Available online at www.CivileJournal.org

Civil Engineering Journal

(E-ISSN: 2476-3055; ISSN: 2676-6957)

Vol. 10, No. 05, May, 2024

Evaluation of Hydraulic Structures for Agricultural Discharge Optimization

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Received 18 January 2024; Revised 13 April 2024; Accepted 18 April 2024; Published 01 May 2024

Abstract

The objective of the research was to evaluate the hydraulic structures on the Al-Gharraf River in southern Iraq and their ability to achieve the required discharge for agricultural areas that depend on them. Al-Gharraf head regulator discharges unstable volumes of water, ranging from 280 m^3/s in winter to 100 m^3/s in summer. The research aimed to determine whether the operational discharges are achievable for the offtakes branching from the Al-Gharraf River when the river's discharge ranges from 60% to 100% of the operational discharge. The researchers utilized a simulation of the irrigation channel (SIC) model to simulate river flow. The researchers used hydraulic indicators such as Delivery Performance Ratio (DPR), Discharge Deviation (ΔQ), and Sensitivity (S) to evaluate the work of the hydraulic structures (regulators), determine the more and less efficient regulators in delivering water to the offtakes, and determine the reasons for inefficiency. Depending on the discharge values for each offtake from simulation results by SIC and calculating the hydraulic indicators, it is observed that some offtakes exceed their operational discharges, such as Al-Zydia and Al-Sabila. Also, some offtakes do not receive their operational discharge (Al-Dawaiya, Shatt Al-Shatra, and Al-Basra) projects, which failed to reach even 10% of their operational discharges. The researchers suggest redesigning some offtakes and ensuring reasonable control of gate openings for other offtakes to make the water distribution proportional.

Keywords: Al–Gharraf River; Delivery Performance Ratio (DPR); Discharge Deviation (ΔQ); Sensitivity (S); SIC Software.

1. Introduction

In addition to the impact of drought and flood seasons, water resource consumption priorities in various sectors include irrigation, agriculture, and industry. That necessitates water conservation plans to save water for future needs, reduce flood risk, and satisfy this requirement [1]. Proper planning and implementation in Iraq's relevant sectors are crucial due to the country's increasing demand for water resources. It is essential to base planning on sound scientific findings to optimize and conserve irreplaceable land and water resources. Even in irrigated areas, there can be water shortages if the amount of available water is less than the expected one or if the irrigation water needs exceed the available water [2].

As the demand for food increases and freshwater resources become rare, evaluating irrigation systems will become more crucial to enhancing the performance of irrigation networks and achieving maximum productivity. Such assessments should examine the irrigation performance indicators and the hydrological and productive impacts of the irrigation systems. That will support crop production, water management, and water policy agents [3]. It is important to

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http://dx.doi.org/10.28991/CEJ-2024-010-05-010

evaluate the hydraulic performance of an irrigation system to conserve scarce water resources and improve the performance of the existing structures. However, no previous study has evaluated the performance of the Al-Gharaf scheme, which is used mainly for irrigation purposes.

Iraq's climate has been experiencing fluctuations between periods of scarcity and abundance, which directly impacts the success of irrigation projects. Unfortunately, the country has endured a severe drought in recent years, leading to low river water levels that have negatively impacted the agricultural sector. It is crucial to conduct detailed studies that examine the hydraulic situation of irrigation projects to determine their ability to adapt to changing climates and meet the needs of surrounding agricultural lands. Given its importance as a vital irrigation project that services vast agricultural areas, it was necessary to conduct a comprehensive study of the Al-Gharraf River to identify any issues in water distribution and recommend effective solutions.

This study aims to assess the hydraulic performance of canal structures using hydraulic performance indicators. Numerous researchers have utilized hydraulic indicators to analyze water distribution in channels to evaluate irrigation performance, assess the economic and environmental impact of changes in irrigation management, and represent the response of outlets to variations in discharges at the source. A study conducted by Sibale et al. [4] evaluated the performance of the Nakhavi irrigation system in terms of water delivery adequacy, efficiency, equity, reliability, and irrigation efficiency. The researchers used the CROPWAT 8.0 computer model to determine the irrigation requirements for crops. The study found that for 2017 and 2018, the adequacy and efficiency of water delivery were 0.74 and 0.82, and 0.70 and 0.80, respectively. The equity of water delivery was 0.15 and 0.20, while the reliability was 0.11 and 0.21, respectively. The overall water delivery performance was 0.80 for both years. Furthermore, the irrigation efficiency of the system was found to be 20% and 25% for the years 2017 and 2018, respectively. This indicated that users of the irrigation scheme needed to provide an adequate and reliable water supply during both growing seasons. Based on the findings, the researchers recommended that major maintenance work be carried out along the canal network to achieve better water delivery performance. The study provided important insights into the status of the irrigation scheme, which could encourage users to improve its water delivery performance.

Fan et al. [5] studied how canals respond to hydraulic regulation or external disturbances. The study used two hydraulic sensitivity indicators—offtake discharge and water level sensitivity—to analyze the influence of different hydraulic elements on the sensitivity indicators. The researchers derived fitting formulas for the hydraulic sensitivity indicators based on the analysis results. The study's findings suggest that canal managers can take various measures to minimize canal sensitivity, such as increasing the water level before the offtake, reducing the elevation difference between the diversion and parent canal, and using the arc-bottom trapezoidal cross-section. This analysis provides theoretical support for improving the rationality of canal regulation and enhancing the service level of irrigation projects.

Wanyama & Bwambale [6] conducted a study to improve the flow conditions of irrigation canals in Uganda's Doho Rice Irrigation Scheme. They used the HEC-RAS hydraulic model to evaluate different canal conditions, such as desilting and vegetation clearing, concrete lining, plastic lining, and brick lining, for their impact on flow dynamics. The study found that all four canal conditions led to significant improvements in flow conditions compared to the current canal state. Plastic lining was the most effective solution, resulting in a remarkable 48% improvement in flow conditions. Concrete lining followed closely with a 37% improvement, while brick lining showed a 39% enhancement. These results highlight the potential of hydraulic modeling in guiding the design and management of irrigation canals to ensure sustainable water use practices.

The current study aims to assess the hydraulic indicators of the Al-Gharraf River by simulating its flow in various scenarios using the Simulation of the Irrigation Canals (SIC) model. Tariq & Latif [7] used hydraulic modeling (SIC) to simulate the irrigation canal to examine the actual operational performance, which was appropriate for analyzing the suggested functional scenarios in the operation of the canals for supplemental irrigation. The study's findings demonstrated that irrigation delivery exceeded crop irrigation needs, and it offered several suggestions for enhancing the manual functioning of the distributary irrigation canal.

Maatooq & Wahad [8] focused on analyzing and evaluating the actual hydraulic operation at the distribution channel (secondary level) and associated outlets on appropriate hydraulic indicators, which uses the hydrodynamic Simulation of the Irrigation Canal (SIC) model for the first time in the analysis in Iraq. One of the distributary canals in the Kifil-Shinafiya project (KSP), located in the middle of Iraq, was selected to study these indicators by evaluating the gaps between demand flows and actual deliveries in the outlet structures along the channel. Based on the indicator analysis and the SIC model, the study concluded that the acceptable DPR for the distributary canal must range from 0.60 to 1.2 of the design discharges. The study highly recommends using the SIC model to simulate the operation of future strategic irrigation projects in the middle and south of Iraq. This process helps manage operations at available discharge levels with a suitable distribution among demand requirements. Additionally, the maintenance program becomes more accessible for diagnosis.

Masood [9] aimed in his study to validate the roughness coefficient value for a lined distributary located in the Chena distributary district of Kasur and to assess its impact on the water drawing capacity of outlets. The study compared the design and field measurements of hydraulic parameters of the canal and outlets and conducted simulations of canal and outlet flows using the SIC (Simulation Irrigation Canal) model. The results showed a considerable difference between the design and the prevailing water surface profiles, which impacted the water drawing capacity of the outlets. Specifically, the roughness coefficient value was 0.02 instead of the design value of 0.016. This increase in roughness coefficient value, possibly due to sedimentation or tampering, increases flow depth in the head. Consequently, the outlets at the head reaches drew more water than their allocated share. The study concludes that regular cleaning and maintenance of the lined portion of the canal is essential to ensuring the sustainable operation of the irrigation system. Furthermore, strict regulations must be in place to prevent tampering with the system.

For the first time, researchers in Iraq are using the simulation of irrigation canals (SIC) model to simulate the flow of the Al-Gharraf River. This large river serves vast areas and has numerous offtakes. The study focuses on the Al-Gharraf project, one of southern Iraq's most significant irrigation projects, as it plays a crucial role in providing water to agricultural lands, orchards, fish basins, and drinking water treatment plants. A detailed investigation is necessary to identify the constraints that prevent water from reaching the river's end streams. Figure 1 displays the flowchart of the applied methodology in the study.

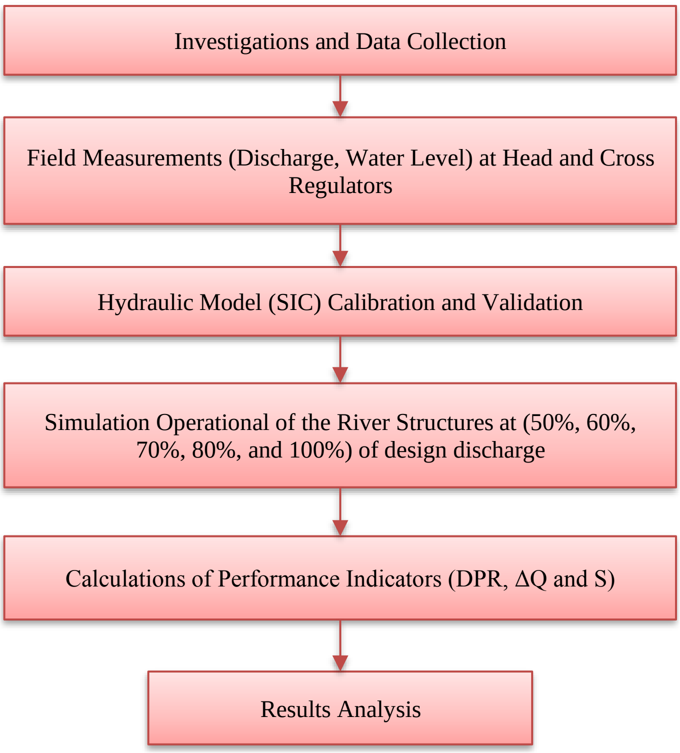

Figure 1. Flowchart of the Applied Methodology

2. Material and Methods

2.1. Study Area

The Al-Gharraf River is a significant tributary of the Tigris River and provides water for communities passing through Wasit and Dhi-Qar governorates in southern Iraq. It connects the Tigris and Euphrates rivers to the east of the Dhi-Qar Governorate. The river has six hydraulic structures, including Al-Gharraf Head Regulator, Cross Regulator No. 1, Cross Regulator No. 2, Cross Regulator No. 3, Cross Regulator No. 4, and Al-Bada Cross Regulator from the beginning to the end of the river, Fahad [10]. Figure 2 shows the location of the cross-regulators. The study focuses on the stretch of the river between the Al-Gharrafhead regulator and the Al-Bada cross regulator, as shown in Figure 2. The following offtakes branching off from the Al-Gharraf river were adopted in this study: Akil and Janabiat al-Hay in Wassit Governorate, Al-Mghyshi, Al-Sabila, Al-Zydia, Al-Hatem, Al-Naumiah, Al-Manaia, Shatt Al-Shattra, Abouda, Basrah Project, and Al-Dwaya in Thi-Qar Governorate. These streams are essential for agriculture, and some are used for drinking water. Figure 3 illustrates the distribution of the offtakes along the river.

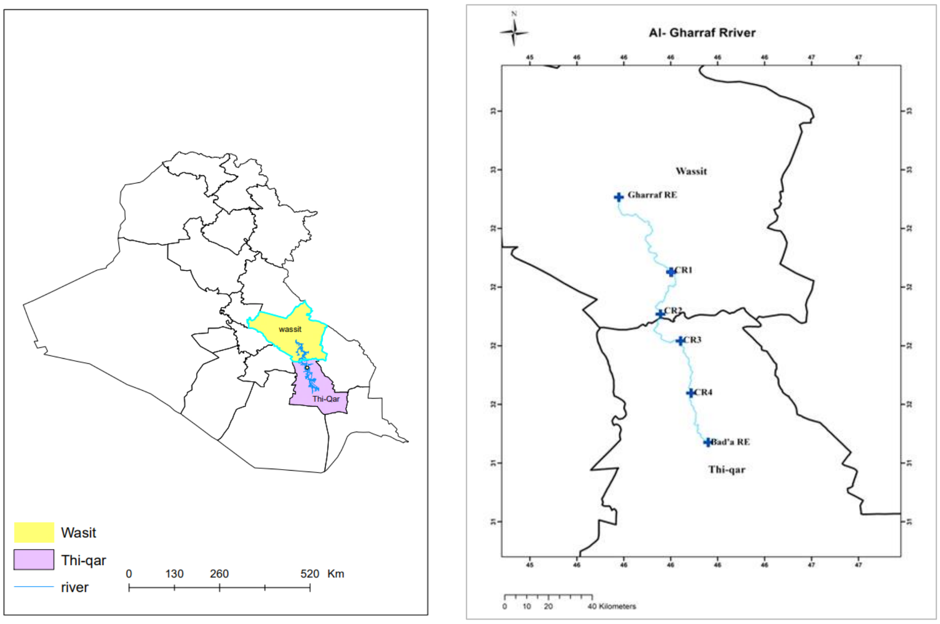

Figure 2. A map showing the locations of the cross regulators on Al-Gharraf River, Wasit and Dhi-Qar Governorates, southern Iraq (by Arc GIS, Directorate of Water Resources in Wasit)

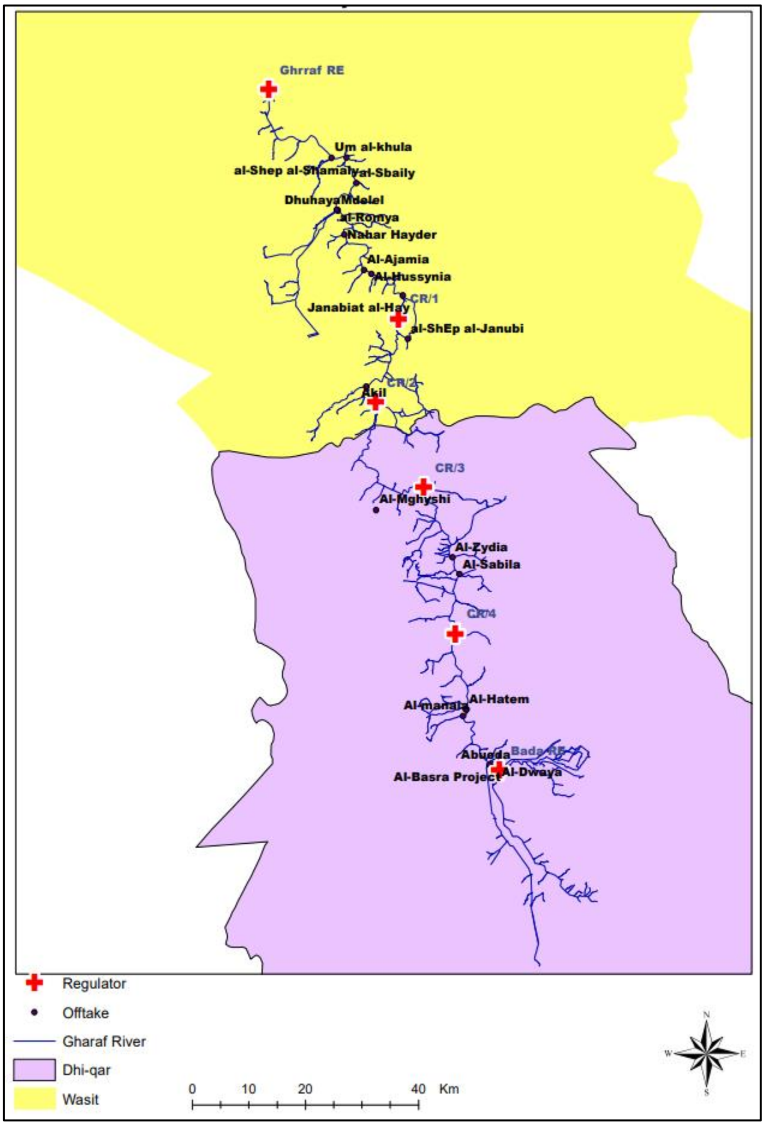

Figure 3. A map showing Al-Gharraf River and its branches, Wasit and Dhi-Qar Governorates, southern Iraq (by Arc GIS, Directorate of Water Resources in Wasit)

2.2. Data Collection

The necessary hydraulic data for the head and cross regulators, design discharge, design water level, bed level, and the dimensions of gates are listed in Tables 1 and 2.

Table 1. The Hydraulic Design Data for the Head Regulator (HR) and Cross Regulators (CR) of Al-Gharraf River

Regulator	Location	Coordinates		Distance from HR (km)	Design Q (m^3/s)	Design W.L (m)	Design B.L (m)	Gates	Gate Dimensions W×H (m)
		X	Y						
HR	Wassit Governorate/Al-kut City	45.80722	32.50236	-	500	18.5	12	7	6×3.8
CR NO.1	Wassit Governorate/Al-hay City	46.01394	32.14728	58	250	16	10.5	5	9×5.6
CR NO.2	Between Wassit and Thi-qar.	45.9776	32.01781	87	200	14	9	4	9×5.6
CR NO.3	Thi-Qar Governorate/Al-Rifa'I City	46.05439	31.88573	112	500	14	7	4	9×5.5
CR NO.4	Thi-Qar Governorate/Al-Rifa'I City	46.10453	31.6595	142	500	12	6	4	9×5.5
Al-Bad'a Regulator	Thi-Qar Governorate/Al-shatrah City	46.17463	31.44751	168	200	10	3.4	6	7×5.2

Table 2. Summary of the hydraulic design data for the outlet's head regulator Al-Gharraf River and its branches *

Offtake	Distance (km)	Design q (m^3/s)	B.L[2] (m)	F.S.L[3] (m)	No of Gate	Gate Dimension (m) W×H
Janabiat Al-Hay	58+000	25	13.8	14.85	4	3*3
Akil	84+000	20	11.2	14	5	1.2*3
Al-Mghyshi	110+000	15	10.2	12.55	2	2*2.5
Al-Zydia	127+000	7	9	11.44	2	1.8*2.6
Al-Sabila	131+000	20	8.7	11.29	1	3.5*3
Al-Naumia	150+000	11	7.5	10.2	3	1.4*3.5
Al-Hatem	151+000	11	7.5	10.16	3	1.4*3.5
Al-Manaia	152+000	8	7.4	10.1	1	3*3
Abuoda	153+000	10	6.5	9.6	2	2*5
Al-Basra Project	165+900	20	7.0	9.6	2	4*4.65
Shatt Al-Shattra	167+700	15	6.5	9.54	4	2*2.5
Al-Dwaya	167+800	20	7	9.5	4	2*2.5

* The data are provided by the Irrigation Management Office in the provinces of Wassit and Dhi-Qar.

2.3. One-dimensional Hydrodynamic Model (SIC)

Based in France, the Irrigation Division of Cemagref Montpellier created the SIC model. This division handles the SIC model's commercial, maintenance, and training aspects. The SIC software, also known as Simulation of Irrigation Canals, is a mathematical model that allows the user to simulate the hydraulic behavior of most irrigation canals and rivers under steady and unsteady flow conditions. The main objectives of the model are:

- To provide detailed knowledge on the hydraulic behavior of a central canal and its secondary canals for research purposes.
- To assess the impact of potential modifications on specific design parameters to enhance or maintain the ability of a canal to meet flow and water level objectives.
- To improve the current management procedures of a canal, identify management rules for regulating structures using a model.
- To evaluate the efficiency of automatic operational procedures, select procedures from a pre-programmed controller's library or write them in MatLab or FORTRAN programming languages.

Various investigations have examined the computational precision of the SIC model. Summing up this accuracy issue in a few general sentences is impossible because it depends on the type of modeled system, its scale, the simulated hydraulic conditions, the number of entered data points, and their precision. However, researchers can evaluate and compare the model's accuracy by conducting experiments on one or more predefined systems and scenarios. Baume et al. [11]. The one-dimensional hydrodynamic model SIC has been used in many studies to simulate irrigation canals' hydraulic and operational conditions. It has led to better management and operation.

2.3.1. Model Calibration and Validation

A model is calibrated when the simulated values correspond to the observed values. Validation involves evaluating the model's predictive capabilities. It entails comparing the model results to the observed data and adjusting the model's parameters until the results fall within the acceptable range of precision. Malaterre and Baume [12]. This study evaluated the model's performance using statistical methods to determine whether the predicted (simulated) outlet discharges and water levels were consistent and reasonably congruent with the observed values. The RMSE observations to standard deviation ratio (RSR), the Nash-Sutcliffe efficiency coefficient (NSEC), and the percent bias (PBIAS) were used to evaluate the efficiency of the SIC model.

Percent Bias (PBIAS)

Percent bias (PBIAS) measures how much calculated or simulated data differs from measured or observed readings. Gupta et al. [13]. An optimal PBIAS value is 0.0, so the model's simulation is very accurate. If PBIAS is higher than 0.0, it indicates an underestimation bias in the model; if PBIAS is lower than 0.0, it indicates an overestimation bias. Understanding PBIAS helps in evaluating the accuracy of models. PBIAS is determined as follows:

$$PBIAS = \frac{\sum_{i=1}^{n}(Qi^{obs} - Qi^{sim}) * 100}{\sum_{i=1}^{n} Qi^{obs}} \tag{1}$$

PBIAS was selected as a statistical measure because it is recommended by ASCE (1993) and thus widely used to calculate water balance errors; it also can illustrate the poor performance of a model where applicable. Gupta et al. [13].

RMSE-observations Standard Deviation Ratio (RSR)

Chu & Shirmohammadi [14] introduced an error measurement technique called Root Mean Square Error (RMSE). The smaller the value of RMSE, the better the model's performance. Singh et al. [15] developed a new criterion called RMSE-Observations Standard Deviation Ratio (RSR) to enhance the error measurement process further. RSR considers the standard deviation of all observations or measurements and standardizes RMSE accordingly. This approach provides additional information by giving an error index in the RMSE ratio to the measurements' standard deviation.

$$RSR = \frac{\sqrt{\left[\sum_{i=1}^{n}(Qi^{obs} - Qi^{sim})^2\right]}}{\sqrt{\left[\sum_{i=1}^{n}(Qi^{obs} - Qi^{mean})^2\right]}} \tag{2}$$

Generally, a lower RSR indicates a lower RMSE, which denotes higher model simulation performance.

Nash-Sutcliffe Efficiency Coefficient (NSEC)

NSEC is a statistical measure that compares the residual variance with the variance of the measured data. It was introduced by Nash and Sutcliffe [16]. NSEC is a dimensionless index that signifies the goodness of fit of the scatter plot between the measured and simulated data with the ideal line. The NSEC can be computed as:

$$\text{NSEC} = 1 - \frac{\left[\sum_{i=1}^{n}(Qi^{obs} - Qi^{sim})^2\right]}{\left[\sum_{i=1}^{n}(Qi^{obs} - Qi^{mean})^2\right]} \tag{3}$$

where Q_i^{obs} is the observed or measured discharge at the outlet, Q_i^{sim} is the simulated discharge at the same outlet simultaneously, Q_{mean} is the mean of measured discharges, and (n) is the number of measurements. NSEC values within 0.0 to 1.0 indicate the model's acceptable performance. If NSEC equals 1, this shows an optimal performance of the model, whereas NSEC values < 0.0 indicate unacceptable performance. This statistic is important and widely used because it is recommended by ASCE (1993) and presents much information about the measured values. NSEC is the best function of simulated data's fitness compared to measured data [8, 9, 15]. Based on Tariq & Latif [7], Maatooq & Wahad [8], Singh A. et al. [17] and Moriasi et al. [18] and the recommended Statistics for model calibration and Validation are listed in the Table 3. Different operational scenarios have been implemented for water level simulation at the head and the cross-regulators to show the model's Validation. The results are listed in Table 4 at 95% confidence level.

Table 3. Recommended Statistics for Model Calibration and Validation

Performance	RSR	NSEC	PBIAS
Very good	0.00≤RSR≤0.5	0.75<NSE≤1.0	PBAIS <±0.10
Good	0.5<RSR≤0.6	0.65<NSE≤0.75	0.10±≤PBIASE<±0.15
Satisfactory	0.6<RSR≤0.7	0.5<NSE≤0.65	0.15±≤PBIASE<±0.25
Unsatisfactory	RSR>0.7	NSE≤0.5	PBIASE≥±0.25

Table 4. Validation of SIC model at different hydraulic scenarios at head and cross regulators of Al-Gharraf river and its branches

Operational Scenario	Feb.2018 Scenario40%		Jan.2016 Scenario45%		April.2017 Scenario50%		March.2019 Scenario70%	
Water Level(M)	**Calculated**	**Simulated**	**Calculated**	**Simulated**	**Calculated**	**Simulated**	**Calculated**	**Simulated**
HR	16.16	16.36	16.38	16.2	16.68	16.78	17.78	17.83
CR1	12.65	12.59	13.9	13.9	13.88	13.78	14.65	14.63
CR2	11.7	11.47	11.05	11.32	12.9	13.01	12.7	12.89
CR3	10.15	10.13	10.45	10.43	11.45	11.49	11.5	11.5
CR4	9.15	9.17	9.4	9.25	10.05	10.1	10.25	10.07
Bad'a RE	8.5	8.58	8.3	8.3	9.15	8.98	8.95	8.96

According to the general criteria and the level of uncertainty listed in Table 3, the simulated results shown in Table 4 can be deemed good and very good if NSEC > 0.65, RSR< 0.6, and PBIAS < 0.15 for canal flow. Based on these criteria, the model is considered a good indicator for 0.4Q 40%Qd, 45%Qd, 50%Qd, and scenarios. The NSEC, RSR, and PBIAS values were very good for all scenarios, as shown in Table 5.

Table 5. Statistics of the SIC Model for Al-Gharraf Hydraulic Structure with Different Scenarios at a Confidence Level of 95%

Scenario	RSR	Status	NSEC	Status	PBIAS	Status
70%Qd	0.07	v.good	0.99	v.good	0.06	v.good
50%Qd	0.04	v.good	0.99	v.good	0.04	v.good
45%Qd	0.045	v.good	0.95	v.good	0.1	good
40%Qd	0.05	v.good	0.99	v.good	0.04	v.good

2.4. Performance Indicators

2.4.1. Delivery Performance Ratio (DPR)

The delivery performance ratio (DPR) is the most straightforward and essential operational performance indicator [8, 18, 19]. It is defined as:

$$DPR = \frac{Actual\ flow}{Intended\ flow} \tag{4}$$

The delivery performance is classified based on the scale of Wahaj [20] as excessive if the DPR is more significant than 1.15, moderate flow if the DPR is within (0.9-1.15), and inadequate flow if the DPR is less than 0.9.

2.4.2. Discharge Deviation(ΔQ)

The percentage of discharge deviation in outlets is evaluated as follows:

$$\Delta Q = \frac{Q2-Q1}{Q1} \times 100 \tag{5}$$

where Q_1 is the desired discharge (m^3/s), Q_2 is the actual discharge (m^3/s), and ΔQ is the deviation in the discharge at a location as a percentage. An outlet's performance was regarded as good if it was restricted to within 30% of the desired discharge. When the percent deviation was more significant, the performance of an outlet was regarded as poor. Wahaj [20].

2.4.3. Sensitivity

The sensitivity of an offtake is defined as the fractional change of discharge (q) caused by the rate of change in the water depth of the parent canal. Bos et al. [21].

$$s = \frac{\Delta q/q}{\Delta y} \tag{6}$$

It can be recommended that if (S) is greater than 2, the outlet is considered highly sensitive; if (S) is within 1 to 2, the outlet is considered medium sensitive; and if (S) is less than 1, that refers to the low sensitivity offtakes. Maatooq & Wahad [8] and Murray-Rust & Van Halsema [22]. Table 6 explains the classification of indicators Based on Several Researchers.

Table 6. Limits of Standard indicators of DPR, ΔQ/Q, and Sensitivity Maatooq & Wahad [8]

Performance Indicator	Poor	Medium	Good	Notes
DPR	1.2 < DPR < 0.70	0.7 - 0.90 < DPR < 1.10 -1.2	0.90 ≤ DPR ≤ 1.10	Molden & Gates (1990)
ΔQ/Q	> ±30%	±30%Murray-Rust & Halsema (1998)	±10% (Molden & Gates) [23]	
Sensitivity S	S > 2 high	1 ≤ S ≤ 2 medium	S< 1 low	Renault [24]

3. Results and Discussion

The regulators' operation process for each offtake was assessed by monitoring the flow in the Al-Gharraf River using the irrigation canals (SIC) model simulation. The river's operational discharge (Q) was tested at different discharges (350, 315, 280, 245, and 210 m^3/s), which represent (100%Q, 90%Q, 80%Q, 70%Q, and 60%Q) with the full opening of the gates of the head and cross regulators. The discharge and water level at each offtake were monitored, and it was observed that some offtakes, such as al-Dawaya, Shatt Al-Shatra, and Al-Basrah projects, experienced a severe shortage of discharge. In contrast, the Zaydiaa and Al-Sabila offtakes exceeded the scheduled discharge volume. The hydraulic indicators (DPR, ΔQ, and S) were calculated based on the results of the SIC model, represented by the discharges and water level, as illustrated in Table 7. The delivery performance ratio (DPR) has exceeded 200% for the Al-Sabila and Al-Zaydiyah offtake gates. This is because the discharge amount has exceeded twice the recommended level. If the delivery indicator exceeds 1.2, this indicates a water distribution defect. The discharge deviation indicator (ΔQ) for the Al-Dawaya, Shatt Al-Shatra, and Al-Basrah project offtakes was 0% because no discharge passed through the gates. These offtakes are located upstream of the Al-Bada cross-regulator. When the gates of the Al-Bada cross regulator are fully opened, the water level upstream of these offtakes decreases so that it becomes lower than the crest level of the gates. The discharge deviation (ΔQ) indicator is related to the delivery performance ratio (DPR). The more the DPR index exceeds the permissible limits, the more the ΔQ indicator will also be exceeded. According to Table 7, the Janabiat Al-Hay offtake's DPR index decreased gradually to zero at the 60% Q scenario. Figure 3 shows that Zaydiya offtake has the highest supply level and discharge deviation. The discharge deviation indicator exceeds ±30%, which means an unacceptable deviation according to the recommendations of Murray-Rust & Halsema (1998) and Molden & Gates (1990).

Table 7. Hydraulic indicators (DPR, ΔQ, and S) at Al-Gharraf river and its branches values for each scenario

Outlet	Indicator	Al-dawaya	Shatt Al-Shatra	Al-Basra Project	Abuda	Al- Manaia	Al-Hatem	Al- Naumia	Al-Sabila	Al-Zydia	Al- Mghyshi	Akil	Janabiat Al-Hay
Scenario100%Q	DPR	0.00	0.00	0.00	1.07	0.76	1.21	1.3	1.23	1.86	1.2	1.46	0.74
	ΔQ	-1.00	-1.00	-1.00	0. 07	-0.24	0.21	0.43	0.23	0.86	0.20	0.36	-0.26
	Sensitivity	0.66	0.83	0.95	-0.09	-0.61	-0.95	-1.21	-4.05	-1.21	-0.85	-1.29	1.54
Scenario90%Q	DPR	0.00	0.00	0.00	1.17	0.83	1.32	1.42	1.36	2.63	1.31	1.6	0.65
	ΔQ	-1.00	-1.00	-1.00	0.17	-0.17	0.32	0.58	0.36	1.63	0.31	0.6	-0.35
	Sensitivity	0.66	0.85	0.95	-0.22	0.36	-1.0	-1.27	-1.63	-5.63	-1.17	-1.68	2.34
Scenario80%Q	DPR	0.00	0.00	0.00	0.98	0.77	1.22	1.3	1.86	2.84	1.16	1.39	0.39
	ΔQ	-1.00	-1.00	-1.00	-0.02	-0.23	0.22	0.3	0.86	1.84	0.16	0.39	-0.61
	Sensitivity	0.64	0.79	0.9	0.03	0.43	-0.51	-0.75	-2.32	-6.15	-0.44	-0.85	0.51
Scenario70%Q	DPR	0.00	0.00	0.00	0.99	0.8	1.26	1.36	1.91	2.86	1.42	1.18	0.11
	ΔQ	-1.00	-1.00	-1.00	-0.01	-0.2	0.26	0.36	0.91	1.86	0.42	0.18	-0.89
	Sensitivity	0.63	0.79	0.87	0.02	0.34	-0.57	-0.82	-2.3	-7.5	-0.04	-0.33	1.09
Scenario60%Q	DPR	0.00	0.00	0.00	0.97	0.92	1.45	1.41	1.89	2.8	0.8	0.86	0.00
	ΔQ	-1.00	-1.00	-1.00	-0.03	-0.08	0.45	0.41	0.89	1.8	0.20	-0.14	-1.00
	Sensitivity	0.63	0.77	0.87	0.04	0.13	-1	-0.79	-2.13	-4.63	-0.35	0.21	0.84

It has been observed that the discharge deviation (ΔQ) indicator values range between negative and positive values. If the indicator is positive for an intake, it exceeds the water quotas prescribed for it. However, if the indicator is negative, it means a decrease in the volume of water passing through the offtakes. The sensitivity S index refers to the ratio of the relative discharge variation of an offtake (Δq/q) to the relative water depth variation (Δy). According to Table 7, the average sensitivity of Al-Sabila and Al-Zydia offtakes was 2.486 and 5.024, respectively. The simulation results show the sensitivity rate of the offtakes to the discharge deviation, as seen in Figure 4. It is noticeable from Figure 4 that the

Zaidiya Al-Sabila intakes are the most affected by the rise and fall of the water level in the main channel because the gates of these two offtakes are located at a low bed level. According to the opinions of researchers, the indicators listed in Table 6 were classified. The offtakes were then distributed based on the performance indicators in Table 8. This was done to determine the percentage of offtakes whose performance was acceptable according to each indicator limit. The findings revealed that only 6% of the intakes achieved a fair water distribution. Additionally, 11% of offtakes had a discharge deviation within the acceptable limit. Moreover, when it comes to the sensitivity index, it was found that only 18% of the offtakes had medium sensitivity to changes in the water level in the main channel.

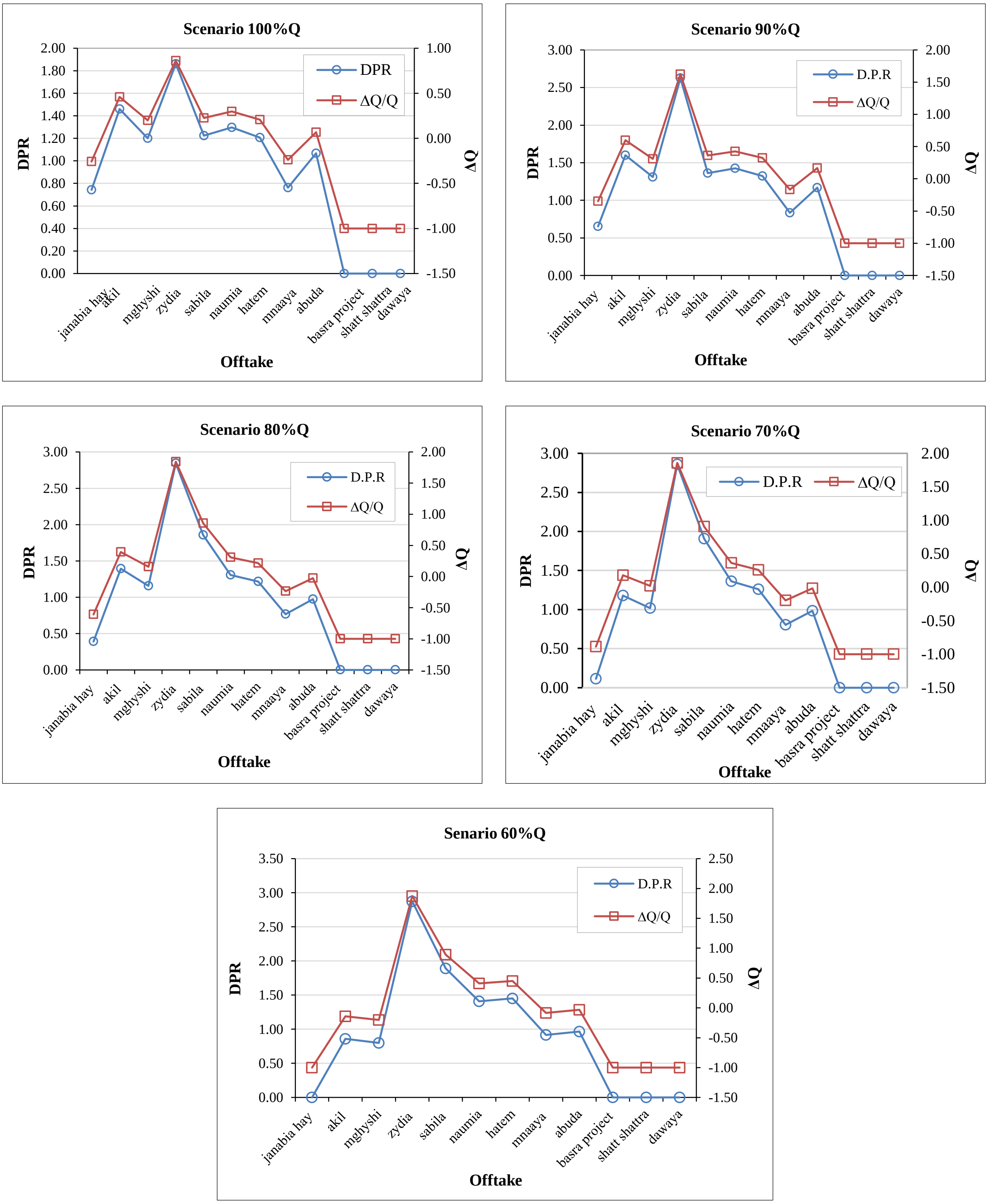

Figure 4. DPR and ΔQ of the offtake structures along Al-Gharraf river for all scenarios

Table 8. Summary discrete a performance type with the number of outlets for each scenario (DPR), (ΔQ), and (S)

Scenario	No. of outlets at performance related to DPR			No. of outlets at performance related to ΔQ			No. of outlets at performance related to S		
	Good	Moderate	Poor	Good	Acceptable	Un acceptable	Low	Medium	High
100% Q	1	4	7	1	5	6	7	4	1
90% Q	0	2	10	2	0	10	5	5	2
80% Q	1	3	8	1	3	8	10	0	2
70% Q	1	2	9	1	3	8	9	1	2
60% Q	1	3	8	2	2	8	9	1	2
Percentage %	6%	23%	53%	11%	21.6	67%	67%	18%	15%

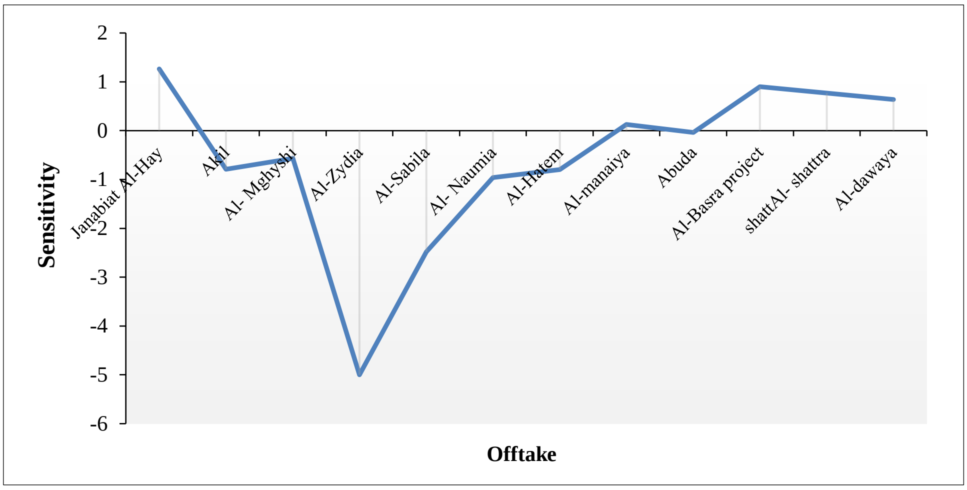

Figure 5. Rate of Sensitivity Indicator (S) of Offtakes

In all scenarios, it has been noted that opening all gates of the al-Bada cross regulator is not a practical solution; it would cause a drop in the water level upstream of the offtake regulator. In each scenario, it is recommended to open a maximum of two gates, with a partial opening not exceeding 1 m. Observations indicate that to achieve the desired water discharge and maintain the water level within the gates in the offtakes of Wasit Governorate, it is necessary to partially open the gates of the cross regulator/2, as fully opening them is impossible.

4. Conclusions and Recommendations

- The Al-Gharraf River Irrigation Project has garnered significant attention from researchers and scholars. However, previous studies have primarily focused on water quality and pollutant levels, with some examination of the river's sedimentary state. Notably, no research has been conducted on the river's hydraulic structures. This study aims to evaluate the efficacy of these structures, including head and cross regulators, in delivering the necessary water supply to the agricultural areas reliant on the Al-Gharraf irrigation project.
- The water delivery performance of the Al-Gharraf River for five operational scenarios has been evaluated using the delivery performance ratio, discharge deviation, and sensitivity. The results revealed that water delivery, in general, was poor.
- There is a high discrepancy in the value of the DPR and ΔQ indices, which are directly proportional, due to a defect in constructing the head regulators for the offtakes. As some of them are located at bed levels higher than the water level, such as Janabiat al-Hay, the value of the DPR index was zero at scenario 0.6Q. At the same time, the Al-Zaydia outlet draws a high volume of water even at low discharges from the al-Gharraf head regulator.
- The sensitivity indicator demonstrates any changes in discharge passing through the structure caused by fluctuations in the depth upstream of the offtakes. Researchers found high sensitivity indicators for Al-Zydia and Al-Sabila offtakes. The Al-Basrah project Shatt Al-Shattra and Al-Dwaya offtakes are experiencing a lack of water, while the discharge at the Al-Zydia outlet exceeds the scheduled amount. Improper construction of offtake gates makes these offtakes highly sensitive to changes in the water depth in the parent channel.
- Al-Gharraf River's flow simulation results using the SIC model for irrigation were presented. It was observed that some regulators require redesigning to be at an adequate bed level, allowing water to pass through during times of scarcity. Moreover, the study suggested that the gates of the Al-Badaa regulator should not be fully opened to maintain an appropriate level of water upstream, enabling water to discharge to the offtakes upstream of the Al-Badaa regulator.

- The offtaleks within Wasit Governorate have a high bed level, and water does not reach them at low releases from the Al-Gharraf head regulator. To achieve operational discharge of these offtakes, we must control the openings of the gates of cross-regulator 2 to ensure that the water level rises to the level of the gates.
- Cross regulators NO. 3 and NO. 4 work simply as weirs, meaning that fully or partially opening them does not affect the water levels upstream of the offtakes. It is because Thi-Qar Governorate's offtakes have a low bed level.

To effectively manage hydraulic facilities and address associated problems, hydraulic models represent the flow in canals and rivers. The recommended model for simulating flow in canals is the SIC model, which allows for the identification of both excessive and deficient water supply at offtakes. This approach also enables the identification of facility design defects, ultimately leading to better water resource management. Proper management of hydraulic structures can be achieved by providing stakeholders with the information necessary to make informed decisions.

5. Declarations

5.1. Author Contributions

Conceptualization, J.S.M. and F.H.K.; methodology, F.H.K. and J.S.M.; resources, F.H.K. and M.S.W.; data curation, F.H.K., J.S.M., and M.S.W.; writing—original draft preparation, F.H.K.; writing—review and editing, J.S.M. and M.S.W.; visualization, J.S.M.; supervision, J.S.M. and M.S.W.; project administration, J.S.M.; funding acquisition, F.H.K. All authors have read and agreed to the published version of the manuscript.

5.2. Data Availability Statement

The Irrigation Management Office provides the data in the Wassit and Dhi Qar provinces, Iraq. The data presented in this study are available on request from the corresponding author.

5.3. Funding

The authors received no financial support for the research, authorship, and/or publication of this article.

5.4. Acknowledgements

The authors are grateful for the scientific support towards this research by the Civil Engineering Department, University of Technology, Baghdad, Iraq.

5.5. Conflicts of Interest

The authors declare no conflict of interest.

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