An-Najah University Journal for Research – A
Natural Sciences

Estimation of the Performance of Stilling Basins under Climate Change Conditions: Experimental Study

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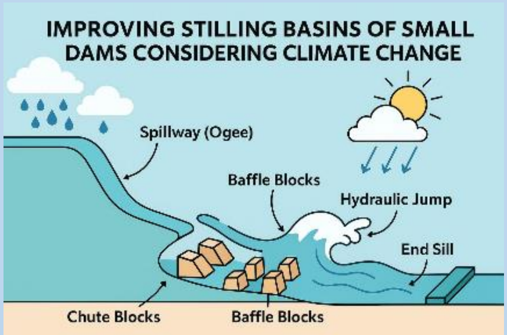
Type: Full Article. Received: 13rd May 2025, Accepted: 11st Oct. 2025. Published: 1st Aug. 2026,
DOI: https://doi.org/10.35552/anujr.a.a2650



Abstract: In recent years, Iraq has experienced climate change that has led to increased drought cycles and prompted authorities to implement small-scale dam projects for water harvesting, particularly in remote areas. These changes have been characterized by irregular and unpredictable rainfall, ranging from heavy downpours to extremely low levels. This has made it difficult to determine effective design specifications for hydraulic structures and has sometimes led to failures in spillways and stilling basins. Flood discharges have also exceeded conventional design limits, reducing the energy dissipation efficiency of these basins and compromising flow safety. This study aims to improve the performance of stilling basins to cope with the increased discharges induced by climate change, through a series of experiments on a physical model of a Type III stilling basin (one of the United States Bureau of Reclamation (USBR) classifications; here defined as a basin with baffle blocks and an end sill designed to produce a strong hydraulic jump) in a small water harvesting dam in Iraq. The study included a standard basin and three modified models, with discharges between 20 and 130 m³/h, exceeding the design discharge of 60 m³/h. The results showed that the energy dissipation efficiency of the standard basin reached approximately 36% at design discharge, decreasing to 26% at higher discharges (a reduction of about 28%). The first modification (redistributing the baffle blocks) did not improve performance, and efficiency remained at 25–26%. The second modification (increasing the block height) increased the efficiency to 41% at design discharge (+14%) but decreased to 27% at higher discharges. The third modification (adding a second row of blocks) was the most effective, with an efficiency of approximately 43% at design discharge (+18%), and maintained over 29% at discharges between 100 and 130 m³/h, with more stable hydraulic performance, making it more suitable for flow conditions under climate change in Iraq.

Keywords: Energy dissipation, Stilling basins, Physical model, Sustainability of hydraulic structures, Climate change.

Introduction

Small dams are of great importance in Iraq. There is a significant trend toward their construction due to the declining water supply from natural resources, namely the Tigris and Euphrates rivers and their tributaries[1][2]. These resources are in constant decline[3]. Therefore, water harvesting projects have become critical in providing water reserves for all sectors[4][5][6]. Among various water harvesting solutions, small dams play a crucial role [7][8] [9][10]. With the growing importance of small dams and the trend toward building such projects, it has become necessary to pay attention to the design of these facilities. As is well known, small dams have not received the same importance as large dams in the past. The focus has been on large dams, and therefore, small dams suffer from a lack of established standards and design guidelines. Consequently, small dams are witnessing far more failures than large dams. The biggest challenge facing small dams today is climate change. Recent years have witnessed severe climate changes, especially in Iraq[11], with significant variations in rainfall[12][13][14]. In recent years, Iraq has witnessed unexpectedly large amounts of rainfall, despite the increase in drought cycles due to climate change, sometimes lasting for more than three years. This situation necessitates comprehensive studies about these effects on the design and operation of small dams, which requires the development of standards and design guidelines for small dams that consider the ongoing climate change to avoid failure and disaster. Many dams have failed in the last two years, which has led to widespread destruction. The Rabat Dam in Sudan collapsed in 2024 due to heavy rains, destroying 20 villages and killing many people. The two dams above the city of Derna in Libya also collapsed in 2023 due to heavy rains, also killing hundreds and destroying the city to a large extent[15]. The Alwa Dam collapsed in 2024 in northeastern Nigeria, causing the death of dozens and the displacement of hundreds, also due to heavy rains[16][17]. One of the most important structures is the stilling basins, which are designed to reduce the flow energy coming from the spillway and prevent erosion or corrosion at the end of the dam. They ensure water reaches the river at an appropriate energy level without causing problems. However, Climate change may render standard stilling basins ineffective. Therefore, the research aims to improve the design of stilling basins so that they are able to adapt to the occurring climate changes, and to be able to handle discharges that exceed the

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design limits, ensuring that no problems or dangers occur to the dam.

Recent decades have witnessed increasing interest in improving the efficiency of stilling basins, particularly in light of the design and hydraulic challenges associated with flow energy dissipation and ensuring stability at the hydraulic jump location. Several studies have focused on modifying conventional designs to achieve more efficient hydraulic performance. In this context, [18] investigated the effect of an in-basin reverse slope; with results showing that this modification enhances energy dissipation efficiency and improves flow stability. Physical and numerical modeling also showed high agreement between the results. In a subsequent study, [19] examined the effectiveness of in-basin vertical barriers in controlling the hydraulic jump location and reducing the basin length by approximately 30%. [20][21] Also investigated modifying the distribution of baffle blocks, with results indicating that this modification reduces flow separation and increases flow stability. A study [22] demonstrated that integrating baffle blocks with inclined angles in spillway design contributes to reducing jump length and outflow velocity. On the other hand, studies [23] and [24] confirmed the effectiveness of numerical modeling in accurately representing flow, which helped reduce reliance on expensive physical models. The results also showed that using stepped dams instead of smooth dams improves flow stability and dissipation efficiency. [25]Studied the effect of the upper slope of dams and concluded that a 60-degree slope achieves the highest energy dissipation efficiency. [26] Also highlighted the importance of determining the optimal Froude number for safer and more efficient design. In a similar vein, [18] also examined the role of modifying the baffles at the inlet and outlet of the basin, demonstrating that these modifications contribute to stabilizing the jump and increasing dissipation efficiency. [27] Demonstrated that a Type II stilling basin (one of the United States Bureau of Reclamation (USBR) classifications; here defined as a basin designed with a horizontal apron and chute blocks to stabilize the hydraulic jump) outperforms a conventional horizontal basin, especially when there are large bed heights, with dissipation efficiency exceeding 88%. [28] Demonstrated that a negative slope at the basin bottom improves hydraulic performance and significantly reduces the jump length. For high discharges and excess energy, several important studies have been devoted to them. For example, [29] tested the performance of the USBR II basin at discharges exceeding the original design limits using physical and numerical modeling. The results confirmed the effectiveness of the proposed modifications in maintaining the basin's efficiency under high hydraulic pressure conditions. [30] Also showed that increased discharges led to partial failure of the conventional basin, but the addition of distributed barrier blocks contributed to an improvement in performance by approximately 20%. Similarly, [31],[32] and [33] demonstrated that geometric modifications to the basin's shape contributed to a reduction in kinetic energy by more than 25% compared to conventional designs. Together, these studies confirm that improving the design of stilling basins has become an urgent necessity to address the challenges resulting from high discharge rates and increased energy, phenomena that are expanding as a result of the effects of climate change. Despite numerous previous studies, most have focused on normal design conditions without taking into account the impact of climate change and increased discharge rates resulting from unexpected hydrological events, which may exceed the design limits and significantly impact the efficiency of stilling basins. This study contributes to addressing this gap by testing some modifications under operating conditions characterized by high variability resulting from climate change, focusing on small water harvesting dams with heights ranging from 12 to 25 meters. This study relies on a physical model that simulates excess discharges and high energy conditions, conditions that have not been adequately studied locally, as most previous models were limited to ideal design conditions. The importance of this research lies in providing realistic experimental data that contributes to improving our understanding of flow behavior and developing conventional basin designs to meet the increasing challenges posed by climate change.

In this context, this study operated a Type III stilling basin (USBR III) at a discharge higher than the design discharge (Q = 1.6 Qd) and tested three modified models under the same operating conditions. These modifications aim to evaluate the energy dissipation efficiency and hydraulic jump stability under unconventional hydraulic conditions that represent the expected future reality of small dams in Iraq.

Function of Stilling Basins

As is well known, stilling basins are used to reduce the flow velocity in hydraulic structures and the high hydraulic energy of water after it exits water structures such as dams and water gates. The design of these basins is based on several standards, the most important of which is the classification of the U.S. Reclamation Authority, which has set numerous standards and developed numerous types of stilling basins based on several factors. Each design is intended for a specific range of conditions.

There are several classifications of slackening basins. The most prominent of these is the US Bureau of Reclamation (USBR) classification. The following is an explanation of them[34]:

USBR Type I: This basin has a flat, horizontal bottom. It must be long enough to contain the hydraulic surge, as it relies on the hydraulic surge to dissipate energy. This basin may sometimes contain an end sill to stabilize the hydraulic surge within the slackening basin. This basin is used when the Froude number is (1.7 < $Fr1$ > 2.5).

USBR Type II: This basin has some accessories to increase turbulence and reduce the basin length by 30%. It is used in high dams where velocities are high ($Fr1$ > 4.5; $v1$ > 18 m/s)

USBR Type III: This basin has attachments (chute blocks, baffle blocks and end sill) that reduce the basin length by 40 to 60%. It is often used in small dams. It is used when velocities are moderate: $Fr1$ > 4.5; $v1$ < 18.3 m/s; q < 18.6 m3/s/m.

USBR Type IV: This basin is used when Froude number is 2.5 to 4.5. It is primarily used for oscillating hydraulic jumps. It contains chute blocks and an end sill. These are the most common types, as there are other types.

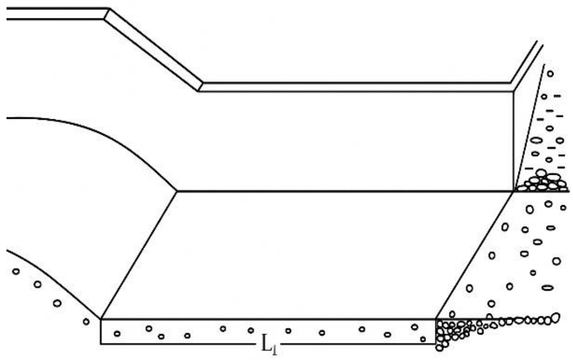

Figure 1(a): USBR Type I basin.

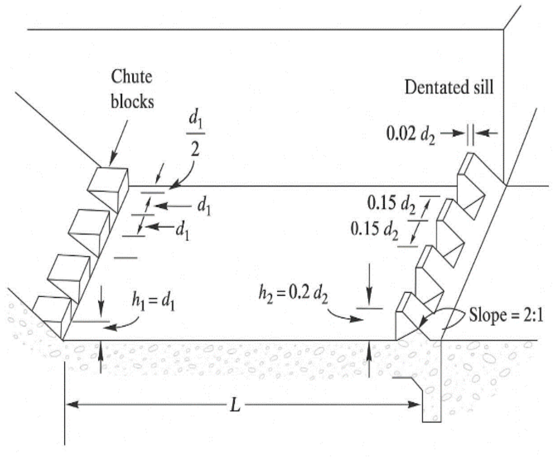

Figure 1(b): USBR Type II basin.

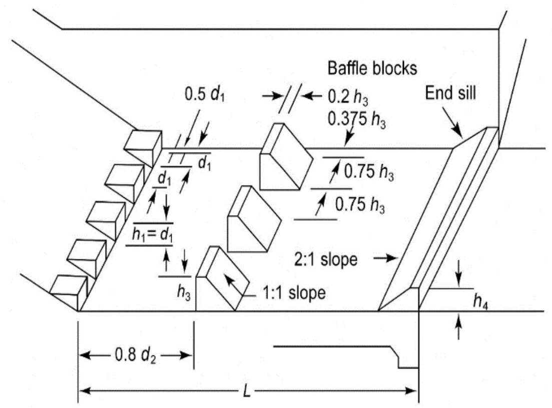

Figure 1(c): USBR Type II basin

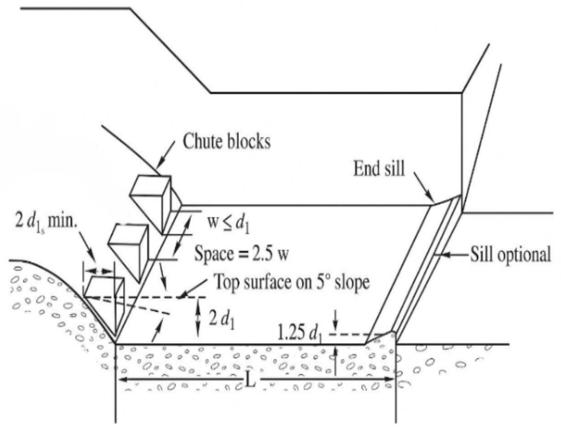

Figure 1(d): USBR Type IV basin.

Governing Equations

Stilling basins are designed based on equations governing hydraulic jump and flow[26], and determining appropriate dimensions, the most important of which are:

The appropriate basin type is selected based on the flow velocity and Froude number[25].

$$Q = A \,.\, v \tag{1}$$

Where Q is a discharge, A is a cross section of water, v is a velocity

$$Fr = \frac{v}{(gy)^{0.5}} \; v \tag{2}$$

where Fr is a dimensionless parameter, v and y are velocity and depth of flow, respectively, and g is the acceleration of gravity.

The characteristics of the hydraulic jump, upon which the stilling basin design depends, are also calculated.

$$\frac{y2}{y1} = \frac{1}{2}\left((1 + 8Fr^2)^{\frac{1}{2}} - 1\right) \tag{3}$$

where $y1$ and $y2$ are the depths before and after the jump. These depths are often called conjugate or sequent depths.

$$yc = \left(\frac{Q^2}{g\,b^2}\right)^{1/3} \tag{4}$$

Where yc critical depth and $Q\,/\,b$, is the discharge per unit width of the channel.

$$Lj = C(y2 - y1) \tag{5}$$

Where Lj is a length of jump and C is a coefficient depend on the type of channel.

Energy loss is also calculated using the following equation.

$$\Delta E = \frac{(y2 - y1)^3}{4\,y1\,y2} \tag{6}$$

Where ΔE is the energy head loss through the hydraulic jump.

Methodology

This study is based on evaluating the performance of a conventional stilling basin under discharges exceeding the design limits, as demonstrated in previous studies such as [30],[28] and [29], which demonstrated the poor efficiency of stander basins under high flow conditions. Based on the results of these evaluations, modifications will be made to the baffle blocks to improve dissipation efficiency and enhance the overall performance of the basin, based on what was reported in studies [20], [22], and [35] which confirmed the effectiveness of this type of modification in improving hydraulic performance.

This laboratory study was conducted in the Hydraulics Laboratory at the College of Engineering, University of Anbar. The purpose of this study was to analyze the efficiency of stilling basins when discharges exceed the design limits. The performance of the stilling basin and the energy dissipation efficiency were evaluated using a physical model of an ogee-type spillway with a height of 33.34 m. The stilling basin was designed below the spillway based on the special design requirements of a dam in the Diyala region of eastern Iraq.

Model Development:

In the current study, to evaluate the extent of variation or oscillation of flow influence resulting from climate change on the hydraulic performance of the stilling basin, a physical model with (1:50) scale was adopted to operate the spillway of dam and stilling basin according to the dimensions of the open channel (17m length, 50cm*50 cm cross section and 60 cm depth) in the Hydraulics Laboratory of the College of Engineering at the University of Anbar, Iraq. The flow cell is connected to the channel entrance to confirm the discharge measurement with a V-notch as in fig (2).

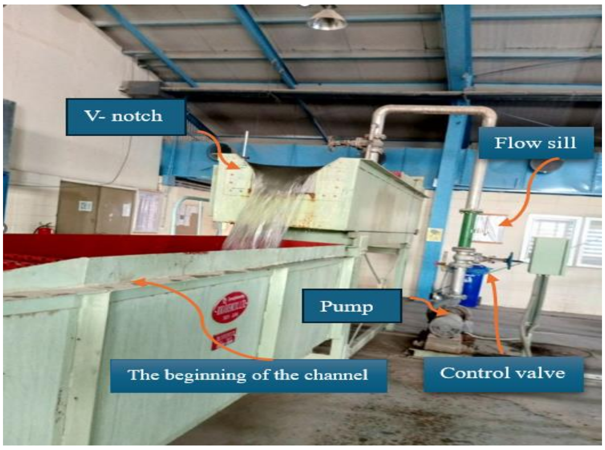

Figure (2): Part of the laboratory channel used for carrying out physical experiments, showing a partial view of the details of the internal structure

Model operation and Experimental Work

The physical model of the dam was operated to determine the hydraulic parameters and to know the type of hydraulic jump and the type of stilling basin by applying the design discharge of the dam, the details of which are shown in Table (2). Through the measurements and design requirements (USBR), the type of stilling basins of (III) type was determined, as shown in Figure (3) and Table (2).

Table (1): Parameters dimensions for spillway (Prototype and model).

Parameters dimensions for spillway	Dimensions of the model (cm)	Dimensions of the prototype (m)
Design head (Hd)	5.8	2.9
Spillway length (L)	50	25
Dam height (P)	33.34	16.67
a = 0.175 Hd	1.015	0.5075
b = 0.282 Hd	1.635	0.8175
r1 = 0.5 Hd	2.9	1.45
r2 = 0.2 Hd	1.16	0.58
Radius of toe (P/4)	10	5
X = 1.096 Hd	6.357	3.18
Y = -0.59 Hd	-3.422	1.71

According to the International Commission on Large Dams (ICOLD)[36], (USBR)[37], and federal emergency management agency (FEMA)[38] the design is based on the Probable Maximum Flood (PMF) discharge, which is equivalent to a recurrence period of 100-500 years. The recurrence period, including the maximum discharge, is determined through several statistical methods, such as (plotting position), which indicates, according to available data, that discharges could reach more than 480 m3/s in the valleys of eastern Iraq (Diyala) where many small dams were constructed, especially with the emergence of the effects of climate change, which caused significant extremes in hydrological events. While many small dams constructed in the region in the seventies and eighties of the twentieth century relied on a recurrence period of 100 years, which corresponds to a design discharge 294 m3/s, based on the data available at the time, which indicates that discharges could increase by 1.6 times with the impact of climate change on Iraq.

The impact of climate change in Iraq, as we mentioned earlier, is represented by the occurrence of significant extremes in hydrological events, such that a drought period may last for three years, followed by years in which very large floods and huge runoff occur. To simulate these floods, the model was run for discharges exceeding the design discharge (Q=1.6 Qd) to determine the extent of the impact of this on the efficiency of the hydraulic performance of the stilling basin and the safety of the structure. The design discharge (Qd) of the basin was adopted at 60 m^3/h, while (Q) denotes the different discharges applied in the experiments, which ranged from (20–130 m^3/h) to covering discharges below and above the design discharge.

A Type III stilling basin was tested in this phase without any modifications to the basin. Tests were conducted and data collected for various flows that exceeded the design flow. Velocity, energy level, dissipation efficiency, and Froude number were measured[10].

Figure (3): Standard model inside the laboratory channel before and during operation.

The First Modified Model

In this case, a modification was made by redistributing the baffle blocks within the basin to study and analyze the effect of their location and distribution on dissipation efficiency and reducing flow energy[39].

Figure (4): The first modified model of redistribution of baffle blocks within the laboratory channel before and during operation.

The Second Modified Model

In this scenario, a modification was made by increasing the height of the baffle blocks only, without changing their location, with the aim of improving basin performance at high flows and increasing dissipation efficiency.

Figure (5): The second modified model with increased height of baffle blocks inside the laboratory channel before and during operation.

The Third Modified Model

In this scenario, a second row of baffle blocks was added within the stabilization basin to examine and compare the impact of multiple obstacles on basin efficiency and flow stability.

Figure (6): The third modified model with a second row of baffle blocks added inside the laboratory channel before and during operation.

Data was collected for each case regarding flow velocity, flow depth, and dissipation efficiency. These cases were then evaluated, compared, and the appropriate modification was determined.

Results and Discussion

The results of the physical model operation of the standard stilling basin (type III) indicate that the basin was inefficient at high discharges (table 2). The basin's efficiency decreased significantly with oscillation or variable rate at high discharges. Also, the Froude number is changed to a lower value, causing the jump type to become an oscillating type. It is recommended to avoid this type of jump because the location of the jump in the basin cannot be estimated accurately. As mentioned before, due to climate change, hydrological events (rainfall and flow rate) have become more extreme, which confirms the possibility of expecting discharges that are significantly higher than the design discharges.

The first modified model (impact block redistribution)

In this scenario, the results indicate the efficiency was lower compared to the standard basin (III basin), especially at high discharges (table 3). There was no significant improvement in hydraulic jump behavior, velocity, or energy dissipation, making it an ineffective option, given its lower performance than the standard basin.

Table (2): The Results of the standard basin III model.

Q (V-notch) (m^3/hr)	Y1 (cm)	V1 (m/s)	Y2 (cm)	V2 (m/s)	Yc (cm)	Fr1	Type of jump	Tail water	η	ΔE (cm)	P (w)
130	3.5	2.06	19.1	0.378	8.1	3.5	Oscillating jump	18.1	21.12	14.2	50.3
100	3.1	1.79	16.5	0.377	6.8	3.25	Oscillating jump	16.3	11.85	11.76	32
80	2.3	1.93	14.6	0.304	5.86	4.06	Oscillating jump	13.9	29.11	13.85	30.2
60	1.9	1.75	12.9	0.258	4.84	5.79	Steady jump	12.7	24.75	13.6	22.2
40	1.2	1.85	10.1	0.22	3.7	5.39	Steady jump	9.7	44.6	14.54	15.8
20	0.6	1.85	7.6	0.146	2.33	5	Steady jump	6.4	57.16	18.8	10.25

Table (3): The Results of the first modified model.

Q (V-notch) (m^3/hr)	Y1 (cm)	V1 (m/s)	Y2 (cm)	V2 (m/s)	Yc (cm)	Fr1	Type of jump	Tail water	η	ΔE (cm)	P (w)
130	3.45	2.1	18.6	0.39	8.1	3.61	Oscillating jump	18.2	26.85	13.55	48
100	2.9	1.916	15.8	0.35	6.8	3.6	Oscillating jump	15.3	26.85	11.7	31.9
80	2.4	1.85	15.1	0.29	5.86	3.8	Oscillating jump	14.2	21.71	14.13	30.8
60	1.9	1.75	12.8	0.26	4.84	4.05	Oscillating jump	12.7	25.14	13.3	21.7
40	1.25	1.78	10.8	0.21	3.7	5.08	Steady jump	10.1	36.78	16.13	17.6
20	0.75	1.48	7.7	0.144	2.33	5.46	Steady jump	6.6	34.45	14.53	07.9

The second modified model (Increased Height of Baffle blocks)

In this scenario, the results showed a significant improvement in efficiency, and high energy was dissipated at high flow rates (table 4). This demonstrates the benefit of modifying the blocks for enhancing flow stability. However, the change in velocity and Froude number at some flow rates indicates that the modification is only of limited benefit.

Table (4): The Results of the second modified model.

Q (V-notch) (m^3/hr)	Y1 (cm)	V1 (m/s)	Y2 (cm)	V2 (m/s)	Yc (cm)	Fr1	Type of jump	Tail water	η	ΔE (cm)	P (w)
130	3.4	2.12	19.2	0.376	8.1	3.68	Oscillating jump	18.2	24.5	15.11	53.5
100	2.8	1.98	16.2	0.343	6.8	3.8	Oscillating jump	15.6	26.5	13.26	36
80	2.3	1.93	14.9	0.298	5.86	4.07	Oscillating jump	14.1	28.01	14.59	31.8
60	1.7	1.96	12.5	0.267	4.84	4.8	Steady jump	11.8	39.6	14.82	24.2
40	1.2	1.852	10.4	0.214	3.7	5.4	Steady jump	9.1	43.06	15..6	17
20	0.6	1.853	7.5	0.148	2.33	7.64	Steady jump	5.9	57.96	18.25	9.95

The third modified model (Addition of a Second Row of Baffle blocks)

This scenario demonstrated excellent performance at higher flow rates and design flow rates (table 5). The results show the basin's ability to dissipate flow energy and reduce velocity after the jump, especially at high flow rates where the jump was steady. The basin demonstrated good efficiency at most flow rates compared to other basins.

Table (5): The Results of the third modified model.

Q (V-notch) (m^3/hr)	Y1 (cm)	V1 (m/s)	Y2 (cm)	V2 (m/s)	Yc (cm)	Fr1	Type of jump	Tail water	η	ΔE (cm)	P (w)
130	3.65	1.98	19.2	0.376	8.1	3.3	Oscillating jump	18.1	15.56	13.4	47.5
100	2.8	1.984	16.2	0.343	6.8	3.8	Oscillating jump	15.5	26.54	13.26	36
80	2.1	2.12	13.9	0.32	5.86	4.66	Steady jump	12.6	42.14	14.07	30.7
60	1.65	2.02	12.5	0.267	4.84	5.02	Steady jump	11.3	42.73	15.48	25.3
40	1.2	1.85	10.3	0.216	3.7	5.4	Steady jump	9.7	43.58	15.24	16.6
20	0.6	1.85	7.6	0.146	2.33	7.64	Steady jump	5.5	57.42	18.8	10.3

The results presented in Tables (2–5) and Figures (7, 8, and 9) indicate that the efficiency of the stilling basin is directly affected by the Froude number and the depth ratio ($y1/y1$). For the standard basin, the maximum efficiency reached approximately 36.7% at the design discharge (60 m³/h), but it decreased to approximately 26% at the discharge (100 m³/h), a decrease of approximately 29%. This illustrates the limitations of the standard basin at high discharges, as the hydraulic jump shifts toward the spillway and the ratio ($y1/y1$) decreases.

In the first modification (baffle blocks redistribution), no significant improvements were recorded, with the efficiency remaining around 25–27% at most discharges, approximately 5–10% lower than the performance of the standard basin, which indicates its hydraulic inefficiency.

The second modification (increasing the blocks height) improved performance at design flow (60 m³/h), increasing efficiency to approximately 42.7% compared to 36.7% for the standard basin, an increase of approximately +16%. However, the decline remained evident at high flows (over 100 m³/h), where efficiency dropped to approximately 28%, limiting its effectiveness under extreme conditions.

The third modification (adding a second row of blocks) demonstrated the best and most stable performance. Efficiency at design flow (60 m³/h) reached approximately 44.6%, a +21% increase compared to the standard basin. More importantly, at high flows (100–130 m³/h), efficiency remained at 29–31%, a +15–20% increase compared to other scenarios. The ratio ($y2/y1$) also increased again when the Froude number exceeded (6), restoring stability to the hydraulic jump within the basin.

Theoretically, this behavior is consistent with the concept of the Froude number, where efficiency increases with increasing velocity up to the limit of (Fr≈5), after which it begins to decline as the jump drifts toward the spillway. However, the third modification succeeded in recalibrating the jump by increasing the hydraulic resistance, which improved energy distribution. Therefore, it can be said that the third modification is most suitable for dealing with extreme discharges resulting from climate change, as it achieves the highest energy dissipation efficiency and maintains the stability of the jump within the basin.

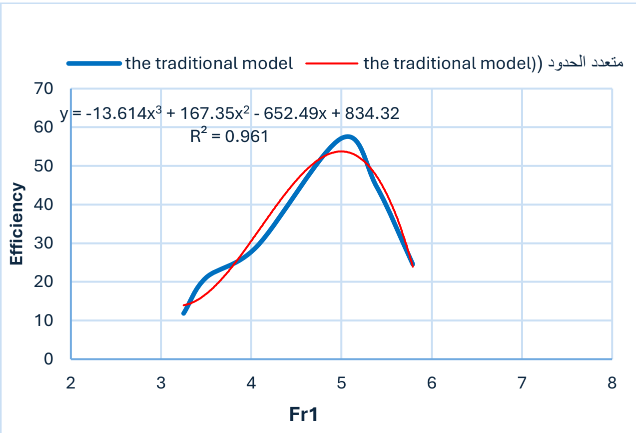

Figure 7 (a): Efficiency – Froude number relation for the traditional model.

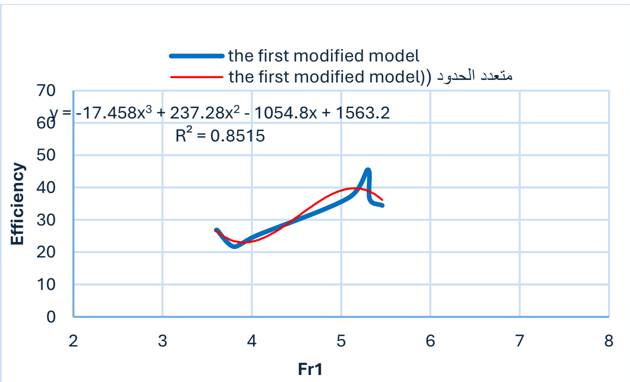

Figure 7 (b): Efficiency – Froude number relation for the first modified model.

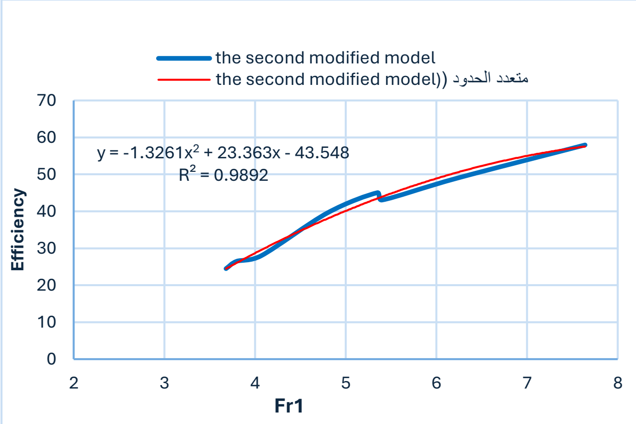

Figure 7 (c): Efficiency – Froude number relation for the first modified model.

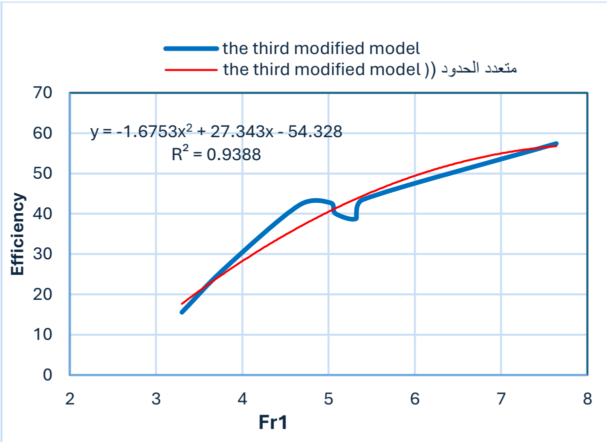

Figure 7 (d): Efficiency – Froude number relation for the first modified model.

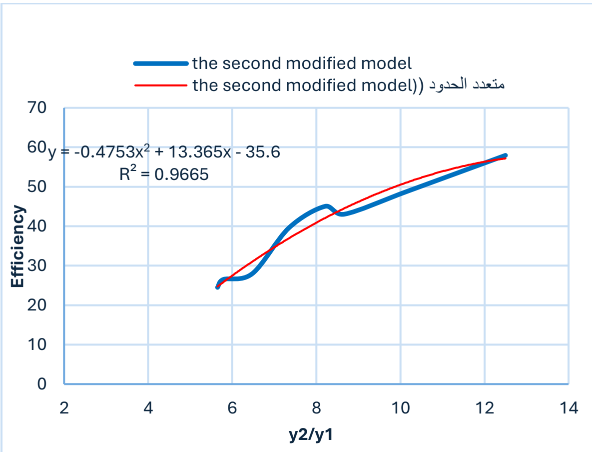

Figure 8 (a): Efficiency – (y2/y1) relation for the traditional model.

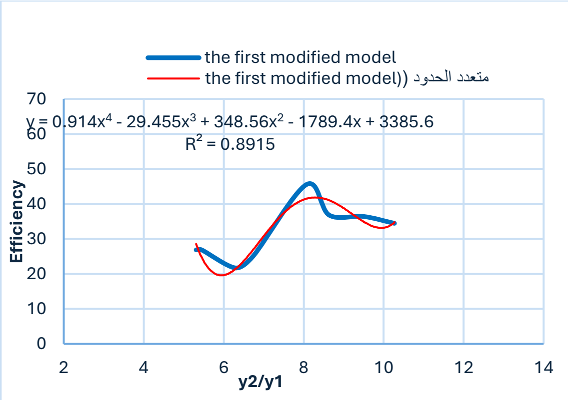

Figure 8 (b): Efficiency – (y2/y1) relation for the first modified model.

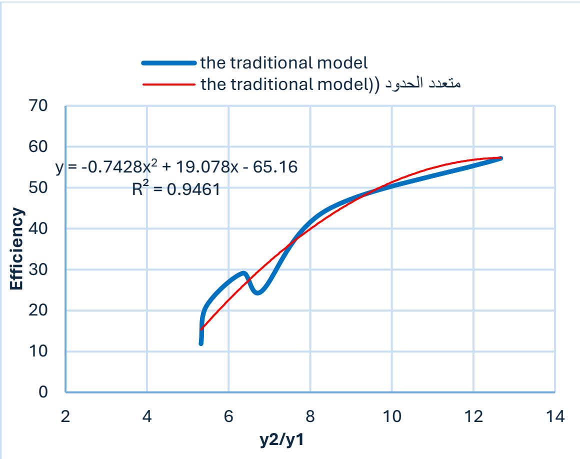

Figure 8 (c): Efficiency – (y2/y1) relation for the second modified model.

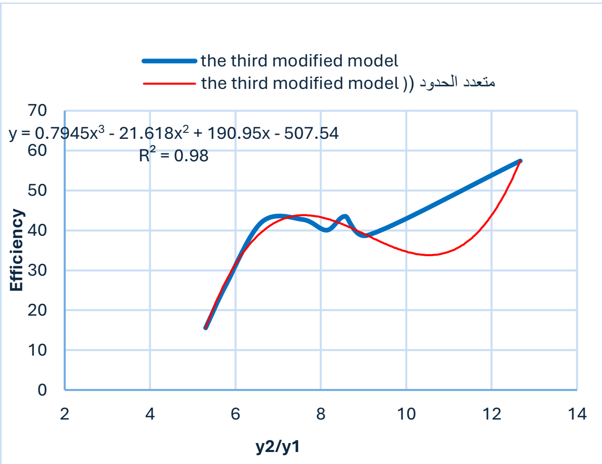

Figure 8 (d): Efficiency – (y2/y1) relation for the third modified model.

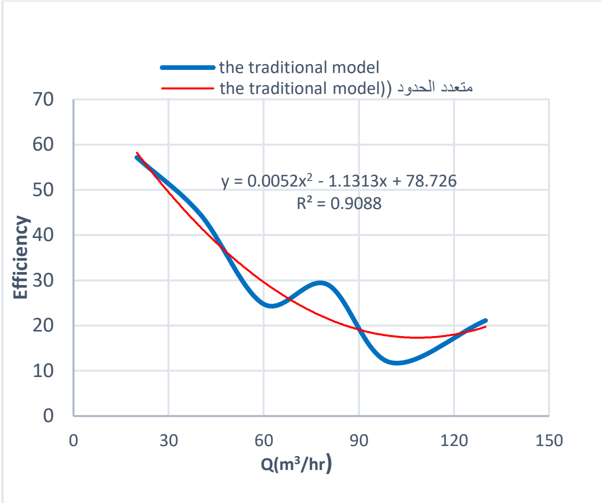

Figure 9 (a): Efficiency – Discharge relation for the traditional model.

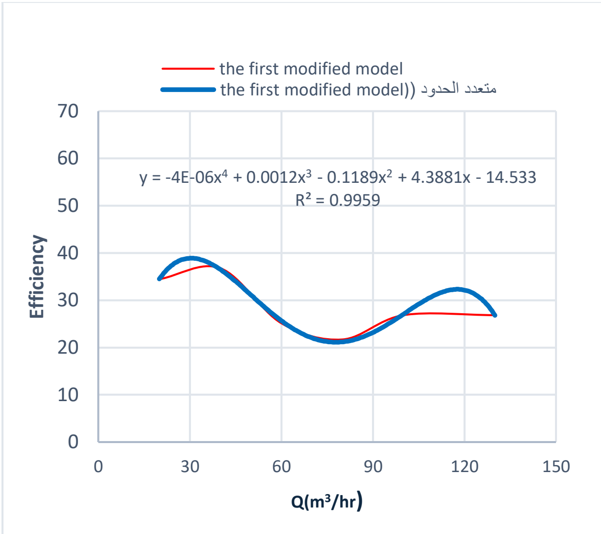

Figure 9 (b): Efficiency – Discharge relation for the first modified model.

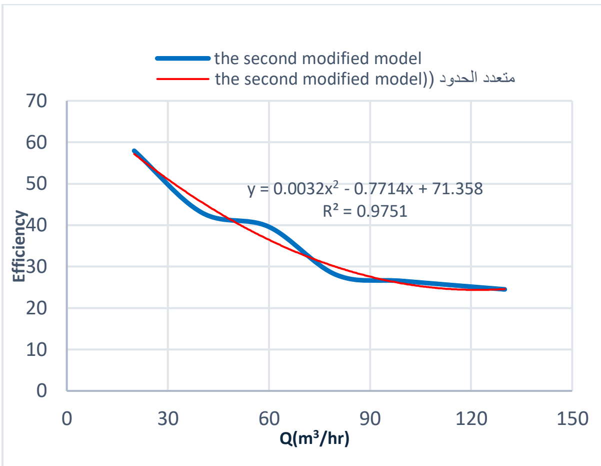

Figure 9 (c): Efficiency – Discharge relation for the second modified model.

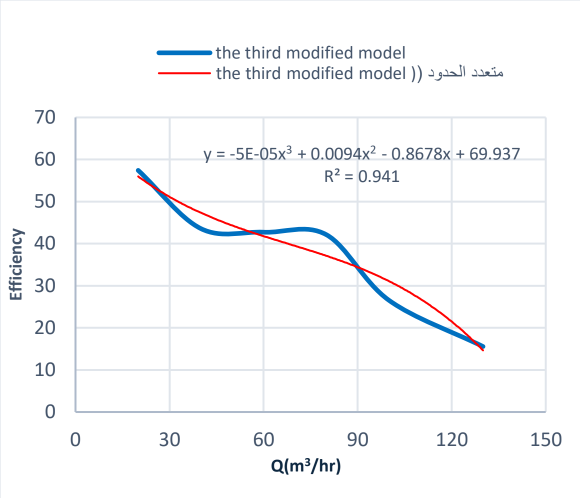

Figure 9 (d): Efficiency – Discharge relation for the third modified model.

Conclusions

The current study demonstrated a set of important indicators that illustrate the behavior of stilling basins under the influence of high discharges resulting from climate change. These indicators can be summarized as follows:

The impact of climate change on the efficiency of stilling basins: The results clearly indicate that extreme hydrological phenomena resulting from climate change—primarily represented by the high and unexpected discharges that hydraulic structures are likely to experience—lead to exceeding the design discharges in many small dams, resulting in poor or declining performance of conventional stilling basins. This is evident when the Froude number ($\boldsymbol{Fr}$) exceeds 5, as the basin efficiency begins to decline as the hydraulic surge shifts toward the spillway.

The relationship between the Froude number and energy dissipation efficiency: Experiments have shown that basin efficiency increases directly as the Froude number increases until it reaches the limit ($\boldsymbol{Fr} \approx 5$), after which it begins to decline sharply. This decrease is attributed to the hydraulic jump shifting toward the spillway area, which reduces the depth ratio ($\boldsymbol{y2/\ y1}$), thus reducing the jump's effectiveness in dissipating energy. This behavior was repeated in the standard basin and in Scenarios 1 and 2, reflecting the efficiency limits of these configurations under supercritical flow conditions.

Outstanding Performance of Scenario 3 Under Severe Flow Conditions: Scenario 3, in which a second row of baffle blocks was added, stands out as the best configuration in terms of overall hydraulic performance. In this configuration, an increase in basin efficiency was recorded once the Froude number exceeded (6), indicating the modified design's ability to reconfigure the jump within the basin, even under severe conditions. This behavior is attributed to increased flow resistance and better energy distribution, which resulted in an improvement in the ratio ($\boldsymbol{y2/\ y1}$) and restored efficiency.

The Role of the Ratio ($\boldsymbol{y2/\ y1}$) as an Indicator of Hydraulic Jump: The study demonstrated that the relationship between efficiency and the ratio ($\boldsymbol{y2/\ y1}$) closely matches the relationship between efficiency and the Froude number. This supports the hypothesis that the ratio ($\boldsymbol{y2/\ y1}$) represents a more accurate indicator for assessing the effectiveness of the hydraulic jump within the basin, especially when flow conditions change.

Hydraulic Jump Location and Instability: Oscillating jumps were recorded within the range $2.5 < \boldsymbol{Fr} < 4.5$, which poses a threat to the basin's efficiency and stability, given the difficulty of accurately determining the jump location within this range. Therefore, it is essential to avoid this range when designing to ensure stable flow within the basin.

Abbreviations

Abbreviation	Full Form
USBR	United States Bureau of Reclamation
ICOLD	International Commission on Large Dams
FEMA	Federal Emergency Management Agency
PMF	Probable Maximum Flood
SWAT	Soil and Water Assessment Tool
GIS	Geographic Information System
AHP	Analytic Hierarchy Process

Symbols

Symbol	Definition	Unit
Q	Discharge	m³/s or m³/hr
Qd	Design Discharge	m³/s or m³/hr
A	Cross-sectional area of flow	m²
v	Velocity	m/s
g	Acceleration due to gravity	9.81 m/s²
y	Flow depth	m
Fr	Froude number (dimensionless)	-
y1	Depth before jump (initial depth)	m
y2	Depth after jump (sequent depth)	m
yc	Critical depth	m
Lj	Length of hydraulic jump	m
ΔE	Energy loss	m (head)
b	Channel width	m
Hd	Design head	m
P	Dam height	m
r1, r2	Radii of spillway curvature	m

Disclosure Statement

- **Ethics approval and consent to participate:** Not applicable.
- **Consent for publication:** Not applicable.
- **Availability of data and materials:** The raw data required to reproduce these findings are available in the body and illustrations of this manuscript.
- **Author's contribution:** First author: Conducted the laboratory work and prepared the research paper. Second author: Proposed the research idea and supervised the work.
- **Funding:** Not applicable.
- **Conflicts of interest:** The authors declare that there is no conflict of interest regarding the publication of this article.
- **Acknowledgements:** The authors would like to express deep gratitude for all the support from the University of Anbar.

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