

Design of a Creager Spillway to Minimize Flooding in a Micro-Basin of the Sabinal River in Tuxtla Gutiérrez, Chiapas, Mexico

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Abstract

This study introduces a design proposal featuring the mitigation of flooding in the 24 de Junio micro-basin. The most flood-prone area is Street Ricardo Flores Magón. The proposed design includes a Creager spillway to minimize flooding in the “24 de Junio” micro-basin of the Sabinal River, located at the following geographical coordinates: 16°45'47" N latitude and 93°05'28" W longitude, in Tuxtla Gutiérrez, Chiapas, Mexico. The primary objective is to intercept sediment, urban debris, rocks, stones, branches, and tree pieces that are transported (by drag force or flotation) within the streamflow (Q). However, to achieve this objective, it is necessary to design a spillway capable of retaining rural and urban debris. This design must be carried out using a specific method, and therefore, a significant portion of this study will focus on the design of a Creager-type spillway using the USBR method. This transport occurs from the upper part of the micro-basin to its discharge point. The discharge point is located at the intersection of Street Ricardo Flores Magón with the elevated North bypass bridge. The General Prosecutor's Office of the State of Chiapas is situated near the discharge point and is adjacent to Rosa del Oriente Street, in the El Bosque Neighborhood of Tuxtla Gutiérrez, which is heavily traveled by people and vehicles. If it rains heavily in SCRS, then Ricardo Flores Magón Street and the zone of the General Prosecutor's Office of the State of Chiapas flood. For a return period (T_r) of 500 years, we estimated Q to be 25.33 m³/s, leading to a flow depth close to 1 meter. So, vehicles could be carried away by the force and velocity of the supercritical flow, posing a risk to individuals in the vicinity. The Creager profile spillway was designed with the USBR method, and its Creager profile is connected to a gabion base to mitigate water erosion during discharge. The upstream face of the Creager profile spillway is vertical ($z = 0$). The design hydraulic head is 0.54 m (H_o).

with a height of 18 m (P) and a width of 35 m (L). The spillway's maximum discharge is 25.33 m³/s (Q_m), associated with a return period (Tr) of 500 years.

Keywords

Open-Channel Flows, Gabion, Creager Profile Spillway, Flooding

1. Introduction

Tuxtla Gutiérrez, Chiapas, México, is situated at coordinates 16°45'17" latitude N and 93°06'15" longitude W. It was founded by the Zoque indigenous people around the V or VI century AD, which predates the arrival of Spanish conquerors such as Luis Marín and Diego de Mazariegos by X or XI centuries [1].

Thus, in the Zoque language, Coyatoc (land of rabbits) was the original name of the Tuxtla Gutiérrez Valley (TG, by its acronym in Spanish), which translates as "tochtli" or Tuxtlan in the ancient language Náhuatl. However, during the XVI century, the Spanish hispanicized it and transformed it into Tuxtla. In 1560, Dominican friars named the TG Valley "San Marcos Evangelista Tuchtla", located on the right bank of the Sabinal River, today known as the historic downtown of the city, where fewer than 100 rural houses once existed.

The TG valley belongs to the Río Sabinal sub-basin (SCRS, by its acronym in Spanish), which has an approximate surface area of 7427.63 hectares [2]. It is essential to note that during the XVI century, the TG valley was a seasonally dry tropical forest and a semi-evergreen midland jungle, replete with autochthonous vegetation. The forest block was not markedly different but richer than the one cited by [3]. The most relevant plants include vascular plants grouped into hundreds of genera and families, ferns, conifers (in the higher parts), hundreds of angiosperms, dicotyledonous and monocotyledonous plants, legumes, asteraceae, poaceae, euphorbiaceae, malvaceae, rubiaceae, acanthaceae, apocynaceae, orchidaceae, and convolvulaceae.

The TG valley also featured hundreds of diverse tree species, shrubs, herbs, epiphytes, and climbing vines. During those centuries, the SCRS had dozens of streams, far more than the 15 official streams accounted for by the National Water Commission (CONAGUA, by its acronym in Spanish) nowadays. These streams had higher concentration times (tc) and lower runoff coefficients (C) than today. The streams originated from the Copoya southern plateau, the north of Cañón del Sumidero, and the west of Loma del Chupadero in the Berriozabal municipality, flowing toward the exit of the SCRS into the Grijalva River. Due to the forest block from those centuries, the floods were better regulated by the SCRS, and the damage to TG was almost negligible. Nevertheless, deforestation began shortly after the founding of TG. It took almost two centuries before the San Marcos municipality was established in 1748. By 1768, the second major municipality was founded in the TG valley, marked by a significant increase in residential construc-

tions. Over those 200 years, the rural populations in the valley expanded, and deforestation processes intensified in the areas adjacent to the Sabinal riverbank. This deforestation was driven not only by housing construction but also by agricultural and livestock activities.

Tree cutting in the valley (large expanses of land) for agricultural and livestock use was carried out using a method inherited from the indigenous people: slash-and-burn agriculture. Almost 50 years later, the Cádiz Courts granted Tuxtla the status of a Villa, and in the XIX century (1829), it was bestowed the rank of a City. During the early 19th century, specifically on February 9th, 1834, the city became the capital of Chiapas. Consequently, by the mid-century, a significant migration to the capital occurred from conurbated rural zones and hundreds of settlements across the Chiapas State, México, in search of a better life. However, this urbanization process generated a footprint that persists to this day.

With the construction of the Angostura Dam (1969-1974) and Chicoasén Dam (1974-1980), Tuxtla Gutiérrez experienced exponential population growth (see Table 2 in [4]). Thousands of workers from Chiapas State and the Mexican Republic changed their residence to Tuxtla Gutiérrez, leading to irreversible changes in its land use and increased deforestation (with the approval of municipal and state authorities). They occupied federal areas of the Sabinal River and its streams (even causing the disappearance of dozens of river channels), disrupting the ecosystems and altering the hydrological cycle during the XVI to XX centuries.

Now, the SCRS has irreversible damage, and one of the most affected areas is the “24 de Junio” micro-basin, where the process has not stopped; on the contrary, it has intensified over the last four decades, causing a substantial decrease in the forest and lowland jungle. The floods occurring result in significant damage to the city [5]. The flow rate in the main channel of the micro-basin is $Q_m = 25.33 \text{ m}^3/\text{s}$, associated with a return period (Tr) of 500 years. During intense rainfall, water rushes down from the mountains of the “Cañón del Sumidero” with supercritical flow on a steep slope ($So = 0.10$). Thus, the National Water Commission [6] recognizes 15 micro-basins (Table 1). The most affected by flooding is the June 24 micro-basin.

Table 1. Micro-basins [7].

#	Micro-basin	Km ²
1	San Francisco	55.81
2	Berriozábal	88.35
3	San Agustín	30.97
4	Chacona	86.62
5	San José el Arenal	5.80
6	Arroyo Centro Sur	19.08

Continued

7	Pomarosa	17.48
8	Potinaspak	30.90
9	San Roque	13.99
10	Totoposte	12.10
11	Poc Poc	6.29
12	24 de junio	7.05
13	Santa Ana	5.06
14	Cerro Hueco	7.71
15	Patria nuevas y otros	19.82
Total		407.00

The exponential population growth in Tuxtla Gutiérrez, Chiapas (see **Table 2**), creates vulnerability for citizens in areas prone to flooding.

Table 2. Population growth and areas [8].

Year	Population	Surface (ha)
1980	196,785	809
2000	494,763	11,385
2010	553,374	12,062
2015	598,710	12,203
2021	604,147	-

2. Background

Due to deforestation and the frequent occurrence of tropical storms, cold waves, heavy precipitation, storm events, and tropical cyclones originating from the Atlantic Ocean, Pacific Ocean, and the Caribbean, the “24 de Junio” micro-basin is consistently exposed to permanent flooding. Additionally, the topography, characterized by elevated slopes, coupled with the absence of adequate infrastructure, such as storm drainage from the city, facilitates sudden flood events. In **Table 3**, we present a summary of the main floods over a 28-year period.

It is worth mentioning that there have been more floods in the “24 de junio” micro-basin and in the Tuxtla Gutiérrez Valley. So, the Civil Protection’s office reported 90 floods of different magnitudes that occurred between 2008, 2009, and 2010, as shown in Annex 13.3 of [8]. In PC’s information, the “24 de Junio” micro-basin floods in each rainy season [4].

Table 3. Floods in Tuxtla Gutiérrez, Chiapas [6].

Year	Event	Damage (rainy season: May-November)
1988	A torrential rain occurred in the northeast area of the SCRS (San Agustín micro-basin).	Flooding occurred in the neighborhoods of Plan de Ayala and Juan Crispín. Seventy-seven houses suffered flooding, causing economic losses, and 370 people were displaced.
1988	A torrential rain occurred in the San Roque micro-basin.	Fourteen houses were damaged, with one being completely destroyed. Seventy people were displaced.
1996	Torrential rains fell in the Santa Ana micro-basin.	The following neighborhoods were flooded: La Gloria, Rincón de los Lagos, Jardines de Tuxtla, El Vergel, Fovissste, San José Terán, El Arenal, and Lum-Ha. 1500 homes were flooded.
1996	A torrential rain occurred in the Potinaspak micro-basin.	The neighborhood Potinaspak was flooded, with over 60 houses affected.
1998	A torrential rain occurred in the Totoposte micro-basin.	The floods swept away cars and resulted in a fatality.
2001	Torrential rains occurred in Tuxtla Gutiérrez city (SCRC). Several streams overflowed.	The following neighborhoods were flooded: Los Pájaros, Bienestar Social, Terán, and Potinaspak. A wall collapsed, and 150 houses suffered severe damage.
2003	On October 6, Tuxtla Gutiérrez was flooded due to Tropical Storm Larry.	This is one of the worst historical floods to occur in Tuxtla Gutiérrez. The maximum precipitation recorded at one of the stations was 225.5 mm per day. Thus, 318 hectares in the Tuxtla Gutiérrez valley were flooded, affecting 49,720 houses.
2010	A torrential rain occurred in the southeast area of Tuxtla Gutiérrez, resulting in floods in various areas of the city.	On August 17th, tropical storm number 23 brought intense and prolonged rainfall to the southwestern part of Chiapas State, and the Plaza Crystal Mall was flooded. Plaza Crystal Mall is a business gallery visited by thousands of locals. On that day, 72.2 mm of precipitation occurred, leading to a flood that affected several neighborhoods in the city and caused significant economic losses.
2016	On September 2nd, intense rains occurred in the southwest area of the Tuxtla Gutiérrez valley.	The San Roque micro-basin was flooded. The force of water collapsed house collapsed [9].

On the other side, in the “24 de junio” micro-basin, houses have been constructed over the streambed, making them extremely vulnerable and dangerous for the families that live there. The street Ricardo Flores Magón is the most dangerous because the runoff is at a high speed and has a high stream flow. Therefore, the stream flow discharge of Ricardo Flores Magón is located right beside the Attorney General’s Office of the Chiapas State in the El Bosque neighborhood in Tuxtla Gutiérrez (see [Figure 1](#)).



Figure 1. Flooding in front of the Attorney General's Office of the Chiapas State [Own work].

3. Materials and Methods

Watershed Simulator. To design a Creager profile spillway using gabions, the area and morphometry of the micro-basin (**Figure 2**) were estimated using the Watershed Simulator (SIATL, by its acronym in Spanish).

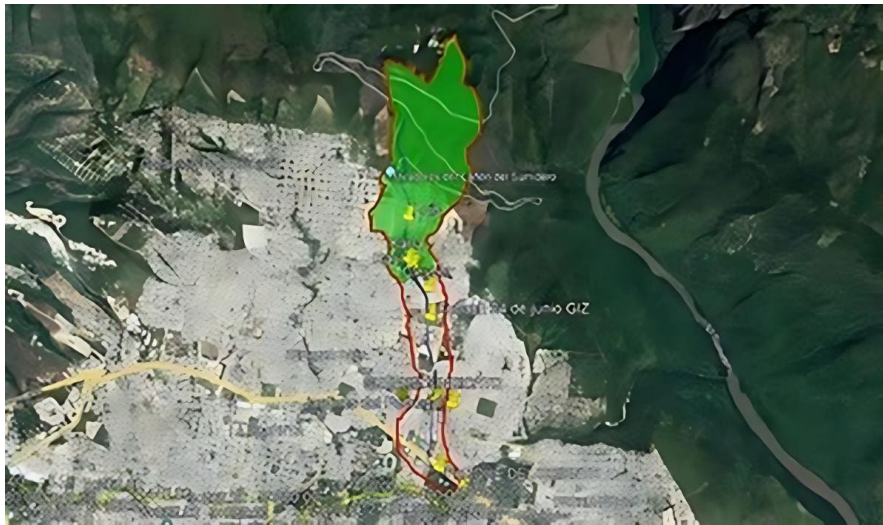


Figure 2. "24 de Junio" micro-basin [Own work].

The topographic of the river was obtained utilizing a model of the area-elevation through a triangulation process of the stream surface using Global Mapper. The slope of the stream was estimated employing the Taylor-Schartz equation, as outlined by [10]:

$$S_0 = \left[\frac{n}{\frac{1}{\sqrt{S_1}} + \frac{1}{\sqrt{S_2}} \pm \dots \frac{1}{\sqrt{S_n}}} \right]^2 \quad (1)$$

where S_0 represents the river slope, n is the number of sections, and S_n is the slope of section n . The maximum runoff of the “24 de Junio” micro-basins was obtained with the following hydrological methods: Chow, Triangular Unit Hydrograph (HUT, by its acronym in Spanish), and Rational Methods with the following return periods: 2, 5, 10, 20, 50, 100, and 500 years. The computed flows for each method are presented in **Table 4**. The Rational Method was calibrated in Mexico by [11]. For this reason, this method was selected. Furthermore, it is widely recommended by [12] and [13]:

$$Q = 0.278CiA \quad (2)$$

where Q is the flow rate in m^3/s , C is the runoff coefficient, i is the rain intensity in mm/h , and A is the micro-basin area in km^2 . This equation is suitable for urban basins. Following the guidelines outlined in the flood control manual [14], we chose the design flow $Q = 25.33 \text{ m}^3/\text{s}$, which corresponds to a Tr of 500 years.

Table 4. Summary of flow rates [Own work].

T (Return period, years)	Q (HUT) (m^3/s)	Q (Chow) (m^3/s)	Q (Rational Method) (m^3/s)
2	5.16	3.85	11.26
5	11.49	8.87	16.57
10	13.14	10.20	17.82
20	14.52	11.31	18.83
50	16.52	12.93	20.26
100	18.37	14.43	21.55
500	23.99	19.00	25.33

We selected a return period of 500 based on **Table 1** and the recommendations of the National Water Commission [14] for urban areas.

Creager-profile spillway. The Creager profile spillway is a hydraulic structure designed to discharge excess stored volume from a reservoir in a controlled manner (using gates) or freely (without gates). **Figure 3** shows a Creager profile spillway. The design equation is [15]:

$$\frac{Y}{H_o} = -k \left(\frac{X}{H_o} \right)^n \quad (3)$$

The Cartesian coordinates Y and X represent the arbitrary coordinates of the Creager profile spillway crest (**Figure 3**), H_o is the design head above the spillway crest, and K and n denote the constants of Equation (3) (**Figure 4**).

Turning radius values R_1 and R_2 from the top of the Creager profile to the intersection with the vertical parapet are derived from **Figure 5**.

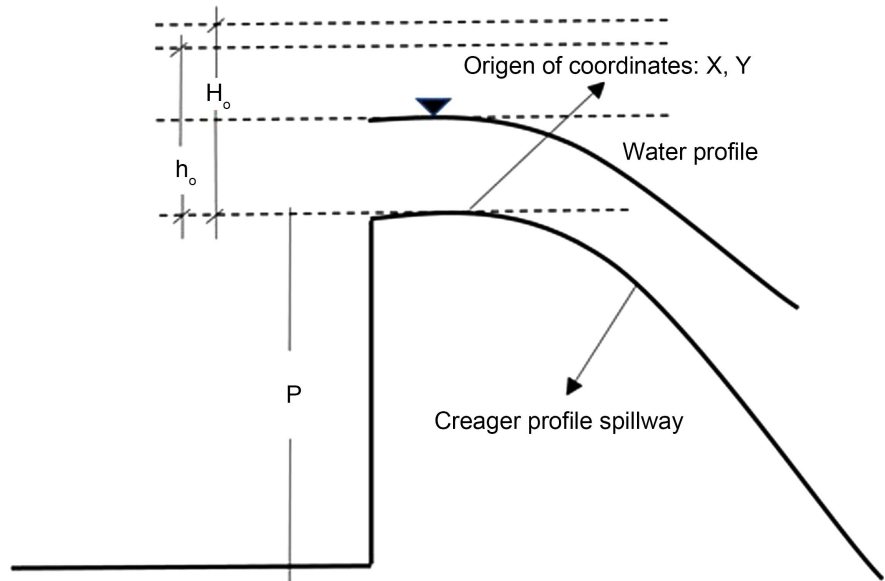


Figure 3. The Creager profile spillway [15].

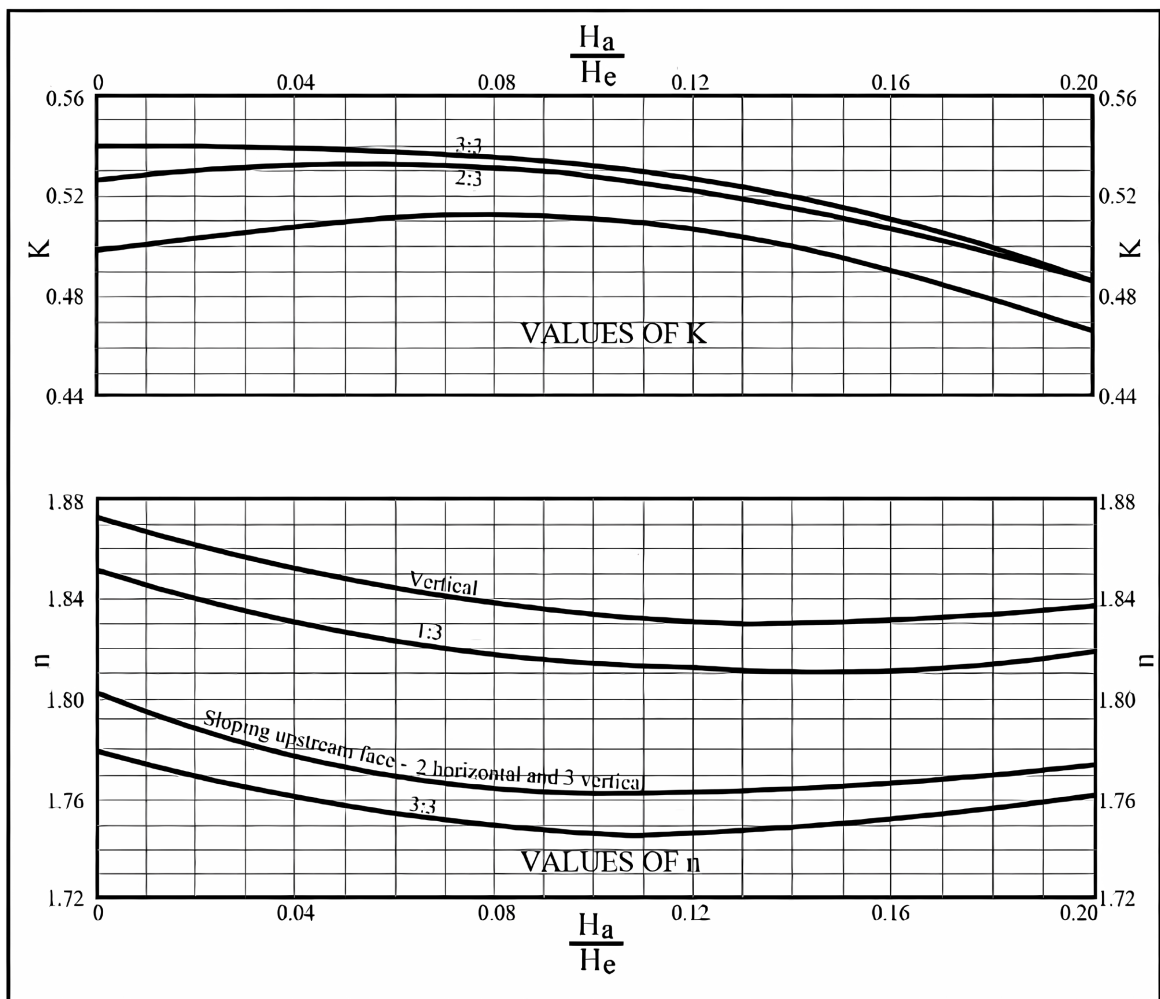


Figure 4. Values of K and n [16].

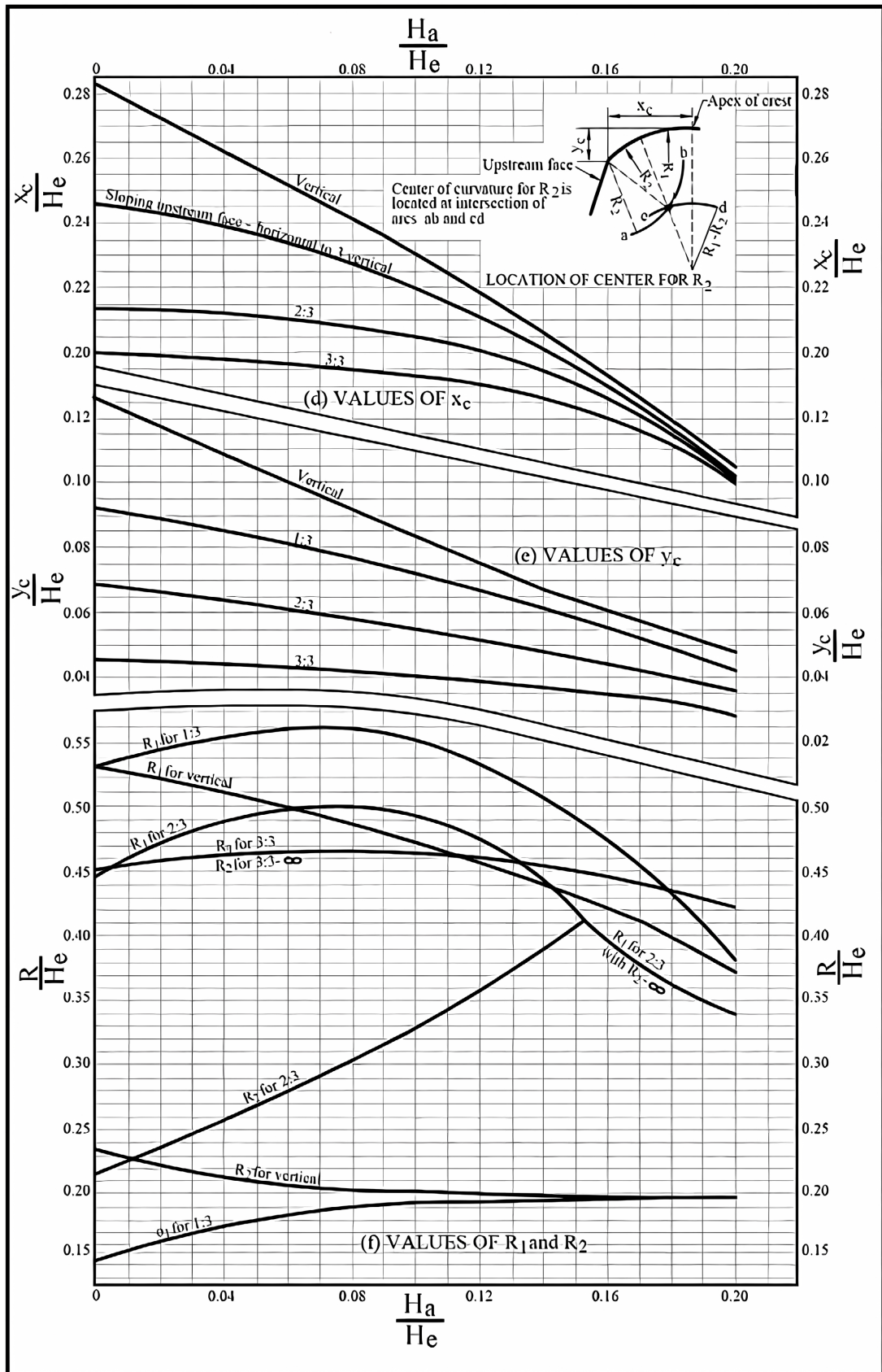


Figure 5. Values of R1 and R2 [16].

To achieve the upper limit of temporary storage and attenuate the peak water flow associated with a return period (Tr) of 500 years, we consider the following design criteria: 1) Estimate the maximum water depth of the access channel based on the topography, 2) Calculate the storage volume of the dam, 3) Propose the head (H_o) over the crest of the Creager spillway, and 4) Minimize the water approach velocity. Thus, HEC-RAS [17] was used to calculate H_o , stream velocity on the Creager profile spillway, and temporary storage volume for $Q = 25.33$ and $Tr = 500$ years. If the value of P is equal to 18 meters and the design head is 0.54, then the approach flow velocity is minimal:

$$\frac{P}{H_o} > 1 \quad (4)$$

To calculate the Creager profile spillway, Equation (3) was utilized, where $K = -0.8557$ and $n = 1.872$ (see Figure 3). Its profile was determined by the following equation:

$$Y = -0.8557X^{1.872} \quad (5)$$

Creager profile length. The effective Creager profile length (L_e) was calculated using the following equation [15]:

$$L_e = \frac{Q}{H_o^{\frac{2}{3}}} \quad (6)$$

Bottom outlet. It was designed with a bottom outlet, that is to say, a rectangular orifice in the bottom of a Creager spillway, to drain the small dam (Figure 6).

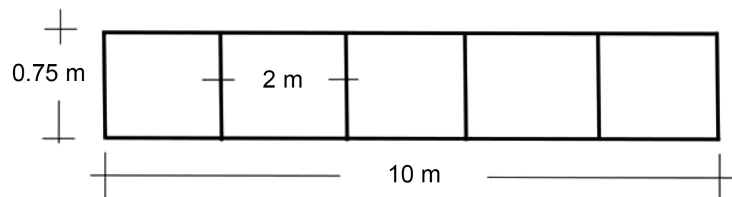


Figure 6. Rectangular bottom outlet (Own work).

To calculate the maximum water flow rate on Ricardo Flores Magón Street, it was simulated using the Manning-Strickler equation [18] with the following data: $n = 0.014$, $S_0 = 0.04$, and a street width of 8 meters. Bottom discharge (Q_f) from the orifice (see Figure 6) was calculated based on the maximum flow rate that would not cause flooding of Ricardo Flores Magón Street. If $S_0 = 0.04$, the maximum flow depth in the street is 0.20 m (which does not exceed the street curb).

Thus, the flow rate result, $Q = 7.5 \text{ m}^3/\text{s}$, will not flood the houses located on Ricardo Flores Magón Street.

$$Q_f = \frac{A_h}{n} R_h^{\frac{2}{3}} S_0^{\frac{1}{2}} \quad (7)$$

This estimation indicates that the maximum hydraulic area of the orifice de-

picted in **Figure 6** can be determined using the following equation [18]:

$$A_f = \left(\frac{Q_f}{C_d \sqrt{2gh}} \right) \quad (8)$$

where $Q_f = 7.5 \text{ m}^3/\text{s}$, $C_d = 0.60$ (discharge coefficient), and $h = 16 \text{ m}$ (hydraulic head over the orifice).

4. Results

The Creager profile spillway profile data can be found in **Table 5** (see Equation (5) and **Figure 3**).

Table 5. Creager profile spillway [Own work].

X	Y
0	0
0.5	-0.24
1	-0.89
1.5	-1.91
2	-3.27
2.5	-4.97
3	-6.99
3.5	-9.33
4	-11.98
4.5	-14.93
5	-18.19

Retention time. **Table 6** depicts the maximum retention times associated with different flow rates in the Creager profile spillway (**Figure 7**).

Table 6. Maximum retention times (MRT) [On work].

Tr (years)	Q (m ³ /s)	MRT (h)
2	11.26	2.20
5	16.57	1.50
10	17.82	1.39
20	18.83	1.32
50	20.26	1.22
100	21.55	1.15
500	25.33	0.98

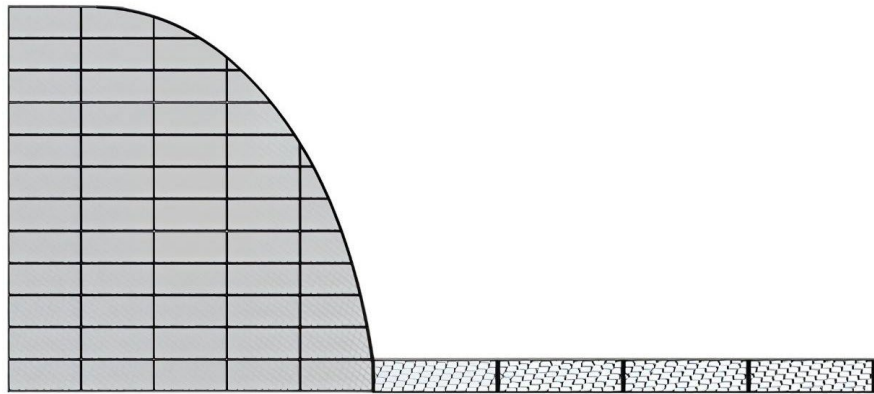


Figure 7. Creager profile spillway [On work].

HDPE geomembrane for the Creager spillway. To prevent issues related to interstitial aeration in the spaces of the gabion of the Creager spillway and to ensure proper operation of the spillway, it must be covered with a 2.5 mm thick high-density polyethylene (HDPE) geomembrane. This geomembrane is suitable due to its high resistance to UV rays. HDPE geomembranes, composed of polyethylene resins, are commonly used for coating channels, reservoirs, dams, and storage ponds.

5. Conclusions

This study presents the design of the Creager spillway using gabions aimed at minimizing and preventing floods in the 24 de Junio micro-basin. The Creager profile spillway is characterized by a vertical parapet with a designed head (H_o) of 0.54 m, a height (P) of 18 meters, and a length of 35 meters. The maximum designed discharge is $25.33 \text{ m}^3/\text{s}$, associated with a return period (T_r) of 500 years. The structure is designed to temporarily retain over 60% of the micro-basin's runoff, equivalent to a total volume of 89231.46 m^3 . The maximum retention time of the volume associated with the designed flow is 1 hour, and the draining time is 3.3 hours. This study is not only about the solution to flood problems in the June 24th micro-basin but also introduces an integral design approach for a Creager profile spillway using gabions.

A Creager spillway was chosen for its stability and uniform flow. If the loading design is correct, it reduces pressure and eliminates vibrations and air displacement in the Creager's profile. Furthermore, its parabolic shape maximizes flow, allowing for energy dissipation and protecting the downstream structure. Additionally, a lower outlet was designed for the Creager spillway, enabling it to retain the full storage volume of the small dam for up to one hour to prevent downstream flooding while discharging a maximum flow rate of $7.5 \text{ m}^3/\text{s}$.

The disadvantage of the Creager spillway is that under extreme flow rate conditions, significantly higher than designed, the flow rate can reach a very high approach velocity along the profile. It can generate negative pressures, increasing the risk of cavitation. Another disadvantage is that the Creager spillway design

and its construction are complex due to its parabolic shape, which requires a high degree of precision to replicate.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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