Engineering and Technology Journal 43 (11) (2025) 939- 946

Engineering and Technology Journal
Journal homepage: https://etj.uotechnology.edu.iq

Hydraulic simulation of Al-Badaa regulator operation and its impact on the flow of Al- Gharraf river

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HIGHLIGHTS

- The flow profile of the Al-Gharaf River was simulated under various hydraulic scenarios.
- The hydraulic performance of the Al-Badaa regulator was evaluated.
- The SIC model was applied to simulate the flow of the Al-Gharaf River.
- The Al-Badaa regulator played a key role in maintaining water levels.
- A partial opening of two Al-Badaa gates raised the water level to match the offtake.

Keywords:

Gharraf River
Operational discharge
Al-Badaa regulator
SIC model
Flow Simulation

ABSTRACT

Surface irrigation is a widely used method for agricultural practices; however, it often suffers from low conveyance efficiency. The research investigates the hydraulic performance of a specific reach of Al-Gharraf River near Al-Badaa regulator located in Nasiriya city in southern Iraq. The primary objective of the present study is to simulate the operational mechanism of Al-Badaa regulator and evaluate its influence on upstream offtake operations. The research employs the Simulation of an Irrigation Canal (SIC) model, which is carefully calibrated and verified using values for the Manning coefficient and the discharge coefficient, alongside real-world operating scenarios. Five distinct flow conditions (100, 90, 80, 70, and 60% of design flow, Qd) were simulated, with cross regulators, head regulator gates, and offtakes fully opened. The findings indicate that Al-Badaa regulator significantly influences the hydraulic dynamics of Al-Gharraf River. Full opening of the gates results in a decrease in upstream water levels, causing reduced discharge at some water intake stations. This study provides critical insights into the hydraulic dynamics interaction between Al-Badaa Regulator and the upstream offtakes serving Al-Dawaya, Shatt Al-Shatra, and Al-Basra water projects, located approximately 200 m, 300 m, and 2 km upstream of Al-Badaa regulator, respectively. A key outcome of this work is to partially open two out of six gates, to a height of less than 1 m, to maintain sufficient water levels. This operational strategy significantly improves the hydraulic performance of the irrigation network and ensures equitable water distribution to critical upstream offtakes.

1. Introduction

Effective water resources management is essential for ensuring the quality and sustainability of water supplies. It improves equitable distribution, reduces wastage, and supports long-term economic growth. Proper management also enhances infrastructure by guiding investments in modern systems. In regions facing water scarcity, integrated strategies are necessary for building resilience. Addressing both quantity and quality of water is essential for safeguarding public health and agricultural production. According to the United Nations (2021) [1], sustainable water management is central to achieving global development goals.

Hydraulic Modeling serves as a robust method for analyzing the performance of irrigation systems. A well-calibrated and validated model can evaluate and improve the operating efficiency of such irrigation systems. Over the past decade, researchers [2-14] have extensively examined intricate irrigation scenarios employing simulation models to improve system efficiency.

Majeed et al. [6], used a digital elevation model (DEM) to simulate and analyze flow in the Tigris River, applying one-dimensional numerical models (steady and unsteady flow) in HEC-RAS software. Field data from 38 stations were collected to determine hydraulic properties such as discharge, velocity, and cross-sectional area. The results identified flow choking that could lead to sedimentation and rising riverbed levels, helping identify critical locations for efficient river management [7].

In Iran's Fars Governorate, the HEC-RAS model, calibrated and validated for 2001 and 2002, was applied to regulate irrigation in the Ordibehesht Canal (Doroodzan system). The study evaluated two operational regulations for optimal water

http://doi.org/10.30684/etj.2025.158423.1921
Received 20 March 2025; Received in revised form 02 August 2025; Accepted 07 August 2025; Available online 25 September 2025
2412-0758/University of Technology-Iraq, Baghdad, Iraq

discharge in tertiary canals and highlighted the need to revise current operational rules. Findings indicated that inaccurate discharge coefficients for gated control structures impact water supply equity and performance. A reduced discharge at the source led to significant water-level declines in tertiary canals, emphasizing the need for proper gate installation, control, and maintenance.

In Iraq, Maatooq and Wahad [9], have made the first attempt to utilize the SIC model to analyze the hydraulic performance of Al-Kifl-Shinafiya distribution channel and its outlets indicators. The study examined discrepancies between actual water deliveries and demand at various outlet structures, including a central regulator and sixteen cross-regulators. The Productivity Equity Index (PE) was mostly positive, except in May and October, while the Dependability Index (PD) was excellent for major outlets but only fair for others. The adequacy index (PA) was weak, with findings showing better reliability and efficiency during winter compared to summer.

Daham and Abed [10], conducted a study in which they used one-dimensional (1D) and two-dimensional (2D) hydraulic models to analyze the unsteady flow characteristics of a 58.2 km reach of Al-Gharraf River between the cities of Kut and Al-Hai. Using HEC-RAS 5.0.4, they simulated multiple gate operation scenarios at Al-Hai regulator, with discharge rates ranging from 100 to 350 m³/s. The results revealed that the 2D model provided greater accuracy in representing velocity and water surface elevation compared to the 1D model, making it more suitable for identifying problem areas and proposing effective solutions. Similarly, Al-khafaji and Al-Merib [11], used HEC-RAS v6.0.1 to simulate flood risks along the Shatt Al-Hillah River, incorporating over 350 surveyed cross-sections. The model was calibrated using discharge data from 2004 to 2022, demonstrating that the current channel capacity (205 m³/s) is insufficient for the design flood discharge (303 m³/s). Simulation results suggested severe flood risk, especially in the northern Babil, where inundation reached 92.2% under 450 m³/s discharge scenarios. Mahmoud et al. [12], examined how the material and hydraulic properties of a dam influence the dimensions of openings caused by dam overflow failure, employing a 2D HEC-RAS program. Six failure scenarios for the Mosul Dam were analyzed, incorporating various material types (core wall dam, concrete face dam, and homogeneous dam) and two distinct erodibility levels. The findings indicated that both material type and erodibility have a considerable impact on the opening width and failure duration, demonstrating a clear sensitivity to the volume of water storage at the time of failure. Abbas et al. [13], investigated the effects of hydraulic structures on flow regulation in the Euphrates River between the Al-Abbassia and Al-Shammia barrages. Using HEC-RAS 2D software, simulations were conducted for maximum, average, and minimum discharge scenarios to analyze variations in flow velocity, water surface elevation, and depth. The findings indicated that the hydraulic behaviour of the river is significantly influenced by differing discharge rates, offering valuable insights for effective water resource management. Kazem et al. [14], evaluated the hydraulic infrastructure along Al-Gharraf River in southern Iraq, focusing on its capacity to deliver adequate water flow to agricultural regions. Discharges from the Gharraf head regulator ranged from 280 m³/s (winter) to 100 m³/s (summer).

This research paper investigated whether the Gharraf River's offtakes could deliver the demanded discharge under flow fluctuations (60 and 100% of its operating discharge) using the SIC model. Hydraulic indicators, including the Delivery Performance Ratio (DPR), Sensitivity (S), and Discharge Deviation (ΔQ), were applied to assess the performance of regulators. It is worth noting that this evaluation aimed to identify the most and least effective regulators that supply water to the offtakes and to analyze the factors contributing to inefficiencies. Results revealed a discrepancy in water distribution: certain offtakes, including Al-Ziadia and Al-Sabila, exceeded their designated operational discharge levels, while others, like Al-Basra, Shatt Al-Shatra, and Al-Dawaya projects, failed to receive their designated operational discharge, receiving less than 10% of the required flow. The study recommended the rehabilitation of specific offtakes and improving gate operations to improve the efficiency of water distribution.

Conventionally, academics have focused predominantly on water scheme outputs while giving little thought to water delivery mechanisms. Hence, Al-Badaa regulator, one of the most significant structures controlling the flow and distribution of water from the Gharraf River, was selected as a case study to analyze how the operation mechanism of the Regulator affects the flow in both the main and the branched channels. Previous studies have primarily focused on assessing water quality and demand satisfaction in Al-Badaa Canal, overlooking the operational or hydraulic aspects of the Regulator. Through the aforementioned overview of related literature, it is clear that no studies have been conducted on gate control mechanisms, operational procedures, and their impact on adjacent regulators and water supply projects. This may be due to the lack of software that can be used to analyze the overlapping effects of these operational parameters. This may be due to the lack of software that can be used to analyze the interaction effects of these operational parameters. Therefore, the novelty of the current study lies in the attempt to use the SIC program, which was originally designed to analyze flow in lined artificial irrigation canals and defined in cross-section, and to employ it for the first time to represent flow management for a regulatory system constructed on an irregular earthen canal. Accordingly, this study might be the first attempt to examine Al-Badaa regulator from a technical and hydraulic perspective, emphasizing its decisive role in the regional water management.

2. Study area

Al-Badaa regulator is situated approximately 168 kilometers downstream of Al-Gharraf Head Regulator. It consists of six vertical sluice gates, each measuring 7 m in width and 5.2 m in height, with a typical discharge capacity of 25 m³/s.The geographical coordinates of Al-Badaa regulator are approximately 31.4475° N latitude and 46.1746° E longitude. Figure 1 demonstrates the upstream section of the Al-Badaa regulator [15].

Figure 1: Upstream of Al-Bada cross-regulator (center of studies and engineering design)

3. One-dimensional SIC hydrodynamics

Cemagref maintains a variety of hydraulic models for different simulations, such as dam failure, river flows, irrigation canals, and drainage systems. Among these, the SIC (Simulation of Irrigation Canals) model is specifically designed to simulate irrigation canal flows. Developed from an existing hydraulic model, SIC incorporates several modifications, including the removal of redundant features, the addition of new features, and an enhanced user-friendly interface, making it readily usable by the canal administrators for daily system operations and maintenance planning. The SIC package implements the one-dimensional Saint-Venant equations that describe open-channel flow through two fundamental partial differential equations representing:

Mass conservation orcontinuity equation (Equation 1) is formulated as follows:

$$\frac{\partial A}{\partial t} + \frac{\partial Q}{\partial x} = q \quad (1)$$

Momentum equation or dynamic equation (Equation 2) can be expressed as:

$$\frac{\partial Q}{\partial t} + \frac{\partial}{\partial x}\left[\frac{Q^2}{A}\right] + g.A\left[\frac{\partial Z}{\partial x}\right] = -(gA) * S_f + K * (qV) \quad (2)$$

where, A: wet area (m^2), Q: discharge (m^3/s), Z: elevation (m), S_f: friction slope, q: lateral discharge by unit length ($m^3/s/m$), x: Longitudinal distance (m), β: momentum coefficient, g: acceleration due to gravity (m/s^2).

The partial differential equations require initial and boundary conditions to be solved. The boundary conditions consist of the hydrographs at the upstream nodes of the reaches and a rating curve at the downstream node of the model. The initial condition corresponds to the water surface profile derived from steady flow computation.

Numerous investigations have examined the computational accuracy of the SIC model. Accurately characterizing this performance remains challenging, as it depends upon: (1) the particular type of system being modeled, (2) its scale, (3) the simulated hydraulic conditions, and (4) the quantity and quality of input data. Scientists typically evaluate the model's accuracy by performing tests on existing systems and predetermined scenarios. The 1-D hydrodynamic SIC has been employed in multiple studies to simulate hydraulic and operational attributes of irrigation canals, thereby improving management methods and operation efficiency [16].

3.1 Model calibration and validation

The calibration mode plays a crucial role in updating the canal's Manning roughness (n) and the discharge coefficients for head regulators, cross regulators, and offtakes (Cd). This process requires field measurements such as water levels along the head and cross regulators of the Gharaf River, downstream levels in watercourse canals, and the discharges from the offtakes.

The SIC model was calibrated by adjusting key hydraulic parameters using the procedure proposed by [17]. This involved estimating a rating curve with the Conveyance Estimation System (CES) and incorporating uncertainty estimation based on the upper and lower roughness values built in. The procedure focuses primarily on Manning's roughness coefficient, established within a range of 0.25 to 0.33, and the gate discharge coefficient. This range of Manning coefficients for the Gharraf River was selected based on a comprehensive review of the literature about the characterization of similar river channels, in conjunction with empirical field data collected during calibration.

The Gharraf River is distinguished by its varied topography, including differing bed conditions, such as clayey bottoms and vegetated banks with trees and shrubs. This diversity increases bed roughness and resistance, thereby influencing the flow dynamics. Furthermore, both natural and artificial obstructions significantly enhance flow resistance, requiring relatively higher

Manning coefficients than typical open channels. Through these aforementioned field investigations that employed the CES and SIC models, the regulators' discharge coefficients were determined to range between 0.59 and 0.63.

The SIC model can automatically calibrate friction and discharge coefficients for gates and weirs using water level data along the canal. During calibration, these coefficients were adjusted to attain optimal alignment between actual and simulated flow data, ensuring the model's accuracy and reliability in representing the hydraulic performance under various operational conditions. Model validation, on the other hand, executes the model with observed input data to generate sufficient simulations- either for a local section or the entire network, while minimizing differences. These simulations help ensure that the model is accurate and reliable.

This study also integrates several performance indicators, previously adopted by researchers, into the SIC model to consolidate the measured performance of the structures. These indicators include: PBIAS "Percent Bias", (Equation 3), RMSE "Root Mean Square Error", (Equation 4), RSR "Ratio of the Root Mean Square Error to the Standard Deviation of Observations", (Equation 5),and NSEC "Nash-Sutcliffe efficiency coefficient". (Equation 6).[9,17-21].

$$PBIAS = \frac{\sum_{i=1}^{n}(Qi^{obs} - Qi^{sim})*100}{\sum_{i=1}^{n} Qi^{obs}} \quad (3)$$

$$RMSE = \left[\frac{1}{n}\sum_{i=1}^{n}(Qi^{obs} - Qi^{sim})^2\right]^{0.5} \quad (4)$$

$$RSR \frac{RMSE}{STDEV\ obs} = \frac{\left[\sqrt{\sum_{i=1}^{n}(Qi^{obs} - Qi^{sim})^2}\right]}{\left[\sqrt{\sum_{i=1}^{n}(Qi^{obs} - Qi^{mean})^2}\right]} \quad (5)$$

$$\text{NSEC} = 1 - \frac{\left[\sum_{i=1}^{n}(Qi^{obs} - Qi^{sim})^2\right]}{\left[\sum_{i=1}^{n}(Qi^{obs} - Qi^{mean})^2\right]} \quad (6)$$

The recommended statistics for model validation and calibration are tabulated in Table 1. The model provided exceptional validation results for DPR (Delivery Performance Ratio) values at 40, 45, 50, and 70% of the design flow rate (Q) as demonstrated in Table 2. Figure 2 illustrates the actual and simulated water level (m.a.s.l) of the Gharraf River by (SIC) at various scenarios. The Nash-Sutcliffe Efficiency Coefficient (NSEC) was consistently excellent across all scenarios. The RSR (RMSE-Standard Deviation Ratio) was also excellent in all cases. Table 3 displays the statistical indicators of the validation process results.

Table 1: Recommended statistical metrics for assessing model validation and calibration (after [9,18-22], arranged by third author)

Performance	NSEC	RSR	PBIAS
Very good	PBIASE≥±0.25	0.7<RSR	0.5≥NSE
Good	0.25±>PBIASE≥±0.15	0.6≥RSR>0.7	0.65≥NSE>0. 5
Satisfactory	0.15±>PBIASE≥±0.1	0.5≥RSR>0.6	0.75≥NSE>0.65
Unsatisfactory	±0.1 >PBAIS	0.5≥RSR≥0.0	1≥NSE>0.75

Table 2: SIC model evaluation across various hydraulic conditions at the cross regulators and head of Al- Gharraf and its tributaries

Calibration scenarios					Validation scenarios			
Operation Condition	**40% Scenario February, 2018**		**45% Scenario January, 2016**		**50% Scenario April, 2017**		**70% Scenario March, 2016**	
Level of water (m.a.s.l.)* m	**Simulated**	**Evaluated**	**Simulated**	**Evaluated**	**Simulated**	**Evaluated**	**Simulated**	**Evaluated**
HR	16.36	16.16	16.2	16.38	16.78	16.68	17.83	17.78
CR1	12.59	12.65	13.9	13.9	13.78	13.88	14.63	14.65
CR2	11.47	11.7	11.32	11.05	13.01	12.9	12.89	12.7
CR3	10.13	10.15	10.43	10.45	11.49	11.45	11.5	11.5
CR4	9.17	9.15	9.25	9.4	10.1	10.05	10.07	10.25
Bad'a RE	8.58	8.5	8.3	8.3	8.98	9.15	8.96	8.95

*(m.a.s.l.): The height of the water surface measured in metres above sea level.

Table 3: SIC statistics of Al- Gharraf hydraulic structure with various scenarios at 95% level*

Scenario	PBIAS	NSEC	RSR
70%Qd	0.06 (VG)	0.99 (VG)	0.07 (VG)
50%Qd	0.04 (VG)	0.99 (VG)	0.04 (VG)
45%Qd	0.1 (G)	0.95 (VG)	0.045 (VG)
40%Qd	0.04 (VG)	0.99 (VG)	0.05 (VG)

*VG=Very good and G=Good

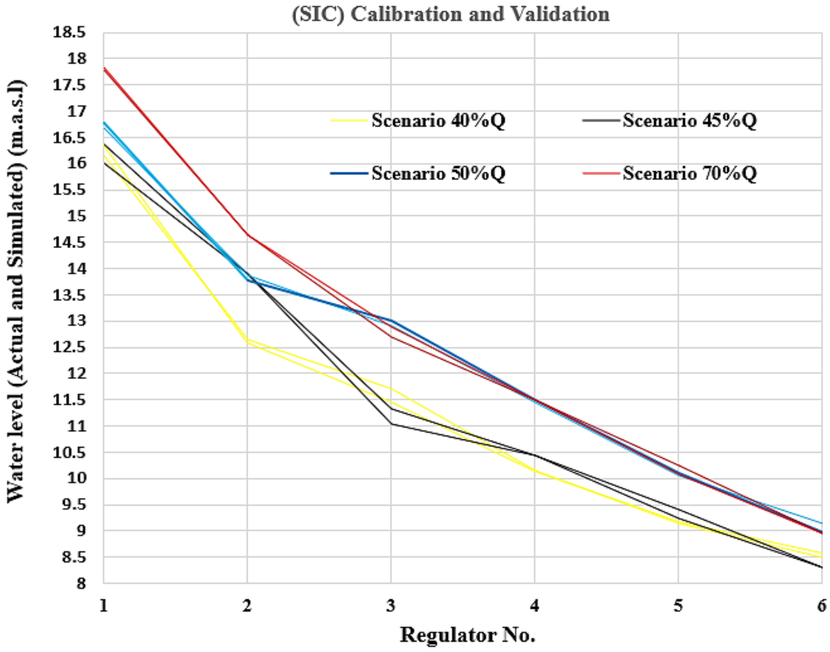

Figure 2: Actual and simulated water level (in meters above sea level) of Al- Gharraf River at various hydraulic scenarios

4. Results and discussion

This study simulated river flow under five operational scenarios (350, 315, 280, 245, and 210 m³/s), corresponding to 100%Qd, 90%Qd, 80%Qd, 70%Qd, and 60%Qd, with all regulator and offtake gates fully opened using the simulation of irrigation canals (SIC) model. A discharge rate of 350 m³/s was selected to assess the Regulator's performance under the initial design specifications, while reduced flows (90%–60%) were simulated to evaluate contemporary low-flow scenarios. This procedure makes clear how discharge variations affect system efficiency and yields valuable insights for future planning and improving irrigation system management.

The findings indicate that Al-Badaa regulator significantly affects the operational plan of the Gharraf River. The research focused on the Regulator's operation, its effects on discharge and water levels (m.a.s.l), and identifying an optimal operational strategy to ensure sufficient discharge for the offtakes situated upstream of Al-Badaa. It is concluded that fully opening Al-Badaa Regulator gates resulted in a substantial water level drop, reducing discharge to the Al-Basra Water Project, Shatt Al-Shatra, and Al-Dawaya offtakes to zero. These offtakes are located upstream of Al-Badaa regulator, at distances of 2 km, 300 m, and 200 m, respectively. Table 4 summarizes the offtake discharge rates across the five scenarios.

Sill levels of Al-Dawaya, Shatt Al-Shatra, and Al-Basra Water Regulators (7, 6.5, and 7 m, respectively) are notably higher than Al-Badaa regulator (3.4 m; see Table 1). Table 5 demonstrates that under all simulated discharge scenarios—including full design discharge (100% Qd = 350 m³/s) — the upstream water levels at these offtakes remain below their respective sill levels (6.5 m to 7.0 m). At 100% Qd, the recorded water levels were 5.62 (m.a.s.l.) for Al-Diwanya, 5.81(m.a.s.l.) for Shatt Al-Shatra, and 6.78 (m.a.s.l.) for Al-Basra project, all insufficient to initiate flow into the offtakes. Further reductions in discharge (90%–60% Qd) exacerbated this issue, culminating in zero flow when Al-Badaa regulator gates were fully opened as depicted in Figure 3. In contrast, Al-Badaa CR, with a sill level of only 3.4 m, consistently receives sufficient flow under all conditions.

These findings underscore the system's vulnerability, whereby the high sill levels of the downstream offtakes prevent water delivery even under nominal flow conditions. This underlines the need to adopt operational modifications to enhance efficiency during low-flow periods. To operate Al-Badaa regulator gates efficiently and achieve the operational discharge for the offtakes Shatt Al-Shatra, Al-Dawaya, and Al-Basra Water Projects.

The study simulated the Al-Badaa regulator with partially opened gates, monitoring water levels and discharge. It was revealed through successive adjustments that only two of six gates (to 1 m or 50 cm) partially mitigated the deficit but still failed to meet offtake requirements (Table 5).

Al-Dawaya Regulator, located 200 meters downstream of Al-Badaa regulator, sits 3.6 meters lower in elevation. As a result, water does not reach Al-Dawaya's sill level when Al-Badaa 's gates are fully open; this is also observed at Shatt Al-Shatra and Al-Basra water gates. Recently, measurements of discharges at Al-Badaa regulator range between 10 and 25 m3/s, resulting in an upstream level of 7-9 m (Dhi-Qar Water Resources Directorate database). To ensure that the water elevation is sufficient for the offtake gates, the regulator operates with two gates opened no more than 1 m high, and thus, confirming the findings of the simulation. Figure 3 illustrates key hydraulic effects of gate operations on water levels at various points along the river. They can be summarized as follows:

1) Fully opened gates lead to an overall decline in water levels upstream of the regulator. However, localized pooling occurs due to variations in the riverbed topography. These irregularities in water elevation and bed structure elevate

water levels in certain areas. Moreover, the obstacles and water structures along the river channel restrict flow, further increasing the water levels in those locations. The fully opened gates notably amplify energy loss, resulting in a significant decrease in water levels immediately upstream. This affects water distribution and prompts localized pooling near terrain changes or obstructions.

2) Partial gate opening lowers flow velocity, minimizes energy loss and enhances the stability of water levels. This improves the efficiency of water transfer and the distribution within the irrigation network. These findings highlight the significance of managing gate operations to balance water discharge and maintain the stability of the hydraulic system.

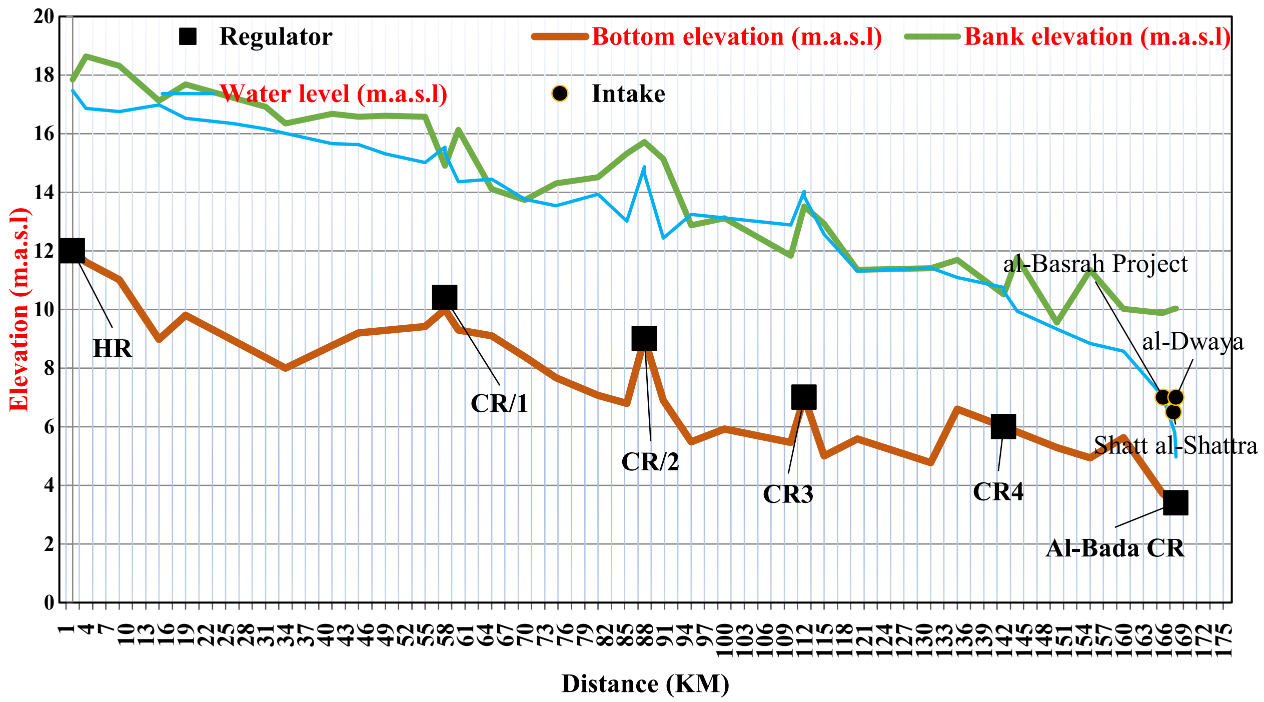

Figure 3: Longitudinal profile along Al- Gharraf river illustrates the water level (in meters above sea level) compared with the current bank level for 100% q_{req}

Table 4: Summary of the Simulated Discharge and water level of Offtakes for all Scenarios undertaken (Q_{River}=350 m^3/s)

Structure	sill level (m)	Scenario 100%Q_d		Scenario 90%Q_d		Scenario 80%Q_d		Scenario 70%Q_d		Scenario 60%Q_d	
		W.L (m.a.s.l)	Q (m^3/s)	W.L (m.a.s.l)	Q (m^3/s)	W.L (m.a.s.l)	Q (m^3/s)	W.L (m.a.s.l)	Q (m^3/s)	W.L (m.a.s.l)	Q (m^3/s)
Al-Bsara Project	7	6.78	0	6.86	0	6.73	0	6.67	0	6.62	0
Shatt Al-Shatra	6.5	5.81	0	5.88	0	5.77	0	5.73	0	5.66	0
Al-Dawaya	7	5.62	0	5.7	0	5.59	0	5.53	0	5.51	0
Al-Badaa CR	3.4	5.07	86	5.34	88	5.2	80	5.17	76	5.15	75

Table 5: Flow simulation results at 100%Q_{REQ} with fully opening of Al-Badaa gates

Offtake	Q_d (m^3/s)	* H=1 m		H=0.5 m	
		Q (m^3/s)	W.L (m)	Q (m^3/s)	W.L (m)
Al-Basra Project	20	5.18	7.59	9.8	7.9
Shatt Al-Shatra	15	10.68	7.46	17.7	7.84
Al-Dawaya	20	3.49	7.45	8.8	7.84

*H: The height of gate opening

5. Conclusion

Analyzing the data resulting from using the SIC software as a tool to extrapolate many possible operating scenarios enables the following conclusions to be determined:

1) The analysis revealed operational deficiencies at certain offtakes, such as Al-Dawaya, Shatt Al-Shatrah, and Al-Basra Project, which constantly failed to receive water even under full gate opening scenarios.

2) The proximal upstream location of these offtakes relative to Al-Badaa regulator and nearby caused the decrease in the offtake discharge. Full opening of all six gates (each 5.5 m high) instigates critical drawdown effects, reducing the upstream water levels below the minimum sill elevation required for the offtake operation.
3) According to the simulation results, optimal hydraulic performance for upstream offtakes can be achieved through controlled operation of two gates with a maximum opening of 1 m. The SIC software facilitated accurate determination of these parameters by repeatedly measuring flow and water levels until the desired water elevation was reached at the offtake structure.
4) In Design Mode, the SIC model resolves through computational calculations any one unknown hydraulic parameter (bed level, gate opening, or gate width) when the target discharge is specified. This way, comprehensive canal system optimization is made possible.
5) Rehabilitation of currently inoperative gates at Al-Badaa regulator to establish emergency operational capacity. Additionally, modifying the river cross-section is necessary to restore connectivity to the intake gates.
6) Successful management should focus on optimal operation of gates at Al-Badaa regulator, where partial opening of select gates maintains sufficient upstream water levels while minimizing flow losses. Implementing a rotating irrigation system prioritizes water allocation to critical drinking water intakes and agricultural demands during drought periods. Temporary earthen banks constructed upstream provide localized water level increases during peak irrigation needs. It is also useful not to neglect regular maintenance interventions, including the removal of accumulated sediments and aquatic vegetation, which further improves system efficiency throughout the distribution network.
7) The findings of this study recommend using the SIC model for simulating flow in irrigation channels, particularly those that include regulators and offtakes.

This model has proved effective and capable of identifying both excessive and insufficient water supply at offtakes, while also revealing systemic design flaws, which impact the efficiency of water allocation. These analytical outcomes provide the necessary data to enable decision makers to plan and manage available water resources effectively, thereby enhancing the operation of hydraulic structures under variable flow conditions.

Author contributions

Conceptualization, **F. Kazim** and **J. Maatooq**; data curation, **F. Kazim, J. Maatooq** and **M. Wahad**; formal analysis, **F. Kazim,** and **J. Maatooq**; investigation, **F. Kazim**; methodology, **F. Kazim** and **J. Maatooq**; project administration, **F. Kazim** and **M. Wahad**; resources, **F. Kazim, J. Maatooq** and **M. Wahad**; software, **F. Kazim** and **M. Wahad**; supervision, **F. Kazim**; validation, **F. Kazim, J. Maatooq** and **M. Wahad**; visualization, **F. Kazim,** and **J. Maatooq**; writing—original draft preparation, **F. Kazim**; writing—review and editing, **F. Kazim, J. Maatooq** and **M. Wahad**. All authors have read and agreed to the published version of the manuscript.

Funding

This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

Data availability statement

The data that support the findings of this study are available on request from the corresponding author.

Conflicts of interest

The authors declare that there is no conflict of interest.

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