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Evaluation of Single Reservoir Performance for Flood Risk Reduction Using a Developed Simulation Model: Case Study of Makhoul Reservoir

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ABSTRACT

The objectives of this study were firstly, to develop a simulation model (SM) for a single reservoir to identify the standard operating policy (SOP) of a reservoir based on a monthly operating period, and secondly, to evaluate the performance of the proposed Makhoul reservoir using a Developed Simulation Model (DSM) in reducing flood risk. This reservoir is located on the River Tigris, approximately 180 km upstream of Baghdad, Iraq. The performance of the reservoir in reducing flood risk was evaluated using two designs and records of flood waves gathered over two years. The first design was the present one, while the second was developed by increasing the operational storage to its maximum, based on the digital maps of the region. The flows downstream of the reservoir were compared, with and without the reservoir in the two years in question. Four parameters resulting from the two designs were compared: storage, surface area, elevation and power. The results suggested that the reservoir would be ineffective in reducing flood risk, but it would have the ability to provide hydroelectric power using the two designs, with the new one showing better ability at doing this. The reservoir can also serve purposes such as irrigation, fish wealth development and recreation. This DSM proved its effectiveness in evaluating the performance of the single storage system used for reservoirs.

Keywords: Flood risk, Iraq, Makhoul reservoir, operation policy, River Tigris, simulation model, Tharthar Reservoir

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INTRODUCTION

The hydraulic system of dams is designed to achieve many purposes such as reducing flood risk, irrigation, development of fish wealth

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and recreation. The design of these hydraulic aspects depends on the observed flows of the river during a specific period. Performance evaluation of the reservoir in the design stage is necessary. One of many software programmes designed to determine and simulate the operation of reservoirs can be used, or an optimisation-simulation model can be created with the ability to evaluate the functions assigned to it.

Many studies have been conducted to determine the optimal operation policy for reservoirs in order to reduce flood risk and for other purposes. Malekmohammadi, Zahraie and Kerachian (2010) developed a new methodology for the management of two reservoirs in real-time floods to minimise flood damage in downstream rivers. The methodology developed has been applied to the Bakhtiari and Dez river-reservoir systems in the southwest of Iran. The results indicated that the proposed models can be efficiently used for flood management and real-time operation of the cascade-river reservoir systems. Liu, Guo, Liu, Chen and Li (2011) derived optimal refill rules for a multi-purpose reservoir, with the objective function of maximising benefits under the condition of flood control safety. A multi-objective refill operation model was proposed, combining flood control and preservation. China's Three Gorges Reservoir was chosen as a case study for application of the proposed model. A multi-objective simulation-optimisation approach was proposed by Richaud, Madsen, Rosbjerg, Pedersen and Ngo (2011) to operate the Hoa Binh reservoir in Vietnam through off-line rule curve optimisation coupled with on-line real-time optimisation. The reservoir operating rules were optimised by studying the trade-offs between control of flooding and hydropower production on the one hand and providing water for irrigation on the other. Bayat, Mousavi and Namin (2011) combined a particle swarm optimisation (PSO) algorithm and a simulation model of river flood routing to derive the optimal operation of river-reservoir systems under flooding conditions. In this case minimising flood damage in downstream areas was the objective function. Bishop Dam, which is a benchmark problem in the HEC-5 software, has been used to test the developed optimisation-simulation models as a case study of flood control operation. Talukdar, Deb and Srivastava (2011) considered multi-objective functioning, which has been represented by first, minimisation of downstream area inundation and second, maximisation of conservation benefits to find the optimal operation policy for reservoirs. The model developed has been used to find the optimal releases for the Sardar Sarovar Project (SSP) reservoir, a multipurpose reservoir on the Narmada River in Central India. The Reservoir Optimisation-Simulation with Sediment Evacuation (ROSSE) model was applied by Khan, Babel, Tingsanchali, Clemente and Luong (2012) with the aim of minimising irrigation deficiency in the Tarbela Reservoir, Pakistan. The simulation results of three groups of rule curves, one existing and two optimised groups, have been compared to some parameters like irrigation deficiency, power generation, sediment evacuation and flood damages. Ngoc, Hiramatsu and Harada (2014) determined the optimal rule curves of reservoir operation based on a multi-use reservoir system. Dau Tieng Reservoir was used as a case study. This reservoir, located on the upper Saigon River in southern Vietnam, is used for multiple purposes (flood control, domestic and industrial demands, flushing out salt water intrusion from the downstream area and agricultural irrigation).

In the present study, a simulation model (SM) was developed to determine a standard operating policy (SOP) in order to evaluate the performance of a single reservoir in reducing flood risk. This Developed Simulation Model (DSM) determines the decision variables that represent the monthly releases and their counterparts of state variables, which represent the monthly storage. In this way, the model used the monthly requirements as the initial outflow, while surplus water was added to the initial outflow when a spill occurred. This DSM was applied to the Makhoul Reservoir located on the River Tigris in the northern area of Iraq; this area is in the design and planning stage. Recorded flood waves that occurred in two different years, 1968-1969 and 1987-1988, were used in the DSM to evaluate the reservoir performance in protecting Baghdad from flood risk using the SOP. The Makhoul Reservoir was evaluated twice, first using its current design and second using the new design. This new design used a new storage option, which represents the maximum operational storage. This maximum was identified based on digital maps.

METHOD

Development of Simulation Model

The simulation model of the single storage system formulated by Al-Aqeeli, Al Mohseen, Lee and Abd Aziz (2015) using Simulink in Matlab was developed to determine the SOP for the operation of the Makhoul Reservoir based on a monthly operating period. Water release using this operating policy achieves the water requirement downstream of the reservoir, and spillage will occur if the storage in the reservoir exceeds the capacity of the reservoir (Loucks, Van Beek, Stedinger, Dijkman, & Villars, 2005). This means that the total monthly outflow includes the monthly water requirement in addition to the surplus water in the reservoir, if any. In each period, the model first computes the storage according to the monthly requirement as the initial outflow as shown in the first formula of the water balance equation (Eq. 1). The monthly requirement is shown in Figure 1. If the calculated storage exceeds the capacity of the reservoir, spillage will occur, and its quantity will be added to the initial outflow as the total outflow as shown in Equation 2. This total outflow is used in the second water balance equation (Eq. 3) to recalculate the storage (Loucks et al., 2005). It is worth mentioning here that the quantity of spillage is released first from the remaining capacity of the outlets leading to the hydropower stations, if available, where the required water is released first. After that, it is released from the bottom outlets and finally, from the spillway. As is clear, this model separates the total monthly outflow to three types of release, relying on the capacity of the reservoir outlets.

$$S_{t+1} = S_t + I_t - D_t - Ev_t + Pr_t \qquad [1]$$

S_{t+1} Storage at beginning of time period (t+1)
S_t Storage at beginning of time period (t)
I_t Inflow during time period (t)
D_t Requirement during time period (t)
Ev_t Evaporation in time period (t)
Pr_t Precipitation in time period (t)
t Time period (month)

$$R_t = D_t + SP_t \quad [2]$$

R_t Total outflow during time period (t)

SP_t Spill during time period (t)

$$S_{t+1} = S_t + I_t - R_t - Ev_t + Pr_t \quad [3]$$

Note: The units used in these equations are millions of cubic metres (MCM).

Storage at the beginning of the operation (S_1) is inserted equal to the minimum operation storage of the reservoir. The Makhoul reservoir was evaluated twice: first using the present design and then using a new design. The new design used the maximum possible operational storage. This new storage was determined according to the digital maps for reservoir location.

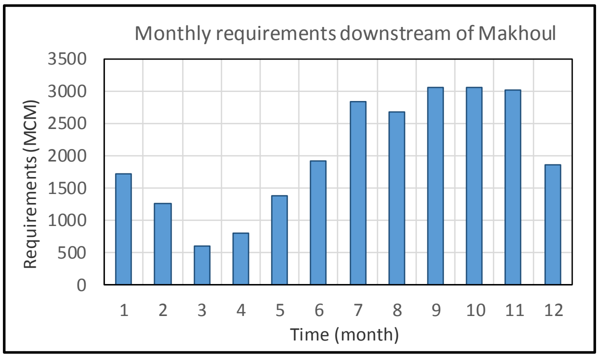

Figure 1. Monthly requirement downstream of Makhoul reservoir

The power generated per month (P_t), measured by megawatt, is calculated as shown in Equation 4, assuming that the efficiency of the power plant (η) equals (80%) (Al-Aqeeli et al., 2015).

$$P_t = k * RP_t * H_t \quad [4]$$

k = Constant (0.003)

RP_t = Release from the tunnels connected to the hydroelectric station (MCM)

H_t = Average head in the time period (metre)

Brief History of the Study Area

Baghdad has suffered from frequent flooding of the River Tigris since ancient times. In the first half of the last century, several measures were taken to protect the city from flooding, including the establishment of soil barriers along the banks of the Tigris. These measures contributed to reducing the damage caused by the flood relatively, but not categorically. Another measure taken to protect Baghdad from flooding was the diversion channel opened in 1956 at the Samarra barrage, located on the Tigris upstream of Baghdad. This barrage diverts surplus water from the Tigris to the Tharthar Reservoir during flood periods. The Tharthar Reservoir is a natural trough located between the Tigris and the River Euphrates, as shown in Figure 2. Surplus water from the Tharthar Reservoir is diverted to the Euphrates through a drainage channel. The main problem with using the Tharthar Reservoir is the high salinity of its soil (Salih, Kadim, & Qadir, 2012), which negatively affects the quality of the water diverted from it to the Euphrates. The Makhoul Reservoir was suggested for use instead of the Tharthar Reservoir, and is being constructed on the Tigris upstream of the Samarra barrage to protect Baghdad from flooding. The Makhoul Reservoir will store water released from three reservoirs, Mosul, Dokan and Bekhma, which are located upstream of its site during the flooding seasons, and manages the release of the water, among other functions. It is worth mentioning that the Mosul and Dokan Reservoirs are working effectively now, while the Bekhma Reservoir is still in the construction stage.

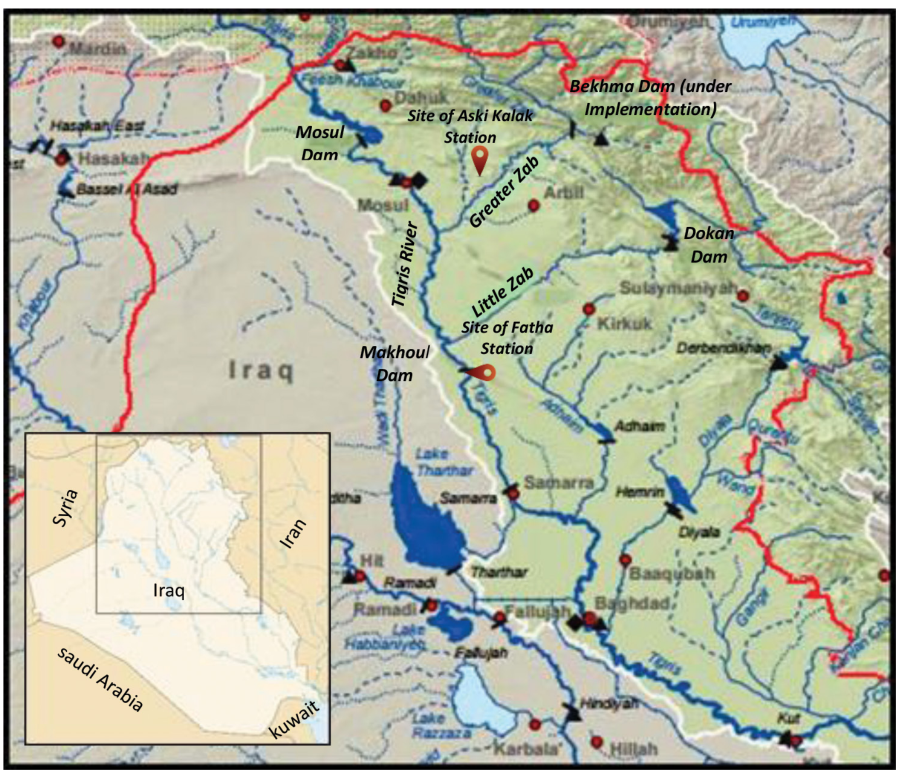

Figure 2. Map of the study area (UN-ESCWA and BGR, 2013)

Makhoul Reservoir: Under Planning

It was proposed that the Makhoul Reservoir be built across the Tigris River around 10 km north of the Fatha station, as shown in Figure 2. The main purpose for building the Makhoul Reservoir was to store water released from the three reservoirs, Mosul, Dokan and Bekhma, located upstream of it, during the flooding season and for the subsequent timely release of the water when needed. The water will be used to generate hydropower and to meet requirements downstream of the reservoir within the permissible limits. The maximum capacity of the hydropower station is 316 MW. One of the major determinants related to the quantity of release from Makhoul is that the water should not exceed 12,000 m^3/sec. From this release, 9000 m^3/sec passes to the Tharthar Reservoir and the remaining 3000 m^3/sec passes through the Samarra barrage in order to protect Baghdad from the risk of flood. The elevation and volumes of storage in the Makhoul Reservoir are shown in Table 1, while Table 2 shows the capacity of the different outlets of the reservoir.

Table 1
The elevation of storage and the volumes of storage of the makhoul reservoir

Minimum level of operational storage (MASL)	140
Maximum level of operational storage (MASL)	150
Crest level (MASL)	155
Minimum operational storage of reservoir (MCM)	744
Maximum operational storage of reservoir (MCM)	2222

Table 2
The capacity of different outlets of makhoul reservoir

Tunnels of generating units (m^3/sec)	Bottom outlet (m^3/sec)	Spillway (m^3/sec)
1235	2000	8400

Storage Volume of Makhoul Reservoir

As mentioned previously, the Makhoul reservoir is currently at the planning and design stage, so its present maximum operational storage could be increased to the maximum possible. In this study, this maximum operational storage was determined. The differential between the maximum and minimum operational storage for the present design was increased by multiplying this differential by increment factors. The results were then added to the minimum operational storage while keeping the other design features unchanged. The corresponding elevation and surface areas of the storage were obtained by extrapolation using the elevation-area-storage curve of the reservoir. In order to identify the appropriate elevation of storage in the new design of the reservoir, all of the new elevations were checked using the digital maps of the reservoir location. The space between the obtained elevation and the highest contour line without overflow was calculated. After that, the suitable elevation was identified.

Application of the DSM

The DSM was applied using two designs for the Makhoul Reservoir, the present design and the new one. The difference between the two designs is the variation in the volume of the maximum operational storage. In each design, the recorded monthly flow during two water years, 1968-1969 and 1987-1988, was adopted in the DSM; two flood waves were recorded in the two years mentioned. The water year in Iraq begins in October and ends in September the following year. The recorded flow was considered the inflow to the reservoir in the DSM. The DSM was initialised to suit both designs to determine the SOP for the reservoir. For each design, the DSM was operated independently in the two years. For each year, the performance of operating the Makhoul Reservoir using the two designs was evaluated by comparing the obtained results. These comparisons included firstly, that of the monthly storage, elevation, surface area of storage and power generation, and secondly, the flow at the Fatha Station before and after the existence of the Makhoul Reservoir. In comparing the flow, the observed flow at the Fatha Station before the existence of the Makhoul Reservoir was compared with the expected outflow of the Makhoul Reservoir when it is built. The Makhoul Reservoir will use the flow observed at the Fatha Station as its inflow.

RESULTS AND DISCUSSION

New Design of Makhoul Reservoir

The new design of the Makhoul Reservoir was identified as described in the methodology above. By increasing the amount of the differential between the maximum and minimum operational storage of the Makhoul Reservoir, three design features were identified. These features included storage, elevation and surface area, as shown in Table 3. The results were then added to the minimum operational storage while the other design features were unchanged. According to the digital maps of the location of the reservoir shown in Figure 3, the highest contour line without an overflow was identified. This contour line was 173 MASL. The space between the obtained elevation and this contour line was identified, as shown in Table 3. From this table, the appropriate elevation was chosen, and thus, the corresponding storage. The suitable elevation and storage represent the maximum possible operational elevation and storage, which were equalled to 162.4 MASL and 5178 MCM, respectively, as shown in Table 3 and Figure 3.

Table 3
Operational storage with corresponding elevation and surface area for new volume of makhoul reservoir

1	2	3	4	5	6
The differential between the maximum and minimum operational storage in the current design (MCM)	Increment factors to increase the differential between maximum and minimum operational storage	New operational storage (MCM) identified from multiplying columns 1 & 2 and then adding the results to the minimum operational storage	New operational elevation of storage (MASL) identified from the Storage-Elevation curve using column 3 (by extrapolation)	New surface areas of storage (km^2) identified from Storage-Area curve using column 3 (by extrapolation)	Space between the new operational elevation of storage identified in column 5 and the contour line 173 (m)
1478	1	2222	150.00	195.00	23
1478	1.5	2961	153.48	231.30	19.52
1478	2	3700	156.50	262.00	16.5
1478	2.5	4439	159.45	291.56	13.55
1478	3	5178	162.41	321.12	10.59
1478	3.5	5917	165.36	350.68	7.64
1478	4	6656	168.32	380.24	4.68

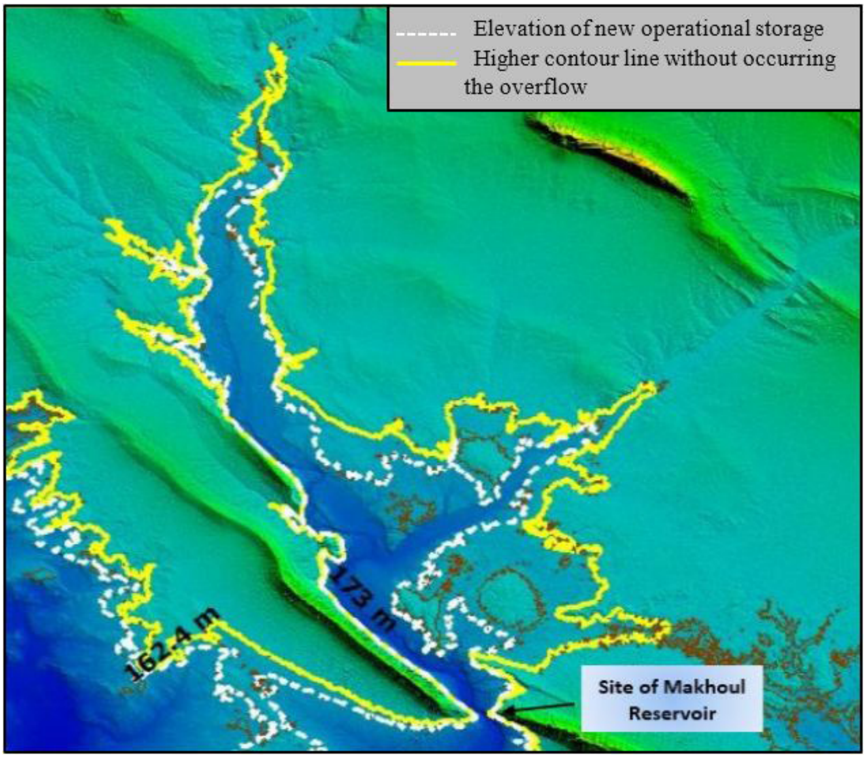

Figure 3. The higher contour line without overflow and the elevation of the new operational storage

Performance Evaluation of the Two Designs of Makhoul Reservoir

The DSM was used in order to evaluate the performance of the Makhoul Reservoir in reducing the flood risk using two designs, the present and the new designs. Recorded flow of two water years, 1968-1969 and 1987-1988, was used separately in this evaluation, when two flood waves were observed. According to the application of the DSM using the two designs (present and new designs) in the two operating years, four features of reservoir design were compared. These features included monthly storage, elevation, surface area and power, as shown in Figures 4 and 5 for the years 1968-1969 and 1987-1988, respectively. From these figures, it can be observed that the reservoir was full during most of the months of the years for both designs. This led to maximum production of hydropower as the outlets of hydroelectric power were full. In addition, the maximum operational storage and its corresponding surface area in the new design increased by 133% and 64.67%, respectively, and the maximum operational level was raised by 8.27 m. In addition, the maximum hydropower generation was increased by 42.8% using the new design.

The flow at the Fatha Station, with and without the Makhoul Reservoir, was compared in the water years 1968-1969 and 1987-1988 using the present and new designs, as shown in Figure 6 i.e. for each year, three flows at the Fatha Station were compared: the first was the recorded flow, the second, the release of the Makhoul Reservoir using the present design, and the third, the release of the Makhoul Reservoir using the new design. From these figures, it can be seen that the inflow of the reservoir was almost equal to the outflow during most of the months of the two years. This occurred because the capacity of the reservoir was insufficient for accommodating the incoming flow of the Tigris River in the two years.

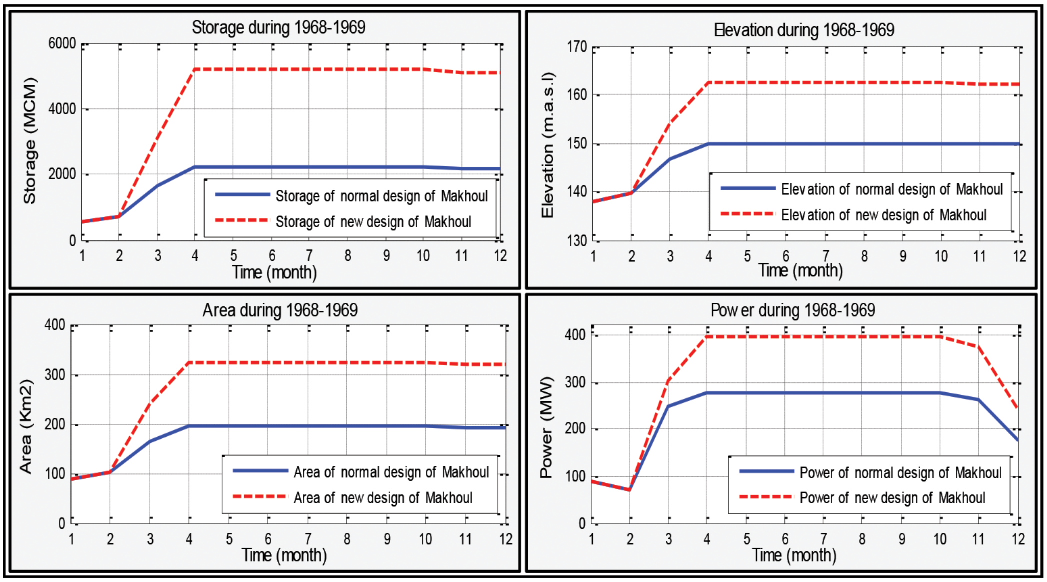

Figure 4. The monthly storage, elevation, surface area and power during the year 1968-1969, using the present and new designs

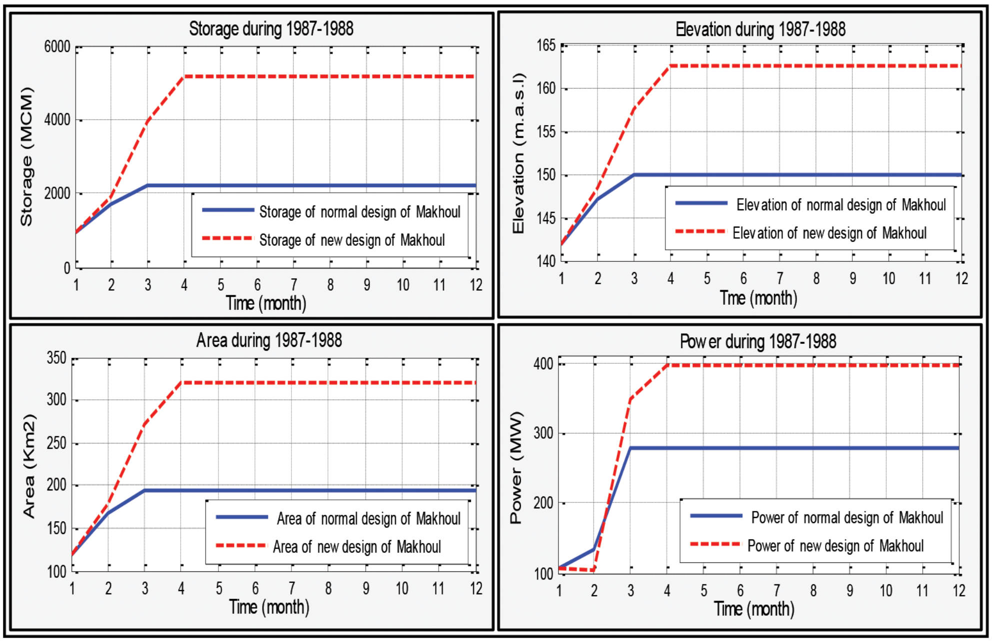

Figure 5. The monthly storage, elevation, surface area and power during the year 1987-1988, using the present and new designs

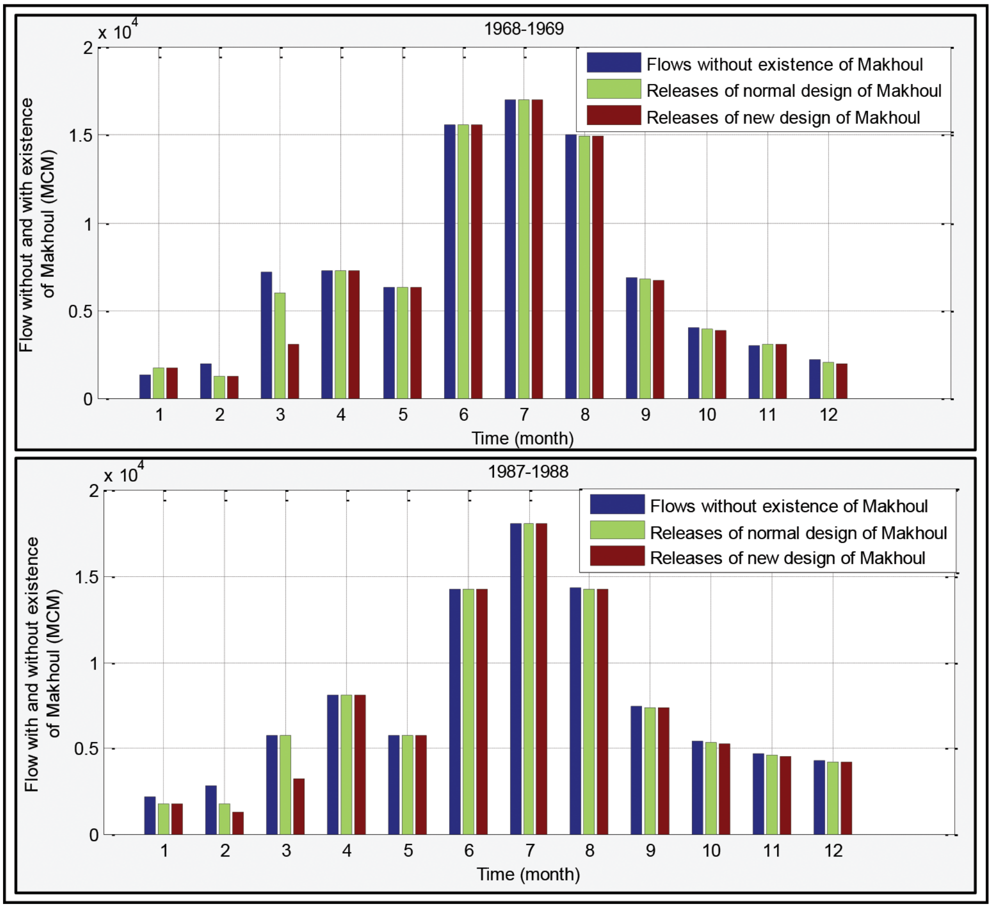

Figure 6. The monthly flow downstream of Makhoul in the years 1968-1969 and 1987-1988

CONCLUSION

In this study, a simulation model was developed to determine the SOP for the evaluation of a single reservoir by adopting two designs for the Makhoul Reservoir in two separate years of flow data. From using the two designs for the Makhoul Reservoir, it was seen that this reservoir would be ineffective should flood waves occur; thus, it would not be effective in reducing flood risk in Baghdad. Reducing flood risk in Baghdad was the main objective in constructing the reservoir. Nevertheless, some advantages were identified from using the new design for the Makhoul Reservoir, such as a rise in the capacity of the related hydroelectric power station and an increase in the elevation of storage.

However, the two designs were ineffective in reducing flood risk. The new design was preferred in terms of the benefits achieved. So, in the case of flood waves, it was clear that the water diversion canal at the Samarra barrage should be used as a precautionary measure to convert excess water at over 3000 m^3/sec to the Tharthar Reservoir in order to avoid flood risk in Baghdad. As mentioned previously, it is not possible to exceed more than this amount of flow downstream of the Samarra barrage. As was evident, when using one of the two designs, the problem of the salinity of the Tharthar Reservoir still existed; this will need resolution by other means. Therefore, the Makhoul Reservoir cannot be used as a substitute for the Tharthar Reservoir, but it can be used for other purposes, such as generating hydroelectric power, developing fishery in the area and irrigating the neighbouring lands. It can also be developed for recreation.

The new design of the reservoir achieved an increase in the volume of storage and hydropower production, but this involved loss of extra land. The maximum operational elevation was increased in the new design, leading to an increase in the height of the dam, and thus, an increase in construction costs. In this case, an economic feasibility study should be conducted for each design in order to choose the best one.

This DSM has many advantages, such as ease of inserting data and effective display of results. The results can be easily shown as values or figures. This DSM can be used initially by adopting the SOP to evaluate the performance of a single-storage system effectively. In addition, this DSM can be used with a multi-reservoir system through connection between reservoirs by taking advantage of the SIMULINK technique available in Matlab.

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