_m} \] \hspace{1cm} \text{(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:

\[ N = \frac{2}{M} \] \hspace{1cm} \text{(10)}

The resurvey data assembled for 20 reservoirs in the USA and Iran showed that the approach proposed by Kaveh et al. (2013) is easy to apply and more precise compared to the method of Mohammadzadeh-Habili et al. (2009) (Kaveh et al., 2013).

3. STUDY AREA 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. 2). 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.

![Fig. 2: The location of the Mosul dam.](image-url)
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 km$^3$ of water at normal operation level, including 8.16 and 2.95 km$^3$ 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 km$^2$ (Iraqi Ministry of Water Resources, 2012) (Fig. 2). 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 km$^2$ shared by Turkey, Syria and Iraq (Swiss Consultants, 1979; Saleh, 2010). A
bathymetric survey of the MDR was conducted in 2011 after 25 years of dam operation (Issa et al., 2013). The
survey results showed that 1.143 km$^3$ of sediment had accumulated over the period 1986-2011. This represents an
annual sediment deposition rate of 45.72 × 10$^6$ m$^3$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. 3).
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).

**Fig. 3:** Area-storage capacity curves for the MDR.

**4. METHODOLOGY AND TECHNIQUES USED**

All the methods employed assumed that the banks of reservoir at maximum elevation will remain 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 and Heidarpour, 2010).

The four methods described above were applied to generate ASC curves for MDR 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 and 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 on log-log
paper. Its mode of operation is classified as Moderate drawdown and the predominant grain size of the sediment
deposited was 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. 1). The empirical curve type
II was used to develop a stage-capacity curve and stage-area curve for 25 years (Figures 4 and 5). 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 Habil 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 Habil and Heidarpour is Mohammadzadeh-Habili and Heidarpour)

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 dam site using sedimentation survey data. Equations 1 and 7 were used to compute the storage capacity for different elevations based on the coefficients of MDR that were computed from dimensionless relationship of its depth-storage capacity curve. Equations 2 and 8 were used to compute the water surface area for the same elevations using the same reservoir coefficient. These results were used to construct the stage-storage capacity (Fig. 4) and stage-area curves (Fig. 5). While equations 3, 5 and 9 were used to determine water depth at 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: Maximum water depth at dam site with sedimentation

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<tbody>
<tr>
<td>$y_m$ (m)</td>
<td>$y_m$ (m)</td>
<td>% error</td>
<td>$y_m$ (m)</td>
<td>% error</td>
</tr>
<tr>
<td>80</td>
<td>78.30</td>
<td>2.125</td>
<td>77.364</td>
<td>3.295</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>80.85</td>
<td>-1.062</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>71.42</td>
<td>10.725</td>
</tr>
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</table>

### 5. RESULTS AND DISCUSSION

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 error ranging between 1.062 to 3.295% 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.

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 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 stage-capacity curve for the surveys of 1986 and 2011 according to the method proposed by Borland and Miller (1958) (Table 3). It was also computed using the relationships proposed by Mohammadzadeh-Habili et al. (2009) Kaveh et al. (2013) using equations 4 and 10 respectively (Table 3). The results of these two methods showed that Kaveh et al. (2013) method gave more accurate results with percentage errors of 1.08% and 5.24% for the 1986 and 2011 surveys respectively (Table 3). 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 it is easy in use and.

### Table 3: Shape factor variation with sedimentation for different methods

<table>
<thead>
<tr>
<th>Year</th>
<th>Based on stage-capacity curve</th>
<th>Kaveh et al. (2013)</th>
<th>Mohammadzadeh-Habili et al. (2009)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>% error</td>
<td>M</td>
<td>M</td>
</tr>
<tr>
<td>1986</td>
<td>1.083</td>
<td>2.77</td>
<td>2.74</td>
</tr>
<tr>
<td>2011</td>
<td>5.24</td>
<td>3.15</td>
<td>2.985</td>
</tr>
</tbody>
</table>

### 6. CONCLUSION

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 and Miller, 1958) and those proposed by Mohammadzadeh-Habili et al. (2009), Mohammadzadeh-Habili and Heidapour (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 site. The percentage errors were 1.06% and 2.125% respectively. The methods also gave a good result for computing shape factor of reservoir that was adopted in the area reduction method.

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