Bathymetry and siltation rate for Dokan Reservoir, Iraq

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Abstract
The Dokan Reservoir dam is a concrete cylindrical arch with gravity abutments, located on the Lesser Zab River about 60 km from the city of Sulaimani in north-eastern Iraq. A bathymetric survey was conducted in November 2014 for a period of 10 days, using an echo sounder of 200-kHz single beam. The survey results indicated an annual average sediment deposition of 3.8 million m³. Thirty-two sediment samples were collected from the reservoir bed. The ratio of gravel, sand, silt and clay was 15:14:48:23, respectively. The reservoir bed is covered mainly with silt. The sediments are composed of silty clay (77.6%), silty sandy clay (10%), sandy gravely silty clay (1.2%) and gravely sandy silty clay (1%).

Key words
Bathymetry, Dokan Reservoir, Iraq, siltation.

INTRODUCTION
Dokan Reservoir is located on the Lesser Zab River, approximately 60 km north-west of the city of Sulaimani in the Kurdistan Region of north-east Iraq (Fig. 1). Dam construction began in 1954 and was completed in 1959. The dam is located in a narrow steep-sided gorge incised in limestone and dolomite rocks. It is a concrete cylindrical arch with gravity abutments (Fig. 1). The maximum height of the dam is 116.5 m (crest level 516.0 m.a.s.l.). The total crest length is 345 m, while the left and right gravity abutments lengths are 41 and 64 m, respectively. The length of the arch is 240 m (Binne et al. 1959). The reservoir catchment area is 11 690 km².

The reservoir surface area is 270 km², and the storage volume is 6.870 × 10⁶ m³ at the normal operation level (elevation of 511.00 m.a.s.l.). The minimum drawdown level is at an elevation of 469 m.a.s.l, with a live storage of 6.14 × 10⁶ m³, with the remainder being dead storage (Water Feature stories, 2008).

METHODOLOGY
Study area
Dokan Reservoir is located in the High Zagros Fold-Thrust Zone (HZFTZ) of the Kurdistan (NW) segment of the Zagros Fold-Thrust Belt (Fig. 2). It comprises harmonic folds with Mesozoic limestone in their cores, and Palaeogene and Neogene limestone and clastics on their flanks (Jassim & Buday 2006).

Hydrology
Lesser Zab River drains an area of 19 780 km², of which 24% lies in Iran and 76% in Iraq (Al-Ansari & Knutsson 2011; Al-Ansari 2013; Al-Ansari et al. 2014, 2015). The river discharge is recorded at two gauging stations (Dokan; Alum-Kupri), which drain 11 690 and 169 600 km², respectively). The average river discharge at these stations is 191 and 249 m³ s⁻¹, respectively. The discharge for both stations is characterized by regular oscillations of wet and dry years (ESCWA 2013). As a result of the hydrological schemes built on the river, its discharge has decreased below the average since 1999 (World Bank 2006; ESCWA 2013).

The peak river flow occurring during April. Bennie and Partners (1987) conducted a study concerning the adopted design flood and estimated probable maximum flood (PMF), as summarized in Table 1. It was concluded reservoir operations were in accordance with the rule curve and spillway operation criteria. World Bank (2006) study of the reservoir water levels (Fig. 3) and the original rule curve indicated the original rule curve has not been observed for a number of years, being attributed to construction of new projects on the river.
The bathymetric surveys are used to directly measure sediment deposited in lakes and reservoirs, with many procedures being introduced for water depth measurements. Murray and Pullar presented a lead-lining recorder method for water depth measured using a winch system which was used in Loch Earn in the Grampian Highlands of Scotland (Al-Ansari & McManus 1980). Weighted wire drag survey methods were introduced in 1904, and acoustic depth sounding (fathometer) was used in the 1930 (USACE 2004; NOAA 2012). Single-beam techniques were used to measure water depth from the 1940s to the 1980s and then multibeam techniques were developed. During this period, up to 1994, three-point sextant fixes to map reference points or else microwave equipment (range–range or range–azimuth) methods were used to determine the position of the boat (USACE 2004; NOAA 2012). Through that period, the range line survey was commonly used, rather than a contour survey, due to its relatively low cost. Important advances in bathymetric surveying technology have occurred since 1994 because of the use of Global Positioning Systems (GPS), instead of the short-range microwave positioning techniques. Furthermore, the field data collection equipment and software have also become more advanced (USACE 2004).

The recent advances in GPS, depth measuring systems (sonar viewer technique) and analysis procedures have also improved with the continued development of computers and data collection software. The contour method has become the preferred method for reservoir survey. This method is the most accurate technique for determining the total volume of sediment deposited, sedimentation pattern, the sediment yield from the watershed and shift in the ASC curves (Ferrari & Collins 2006; Morris & Fan 1998).

Fig. 1. Location map of (a) Dokan Reservoir, with (b) upstream view of emergency spillway.
Fig. 2. Geological map showing surface distribution of stratigraphic units in study area (Sissakian 2000).
Field techniques and collecting data

A bathymetric survey for Dokan Reservoir (DDR) was conducted in November 2014, using an echo sounder with a 200-kHz single beam. The bathymetric survey was for about 10 days, starting on 22 November, 2014, and ending on 2 December, 2014. Details of the transect lines during the DDR bathymetric survey are shown in Figure 4. The survey was conducted according to U.S. Army Corps of Engineers standards for distances between transverse sections, boat types and calibration methods (USACE 2004). The echo sounder was calibrated before the bathymetric survey, according to the methods of Ferrari and Collins (2006) and Eagle Electronics (2003). The error values of the water depth measurements were ±4 cm, depending on the reservoir water depth. The water temperature ranged between 20 and 22 °C during the survey period. According to Ferrari and Collins (2006), this small water temperature variation has negligible effects on water depth measurements. The bathymetric survey was performed in calm water to avoid wave-related errors in water depth measurements. The water surface elevations during the survey were measured at the dam site, being between 482.47 and 482.84 m.a.s.l.

Data processing

The echo sounding survey system produces data files (slg format) of water depth and boat position, with each file converted to E, N, Z coordinates in Excel. All water depths were transformed to the reservoir bed elevations, according to the reservoir water elevations on the survey date. The survey was conducted during calm periods when wave heights were less than 10 cm, meaning the effects of waves were negligible. The final bathymetric survey data were about 65 416 points within the reservoir area, being used to develop a triangulated irregular network (TIN) surface of the reservoir topography using ArcGIS software (Fig. 4). Contour lines at certain elevations were generated from the TIN surface. Longitudinal and transverse profiles were extracted from the TIN surface along the two parts of the reservoir in order to better understand the reservoir topography (Fig. 5).

Reservoir topography and characteristics

The bathymetric map produced from the bathymetric survey in 2014 (Fig. 4) illustrates the minimum elevation, being 430 m.a.s.l. in the southern part of the larger triangle-shaped reservoir. The eastern part has a relatively gentler slope of approximately 1:180, while the western slope is about 1:53 (Fig. 5). The northern part of the reservoir (i.e. the base of the triangle) has the relatively gentler slope reaching 1:150. The gentler slope is towards the north-east of the reservoir because most of the sediment is deposited in that part of the reservoir where the valleys enter it. The longitudinal section of the reservoir confirms this observation, with the slope gradually

Table 1. Summary of Dokan Reservoir flood studies (Binnie & Partners, 1987)

| Parameter                          | Maximum recorded values | Project design flood | Bennie PMF |
|-----------------------------------|-------------------------|----------------------|------------|
| Maximum reservoir level (m)       | 510.77                  | 514.70               | 513.70     |
| Date                              | 28-29/04/1974           | –                    | –          |
| Minimum reservoir level (m)       | 441.91                  | –                    | –          |
| Date                              | 15,16/12/1988           | –                    | –          |
| Peak inflow (m³ s⁻¹)              | –                      | 18 700               | 24 400     |
| Freeboard                         | 5.23                    | 1.30                 | 2.30       |
| Maximum total outflow (m³ s⁻¹)    | 1800                    | 4180                 | 3470       |
| Maximum spillway outflow (m³ s⁻¹) | 1500–1800               | 4180                 | 3470       |
| Date                              | 10–12/04/1969           | –                    | –          |

Fig. 3. Dokan Reservoir water level, 1990–2002 (World Bank, 2006).
decreasing towards the south, where it reaches its minimum bed elevation. The southern part of the reservoir, with a rectangular shape, exhibits a steeper slope reaching 1:8 close to the dam axis.

The bathymetry and field observations indicate bank sediment erosion in both parts of the reservoir. Further, it is clear most of the deposition takes place within the upper part of the reservoir.

RESULTS

Storage–area–elevation curves

Based on the 2014 bathymetric survey, updated storage–area–elevation curves can be implemented for Dokan Reservoir. The new curves were based on accumulative surface areas and storage volumes determined from the TIN surface for certain water elevation ranges bounding around 430 m, the lowest bed elevation in the reservoir, and 480 m, close to the water elevation on the surveying date (Fig. 6). These figures include the area–storage–elevation curves previously conducted in 1950 (before dam construction) by Bennie and Partners in 1987 and SGI in 2008 (Iraqi Ministry of Water Resources 2014) as the first survey after construction of the dam in cooperation with Iraqi local authorities. A good understanding of the changes in reservoir capacity and the quantity of trapped sediment from different occasions can be achieved by combining the new area–storage–elevation curves with the previous ones on the same figures.

Comparing the new storage–elevation curve with the first one, based on the dam design in 1959, can illustrate a siltation of 209 million m³ at an elevation of 470 m.a.s.l. resulting in an annual average of 3.8 million m³ of sediment deposition within the reservoir. It is believed the actual siltation rate is higher because of the fact that the survey did not cover areas above an elevation of 490 m.a.s.l.

The cumulative differences between the storage capacity of the previous 2008 survey and the current one (Fig. 6c) indicates the highest deposition rate occurs within the elevation ranges of 470–477 m.a.s.l., where the differences are the highest, and at lower rates in the range of 460–470 m.a.s.l., and then in the range of 450–460 m.a.s.l., while the differences tend to be constant at the elevation range of 477–480 m.a.s.l. The deduced results indicate the dominant water depth of 470 along the front of the counter was sufficiently high to deposit most of the incoming sediment load during the 2008–2014 period, and the remaining transported load has been gradually accumulating during its incursion into the deeper reservoir water.
Bed sediment characteristics

A total of 32 sediment bed samples were gathered from Dokan Reservoir, using a Van Veen Grab. The sample analyses indicated the bed sediment consists of 15, 14, 48 and 23 per cent of gravel, sand, silt and clay, respectively. The clay sediments are composed of silty clay (77.6%; Fig. 7), silty sandy clay (10%), sandy gravely silty clay (1.2%) and gravely sandy silty clay (1%; Hassan et al. 2016).

The gravel sediment (sandy silty clayey gravel; sandy gravel) are deposited at the shore lines of the bigger and smaller reservoirs (Fig. 8a), perhaps attributable to the erosion from the reservoir boundary soil because of applied wave action on the cliffs or the run-off in the valleys discharging into the reservoir. The gravely silty clayey sand and gravely sand sediments are mostly deposited in the smaller rectangle-shaped reservoir, and as small patches at the east and west shore lines of the lower part of the bigger triangle-shaped sublake (Fig. 8b). More than 75% of the sandy silt sediments are deposited near the entrance of the Lesser Zab River into the bigger reservoir. The remainder of the bigger reservoir, and the smaller reservoir next to the dam site, are covered by (>50–75%) of sandy silt sediments (Fig. 8c). More than 30–45% of the clay sediments are deposited where the Hizop stream enters the smaller reservoir next to the dam site (Fig. 8d). The abundance of clay and silt sediments in Dokan Reservoir might be due to low energy, and a calm depositional environment.

Fig. 5. Cross section profiles of Dokan Reservoir bathymetric survey, 2014.
The clay percentage profile along Dokan Reservoir (Fig. 9) indicates an oscillation in the percentage of clay (between 20 and 45%) in the bigger reservoir (i.e. A–A’ profile in Figure 9), possibly attributable to the oscillation in the reservoir storage level during over the past that could produce different stages of siltation of the incoming clay sediment. The clay percentage increases gradually in the gorge (i.e. A0–A” profile) and exhibits a quasi-constant percentage in the smaller reservoir (i.e. B–B0 profile).

The silt percentage profile along Dokan Reservoir (Fig. 10) indicates a quasi-constant percentage of silt in the bigger reservoir (i.e. A–A’ profile) around 60%, attributable to sufficient storage level in the reservoir that could produce siltation of incoming silt sediment. The sudden drop in the percentage between stations 10 and 12 km in the A–A’ profile is due to increasing incoming coarser sediment (sand) via the valleys at the end of the bigger reservoir. The percentage of silt has increased continuously along the gorge (i.e. A’–A” profile) and the smaller reservoir (i.e. B–B’ profile). It exhibits the highest percentage close to the dam axis, with the increase in this part of the reservoir attributable to the supply from nearby valleys, and deposition of suspended material in the water in this area because of the extremely low water velocity.

**SUMMARY**

The 2014 bathymetric map produced from the Dokan Reservoir survey indicated the minimum elevation (which reaches 430 m.a.s.l.) is located at the southern part of the bigger triangle-shaped reservoir. The eastern part has a relatively gentler slope of approximately 1:180, while the western slope is about 1:53. The northern part of the reservoir has the relatively gentler slope, reaching...
Fig. 8. Surface distribution area percentages of deposited gravel sediments (a); sand sediments (b); silt sediments (c); clay sediments (d) (Hassan et al. 2016).
Fig. 9. Bottom sediment profile of clay percentage along Dokan Reservoir.
Fig. 10. Bottom sediment profile of silt percentage along Dokan Reservoir.
The results indicate that annual rate of sediment deposition is 3.8 million m$^3$. Analysis of thirty-two bed sediment samples indicated the bed sediment consists of 15, 14, 48 and 23% gravel, sand, silt and clay, respectively. The sediments are composed of silty clay (77.6%), silty sandy clay (10%), sandy gravely silty clay (1.2%) and gravely sandy silty clay (1%). The reservoir bed is covered mainly with silt. Both silt and clay percentage increased towards the dam in the smaller reservoir. This is believed to be attributable to the decreased water velocity in the, leading to deposition of the suspended material.

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