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Improving Water Quality Using Broad-Crested Weirs Under Laboratory Flume Conditions

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ABSTRACT

Maintaining sustainable water quality remains a major challenge for protecting ecosystems and ensuring safe water for people. Among the many hydraulic structures used in rivers, weirs play an important role in controlling flow and water levels. Their ability to create turbulence makes them particularly useful for improving water quality. The objective of the current study is to quantify the changes in dissolved oxygen (DO), turbidity (TUR), total dissolved solids (TDS), electrical conductivity (EC), and pH downstream of a broad-crested weir under controlled laboratory conditions. Also, establish an empirical relationship between aeration efficiency and flow rate. Experiments were conducted in a 12 m long, 0.30 m wide, and 0.46 m deep glass-sided flume equipped with a closed-loop pumping system and precise flow control. The dimensions of a broad-crested weir model were 0.29 m width, 0.25 m height, and 0.40 m length. The models were installed at a distance of 3.27 m upstream of the flume. The location of water quality sensors was at a distance of 1 m upstream and downstream of the weir. The range of discharges was from 0.003 to 0.009 m³/s. The results indicated that DO is increased by 8-12% in the downstream, with the maximum increment of 0.9 mg/L at discharge (Q) = 0.009 m³/s. The maximum aeration efficiency was 13.69%. TDS slightly increased in the downstream for the given discharge. The percentage of reduction was approximately 14.5%. Turbidity showed a clear decreasing trend with increasing discharge, and the percentage of reduction was approximately 17.5%. pH remained stable (7.25–7.30), while EC generally decreased with discharge but was slightly higher downstream. Aeration efficiency was 13.69% in the present study compared to 13% by previous study. The main significance of this study is to show the efficiency of the broad-crested weirs as hydraulic structures capable of improving dissolved oxygen levels and reducing pollutant concentrations under controlled laboratory conditions, while also highlighting the applicability and limitations of such findings for real river systems.

1. INTRODUCTION

The water properties of chemicals and physical materials include both organic and inorganic substances. These properties provide a significant source for evaluating water quality [1]. A study of water quality is necessary for aquatic life, and climatic changes and geological conditions [2]. Water quality elements affect the self-purification capacity of rivers and streams. The concentration of DO in water has long been a key criterion for evaluating the health of river ecosystems. Generally, rural streams exhibit higher levels of DO due to lower levels of pollutants compared to urban channels. Enhancing DO levels in lakes and urban rivers promotes aerobic processes that support aquatic life. Therefore, restoring oxygen balance in freshwater systems is a critically important environmental goal [3].

The weir aeration mechanism depends essentially on energetic hydraulic turbulence downstream of the weirs, which assists in increasing transfer of gases across the air–water interface, thus enhancing river aeration. Rapid fluctuations of flow velocity and pressure variations lead to falling nappes, plunging jets, hydraulic jumps, and highly turbulent roller zones at the downstream side of the weirs. These flow characteristics allow for dramatic increases in interfacial surface area and turbulence intensity, enhancing passive atmospheric oxygen uptake and natural reaeration processes [4]. According to Puri et al. [5] and Ljubičić et al. [6], experimental and numerical studies have shown that the two zones that contribute the most to oxygen transfer in plunging jets are the plunging jet and the downstream eddy zones due to high shear stress and vorticity generation. Thus, weirs are considered passive aeration facilities that can enhance DO levels in a local area without requiring external energy. Although the contact time between water and hydraulic structures is very short, such structures can significantly increase the DO concentration.

Further studies showed that, under self-aeration of natural systems, the quantity of oxygen transferred over numerous kilometres can be achieved by utilising individual hydraulic structures. Aeration has been advanced mainly by adding a large quantity of oxygen in the form of bubbles, which enhances the available contact surface area for gas transfer. Macaitis and Reclamation [7] developed a system to improve aeration in stations built in the stream and found an alternative method to maintain DO in wastewater treatment at the district's three largest water reclamation plants.

The aeration efficiency can be significantly influenced by weir type and geometry. In general, stepped, labyrinth, and sloped weirs showed much higher aeration efficiency compared to traditional sharp crested weirs, as a result of the greater flow disintegration, longer nappe contact length, and multiple turbulence formations along the steps [8]. Although general characteristics such as crest shape, step height, number of steps, slope angle, and the presence of internal obstructions or barriers directly affect flow regime transitions and turbulence structure [5]. Recent studies demonstrated that changing weir geometry can lead to a significant enhancement in oxygen transfer efficiency [9, 10]. The impact of surface roughness on the coefficient of discharge of a broad-crested weir was examined by research [11]. The results showed that surface roughness enhanced aeration downstream of the broad-crested weir. Jaiswal and Goel [12] showed that triangular weirs produced better aeration performance than any other weir shape or even other aeration structures such as cascades, labyrinth weirs. Air transfer at weirs remains the most common case for aeration of hydraulic structures. Freely falling water jets from a weir plunge into the downstream water, entraining air bubbles that accelerate oxygen transfer. Researchers have studied the factors affecting aeration, weir properties, and their shapes to achieve the highest possible aeration efficiency. Gulliver et al. [13] showed that smart modelling devices were more accurate in predicting complex environmental and hydrodynamic schemes. Emiroglu and Baylar [14] explained that flow status varied from subcritical to supercritical, which causes turbulence at downstream weirs. This process assists oxygen in transferring and the formation of air bubbles. This process was essential for increasing DO levels. Baylar et al. [15] illustrated that aeration efficiency and air entrainment rate were both increased by this interaction. Idrees et al. [16] demonstrated that nappe interference at the downstream of the labyrinth weir was a good option for reaeration flow. Srinivas and Tiwari [17] also used soft computing techniques to compare predictive models and empirical equations for estimating the aeration efficiency of a gabion weir. The findings showed that the DNN model had the highest correlation (CC ≈ 0.9757) and the lowest prediction errors. They also found that the porosity of the gabion material was the most significant factor affecting aeration efficiency. Idrees and Al-Ameri [18] conducted a comprehensive review of hydraulic performance and design methods of labyrinth weirs. The results showed that nappe interference still needs further investigation to discover reaeration phenomena downstream of a weir. Jahad et al. [19] used various shapes of step and chute slopes to study aeration efficiency. The results showed an 11.51% increase in the efficiency of aeration. Idrees and Al-Ameri [20] investigated nappe flow aeration for a labyrinth weir utilising an artificial ventilation method. The results demonstrated that artificial ventilation had a significant impact on improving aeration behind nappe flow.

While most weir studies have focused on DO, growing evidence suggests weirs and reservoirs also modify a diverse set of other water quality variables, including turbidity (TUR), total dissolved solids (TDS), and electrical conductivity (EC). Tomczyk and Wiatkowski [21] found that weir has a change in flow velocity, and residence time influences sediment transport and deposition. They demonstrated that TUR was reduced in upstream regions and suspended solids increased in downstream regions, especially during high-flow events. Nürnberg [22] and Wang et al. [23] showed that weirs associated with reservoirs may enhance nutrient trapping and stratification, which can also increase TDS, increase internal resupply of phosphorus, and promote algal blooms in stagnant conditions. Saeed et al. [24] showed that a sharp crested weir improved DO in the downstream by 14.7%. The results also showed that TUR dropped by 17.2% at the downstream of the weir. Also, TDS values were slightly higher in the downstream. In contrast, EC and pH values displayed the smallest difference, therefore remaining within stable ranges.

Laboratory tests, on the other hand, are quite different from the ongoing field studies of weir-based measures to improve water quality. Though laboratory studies provide controlled conditions that permit accurate quantification of hydraulic performance, aeration efficiency, and geometric effects, they typically oversimplify boundary conditions and neglect long-term biogeochemical interactions [4]. Hashim et al. [25] showed that the field results represented cumulative effects of variability in discharge, annual changes in temperatures, sediment load, and human effluents, which may lead to more complicated and occasionally opposing results. Furthermore, scaling effects and the general inability of laboratory experiments to simulate real rivers can limit translation from laboratory to river. Nakulopa et al. [26] showed that some comparisons need combined approaches that combine laboratory experiments, field surveys, and water quality model simulations to provide a comprehensive understanding of weir-related impact. Field-based research shows that these effects vary considerably depending on local context, hydrologic regime, climate, and upstream contaminant inputs.

Chabuk et al. [27] assessed the water quality of the Shatt Al-Hillah River using physical, chemical, and heavy metal factors. The results showed that the water quality indices at the selected locations along the Shatt Al-Hillah River were very low. Fesal [28] confirmed that generating turbulence produced mixing air into the water body through the free fall of water jets. Air mixing improved aeration in the downstream of the channel.

To calculate the broad-crested gabion weirs' aeration performance efficiency at reference temperature, the efficacy of several predictive models (soft computing techniques) was compared by Tiwari et al. [29]. In their lab flume experiments, they varied the unit discharge, porosity, drop height, gabion particle size, and weir width. With the lowest validation errors and an NSE of 0.934, the deep neural network (DNN) model performed better than the others, they found. Additionally, they discovered that drop height was the second most important factor influencing aeration efficiency, after unit discharge. They concluded that designers can more precisely estimate aeration efficiency by using such models, particularly DNN. Begum et al. [30] proposed ways to provide baseline data for watershed management. They used statistical methods to evaluate watershed conditions and the water quality index (WQI). Kim et al. [31] studied the impacts of the environmental conditions on the water quality of the South Han River by monitoring sites, and they found significant differences.

Although numerous researchers have investigated aeration mechanisms for weirs using theoretical approaches and field measurements, few studies have examined water quality in a laboratory. Moreover, quantitative relationships between discharge parameters, such as Froude number (Fr), are not clearly debated. The degree of improvement in water quality is therefore still unknown. Laboratory experiments directly measure the reactions of TUR, TDS, and DO using sensors. The objective of the current study is to quantify the changes in DO, TUR, TDS, pH, and EC downstream of a broad-crested weir under controlled laboratory conditions. Also, establish an empirical relationship between aeration efficiency and flow rate.

2. MATERIAL AND METHODS

The present effort is achieved in the hydraulic laboratory at the University of Babylon. As shown in Figure 1, a rectangular flume is used to perform all tests. Dimensions of the flume were 12 m long, 0.30 m wide, and 0.46 m deep. A rectangular test flume's bottom consists of an iron plate with glass sidewalls, mounted on a steel frame, and its base is made of iron coated with moisture-resistant paint. The water was supplied to the flume by a centrifugal pump and a closed-loop technique. The flow rate was controlled by using an adjusting valve and an ultrasonic discharge. The water level was measured by a pointer gauge with an accuracy of 0.01 m.

Figure 2 shows a broad-crested weir model with a width of 0.29 m and a height of 0.25 m. A broad-crested weir is a scale model made of wood coated with a waterproof finish. The study was focused on controlled laboratory behaviour rather than direct simulation of the prototype. The models were fixed at a distance of 3.27 m from the flume outlet. Water quality parameters often vary vertically due to thermal stratification, sunlight penetration, biological activity, and mixing. Temperature and DO often show significant differences between surface and deeper water, especially in stratified lakes or reservoirs. pH, conductivity, and TUR can also vary with depth, though they may be more homogeneous in well-mixed waters. However, water quality sensors were placed at fixed locations, one meter upstream and one meter downstream of the broad-crested weir. As recommended by USEPA [32], the water sample is measured near the mid-depth of the water column for shallow water depth (≤ 2 m). Therefore, in the present study, two sensors were fixed at depths of 18 cm and 10 cm below the water surface upstream and downstream of the weir, respectively. This helps ensure that the lab sample represents the water column and not just the surface or bottom layer. The water depth at the upstream was measured when the water surface was steady. This process ensures the bubble level is under the pool depth. Thus, it prevents the influence of depth differences on the efficiency of aeration [33]. The range of flow was tested at 0.003, 0.004, 0.005, 0.006, 0.007, 0.008, and 0.009 m^3/s. Untreated raw water was used for all tests, which was sourced directly from the Al-Hillah River, Babylon city, Iraq. This choice was used to study flocculation dynamics under realistic, natural water conditions. The raw water was changed before each new experiment. A fresh batch of river water was used for every trial run to prevent cross-contamination of chemicals or alteration of background chemistry from previous tests. The oxygen depletion method has been adopted. A solution of sodium sulfite (Na_2SO_3) with cobalt dichloride ($CoCl_2$) has been used to reduce the initial concentration of DO for each run [34]. For titration, 0.4 g of $CoCl_2$ was used, which is within the recommended effective dosage range of 0.1–0.5 g. For each experimental run, the circulating flow in the system must be stabilised. After flow stabilisation, key initial parameters (DO, TUR, and TDS) were measured. Water quality parameters are measured for each run after two minutes of flow stabilisation. The accuracy was calculated by averaging three consecutive readings. EC, TUR, pH, TDS, and DO were among the parameters that were examined. The specifications of the sensors used are compiled in Table 1.

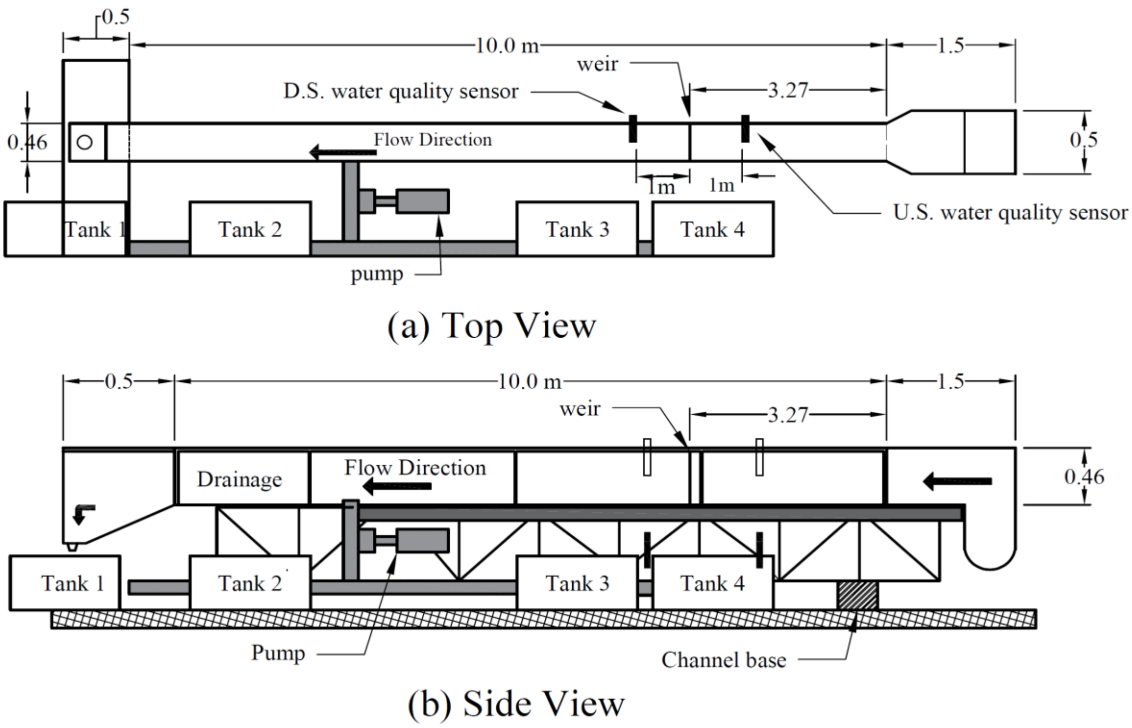

Figure 1. The flume facilities schematic: (a) Top view, (b) Side view

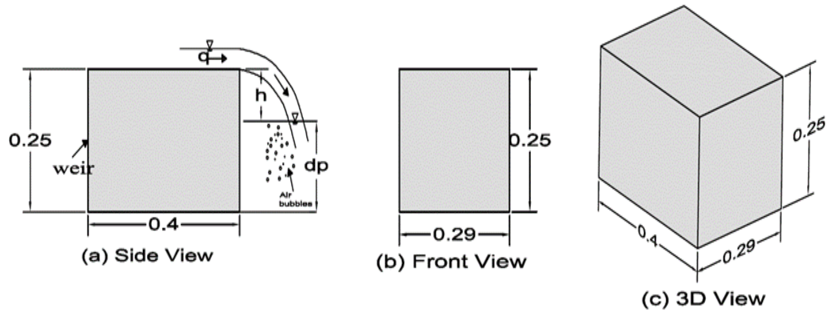

Figure 2. A broad crest weir: (a) Side view, (b) Front view, and (c) 3D view

Table 1. Sensors specifications for collecting water quality data

Sensor Type	Description
DO	Pen-style smart oxygen meter equipped with an Aurora sensor and Bluetooth connectivity. It measures DO levels from 0 to 30 mg/L. It connects to a digital display with a backlit for easy reading.
pH	• Operating voltage: 5.00 V • Range of readings: 0–14 pH • Temperature tolerance: 0–60℃
TDS	Sensor consistent with Arduino systems, a pen-type. Provides analogue output from 0–2.3 V, requires an input voltage of 3.3–5.5 V, and is designed to be waterproof for extended submersion.
Temperature	DS18B20 sensor enclosed in waterproof tubing with heat-shrink protection. It is consistent with systems 3.0–5.0 V, including Arduino. Maximum measurable temperature: 125℃.
TUR	Measures water clarity and is fully Arduino-compatible. Includes a 20 cm cable, operates at 0–4.5 V, and provides both digital and analogue output signals.
EC	EC values estimated by applying the formula: EC = TDS / K, where the calibration constant K = 0.64 [35].

Table 2. Summarising key hydraulic parameters

Q_n (m³/s)	h_{up} (m)	h_0 (m)	h_{down} (m)	V_{up} (m/s)	V_{down} (m/s)	Fr_{up}	Fr_{down}
0.003	0.324	0.026	0.158	0.030	0.063	0.017	0.050
0.004	0.332	0.026	0.166	0.040	0.080	0.022	0.062
0.005	0.337	0.03	0.17	0.049	0.098	0.027	0.075
0.006	0.345	0.034	0.175	0.057	0.114	0.031	0.087
0.007	0.352	0.037	0.187	0.066	0.124	0.035	0.092
0.008	0.355	0.04	0.183	0.075	0.145	0.040	0.108
0.009	0.361	0.044	0.198	0.083	0.151	0.044	0.108

where, Q is the flow rate m³/s, h_{up} and h_{down} are the upstream and downstream water heads (m), respectively. V_{up} and V_{down} are upstream and downstream velocities (m/s), respectively. Fr_{up} and Fr_{down} are upstream and downstream Froude numbers, respectively.

The DO sensors were a pen-shaped digital meter with a Bluetooth connection. Aurora probe ranges from 0 to 30 mg/L. An Arduino-compatible probe was used to measure TDS and TUR. pH sensors were used with high precision between 0 and 14. The DS18B20 waterproof sensor was used to measure the temperature. Eq. (1) is the practical equation commonly used in studies of freshwater.

$$EC = TDS / K \tag{1}$$

where, EC is the electrical conductivity, TDS is total dissolved solids, and K = 0.64 is a constant [35].

The manufacturer calibrated every instrument in the factory. Before experimentation, calibration was confirmed by testing samples of tap and drinking water to ensure further accurate measurements. The Iraqi standard of water quality was compared with the measurements. The outcomes proved that sensor readings were within satisfactory tolerances. Aeration is a process of transferring oxygen from the atmosphere to water through a mixing process. The efficiency of aeration is the quantity of oxygen pervaded in the water by flow over the broad crested weir. Aeration efficiency (η) is a criterion for finding the weir's ability to improve water quality in rivers. Eq. (2) is used to estimate aeration efficiency, which was adopted from research [36].

$$\eta = \frac{DO_{down} - DO_{up}}{DO_{sat} - DO_{up}} \times 100 \tag{2}$$

where, DO_{down} is DO in the downstream (mg/L), DO_{up} is DO in the upstream (mg/L), and DO_{sat} is the concentration of the saturation oxygen (mg/L) at a temperature (20℃), which is obtained from a reference table in research [37]. Summarising key hydraulic parameters shown in Table 2.

3. RESULTS AND DISCUSSIONS

3.1 Fr

The Fr expresses the ratio of flow force to gravity and is used to determine the nature of the flow. As shown in Figure 3, the results showed that they gradually increased with increasing discharge from approximately 0.003 to 0.009 m³/s.

The values in the downstream region are significantly higher than those in the upstream region at all discharges. The Fr values in the downstream region start at around 0.05 at the lowest discharge and increase to 0.11 at higher discharge. In contrast, in the upstream region, the values remain below 0.02 and then rise to exceed 0.04 at the highest discharge, reflecting a significant increase in flow energy and velocity below the weir. The Fr number in the downstream region steadily rose as flow increased, which caused more turbulent conditions and the approach of the critical state. The hydraulic effect of the weir causes an increase in kinetic energy and turbulence after the water flows over it. It helps break up the water's surface and increase air-water mixing, which improves aeration and raises the amount of DO in the water. To fully evaluate a weir's efficacy in enhancing water quality, it is not enough to rely solely on the Fr, even though it offers a useful first indication of flow characteristics and aeration capacity.

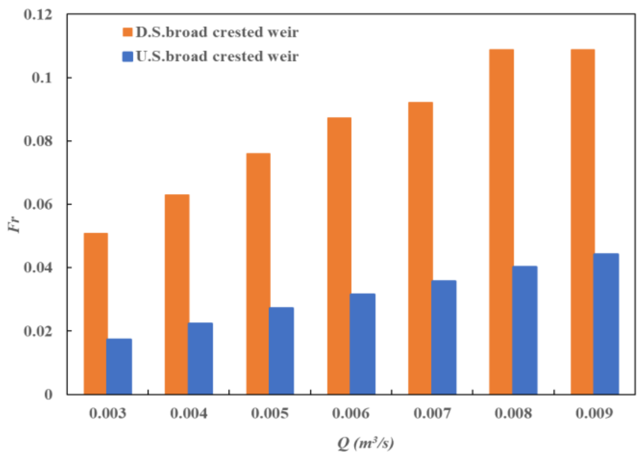

Figure 3. Relationship between Q and Fr for downstream and upstream of a broad-crested weir

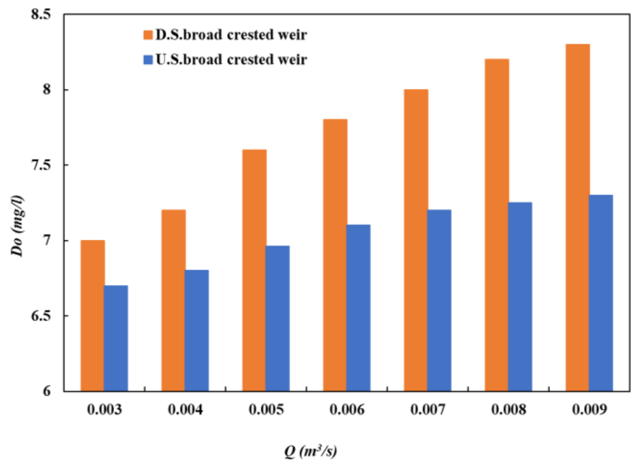

Figure 4. The Q against the DO at the downstream and upstream of a weir

3.2 Concentration of DO

The connection between DO and Q is depicted in Figure 4. Across all tested discharges, the results consistently demonstrated a rise in DO downstream relative to the upstream side. DO rose from roughly 6.7 mg/L upstream to 7.0 mg/L downstream at the least discharge of 0.003 m³/s, from 6.9 mg/L to 7.6 mg/L for upstream and downstream at the moderate discharge of 0.005 m³/s, and from 7.4 mg/L upstream to 8.3 mg/L downstream at the highest tested discharge of 0.009 m³/s. As the discharge increased, the maximum improvement in oxygen concentration was 12%. Trapped air and self-aeration, bubble formation, and subsequent oxygen transfer were responsible for the increase in enhancement percentage. These results are consistent with earlier research that found comparable DO gains in triangular and broad-crested weirs [29]. Trapped air depends on the nappe condition to produce aerated, partially aerated, or submerged. Lines of flow separate from the broad crested weir because the nappe condition is aerated and then raises confined air behind the dropping water sheet. That led to an increase in the air cavities at the downstream of a sharp crested weir, as shown in Figure 5.

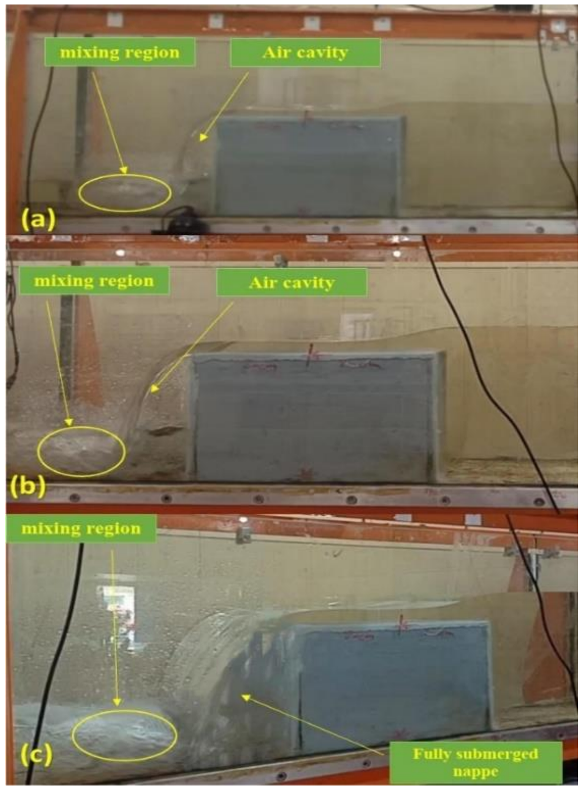

Figure 5. Conditions of nappe flow for broad crested weir: (a) Aerated, Q = 0.003 m³/s, (b) Partially aerated, Q = 0.005 m³/s, and (c) Fully submerged, Q = 0.009 m³/s

Air pockets behave as a temporary air basin, while vortices exchange air with the water. The number of air pockets has increased due to the increase in remaining time in the bubbles mixing region. In contrast, the amount of air cavities decreased due to the submerged nappe condition, thus reducing the capacity of aeration. The condition of nappe flow changed from aerated to partially aerated and submerged while discharge increased. The tailwater at the downstream, the flow depth, and the energy of the falling water jet were controlled to develop air voids.

Figure 6 shows the Q against aeration efficiency. The efficiency of aeration improved with increasing discharge. The reason is attributed to creating turbulence states at the downstream broad crested weir. The downstream velocity increased as turbulence increased. At high Q, the efficiency of aeration was 13.69% for Q = 0.009 m³/s. The aeration efficiency by weirs is a significant condition to reflect the quality design of weirs. The curve fit for the efficiency of aeration with a coefficient of regression of 0.979 was shown in Eq. (3) and Figure 6.

$$\eta = 8.7212 ln(Q)+54.776 \quad (3)$$

where,

η: efficiency of aeration

Q: discharge over a broad crested weir (m^3/s)

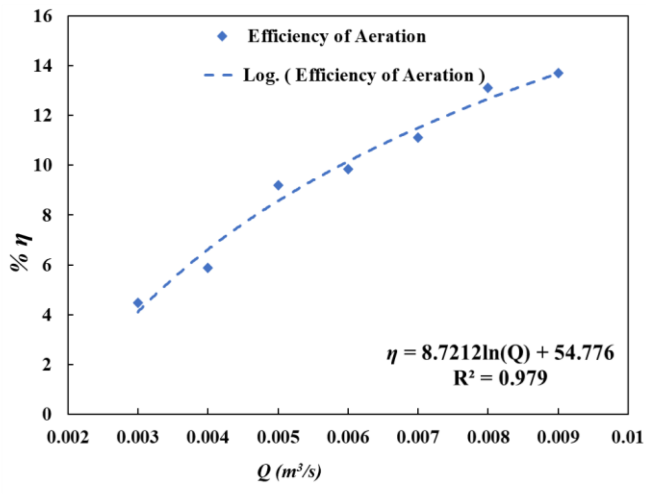

Figure 6. The aeration efficiency by a broad-crested weir

Figure 7 clarifies the difference between upstream and downstream DO (DO_u-DO_d) concentrations as a function of the Fr_d for a broad-crested weir. The upstream DO_u represents pre-aeration conditions, while the downstream DO_d reflects the effect of hydraulic action induced by the weir. The Fr is used as a hydraulic indicator of flow regime and turbulence intensity downstream of the structure.

Figure 7 presented a clear increasing trend in $\Delta DO/DO_u$ with increasing downstream Fr_d.

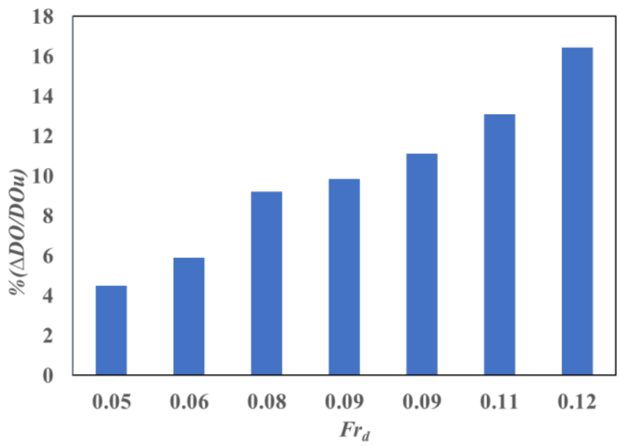

Figure 7. Difference between upstream and downstream DO ($\Delta DO/DO_u$ %) against Fr_d for a broad-crested weir

At low Fr (subcritical flow), the DO increment across the weir is relatively small, indicating limited air–water interaction. As the Fr increases toward transitional and supercritical regimes, the $\Delta DO/DO_u$ becomes more pronounced, reflecting enhanced turbulence, surface breakup, and air entrainment. Although broad-crested weirs are primarily designed for flow measurement and regulation, they can act as effective passive aerators under high-energy flow conditions. Therefore, Figure 7 highlights the potential of such structures to improve DO levels in rivers, particularly in reaches suffering from oxygen depletion due to organic pollution or low reaeration rates.

3.3 Concentration of TDS

Figure 8 explains the correlation between TDS and Q of broad-crested weirs in both the downstream and upstream. The outcomes showed that downstream TDS concentration ranged from 690 to 710 mg/L, while upstream concentrations decreased from 570 to 620 mg/L (≈ 14.5% reduction). Moreover, the findings demonstrated that TDS concentration in both upstream and downstream was slightly increased. It is attributed to strong turbulence in the downstream of the weir. In addition, the outcomes confirmed that the TDS concentration in the downstream was slightly better than that in the upstream weir. That was attributed to the significant DO situation. The observed fluctuations in TDS concentrations are mainly due to hydraulic mixing, the settling and resuspension of particles, and the sensitivity of the sensors in turbulent, aerated flow conditions. The findings highlighted the role of hydraulic structures in decreasing downstream salinity and improving water quality in rivers.

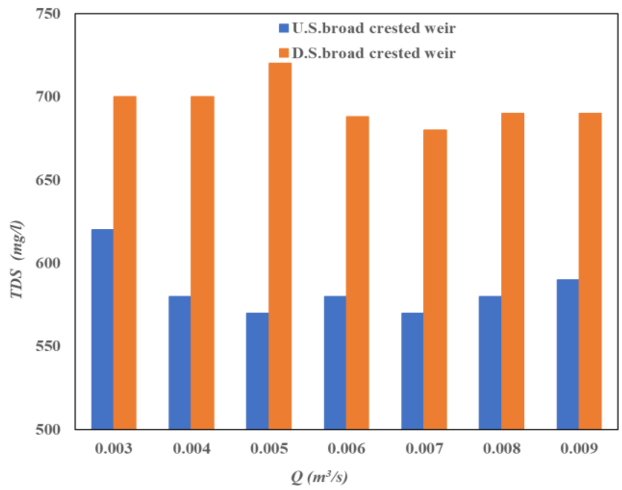

Figure 8. TDS concentrations at both downstream and upstream of a broad-crested weir

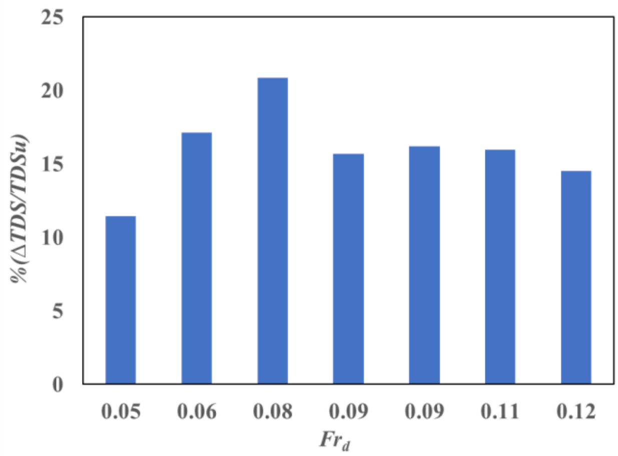

Figure 9. The TDS reduction percentage ($\Delta TDS/TDS_u$ %) between upstream and downstream versus the Fr_d

Figure 9 shows the difference between upstream and downstream TDS (ΔTDS = TDS_u - TDS_d) concentrations plotted against the Fr_d. TDS is an indicator of dissolved mineral and ionic content in water, reflecting salinity and overall chemical composition. Figure 9 showed only minor variations in TDS Reduction Percentage ($\Delta TDS/TDS_u$ %) across the full range of Fr_d. No strong increasing or decreasing trend is evident, and the upstream and downstream values remain relatively close for all flow conditions. These results confirmed that the stability of TDS values before and after the weir does not induce dilution, precipitation, or concentration effects. It demonstrated that while the weir enhances DO, it does not adversely alter the chemical integrity of the water. Therefore, broad-crested weirs can be considered hydraulically safe from a salinity and dissolved solids perspective.

3.4 Concentration of TUR

Figure 10 demonstrates the Q versus TUR for the broad-crested weir at both downstream and upstream locations. The findings of TUR in both downstream and upstream of the weir showed a clear decreasing trend with increasing discharge. The TUR values were consistently lower downstream of the weir, about 8 NTU, compared to upstream, about 9.4 NTU. The percentage of decrease was 17.5%. TUR reduction is attributed primarily to sedimentation and flow deceleration zones downstream of the weir, which are increased by turbulence and mixing. Also, particle flocculation and their collisions due to turbulence may be responsible for the decrease in TUR. The reduction of TUR improves light penetration, which benefits environmental equilibrium and aquatic photosynthesis. Moreover, it demonstrates how the weir can improve the settling and mixing of sediments when water passes over the crest. This behaviour suggests that reducing TUR downstream of the broad-crested weir assists in improving the water quality and clarity.

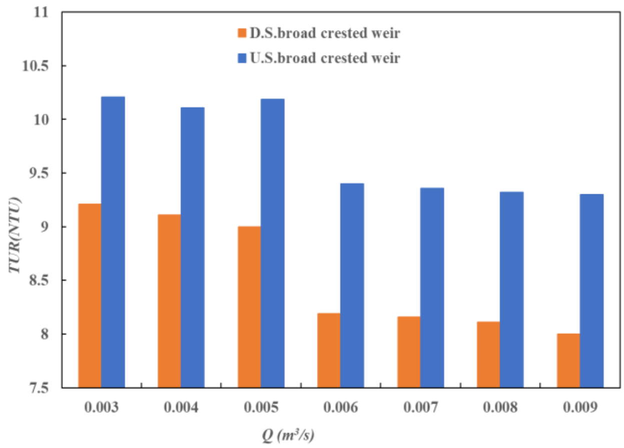

Figure 10. The TUR against the flow rate of a broad-crested weir in both upstream and downstream

Figure 11 shows the difference in TUR ($\Delta TUR = TUR_u - TUR_d$) between upstream and downstream locations as a function of the Fr_d. Turbidity represents the concentration of suspended particles and colloidal matter in water. The results indicated a noticeable increase in turbidity reduction percentage ($\Delta TUR/TUR_u$ %) with increasing Fr_d. At higher Fr, the downstream turbidity tends to be lower than upstream. The decrease in turbidity downstream is attributed to intensified turbulence and higher flow velocities.

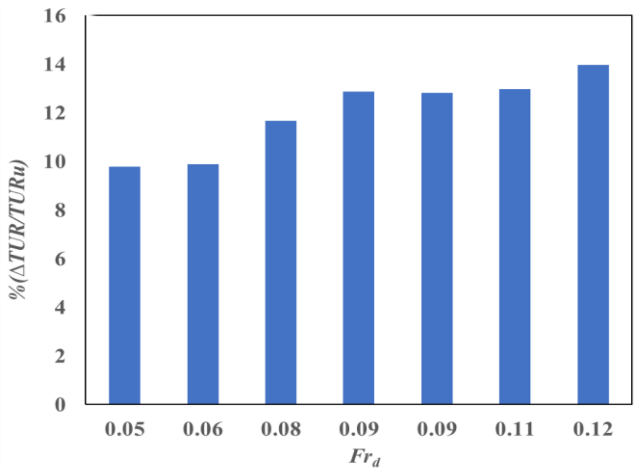

Figure 11. The turbidity reduction percentage ($\Delta TUR/TUR_u$ %) between upstream and downstream broad crested weir against the Fr_d

3.5 Concentration of pH

The concentrations of pH at both test locations, downstream and upstream of the weir, are shown in Figure 12. The findings demonstrated that the pH values were slightly different at both the downstream and upstream sections, remaining within the 7.25–7.30 range. pH values at the upstream location were slightly higher than those at the downstream of the weir, and both positions of the measurement sensors showed a slight increasing trend with discharge. These outcomes suggested that the water remained almost neutral. The results also showed that the broad-crested weir had a minor impact on changing pH values. Generally, pH stability reflects the balance in the chemical environment and has little effect on flow variations.

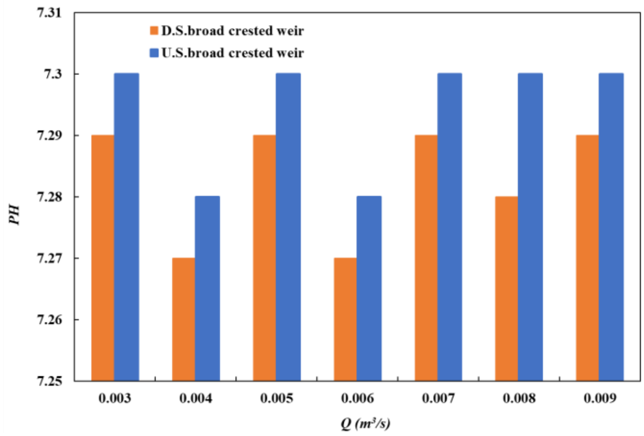

Figure 12. pH values at the downstream and upstream of the broad-crested weir

Figure 13 explains the variation in pH values ($\Delta pH = pH_u - pH_d$) measured upstream and downstream of the broad-crested weir against the Fr_d. The results showed that pH reduction percentage ($\Delta pH/pH_u$ %) was very small in pH across all Fr_d, with no systematic trend of increase or decrease. The upstream and downstream pH values remain nearly identical. The stability of pH across the weir is a positive outcome from an environmental standpoint. It confirms that the broad-crested weir enhances physical water quality (oxygenation) without disturbing chemical equilibrium. This is particularly important in river systems where pH stability is critical for aquatic life and regulatory compliance.

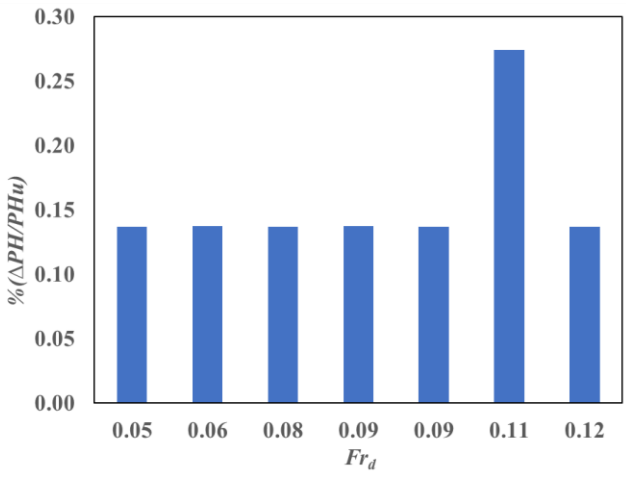

Figure 13. pH reduction percentage ($\Delta pH/pH_u$ %) between upstream and downstream broad crested weir against Fr_d

3.6 Concentration of EC

Figure 14 presents the Q versus EC for the broad-crested weir at the downstream and upstream sections. The findings proved that EC at both upstream and downstream locations changed slightly as discharge increased. Since EC is directly proportional to the concentration of dissolved ions, dilution effects are the cause of the decrease in EC at higher flow rates.

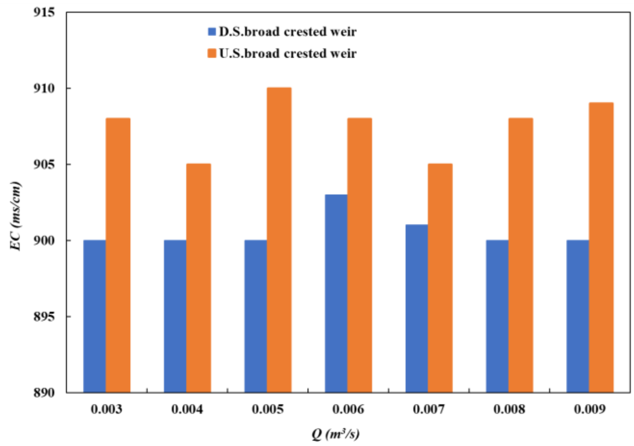

Figure 14. Relationship between Q and EC for the broad-crested weir at upstream and downstream sections

The fact that downstream EC values were slightly lower than upstream values is an intriguing observation. Scouring and localised turbulence may have caused trace amounts of dissolved ions to be released into the water column. The results indicate that EC stayed relatively stable, even though turbulence and reoxygenation may have had an impact on ion distribution. Since EC is estimated from TDS using Eq. (1), the results observed slight variations that closely match TDS trends. Thus, rather than representative ionic disruption or detoxification, the outcomes found that the stability of EC showed a low effect on concentrations of ions. However, these variations remained within acceptable ranges and did not offset the overall improvement in water quality.

Figure 15 illustrates the difference in EC ($\Delta EC = EC_u - EC_d$) between upstream and downstream measurements as a function of Fr_d. EC is closely related to ionic concentration and is directly linked to TDS. Similar to TDS results, the EC difference remains minimal across the entire Fr range. The results showed no clear dependence on hydraulic conditions.

These findings reinforce the conclusion that broad-crested weirs function primarily as physical aeration devices rather than chemical modifiers. The hydraulic energy dissipated at the weir does not alter dissolved ionic content, making such structures suitable for increasing water quality without chemical side effects.

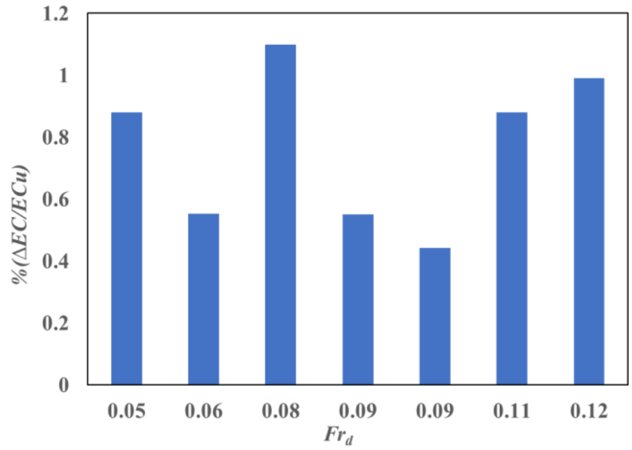

Figure 15. The difference in EC reduction percentage ($\Delta EC/EC_u$ %) between upstream and downstream measurements versus the Fr_d

3.7 Aeration efficiency comparison

Figure 16 explains aeration efficiency against Q. The efficiency of aeration showed a significant correlation with Q in both the present study (laboratory scale and used natural river water) and the previous study conducted by Küçükali (prototype scale and used clean water) [38]. The current examination proved that the aeration efficiency increased as the flow also increased. Turbulence and mixing occurred with increasing discharge. This process improved oxygen transmission at the air–water interface. The results also showed that the current study confirmed that the aeration efficiency was constantly greater than that illustrated by Küçükali [38] for the equivalent flow rate. At a discharge of 0.003 m³/s, aeration efficiency was 4.5% in the present study compared with 3% by Küçükali [38]. While at discharge of 0.009 m³/s, aeration efficiency was 13.8% in the present study compared with 13% by Küçükali [38]. Furthermore, Küçükali [38] confirmed a similar increasing trend, but with lesser values compared to the current investigation. Enhancement of aeration efficiency in the present work is attributed to increased conduction of oxygen by the broad crested weir. The major reason was a change in broad crested weir geometry, nappe trajectory, and tailwater depth, which may have supported turbulence and greater air entrainment, as shown in the current investigation. Moreover, the impact scale between the field-scale and lab-scale produced changes in the amounts of turbulence and bubbles, therefore varying the aeration performance. Differences in the water quality concentration, such as initial DO and water temperature, could have affected the differences in the determined aeration efficiency. In the current study, the nappe flow conditions were more aerated due to a free-falling nappe with increased void formation behind the nappe. This assisted in enhancing oxygen transmission.

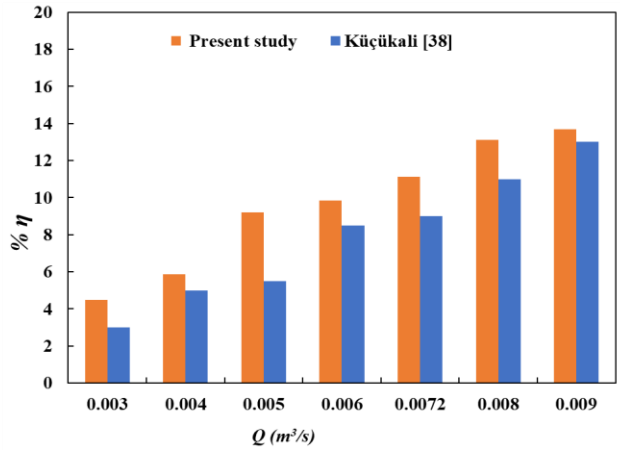

Figure 16. Efficiency of aeration collected data from the current study and compared with the previous study

4. CONCLUSIONS

The current experiments investigated increasing water quality using a broad-crested weir under laboratory conditions. The main conclusions were drawn as follows:

1) DO concentrations in the downstream were more than upstream for the given Q. A maximum enhancement in DO was 12%. Aeration efficiency increased with increasing Q. The maximum efficiency of aeration was 13.69%.
2) TDS slightly increased in the downstream for the given Q. The percentage of reduction was approximately 14.5%.
3) The results of turbidity in both upstream and downstream of the weir showed a clear decreasing trend with increasing Q. The turbidity values were consistently lower downstream of the weir. The percentage of reduction was approximately 17.5%.
4) pH remained stable, both upstream and downstream sections maintained nearly neutral conditions (7.25–7.30) with only minimal change across the Q range.
5) EC decreased overall with Q but was slightly higher just downstream than upstream at each flow. These variations remained within ecologically acceptable limits and did not offset the general improvement in quality.
6) The current study demonstrated that the aeration efficiency increased as the flow also increased. The aeration efficiency was constantly greater than that illustrated by Küçükali [38] for the same discharges. In the high discharge, aeration efficiency was 13% for Küçükali [38], compared to 13.8% in the present study.
7) Practically, the study shows that broad-crested weirs are inexpensive, efficient devices for raising DO levels and lowering the concentrations of pollutants in rivers and channels.

Broad-crested weirs can help restore degraded waterways ecologically and supplement treatment systems. These results, however, are based on carefully monitored flume tests conducted in laboratories. Additional complexity is present in natural rivers, such as the movement of sediments, aquatic life, seasonal fluctuations in flow, and a variety of pollutants that could affect their functionality. Therefore, field-scale monitoring of broad-crested weirs in actual river conditions should be the main focus of future research. assessing how particular pollutants—such as nutrients, heavy metals, and organic contaminants—respond to direct integrated water-quality management. Also, specific future work is proposed for conducting system experiments with different geometric parameters (weir height, crest length, slope); studying scenarios involving sediment-laden water flow or specific pollutants; and conducting field pilot-scale studies.

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