RESEARCH PAPER

Hydrodynamic Modeling of the Mamón de Leche Stream for Flood Risk Analysis in Valledupar

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ABSTRACT

This project consisted of establishing the risk of flooding in a section of the Mamón de Leche stream (AML) through hydrological and hydraulic modeling in runoff scenarios, delimiting the basin from a general, environmental and urban context, in which all morphometric parameters were characterized and historical precipitation records were analyzed from 1993 to 2023. From these data, hyetograms were generated using the alternating block method and peak flows were calculated with the SCS model in HEC-HMS and the hydraulic scenarios in HEC-RAS for a return period of 100 years and AMC II and III conditions. Based on IDEAM's FEMA methodology, a hazard map was developed in ArcGIS Pro software. The results identified that the final stretch of the AML that is located in the Fonvisocial sector and the El Porvenir neighborhood presented critical flood areas at high risk.

Keywords: Hydrological and hydraulic modeling; environmental impact; flooding; risk; GIS.

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INTRODUCTION

Floods are recognized as one of the most recurrent and impactful natural events in the world, due to the damage they cause to the population, infrastructure and ecosystems. Its incidence tends to be aggravated in territories where urban growth occurs at an accelerated rate, naturally floodable areas are occupied, and there are alterations in precipitation patterns. In the case of Colombia, different institutional records have shown that this phenomenon has represented a significant part of the disasters that have occurred in the country over the last century, mainly affecting vulnerable communities settled in water roundabouts, floodplains and urban sectors with little planning [2], [15]. Faced with this reality, national entities have formulated technical guidelines, methodologies and cartographic tools aimed at hydrological and hydraulic analysis, with the purpose of strengthening risk management and supporting territorial planning processes [1], [4], [16], [17].

Within this panorama, small and medium-sized urban basins present particularly critical conditions, as they tend to undergo intense transformations associated with soil waterproofing, the modification of natural channels and the simultaneous presence of conventional drainage systems and natural surface flows [6], [7]. These characteristics reduce infiltration capacity, accelerate runoff, and favor rapid hydrological responses during heavy rainfall events, increasing the likelihood of flash floods and overflows [2], [7], [13]. Studies carried out in different urban contexts in Colombia have shown that the articulation between rainfall-runoff models and hydraulic models based on the SCS method and the HEC-HMS/HEC-RAS model allows for a more accurate representation of the behavior of floods, the identification of areas susceptible to flooding and the generation of useful technical inputs for planning and decision-making [5]. [8], [10], [14], [17], [21].

The city of Valledupar is a representative example of this situation. Various territorial and environmental diagnostic studies have warned that its urban and peri-urban area faces increasing pressures derived from change in land use, the expansion of settlements and the occupation of spaces associated with bodies of water, wetlands and water rings [9], [18],

[19], [25]. In this context, the Mamón de Leche stream, located in the southwestern sector of the city, crosses an urban basin where housing projects of priority interest, informal settlements and facilities of strategic importance converge; in which a scenario of high physical exposure and marked social vulnerability is configured [12], [18], [22], [26]. In addition, journalistic, institutional, and community records have repeatedly reported flooding events in neighborhoods such as El Edén, Villa Jaidith, Chiriquí, and El Porvenir, where the effects on homes, roads, and public works show the persistence of the problem [9], [12], [23], [24].

Despite these conditions and the recurrence of the events recorded, the Mamón de Leche stream basin did not have a comprehensive study that addressed in detail its hydrological and hydraulic behavior based on recent information, high-resolution cartography, and official socio-spatial databases [1], [17], [19], [22], [25]. This absence of analysis limits the institutional capacity to more accurately delimit flood zones, adjust threat and risk zoning, define water rounds with technical support, and formulate structural and non-structural intervention measures in accordance with current regulations; making it difficult to implement effective strategies for risk reduction and protection of the exposed population [27], [29], [30].

In response to this problem, the main purpose of this study is to model the hydrological and hydraulic response of the urban basin of the Mamón de Leche stream, in the city of Valledupar, in order to evaluate the flood threat and establish a risk zoning that serves as a technical basis for the management of the territory and water resources. To this end, it is proposed, firstly, to characterize the design precipitation and the main hydrological parameters of the basin based on the SCS method and the national modeling criteria [4], [7], [17]; second, to simulate the rainfall-runoff transformation using HEC-HMS and the hydraulic propagation of flows using HEC-RAS under different hydrological scenarios [5], [10], [13], [14]; and finally, to delimit the potentially floodable areas and integrate this information with physical, social and regulatory variables to identify the spatial distribution of risk [2], [15], [18], [19], [22], [27], [29], [30]. In this way, it was sought to generate quantitative and cartographic evidence that complements the existing diagnoses and contributes to the strengthening of flood risk management in Valledupar.

6. MATERIALS AND METHOD

The study was carried out in the urban basin of the Mamón de Leche stream (AML), located in the south-western sector of Valledupar (Cesar, Colombia), with an approximate area of 6.85 km² and an analysis section of about 2.4 km between the box culvert in front of MERCABASTOS and the access road to the El Porvenir urbanization. This sector crosses communes with a high density of low-income population and the presence of VIP housing and informal settlements, representing a critical flood zone under the parameters of the municipality's territorial planning and risk [9], [12], [18], [19], [22], [25], [26].

For the analysis, historical records of daily and sub-daily precipitation corresponding to the period 1993–2023, obtained from the Valledupar airport station operated by IDEAM, were used. This information was supplemented with recent Meteoblue climate files, used to contrast rainfall ranges and interannual variations [3], [4]. Subsequently, the hydrometeorological base was subjected to a process of purification and quality control that included the review of consistency, the exclusion of evidently erroneous data and the estimation of short gaps. Likewise, a descriptive statistical analysis was carried out with the purpose of identifying the maximum daily multiannual rainfall and extreme events in accordance with the climatic dynamics of the Colombian Caribbean [3], [4], [7]. From the official IDF curves for Valledupar, the design rainfall was established, and based on them, 24-hour hyetograms were constructed for return periods of 2, 5, 10, 25, 50 and 100 years, incorporating the Fhrüling areal factor according to the surface of the basin.

The morphometric and geomorphological characterization of the AML was developed using a Digital Terrain Model (DTM) LIDAR with a spatial resolution of 1 m, complemented with official cartography of drainage and land use cover. The processing of this information was carried out in ArcGIS Pro (Esri, Redlands, CA, USA), applying conventional procedures for the generation of hydrological models of elevation, direction and accumulation of flow, as well as for the automatic delimitation of the basin and its drainage network, in accordance with the guidelines of IDEAM and the technical guidelines for the study of watersheds [1], [6], [17]. Based on these inputs, variables such as the area of the basin, the length of the main channel, the average slopes and the shape coefficients were calculated, parameters that were later used to estimate the concentration time and to structure the hydrological and hydraulic models [4], [6], [7].

The hydrological parameters were obtained using the Curve Number (CN) method of the Soil Conservation Service (SCS), using information on land use and cover, soil type and hydrological condition reported for the study area [7], [8]. The basin was sectored into relatively homogeneous units and a weighted NC was calculated for the preceding moisture conditions AMC II and AMC III, with slope adjustment, following national guidelines for flood modeling [4], [17]. The maximum potential storage S (mm) and the initial abstraction Ia were calculated using the SCS equation:

$$S = \frac{25400}{CN} - 254 \quad (1)$$

$$Ia = 0{,}2S \quad (2)$$

The effective rainfall was determined from the total accumulated precipitation in 24 h, using the traditional formulation of the SCS. Similarly, reference theoretical peak flows were estimated by applying the synthetic unit hydrograph of the SCS, in accordance with previous studies developed in urban basins of Colombia [5], [8], [10], [13], [14]. Various empirical expressions were used to estimate the concentration time, including those proposed by Kirpich, Giandotti, Temes, Johnstone and Cross, considering the morphometric parameters obtained from the TDM and the guidelines established in the Hydrological and Hydraulic Modeling Protocol of IDEAM to select the most representative value [4], [5], [17]. As a result, two concentration time scales were adopted: one close to 0.5 h, used in the hydrological simulation of high-intensity events, and another equivalent to 2.42 h, used in the estimation of the peak flow associated with the maximum daily rainfall.

The rainfall-runoff transformation was simulated at HEC-HMS (Hydrologic Engineering Center – Hydrologic Modeling System, U.S. Army Corps of Engineers, Davis, CA, USA) using an event-based approach applied to the entire AML basin, taking into account its small size and high level of urbanization. The model incorporated a loss modulus based on the curve number (CN) of the SCS, with an initial abstraction Ia calculated according to equation (2), as well as a direct runoff transformation module based on the SCS unit hydrograph and a constant baseflow component, representative of both the underground input and the gradual release of moisture stored in the soil [4], [5], [7], [13]. Under this scheme, hydrological scenarios were evaluated for return periods between 2 and 100 years under AMC II and AMC III conditions, obtaining outflow hydrographs, peak flows and peak times. Subsequently, these results were contrasted with the theoretical flows of the SCS in order to verify the hydrological coherence of the implemented model.

The hydraulic modeling of the urban section of the AML was carried out in HEC-RAS (River Analysis System, U.S. Army Corps of Engineers, Davis, CA, USA), by configuring a one-dimensional (1D) model in a gradually varied permanent regime. The geometry of the channel was defined based on the 1m resolution LIDAR TDM and cross-sections extracted approximately every 200 m, which were subsequently verified in the field in accordance with the recommendations of the IDEAM Modeling Protocol [1], [17]. The Manning roughness coefficients were assigned according to the characteristics of each section, considering conditions such as natural channels with vegetated slopes, enclosed channels and sectors with accumulation of waste or dense vegetation. To this end, Chow's reference tables [21] and local information related to wetlands and water rounds [19], [25] were used. Regarding the boundary conditions, the peak flows obtained in HEC-HMS were introduced in the inlet section, while in the outlet a normal depth condition was established in accordance with the energy slope of the lower section.

The results of the hydraulic simulation, such as the stay profile, power line, and lateral overflows, were exported to RAS Mapper and then integrated into ArcGIS Pro for flood extent and depth mapping. The delimitation of the flood zones was carried out following the IDEAM methodological guidelines for the preparation of flood maps and the hazard classification adapted by IDEAM and the UNGRD based on FEMA criteria [1], [2], [15]–[17]. Layers corresponding to neighborhoods, census blocks, facilities and VIP housing, built from the information of the CNPV 2018, the POT of Valledupar and other regional environmental planning and management instruments [9], [12], [18], [19], [22], [25], [26] were superimposed on this cartography. Finally, the risk zoning was defined by integrating the intensity of the threat expressed in the depth and effective width of the water surface; with the exposure of the population and assets, as well as with socioeconomic vulnerability, in accordance with Law 1523 of 2012, the National Policy for the Integrated Management of Water Resources and the guidelines of the Ministry of Environment and Sustainable Development for the delimitation of water rounds [15], [27], [29], [30].

7. RESULTS

3.1. Hydrological

3.1.1. Precipitation.

The hyetograms generated allow us to understand the hydrological behavior of AML under extreme conditions and serves as a basis for subsequent simulations in HEC-HMS taking into account the historical precipitation series (1993–2023) and the official IDF curves for Valledupar, which allowed these graphs to be established for the return periods of 2, 5, 10, 25, 50 and 100 years by the Alternating Blocks method. According to the graph, it is evident that the maximum intensity corresponded to the 100-year event with an accumulated rainfall of more than 120mm with a duration of 24h (Figure 1).

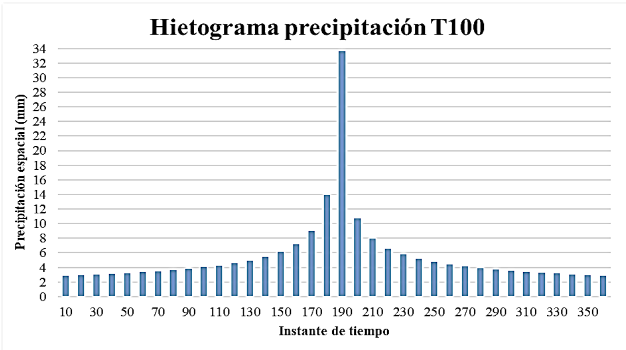


Figure 1. Design hyetogram for T = 100 years using the Alternating Blocks method. In original Spanish language

3.1.2. Flow base

This subsection presents the hydrometeorological values used to estimate the base flow of the Mamón de Leche stream (AML), understood as the permanent flow generated by the underground input and by the gradual release of moisture stored in the soil.

To determine it, a hydrological balance was applied based on a historical average rainfall of 1,116.7mm/year, a potential evapotranspiration (ETP) of 618.2mm/year, an estimated surface runoff of 346.45mm/year, an excess rainfall of 181.45mm/year and a base flow dynamics of 16.65mm/year.

Based on these values, a final base flow of 0.015m³/s was adopted, which represents the underground inputs and the remaining soil moisture, as shown in Table 1.

Table 1. Values obtained for the calculation of the AML base flow.

Time	Travel (sec)	Distance traveled (m)	Surface Velocity (m/s)	Fc	Average speed (m/s)2
S1	4.77	2	0.434	0.7	0.304
S2	4.5	2			
T3	4.47	2			
T4	4.27	2			
T5	5.03	2			
Average	4.608	2			

3.1.3. Concentration Time

This subsection presents the estimation of the concentration time of the Mamón de Leche stream (AML) basin, defined as the time it takes for a drop of rain to move from the furthest point of the basin to its exit.

Three empirical methodologies were used to determine it, based on the geomorphological characteristics of AML, obtaining values of 0.51h using the Chen method (1983), 0.52h with Kirpich's equation and 0.46h from Giandotti's method. Based on these results, an average concentration time of Tc = 0.50h, equivalent to 30 minutes, was adopted for hydrological modeling.

Table 2. Concentration times estimated by different methods.

Method	Tc(h)	Tc(min)	Tc(max)	Acceptance	Valid Tc (h)
Kirpich Method	1.75	0.38	3.13	Yes	1.75
Temes Method	1.28	0.10	2.65	Yes	1.28
Johnstone and Cross Method	3.88	2.50	5.26	Yes	3.88
Giandotti Method	0.18	1.19	1.56	No	-
SCS Method - Ranser	1.75	0.38	3.13	Yes	1.75
Ventura Method - Heras	1.25	0.13	2.63	Yes	1.25
V.T. Chow Method	4.15	2.78	5.53	Yes	4.15
U.S. Army Engineer Corps	2.85	1.48	4.23	Yes	2.85
SCS Delay Equation	-				-

Federal Aviation Administrator.		-
Valid Tc of the Basin		**2.42**
Average of the calculated Tc	2.14	
Standard deviation Tc cal.	2.38	

3.1.4. SCS hydrological parameters

The Curve Number (CN) parameter synthesizes soil properties, land use, and antecedent moisture, and allows estimating the amount of rainfall that is converted into runoff. This subsection presents the NC values used, as well as the potential storage and initial abstraction, which define the initial hydrological response of the basin. The Curve Number (CN) was determined from land use, local hydrology and soil type (A/B): INITIAL CN = 75.65 [adjusted CN (slope 7.69%) = 77]. On the other hand, the resulting maximum storage potential was S = 78.91mm with an initial abstraction of Ia = 15.78mm.

Table 3. Estimated SCS parameters in the basin. In original Spanish language

Sondeos Infiltracion	Gricode ArcGis	Cobertura	Grupo HSG	Condición hidrológica	Cni	Área (km2)	Implicaciones Hidrológicas	CN Ponderado
	1	Agua	D	Insaturado	94	0.03	No está completamente saturadapero por su baja infiltración genera escorrentía directa	83.64
1 y 3	2	Árboles (Bosque)	A	Pobre	45	1.25	Alta infiltración, escasa escorrentía; contribuye significativamente al almacenamiento hídrico.	
	5	Cultivos	B	Fila recta (SR) - Pobre	81	0.13	Moderada escorrentía por laboreo pobre; baja retención y riesgo de pérdida de suelo.	
2	7	Áreas Construidas	A	Zonas impermeables	98	4.45	Superficie impermeable, escorrentía máxima; afecta negativamente la regulación natural del flujo	
4 y 5	11	Pastizales	A	Pobre	68	0.99	Escorrentía moderada por baja cobertura vegetal; capacidad limitada de infiltración y retención.	
Total		**Total**				**6.85**		

3.1.5. Theoretical flows

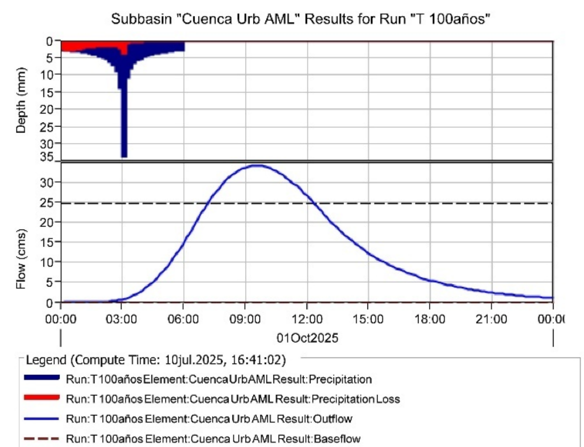
The results of the theoretical flows constitute a reference basis for comparison with the flows obtained through more detailed hydrological modelling, such as that developed in HEC-HMS, and allow the influence of the antecedent soil moisture conditions on the response of the basin to be identified. For the AMC II condition, corresponding to a mean antecedent humidity and a CN = 77, the peak flows obtained show a progressive increase as the return period increases. In this sense, for a return period of 2 years, a flow of 283.73 m³/s was estimated; for 5 years, a value of 560.86 m³/s; and for 10 years, a flow of 751.63 m³/s. Similarly, for events of greater recurrence, values of 988.77 m³/s for 25 years, 1,171.05 m³/s for 50 years and 1,347.08 m³/s for 100 years were calculated. With these values obtained, they allow establishing a baseline to analyze the sensitivity of the basin to variations in the infiltration and storage capacity of the soil.

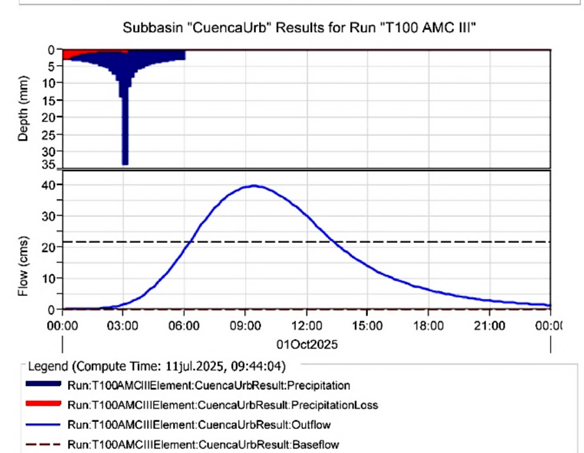
On the other hand, under conditions of greater soil saturation, corresponding to AMC III, the estimated flows showed increases ranging from 15 % to 32 %, depending on the return period analyzed. This behavior confirms that the previous saturation of the soil reduces the infiltration capacity, favors a greater generation of surface runoff and, consequently, increases the magnitude of peak flows in the event of extreme rainfall.

3.2. HEC-HMS Modeling

3.2.1. Hydrographs

The modelling developed in HEC-HMS allowed to simulate the transformation of precipitation into runoff at the basin scale, representing in a temporal way the hydrological response of the system to different rainfall events. In this subsection, the hydrographs obtained and the estimated maximum flows for various return periods are presented, which allow interpreting the behavior of the flows generated, the speed with which the flood peak is reached and the existing variations between different scenarios of antecedent humidity in order to establish the link between the hydrological characterization of the basin and the subsequent hydraulic simulations.





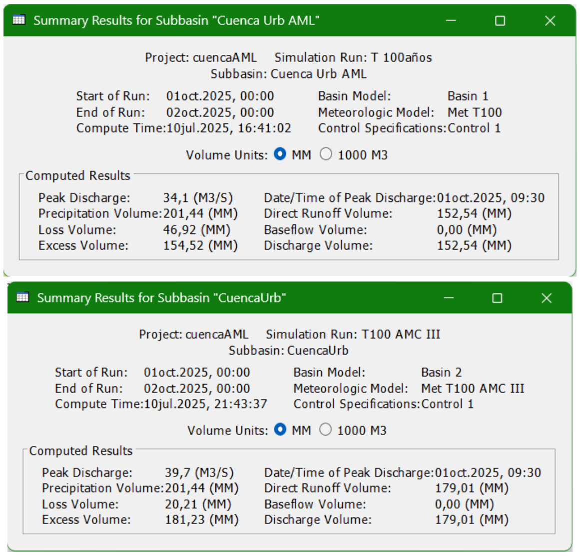


Figure 2. Comparison of theoretical peak flow rates for AMC II and AMC III. In original Spanish language

The HEC-HMS model allowed to represent the hydrological response of the basin for the different return periods established. The highest peak flow was recorded in the scenario corresponding to the 100-year return period under AMC III preceding moisture condition, with a value of 1,312.70m³/s, followed by the same return period under AMC II condition, which reached 1,221.80m³/s (Figure 2). Likewise, the hydrographs showed a rapid concentration of the flow, with peak times between 35 and 45 minutes, results that are consistent with the previously estimated concentration time.

3.3. Hydraulic modelling in HEC-RAS

3.3.1. Hydraulic behaviour

This subsection describes the hydraulic response of the stream to the flows obtained in HEC-HMS. The hydraulic results showed overflows in several sections of the stream, especially downstream, where the natural cross-section is insufficient to contain the design flows. Maximum velocities ranged from 2.5 to 4.2m/s with depths greater than 2.0m (Figures 3).

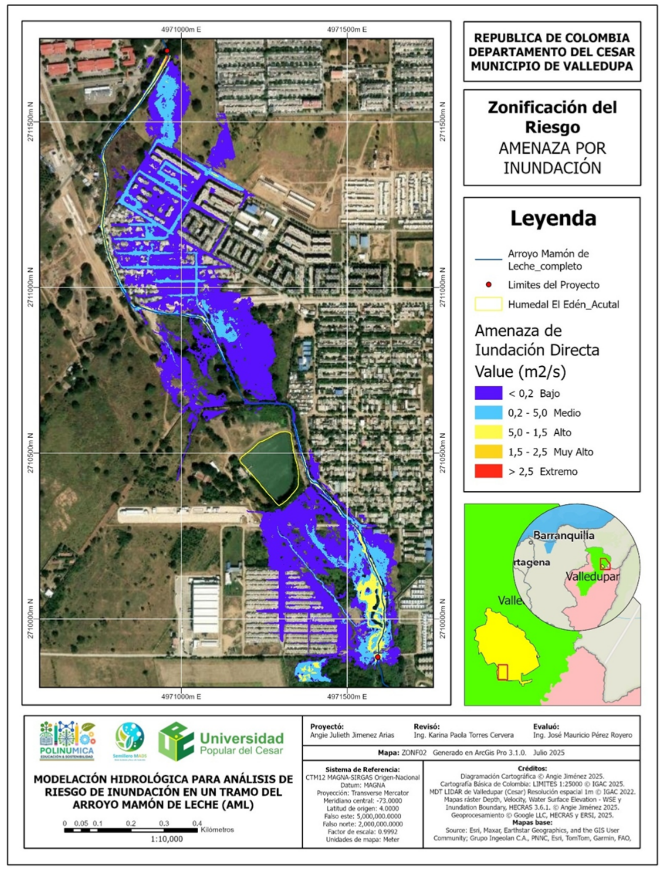


Figure 3. Flood Risk – Scenario in AMC III. In original Spanish language

3.3.2. Sections with overflow in a return period of 100 years

The analysis of the longitudinal profile allowed the identification of the following sectors as critical: the El Porvenir area (WP6–WP9) with recurrent overflows for AMC II and AMC III; and Fonvisocial, representing itself as the most affected area, especially in AMC III.

3.3.3. Extension of flood zone

This subsection shows the spatial extent reached by the flood sheet under different conditions of antecedent humidity. Based on the flood map prepared in ArcGIS Pro using the FEMA–IDEAM procedure, it showed that: The flood sheet expands up to 50–80m on both banks; In AMC III the flooded area increased by up to 18–23% compared to AMC II; and, the area with the greatest urban impact corresponds to the Fonvisocial neighborhood, followed by El Porvenir.

3.3.4. Effective flood width

The effective flood width allows the real amplitude of the overflowing flow in different sections of the stream to be quantified. This metric is essential to identify critical areas and define water protection strips. The CNC–AMC scenarios indicated significant variations: in the Upper Zone with an average width of 12–25m; the middle zone with 32–48m; and the lower area with 50–79m, with a maximum peak in Fonvisocial (see Figure 4).

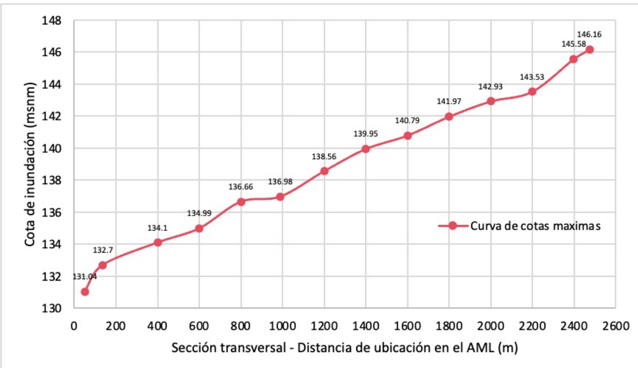


Figure 4. Longitudinal profile with curve of maximum flood levels. In original Spanish language

8. DISCUSSION

The hydrological results obtained allow us to establish that the urban basin of the Mamón de Leche stream (AML), with an approximate area of 6.85km², presents a rapid and markedly amplified response to extreme precipitation events, a behavior that is characteristic of small and medium-sized urban basins with high levels of waterproofing [1], [2]. The conversion of point rain into space rain by applying the Fhrüling factor [f(a) = 0.72], together with the elaboration of hyetograms for return periods ranging from 2 to 100 years, showed increasing intensities concentrated in reduced time intervals, which is consistent with the bimodal rainfall regime and with the occurrence of intense convective events described for Valledupar and the Colombian Caribbean [3]. [4].

From the temporal perspective, the study adopts two concentration time scales (Tc), each associated with a specific purpose within the hydrological analysis. On the one hand, a Tc close to 0.50h (30min) was considered, estimated using empirical methods such as Chen, Kirpich and Giandotti, appropriate to represent the rapid response of the basin to intense rainfall of short duration. On the other hand, a Tc of 2.42 h was used in the calculation of the peak flow using the SCS method based on the maximum daily multiannual rainfall (P = 84.3mm). This methodological differentiation is consistent with what has been pointed out by Torres et al. [5] and by IDEAM [4], who state that the concentration time may vary depending on the time scale of the event analyzed and the objective of the modeling, either for detailed hydrological design or for regional estimates. In urban basins with areas between 5 and 10 km², several authors report typical Tc values between 0.3 and 3h, conditioned by factors such as the average slope, the length of the channel and the degree of urbanization [5], [6], which places the results obtained in this research within technically acceptable ranges.

On the other hand, the parameters derived from the SCS method show a limited soil storage capacity in the basin, reflected in a weighted curve number (CN) of 83.64 for the AMC II condition and 93 for AMC III. These values correspond to potential S storages of 49.69 mm and 19.12 mm, respectively, and initial Ia abstractions of 9.94 mm and 3.82 mm. From this, the estimated net precipitation (Pn) reached 44.57mm for AMC II and 65.03mm for AMC III, indicating that approximately 53% and 77% of the total recorded precipitation (84.3mm) is transformed into direct runoff. This behavior is consistent with scenarios dominated by moderately permeable soils, but subject to strong urbanization processes, in which infiltration and evapotranspiration decrease significantly [7]–[9]. In this sense, Sánchez [7] and Cabarcas et al. [8] describe similar patterns in tropical urban basins, where the combination of sandy-loam texture, compaction and surface sealing favors that more than half of the intense precipitation ends up becoming runoff.

The reference flows calculated using the SCS method, equivalent to 26.26 m³/s for AMC II and 38.31 m³/s for AMC III, are within the range of 20–40 m³/s reported by Pérez [10], Díaz and Ibarra [11] and Mejía [12] for Colombian urban basins with areas between 5 and 10 km² subjected to design rainfall associated with return periods between 50 and 100 years. This coincidence reinforces the hydrological consistency of the results and confirms the relevance of applying the SCS method in combination with the estimated concentration time for the basin studied.

Similarly, there is evidence of adequate coherence between the theoretical flows estimated using the SCS method and the flows simulated with the HEC-HMS model. For the AMC II condition, the reference peak flow calculated with SCS corresponds to 26.26 m³/s, while the simulation in HEC-HMS yields a maximum flow rate of 34.1 m³/s for a return period of 100 years. Although the latter value is approximately 30% higher than the theoretical flow, this difference remains within an acceptable range when moving from a simplified approach to a rainfall-runoff model distributed over time and adjusted with physical parameters of the basin [7], [13].

For the AMC III condition, the comparison is even more significant. In this case, the SCS method estimates a peak flow of 38.31 m³/s, while HEC-HMS simulates a value of 39.7 m³/s, with a relative difference of just 3.6%. This result shows a high consistency between both approaches under saturated soil conditions. Research such as that carried out by Torres [5], Díaz y Ibarra [11] and Chilito [14] reports differences between 0% and 20% when comparing flows obtained with SCS versus simulations carried out in HEC-HMS or similar models, which places the results of this study within a fairly solid margin of coherence.

Likewise, the comparison between the preceding humidity conditions shows important variations in the hydrological behavior of the basin. The simulated peak flow rate in HEC-HMS increases from 34.1m³/s in AMC II to 39.7m³/s in AMC III, representing an increase of 16.4%. For its part, the theoretical flow calculated with SCS goes from 26.26m³/s to 38.31m³/s, with an increase of close to 46%. This relative difference suggests that the SCS method presents a greater sensitivity to CN variations, while the HEC-HMS model jointly integrates the effect of net rainfall, initial losses and the temporal dynamics of the event, partially attenuating the contrast between AMC II and AMC III. This behavior coincides with what was reported by Torres [5] and Sánchez [7], who point out that in continuous simulation models or by events, the increase in peak flow between "normal" and "saturated" humidity conditions usually ranges between 15% and 40%, depending on the intensity and temporal distribution of precipitation.

When comparing the maximum flows obtained with the base flow measured in the field (0.081 m³/s), the results show a highly significant increase. Flow is increased by more than 42-fold for the AMC II condition and by approximately 49-fold for AMC III. This marked amplification factor is consistent with what has been pointed out by the UNGRD and the OSSO Corporation [2], [15], who indicate that flood events in Colombia tend to present a pronounced contrast between ordinary flows and flood flows, especially in urban basins characterized by the occupation of water rings and limited regulation capacity.

In the hydraulic field, the HEC-RAS results show that, under the T = 100 years scenario, AML is not able to contain the simulated flows without overflowing, especially in the middle and lower sectors of the modeled section. Depths greater than 2.0m and velocities between 2.5 and 4.2m/s in critical stretches coincide with the high-energy flow thresholds defined by FEMA and IDEAM as potentially destructive to homes and light structures [16], [17]. In fact, the conditions identified in sections such as RS 1400, 400 and 138 are comparable to those reported by Díaz & Ibarra in the Culagá River [11] and by Chilito in Caño Grande [14], where the 100-year design flows generate hydraulic overloads and recurrent overflows in the vicinity of urban infrastructure.

Regarding the lateral extension of the flood, the results (50–80m per margin) are consistent with the areas of alluvial plain and urban landfills described in the POT of Valledupar and in the POMCA of the Medio Cesar River [18], [19]. Mejía [12] identifies precisely the southwestern strip of the city, where El Edén, Villa Jaidith, Chiriquí and El Porvenir are located, as one of the areas with the highest risk of flooding due to the combination of flat topography, high population density and the presence of water bodies and wetlands. The coincidence between the hazard zoning of this study and the previous risk maps reinforces the robustness of the hydraulic model used.

The longitudinal profiles obtained show a systematic increase in specific energy (EG line) and tie rod (WS) from the base flow scenario to the AMC III scenario, with steeper energy slopes between the RS 1800–1600 and 400–138 sections. This pattern indicates significant frictional losses associated with channel narrowing, high roughness (Manning's n ≈ 0.05–0.065) and the presence of obstacles such as garbage and dense vegetation, as has already been documented in studies of urban canals in Colombia [10], [14], [20]. The choice of Manning coefficients based on Chow [21] and field inspections is consistent with the literature and with the conditions observed in AML.

From a comparative perspective, the methodology applied using 1m LIDAR TDM, sections every 200m, 1D simulation in HEC-RAS and subsequent 2D interpolation in RAS Mapper is consistent with the guidelines of the IDEAM Hydrological and Hydraulic Modeling Protocol [17] and with the good practices described in research such as those of Torres [5], Pérez [10] and Chilito [14]. In all these cases, the authors highlight that the use of high-resolution mapping and dense sections significantly improves the accuracy of the delimitation of flood zones.

The risk zoning carried out for the AML, especially under AMC III and T = 100 years, confirms that the MERCABASTOS – El Porvenir section is part of the national flood problem identified by the UNGRD and the OSSO Corporation, where floods represent about 31% of the country's disasters and disproportionately affect low-income populations [2]. [15]. In the case of AML, the sectors of greatest threat (particularly Sector 3 – El Porvenir) coincide with stratum 1 communities, high population density and presence of displaced populations, as documented by DANE, the POT of Valledupar and local studies [18], [19], [22].

The three defined sectors (upper, intermediate and lower) show an increasing gradient of risk from upstream to downstream:

- In the upper part, the floods mainly affect roads, facilities such as the Nelson Mandela School and settlements on the ring road (Invasion El Edén), with sheet heights close to 1 m in recent events [23], [24].
- In the intermediate zone, although the model does not show direct flooding over all neighborhoods, the empirical evidence collected (flooding in Villa Jaidith and Chiriquí, a mixture of runoff and sewage) indicates a high hydrosanitary risk [24], [25].
- In the lower part, El Porvenir registers the highest water heights (greater than the chest of an adult in some events) and the greatest lateral extension, affecting access, housing and strategic infrastructures such as the mega-school and the logistics CEDI [22], [26].

This pattern is consistent with the literature on flood risk in Latin American urban areas, where the informal occupation of floodplains and water roundabouts by vulnerable populations generates very high or non-mitigable risk scenarios [2], [27]. The concentration of threat in Sector 3 and the exposure of more than 700 VIP homes associated with resettlement processes reaffirm the need to articulate the results of this study with the provisions of Law 1523 of 2012 and the policy of resettlement of settlements in risk areas [27], [28].

On the other hand, the delimitation of maximum flood levels between 146.16 meters above sea level (upstream) and 131.04 meters above sea level (downstream), and its incorporation into the proposal for the delimitation of the water round, is in accordance with the criteria of Resolution 957 of 2018 and the Technical Guide for Water Rounds of the Ministry of the Environment [29]. The use of the flood level associated with T = 100 years as a normative reference is consistent with national practice to define the minimum protection strip of 30 m on each side of the channel [29], [30]. In this sense, the results of the model not only have scientific value, but also a high potential for use as a technical input for the POT and the POMCA.

5. CONCLUSIONS

The cartographic and morphometric analysis showed that the urban basin of the AML has a medium-low slope and an elongated shape, characteristics that tend to prolong the transit time of water and favor accumulation processes in the middle and lower sections; in which it acquires an inverse behavior due to the high degree of urban waterproofing, the occupation of the ring area and the reduction of the section of the channel.

On the other hand, the comparison between the hydrological results obtained by SCS and HEC-HMS, the hydraulic results generated with HEC-RAS and the social analysis carried out from the cross-referencing with the information from the CNPV 2018 and the location of equipment, allows us to conclude that the hydrological response of the Mamón de Leche stream (AML) is consistent with that expected for a tropical urban basin of 6.85km². characterized by high levels of runoff (between 53% and 77% of rainfall), peak flows between 26 and 40 m³/s and concentration times in accordance with the ranges reported by other studies [5], [7], [10]–[12]. This disparity between the behavior in dry and wet weather not only confirms the torrential nature of the stream, but also raises a relevant conjecture: the water system may be influenced by underground processes and non-visible inputs, which merits hydrogeological studies and complementary modeling to obtain a more complete understanding of the water balance.

Similarly, the correspondence observed between the flows estimated by SCS and those simulated in HEC-HMS, particularly under the AMC III condition, where the differences were less than 5%, supports the robustness of the modelling scheme adopted and shows comparable results with reference hydrological investigations carried out in Colombia [5], [11], [14]. In the hydraulic component, the model implemented in HEC-RAS, based on a 1m resolution LIDAR TDM and cross-sections spaced every 200m, reproduced overflow and flood patterns that coincide with recent empirical evidence, including photographic records, journalistic reports and community testimonies, in addition to showing similarity with studies carried out in other urban basins [10]. [12], [14], [23]–[26].

In the HEC-RAS model, it was possible to accurately identify the sections where the channel loses its capacity and overflows occur. Although some sectors maintain relatively stable hydraulic conditions, in which recurrent overflows are evident even under lower return scenarios. The spatial progression of flood depth and width reveals a marked inequality between the upper and lower sections, where the flow acquires greater energy, greater erosive capacity and greater destructive potential.

Likewise, the risk zoning obtained corresponds to the diagnoses formulated at the national and departmental levels by the UNGRD, the POT and the POMCA, showing that the AML constitutes a high and very high risk sector, especially in the El Porvenir neighborhood, where extreme levels of threat, high exposure and a marked socioeconomic vulnerability converge [2]. [15], [18], [19], [22].

The integration of hydrological and hydraulic results with socio-spatial information led to the conclusion that there is a critical overlap between physical threat and social vulnerability. The areas of greatest risk correspond to stratum 1 neighborhoods with high levels of overcrowding, invasion or resettlement processes, and limited drainage infrastructure. This finding raises a major implication: risk management in AML cannot be addressed only through hydraulic works, but requires coordinated urban, social and environmental interventions. In particular, the maximum flood levels obtained in this study offer a direct input for the regulatory delimitation of the water round, whose management could significantly reduce exposure if articulated with national policies for water resource and disaster risk management.

Therefore, the findings of this study not only conform to the technical and hydrological criteria currently in force, but are also consistently articulated with the specialized literature and with national policies, consolidating itself as a solid support for the formulation of structural and non-structural risk management measures proposed in the research. Future work should focus on three main lines: (i) improving the accuracy and resolution of the models through new measurements and 2D schematics; (ii) complement the risk assessment with analysis of social vulnerability, structural fragility and community response capacity; and (iii) moving towards the implementation of local early warning systems that articulate science, institutions, and the community. With this, it will be possible to transform the results of this study into concrete actions that increase urban resilience and effectively reduce the risk associated with flooding in the Mamón de Leche stream.

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