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Impact of gate operations and environmental implications on downstream scour at Kalat Saleh regulator

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Abstract: Regulators and other hydraulic structures are essential for managing flow in open channels. However, improper operation of these structures' gates can lead to unpredictable and potentially damaging scour patterns. This study investigates the optimal operation of the Kalat Saleh Regulator's gates in Iraq, focusing on sediment movement and sedimentation issues. Using Flow-3D software and the RNG turbulent model, sediment movement was simulated under various flow conditions and gate opening scenarios. The study found that the number of open gates and their operational sequence significantly affect scour development downstream of the regulator. Specifically, the maximum scour depth was observed when a single gate was opened, resulting in an eight-fold increase compared to the scenario where all gates were opened at a flow rate of 125 m^3/s. Additionally, a direct correlation between flow rate and scour depth was established, with the maximum scour depth recorded at -2.6 m for a flow rate of 75 m^3/s, and -4.41 m for a flow rate of 125 m^3/s, representing a 1.7-fold increase. These findings suggest that careful management of gate operations can mitigate the risk of excessive scouring, which has practical implications for the design and operation of similar hydraulic structures. By optimizing gate operations, it may be possible to reduce sediment-related issues, enhance structural integrity, and improve the efficiency of water flow management in open channels.

Keywords: *Flow-3D, Kalat Saleh Regulator, Open channel flow, RNG model, Tigris River.*

1. Introduction

Due to incorrect multi-opening operations, which result in unusual scour patterns, many of the hydraulic infrastructures that are still in place in Iraq, such as regulators, have experienced problems with scouring both upstream and downstream. So, the most efficient use of water is directly and significantly impacted by the management and operation of water resource projects [1]. The hydraulic properties of unsteady flow in rivers must be specified by hydraulic model simulations in order to identify problems and recommend appropriate remediation measures [2].

The gates' and their mechanical devices' insufficient and irregular maintenance, as well as a strict and defined routine operation rule that is followed, may lead to improper operation in such hydraulic systems. Around the world, numerous structures have collapsed as a result of severe dredging. Thus, after crushing, the safety of the current facility primarily rests on the ongoing observation of local scour [3].

The local scour depth and sediment accumulation could be influenced by a range of particular factors. The characteristics of particle, rate of flow, flow time, Froude Number, operating regime, and gate opening sequence are the most important ones to consider when analyzing the parameters that will be investigated for their effects on local scour downstream the regulator with different flow conditions. The most recent research in this area was carried out by Abdulridha and Al Thamiry [4] They developed a mathematical model in their study and used it to examine the Samarra-Al Tharthar system

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hydraulically. They showed that sediment accumulates and forms islands upstream of regulators at low velocities. The system's efficiency is reduced, and its structural stability is threatened by these islands and sedimentation.

Ibrahim and AL-Thamiry, 2018, showed in their lab experiment that they conducted to look at the many conditions surrounding local scour around curved groynes. The study revealed that, although significant, the Froude Number does not dominate the processes governing scour and sediment movement. We have demonstrated that the scouring amount and flow velocity are directly correlated with the Froude Number, even when all other factors remain constant.

Abed and Majeed [5] in their research, the behavior of the scouring pattern between bridge piers under particular hydraulic circumstances was investigated using a mathematical simulation. They observed in their study that the scour depth rises over time, sediments are carried away from the scour site, and erosion continues until equilibrium is reached. Mobile bed scour, where sediment is transported from the inflow load, initially increases and varies over time. Equilibrium occurs when transported sediment equals removed sediment.

Al-Hassani and Mohammad [6] state that the size of the bed material directly affects how sediments are transported. They created a lab experiment, and according to their research, the diameter of the scour hole, the maximum level of scour volume, and the scour process itself are all highly influenced by grain size. They concluded that the highest depth and area of scour decreased as the median size, d50, and geometric standard deviation increased.

Majeed, et al. [7] through the mathematical model they created for the purpose of conducting a numerical simulation of the operational impact of the Al-Hay Regulator's Gate Openings on Local Erosion, they found that increasing the Froude Number results in more soil removal and scour depth around the regulator. The depth of scour depends on gate numbers, order, and operation system. Unevenly distributed or open gates increase scouring depth.

Altawash and Al Thamiry [8] investigated the velocity patterns in the reservoir using different operating techniques for the planned Makhool Dam. Because the velocity values were lower than those obtained by operating successive gates with the same discharge, the study concluded that operating non-consecutive gates was the best course of action. A more appropriate velocity distribution is produced by operating gates with more openings and fewer numbers with a specific outflow than by running gates with fewer openings and more numbers with the same outflow.

Other researchers, such as Zhang, et al. [9] emphasized the significant impact of bed material size on sediment transport. Their laboratory experiments showed that grain size strongly influences the diameter of the scour hole, the maximum scour volume, and the overall scour process. Nevertheless, their work focused on sediment characteristics rather than on the operational strategies of gate systems. Majeed, et al. [7] developed a mathematical model to simulate the operational impact of the Al-Hay Regulator's gate openings on local erosion. Their results indicated that unevenly distributed or open gates lead to increased scouring depth, with the depth of scour being influenced by the number of gates, their order, and the operation system. However, their study did not explore the combined effects of flow rate and gate opening sequence in detail.

In contrast, Omara and Tawfik [10] investigated velocity patterns in the reservoir of the planned Makhool Dam using different operating techniques. Their study concluded that operating non-consecutive gates with the same discharge produced lower velocity values compared to operating successive gates. They also found that operating gates with more openings and fewer numbers at a specific outflow resulted in a more appropriate velocity distribution. However, their focus was more on velocity patterns than on scouring

Nkad, et al. [11] looked into how well silt was removed from reservoirs by considering the effects of sediment nonuniformity, slit weir diameters, weir slit position, and discharge. It was discovered that, in comparison to finer material, coarser sediment reduces scour volume by a factor of 22. Regardless of bed material nonuniformity, the study investigated five alternative slit weir dimensions and discovered that a three-fold increase in discharge correlates to a ten-fold increase in scour volume.

This study makes a novel contribution to hydraulic engineering and sediment management by focusing on the Kalat Saleh Regulator, uncovering its unique scouring phenomena. It delves into how various gate operations affect scour depth, providing insights that go beyond the general approaches of past research. By utilizing Flow-3D for advanced CFD simulations, the study offers more precise modeling of scouring effects. Additionally, it incorporates sediment characteristics and upstream flow conditions into a comprehensive analysis, enhancing the accuracy and applicability of the findings.

Addressing gaps in existing literature, this study aims to enhance understanding of the factors affecting scouring downstream of the Kalat Saleh Regulator. By developing a mathematical model with Flow-3D, it simulates sediment transport in the regulator's reach, focusing on how varying flow rates, gate openings, and their sequences influence erosion. The objective is to identify the most effective gate operation strategy to minimize downstream erosion, thus improving the efficiency and safety of hydraulic structures.

2. Mathematical Model

VOF and FAVOUR techniques are used by Flow Science Inc.'s Flow-3D v11.2 CFD program to determine the free surface and any obstacles in its path. This guarantees the tracking of the liquid/gas contact and the realistic representation of the dynamics of the free surface. Hirt and Nichols [12] Flow-3D comprises the fluid volume function, the transport equation, and the boundary conditions as its three primary parts (FLOW3D manual, 2014).

The FLOW3D program employs the Volume of Fluid method to model free surface flow in simulation. In order to obtain precise free surface conditions for the VOF method, the program must fulfill three requirements:

1-The fraction variable (F) needs to be found for each and every cell. When F = 0, it denotes an empty cell, and when F = 1, it indicates that the cells are completely filled with fluid.

2-Achieving a sufficient free surface is crucial. As F is calculated for every cell, the free surface can be reached appropriately.

2.1. Formulation and Theory of CFD Model

The RANS equation is used to model the movement of an incompressible viscous fluid. It describes in detail how viscous fluid substances move in three dimensions within the Flow-3D software. By including extra terms in the x-, y-, and z-coordinates, the motion equations for the fluid velocity sections (u, v, and w) can be given.

$$
\begin{gathered}
\frac{\partial u}{\partial t} + \frac{1}{V_F}\left(uA_x \frac{\partial u}{\partial x} + vA_y \frac{\partial u}{\partial y} + wA_z \frac{\partial u}{\partial z} \right) = -\frac{1}{\rho}\frac{\partial p}{\partial x} + G_x + f_x \\
\frac{\partial v}{\partial t} + \frac{1}{V_F}\left(uA_x \frac{\partial v}{\partial x} + vA_y \frac{\partial v}{\partial y} + wA_z \frac{\partial v}{\partial z} \right) = -\frac{1}{\rho}\frac{\partial p}{\partial y} + G_y + f_y \\
\frac{\partial w}{\partial t} + \frac{1}{V_F}\left(\frac{uA_x \partial w}{\partial x} + vA_y \frac{\partial w}{\partial y} + wA_z \frac{\partial w}{\partial z} \right) = -\frac{1}{\rho}\frac{\partial p}{\partial z} + G_z + f_z
\end{gathered} \tag{1}
$$

The variables in the equation are defined as follows: V_F denotes the proportion of volume, Ai represents the proportion of the area, ρ represents the fluid density, p represents the average hydrodynamic pressure, the symbols Gi and denote the body acceleration and fi viscous acceleration.

2.2. Model of Turbulence

Turbulence is the absence of a stabilizing force and is typified by oscillations at high frequencies and the creation of different eddies with varying energy [13]. Turbulence is a chaotic and erratic fluid motion, based on the Reynolds number. High Reynolds numbers cause the emergence of eddies with different length scales due to the flow's inherent instability.

The Flow-3D software provides a selection of six turbulent flow models. The recommended topics encompass Prandtl mixing length, one-equation, two-equation, renormalized group, and large eddy simulation.

Flow-3D software is commonly employed in numerous studies to replicate sediment scour, and the renormalized group model is the prevailing choice for this purpose. This model provides an accurate description of low-intensity turbulent flow, particularly in areas with a greater shear zone. The computational efficiency of this model surpasses that of the Large Eddy Simulation (LES) model. which necessitates a smaller mesh size. This is the reason it was chosen for the studies conducted by Zhang, et al. [9] and Omara and Tawfik [10]. Using statistical methods, the renormalized group k-ε turbulence model Yakhot and Smith [14] and Smith and Woodruff [15] generated averaged formulas for turbulence parameters, including the rate at which turbulent kinetic energy dissipates. This model is more widely applicable than the k-ε model since it makes use of equations that are similar to it; nonetheless, the turbulent model RNG k-ε generates the equation constants explicitly. It's governed by the following equations:

$$\frac{\partial k_T}{\partial t} + \frac{1}{V_F}\left(uA_x \frac{\partial k_T}{\partial x} + vA_y \frac{\partial k_T}{\partial y} + wA_z \frac{\partial k_T}{\partial z} \right) = P_T + G_T + D_iff_{kT} - \varepsilon_T \tag{2}$$

$$\frac{\partial k_T}{\partial t} + \frac{1}{V_F}\left(uA_x \frac{\partial k_T}{\partial x} + vA_y \frac{\partial k_T}{\partial y} + wA_z \frac{\partial k_T}{\partial z} \right) = \frac{CDIS1 \cdot \varepsilon_T}{k_T}(P_T + CDIS3 \cdot G_T) + D_iff_\varepsilon - CDIS2 \frac{\varepsilon^2{}_T}{k_T} \varepsilon_T \tag{3}$$

where P_T generation of chaotic kinetic energy, G_T Generation of turbulent buoyancy, k_T is the turbulent kinetic energy refers to the distinct form of kinetic energy associated with fluctuations in the velocity of turbulent flow (turbulent kinetic energy), V_F, A_x, A_y, and A_z are the FAVOUR functions, and the terms D_iff_{kT} and D_iff_ε Express the phrases that describe the spreading and dissipation of turbulent kinetic energy, while ε_T Turbulent dissipation rate refers to the speed at which turbulent energy is lost or dissipated. The dimensionless parameters *CDIS1*, *CDIS2*, and *CDIS3* can be adjusted by the user. The default values for these parameters are 1.44, 1.92, and 0.2, respectively.

2.3. Model of Sediment Scour

The model of sediment scour is a method for Forecasting the erosion, sedimentation, and deposition of packed and suspended sediments [9, 16].

According to FLOW Science [13] The physical properties of packed and suspended sediments, encompassing processes such as transport, erosion, sedimentation, and accumulation, is predicted using sediment scour models. The models include drift, scour, bed-load transfer, and deposits. Sediment moves with the river, settles due to gravity, and gets caught in the water's flow. When Sediment undergoes rolling and sliding movements down the packed bed surface as a result of fluid flow shear stress, bed-load transfer takes place. Gravity, buoyancy, and friction cause deposits to settle and solidify. The key variables in the model consist of the critical Shields number, the equation for bed-load transit rate, the maximum packing percentage, the bed shear stress, and the characteristics of the sediment.

The minimum or critical value for shear stress τ_{cr} needed to remove sediment particles from the surface of the compacted bed is linked to the critical shields value $\theta_{cr,i}$ [17]. Sediment erosion can occur based on factors such as the size, density, and external pressures acting on the silt [13].

$$\theta_{cr,i} = \frac{\tau_{cr,i}}{g d_i(\rho_i - \rho_f)} \tag{4}$$

The variables in question are: g which denotes the magnitude of gravity, d_i which represents the size of sediment grains and ρ_i and ρ_f, which stand for the mass density of sediment grains and the density of the fluid, respectively.

The Flow-3D software calculates the critical Shields number $\theta_{cr,i}$using either a predefined value computed internally or a calculated value obtained from the Soulsby-Whitehouse equation shown below [18].

$$d_{*,i} = d_i \left[\frac{g(s_i-1)}{\vartheta_f}\right]^{\frac{1}{3}} \tag{5}$$

$$\theta_{cr,i} = \frac{0.3}{1+1.2d_{*,i}} + 0.055\left[1 - \exp\left(-0.02d_{*,i}\right)\right] \tag{6}$$

The variable $d_{*,i}$represents the dimensionless grain size, ϑ_f refers to the fluid's kinematic viscosity, whereas s_i reflects the ratio of the density of the grains to the density of the fluid. $\theta_{cr,i}$ could be set to a default value of 0.05, as suggested by Wei, et al. [19].

Transport of bed loads the process of rolling or bouncing sediment across the packed sediment bed surface is called Φi. The Flow-3D program knows three distinct formulas that can be used to get the volumetric sediment transfer rate per bed width:

1- Müller, Peter, and Meyer formula

$$\Phi i = \beta_{MPM,i}(\theta_i - \theta'_{cr,i})^{1.5} c_{b,i} \tag{7}$$

where$\beta_{MPM,i}$ is the bed-load coefficient can reach 13.0 for extremely high transport, 5.0 to 5.7 for moderate transport, and 8.0 for low transport [20].

2-Nielsen formula [21]

$$\Phi i = \beta_{Nie,i}\theta_i^{0.5}(\theta_i - \theta'_{cr,i})c_{b,i} \tag{8}$$

where $\beta_{Nie,i}$ is known as the bed-load coefficient, and the default setting is 12.0.

3-Van Rijn formula [22]

$$\Phi i = \beta_{VR,i}\theta d_{*,i}{}^{-0.3}\left(\frac{\theta_i}{\theta'_{cr,i}} - 1\right)^{2.1} c_{b,i} \tag{9}$$

where the standard value of the bed-load coefficient $\beta_{VR,i}$ is 0.053. Consequently, the volume fraction of species I in the bed material is represented by $c_{b,i}$ in all mathematical expressions.

2.4. Physics

To provide accurate simulations of the data needed for this investigation, just four of the various physics options must be chosen. When the gravitational acceleration in the vertical, or z-direction, is adjusted to - 9.81 m/sec^2, the gravity option. The option of turbulence and viscosity is enabled by imposing Newtonian viscosity on the flow and choosing a suitable turbulence model. After the FLOW-3D model was finished being constructed, one turbulence model may be used in this investigation as long as the renormalized group (RNG) model was selected. The sediment scour model activated and was set to median diameter and density.

2.4.1. Sediment Properties

Before using the Flow-3D program to model sediment scour, the user needs to determine the exact properties of the sediment, depending on the real circumstances. The entrainment coefficient, which has a preset value of 0.018, regulates how quickly the bed material erodes. It also determines how quickly the particles rise to the surface and fall off of the packed bed. The angle of repose parameter determines how much the local critical shielding value is changed, typically ranging from 30 to 40 degrees with a default of 32 degrees. This parameter takes into consideration the maximum bed slope angle at which grains start to slide on their own [13].

Two additional parameters and settings are Bed Shearing Stress and Max Packed Portion. The Maximum Packing Fraction represents (1-porosity), the total volume of all sediment species and open volume in the cell. A sand's maximum packed portion ranges from 0.55 to 0.7 when its porosity falls between 0.3 and 0.45. The number by default is 0.64. In terms of the bed shear stress, the standard wall function for three-dimensional turbulent flow is used to calculate the fluid's shear force on the packed bed's surface, accounting for the roughness of the wall. By dividing the median grain diameter d50 in packed sediment by the Nikuradse roughness ks, one can determine the Crough coefficient, which is user-adjustable. For simulations involving many species, the default value of this coefficient is 2.5; for simulations involving a single species, it is 1.0 [13].

2.5. Material Properties

It is important to define fluid properties like density, temperature, and viscosity precisely. While fluid properties can be set on the Fluids tab, the fluid can be selected based on the fluid database tab. To aid the user, FLOW-3D includes a library of widely available resources. Depending on the Meshing and Geometry tab, each component's solid characteristics can be defined. In the present investigation, water at 20°C is chosen.

2.6. Geometry

The AutoCAD-3D modeling tool is used to draw the 3D solid geometry of the model. The geometry used in the simulations is exported as a stereolithographic (.stl) format that Flow 3D from AutoCAD can recognize, depending on the information available from the field data. After that, the STL files are directly imported into FLOW 3D, allowing for the generation of the necessary mesh.

2.7. Meshing

The creation of a grid is crucial for achieving an exact solution in numerical models. A precise mesh quality is essential for producing realistic results. The choice of grid and cell size significantly impacts the accuracy of results and simulation time. The ideal cell size should be estimated by starting using a big mesh and progressively shrinking the size until the output remains consistent.

Increasing the number of cells can slow down computation, so it is essential to select the ideal cell count. Flow-3D allows for the specification of orthogonal meshes using either cylindrical or cartesian coordinates. The FAVOR option is reliable for obtaining the optimal cell count. Each cell's aspect ratio must not exceed 3:1 in any two dimensions, and the ratio between neighboring cells must not exceed 1.25 in the same direction. We recommend using cells with a 1:1 size ratio to achieve the best results, and a mesh configuration between each block should not exceed a 2:1 ratio (FLOW3D manual, 2014).

2.8. Conditions at the Boundaries

Determining the exact boundary conditions is a crucial step in the numerical simulation process. Accurate alignment of the physical parameters of the investigated situation is necessary. To represent the Cartesian coordinates and determine the 3D flow domain, FlOW-3D employs perpendicular hexahedral meshes. Therefore, it is necessary to build six distinct borders on the rectangular mesh prism. The current study's applied boundary conditions are displayed in Figure 1.

Upstream boundary (X-min): An inflow condition Qin. Qout, or the downstream boundary (X-max), is the outflow condition.
Upper limit (Z-max): Pressure state (P).
Lower limit (Z-min): Wall state (W).

Side boundary: Wall condition (W) (Y-min, Y-max).

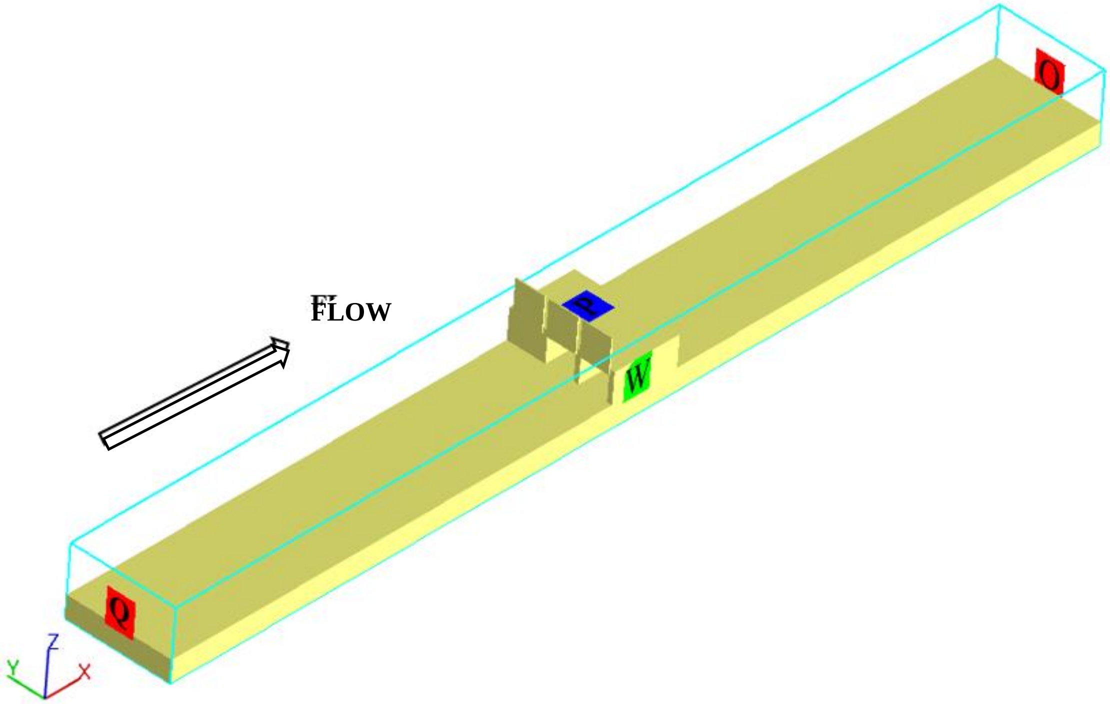

Figure 1.
Boundary conditions for Kalat Saleh regulator.

2.9. Model Configuration

The model configuration involves specifying the numerical and physical settings that will govern the simulation parameters and processes. Key aspects include:

Time Step: The choice of time step is crucial for maintaining numerical stability and accuracy. A small-time step can capture transient phenomena but increases computation time. The Courant-Friedrichs-Lewy (CFL) condition is typically used to determine an appropriate time step.

Turbulence Model Configuration: As previously mentioned, the Renormalized Group $(RNG)\ k-\varepsilon$ model was selected for this study due to its efficiency in simulating low-intensity turbulence in shear-dominated regions. This model is configured with default constants C_{DIS1}=1.44, C_{DIS2}=1.92, and C_{DIS3}=0.2.

Sediment Scour Parameters: Parameters such as critical shear stress, Shields number, and sediment transport rates were carefully set based on the characteristics of the sediment in the study area. The entrainment coefficient was adjusted to 0.018, and the angle of repose was set to 32°, reflecting the physical properties of the sediment.

2.10. Boundary Conditions

Boundary conditions are critical to ensuring the physical realism of the simulation. In this study, the following boundary conditions were applied:

Inflow Condition (Q_{in}): The upstream boundary *(X-min)* condition was defined as a specified inflow rate based on field measurements or historical data of flow rates through the Kalat Saleh Regulator.

Outflow Condition (Q_{out}): The downstream boundary *(X-max)* condition was defined with a specified outflow condition, ensuring that the water level and flow dynamics are consistent with observed or expected conditions downstream of the regulator.

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Pressure Condition (P): The upper boundary *(Z-max)* condition was set to atmospheric pressure, allowing for the free movement of the fluid surface and accommodating variations in water level.

Wall Condition (W): The lower boundary (*Z-min*) condition was treated as a no-slip wall, where the fluid velocity relative to the wall is zero. This boundary simulates the interaction between the fluid and the riverbed, which is crucial for accurate sediment transport modeling.

Wall Conditions (W): The side boundaries (*Y-min*, *Y-max*) were also treated as no-slip walls, which confine the fluid within the simulation domain and prevent lateral flow out of the computational mesh.

2.11. Model Validation

Validation is essential to verify the accuracy of the numerical model by comparing its outputs with experimental or field data.

Laboratory Tests: If experimental data were available, they could include controlled laboratory tests that replicate the conditions of the Kalat Saleh Regulator. Key metrics such as water levels, flow velocities, and sediment transport rates would be measured and compared to the simulation results.

Field Observations: Field data should be collected from the Kalat Saleh Regulator site, including measurements of flow rates, water levels, sediment deposition, and erosion patterns. These data provide a real-world benchmark to which the simulation results can be compared.

Model Calibration: Discrepancies between the simulation results and the experimental or field data should be analyzed. The model parameters, such as turbulence coefficients, sediment transport rates, and boundary conditions, may need to be adjusted (calibrated) to improve agreement.

Statistical Analysis: Use statistical measures such as the Root Mean Square Error (RMSE), Nash-Sutcliffe Efficiency (NSE), or Coefficient of Determination (R^2) to quantitatively assess the model's accuracy. A high degree of correlation between the model outputs and the observed data would validate the model's reliability.

2.12. Sensitivity Analysis

Performing a sensitivity analysis helps identify which parameters have the most significant impact on the model's outputs. This analysis involves varying key parameters (e.g., turbulence model coefficients, sediment properties) within realistic ranges and observing the effects on simulation results. Sensitivity analysis can provide insight into the robustness of the model and highlight areas where more precise data or modeling techniques are required.

3. Validation of the Current Model

A validation was performed using the results of the experimental research to verify the precision of the current numerical model. In order to confirm the accuracy of the information, employ the highest recorded sediment scour depth as shown in the results of the study of Kumer [23] the numerical findings generated using Flow-3D program were compared. The current model was built using the identical methods as in the study that was experimental. and operated until the point of reaching a stable depth of scour.

The experiment entailed the examination of clear-water scour using a bed that is flat elevation, which was observed through the use of a high-resolution digital camera, to accurately measure sediment erosion and the ultimate depth of the resulting scour.

The channel was constructed with parameters of 12 meters in length, 0.5 meters in width, and 7.5 meters in height. working section filled with 0.2 m depth of erodible uniform sand. The barrage floor had dimensions of 87.5, 50, and 20 cm, with slopes of 0.1 and 0.05 respectively.

A case was selected for verification, with an average diameter of sediment particles of 0.00085 m and 1496 kg/m3 density. The water depth at the upstream location was 0.072 m, whereas at the downstream location it was 0.025 m. and the discharge was 0.055 m3/s. The highest recorded scour depth was around 0.048 m at a gate opening of 0.03 m.

The mathematical model was constructed to replicate the experimental setup, including its geometry and associated parameters, in order to assess the suitability and precision of the numerical approach [24, 25]. The turbulence model was used for the validation model due to the model demonstrates excellent performance in simulating sediment scour and accurately describes low-intensity turbulence flows, particularly in places with larger shear where it exhibits higher precision.

The simulation was conducted utilizing the Flow-3D. The study uses scour depth as the parameter to assess the suitability and precision of the mathematical model. Figure 2 Indicates the current numerical outcome and the prior experimental finding [23, 26] exhibit comparable patterns in the temporal progression of scour depth downstream of the barrage [27]. The existing outcome and the empirical outcome exhibit a clear and satisfactory level of concurrence.

The depth of local scour obtained from the laboratory research exhibited rapid initial growth within the first 10 minutes, Subsequently, there was a gradual rise until it reached a steady state at a value of 0.048 m approximately 180 minutes later. The maximum depths of scour observed in both experimental and numerical studies were 0.048 m and 0.0496 m, correspondingly at the identical time following the completion of the run. At the state of equilibrium stage, Figure 3 Presents the current findings of the surface scour depth downstream of the barrage, using different colors to indicate the depth of scour and deposition.

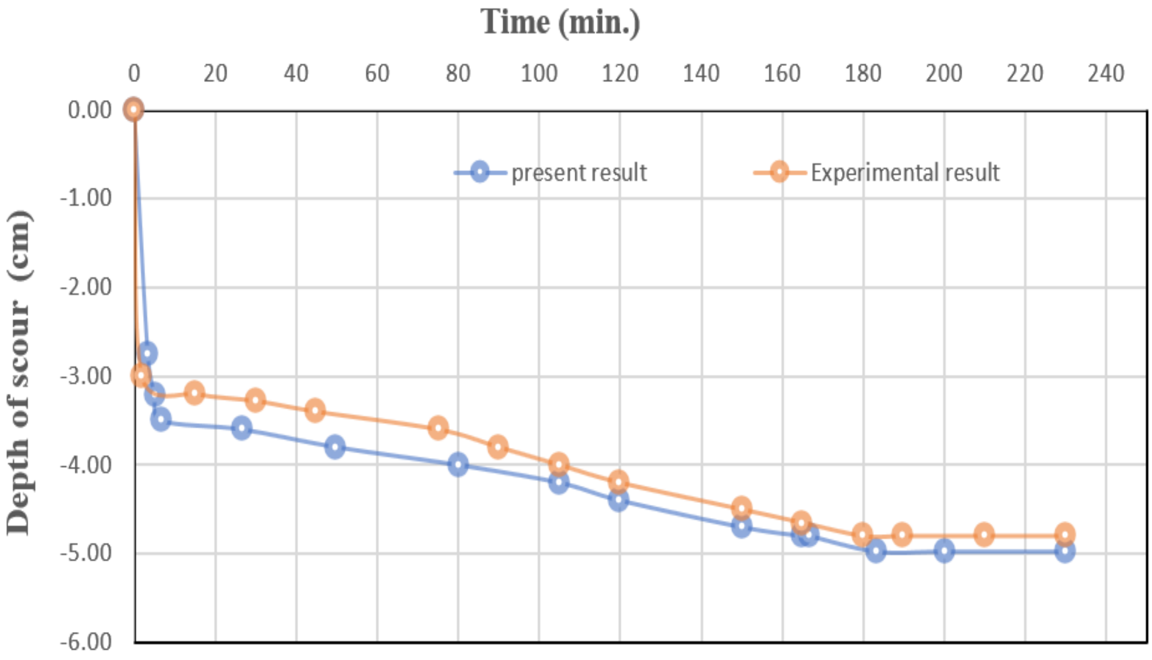

Figure 2.
An analysis of the temporal variations in the depth of scouring, comparing the current model with the experimental data.

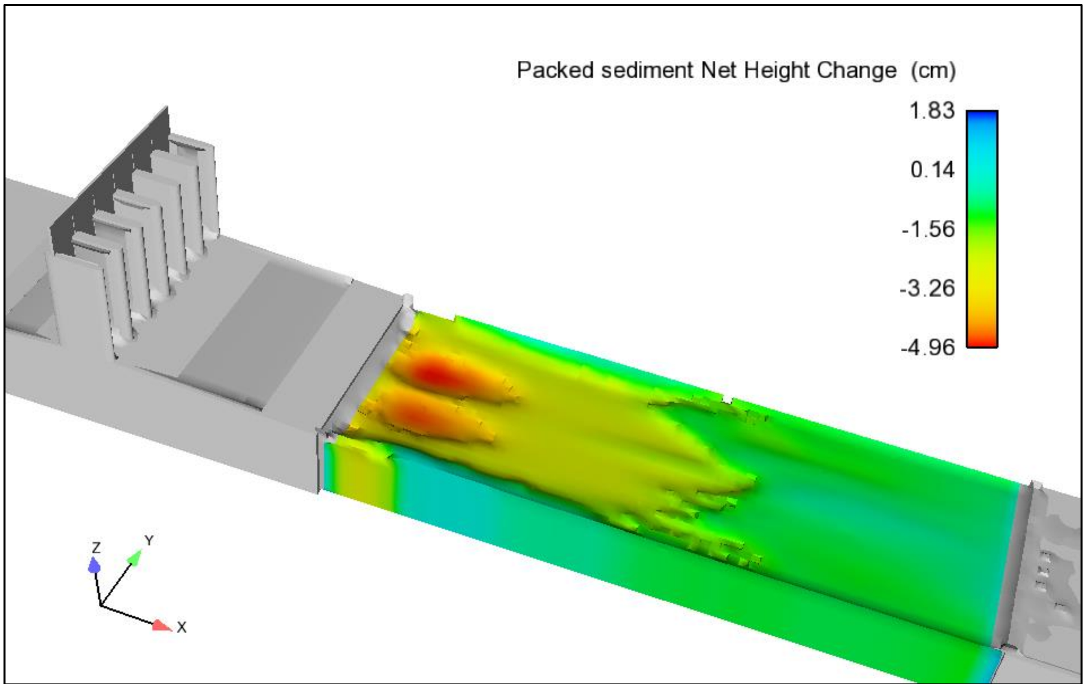

Figure 3.
Net height change of surface with six gates opening and a (d50) of 0.8mm.

4. Numerical Simulation for Kalat Saleh Regulator

4.1. Study Area

Kalat Saleh Regulator is considered as one of the important Regulator on Tigris River at Mysan Governorate in Iraq. it is located in (34°31'53.26" North, 47°16'46.18" East), **Figure 4**. represents the location of the study area.

Figure 4.
This is a satellite image of the Kalat Saleh Regulator located on the Tigris River, as seen on Google Earth.

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4.2. *Field Measurements*

The study gathered field data by collaborating with the management of the Amara barrage project in Maysan Governorate, which includes the dimensions of the regulator and everything related to the gates, such as dimensions, number, and the distance between each two gates. In addition to measuring the discharge, a constant grain size was used for the sand layer based on the investigation carried out by Ismaeel, et al. [28] Table 1 provides an explanation of the attributes of the Kalat Saleh Regulator.

Table 1.
Information of Kalat Saleh regulator.

Regulator's name	No. of gates	width of gate (m)	distance between each two gates (m)	Normal discharge m^3/s
Kalat Saleh	3	8	1.4	75-125

4.3. *Geometry and Numerical Setup*

This section describes an examination of a regulator that has three gates located in a rectangular channel. The bed of the canal is moveable and level, with a fixed height of seven meters. The investigation was conducted using computational fluid dynamics (CFD) simulation [29]. Figure 5. The model's 3D solid shape, as previously stated, is drawn using the AutoCAD-3D modeling tool, and the geometry used in the simulations is exported as a stereolithographic (.stl) format that can be recognized by Flow 3D [30]. To examine the influence of gates opening on scour, the gates have been assigned numerical values spanning from G1 to G3. The flow rate in this investigation varies between 75 and 125. m^3/s. A uniform grain size of the sand bed was consistently employed for all instances of the gate opening. The regulator's design, number of gates, and dimensions closely resemble those of the Kalat Saleh Regulator. The channel features, including the flow rate, have been modelled after the Tigris River reach leading to the regulator in Kalat Saleh district, as shown in Figure 5. The open channel has a total length of 300 meters, with 150 meters placed upstream of the regulator. The waterway has a width of 67 meters and a height of 8 meters.

This research has assessed the situations by considering the total number of gates that were opened and the precise order in which they were opened. The cases were divided into three groups, with a total of eleven cases, five of which were to study the effect of operating the gates with a constant discharge for all cases, and then the worst case was chosen from each group to study the effect of the flow rate. i.e., in case $G_{2(1,2)}$, the first number indicates the number of open gates, while the number in parentheses indicates the open gate number. In this case, the number of open gates is only two, namely Gate No. 1 and Gate No. 2, where the gates are numbered from right to left. State G_3 indicates that all gates are open, and so on for all states. Table 2. shows the cases studied in this research.

The mesh, with an adequate cell size, is crucial for achieving accurate results in numerical simulation, particularly in the context of scouring. Nevertheless, the simulation time's efficiency must also be taken into account due to the substantial quantity of cells. The maximum cell size of 0.3 m was used in this mathematical model, The limits for all models were set to match those of the validation model used in the earlier simulation. Except for flow rate, the field-measured value was set and changed in all cases with values ranging from 75–125 m^3/s to investigate the impact of increasing it on the Scour depth. In this numerical investigation, the validation model is utilised to address sediment scour and turbulence setup. However, additional factors such as the composition of sediment and the average size of particles d_{50}, and sand density, where a constant grain size was used for the sand layer based on the investigation carried out by Ismaeel, et al. [28] to be close to reality.

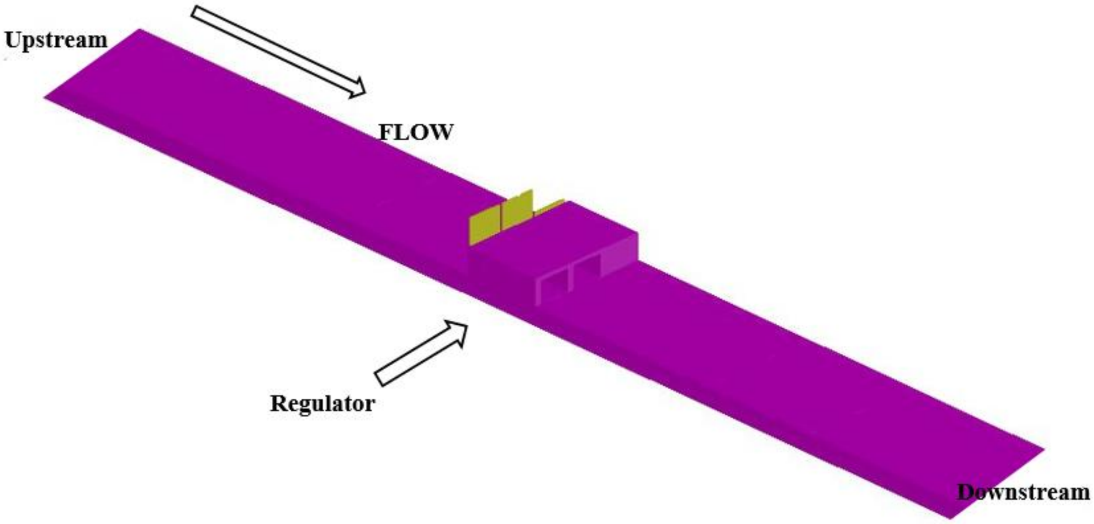

Figure 5.
The channel and regulator geometry.

Table 2.
Pattern and operation scenarios for Kalat Saleh regulator.

No.fo group	The case	Number of open gates	Open gate number
1	$G_{1(1)}$	1	1
	$G_{1(2)}$	1	2
2	$G_{2(1,2)}$	2	1&2
	$G_{2(1,3)}$	2	1&3
3	G_3	3	1&2&3

5. Results and Discussion

This section presents the outcomes obtained through Flow-3D software simulations, focusing on the effects of gate operations and flow rates on the maximum depth of scouring. The findings are analyzed statistically and through sensitivity analysis to provide a more comprehensive understanding of the impact of operational strategies on the Kalat Saleh Regulator.

5.1. The Impact of Gate Operation on the Maximum Scouring

The initial analysis indicates that the depth of scour at the regulator varies significantly depending on the gate operation scenarios (Table 3). With a constant flow rate of 100 m^3/s, the depth of scouring in case G1(1) reaches -3.15 meters, which is substantially deeper compared to other scenarios.

To statistically validate the differences in scour depth across different gate operations, an Analysis of Variance (ANOVA) test was performed. The results of the ANOVA test ($p < 0.01$) indicate that the variations in scour depth between different gate operation scenarios are statistically significant. Post-hoc pairwise comparisons using the Tukey test further confirmed that the scour depth in G1(1) is significantly greater than in G3 and G2(1,3), indicating the critical impact of asymmetric gate operations on erosion.

A sensitivity analysis was also conducted to assess the influence of gate operation on scour depth. The analysis revealed that the number of open gates and their configuration are the most sensitive parameters affecting scour depth. Specifically, opening a single gate (as in G1(1) and G1(2)) results in a much higher sensitivity to changes in flow conditions, leading to greater scour depths.

These findings suggest that careful management of gate operations is crucial for minimizing scouring at the Kalat Saleh Regulator. Operating all gates symmetrically appears to be the most effective strategy for reducing erosion, as demonstrated by the shallowest scour depth in case G3.

Table 3.
The maximum scour depth for various scenarios of gate operation with a constant flow rate.

No.fo group	The case	Flow rate m³/s	Maximum scour depth (m)
1	$G_{1(1)}$	100	-3.15
	$G_{1(2)}$		-1.7
2	$G_{2(1,2)}$		-1.1
	$G_{2(1,3)}$		-0.83
3	G_3		-0.47

5.2. Influence of Flow Rate on the Greatest Depth of Scouring

The impact of varying flow rates on the maximum depth of scouring was further examined by selecting the worst-case scenario from each group (Figure 6). The results indicate that the increase in scour depth is relatively moderate when all gates are open (G3), even at higher flow rates. However, when fewer gates are open, the increase in scouring depth becomes more pronounced as the flow rate rises.

A regression statistical analysis was performed to explore the relationship between flow rate and scour depth for each gate operation scenario. The regression model for case G1(1) showed a strong positive correlation ($R^2 = 0.92$) between flow rate and scour depth, indicating that as the flow rate increases, the depth of scouring also increases significantly [30]. In contrast, the model for case G3 showed a weaker correlation ($R^2 = 0.45$), suggesting that the scour depth remains relatively stable despite increases in flow rate.

The sensitivity analysis further confirmed that the flow rate is a critical factor influencing scour depth, particularly in scenarios where fewer gates are open. For instance, in case G1(1), the scour depth was found to be highly sensitive to changes in flow rate, with small increases in flow leading to substantial increases in scouring. In contrast, the sensitivity was much lower in case G3, where the impact of increased flow rate on scour depth was minimal.

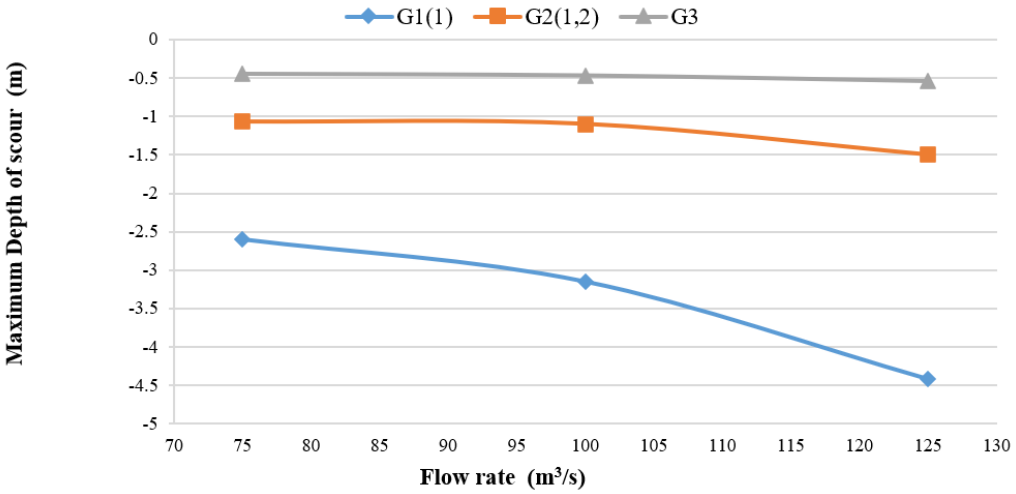

Figure 6.
Relationship between flow rates and maximum scour depth variation.

Figure 7 illustrates the topography of the scour for the worst operating condition (G1(1)) and the best operating condition (G3) at a flow rate of 125 m³/s. The visual representation in Figure 7(a) highlights the severe erosion that occurs when only one gate is open, while Figure 7(b) demonstrates the reduced erosion when all gates are open.

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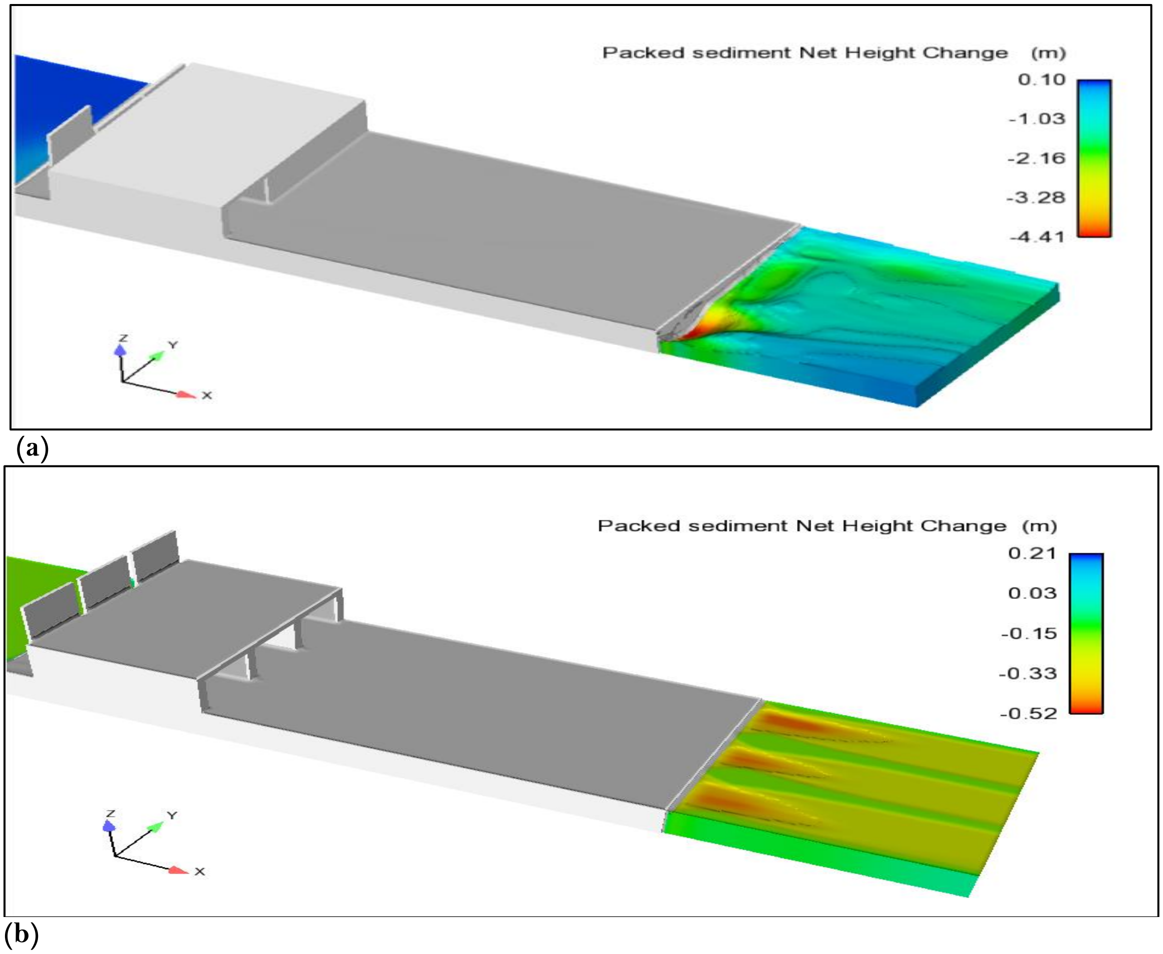

Figure 7.
The topography of the scour. (a) case $G_{1(1)}$ worst operating, (b) case G_3 best operating.

5.3. Implications for Regulator Operation

The findings from the statistical and sensitivity analyses emphasize the importance of strategic gate operations to mitigate scouring at the Kalat Saleh Regulator. The significant differences in scour depth between scenarios suggest that asymmetric gate operations, especially those involving fewer open gates, should be avoided to minimize erosion. Furthermore, the analysis confirms that managing flow rates effectively, particularly under high discharge conditions, is crucial for controlling scour depth.

These insights provide valuable guidance for the operational management of the Kalat Saleh Regulator, helping to ensure the long-term stability and functionality of the structure.

5.4. Broader Implications of the Findings

The findings from this study have significant implications beyond the immediate context of the Kalat Saleh Regulator. The insights gained from the analysis of gate operations and flow rates can inform broader strategies in reservoir management, flood risk mitigation, and the sustainable operation of hydraulic structures.

5.4.1. Reservoir Management

The results highlight the critical role that gate operation strategies play in managing sediment deposition and erosion around hydraulic structures. Effective gate management can help control the sedimentation process, which is a common challenge in reservoirs worldwide. By minimizing scour through optimal gate operations, the lifespan of reservoirs and associated infrastructure can be extended. This is particularly relevant for aging dams and regulators, where sediment management is crucial for maintaining storage capacity and operational efficiency.

Sediment Control: The findings suggest that operating all gates symmetrically, as seen in the case G3 scenario, leads to reduced scouring and, by extension, more stable sediment patterns. This approach can be incorporated into broader sediment management plans for reservoirs, ensuring that sediment is evenly distributed and does not accumulate excessively near critical infrastructure. In the long term, this can reduce the need for costly dredging operations and help maintain reservoir capacity.

Operational Flexibility: The sensitivity of scour depth to flow rates and gate operations also underscores the need for flexibility in reservoir management. Operators may need to adjust gate settings dynamically in response to changing hydrological conditions, such as during periods of high inflow or following major storm events. This flexibility can help mitigate the impact of unexpected sediment movements and maintain the stability of the reservoir environment.

5.4.2. Flood risk Mitigation

The study's findings are also relevant for flood risk management, particularly in regions prone to high discharge events. The relationship between gate operation, flow rates, and scouring depth has direct implications for how regulators and dams can be used to manage floodwaters effectively.

Scour Risk During Flood Events: During high-flow conditions, improper gate operations can lead to excessive scouring, potentially undermining the structural integrity of regulators and associated flood control infrastructure. The study indicates that opening all gates, as in the G3 scenario, minimizes scour depth, suggesting that this could be a preferred strategy during flood events to reduce the risk of damage. Ensuring that all gates are functional and can be operated symmetrically during floods could be critical for maintaining the safety and effectiveness of flood control measures.

Infrastructure Protection: By reducing scouring, optimal gate management not only protects the regulator itself but also downstream infrastructure, such as bridges and levees, which could be compromised by excessive sediment movement. This is particularly important in densely populated or agriculturally significant regions where infrastructure failure could have severe economic and social consequences.

Adaptive Flood Management: The insights from this study can be integrated into adaptive flood management plans, where gate operations are adjusted in real-time based on flood forecasts and real-time monitoring of scour conditions. This approach could help mitigate the impact of extreme weather events, which are becoming more frequent and severe due to climate change.

5.4.3. Environmental and Ecological Considerations

The operation of gates and the management of flow rates have ecological implications, particularly in terms of sediment transport and deposition, which are critical for maintaining healthy aquatic ecosystems.

Habitat Preservation: Scour and sediment deposition patterns can significantly impact riverine habitats, particularly for species that rely on specific sediment types or depths for spawning. The study's findings suggest that careful management of gate operations can help maintain these habitats by preventing excessive erosion or sediment buildup in sensitive areas. This is especially relevant in regions where regulators and dams intersect with protected or ecologically significant areas.

Water Quality: Sediment movement also affects water quality, particularly in terms of turbidity and the transport of pollutants attached to sediment particles. By controlling scouring through optimal gate operations, water managers can reduce the risk of degrading water quality downstream of the regulator. This has important implications for both human health and ecosystem services, such as water purification and fisheries.

In conclusion, the findings from the numerical simulations of the Kalat Saleh Regulator provide valuable insights that extend beyond the immediate scope of the study. The implications for reservoir management, flood risk mitigation, and environmental preservation underscore the importance of strategic gate operations in maintaining the stability and functionality of hydraulic infrastructure. By applying these insights, water managers can improve the resilience of reservoirs and regulators, enhance flood protection, and contribute to the sustainable management of water resources in the face of growing environmental challenges.

5.5. The Impact of Other Relevant Factors

To provide a more comprehensive analysis of the scouring process at the Kalat Saleh Regulator, it is essential to consider additional factors such as sediment characteristics and upstream flow conditions. Here's an expanded discussion and analysis:

Particle Size Distribution: Sediment size distribution affects both the erosion and deposition processes. Coarser sediments generally require higher shear stresses to mobilize compared to finer sediments. The model can be enhanced by including a range of particle sizes rather than a single, uniform grain size. This would account for the variability in sediment behavior and how different sizes interact with flow dynamics.

Sediment Density and Cohesion: Sediment density influences the sediment's response to hydraulic forces, while cohesion affects particle stability. Sediments with high cohesion are less likely to be eroded compared to non-cohesive sediments.

Flow Velocity and Turbulence: The velocity and turbulence of upstream flow significantly impact scouring. High velocities and turbulence increase the energy available for sediment transport and can enhance scouring around structures.

Sediment Load: The concentration of sediments in the upstream flow can influence the rate of deposition and erosion downstream. High sediment loads might increase the potential for sediment accumulation and scouring.

To accurately incorporate these factors into the model:

Multiphase Flow Modeling: Implement a multiphase flow model to handle different sediment sizes and densities. This approach allows for more precise simulation of sediment transport and scour dynamics.

Variable Flow Conditions: Include a range of upstream flow conditions in the simulations, such as varying velocities and sediment concentrations, to assess their impact on scouring under different scenarios.

Advanced Turbulence Models: Use turbulence models that can capture the complex flow patterns and interactions at the gates, providing a more accurate depiction of scouring phenomena.

Field Data Integration: Collect detailed field data on sediment characteristics and upstream flow conditions to validate and refine the model. This real-world data will enhance the accuracy of simulations and predictions.

Incorporating detailed sediment characteristics and varying upstream flow conditions into the model will lead to a more accurate and comprehensive understanding of the scouring process at the Kalat Saleh Regulator. By addressing these factors, the model can provide better insights into sediment management and flood risk mitigation strategies, ultimately improving the design and operation of similar hydraulic structures.

5.6. Model Validation

The validation efforts undertaken in this study were integral to ensuring the reliability of the CFD model. The following key findings emerged from the validation process:

Comparison with Field Data: The CFD model's predictions of scouring depth and sediment transport were compared with empirical data collected from the Kalat Saleh Regulator. The model effectively replicated the observed scouring patterns and sediment movement, demonstrating a high level of accuracy in simulating real-world conditions. This alignment with field data confirmed that the model was capable of providing reliable predictions for the specific characteristics of the Kalat Saleh Regulator.

Utilization of Experimental Results: The study incorporated data from previous experimental studies and lab experiments, particularly those involving similar hydraulic conditions and sediment types. The model's results were consistent with these benchmark experiments, validating the model's ability to reproduce established physical phenomena. This consistency underscored the model's robustness in replicating known behavior in controlled environments.

Numerical Study Comparison: In instances where direct validation with field data was challenging, the study compared the model's outputs with results from other numerical studies. This cross-verification with similar CFD simulations and hydraulic models provided additional confirmation of the model's accuracy. By aligning with established numerical findings, the model's predictions were reinforced as reliable and consistent within the broader context of hydraulic and sediment transport research.

The validation process highlighted the model's effectiveness in simulating the scouring phenomena associated with the Kalat Saleh Regulator. The alignment with field data and experimental results confirms that the model can accurately capture the complex interactions between flow, sediment, and gate operations. This validation also suggests that the model is a useful tool for predicting scouring impacts and assessing different operational scenarios.

However, it is important to acknowledge that while the validation process has reinforced the model's reliability, there are inherent limitations. For instance, the study utilized a simplified sediment characterization and did not explore all possible gate operation scenarios. Future research should address these limitations by incorporating varied sediment types, enhancing upstream flow modeling, and exploring a broader range of gate configurations. Additionally, higher model resolution and further field validation would contribute to refining the model and improving its applicability to real-world conditions.

Overall, the successful validation of the CFD model underscores its potential as a valuable tool for hydraulic engineers and sediment management professionals. The insights gained from this study can inform operational strategies and design considerations for similar hydraulic structures, ultimately contributing to more effective management of sediment transport and scouring in regulated river systems.

5.7. Limitations of the Current Model and Potential Improvements

The section on limitations and potential improvements acknowledges the assumptions made in the modeling process, such as the use of uniform sediment size, simplified boundary conditions, and idealized gate operations, which could impact the accuracy of the results. These assumptions may lead to errors in estimating scour depth and predicting worst-case scenarios, limiting the generalizability of the findings.

To improve the model, future work could incorporate variable sediment sizes, advanced turbulence modeling, dynamic boundary conditions, and more realistic gate operation scenarios. Additionally, further validation with experimental or field data would enhance the model's accuracy and reliability. These improvements would help make the numerical simulations more representative of real-world conditions and more applicable to hydraulic engineering and sediment management.

6. Conclusion

This study focuses on simulating sediment movement downstream from the Kalat Saleh Regulator using Flow-3D software. The simulations were conducted to assess the impact of gate operations on the maximum erosion depth downstream. The key findings and considerations are as follows:

1. Flow-3D software effectively replicated the flow dynamics and sediment movement, demonstrating a strong alignment with experimental results used for validation.

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2. The study found that the number, order, and operational mechanism of the gates have a significant impact on erosion. Uneven gate openings on one side of the regulator result in increased scouring depth. Additionally, the depth of the scour hole increases with the number of gates opened.
3. There is a direct relationship between flow rate and scour depth. As the flow rate increases, the depth and extent of scouring also rise, highlighting the influence of flow rate on erosion severity.

The study has several limitations, including the use of a constant sediment grain size, which may affect the accuracy of scouring predictions. It also might not fully capture complex upstream flow conditions, and the range of gate operation scenarios tested was limited. Additionally, the model's resolution might not be fine enough to capture detailed sediment movement.

Future research should address these limitations by incorporating varied sediment sizes, improving upstream flow simulations, exploring more gate operation scenarios, using higher model resolution, and conducting field validation to ensure theoretical predictions align with practical observations.

Transparency:

The authors confirm that the manuscript is an honest, accurate, and transparent account of the study; that no vital features of the study have been omitted; and that any discrepancies from the study as planned have been explained. This study followed all ethical practices during writing.

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