Revista Facultad de Ingeniería

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DOI: **10.17533/udea.redin.20241251**

To appear in: *Revista Facultad de Ingeniería Universidad de Antioquia*

Received: November 30, 2023
Accepted: December 04, 2024
Available Online: December 09, 2024

Please cite this article as: A. M. Solís-Encarnación and C. Rojas-Serna. Determination of the inflow time of maximum floods in a dam, *Revista Facultad de Ingeniería Universidad de Antioquia*. [Online]. Available: https://www.doi.org/10.17533/udea.redin.20241251

Revista Facultad de Ingeniería, Universidad de Antioquia, No.117, pp. x-xx, xxx-xxx 2025

Determination of the inflow time of maximum floods in a dam

Determinación del tiempo de entrada de avenidas máximas en una presa

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KEYWORDS
Flood routing; maximum floods; inflow time; El Caracol dam
Tránsito de avenidas, avenidas máximas, tiempo de entrada, presa El Caracol

ABSTRACT: A methodology is proposed for the determination of the maximum floods entering a dam based on the analysis of different regression relationships between parameters characterized and identified from the maximum floods of a cascade dam system. It is possible to know the behavior of the inflow time of the maximum floods to a dam, taking as an application case the El Caracol dam in the Balsas river basin in Mexico. The characterization of the hydrographs made it possible to define models that provide advanced knowledge of the maximum flows and the time at which they will enter the dam, thus offering a model for forecasting maximum floods in a dam system.

RESUMEN: Se propone una metodología para el conocimiento de las máximas avenidas que entran a una presa basada en el análisis de diferentes relaciones de regresión entre parámetros caracterizados e identificados a partir de las avenidas máximas de un sistema de presas en cascada. Es posible conocer el comportamiento de los tiempos de entrada de las avenidas máximas a una presa, tomando como caso de aplicación la presa El Caracol en la cuenca del río Balsas en México. La caracterización de los hidrogramas permitió definir modelos que proporcionan con antelación el conocimiento de los caudales máximos y el tiempo en que entrarán a la presa, generando así un modelo de pronóstico de avenidas máximas para un sistema de presas.

1. Introduction

Given the need for methodologies that help understand the rainfall-runoff processes of large basins for the monitoring of hydraulic control works, it is necessary to develop mathematical models that are a practical and timely tool which facilitate the determination of the response of hydrographic units in extreme precipitation events.

Advanced knowledge of the floods that could enter a storage reservoir has different interdisciplinary implications, since the volume of water that enters the dam is decisive in deciding the volume of water that will be allowed to leave the reservoir, i.e., the operation of the dam. For example, the operation of hydropower plants has socioeconomic and environmental implications [1, 2]. The climatic variability in a basin, especially in the face of extreme hydrometeorological phenomena, could imply the decision to rapidly extract water from the reservoir, for which the risk of possible effects on the population and the safety of the dam must be known. [3].

Currently, in Mexico, large dam systems are adequately monitored and controlled. However, the instrumentation is not always effective in crisis situations, since the equipment can suffer damages, failures, or be swept away by the force of the floods. It is here where the knowledge of the "normal" behavior of a river can be a very useful tool to forecast the expected flow associated with the expected rainfall.

Currently, there are different formulations to estimate the expected flow, and specific programs such as HEC-RAS, IBER, MIKE have been developed, which simplify to some extent the analysis of a rainfall-runoff event.

However, these programs have limitations because of their demand for processing time in large basins and because of their information requirements, such as physical parameters and gauging. The results obtained can be very generalized without explaining the hydrometeorological event and its possible effects. For example, the results only indicate the volume of inflow to a dam, or the flow associated with a given event.

In the operation policies of hydraulic structures, such as dams, it is important to take into account the time it will take for the discharge to occur in the storage vessel, as this knowledge increases the safety of the operation and the structure.

Although traditional equations can be used to obtain the inflow time, it is important to verify if they are applicable in the study basin.

This work proposes a practical and useful methodology to determine the characteristics of the flood hydrographs and the time in which they are expected to reach the inlet of a storage basin in the face of hydrometeorological events recorded in the upper part of the basin. The results of the proposed methodology are better than those obtained with traditional theoretical equations.

2. Materials and methods

2.1. Dam system

The dam system is located on the Balsas River in the state of Guerrero, Mexico. The Caracol dam is part of the Infiernillo hydroelectric system, and there are communities such as "Nuevo Poblado del Caracol" and "Tetela del Río", 11 and 18 kilometers downstream, respectively. This makes them points of special attention in the event of any type of risk associated with the dam.

The Federal Electricity Commission of Mexico (FEC) has installed a monitoring network consisting of six hydrometric stations in this system. In this work, the basins were delimited to the coordinate points of five of the hydrometric stations. **Figure 1** shows the hydrometric stations, as well as the confluence points of the most important inputs of this hydrographic unit (red dots on the Balsas riverbed). The sixth hydrometric station located at the dam curtain was used to validate the analysis. Physical parameters were determined for each of the sub-basins, with time of concentration being the parameter of greatest interest.

Table 1 shows the physical characteristics of the sections of the Balsas River defined for this work and shown in **Figure 1**

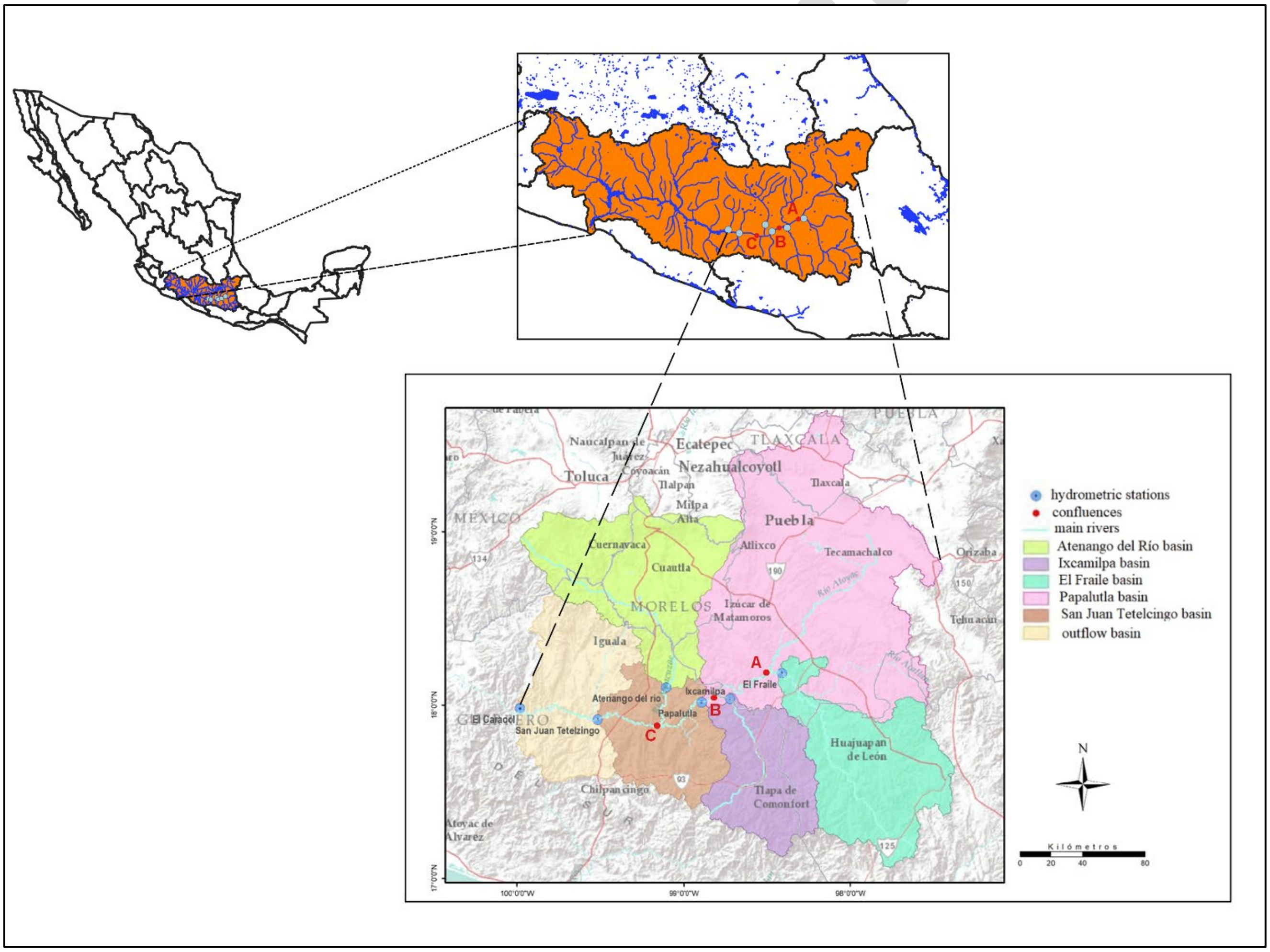


Figure 1. Catchment basin up to El Caracol dam and its hydrometric monitoring network

Table 1. Sections defined for analysis. L and S are the length and slope of the channel, respectively

reach	Inflow	Outflow	L [km]	S [%]
0	Mixteco river	El Fraile station	263	0.33
1	El Fraile station	Site A	22	0.26
2	Site A	Site B	74	0.20
3	Ixcamilpa station	Site B	12	0.38
4	Site B	Papalutla station	12	0.12
6	Balcón del Diablo basin	Site A	137	0.57
7	Amacuzac River	Atenango station	231	0.39
8	Atenango station	Site C	44	0.16
9	Tlapaneco river	Ixcamilpa station	135	0.50
10	Papalutla station	Site C	53	0.13
11	Site C	San Juan Tetelcingo station	57	0.35

2.3 Traditional theoretical equations

2.3.1 Time of concentration

The time of concentration was determined for the reaches defined in **Table 1** and with the formulations developed by various authors. Some of them consider basin shape parameters such as basin area. The empirical formulas used are presented below.

Kirpich [4, 5]

$$\mathrm{t}_c = 0.000325 \frac{L^{0.77}}{S^{0.385}} \tag{1}$$

California Culverts Practice [6]

$$\mathrm{t}_c = 60(\frac{0.87075L^3}{H})^{0.385} \tag{2}$$

Soil Conservation Service (SCS) [7]

$$\mathrm{t}_c = 0.00526L^{0.8}(\frac{1000}{CN} - 9)^{0.7}S^{-0.5} \tag{3}$$

Témez [8]

$$\mathrm{t}_c = 0.3\left(\frac{L}{S^{0.25}}\right)^{0.7} \tag{4}$$

Bransby-Williams [9]

$$\mathrm{t}_c = 14.6LA^{-0.1}S^{-0.2} \tag{5}$$

Valencia & Zuluanga [10]

$$\mathrm{t}_c = 1.7694A^{0.325}L^{-0.096}S^{-0.29} \tag{6}$$

In **Equations** (1), (4) and (6), t_c is expressed in hours, while in (2), (3) and (5) t_c is expressed in minutes. The length of the main channel L for (1) is in meters, in (3) the length of the basin is in feet and for the rest it is in kilometers, H is the slope of the ends of the main channel and is in meters. L_{ca} is the length of the basin centroid at the basin outlet, S is the slope of the main channel, A is the area of the basin in km2 and CN is the curve number that relates the type and use of land in the basin.

Table 2 presents the results of the time of concentration for each of the reaches defined in this work. The average time of concentration $\overline{\mathrm{t}_c}$ was performed considering only the Kirpich, California Culverts Practice and SCS methods.

This is because, as can be seen in the results, for all the sections, the values are closer to each other.

2.3.2 Muskingum method

The Muskingum method is a hydrologic routing method based on the continuity equation [11]:

$$I - O = \frac{dS}{dt} \tag{7}$$

Where for a river reach, I is the inflow, O is the outflow, and dS/dt is the change in storage volume. From Equation (7), Muskingum's equation is written as follows [8]:

$$O_2 = C_0I_2 + C_1I_1 + C_2I_1 \tag{8}$$

Where:

$$C_0 = \frac{-KX+0.5\Delta t}{K-KX+0.5\Delta t} \tag{9}$$

$$C_1 = \frac{KX+0.5\Delta t}{K-KX+0.5\Delta t} \tag{10}$$

$$C_2 = \frac{K-KX+0.5\Delta t}{K-KX+0.5\Delta t} \tag{11}$$

and from the three equations above we get:

$$C_0 + C_1 + C_2 = 1 \tag{12}$$

In these equations Δt is the time interval for the routing period in the reach and has the same units as K (dimension of time), which is known as the storage constant, since it is the ratio of storage to discharge. The constant X represents the ratio of inflows and outflows to the river reach to its storage. K is approximately equal to the travel time of the wave (flood) through the river reach.

2.4 Proposed methodology

2.4.1 Characterization of floods between gauging stations

Hypothesis. The expected floods at a specific river point can be determined from what has been recorded at upstream hydrometric stations. That is, to relate the floods recorded upstream with those recorded downstream. If these relationships are reliable, the amount of water entering a storage reservoir should be related to the information of the floods recorded upstream. In addition, for each recorded flood, the volume of water between stations should be related to the amount of water entering the storage vessel. Therefore, knowledge of the relationship between the characteristics of the floods recorded at the stations should provide knowledge of the expected floods at the inlet of the reservoir.

Application of the case study. With the historical information provided by the FEC, different relations between the records of the hydrometric stations were analyzed. This allowed us to propose and validate a tangible relationship that provides knowledge to differentiate the behavior of flood entry time to the storage basin. The analysis period used for the five stations was defined starting with the station with the shortest period, that is, with the records of the Papalutla station. The first relationship was based on the overlapping analysis of the diagrams of rainfall recorded at the five stations, as well as at other stations located within the basin and managed by CONAGUA. The baseflow of the recorded hydrographs was identified, since it is necessary to distinguish the stormflow from the total runoff. The months in which the rainy season is already declared were also identified, and, therefore, the basin responds immediately in stormflow. Thus, no losses in the edaphological stratum are considered. However, a low correlation was observed between rainfall and recorded runoff, an example presented in **Figure 2.**

3. Results and discussion

Time of concentration. Similar results were found with the Kirpich, California Culverts Practice and SCS equations. This is consistent with the fact that they relate the same parameters.

Table 2. Time of concentration (days) obtained with different empirical equations for the defined reaches for the analysis

reach	Kirpich	Bransby-Williams	Témez	California Culvert Practice	Valencia & Zuluanga	SCS	$\bar{t}_c$
0	1.81	3.41	2.55	1.23	1.09	1.20	1.41
1	0.29	0.48	0.40	0.28	0.31	0.28	0.28
2	0.82	0.94	1.07	0.82	2.05	0.80	0.81

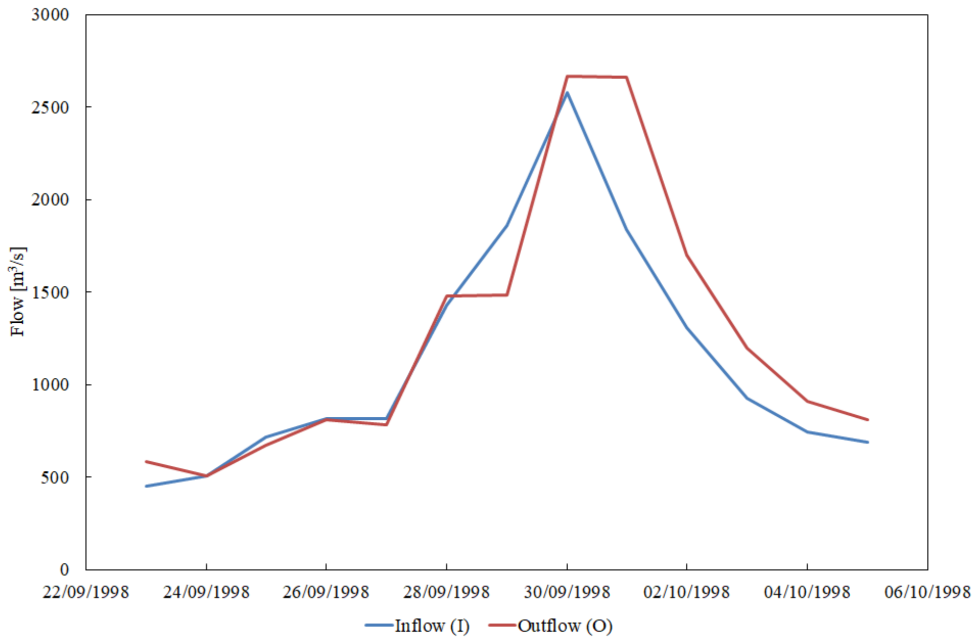
3	0.16	0.23	0.23	0.16	0.31	0.15	0.16
4	0.25	0.31	0.30	0.25	0.40	0.24	0.25
6	1.36	2.49	2.13	0.94	1.31	0.92	1.07
7	1.55	2.86	2.25	1.13	1.10	1.10	1.26
8	0.61	0.85	0.78	0.59	0.71	0.57	0.59
9	0.93	1.68	1.42	0.69	0.90	0.67	0.76
10	0.77	0.94	0.91	0.74	1.14	0.71	0.74
11	0.55	0.84	0.79	0.80	0.79	0.77	0.71

Muskingum Flood Routing. Although this process only indicates the time of the flood wave in the channel, it is very useful to know the characteristics of the cross sections, and thus, their eventual response. **Figure 2**, a) and b) show the maximum flood recorded in 1998 in San Juan Tetelcingo and the results of the X and K parameters, respectively.

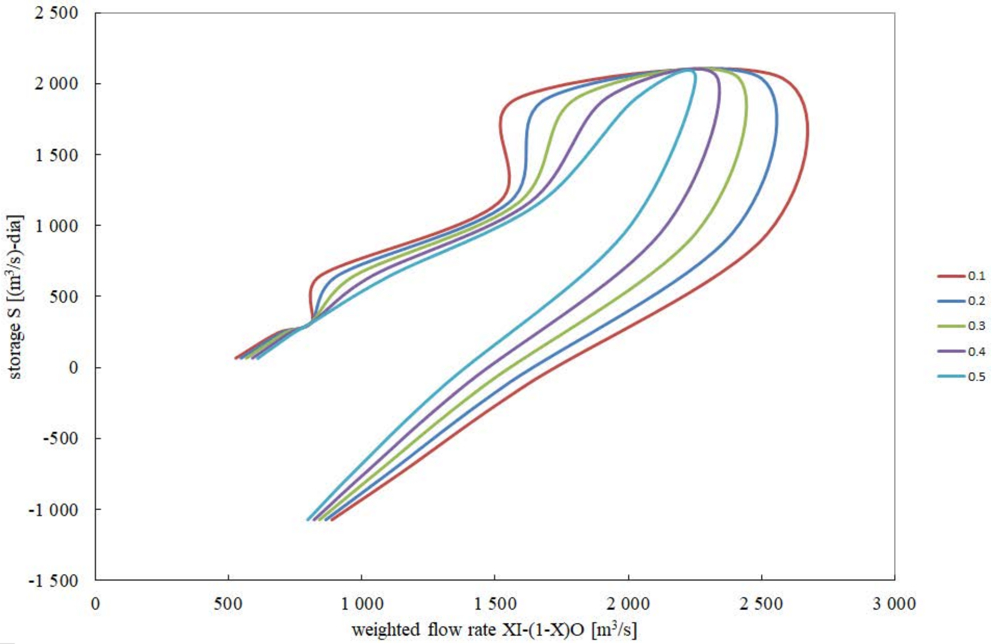
None of the graphs in b) are close to a straight line; they do not even form a "curl", so it was not possible to determine the K value.

With these results, it is observed that this method is not applicable to the study area, since it does not consider other factors that affect the natural response behavior, such as the management that exists within the basin, either by detour unknown systems outflow, small protection works that are not easily identified within the system, regulation zones, etc., in addition to other physical characteristics and magnitude. Therefore, the law of conservation of mass is not fulfilled since this method is based on the continuity equation.

Overlapping rainfall-runoff. In **Figure 3**, the daily rainfall train for the months of September and October, are mostly rainfall sheets of up to 20 millimeters per day. It was also observed that there was no cessation of storms. This conditions the soil to be in a state of saturation during this time window and would indicate an immediate response of the basin to any storm. However, the opposite is shown, since the maximum recorded precipitation does not coincide in time with the maximum recorded discharge. Probably the storm developed in a shorter time interval. It is important to remember that the analyzed outflows are daily average outflows, so hourly behaviors are not visualized.



a) maximum flood recorded in 1988 in San Juan Tetelcingo



b) estimated K and X coefficients for X=0.1, 0.2, 0.3 and 0.4

Figure 2. Search for the values of the K and X coefficients of the Muskingum method

Given the above, it was decided to use regression relationships of the variables involved in the rainfall-runoff processes, considering them as a fundamental part of this work, due to the development of a formulation that allows understanding the intervention of the factors of the rainfall-runoff process. In addition, they can also describe the time in which runoff occurs considering anthropogenic factors.

The most relevant events, due to their magnitude in the period considered and in the stations near the dam, are presented in **Table 3**. It is known, from CFE records, that the maximum instantaneous discharge recorded on September 30 reached 3,232 m³/s, but the behavior of this event around that day is not known; even so, the large difference in water volume between discharges is evident. As shown in **Figure 1**, the Papalutla station is associated with a basin of considerable extension: its records include the runoff processes of the upstream basins, monitored by the Atenango del Río, and El Fraile stations, so only the information from Papalutla was taken. However, there is also a contribution from the Atenango del Río basin, where although the flows are not of the same magnitude as the previous station, it is important to take them into consideration. Having said this, the average records of the Atenango and Papalutla stations were added to find the relationship between San Juan Tetelcingo and these two.

Table 3. Extreme events

Date	Average flow (m^3/s)	
	San Juan Tetelcingo	**Papalutla**
30-Sep-1998	2,664	1,485
28-Sep-1980	1,112	1,076
08-Sep-1984	1,486	942
10-Sep-1999	1,243	942
09-Jul-1991	1,188	876

Important variables in the relationship between two hydrographs were considered: the total duration of the floods (dT), the lag time of peak discharge (Δd), the time to peak discharge (dQ) and the respective records of peak discharge (Q) (**Figure 4**).

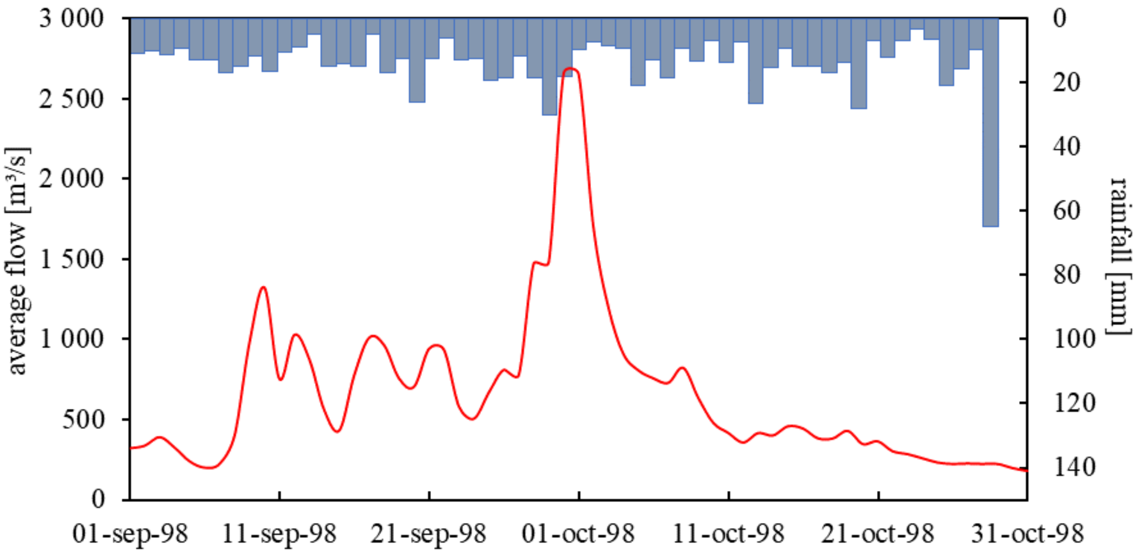


Figure 3. Rainfall-runoff in the San Juan Tetelcingo station

Several regression adjustments were applied to these variables: simple linear, multiple linear and nonlinear. It was observed that the correlation between the linear models did not reach acceptable values, so the relationships retained were those of the nonlinear models.

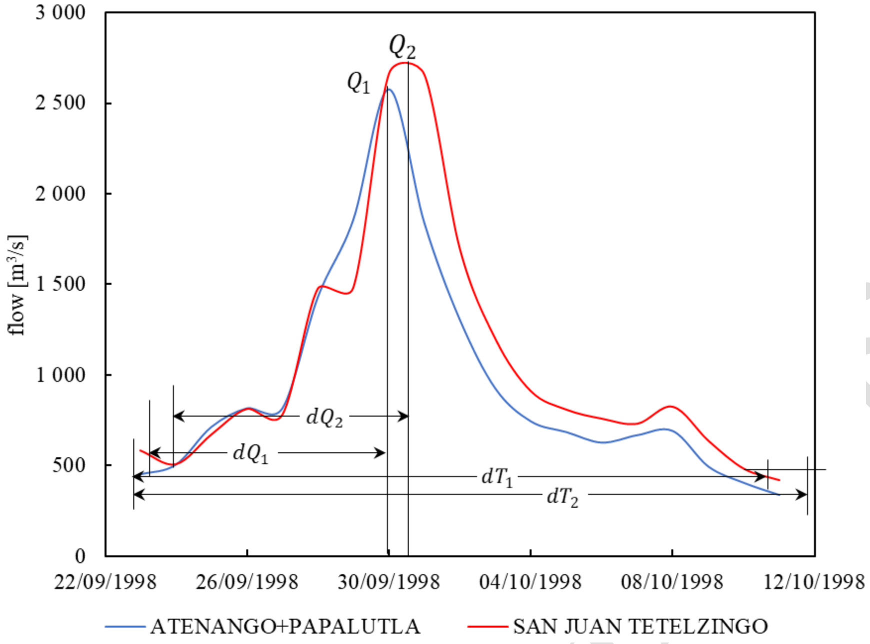


Figure 4. Representation of the variables considered in the development of the regression models

Table 4. Events considered to generate the sample set

1st flood (in 1998): dT1= 8 dT2=6 Δt=1 dQ1=4 dQ2=3 Q1=362 Q2=391								
Date	30-Aug	31-Aug	01-Sep	02-Sep	03-Sep	04-Sep	05-Sep	06-Sep
Atenango+Papalutla	163.3	267.9	198.0	362.0	303.0	222.4	162.8	157.4
San Juan Tetelcingo	209.0	203.0	322.0	338.0	391.0	325.0	240.0	201.0

2nd flood (in 1998): dT1= 4 dT2=4 Δt=1 dQ1=3 dQ2=4 Q1=1220 Q2=1324				
Date	07-Sep	08-Sep	09-Sep	10-Sep
Atenango+Papalutla	223.2	609.0	1220.0	969.0
San Juan Tetelcingo	225.0	401.0	983.0	1324.0

3rd flood (in 1998): dT1= 5 dT2=5 Δt=0 dQ1=1 dQ2=1 Q1=1022 Q2=1030					
Date	11-Sep	12-Sep	13-Sep	14-Sep	15-Sep
Atenango+Papalutla	787.0	1022.0	717.0	420.0	558.0
San Juan Tetelcingo	754.0	1030.0	876.0	558.0	433.0

4th flood (in 1998): dT1= 4 dT2=4 Δt=1 dQ1=1 dQ2=2 Q1=792 Q2=1012				
Date	16-Sep	17-Sep	18-Sep	19-Sep
Atenango+Papalutla	792.0	788.0	950.0	625.0
San Juan Tetelcingo	777.0	1012.0	965.0	757.0

The procedure for obtaining the variables adjusted with the models was based on the selection of the years with the most extreme records, and for each of the events, each of the increases in flow were identified, grouping "small floods" in the event. To better explain the above, see **Figure 4**, where the subscripts identify the upstream and downstream series on the channel. These data are an extract of the events that were considered. **Table 4** shows, as an example, some of the events considered for the development of the models. **Figures 5 to 7** show the models found that describe the relationships between the floods recorded upstream of the basin, which are expected to reach the dam.

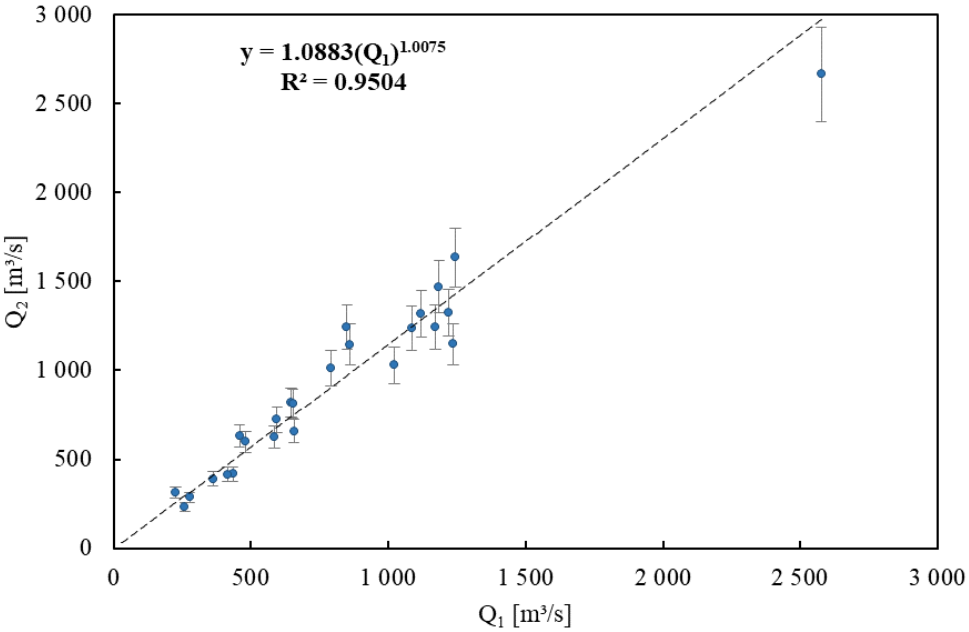


Figure 5. Model that relates the peak discharge of the floods recorded in the upper part of basin Q_1 to the peak discharge at the inlet of storage basin Q_2

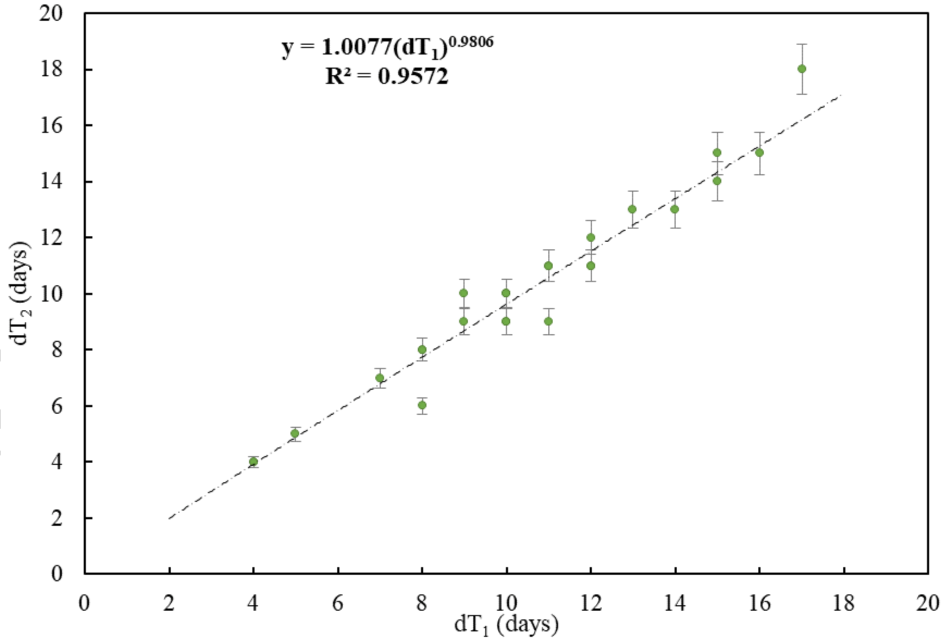


Figure 6. Model that relates the duration time of the floods recorded in the upper part of basin dT_1 with the time the flood would last when entering storage basin dT_2

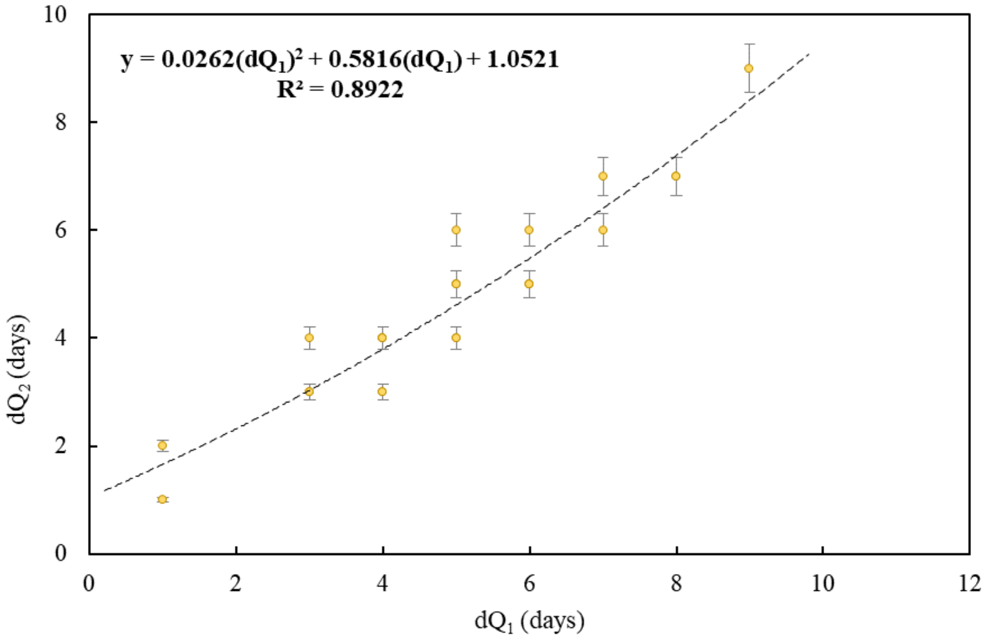


Figure 7. Model that relates the time in which the peak discharge of the floods recorded in the upper part of the basin dQ_1 occurs, with the time in which the peak discharge dQ_2 occurs at the entrance to the storage basin

4. Conclusions

The proposed models provide knowledge to determine the time it takes for floods to reach the storage basin of El Caracol Dam. It is known that the upstream flow relationship usually follows a potential function downstream, regardless of how the storm occurred.

Figure 6 presents the model that relates the duration time of the floods recorded upstream with respect to those downstream, also interpreted as the time of concentration between one station and another. Finally, the most important variable, which is the peak time of the hydrographs, corresponds to a polynomial model, i.e., the time it takes for the peak discharge to occur at the inlet of the basin follows a polynomial function that relates the time of the upstream flood to that of the downstream flood.

Evidently, the results obtained speak in a general way of the behavior of floods throughout the basin, without knowledge of the events that caused them, the physical distribution of the phenomena, or their origin. Nevertheless, these results may lead to new proposals for a detailed analysis of the events that have generated the greatest risk or associated disasters.

Declaration of competing interest

We declare that we have no significant competing interests including financial or non-financial, professional, or personal interests interfering with the full and objective presentation of the work described in this manuscript.

Acknowledgment

We are grateful to the Comisión Federal de Electricidad for the records of the hydrometric stations provided to us.

5. Funding

The authors received no financial support for the research, authorship, and/or publication of this article.

Author contributions

Claudia Rojas-Serna: Conceived and designed the analysis. Ana María Solis-Encarnación: Conducted the study and collected the data. All authors contributed to the analysis of the results.

Data availability statement

The data supporting the results of this work are available with the authorization of the Comisión Federal de Electricidad at https://www.gob.mx/ineel/prensa/red-automatica-de-estaciones-hidroclimatologicas-de-la-cfe

References

[1] J. Andrade & A. Olaya, “Impactos ambientales asociados a las hidroeléctricas en Colombia”, Revista de Investigación Agraria y Ambiental 14(2), 217 – 250, 2023 https://doi.org/10.22490/21456453.6074

[2] O. F. Clavijo-Bernal, “Represando el alto Magdalena: conflicto ambiental por la construcción y operación de la central hidroeléctrica El Quimbo”, Gestión y Ambiente, 24(Supl2), 75–90, 2021. https://doi.org/10.15446/ga.v24nSupl2.94349

[3] G. Tapia G. & G. Beltrán, “Estudio del comportamiento de una presa en tierra durante desembalse rápido. Caso: Presa Mancilla en Colombia”, Geotechnical Engineering in the XXI Century: Lessons learned and future challenges, 1777-1785, 2019. doi:10.3233/STAL190234

[4] Z. P Kirpich, “Time of Concentration of Small Agricultural Watersheds. Civil Engineering”, 10(6): 362, 1940.

[5] F. J. Aparicio-Mijares, *Fundamentos de Hidrología Superficial*, 2nd ed. Noriega Editores, México, 1997.

[6] U.S. Bureau of Reclamation, *Flood Hydrology Studies. Design of Small Dams,* Department of the Interior (29-35), United States, 1987.

[7] Soil Conservation Service SCS, *Urban Hydrology for Small Watersheds,* Tech. Release 55, Washington, DC, 1986.

[8] J.R. Témez, “Extended and improved rational method. Version of the highways administration of Spain”, *In Proc. XXIV Congress*, pp. 33-40, 1991.

[9] M. Wanielista *et al.*, *Hydrology: Water quantity and quality control*, John Wiley and Sons, US, 1997.
[10] C. Valencia and O. Zuluaga, *Estudio preliminar del tiempo de concentración en algunas cuencas de Antioquia*, Trabajo de grado, Universidad Nacional de Colombia, Medellín, Colombia, 1981.
[11] V.T. Chow *et al.*, *Hidrología aplicada*, McGraw-Hill, Santafé de Bogotá, Colombia, 1994.