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Al-Qadisiyah Journal for Engineering Sciences

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[†]Research Paper

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Experimental investigation of enhanced NaCl removal using porous broad crested weirs with different alumina-limestone configurations

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ARTICLE INFO

Article history:
Received 04 March 2025
Received in revised form 20 June 2025
Accepted 18 April 2026

keyword:
Porous media
Alumina
Open channel
Limestone
NaCl
Weirs

ABSTRACT

An innovative experimental approach was developed to enhance NaCl removal using porous broad-crested weirs with different alumina-limestone configurations in an open-channel flow under controlled hydraulic conditions. Eight experimental cases were systematically evaluated, examining pure limestone, pure alumina, and mixed arrangements (Al-Ls-Al, Ls-Al-Ls) under two flow rates over 240 minutes. Results demonstrate that pure alumina achieved superior performance with 5.88% average removal efficiency, significantly outperforming pure limestone (2.01-4.27%) and mixed configurations (4.41-5.01%). Limestone exhibited significant hydraulic dependency, with removal efficiency increasing by 112% when flow rate increased from through flow to through flow limit conditions, while alumina demonstrated consistent performance across both flow regimes. All configurations showed initial rapid removal followed by a gradual approach toward equilibrium efficiency, with the most significant removal occurring within the first 10 minutes. Mixed material configurations (Al-Ls-Al and Ls-Al-Ls) achieved removal efficiencies that fell between those of pure materials, indicating no enhancement beyond the individual material properties. The study reveals that while alumina provides optimal NaCl removal, limestone under enhanced flow rates offers economically viable alternatives, achieving 71% of alumina's performance. Porous broad-crested weirs represent promising technology for sustainable water treatment applications.

1. Introduction

Global freshwater shortage continues to deteriorate as population growth, industrial expansion, and climate change intensify the demand for effective water treatment solutions that remain economically feasible [1–4]. It is staggering to consider that approximately two-thirds of countries worldwide face water shortages, leaving over 700 million people without basic access to clean drinking water [5]. Out of the plethora of pollutants found in water sources, elevated concentrations of sodium chloride (NaCl) are associated with particularly challenging environmental and public health effects and require better strategies towards their removal [6–8]. Industrial waste, agricultural effluents, and natural geological processes have resulted in elevated salinity of water sources, posing complex environmental issues in the wake of treatment technologies and strategies [6, 7, 9]. The water must be of a quality that meets the drinking water standards, which is of major concern for public health and the environment [5]. Conventional processes for the desalination of water are effective, but are high-energy intensive and infrastructure dependent, which are not appropriate to be applied in resource-poor settings [10–12]. Researchers and practitioners worldwide want to develop environmentally friendly mine water treatment methods that can adapt to various water characteristics while being technically and economically feasible [13, 14]. Membrane filtration technologies include reverse osmosis (RO), ultrafiltration, microfiltration, and activated carbon filters, each with unique benefits based on treatment goals [15]. Porous media filtration has gained recognition as a promising approach for contaminant removal due to its straightforward implementation, cost-effectiveness, and adaptability to various operating conditions [16, 17]. Activated alumina, produced by treating aluminum hydroxide through dehydroxylation processes, creates an extremely porous material with surface areas exceeding 200 m^2/g. This compound serves dual purposes as both a desiccant and a filter for removing fluoride, arsenic, and selenium from water systems. Recent advances in porous media technology have emphasized optimizing material combinations to enhance treatment performance while reducing operational costs [18, 19]. $La^{3+}-modified$ activated alumina (La-AA) adsorbent has been developed for effective fluoride removal from water, demonstrating improved F^- removal performance [20]. Ozone-treated activated alumina achieved high fluoride removal rates ($> 94\%$) across wide pH ranges (4–8), demonstrating enhanced adsorption capacity [21]. Limestone has been extensively utilized in water treatment applications due to its availability, cost-effectiveness, and natural buffering capacity. Limestone can be an option for sulfate sorption, particularly from neutral mine drainages, because calcium ions on the solid surface can bind sulfate ions [10]. The neutralization process occurs when strong acids, in intimate contact with limestone chips, react with Calcium Carbonate ($CaCO_3$, the primary constituent of limestone) to form water, carbon dioxide, and calcium salts. Activated alumina filters can effectively reduce fluoride levels from 10 ppm to less than 1 ppm, with removal efficiency dependent on contact time, pH levels, and water temperature. Defluoridation of water using activated alumina in the presence of natural organic matter showed that while the presence of NOM and increased pH enhance fluoride adsorption, the initial concentration of fluoride has an adverse effect on efficiency [13]. Simultaneous removal of fluoride, manganese, and iron by manganese oxide-supported activated alumina exhibited 59.4% improved fluoride performance compared to the control [22].

[†]This article is part of a special issue of the 4th International Conference for Civil Engineering Sciences (ICCES-2025), Malaysia.

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https://doi.org/10.30772/qjes.2026.163860.1689

Nomenclature

Al	Interfacial Shear Strength	*pH*	Hot Mix Asphalt
C	Styrene-Butadiene-Styrene	*Re*	Nominal Maximum Aggregate Size
Da	Polylactic Acid	*Greek Symbols*	
Ls	Mean Texture Depth	η	efficiency Area
NOM	Three-Dimensional		

Broad-crested weirs represent a class of hydraulic structures that have found widespread application in water management and flow control systems [23]. A broad-crested weir is a flat-crested structure with a crest length large compared to the flow thickness [24]. The hydraulic characteristics of broad-crested weirs have been extensively studied, with research demonstrating their effectiveness in creating controlled flow conditions [25, 26]. When the crest is "broad,"the flow streamlines are parallel to the crest, and the pressure distribution above the crest is hydrostatic [24]. The broad-crested weir is characterized by insensitivity to tailwater submergence, with the modular limit found practically constant at 75% of the tailwater level [25]. Recent studies have investigated flows over broad-crested weirs of different cross-sectional geometry and their effect on air entrainment rate [23, 26]. Despite the promising potential of porous media systems, significant knowledge gaps remain regarding the optimization of material configurations and hydraulic conditions for specific contaminant removal applications. Limited research has been conducted on the systematic evaluation of different material arrangements, particularly the combination of alumina and limestone in multi-layered configurations within broad-crested weir structures. The integration of porous materials within broad-crested weirs offers a significant environmental benefit by providing preliminary treatment that reduces pollutant loads in river systems before water reaches downstream treatment plants. Even modest reductions in contaminant concentrations can substantially decrease the burden on conventional water treatment facilities, improving their efficiency and reducing operational costs. This approach represents a sustainable strategy for distributed water treatment that can provide cumulative benefits across watershed scales. These objectives are designed to fill the current knowledge gaps in porous media filtration technology and provide a comprehensive understanding of the factors governing NaCl removal efficiency in broad-crested weir systems. This study presents an innovative experimental investigation that systematically evaluates eight different material-flow configurations using a custom-designed flume system, providing new insights into the optimization of porous broad-crested weirs for sustainable water treatment applications. The findings contribute to the development of cost-effective treatment technologies that can be implemented in resource-constrained environments while maintaining acceptable removal efficiencies.

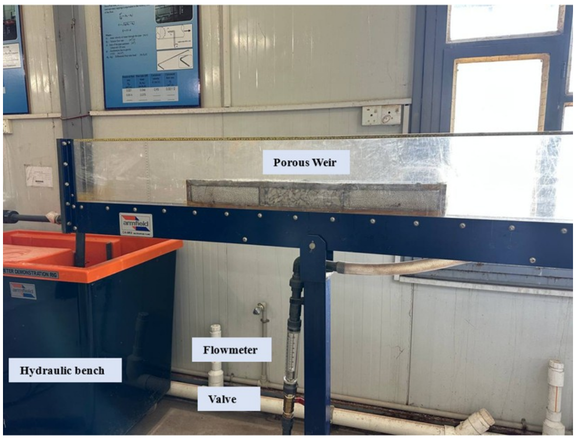

Figure 1. Experimental set-up flume.

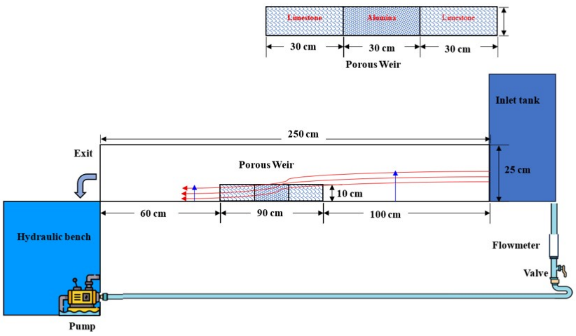

Figure 2. Schematic diagram of experimental setup.

2. Experimental Setup

2.1 Apparatus

The experimental work was conducted in the hydraulic laboratory of the faculty of engineering of Al-Qadisiyah University, where a new flume was designed and built to fit the needs of testing the permeable weir. The experimental flume has a rectangular cross-section, which is 2.5 m in length, 7.5 cm in width and 25 cm in depth, as shown in Fig. 1. The hydraulic system consists of two main storage tanks; a rectangular feeding tank to carry out the initial water preparation and a collection tank to collect the treated water that is of equal storage capacity, which is located besides the flume on the laboratory floor side. Water circulation is circulated by a submersible pump which is rated to discharge flow at their max rate of 2.75 m^3h^{-1} was selected specifically to meet the range of the hydraulic conditions needed in the complete testing of porous weirs [27]. The flume can accommodate flow rates ranging from 0.5 to 2.75 m^3h^{-1} based on pump capacity and hydraulic constraints.) (The two specific flow rates used in the experiments were: through flow conditions ($\leq 1.84\ m^3h^{-1}$) and through flow limit conditions (1.85 m^3h^{-1}). The hydraulic heads maintained during experiments were 12.5 cm for through flow conditions and 13.2 cm for through flow limit conditions, measured upstream of the porous weir. The pump's discharge was calibrated following standard filtration design guidelines to ensure accurate flow rates for effective contaminant removal. Water distribution occurs through a 4-inch diameter pipe equipped with a calibrated flow meter for precise discharge measurements, plus a manually operated valve system that enables flow rate control and adjustment. All experiments were conducted under uniform flow conditions with subcritical flow state (Froude number < 1), which ensures stable hydraulic conditions suitable for treatment evaluation in broad-crested weir applications. The weir construction was separated into three equal 30 cm pieces, allowing for a methodical examination of various material arrangements, as shown in Fig. 2.

2.2 Porous Media Preparation and Characterization

For this investigation, two different forms of porous media were used: limestone and alumina, which were chosen for their complementary filtration qualities and easy availability. Limestone particles had an average diameter of 19 mm while alumina particles had an average diameter of 3.66 mm. These materials were not mono-sized but exhibited narrow size distributions with uniformity coefficients of 1.84 and 1.45, respectively. The particle diameter-to-flume width ratios were approximately 1:4 for limestone and 1:20 for alumina, ensuring adequate flow representation without wall effects. Limestone was chosen because it is abundant in Iraq's western desert region and has high cost-effectiveness, durability, and established water treatment capabilities. The limestone material was thoroughly washed with distilled water before being dried in a controlled oven at 105°C for 24 hours to remove all moisture and produce uniform material qualities. For preservation purposes during the experimental period, the limestone was stored in sealed plastic containers. This storage method should not be confused with gabion construction, which involves wire mesh containers for structural applications. Alumina media was used to improve the treatment system's ability to absorb pollutants and perform pollutant removal. Both materials were tested for particle size distribution, porosity, and chemical content to guarantee uniform experimental conditions throughout all test configurations. The specific surface area and permeability values presented in Table 1 were obtained from previous studies in the literature for similar limestone and alumina materials with comparable particle size distributions and preparation methods [27]. Based on the calculated Reynolds numbers ($Re = 6,806 - 7,656$), flow through both porous media follows Darcian flow conditions ($Re < 10$), indicating a laminar flow regime throughout the experiments. Table 1 provides complete characteristics for both materials used in this experiment. Figure 3 depicts representative samples of the limestone and alumina materials used in this investigation.

Table 1. Material specifications for limestone and alumina used in the experimental study [28, 29].

Property	Limestone	Alumina	Units
Specific Surface Area	20	4.5	$m^2\ g^{-1}$
Bulk Density	1.56	0.87	$g\ cm^{-3}$
Real Density	2.36	1.24	$g\ cm^{-3}$
Porosity	34	30	%
Uniformity Coefficient	1.57	1.25	d_{60}/d_{10}
Permeability	0.36	0.23	$cm\ s^{-1}$

(a) Model 01

(b) Model 02

Figure 3. Sample of limestone and Alumina used.

2.3 Synthetic Water Preparation and Characterization

To imitate real-world saltwater contamination scenarios, synthetic contaminated water was generated with analytical-grade sodium chloride (NaCl). The starting NaCl content was determined using typical amounts from industrial effluent and regional groundwater pollution situations. Stock solutions were produced with distilled water and kept at room temperature to ensure chemical stability throughout the experiment. Water quality indicators such as pH, electrical conductivity, and total dissolved solids were measured and modified to simulate actual contamination conditions [30]. The synthetic water production process ensured equal starting conditions for every experimental run while retaining the chemical constancy essential for precise performance evaluation [28].

2.4 Experimental Matrix and Flow Conditions

The experimental program included eight different test cases to systematically evaluate how porous media configuration interacts with hydraulic flow conditions. The material setups comprised: (1) pure limestone, (2) pure alumina, (3) alumina-limestone-alumina (Al-Ls-Al), and (4) limestone-alumina-limestone (Ls-Al-Ls) arrangements. Each material setup was tested under two hydraulic conditions: through flow ($< 1.84\ m^3h^{-1}$) and through flow limit ($1.85\ m^3h^{-1}$), resulting in a comprehensive 8-case experimental matrix:

- Case 1: Through flow conditions with limestone configuration
- Case 2: Through flow conditions with alumina configuration
- Case 3: Through flow conditions with Al-Ls-Al configuration
- Case 4: Through flow conditions with Ls-Al-Ls configuration
- Case 5: Through flow limit conditions with limestone configuration
- Case 6: Through flow limit conditions with alumina configuration
- Case 7: Through flow limit conditions with Al-Ls-Al configuration
- Case 8: Through flow limit conditions with Ls-Al-Ls configuration

These hydraulic conditions were selected based on preliminary flow studies that identified five distinct flow patterns: through flow, through flow limit, transition flow, overflow limit, and overflow, as illustrated in Fig. 4. The investigation focused on the first two patterns to ensure that contaminated water had sufficient contact time with the porous media, optimizing treatment effectiveness.

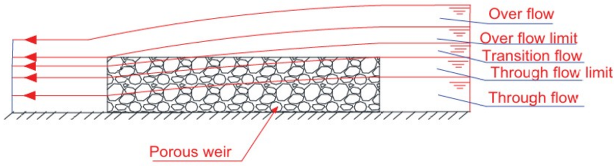

Figure 4. Types of flow through and over porous weir, [28].

2.5 Experimental Procedures and Data Collection

Prior to each experimental run, the porous weir was installed at a distance of 1 m from the flume entrance and filled with the designated material configuration according to the test case specifications. The submersible pump was calibrated and operated at the predetermined discharge rate, with continuous monitoring of flow conditions throughout each 4-hour experimental period. For each test case, 50 L of synthetic contaminated water was prepared in the feeding tank and pumped at constant flow rate through the porous weir system. Water samples were collected at predetermined time intervals: 5, 10, 30, 60, 90, 120, 150, 180, 210, and 240 minutes, providing comprehensive temporal resolution for removal efficiency evaluation. Sampling locations included upstream (initial) and downstream (treated) positions relative to the porous weir to enable accurate performance assessment. Experimental conditions were carefully controlled throughout all test runs, with laboratory temperature maintained between 20°C and 29°C, and pH adjusted to neutral conditions to ensure consistent chemical behavior. Each experimental configuration was replicated to verify result reproducibility and statistical significance. Sodium and chloride concentrations were analyzed using established analytical procedures, with measurements conducted both before and after treatment for each time interval. The analytical methodology ensured precise quantification of both elemental contents, allowing for the computation of overall NaCl removal efficiency. NaCl compound concentrations were calculated using stoichiometric principles that took into consideration the salt compound's 1:1 molar ratio of sodium and chloride ions. The limiting reactant technique was used to precisely depict the maximum NaCl concentration possible from the measured elemental concentrations, resulting in chemically consistent results. Treatment performance was measured using the conventional removal efficiency relationship, Eq. 1.

$$\eta_{Re} = \frac{C_o - C_f}{C_o} \times 100\% \tag{1}$$

where C_o represents the initial NaCl concentration, C_f represents the final (treated) concentration, and η_{Re} represents the removal efficiency percentage. This methodology enables direct comparison of treatment performance across all experimental configurations while maintaining scientific rigor and reproducibility.

3. Results

The experimental investigation evaluated the NaCl removal performance of different porous media configurations under two distinct hydraulic conditions over a 240-minute treatment period. The results demonstrate varying removal efficiencies depending on material composition, arrangement, and flow rate conditions, providing insights into the underlying physical mechanisms governing contaminant removal in porous broad-crested weir systems. Figure 5 illustrates the time-dependent NaCl removal efficiency under through flow conditions ($\leq 1.84\ m^3h^{-1}$). Pure alumina (Case 2) demonstrates superior performance with initial efficiency of 7.2% declining to 4.7% after 240 minutes. The Al-Ls-Al configuration (Case 3) exhibits similar initial performance (7.1%) but shows more rapid decline to 3.1%. The rapid decline in Case 3 efficiency is attributed to the layered configuration creating flow instabilities and potential channeling effects between different material interfaces, where the alternating alumina-limestone-alumina arrangement disrupts uniform flow distribution and reduces contact efficiency over time. Pure limestone (Case 1) consistently shows the poorest performance, with efficiency dropping from 3.1% to 1.2%. The Ls-Al-Ls arrangement (Case 4) maintains intermediate performance between pure materials. This temporal decline indicates breakthrough behavior as active adsorption sites become saturated over time. Figure 6 presents the corresponding performance under through flow limit conditions (1.85 m^3h^{-1}). Notably, pure alumina (Case 6) achieves the highest initial efficiency of 8.8%, though it decreases to 3.9% by the end. The increased flow rate enhances limestone performance significantly, with Case 5 showing 6.6% initial efficiency compared to 3.1% under lower flow conditions. The minimal flow rate increase of 0.54% (from 1.84 to 1.85 m^3/hr) resulted in a remarkable 112% improvement in limestone removal efficiency. This dramatic enhancement is attributed to the grain size distribution characteristics, where larger limestone particles (19 mm diameter) experience significantly improved mass transfer at higher velocities compared to smaller alumina particles (3.66 mm diameter). The increased flow velocity overcomes boundary layer limitations around the larger limestone particles, enhancing ion transport and adsorption processes. This 113% improvement for limestone suggests that mass transfer limitations at lower velocities restrict its effectiveness, while higher flow rates enhance diffusion and convection within the porous structure. Figure 7 summarizes the time-averaged removal efficiencies across all configurations. Pure alumina consistently outperforms other materials, achieving 5.88% efficiency under through flow and 5.68% under flow limit conditions. This superior performance is attributed to alumina's higher specific surface area ($> 200\ m^2/g$) and stronger adsorption affinity for ionic species. Pure limestone shows the greatest sensitivity to flow rate, improving from 2.01% to 4.27% (112% increase) with increased flow velocity. Mixed configurations (Cases 3, 4, 7, 8) demonstrate intermediate performance ranging from 4.41% to 5.01%, indicating that material mixing does not produce synergistic effects but rather averages the individual material properties. Figure 8 displays photographs of water surface profiles through porous weir for different cases, revealing distinct hydraulic behaviors and flow characteristics. Cases 1 and 5 (limestone configurations) show relatively smooth water surfaces with minimal surface disturbances, consistent with limestone's larger particle size (19 mm) creating wider flow channels and lower hydraulic resistance. The uniform flow pattern indicates stable hydraulic conditions with minimal energy dissipation. Cases 2 and 6 (alumina configurations) exhibit more pronounced surface variations and increased turbulence, indicating higher hydraulic resistance due to alumina's smaller particle structure (3.66 mm diameter). This increased resistance creates more complex flow patterns with enhanced mixing, contributing to improved removal efficiency despite potential reduction in residence time. The surface profile differences clearly demonstrate how particle size distribution influences hydraulic behavior and subsequently affects treatment performance.

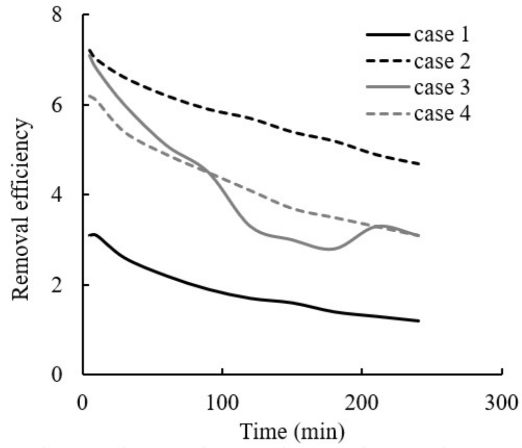

Figure 5. Time variation of NaCl removal efficiency in the case of through flow.

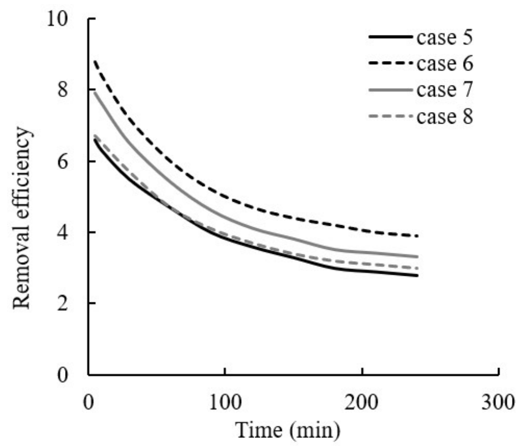

Figure 6. Time variation of NaCl removal efficiency in the case of through flow limit.

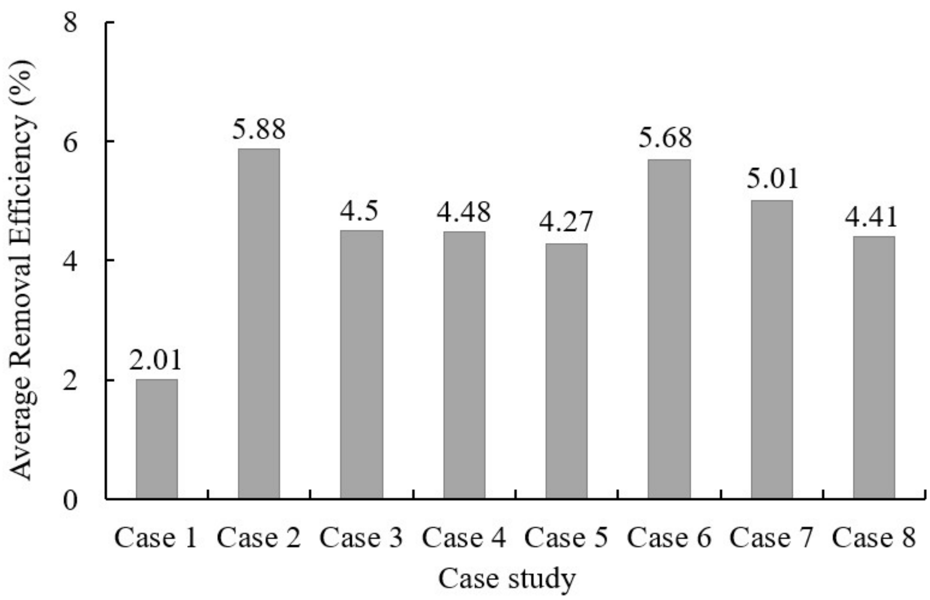

Figure 7. time average removal efficiency for different cases.

(a) Case 01

(b) Case 02

(c) Case 05

(d) Case 06

Figure 8. Photographs of water surface profiles through porous weir for different cases.

4. Conclusions

This experimental investigation successfully evaluated the performance of porous broad-crested weirs with different alumina-limestone configurations for enhanced NaCl removal from contaminated water. The study systematically examined eight test cases under two hydraulic conditions over a 240-minute treatment period, providing comprehensive insights into the effectiveness of various material arrangements.

- Pure alumina consistently achieved the highest NaCl removal efficiency (5.88% average), significantly outperforming pure limestone (2.01-4.27%) and mixed configurations (4.41-5.01%). This superior performance is attributed to alumina's higher specific surface area and enhanced adsorption capacity for ionic species.
- Limestone configurations showed remarkable sensitivity to hydraulic conditions, with removal efficiency improving by 112% under increased flow rates (2.01% to 4.27%), while alumina performance remained relatively stable (5.88% to 5.68%). This limestone enhancement occurs because higher flow rates overcome mass transfer limitations inherent in limestone's larger particle structure 19 mm vs 3.66 mm for alumina. At low velocities, thick boundary layers form around limestone particles, limiting ion transport to active sites. Increased flow causes turbulence that breaks down boundary layers, boosts mixing, and improves convective mass transfer. This allows for improved utilisation of limestone's accessible surface area (12.5 m^2/g) and internal porosity. The increased flow also speeds up chemical activities including ion exchange with calcium ions and $CaCO_3$ buffering reactions by preserving concentration gradients and reducing local saturation near particles.
- All configurations exhibited declining efficiency over time, with initial peak performance occurring within the first 10 minutes followed by gradual decrease due to adsorption site saturation and breakthrough phenomena.
- The Al-Ls-Al and Ls-Al-Ls arrangements demonstrated intermediate performance between pure materials, indicating that material mixing averages rather than enhances individual material properties, with no significant synergistic effects observed.

The study concludes that porous broad-crested weirs represent a promising technology for NaCl removal, with material selection and hydraulic design optimization being critical factors for achieving effective treatment performance. Future research should focus on longer-term performance evaluation, regeneration strategies, and economic optimization to enable practical implementation of these systems in water treatment applications.

Authors' contribution

All authors contributed equally to the preparation of this article.

Declaration of competing interest

The authors declare no conflicts of interest.

Funding source

This study didn't receive any specific funds.

Data availability

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

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How to cite this article:
A. Jabbar, Thulfikar R. Al-Husseini, and Ali H. Ghawi, (2026). 'Experimental investigation of enhanced NaCl removal using porous broad crested weirs with different alumina-limestone configurations', Al-Qadisiyah Journal for Engineering Sciences, 4th International Conference for Civil Engineering Sciences (ICCES), Malaysia, July 2025, Special Issue, pp. 323- 328. https://doi.org/10.30772/qjes.2026.163860.1689