Sediment flux from Lesser Zab River in Dokan Reservoir: Implications for the sustainability of long-term water resources in Iraq

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Abstract
Prudent management of Iraqi water resources under climate change conditions requires plans to be based on actual figures of the storage capacity of existing reservoirs. With the absence of sediment flushing measures, the actual storage capacity of Dokan Reservoir (operated since 1959) has been affected by the amount of sediment delivered during its operational life leading to an undetermined reduction in its storage capacity. In consequence, there has not been an update on the dam’s operational storage capacity curves. In this research, new operational curves were established for the reservoir based on a recent bathymetric survey undertaken in 2014. The reduction in reservoir capacity during the period between 1959 and 2014 was calculated by the mean of the difference between the designed storage capacity and the storage capacity which was concluded from the 2014 bathymetric survey. Moreover, the rate of sediment transported to the reservoir was calculated based on the overall quantities of accumulated sediment and the water discharge of the Lesser Zab River into the reservoir. The results indicate that the dam capacity is reduced by 25% due to sedimentation of an estimated volume of 367 million cubic metres at water level 480 m.a.s.l. The annual sedimentation rate was about 6.6 million cubic metres, and the sediment yield was estimated to be 701.2 t km⁻³·year.

KEYWORDS
Dokan Dam, Dokan Reservoir, sediment transport, storage capacity

1 | INTRODUCTION

Water shortage problems are becoming a daily issue globally. Future prospects are potentially gloomier as it is expected that 37 countries by 2025 will have a shortage of water for all basic needs (Biswas, 1991). Reservoirs play an important role in strategic plans to face such problems for countries of limited water resources. But the road to implementing such plans is not fully paved, either in terms of economic or practical perspectives. One of these practical perspectives is represented in the long-term efficiency and sustainability of reservoirs in terms of sediment delivered from the upstream catchment and its effect on the long-term sustainability of adequate storage. Many investigations for estimating the current state and the possible future sedimentation rates in world reservoirs have been conducted. The results of these investigations have indicated that the highest rates of sedimentation occurs in arid regions, such as the Middle East and Australia (Schlesis, Franca, Juez, & De Cesare, 2016).
Iraq is located within the northern part of the Middle East. It was once considered as one of the richest countries in terms of its water resources due to the availability of water from the Tigris and Euphrates rivers. Regional and climate changes challenge to water resources plague Iraq. In part, this is because of the construction of dams and irrigation projects in the upper parts of the catchment of these rivers, and in part, it is due to the effect of climate change, where rainfall within the catchment areas of the Tigris and Euphrates is decreasing; Iraq is experiencing significant water shortage problems that are likely to become more severe in the future (see Abbas, Al-Ansari, Wasimi, & Al-Rawabdeh, 2019; Al-Ansari, 2013; Al-Ansari, 2016; Al-Ansari, Abdellatif, Ali, & Knutsson, 2014; Al-Ansari, Abdellatif, Ezeelden, Ali, & Knutsson, 2014b; Al-Ansari, Abdellatif, Ezeelden, Ali, & Knutsson, 2014c; Al-Ansari et al., 2014d; Al-Ansari, Knutsson, & Ali, 2012; Hilo & Saeed, 2019; Osman et al., 2017a; Osman et al., 2017b).

To minimize the effect of water shortage problems, a prudent water management plan is to be adopted in Iraq. To set such a plan in place, the exact storage capacity of the existing reservoirs has to be evaluated, especially with the absence of sediment flushing measures in any existing structures.

In this research, the principal objective of this study is to calculate the accumulated amount of delivered sediment to the Dokan Reservoir to assess the loss in the original storage capacity so that decision makers can take the reduction of capacity into consideration when allocating future resources. In addition, when the rate of sediment deposition is known, then measures can be taken in order to try and reduce the rate of sediment delivery to the reservoir.

### 1.1 River basin sediment yield and loss of reservoir storage capacity

Sediment yield is defined as the total outflow of sediment from a drainage basin that can be measured at a cross section over a specified time period. It can be predicted based on gross erosion in the drainage basin and sediment delivery ratio. The gross erosion is the total soil erosion over a specific drainage basin, and it is affected by erosion type (sheet, gully, or streambank erosion). Sediment delivery ratio is defined as the efficiency of the drainage basin in transporting sediment from eroding areas to the measuring point of sediment yield (World Meteorological Organization [WMO], 2003). Sediment yield is affected by different parameters that are related to catchment characteristics or to environmental conditions including climate change and anthropogenic activity (Walling, 2008).

Anthropogenic activities include major changes in vegetation cover across the catchment. Land use activities disturb a wide range of surface materials as a result of infrastructure development and mineral exploitation. Population growth pressure has increased the global area of pasture land by about 75% and has decreased the area of the global tropical forests by about 25%. Exploiting water resources might also produce a modification to the hydrological cycle and exerts a significant influence on global erosion rates and the sediment loads of rivers around the world (Walling, 2008). Such changes might increase erosion rates at the level of catchment and accelerate rates of sedimentation in water conveyance system or in downstream reservoirs. Dam construction in the upper basin of the Yangtze River in China since the mid-1980s, however, have led to a reduction in the annual sediment load transported to the estuary and is estimated to have almost twice the effect of decreased annual precipitation (Wang, Li, & He, 2007).

There have been many attempts to assess global rates of sediment yield and to produce world maps of global sediment yields. The global sediment yield estimates have ranged from $8.3 \times 10^9$ to $51.1 \times 10^9$ t during the period 1952 to 1992 (Walling & Webb, 1996). These estimates have been built on the available sediment databases of the world's rivers. Undoubtedly, these estimates are only tentative estimates of the detailed global patterns observed in the past. The sediment yield of the basin of the Lesser Zab River in Iraq has been classified to be within the range of 500–750 t km$^{-2}$ year$^{-1}$ according to Walling and Webb classification map in 1983 or an even lower sediment yield range of 20–200 t km$^{-2}$ year$^{-1}$ according to Lvovich et al. in 1991 (Walling & Webb, 1996). The current actual global yield of sediment is unknown in terms of climate change, and the enormous human activity that has continuously changed many of river basin characteristics and the current study will provide an estimate for the Dokan catchment.

The global estimate for reservoirs sedimentation rates has been evaluated to be below 1.0% per year of the original dam capacity for most of the countries reviewed (International Commission On Large Dams [ICOLD], 2009), which is similar to a previous estimate by Basson (2008) of a 0.8% reduction in total storage per year. Official values of dam sedimentation rates of 0.3% to 2% of the original dams’ capacity have been reported as being lost per year (ICOLD, 2009). However, specific countries such as Tanzania and China have shown extraordinary storage losses well above 2.0% annually, so excluding them from counting average rates is quite reasonable. The lack of reported sedimentation data for the majority of the Middle East countries means that the data are not included in global estimates of storage loss. The reported sedimentation data from neighbouring Iran has indicated that the average sedimentation rate is equivalent to a storage loss of 1.65% per year (ICOLD, 2009). Assessing the sediment yield of a drainage basin by measuring the amount of deposition in a large reservoir in the river is a reliable way in light of the absence of flushing measures because most of the sediment load from the upstream areas will be impounded by the reservoir (WMO, 2003). Similar procedures have been implemented on the Muela Reservoir in northern Lesotho (Khaba & Griffiths, 2017). Eight bathymetric surveys, conducted between 1985 and January 2015, were analysed to assess the volumetric change between each survey and to obtain the loss of storage capacity due to sedimentation. Four interpolation methods were used to create digital terrain models from survey data sets as well as creating a triangulated irregular network (TIN) surface. The interpolation is smoothest for surveys containing a larger number of data points and transects and surveys of lower resolution might introduce uncertainty in bathymetric change estimation. The results indicated high variability in the sedimentation
rate taking account of errors in the bathymetric survey and reservoir volumetric calculation methods. A large degree of uncertainty of ~37% was estimated due to measurement uncertainty during the creation of the bathymetric survey. Although uncertainty in the estimates is relatively high, the methodology often provides the only practical way of assessing sediment transport rates in ungauged catchments.

## 2 | MATERIALS AND METHODS

### 2.1 | Study area

Dokan Dam is a multipurpose concrete cylindrical arch dam with gravity abutments and is located on the Lesser Zab River (Figure 1a). Its maximum height is 116.5 m (crest level 516.0 m above sea level [m.a.s.l.]) with a total crest length of 345 m (see Table 1). The left and right gravity abutment lengths are 41 and 64 m, respectively. The length of the arch is 240 m (Binne, Campbell, Edginton, Fogden, & Gimson, 1959; Figure 1b). The dam has been in operation since 1959. The purposes of the dam are to serve local irrigation, provide power generation, domestic water supply, and flood control needs.

The catchment area of the dam including the reservoir area at the normal operation level (El. 511 m.a.s.l.) is 11,690 km², and the minimum drawdown level is at an elevation of 469 m.a.s.l. (Binne et al., 1959). The dead and live storage capacities of the reservoir are $0.73 \times 10^9$ and $6.14 \times 10^9$ m³, respectively (World Bank, 2008).

### TABLE 1 | Properties of the Dokan Dam and its catchment

| Property                          | Value     | Unit |
|-----------------------------------|-----------|------|
| High                              | 116.5     | M    |
| Crest level                       | 516       | m.a.s.l. |
| Crest length                      | 345       | m    |
| Normal operation level            | 511       | m.a.s.l. |
| Normal storage capacity           | 6.8       | km³  |
| Maximum storage capacity          | 7.3       | km³  |
| Minimum storage capacity          | 0.73      | km³  |
| Minimum drawdown level            | 469       | m.a.s.l. |
| Catchment area                    | 11,690    | km²  |
| Max. elevation                    | 3,557     | m.a.s.l. |
| Min. elevation                    | 511       | m.a.s.l. |
| Average slope                     | 26.5      | %    |
| Max. annual rainfall              | 1,125     | mm   |
| Min. annual rainfall              | 182       | mm   |

**FIGURE 1** (a) Location of Dokan Dam. (b) Photograph of Dokan Dam and the emergency funnel spillway. (c) Dokan upper triangular reservoir (Reservoir A) and Dokan lower square reservoir (Reservoir B). https://www.researchgate.net/profile/Nadhir_Al-Ansar2/publication/317594021/figure/fig1/AS:505411193507840@1497510827032/Location-map-of-a-Dokan-Reservoir-with-b-upstream-view-of-emergency-spillway_Q320.jpg
exposed rocks within the catchment are mainly limestones and dolomites (Ezz-Aldeen, Ali, Hassan, Al-Ansari, & Knutsson, 2018; Karim, Al-Hakari, Kharajany, & Khanaqa, 2016; Sissakian, Abdulahad, Al-Ansari, Hassan, & Knutsson, 2016; Sissakian, Al-Ansari, & Knutsson, 2015). Dokan is composed of two separate reservoirs. The larger reservoir is in the northern part of an almost triangular basin (see Figure 1c). The maximum base length of the triangle reaches 16 km, whereas the hypotenuse is about 20.5 km in length. The smaller reservoir is roughly a square shape with a length and width of 3 and 4 km, respectively. At the southern end of this smaller reservoir lies Dokan Dam with its power plant. The turbines are located at the bottom part of the dam. The two reservoirs are connected through an open channel, which is 9 km in length, with a width varying from 120 to 800 m (see Figure 1c).

The maximum annual rainfall for the period 1959–2014 within the catchment area was 1,125 mm, whereas the minimum was 182 mm (see Figure 2a). The average discharge of the Lesser Zab River for the period 1959–2014 at Dokan is 167 m$^3$ s$^{-1}$, and it is

![Figure 2](image-url)
characterized by oscillations according to the prevailing weather conditions. Usually, the peak flow occurs during April (see Figure 2b) when the snow melts and might be accompanied by rainfall. The discharge of the river has been decreasing with time particularly in the past two decades (see Figure 2c). This is due to the effect of climate change as well as continuous building of hydrological schemes in Iran. In addition, the records of flow at the Iraqi Ministry of Water resources show that the average flow for the period 2010–2018 was 103 m$^3$ s$^{-1}$. Climate change predictions (Al-Ansari & Adamo, 2018) indicates that there will be periods where intensive rainfall occurs in short periods of time. This trend is demonstrated by floods in March and April 2019, where the average flow during these two months reached 769 m$^3$ s$^{-1}$.

The drainage basin area is located within the Zagros Fold–Thrust belt (Jassim & Goff, 2006). The exposed formations date back to the lower Jurassic. Most of the formations are composed of limestones up to the lower Miocene formations (Fatha, Injana, Mukdadia, and Bi Hassan formations; Hassan, Al-Ansari, Ali, Ali, & Knutsson, 2017). These formations are composed of limestones, gypsum, sandstones, conglomerates, and marl (Sissakian et al., 2016). The exposed rocks at the Dokan drainage basin are mainly limestone and minor exposures of dolomitic limestone, dolomite, and Quaternary alluvial deposits (Berding, 2001).

Most of the drainage basin area (85.6%) is covered by gravelly sandy mud; 6.9% is gravelly mud; and 7.5% of two types of muddy gravel (the main differences between the two types are the percent of gravel, which is 74% and 56% for types 1 and 2, respectively; see Figure 3a; Ezz-Aldeen et al., 2018).

The main part of the land is used for growing winter plants and pastures that depend on rainfall as the main source of irrigation. The other parts vary between forests and vegetable growing around dispersed villages (Ezz-Aldeen et al., 2018; see Figure 3b). Due to the geology of the area and the irrigation source that depends mainly on rainfall, change in land use over time has been minimal and it did not change significantly through the study period since the operation of the dam from the year 1959 to the year 2014. Active urban areas (big cities) are located away from the dam and the catchment, so changes in both urban and rural areas are limited. Table 2 shows the percentage of different land use cover for the two periods of the available land use map. The terrain elevation of the drainage basin is varied between 511 m.a.s.l. as minimum elevation (normal operation level of the reservoir) and 3,557 m.a.s.l. as maximum elevation (see Figure 3c).

2.2 Estimating sediment yield

An attempt was previously conducted to assess the annual sediment yield of the Dokan Dam drainage basin using the modified universal soil loss equation within the soil and water assessment tool (SWAT) model (Ezz-Aldeen et al., 2018). Due to limited measurements of flow and unavailable sediment records of the Dokan Dam drainage basin, the model was calibrated for flow and sediment load based on the available field measurements of the adjacent Derbendekhan Dam drainage basin using the SWAT-CUP software. The similarity in geological formation, soil type, land use, drainage basin characteristics, and weather data has helped to transform the effective hydrological parameters obtained from the Derbendekhan (gauged) drainage basin to the Dokan (ungauged) drainage basin. A regionalization technique was applied to transform parameters from Derbendekhan to Dokan drainage basin. A digital elevation model (DEM) of 30 m resolution (see Figure 3c) was used as topographical map of the Dokan drainage basin in SWAT model. Additional maps for soil type, land use, and land cover (see Figure 3) were also used in the model.

The results of simulation for Dokan drainage basin for the period (1959–2014) have shown that the average annual volume of runoff was about 2,100 million cubic metres (MCM) and the total delivered sediment was about 72 MCM that is equivalent to 10% of the reservoir dead storage. Moreover, a spatial distribution map of erosion and annual sediment yield for the subbasins has been established (see Figure 3d). The average annual sediment yield was estimated to range from 13 to 950 t km$^{-2}$, and the nearest subbasins of steeper slopes (25% to 45%) have higher sediment contribution, where their sediment yields were estimated to range between 400 and 950 t km$^{-2}$.year$^{-1}$ (Ezz-Aldeen et al., 2018).

The results obtained by Ezz-Aldeen et al. (2018) have shown that the total water inflow into the reservoir during the period 1959 to 2014 was 115.5 km$^3$, which is less than ~40% of the inflow records at Dokan gauging station. The estimated sediment yield was 197 t km$^{-2}$.year$^{-1}$ that is closer to the estimates of Lvovich et al. in 1991 (Walling & Webb, 1996).

2.3 Methodology

2.3.1 Estimating storage capacity

To work out the reduction in storage capacity since initial construction required three key pieces of information: the initial design storage capacity at maximum elevation, the construction of a new bathymetric map from a detailed field survey and the calculation of present volume, and the calculation of the difference in volume between the two dates. The following sections consider each of these procedures in turn.

To calculate the initial design storage volume of Dokan Reservoir the 1952 topographic maps (Scale 1:20,000) were digitized. These maps were drawn by Hunting Aero surveys LTD in 1951–1952 (Directorate General of Surveys-Iraq, 1956). A set of contours between 420 and 520 m.a.s.l. were drawn at 10-m intervals. The enclosed areas of the digitized contours were obtained from the properties of contours’ polygons using ARC GIS software, and the confined volume between every successive contour line was calculated based on Average-End-Area method (trapezoidal rule), where the average of areas of the upper and the lower contours are multiplied by the contour interval. The total volume was obtained from the summation of the individual volumes between the contours (Malvić, Rajić, Slavinić, & Zelenika, 2014).
FIGURE 3  (a) Soil type classification map. (b) Land use and land cover classification map. (c) Topographic map. (d) Spatial distribution of sediment yield of the Dokan Reservoir watershed (Ezz-Aldeen et al., 2018)

TABLE 2  Percentages of different land use types for two years of the studied period (Ezz-Aldeen et al., 2018)

| Year   | Winter plant and pasture | Forest | Vegetables | Urban area (villages) |
|--------|--------------------------|--------|------------|-----------------------|
| 1976–1979 | 77.3                     | 22     | 0.5        | 0.2                    |
| 2007   | 82.7                     | 15.6   | 1.6        | 0.1                    |
The updated volume required a new bathymetric survey for the reservoir that could then be converted to DEM. The recent bathymetric survey carried out in November 2014 by Hassan et al. (2017) was used as the newest survey for the reservoir. It was conducted using a single beam echo sounder (EAGLE SeaCharter 480DF sonar) manufactured by Lowerance®, where the water surface elevations varied between 482.47 and 482.85 m.a.s.l. during the survey. The paths of the transect lines of the bathymetric survey that were laid out by the GPS are shown in Figure 4. The weather was calm during the bathymetric survey in order to avoid water surface fluctuation due to wind-generated waves. The echo sounder outputs were converted to 65,416 bed level points by means of water surface elevation. The TIN of the reservoir bed was created using ArcGIS software (3D Analyst/Create TIN tool) then it was converted to a DEM using natural neighbour interpolation tool in ArcGIS software. This DEM was created for the inundated part of the reservoir up to an elevation 483 m.a.s.l.

Based on the DEM generated from the bathymetric survey in 2014, a set of contour lines were generated with a contour interval of 10 m. The confined volume between every successive contour line was calculated. By summing up the calculated volumes ascending, an accumulated storage capacity curve was established for the Dokan Reservoir according to the most recently bathymetric survey.

Based on the result of digitizing the topographic maps of 1952, a DEM was built for the initial topography of the reservoir as shown in Figure 5a. Another DEM was built from the recent bathymetric survey of the reservoir up to an elevation of 483 m.a.s.l as shown in Figure 5b. For the dry portion of the reservoir, above 483 up to 520 m.a.s.l., there is no available land survey to pair with the bathymetric survey to accomplish the DEM for the whole range of reservoir’s elevations.

The volume concentration (fraction) of delivered sediment can be estimated by dividing the accumulated volume of deposited sediment by the total volume of the inflow water during the same time period considering sediment porosity of 35%. Mass concentration can be estimated by multiplying the volume concentration by sediment density. Comparing this concentration with the measured one downstream of the dam might give a rough indication about the sediment trap efficiency in the reservoir.

It should be mentioned however that result of sediment delivery from small subvalleys on both sides of the two reservoirs: the distribution of coarse sediment was concentrated on the southern half of the upper reservoir and the whole of the lower reservoir according to sediment size analysis of 32 samples of bed sediment (Hassan et al., 2016).

2.3.2 | Uncertainty and the errors in estimating the sedimentation rate

Every field survey or calculation process related to sediment yield have some assumptions and potential sources of error that result in uncertainty in the results of any work. Estimating the uncertainty requires recognizing the size of the individual errors and their cumulative effect upon the volume estimate.

In the bathymetric survey, positioning error and bottom depth error are important to consider in the calculation of three dimensional position. The positioning error includes the two dimensional error of x and y, whereas the depth error is a one-dimension error of z. The antenna of the echo sounder (EAGLE SeaCharter 480DF sonar) has a minimum position error of 4 m, and the transducer probe has a variable error proportional to the depth plus a constant error (Byrnes, Baker, & Li, 2002). Water surface fluctuation may derive another source for random errors.

Creating a reservoir bed topography map (DEM) from surveying points usually introduces an error associated with the interpolation method of the DEM. The Kriging approach has been effectively used in many studies and it is argued to produces reasonable results. However, for surveys of a large number of elevation data points, Kriging interpolation will being impractical due to the high demand of the calculation requirements (Khaba & Griffiths, 2017).

The accuracy of a contour map for the topography of the reservoir and its digitizing will introduce another uncertainty to the calculations of reservoir volume change. Moreover, assuming prismatic cells for the calculated volume between two successive contours would introduce more uncertainty to the calculation of the reservoir volume. Previous studies have shown that the combination of these errors could be of the order of 37% (Khaba & Griffiths, 2017).
RESULTS AND DISCUSSION

3.1 Overall sediment deposited

The procedure of converting the DEM data into a storage capacity curve was applied on both DEMs to obtain the initial and the most recent storage capacity curves as shown in Figure 6a.

The reduction in the storage volume during for the period between 1952 and 2014 was determined from the difference between the two storage-elevation curves at water level 480 m.a.s.l. and was found to be about 367 MCM (0.367 km³) that represents 25% of the design capacity at the water level of 480 m.a.s.l. Considering this deposition as the loss of storage capacity during the operation period, it is equivalent to 0.45% annual loss of the original design capacity. However, it is still considered as a relatively low sedimentation rate according to the official estimates (WMO, 2003). The average annual sedimentation rate was determined as 6.6 MCM that is five times higher than that estimated by Ezz-Aldeen et al. (2018) assuming sediment dry density of 1,200 kg m⁻³. The obtained sediment volume is equivalent to a sediment yield of 701.2 t km⁻² year⁻¹ that is within the estimates range of Walling and Webb by 500–750 t km⁻² year⁻¹ (Walling & Webb, 1996).

According to the daily records of Dokan Reservoir, the total volume of inflow water during the period between 1959 and 2014 (the period between starting operation of the dam and recent bathymetric survey) was calculated as 293.86 km³. Accordingly, the delivered sediment volume concentration was calculated as $566 \times 10^{-6}$ m³ sediment m⁻³ water considering sediment porosity of 55%. Then mass

FIGURE 5  (a) Topographical map of Dokan Reservoir in 1952 (prior dam construction). (b) Topographical map of the inundated portion of Dokan Reservoir in 2014

FIGURE 6  (a) Storage-elevation curves of Dokan Reservoir. (b) Reduction in storage capacity of Dokan Reservoir at different water levels up to 480 m.a.s.l.
concentration of delivered sediment was calculated considering sediment density of 1,200 kg m$^{-3}$ as 1,500 g m$^{-3}$. This mass concentration is almost eight times higher than the average measured concentration in the Tigris River in Baghdad (Ali, Al-Ansari, Al-Suhail, & Knutsson, 2019) and approximately 2.3 times the estimates by Ezz-Aldeen et al. (2018).

The wide difference in estimating sedimentation volume between the SWAT model (Ezz-Aldeen et al., 2018) and the bathymetric survey method might due to three different errors’ categories individually or altogether. The first category is related to the calibration process that depended on the available flow and sediment measurements of the adjacent drainage basin and the accuracy of the geospatial data that might give an underestimated sediment rate. The second one due to the associated errors with the bathymetric survey (positioning error, bottom depth error, etc.) and the interpolation error of converting surveying points to DEM. The third one might due to the accuracy of the contour maps and their digitization that might give an overestimated sediment rate.

According to Figure 5, the storage volume at contour 420 has been fully filled with sediment by 2014. Contour 440, which extends from the southern reservoir (Reservoir B) to the south of the northern reservoir (Reservoir A), is 75% full of sediment. A total of 47% of the contour at 460 m.a.s.l. and 25% of the contour at 480 m.a.s.l. have also been filled by sediment (see Figure 6b). The dead storage at 469 m.a.s.l. has a volume reduction of 36%, whereas the live storage has reduced by 64% of the volume.

### 3.2 Upper reservoir sediment deposited

The reduction in the storage capacity of the upper reservoir at water level 480 m.a.s.l. was 24% of the capacity for the period between 1952 and 2014, whereas the storage capacity at 460 m.a.s.l. and 440 m.a.s.l. has lost 48% and 72% of capacity, respectively (see Figure 7). The volume of the deposited sediment is estimated to be around 274 MCM.

The reduction percentages in the upper reservoir are quite similar to those of the whole reservoir because it represents the majority of the reservoir area.

### 3.3 Lower reservoir sediment deposited

The percentage of the lower reservoir area as a percentage of the whole reservoir area varied in 1952 from 4% at water level 520 m.a.s.l. to 100% at 420 m.a.s.l. (see Figure 8a). A significant bend in the curve is shown at 460 m.a.s.l. where the slope of the curve is steeper above this level indicating that the lower reservoir has smaller areas below that level with respect to the whole reservoir. The share of the lower reservoir’s area will be higher down to the lowest point at the level of 420 m.a.s.l. A significant shifting in the area percentage curve was detected in 2014 at elevations lower than 460 m.a.s.l. (see Figure 8a). At elevation 420 m.a.s.l., the area of the reservoir is almost zero, where it represents the lowest point within the reservoir that is reflected on the 2014 curve.

The pattern of storage reduction in the lower Dokan Reservoir is quite similar to that in the upper reservoir. As a result of sediment deposition, the dead storage at 469 m.a.s.l. has a volume reduction of 36%, whereas the live storage has reduced by 64% of the volume.
delivery from small subvalleys on both sides of the two reservoirs, the distribution of coarse sediment was concentrated on the southern half of the upper reservoir and the whole of the lower reservoir (see Figure 9) according to the sieve and hydrometer analysis of 32 samples of bed sediment, those were gathered over the reservoir area (Hassan et al., 2016). The storage volume at 440 m.a.s.l. has been filled to 71% by sediment, whereas the storage volume at 460 m.a.s.l. and 480 m.a.s.l. have been filled by sediment to around 42% and 26%, respectively (see Figure 8b). The volume of the deposited sediment is estimated to be about 62.9 MCM.

4 | CONCLUSIONS

The reduction in the storage capacity of Dokan Dam Reservoir was calculated using the volumetric change between topographic maps constructed before building the dam and the bathymetric survey conducted in 2014. The delivered sediment over the operation period (1959–2014) was estimated to be of the order 367 MCM at water level 480 m.a.s.l. that is equivalent to a 0.45% annual loss of the design capacity. Such annual loss was considered to be low according to the official estimates. However, the sedimentation rate was higher than another estimate for the reservoir using the modified universal soil loss equation. The estimated sediment yield was similar to the regional estimates given in the global classification map of the world by Walling and Webb (1996). The average sediment concentration was eight times higher than the measured one in the Tigris River to the south indicating that the reservoir has high sediment trap efficiency.

The storage volume at contour 420 was fully aggraded with sediment by 2014, whereas contour 440 has been occupied by 75% by sediment. The contours 460 and 480 have been filled by sediment to 47% and 25%, respectively. The dead storage at the level 469 m.a.s.l. has a share of volume reduction of 36%, whereas 64% of the volume reduction is the share of the live storage.

Because the upper reservoir represents the majority of the reservoir area, volume reduction percentages over different contours are similar for the whole reservoir. The pattern of sediment deposition in the lower Dokan Reservoir is similar to that in the upper reservoir. The distribution of the coarse sediment in the upper and the lower reservoirs indicates that the small subvalleys on both sides of the two reservoirs are still active and deliver sediment to the reservoir.

The area’s percentage of the lower reservoir has varied over the whole reservoir from 4% at water level 520 m.a.s.l. in 1952 to 100% at 420 m.a.s.l. in 2014. As much as water rises in the reservoir, the ratio of the storage volume of the lower reservoir reduces with respect to the whole reservoir and vice versa until the limit there is no area at elevation 420 m.a.s.l. other than the lower reservoir.

The estimated annual deposition rate of 6.6 MCM, the projected useful lifespan might extend for another 155 years until 2,169, where the sediment will fully occupy the live storage. This rough prediction has to investigate in details in further work using the sediment trap efficiency approach. This provisional estimate assumes no increase caused by climate change or land use and in the long term will be affected by the trap efficiency of the reservoir, which will decrease significantly as it fills with sediment.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author, [N. Al-Ansari], upon reasonable request.

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FIGURE 9  Distribution of bed sediment classes of the Dokan Dam Reservoir (Hassan et al., 2016)
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