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Environmental and hydraulic study of novel limestone porous weir for river aquatic life protection and treating selected contaminants

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ABSTRACT

Generally, porous weirs are considered as friendly environmental structures used to reduce the negative impact of flash floods. All previous studies used solid concrete weirs or gabion weirs that used gravels. Researches rarely deal with the performance of porous weirs hydraulically and environmentally together. In this study the hydraulic characteristic, flow types, and environment effect for porous weirs were studied experimentally and theoretically. Limestone was used instead of gravel as an adsorbent material for the porous weir to improve its efficiency for removing selected contaminants, including lead (Pb), turbidity and total suspended solids (TSS). The effect of limestone porous weir onto pH of the effluent water samples was also measured. The limestone permeable weir was investigated as an alternative to the solid concrete weir as it is cheaper, more environmentally friendly and also efficient in the removal of some river contaminants at the same. Two-dimensional numerical computational fluid dynamics (CFD) modeling for flow over and through porous weirs was performed using the volume of fluid method and shear stress transport k-ω model for turbulence through ANSYS 16.1. Many samples of water were collected before and after the porous weir for environmental analysis. The results showed a good convergence between the CFD model and experimental results. Moreover, the results showed that the CFD model gave root mean square error values equal to 0.877, 0.979, and 0.625 cm, respectively for the three discharges selected, 0.4, 1.85, and 2.75 $m^3 h^{-1}$, respectively selected for comparison between the CFD model and the experimental work. On the environmental side, the effects of flow rates were studied at an initial concentration equal to 1.5 mg L^{-1} of Pb ions and 50 mg L^{-1} for turbidity. The designed weir shows good removal efficiency for both lead and turbidity. The maximum removal efficiency was found to be 92.5%, 72% and 59% for lead, turbidity and TSS, respectively. The greater the time the lower the removal of pollutants, and lower discharge resulted in a greater percentage of removal.

Keywords: Gabion weir; Concrete solid weir; CFD model; Limestone; Lead; Turbidity

1. Introduction

Rivers transport sediments from upstream to their outlets, but solid dams hold the sediments in front of them, especially the gravels as beds load. Therefore, the river after a dam becomes deprived of gravel, and its bottom is eroded and its level is reduced. After seven years of operation of the famous Hoover Dam construction in the United States, it bottoms level dropped four meters because of this type

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of solid dam. This phenomenon also leads to soil erosion at the foundations of bridges and installations along the river. Moreover, depriving the river of gravel leads to the displacement of fish groups where lay their eggs among the gravel [1].

The annual floods which cover the banks of the river with silt and water, on which the animals and plants depend for growth, migration and so forth, stop with the construction of impermeable dams. In addition, the considerable weight of the concrete impermeable dams leads to earthquakes, according to some studies [2].

In general, the major functions of weirs are to regulate river flow and to reserve water. Impermeable or solid weirs prevent transportation of chemical and physical substances in water and the movement of aquatic life. Nowadays, alternative hydraulic structures to solid concreate weirs, made of porous media such as gravels or stones, are used and these types of weirs are preferred since they can meet the natural, ecological, and environmental requirements better. In general, rivers have many contaminants and governments find these costly to treat. Some of these contaminants are hazardous to health, such as the heavy metals. Previous researches deal with gabion weirs (gravel weirs) hydraulically alone, rarely dealing with these weirs environmentally and hydraulically together [3].

From an environmental point of view, the impermeable weir usually prevents the longitudinal movement of aquatic life and transportation of physical and chemical substances in water, so this has a negative impact on the river environment [4].

The porous weirs are permeable, allowing stream wise migration of aquatic life. In addition, physical and chemical substances, such as suspended organic matter and sediments, can pass downstream through the porous permeable body which minimizes the negative impact of impermeable weirs. However, many researchers focused on these structures hydraulically alone [5,6].

Al-Mohammed and Mohammed [7,8] performed an experimental study on flow through and over a gabion weir. They focused on two cases of flow regimes which are through-flow and transient flow using different gabion weirs in a horizontal flume. The results indicated that the relation between upstream water depth and discharge passing through the gravel weir is linear for the two cases of flow selected.

In the present study we suggested the use of limestone media in the porous weir. Limestone is inexpensive, locally available in many countries, environmentally friendly and efficient in removing heavy metals, total suspended solids (TSS) and turbidity [9, 10]. We try to investigate if this material will work efficiently when used as a main material for weirs, taking account of the hydraulic and environmental design considerations. Lead is the heavy metal that was chosen because previous investigations show that the concentration of lead in the rivers of Iraq is higher than the permissible limits [11]. Also, the turbidity is indicative of flash flooding and sediments transport in rivers and its measurements are quick and simple to perform in the field, and on-site personnel can easily monitor raw water quality [12].

The aim of this paper is to perform a hydraulic and environmental study to investigate the performance of a permeable weir filled with local limestone. The efficiency of the designed limestone weir to remove lead (Pb), turbidity and TSS from simulated wastewater was investigated. The effect of limestone porous weir was also studied. A 2-D computational fluid dynamics (CFD) numerical model with "ANSYS 16.1; FLUENT" was solved to represent the flow over and through this porous weir. A comparison between the experimental water profile and those obtained from the numerical model was evaluated.

2. Materials and methods

2.1. Laboratory flume, instruments and weir model

A flume at the hydraulic laboratory, Faculty of Engineering, University of Mustansiriyah was used for the hydraulic experimental works. The flume cross section is rectangular with 5 m length, 30 cm width, and 30 cm depth as shown in Fig. 1. There are two tanks in the system: a rectangular feeding tank with a capacity of 3,000 L and the collecting tank, which is constructed beside the flume above the laboratory floor, with the same capacity. Simulated water is prepared in the feeding tank and pumped by a submersible pump having a discharge up to 2.75 $m^3 h^{-1}$. This discharge was designed and selected according to the standard filtration rate (flow rate normalized by filter surface area) which is one of the most important design parameters for rapid filtration [12]. Then water flows through a pipe of 4-inch diameter connected to a calibrated flow meter to measure the discharge of water before entering the flume, and a manually operated valve installed on the circulation system pipe controls the flow discharge. The water depths were measured every 5 cm upstream, through, and downstream of the porous weir using a point gauge reading to 0.1 mm to determine the water profile, after 15 min to allow the water to reach the equilibrium state. The weir was designed according to the hydraulic and environmental requirements together. For hydraulic requirements, the mold of the weir used in the study is made from stainless steel and is rectangular in section with a curvature of 10 mm at the top of the front face to prevent the separation of stream flow at the entrance. Also, for the environmental requirements the mold was designed according to the maximum filtration rate (11 $m h^{-1}$) and detention time of about 4 h. depending on the properties of the material used. Weir height was 15 cm and this height is equal to about 50% of the flume height, to ensure upstream head without water spills from both sides of the channel; the width of the model is 30 cm, equal to the width of the flume; and the length is 1 m. Fig. 2 shows the limestone weir mold with its dimensions.

2.2. Preparation of porous media

Limestone is widely available in the western desert of Iraq. It was selected due to its availability, low cost and durability. The limestone was brought to the construction material laboratory and mixed well then washed using distilled water then dried in an oven for 24 h at 105°C and kept in a plastic container ready for use. Fig. 3 shows a sample of the limestone media used in the present study. The properties of the limestone were measured and are listed in Table 1.

Fig. 1. Experimental set-up flume.

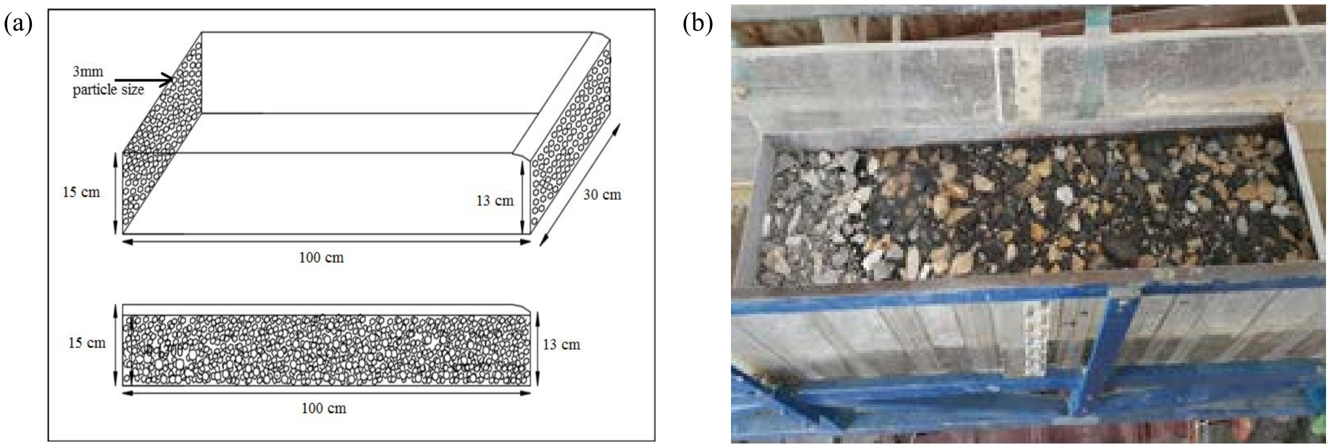

Fig. 2. Porous weir filled with limestone (a) schematic and (b) photo.

Fig. 3. Sample of limestone used.

The limestone used in this study contained 97.96% of $CaCO_3$, 0.90% of MgO, and 1.14 other oxide minerals according to X-ray fluorescence analysis. This indicated that the pure limestone (>97% of $CaCO_3$) was used in this research work. The high concentration of $CaCO_3$ influenced the removal of Pb. The solubility of $CaCO_3$ material might increase the adsorption capacity of Pb through the precipitation process.

Table 1
Properties of the prepared limestone

Property	Value
Particle diameter, average, mm	6
Surface area, $m^2\ g^{-1}$	28
Bulk density, g cm^{-3}	1.42
Real density, g cm^{-3}	2.62
Porosity, %	34
Coefficient of uniformity, d_{60}/d_{10}	3.6
Permeability, cm min^{-1}	6.2

2.3. Preparation of simulated wastewater

A standard solution of lead with a concentration of 1,000 mg L^{-1} was prepared using lead nitrate $Pb(NO_3)_2$ salt. A total of 1.59 g of this salt was dissolved in 1 L of distilled water to prepare this concentration. The prepared solutions were kept at room temperature and used as stock solutions to prepare an initial concentration of 1.5 mg L^{-1}. Turbidity of simulated wastewater was prepared using kaolin. The initial prepared turbidity was 50 nephelometric turbidity units (NTU). The lead concentration and turbidity before and after the limestone porous weir were measured using atomic absorption spectroscopy (Accusys 211, Buck, USA) and a turbidity meter (Micro TPW, Water Proof Scientific, Inc., USA).

2.4. Experimental procedures

Firstly, for the hydraulics experiments, the model of the fabricated porous weir was installed at the flume at a distance of 1 m from the flume entrance and filled with limestone. After that, the submersible pump was operated at 10 different discharges: 0.4, 0.6, 0.8, 1, 1.5, 1.85, 2, 2.3, 2.5 and 2.75 m^3 h^{-1}. For each flow rate, the water surface depth was measured along the longitudinal section of the flume using an accurate point gauge. The depths were measured at selected distances. These depths included: the depths of flow at two locations upstream of the model: $y_{u/s1}$, and $y_{u/s2}$, eight depths of flow through the porous weir: y_1, y_2, y_3, y_4, y_5, y_6, y_7 and y_8 and finally the depths at three locations downstream of the model: $y_{d/s1}$, $y_{d/s2}$ and $y_{d/s3}$, as shown in Fig. 4.

According to flow mode there are five types of flow which are: through flow, through flow limit, transition flow, over flow limit, and over flow [13] as shown in Fig. 5. In this study the submersible pump was selected to pump only the first three types which were: through flow ≤1.84 m^3 h^{-1}, through flow limit = 1.85 m^3 h^{-1}, and transition flow (1.86–2.75) m^3 h^{-1} to ensure sufficient contact time with the limestone porous media for best treatment performance.

To investigate the performance of the limestone weir as a filtration treatment system, 3,000 L of synthetic water contaminated with 1.5 mg L^{-1} of lead ions, as an initial concentration, was prepared in the feeding tank. The contaminant water was pumped at constant flow rate to the flume for treatment by flow through the porous weir. The samples

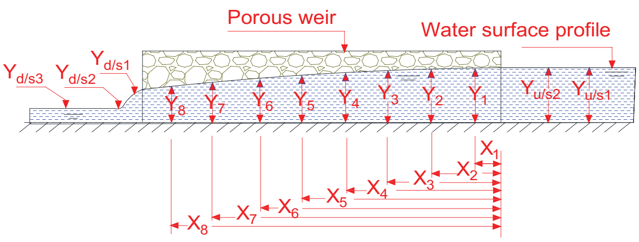

Fig. 4. Schematic showing the locations of distances and depths measured.

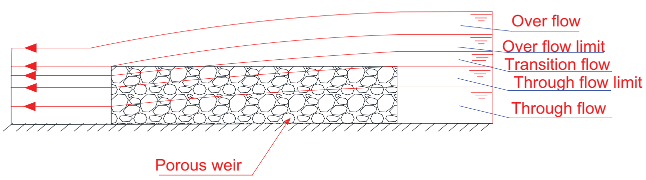

Fig. 5. Five types of flow through and over limestone porous weir.

of contaminant water were taken at different interval times (10, 20, 30, 45, 60, 75, 90, 120, 150, 180, 240, 300, 360 and 420 min). The samples for each time were taken downstream of the porous weir and the initial sample was taken from the storage tank. The experiments were repeated for three flow rates: 0.4, 1, and 1.85 m^3 h^{-1}, the experimental conditions were: lab. Temperature ranging from 20°C–29°C, time of experiments 7 h, and the pH was adjusted to 6 to prevent lead precipitation [14].

By the same method, the experiments were repeated for the turbidity test where the initial value was 50 NTU. The removal efficiency is calculated by the following relationship:

$$\text{Re} = \frac{(C_0 - C_e)}{C_0} \times 100\% \quad (1)$$

where C_0 and C_e are the initial and final concentrations in mg L^{-1}.

3. CFD model

CFD was used to simulate the water surface profile. This modeling method is capable of simulating the dynamic and steady state behavior of liquids and gases in one, two or three dimensions. It does so through solution of the complete Navier - Stokes equations of fluid dynamics. It is applicable to almost any type of flow process and capable of simulating free surface flow. These capabilities make the model well suited for simulating the varied and complex flow conditions, which typically occur in a variety of hydraulic design and analysis problems. The k-ω dependent on shear stress transport (SST) model was developed by Menter [15]. The SST k-ω model deals with the transportation of the shear stress of turbulence and gives results which are more accurate [15]. Due to high performance for numerical solution, the SST k-ω model which consists of two equations is adopted. The following equations represent the SST k-ω model [16]:

$$\frac{\partial \rho k}{\partial t} + \frac{\partial}{\partial x_j}\left\{\rho u_j k - \left(\mu + \frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_j}\right\} = P_k - C_\mu \rho \omega k \quad (2)$$

$$\frac{\partial \rho \omega}{\partial t} + \frac{\partial}{\partial x_j}\left\{\rho u_j \omega - \left(\mu - \frac{\mu_t}{\sigma_\omega}\right)\frac{\partial \omega}{\partial x_j}\right\} = \alpha \frac{\omega}{k} P_k - \beta \rho \omega^2 + 2(1 - F_1)\frac{\rho}{\sigma_{\omega 2}\omega}\frac{\partial k}{\partial x_j}\frac{\partial \omega}{\partial x_j} \quad (3)$$

where ρ is the fluid density, P_k is the production of kinetic energy of turbulence, and k and ω are the turbulent kinetic energy and its dissipation frequency, respectively. u_j is the velocity of the fluid, μ is the dynamic viscosity, and F_1 is a blending function. C_μ, σ_k, α, and β, are constants equal to 0.09, 1, 0.52, and 0.09, respectively. The eddy viscosity in the SST k-ω model is given by:

$$\mu_t = \rho \frac{k}{\omega} \quad (4)$$

$$\sigma_\omega = \frac{1}{\frac{F_1}{\sigma_{\omega,1}} + \frac{1-F_1}{\sigma_{\omega,2}}} \tag{5}$$

where $\sigma_{\omega,1}$ and $\sigma_{\omega,2}$ are constants equal to 2 and 1.168, respectively. The relationship between ω and ε can be concluded as:

$$\omega = \frac{1}{C_\mu}\frac{\varepsilon}{k} \tag{6}$$

The properties of the mesh used to solve the model are: max face size = 0.05 m, and max size = 0.05 m, high smoothing, and relevance = 100%. The properties of the solver are: pressure-based type, absolute, and transient. The multiphase models used are: volume of fluid (VOF), implicit, and sharp interface modeling. The materials that used are air, water, and calcium-carbonite ($CaCO_3$ – limestone). The velocity inlet for water was used in the beginning of the channel. One outlet was utilized at the end of the channel. The top of the channel was used as an ambient and the base of channel considered as a wall. Two porosity inlets (porosity inlet1 and porosity inlet2) were used for the front and top face and one porosity outlet was used at the rear face of the porous weir using ANSYS 16.1 for the mesh interface. The boundary conditions used are shown in Fig. 6 which was obtained using ANSYS 16.1.

4. Results and discussion

4.1. Water surface profile

Six discharges were performed experimentally to investigate the water surface profile over and through the limestone porous weir to satisfy the three types of flow (through flow, through flow limit, and transition flow) as mentioned previously. The three types of flow were conducted in this study to allow for every droplet of water to contact with limestone for improving the efficiency of removing contaminants. The through flow was the best one that removes the contaminants due to slow velocity of water and maximum contacted time with limestone. The transition flow has the minimum removal efficiency among the other flow types due to high velocity, minimum detention time, and establishing vortex near the corner at downstream of porous weir. Fig. 7 represents the water surface profiles that were obtained experimentally. A previous study concluded that the upstream depth of water increased by decreasing the size of the gravel used for a gabion weir and was occurred in this study. Moreover, the upstream depths increased by increasing the length and height of the weir and that what was happened in this study also. In this study, the hydraulic results obtained focused on the relationship between upstream depths and discharges. The results show that water surface depth decreased with increased flow rate. Both linear and nonlinear relationships can be used. The results obtained agreed with the results of previous studies that there is a linear relationship between upstream depths and discharges [17]. Empirical equations were established depending on experimental results to determine the relationship between upstream depths and discharges. The following linear and nonlinear before/after and through limestone weir, respectively, were obtained using the DATA Fit 90 program. Equation 7 is an alternative equation for Equation 8. The two proposed equations show that both linear and non-linear form can be used to represent the relationship between discharge and head for porous weir although the previous studies show that the relationship between the two mentioned parameters was linear [1].

$$H_u = A \cdot Q + B \qquad \left(R^2 = 0.94\right) \tag{7}$$

$$H_u = T \cdot Q^2 + G \cdot Q + C \qquad \left(R^2 = 0.97\right) \tag{8}$$

where *A*, *B*, *T*, *G*, and *C* are constants equal to 5.39, 1.278, –0.909, 8.278, and –0.501 respectively.

4.2. Removal of lead, turbidity and TSS

For testing the efficiency of the limestone porous weir in removal of lead ions and turbidity, three different discharges: 0.4, 1.85 and 2.3 $m^3\ h^{-1}$ flowed through the flume, where

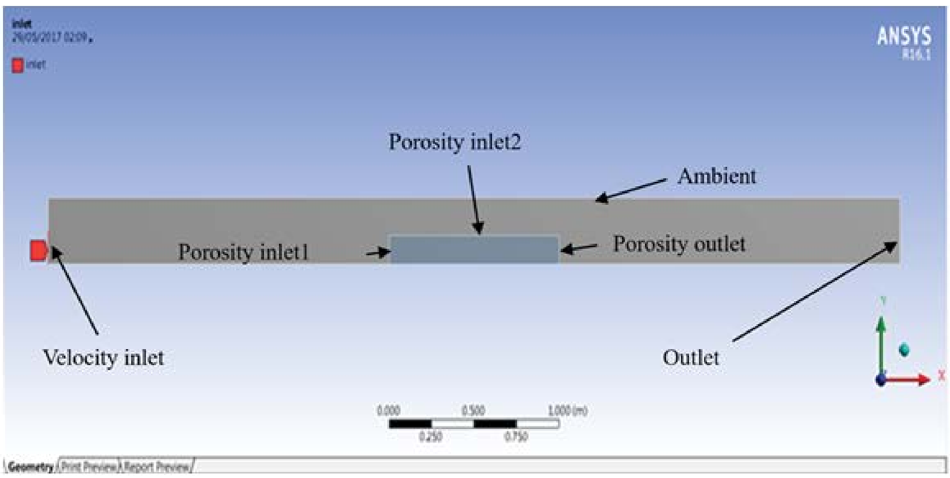

Fig. 6. Boundary conditions for numerical simulation of weirs.

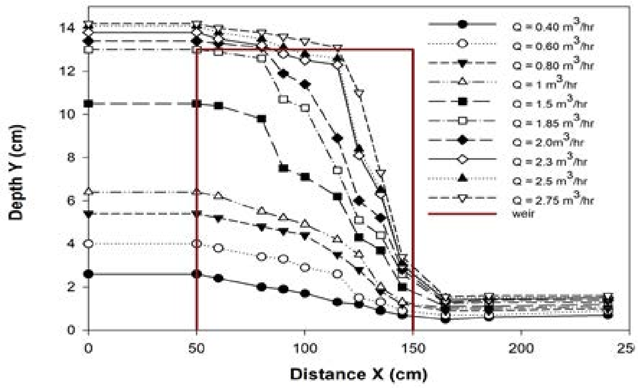

Fig. 7. Experimental water surface profile.

each flow represents one type of flow through the porous weir. The effect of flow rates was studied at an initial concentration equal to 1.5 mg L^{-1} for Pb ions. Fig. 8 shows the removal efficiency of lead ions at different interval times up to 420 min. It is clear from the figure that as the flow rate increases a relative decrease occurs in removal efficiency at all times. This is due to the decrease in the residence time of the solute in the bed as the flow rate increases, meaning there is not enough time for adsorption equilibrium to be reached which results in lower bed utilization and the adsorbate solution leaving the porous weir before equilibrium. This is consistent with the result obtained by Ali [18]. The maximum removal efficiency occurred at the beginning of the operation and was equal to 92.5% at a flow rate of 0.4 $m^3 h^{-1}$, while it was 76.92% at 2.3 $m^3 h^{-1}$ flow rates for the same period. Also, the results show that the removal efficiency after 7 h decreased to become: 44.62%, 40.77% and 38.46% at flow rates 0.4, 1.85, and 2.3 $m^3 h^{-1}$, respectively. This means the removal efficiency values become close to constant after 300 min.

Akbar et al. [19] used lime stone as adsorbent for iron and manganese removal from ground water in batch reactor. They found that both iron and manganese removal was 95% and 80% respectively at optimum dose of 40 g for lime stone.

Fig. 9 shows the turbidity removal efficiency at different interval times up to 180 min. The effect of three values of flow rate was studied at an initial concentration of turbidity equal to 50 mg L^{-1}. Measurement of turbidity provides a rapid means of process control to determine when, how, and to what extent the raw water must be treated to meet specifications [20–22]. Maximum turbidity removal was obtained at 0.4 $m^3 h^{-1}$ to be 72% at 10 min. While it was 69% and 60% at flow rates of 1.85, and 2.30 $m^3 h^{-1}$, respectively. Then the removal efficiency decreased until reaching equilibrium after about 300 min of operation.

In the same sequence for turbidity, the TSS removed at 59%, 50% and 42%, for flow rate of 0.4, 1.85 and 2.30 $m^{-3} h^{-1}$, respectively as shown in Fig. 10. Mortula and Shabani [23] used different adsorbents like limestone aggregate, activated alumina, activated carbon, and steel slag for removal of biochemical oxygen demand and TDS. They found that the removal efficiency was 45.6% and 76.76% using limestone and it's more efficient than other adsorbents [24]. The removal of TSS from river water will help control the release the clay-bound metals including iron, aluminium, manganese and phosphate. Also, the removal of suspended solid will reduce the load onto water treatment plant and this reflects on its performance. In addition to that, the removal of suspended solid using the limestone porous weir will reduces the accumulation of sediments in rivers bodies and reduces the scattering of sunlight necessary for plant growth.

According to flow types, the through flow gives the best results for removal efficiency of lead turbidity and TSS, and transition flow gives the lowest efficiency. The relationship between effluent concentration, flow rate, time and the removal efficiency of lead and turbidity was estimated using SPSS 17 to be:

For lead with $R^2 = 0.941$:

$$Y = 10^{2.157} \times \left(X_1^{-0.191} \times X_2^{-0.077} \times X_3^{-0.005} \right) \tag{9}$$

For turbidity with $R^2 = 0.981$

$$Y = 10^{2.816} \times \left(X_1^{0.011} \times X_2^{0.014} \times X_3^{-0.875} \right) \tag{10}$$

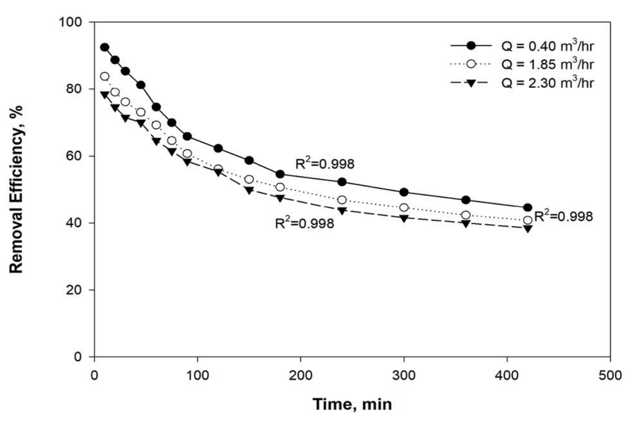

Fig. 8. Experimental curves for removal efficiency of lead ions at different flow rates.

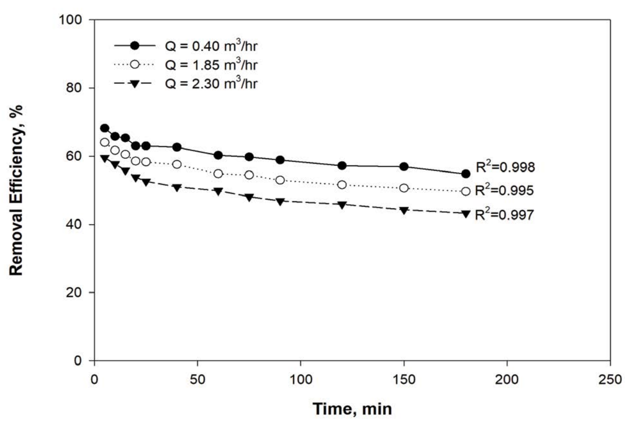

Fig. 9. Turbidity removal efficiency of limestone porous weir at different flow rate.

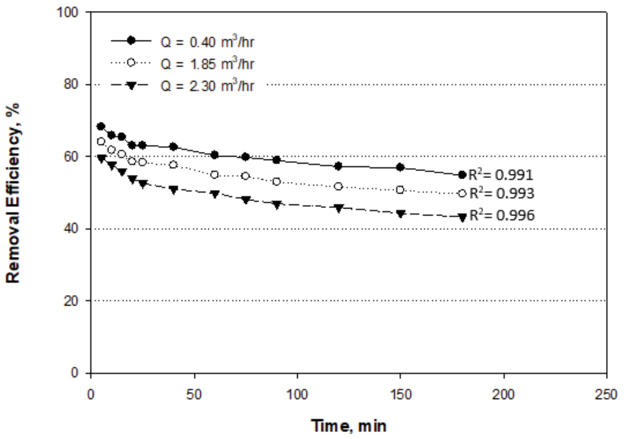

Fig. 10. TSS removal efficiency of limestone porous weir at different flow rate.

For TSS with $R^2 = 0.961$:

$$Y = 10^{1.967} \times \left(X_1^{0.012} \times X_2^{-0.017} \times X_3^{-0.753} \right) \quad (11)$$

where Y: removal efficiency (%), X_1: time (min), X_2: discharge ($m^3\,h^{-1}$), X_3: final concentration.

4.3 Effect on pH

The effect of using limestone in porous weir on pH is shown in Fig. 11. It is clear from this figure that the pH of water raises from 5.6 to 7.4, 7.15 and 7 for flow rate of 0.4, 1.85 and 2.3, respectively. The pH of all effluents is within acceptable limits for drinking water (6.5–8.5). This means

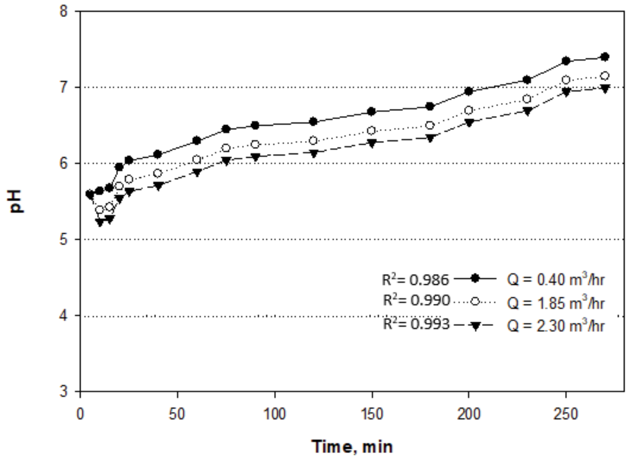

Fig. 11. Effect of limestone porous weir on pH at different flow rate.

that, lime stone have environmental benefit as neutralization agent for acidic water since it composed mainly of $CaCO_3$ as mentioned before in preparation of limestone. Nath and Dutta [24] used crushed lime stone for fluoride removal form pre-acidified water. They conclude that using of lime stone improved the fluoride removal and this increase with increased in the concentration of acids.

4.4. Application of CFD model

The software used in this study was ANSYS 16.1 FLUENT with unsteady state and pressure based. The solution method that used in this software was: SIMPLEC for

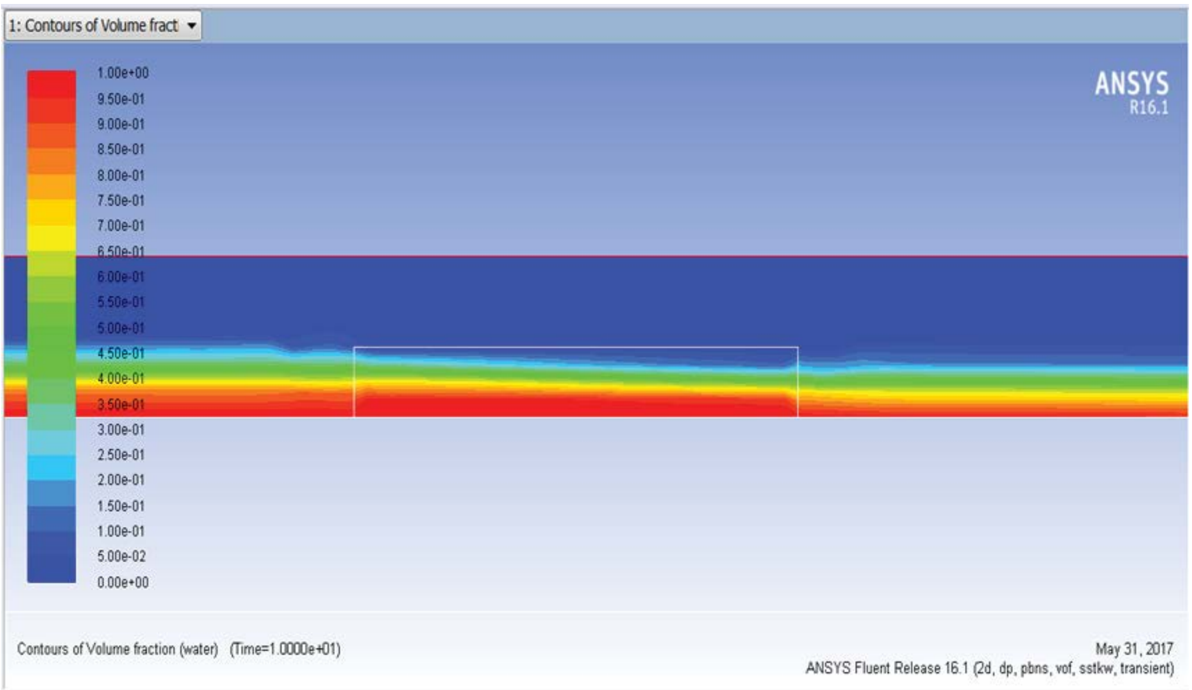

Fig. 12. Water surface profile for $Q = 0.40\ m^3\,h^{-1}$.

scheme, least squares cell based for gradient, and second order upwind for momentum and turbulent kinetic energy, and the VOF model was used for multiphase flow. Moreover, for run calculation: 0.05 s for time step size, and number of time steps = 200 were adopted. This method of simulation was approximately compatible with the results of Reza et al. [25,26] except using SST k-ω instead of RSM k–ε. They used a similar method of modeling with 3D for a weir filled with gravels. Figs. 12–14 represent the contour of the water surface profile, for discharges: 0.4, 1.85, and 2.75 $m^3 h^{-1}$,

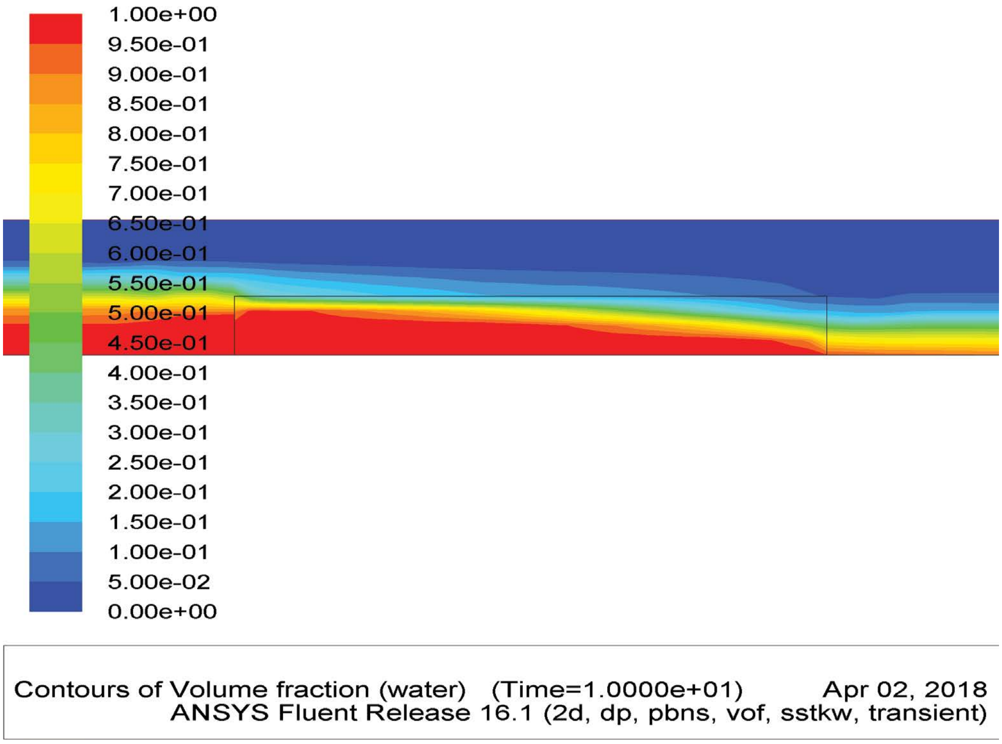

Fig. 13. Water surface profile for $Q = 1.85\ m^3 h^{-1}$.

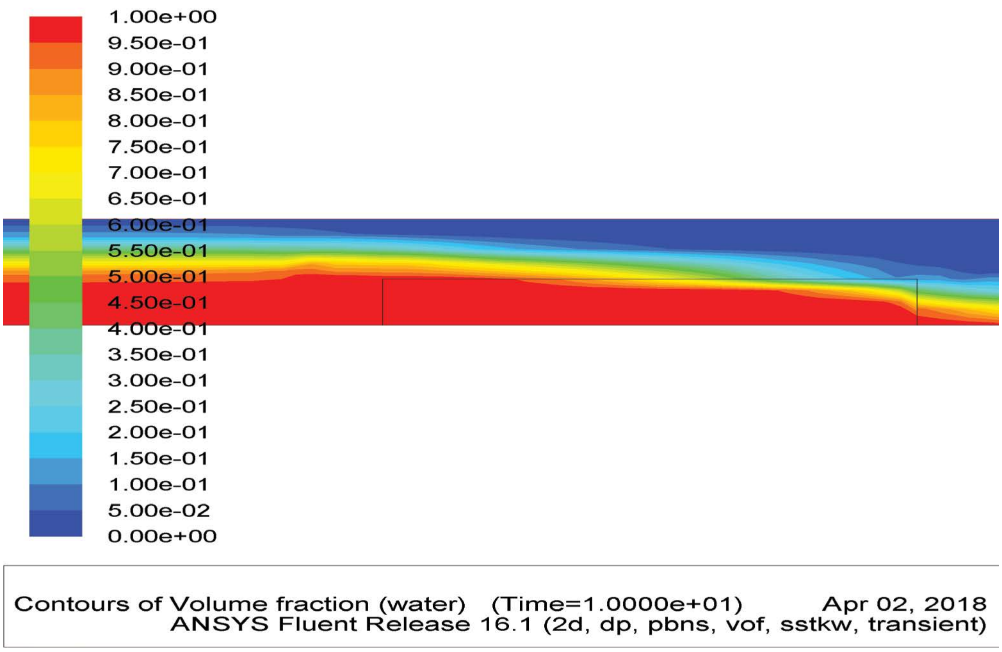

Fig. 14. Water surface profile for $Q = 2.75\ m^3 h^{-1}$.

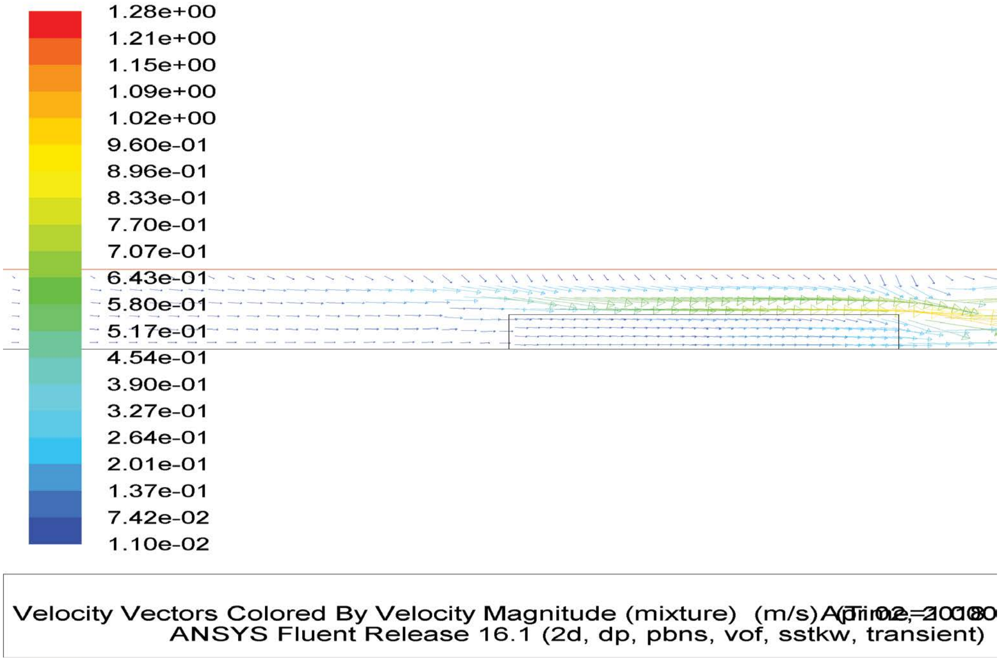

Fig. 15. Velocity vectors for $Q = 2.75\ m^3\,h^{-1}$.

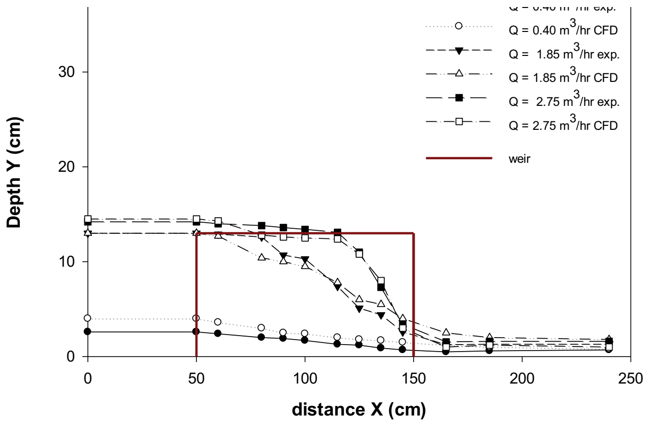

Fig. 16. Comparison between theoretical model (CFD) and experimental work.

respectively which represents the three flow types (through flow, through flow limit, and transition flow). The colors used represent the volume fraction of water the red color for 100% water and the blue for 0% water. Fig. 15 represent the velocity vector for the CFD model at $Q = 2.75\ m^3\,h^{-1}$. This Figure shows that, the velocity of water was increased above the porous weir and decreased though it. So, each droplet of water that enter the porous weir subjected to decelerations due to impinging with stones of limestone and that allowed to increase the detention time and lead to improve the efficiency of contaminants removal [27].

For verification between experimental results and the CFD model, three discharges were selected, as shown in Fig. 16. The root mean square error (RMSE) values calculated for the three discharges were equal to 0.877, 0.979, and 0.625 cm, respectively, which indicate the success of using this model in representing the resulted experimental data for the limestone porous weir. The application of this model in such cases could save money and time and could predict the water depths at different locations through the porous weir.

5. Conclusions and recommendations

A hydraulic and environmental experiment and theoretical study on a limestone porous weir were conducted. The aims of this study were to investigate replacing the environmentally-unfriendly solid concrete and gabion weirs with permeable limestone weirs which are cheaper, environmentally-friendly, and more efficient in the removal of pollutants, such as heavy metals and turbidity, from rivers. For hydraulic experiments different discharge types representing different modes of flow were used to study the hydraulic water surface depth profile and compare with CFD model findings using ANSYS 16.1 FLUENT. The results showed that the CFD model gave RMSE values equal to 0.877, 0.979, and 0.625 cm, respectively for the three discharges selected, 0.4, 1.85, and 2.75 $m^3\,h^{-1}$, respectively. Both linear and nonlinear empirical equations can be derived for the relationship between depths and discharges upstream, through and downstream of the limestone porous weir.

From an environmental point of view, the maximum removal efficiency was found to be 92.5%, 72% and 59% for lead, turbidity and TSS, respectively. Furthermore, the using of lime stone could play as neutral agent for acid water. The greater the time the lower the removal of pollutants, and lower discharge resulted in a greater percentage of removal. The findings of this study could be used for design of submerged porous weirs for small irrigation channels.

These weirs are attractive alternatives to the concrete solid weirs that are expensive and have negative environmental impacts. Also, limestone can be mixed with gravel in large gabion weirs to meet the environmental requirements. The cost of construction this type of weir is considered low and it can be maintained or replaced easily.

A comparison between two dimensional and three dimensional models could be studied in future studies for studying the behavior of flow inside the porous limestone weir and the streamlines curvatures.

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