A numerical study of pumping effects on flow velocity distributions in Mosul Dam reservoir using the HEC-RAS model

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Abstract
Water flow direction and velocity affect and controls erosion, transport and deposition of sediment in rivers, reservoirs and different hydraulic structures. One of the main structures affected is pumping stations within the dams wherein the velocity distribution near the station intake is disturbed. The two-dimensional (2-D) HEC-RAS 5.01 model was utilized to study, analyse and evaluate the effects of pumping rates and flow depth on the flow velocity distribution, flow stream power and their effects in the Mosul Dam reservoir. The pumping station was considered as a case study. The station is suffering from sediment accumulation around, and in, its intake and suction pipes. The main inflow sources to the reservoir are the Tigris River and run-off from the valleys within its basin. The reservoir was divided into two parts for the present study, including the upper part near the pumping station (analysed as a two-dimensional zone), while the lower part was analysed as a one-dimensional flow to reduce the simulation period computation time (1986–2011). Different operation plans (i.e. pumping rate and water depth) were considered. The results of the depth-averaged velocity model indicated that when the pumping station was working at a range from the designed full capacity (100% to 25% of its full capacity), the maximum flow velocity increased from 75 to 4 times the normal velocity when there is no pumping dependent on pumping rate and flow depth. For the same operation plans, the flow stream power varied from around zero values to 400 times at full pumping capacity and low flow depth. For sediment routing along the reservoir, the considered statistical criteria indicated the model performance in estimating the total sediment load deposition and invert bed level is much better than in the case of erosion and deposition areas for different considered bed sections of the reservoir.

Keywords
pumping station, sediment concentration, stream power, velocity distribution
1 | INTRODUCTION

Sediment deposition in reservoirs is one of the most common problems for all dam storage works around the world. Sediment deposition generally reduces the water storage capacity by as much as 0.8% annually (Basson, 2009), leading to a reduced project life, even with increasing water demands. Another problem arises from sediment deposition near the gates of power generation plants, which can affect the operation efficiency of a dam.

Pumping stations are one of the main structures in some multipurpose dam and reservoir projects, especially in cases where water supply and land irrigation occur at a higher elevation than the reservoir water level. As the reservoir is the source of pumped water for such stations, the sediment concentration, sediment properties, and pumping rate affect the total quantity of water delivered, the quantity entering the intakes and the water pumping capacity. The mechanical elimination of sediment, particularly from a large reservoir, is an expensive process, compared to utilization of a suitable hydraulic method for controlling or reducing the sediment effects.

Physical models are typically used to study, analyse and formulation solutions to different sedimentation problems in reservoirs and other hydraulic structures. These types of models are scaled descriptive of water flow state and geometry, usually being used for design and optimizing the efficiency and safety of different hydraulic structures.

As an example, the effects of reservoir water levels and upstream inflow rates on sediment load transportation in the upper part of Mosul Dam reservoir were studied by Issa, Al-Ansari, Knutsson, and Khaleel (2012), using a moveable bed distortion model. This type of model, however, is considered expensive, compared to mathematical or numerical models, which are more widely used techniques. A major advantage of using computational models is that they can be employed with different physical domains more easily than physical models, the latter tending to be more site-specific (Papanicolaou, Elhakeem, Krallis, Prakash, & Edinger, 2008).

The most common models for reservoir sedimentation include: (a) the Hydrologic Engineering Centers River Analysis System models (HEC-RAS 1-D and 2-D) (U.S Army Corp of Engineers, 2016), (b) the National Center for Computational Hydro Science and Engineering models (CCHE, one-dimensional and two-dimensional) (Khan, 2003), (c) the Hydrodynamic and Sediment Transport Model, known as the Estuarine Coastal Ocean Model (ECOMSED, 3-D) (Blumberg & Mellor, 1987) and (d) the Simulation of Sediment Movements in Water Intakes with Multi Blocks Options model (SSIIM, 3-D) (Olsen, 2018).

Some previous studies applied 1-D, 2-D or 3-D models to simulate flow, sediment transport and reservoir bed formation. (Jungkyu & Song, 2018) applied a 1-D numerical sediment transport model to study the effects of the number stream tube on sediment on the model performance by comparing the results with 14 years of actual sediment data. Reasonable results were obtained with three stream tubes, with the numerical results varying depending on the densities of deposited sediments. Hu, Cao, Pender, and Tan (2012) presented a coupled layer-averaged 2-D model that absorbed both the current sediment transport and morphological formation. It was applied to simulate two measured turbidity current events in the Xiaolangdi Reservoir on the Yellow River, with the results indicating the model was a suitable tool to define both the current front location and the suitable time of opening the bottom outlets to implement reservoir sediment management. Isaac & Eldho (2019) presented a 3-D model and experimental work focusing on hydraulic flushing of the reservoir to identify the suitable orientation intake and to optimize hydraulic flushing. The variations between the 3-D model results and experiments were between 4% and 6% for the different discharges and durations considered in their analysis. Their results also indicated the 1-D model for sedimentation and the 3-D model for sediment flushing can be efficiently applied for planning and design purposes.

Previous studies have applied HEC-RAS to evaluate the sedimentation process in the Tuttle Creek Reservoir (Shelley et al., 2015) and the Olmsted Locks in the United States (Ghimire & DeVantier, 2016), with the results indicating the model is an efficient tool for sediment studies. The HEC-RAS model as a one-dimensional (1-D) model was applied to simulate the flows and evaluate the total sediment deposited in Mosul Dam Reservoir within 25 years of its operation from 1986 to 2011 (Mohammad et al., 2016). The results indicated the model performance was good for estimating the total load deposited in the reservoir, compared to the bathymetry survey (Issa, Al-Ansari, & Knutsson, 2013, 2013a,b).

For some storage reservoirs with a pumping station as one of the main attached structures, the pump operation changes the flow regime and sediment transport in the area. Sediment movement today and inside the pump results in a reduced pumping efficiency and capacity. A number of previous studies looked at sedimentation problems near intakes and pumping stations. As one example, the CCHE two-dimensional model was applied to analyse the sedimentation problem at the Rowd El-Farag pump station intake (Moussa, 2011). The SSIIM2 model was applied to simulate the flow velocity distribution and sedimentation in the intake in a rectangular channel (Ashari & Merufinia, 2015), with the 3-D model exhibiting a good agreement with measured values from previous studies.

The effects on the flow pattern resulting from pumping from a reservoir was studied, and a numerical simulation model was compared with field measurements to better understand the flow pattern near a reservoir pumping station intake (Michael, Cesare, & Schleiss, 2018). The results indicated the pumping effect on the flow pattern in front of the intake was not significant, while injected water by a turbine model had an important effect in the nearby area. The problem of sediment deposition near the Mosul Dam Reservoir pumping station was studied by Mohammed (2001), including field measurements of the flow velocity at selected points, sediment depth, grain size distribution of the deposited sediment material and grain size distribution of the suspended load.
The general objective of the present study was to analyse the flow velocity and direction near the pumping stations in reservoirs using a two-dimensional model, which help identify extent of pumping effects on the reservoir’s flow regime. This is in addition to better understanding the effects of the stream power as an indication of the sediment transport capacity of the flow towards the pump intakes. The flow velocity and direction are the most important factors driving the sediment movement, which leads to deposition or erosion. Further, identification of the sediment concentration along the reservoir helps to evaluate the effects of the main river flow and different additional run-off on the reservoir sediment concentration.

2 | STUDY AREA AND INPUT DATA

2.1 | Mosul Dam

Mosul Dam, a reservoir located on the Tigris River about 60 km northwest of Mosul City, is the study area (Figure 1). The Mosul Dam is a multipurpose dam used for flood control, irrigation, power generation and supplying water to the downstream cities. The pumping station at Mosul Dam is one of the main structures of the dam project, meant primarily to supply irrigation water.

The Tigris River, as well as the sediment carried in run-off flows from the ten valleys on both sides of the reservoir, comprises the main sources of flows and sediments delivered to the reservoir. These valleys are seasonal, carrying significant rainfall run-off flows and sediment loads in the winter, and being mostly dry in the summer. The reservoir was divided into two zones for the present study. Zone 1 is the upper part, extending for 24 km from the reservoir inlet (Figure 1). The flow velocity and direction in this zone were analysed as a two-dimensional flow. In contrast, the lower part (zone 2) was considered as a one-dimensional flow to reduce the simulation computation times.

2.2 | Pumping station

The pumping station within Mosul Dam was constructed in 1985 at the time of the dam’s construction. It is located on the right bank of the reservoir, about 20 km from the simulated reservoir along the thalweg path (Figure 1). The station started to supply supplementary irrigation water to the North Jazeera Irrigation Project in 1991. The project is located in the northwest of Ninawa Governorate’s Rabeaa Sector, covering an area of about 600 km². The main station components are the stilling basin, the intake structure and the central pumping station. The pumping unit consists of twelve pumps with a maximum pumping capacity of 4 m³/s for each unit. One of the station’s main problems is sediment accumulation in the approach to the intake structure and in the suction pipes, affecting the pumping efficiency and capacity, and threatening the continuation of the station’s operations (Mohammed, 2001).

3 | METHODOLOGY

The present study was undertaken using the River Analysis System developed by the Hydrologic Engineering Canter (HEC-RAS model, 5.06). The model simulates the flow in rivers, channels and reservoirs with different hydraulic structures, including embankments, bridges, culverts and weirs. The model can also simulate the sediment transportation as a one-dimensional flow, including deposition and erosion for long periods. In the case of reservoir flow, the plane flow distance is much greater than the perpendicular distance; thus, the vertical velocity was considered to be low, meaning the vertical velocity and its derivative in the mass and momentum equations can be neglected in the analysis.

Based on the hydraulic of fluid flow, the two-dimensional equation of flow uses an implicit finite volume algorithm for the continuity equation. For sediment load calculations, the model considers a control volume for each cross-section to solve the sediment load continuity equation as a one-dimensional model. The advantages of such a model are a reasonable computing time, and suitability for simulating and solving sedimentation problems with limited calibration data (Molinas and Yang, 1986).

The deposition or erosion (i.e. change in bed section) that will occur for each control volume can be estimated on the basis of the difference between the load entering and released by the control volume. The released load depends on the flow transport capacity, which can be estimated at more than one section for non-cohesive sediment, depending on the hydraulic and sediment particle properties.

For all approaches, the instigation of bed particle movement generally depends on such flow characteristics as the flow velocity, depth and sediment properties. The shear stress can be used to identify the creation of particle motion and the flow transport capacity, expressed using the stream power. The stream power is the product of the average flow velocity and the average shear stress. Assessment of the shear stress helps confirm whether or not the flow can detach and transport sediments on the basis of a critical shear stress value.

4 | INPUT DATA AND MODEL CALIBRATION

4.1 | Geometry data

The geometry of Mosul Dam was based on available contour maps for the area prior to the construction of the dam, as well as available digital elevation model data (USGS). The reservoir length along the river basin at a maximum operation level is about 80 km (335 m.a.s.l.) and was divided into 80 sections with an average length of 1-km interval between each section. The projected section was then converted to a terrain map to represent the reservoir geometry for consideration in the HEC-RAS model. The elevation-storage curve of the reservoir geometry (considered in the model as a terrain file) was compared with
**FIGURE 1** Mosul Dam Reservoir zones 1 and 2, valleys and pumping station location

**FIGURE 2** Storage-elevation curves for Mosul Dam at dam construction in 1986
the rating curve of the reservoir before the dam operation began in 2.983 (Issa et al., 2013) with the two curves exhibiting good agreement with a determination coefficient ($r^2$) of 0.98 (Figure 2).

4.2 | Flow and sediment data

The recorded daily flow rate of the Tigris River upstream of the reservoir and the sediment rating curve was created to represent the sediment load carried by the river upstream of the reservoir. In addition to the main river flow, seasonal valleys also add to the reservoir. The estimated daily flow rate and sediment load for the valleys located on the right and left banks of the reservoir were previously estimated and considered as model input (Mohammad et al., 2012; Mohammad, Al-Ansari, & Knutsson, 2013).

4.3 | Model calibration

The model was calibrated for both flow and sediment load. The measured inflow and outflow data were considered, with the reservoir water level determined from the model simulation. The simulated reservoir levels were compared with measured values through the study period (1986 to 2011) to evaluate the model performance. The determination coefficient, Nash–Sutcliffe model efficiency, and paired t test values were used to evaluate the model performance. The obtained determination coefficient was 0.87, the Nash–Sutcliffe model efficiency was 0.88, and the paired t test value was 0.37 (tabulated value at a significance level of 0.05 is 1.96), indicating there was no significant difference between the observed and simulated values.

For sediment routing, the model can simulate the continuity, momentum and sediment transportation equations only as a one-dimensional flow. Nine scenarios were considered to simulate the sediment trapping in the reservoir and the sediment distribution as deposition or erosion. The nine scenarios resulted from combining three sediment transport capacity approaches with three fall velocity approaches to assess how rapidly the particles can drop out of the water control volume and be deposited.

| No | Sim. Method, Transport capacity function | Fall velocity | Determination coefficient ($r^2$) | Nash–Sutcliffe model efficiency | t test value |
|----|------------------------------------------|---------------|----------------------------------|-------------------------------|-------------|
| 1  | Ruby                                     | 0.80          | 0.79                             | −0.514                        |             |
| 2  | Ackers–White                             | 0.80          | 0.81                             | 0.462                         |             |
| 3  | Van Rijin                                | 0.80          | 0.80                             | −0.445                        |             |
| 4  | Ruby                                     | 0.81          | 0.81                             | −0.466                        |             |
| 5  | Laursen                                  | 0.84          | 0.83                             | 0.481                         |             |
| 6  | Van Rijin                                | 0.81          | 0.80                             | −0.467                        |             |
| 7  | Ruby                                     | 0.82          | 0.79                             | −0.672                        |             |
| 8  | Toffaleti                                | 0.81          | 0.8                              | −0.099                        |             |
| 9  | Van Rijin                                | 0.80          | 0.79                             | −0.672                        |             |

The three sediment transport approaches considered were the Ackers–White, Laursen and Toffaleti models. The three equations considered for the fall velocity were the Rubey, Toffaleti and Van Rijin approaches.

The selected approaches for both the sediment transport capacity and fall velocity are suitable for the size of the sediment load entering Mosul Dam. The considered material size of the sediment load for the Tigris River ranged from 0.0008 to 0.6 mm, while the sediment load from the valleys on both sides of the reservoir ranged from 0.001 to 0.4 mm. The soil classifications for both the right and left valleys generally were clay, clay loam, silty clay, silty clay loam and silty loam.

The evaluation of each simulation scenario was based on comparison of the model results with bathymetry survey data for 54 sections (Issa, 2015). The average bed level of the sections extending from the dam axis to 60 km upstream was compared with the measured values, with the final simulation values being based on statistical criteria, the determination coefficient, Nash–Sutcliffe model efficiency coefficient and t test values. The average change in bed level of the sections was considered in a calibration process to evaluate each scenario.

The results in Table 1 indicate all the considered scenarios gave acceptable values, compared to the measured values for the average bed levels of the sections. The determination coefficient ranged between 0.80 and 0.84, and the Nash–Sutcliffe model efficiency was between 79% and 83%. The best values were obtained for scenarios 2 and 5, being attributed to the selected simulation methods being suitable sediment grain sizes. The long period of the simulation (25 years), however, and the wide inflow rate variation (between 60 and 3,250 m$^3$/s) may also have partially affected the difference observed between the methods. The t test values ranged from −0.672 to 0.46, indicating most of the scenarios exhibited negative values significantly different from the measured values (the t test values out of the tabulated value (0.65) at a significance level of 0.05), except for scenarios 2 and 5, which exhibited positive values less than the tabulated values. The absolute values of the negatives were below the tabulated value, indicating a significant difference compared to the measured values. These results match the determination coefficient and Nash–Sutcliffe model efficiency evaluations.
As a model verification, the measured average depth velocities in front of the pumping station intake were 0.366 and 0.113 m/s at the 50% pumping rate at distances of 5 m and 25 m from the intake around the normal operation level, respectively (Mohammed, 2001). The simulated values were 0.372 and 0.212 m/s at the same respective distances, indicating good model performance, especially near the intake at a distance of 5 m. The difference from the measured values at 25 m is considered high, possibly attributable to the low flow velocity measured with a current metre, whose accuracy depends on the accuracy of the device used for the measurement.

5 | SIMULATION OF FLOW AND SEDIMENT

The applied model has the ability to simulate the flow hydrodynamics as an unsteady flow for one-dimensional and two-dimensional cases, as well as a hybrid between these two cases. The two-dimensional model provides more details and accuracy for different hydrodynamic parameters of the flow, although a drawback compared to the one-dimensional model is the computational time, which depends on the mesh number and size. The surface area of Mosul Dam is about 375 km² at the normal operating level, with 37,500 100-m² cells being required to cover the whole area. The main concerns are the flow analysis near the pumping station zone, and the reduced computation time, so it was not deemed necessary to simulate the entire reservoir area as a two-dimensional flow.

The study area was divided into two main parts. The upstream part extends for 24 km from the simulated reservoir inlet to about 4.0 km downstream of the pumping station, being simulated as a two-dimensional zone. The other part of the area was simulated as a one-dimensional zone (Figure 1). The main improvement of this hybrid simulation model is a reduced number of cells from 37,500 to about 6,600 cells, and a lower computation time because the study focus was on zone 1.

The simulation was executed for the unsteady two-dimensional flow case for the daily data with computation time steps of 120 s. The inflow within the study period (1986–2011) varied between 60 and 3,250 m³/s, while the water depth varied by as much as 30 m between the minimum operation level (300 m.a.s.l) and the normal operation level (330 m.a.s.l.). Different plans were considered to evaluate the extent and effects of pumping on the flow velocity and stream power, based on the variation of water storage levels between the minimum operation level of the station (305 m.a.s.l or 5 m inlet head) to the normal operation level (330 m.a.s.l or 25 m inlet head) and four pumping rate capacities (25%, 50%, 75% and 100% pumping capacity).

Scenario 5, which is combined between Laursen as a sediment transport capacity approach and Toffaleti as fall velocity approach, gave the best statistical values of the considered criteria, therefore, justifying its use for sediment analysis as a one-dimensional model.

6 | RESULTS AND DISCUSSION

6.1 | Flow analysis

The flow simulation for the upper part of the reservoir (i.e. two-dimensional zone) indicated the depth-averaged flow velocity in this part of the reservoir was between 2.40 and 0.25 m/s in the narrow river sections, and between 0.06 and 0.007 m/s near the reservoir expansion sections. This variation depends on the inflow rates and the reservoir’s water storage level. Figure 3a illustrates the depth-averaged velocity distribution in the two-dimensional zone with an inflow rate of 560 m³/s and an operation level at 330 m.a.s.l. The velocity distribution indicates a high velocity in the upper part of the two-dimensional area, reaching maximum values of about 0.6 m/s. The velocity then decreases gradually at a distance of 12 km from the inlet, before reaching a relatively constant velocity of 0.01 m/s at a distance of 15 km. Knowledge of the velocity distribution pattern is important in order to better understand how it can affect the stream power and the transport and deposition of the sediment load.

The operation of the pumping station changes the flow depth-averaged velocity distribution near that location (although not clearly illustrated in Figure 3a). The operation affects the flow velocity because of flow suction. The shape of the depth-averaged velocity distribution near the intake looks like a semi-circle attached to the intake. Figure 3b illustrates the contour lines of the depth-averaged velocity near the pumping intake at a pumping rate of 50% of the maximum capacity and an operation level of 315 m.a.s.l. It indicates the pumping changes the velocity, the extent of the affected area and the velocity distribution in the reservoir, indicating the pumping changes the flow in all these areas. As the horizontal pressure gradients result from movement of the water surface, the horizontal velocity is generally relatively constant over the depth (Dorfmann, 2017), enhancing the application of the 2-D model. The situation near the water intakes, outlets and the vertical profile of horizontal velocity, however, is different, meaning a 3-D model is better able to simulate the case study. At the same time, however, the considered depth-averaged model can also provide insights about how the pumping from the reservoir can affect the depth-averaged flow velocity distribution and its effects on sediment transport.

Different pumping plant operation plans were considered to examine the effects of water storage levels and pumping rates on the depth-averaged flow velocity, effective radius and stream power, as a measure of flow ability to detach and transport sediment. The relation between flow area (depth) and with flow velocity is generally inverse, while the pumping rate is positive. The variation of this relationship with different flow depths was considered in the present study, however, for different pumping rates.
MOHAMMAD et al.

Figure 4(a) illustrates the flow velocity variations associated with a 25-m flow depth reduction for 100%, 75%, 50% and 25% of the maximum pumping rate. The depth-averaged velocity at a 100% pumping rate varied from 0.25 to 1.12 m/s, while it varied at a 25% pumping rate from 0.056 to 0.34 with a 25-m reduction in flow depth. The figure indicates how the flow depth (area) considerably affected the flow velocity. At a first 10-m reduction, the relative increase in the depth-averaged flow velocity varied between 0.8 and 1.1 for 100% and 25% pumping rates, respectively, while the remaining 15-m reduction in flow depth results in a relative flow velocity increase up to 2.6 and 4.0 at 100% and 25% pumping rates, respectively, compared to the velocity at maximum depth. This indicates the effect of the flow depth on the depth-averaged flow velocity and, consequently, the sediment transport capacity. The flow velocity is a main effective parameter regarding the sediment transport capacity (Ali, Sterk, Seeger, Boersema, & Peters, 2012), and as the water withdrawals towards the intake help transport and deposit sediment in that direction, the flow direction controls the sediment movement and bed formation (Hekal & Abd El-Aziz, 2015). Based on this numerical simulation results, the operation schedule of the pumping station should be considered, especially at a low reservoir water level, which means that at the lower flow area in front of the intake, and higher depth-averaged flow velocity; it is important to lower the pumping rate and increase the pumping time to achieve the required pumping volume during that period and reduce the pumping effects on the detach, transport and accumulation of sediment in front of the intake.

The effects of flow area and pumping rate on the effective radius were also studied (Figure 4b) on the basis of a numerical model. The effective radius was evaluated on the basis of the reference flow velocity near the pumping zone when the pumping plant is not operating. During pumping, the effective radius is the distance from the intake to a point where the velocity in the reservoir is equal to the reference depth-averaged velocity. The effective radius increased essentially linearly with a reduction in flow depth for different pumping rates (Figure 4b). The effective radius is affected by the water storage level (flow depth), increasing up to 0.4 as a relative increase, respectively, in response to a 25 m reduction in storage level for different pumping capacities. Based on the continuity equation, the depth-averaged velocity should be greater to achieve the same flow rate with a reduced flow area, and the extent of the contribution area should be increased to satisfy the flow rate.

The stream power is the most important factor reflecting the effects of the flow velocity on the sediment transport capacity. The
FIGURE 4 Velocity (a), effective radius (b) and stream power variations with flow depth (c) for different pumping rates.
flow depth (flow area) and pumping rate effects on stream power are shown in Figure 4(c), highlighting from the numerical model results that a reduced storage level (flow depth) resulted in an increase of the flow stream power by 70 to 400 times because of the decreased flow area and increasing depth-averaged flow velocity for the same flow rate. In addition, for different pumping rates, the 10-m reduction in flow depth from 30 to 20 m had a minor effect on the stream power values. Through the rest 15-m flow depth reduction, however, the stream power increased significantly, especially for a high flow rate. These illustrations provide an analysis of how the flow depth affects the stream power, or the ability of the flow to detach and transport the sediment towards the intake. Thus, the indirect effect of flow depth on flow stream power should be considered in order to reduce the quantity of sediment movement and accumulation near the intake. As it depends on the reservoir water storage level and other factors affecting it (e.g. inflow; different demands, this value is not under control to reduce the sediment transport. Thus, the dam operation schedule should consider the importance of lowering the pumping rate and increasing pumping time under low water level conditions. The selection of pumping station location was not considered in the present study. At the same time, the effective reservoir parameter on flow properties near the station is the reservoir level (water depth), which does not vary with the station location. Thus, the hydraulic performance of the pumping station at any other location will remain similar to the current designated location for same operation plan.

6.2 Sediment transport analysis

The HEC-RAS 5.06 model was applied as a one-dimensional model for sediment transport and accumulation along the reservoir for a simulation period from 1986 to 2011. Although the sediment-routing model is one-dimensional, it provides an estimation of the sediment load concentration along the reservoir, as well as its distribution, erosion and deposition. Thus, a one-dimensional model can achieve reasonable results in predicting sediment deposition in reservoirs over a long-term simulation period (United States Society on Dams, 2015).

The average cross-velocity and sediment concentration along the reservoir on a rainy day is illustrated in Figure 5a. For the two-dimensional zone (from the reservoir inlet to a length of 24 km), the Althaher (192 km²) and Kalac (100 km²) valleys are located near the inlet and about 8 km from the inlet, respectively. They add to the reservoir on the left side, increasing the sediment concentration from about 3.2 kg/m³ to about 3.6 kg/m³ on the study day. Although these valleys have a watershed area less than the area of the next valley (Sweedy Valley) located 450 km² distance, they increased the sediment concentration. This is attributable their flows entering the reservoir near a relatively narrow section (about 1.8 to 2.0 km at maximum water level), with a gradual reduction being observed because of the expansion of the flow section, with the sediment load becoming greater than the reservoir flow transport capacity.

A sudden sediment concentration increase of 20% (3.6 kg/m³) can be observed when the flow approaches the third and biggest valley (Sweedy Valley), adding to the reservoir at approximately 17 km from the inlet on the reservoir’s right side (Figure 5a). Although the outflow is located near a wide reservoir section, it significantly affects the concentration. The increased reservoir sediment concentration up to 45% attributable to the valley flow depends on the reservoir sediment concentration, flow rate and sediment load carried by valleys. The sediment concentration then decreases suddenly within about 3 km from 3.6 to 1 kg/m³, indicating the sediment load is higher than the flow transport capacity because of the reduced flow velocity.

Further, the valley loads might be coarser than that carried by the reservoir because of the settling of coarse particles carried by the main river flow before this location (after 17 km from the simulated reservoir inlet), with about two thirds of the sediment load is deposited in this area. The sediment load concentration subsequently is reduced gradually beyond that with the expansion of the reservoir section because of its effects on the water flow velocity, reaching an average value in the reservoir (0.06–0.007 m/s). Even though the simulated values of flow velocity and sediment concentration along the reservoir on the simulation day in Figure 5a were not compared with measured values, although it provides an idea of how the average depth flow velocity and sediment load concentration varied. The sediment concentration variation indicates how the run-off flow yields from the valleys to the reservoir sides significantly affect the reservoir concentration.

As the sediment transport simulation model is one-dimensional, the flow velocity and distribution of the sediment concentration are uniform across each section. At the Sweedy Valley outlet, there is a significant effect on the sediment concentration, with the effect distributed uniformly across the section in the one-dimensional model (Figure 5a). There is a greater effect, however, near the outlet side near the bank, meaning the load from the valleys generally has a significant effect on the sediment load concentration and affects the sediment load accumulation near the pumping station located just downstream of the valley. A two- or three-dimensional model of the flow and sediment routing could give more confidence to consider this valley as the main source of sediment accumulation near and inside the pumping station.

The sediment concentration along the reservoir and the average velocity from a simulation on a dry, non-rainy day in April 1988 is illustrated in Figure 5b. This time period was selected because it has a similar sediment concentration at the inlet illustrated in Figure 1. The only sediment source is the main Tigris River, with the load gradually decreasing along the length of the reservoir, based on the flow velocity which reflects the sediment transport capacity. The main reduction is near the beginning of the expansion of the reservoir section, with most of the sediment load being deposited and accumulated in this zone. The reduced sediment load reaches about half of its concentration (3 kg/m³) at about 15 km from the beginning of the expansion, gradually reducing thereafter. Based on the numerical model results, the distribution
of the average sediment load concentration along the reservoir indicates the importance of the selection of the pumping station for the pumping efficiency, and sustainability of the project. The selection of the station intake is not considered in this study, however, with implications for the effects of pumping on the flow properties.

To compare the inverted levels along the reservoir bed, Figure 6a illustrates the original levels before dam construction (1986), the bathymetry survey results (Issa, 2015) and the best simulation results (scenario 5). The determination coefficient, Nash–Sutcliffe model efficiency and t test value were considered as statistical criteria to evaluate the model performance, with values of 0.93, 0.91 and 2.78 (less than the tabulated value, 2 at a 0.05 significant level), respectively. These criteria all indicate the model performance is acceptable in estimating the invert bed level. As noted in the figure, there is a high percent of sediment deposited in the upper third part of the reservoir, attributable to a sudden reduction of flow velocity. The simulated invert level is lower than that measured in some locations in the upper part of the reservoir, which may be attributable to the fact that the considered sediment model is a one-dimensional model, meaning the flow velocity and sediment concentration are uniform across the section. This assumption, however, does not represent reality, noting the flow velocity near the thalweg is much higher than at the sides, leading to an increased sediment transport capacity.

For the total cut and fill depth of each section, the model performance is different from that of the longitudinal invert bed level profile. Figure 6b illustrates a selected section downstream of the pumping station, including the original profile (1986), the bathymetry survey (Issa, 2015) and the resultant profile from the model simulation (scenario 5). The results indicate how the deposition and erosion depth are distributed, noting differences in the sediment depth distribution. It appears the results of the simulated sediment deposition are similar to the original bed section, while the bathymetry survey is different, likely because of the model being one-dimensional, and the sediment simulation being uniform across the section.
The statistical criteria indicate the model performance is weak for the load distribution across the section, with the values of the determination coefficient, Nash–Sutcliffe model efficiency and $t$ test are 0.29, 0.15 and $-0.35$ (out of the tabulated value range), respectively. Thus, the one-dimensional model cannot produce details about the effects of different flow directions on the sediment flux when dealing with the sediment load distribution across the sections. Thus, it is not an effective model in this case, especially when focusing on a certain flow area.

7 | CONCLUSIONS

The HEC-RAS 5.06 model was applied to simulate the depth-averaged flow velocity, direction and sediment load distribution resulting from the effects of a pumping station in the reservoir. The effects of the storage level and pumping rate under different operation cases were considered, based on operation levels of the reservoir and pumping station capacity. Three sediment load transportation approaches and three particle-fall velocity equations were selected to estimate the sediment transportation. Mosul Dam was considered a case study, especially the upper part of the reservoir near the pumping station. This part of the reservoir was simulated as a two-dimensional flow zone, while the other part of the reservoir was simulated as a one-dimensional flow in order to reduce the simulation run time, with the present study focusing on the reservoir pumping station.

Although the results of the numerical model represent the depth-averaged flow velocity, they generally indicated the flow depth around the intake has varied indirect effects on the flow stream power as a measure of sediment transport capacity towards the pumping intake for different flow rates. This effect is minor at about a 30% reduction in flow depth, then increases up to 400 times for the maximum pumping rate with an approximately
70% reduction in flow depth. Further, the pumping rate affects the stream power value and effective radius. Although the variation of the effective radius is not severe under different pumping rates, the stream power varied considerably. Thus, the pumping rate should be especially considered in a reservoir operation schedule, especially at low flow depth by reducing the water withdraw rate and increasing the pumping time, in order to reduce the depth-averaged flow velocity and its effects on sediment transport and accumulation near, and inside, the intakes and pumps. Further, the run-off flow from the valleys on the left side of the reservoir near the pumping station moved towards the station, carrying the sediment load. This flow increased the sediment concentration by different percentages at different times of the rainy season, with the increase reaching about 45%, depending on the sediment load carried and the sediment concentration in the reservoir. Overall, the results of present study could likely be improved by applying a 3-D numerical model.

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