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INVESTIGACIÓN

Numerical modelling in a 1D dimension of drainage structures in sewage systems

Modelización numérica en una dimensión 1D de estructuras de drenaje en sistemas de alcantarillado

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Abstract

Context: Urban development leads to the alteration of natural landscapes and the modification of vegetation coverage. As a result, floods are becoming increasingly frequent and more devastating than in the past. To better understand and address these impacts, advances in computational technology has facilitated the broader use of modelling tools. Since the 1970s, mathematical modelling has become an important resource in the diagnosis and design of drainage systems. Numerical models have been developed that allow the Saint-Venant equations to be solved in a simplified way (diffusive and kinematic models) or in their complete form (conservation of mass and momentum).

Objective: To develop an integrated hydrodynamic model using the Stormwater Management Model (SWMM) software to simulate the joint operation of surface and subsurface drainage structures in the combined sewer system of the Santa-Inés neighborhood of Tunja. The model aims to evaluate the flows generated, the urban hydrological balance, and the flow hazard in the streets.

Methodology: Modeling is carried out using the Stormwater Management Model (SWMM) software. This is a dynamic rainfall-runoff model used for the simulation of the quantity and quality of water in urban areas. This study analyzed the integrated hydraulic operation of drainage structures such as sinks and spillways in the existing combined sewerage system of the Santa-Inés neighborhood in the city of Tunja, Colombia. The surface drainage (street

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model) was examined to assess its effects on the generated flows and on the hydrological balance of the urban basin, allowing for the hazard of the flow in the streets of the area to be determined.
Results: The study produced an integrated numerical model of urban drainage structures. Water and hydraulic analysis were generated between the surface model and the subsurface model. As a result, the volume fraction of effective rainfall generated by the road and domicile connections was determined, and the volume of runoff captured by the sinks was estimated
Conclusions: The findings highlight the importance of the integration of the surface and subsurface models in urban drainage systems and allow for an evaluation of the hazard of the flow in the streets of the drainage district under study.
Keywords: Surface system; sewerage; hydraulic model; SWMM.

Resumen

Contexto: Los procesos de desarrollo urbano conducen a la alteración de los paisajes naturales y a la modificación de la cobertura vegetal. Como resultado, las inundaciones son cada vez más frecuentes y más devastadoras que en el pasado. Para comprender y abordar mejor estos impactos, la evolución computacional ha facilitado un uso más amplio de las herramientas de modelado. Desde la década de 1970, el modelado matemático se ha convertido en un recurso importante para el diagnóstico y diseño de sistemas de drenaje. Se han desarrollado modelos numéricos que permiten resolver las ecuaciones de Saint Venant de manera simplificada (modelos difusivos y cinemáticos) o en su forma completa (conservación de la masa y del momento).
Objetivo: Desarrollar un modelo hidrodinámico integrado mediante el software Stormwater Management Model (SWMM) para simular la operación conjunta de las estructuras de drenaje superficial y subsuperficial en el sistema de alcantarillado combinado del barrio Santa-Inés de Tunja, con el fin de evaluar los caudales generados, el balance hidrológico urbano y la peligrosidad del flujo en las calles.
Metodología: La modelización se lleva a cabo mediante el programa informático Stormwater Management Model (SWMM). Se trata de un modelo dinámico lluvia-escorrentía utilizado para la simulación de la cantidad y calidad del agua en zonas urbanas. En el presente estudio se desarrolló un análisis de la operación hidráulica integrada de estructuras de drenaje, como sumideros y aliviaderos, en el sistema de alcantarillado combinado existente en el barrio Santa-Inés de la ciudad de Tunja, Colombia. Se analizó el drenaje superficial (modelo calle), estudiando los efectos sobre los caudales generados y el balance hidrológico de la cuenca urbana, permitiendo determinar la peligrosidad del flujo en las calles de la zona.
Resultados: A través de este estudio, fue posible construir el modelo numérico integrado de estructuras de drenaje urbano. Se generaron análisis hidráulicos entre el modelo de superficie y el modelo de subsuelo. Como resultado, se pudo determinar la fracción volumétrica de precipitación efectiva generada por las conexiones viales y domiciliarias. Además, se estimó el volumen de escorrentía captado por los sumideros.
Conclusiones: Estos resultados ponen de relieve la importancia de la integración de los modelos superficial y subsuperficial en los sistemas de drenaje urbano y permiten evaluar la peligrosidad del flujo en las calles del distrito de drenaje estudiado.
Palabras clave: Sistema superficial; alcantarillado; modelo hidráulico; SWMM.

Introduction

Cities constitute the main axis of national development. The most complex and value-added production processes, as well as the greatest number of economic opportunities, are centralized in urban areas. This has been demonstrated by the accelerated increase in urbanization, first in countries where the Industrial Revolution occurred, and subsequently in the rest of the world (1). The process of urban development causes alterations to natural landscapes and modifies vegetation coverage in impermeable areas (2). Consequently, urban areas are becoming both more extensive and more impermeable, resulting in both an increased frequency of flooding and an increase in the devastation they cause (3).

Flooding in urban areas has caused material damage and adverse social consequences. Over time, the importance of this issue has increased, prompting substantial efforts to understand and numerically model the phenomena occurring within urban drainage systems. These efforts may allow us to mitigate and control the effects of flooding. Urban drainage consists of two separate and distinct components: a major (surface) drainage system, comprising streets, gutters, and artificial and natural longitudinal channels, and a minor (subsurface) drainage system, composed of collectors, junctions, control structures, weir, sluicegates, etc (4) citing other authors.

The major or surface drainage system is typically designed to operate under free-surface flow conditions for a discharge associated with a return period. When a rainfall event occurs with a return period greater than the design allows, the collectors (minor drainage system) can take load or pressure, the water may even flow to the urban surface, namely flood, and be transported by the surface drainage system, or streets (5). The connection between the two systems is dynamic. The flow can be transferred from the surface drainage system to the subsurface drainage system and vice versa. This bidirectional interaction is currently known as dual urban drainage (6).

Since the 1979s, mathematical modeling has become an important tool for the diagnosis and design of drainage systems. Numerical models have been developed to solve the Saint Venant equations in a simplified way (diffusive and kinematic models) or in full (conservation of mass and momentum) (7). The models are approximations of real systems, their reliability depends on numerical formulation and on how well they have been parameterized with primary information obtained from the study area (8).

Various authors have documented the common problems faced in urban drainage, including estimating the volume of runoff water the systems manages, conveying flow into the drainage network, designing a network of ducts that is sufficient for the transport of the calculated flows, and pouring these flows into a receiving medium. From the hydrological and hydraulic perspective of these problems, the runoff flows must be introduced into the drainage network and at the planned points so that the flow does not circulate uncontrollably on the urban surface (9).

At present, the city of Tunja is experiencing considerable and accelerated urban development in the north- eastern area, where frequent drainage system overflows and flooding have been reported. In the design process of a drainage network, it is frequently hypothesized that the rain that falls, which is transformed into surface runoff or effective precipitation, enters the drainage network in the same place where it falls. According to this hypothesis, a series of hydrological sub-basins are defined under the premise that surface runoff will not exceed them. However, when these assumptions are incorrect, the hydrological and hydraulic scheme of the city can be modified in fractions. This is because the runoff that is not captured by the sink can enter the underground system at another site downstream from where it had been planned (10).

Through this study, it was possible to build the integrated numerical modeling of urban drainage structures. Water and hydraulic analyses were generated between the surface model and the subsurface model. As a result, the volume fraction of effective rainfall generated by the roadways and domestic connections was determined, and the volume of runoff captured by the inlets was estimated. These results highlight the importance of the integration of the surface and subsurface models in urban drainage systems and allow for an evaluation of flow hazards along the streets within the drainage district under study.

Previous research in the city of Tunja has documented recurrent overflow problems in the Santa Inés district, particularly in its northeastern sector, where flow accumulation has been reported during intense rainfall events. Monitoring campaigns conducted by Veolia Aguas de Tunja and research projects carried out by Universidad Santo Tomás provided hydrographs, rainfall records, and field surveys that confirmed the limited capacity of the existing drainage network. These studies highlight the need to evaluate the hydrodynamic behavior of streets and inlets under real efficiency conditions, which justifies the development of the present work.

Methodology

Location

After considering several factors and characteristics, such as vulnerability to flooding, a high percentage of impervious surfaces, and urban density, the Santa Inés district was selected as the specific area of study for the development of this research. The neighborhood covers an area of 21.89 ha and represents a typical urban sector with mixed residential and commercial land use, narrow streets, and low longitudinal slopes. Within the municipal context, Tunja is the capital of the Boyacá Department, located in the Eastern Cordillera of Colombia. Rainfall data were obtained from the IDEAM station "Tunja Aeropuerto" and from a local rain gauge installed by Universidad Santo Tomás, while flow measurements were taken at the main

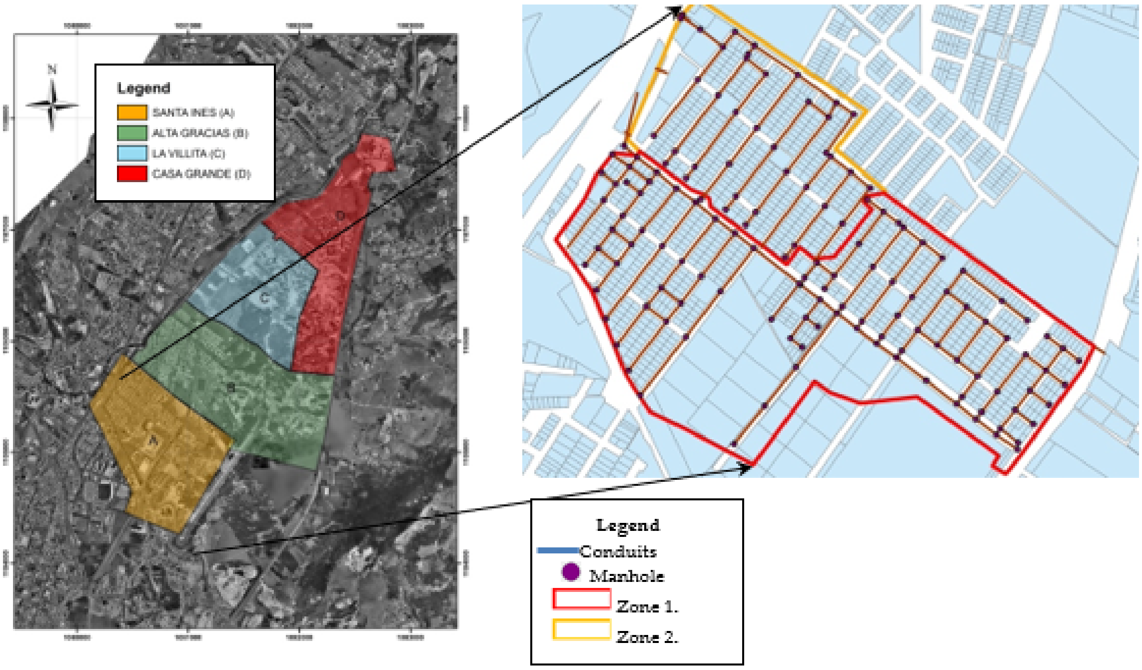

Figure 1. General Location – North-eastern sector of Tunja

Source: POT Tunja 2014. Author.

basin outlet operated by Veolia Aguas de Tunja. Topographic and geometric information was derived from the municipal cadastral plan at 1:2000 scale and complemented with field surveys to measure street slopes, manhole elevations, and inlet locations. This information was used for basin discretization and for the hydrodynamic modeling performed in SWMM. This research continues the analysis of this drainage system supported by rainfall and flow monitoring equipment and builds upon previous investigations. Earlier studies have identified initial manholes, delimited the Santa Inés district, and determined that the district is divided into two different zones (Zones 1 and 2) with a total area of 21.89 Ha (11) (see Figure **1**).

SWMM Model

Stormwater Management Model (SWMM) software was used for the modeling process. SWMM is a dynamic rainfall-runoff model used for the simulation of the quantity and quality of water in urban areas (12). The model is primarily used for the planning, analysis, and design of urban drainage systems. It includes a water quality module that allows for the temporal evolution or transport of pollutants to be determined, and affords the inclusion and design of LIDs (Low-Impact Development) controls, which are represented by a combination of vertical layers whose properties are defined per unit area. This allows LIDs of the same design but with different area coverage to be easily placed within different sub-watersheds of a study area (13).

The latest version, SWMM 5, provides an integrated Windows environment for editing input data, running simulations, and displaying the results in the form of thematic maps, graphs, tables, profile plots, and statistical reports. SWMM5 has modernized both the model structure and the interface, making it more accessible to water resources specialists while remaining too complex to be used by the general public or planners with no modeling experience (14).

Rain runoff module

SWMM treats each basin as a non-linear deposit (Equation 1), this is obtained by combining the Manning equation and the continuity equations for each sub-basin (Equation 2). The two previous equations are combined to give rise to the non-linear differential equation for the water depth (15) (Equation 3), (see Figure **2**):

$$Q = \frac{W}{n}(d - d_p)^{5/3} s^{1/2} \quad \text{Outlet Flow} \tag{1}$$

$$\frac{dV}{dt} = A\frac{dd}{dt} = A^{*}i - Q \quad \text{Continuity for each sub-basin} \tag{2}$$

$$\frac{dd}{dt} = i - \frac{W}{A^{*}n}(d - d_p)^{5/3} s^{1/2} \quad \text{Differential non-linear deposit} \tag{3}$$

Where:

- W = Sub-basin width (m)
- n = Manning roughness coefficient
- d = Depth of water (m)
- d_p = Depression depth (depth store), (m)
- s = Sub-basin slope (m/m)
- A = Sub-basin surface, (m^2)
- i = Effective rainfall (precipitation minus infiltration and evaporation), (m/s)

This nonlinear differential equation is solved using a Newton-Raphson finite difference scheme for each time increment. It should be noted that the parameters introduced in the model can be adjusted to calibrate its response. Among these parameters, the basin width W plays an important role in determining the magnitude and timing of the hydrological response within the contribution zone. Considering a rectangular basin of the same surface, a greater width reduces the length of the basin, producing outlet hydrographs with shorter duration and higher peak discharge. Conversely, a smaller width will delay the tip of the hydrograph, producing a lamination effect. The width of the basin is estimated from its real geometric shape (16).

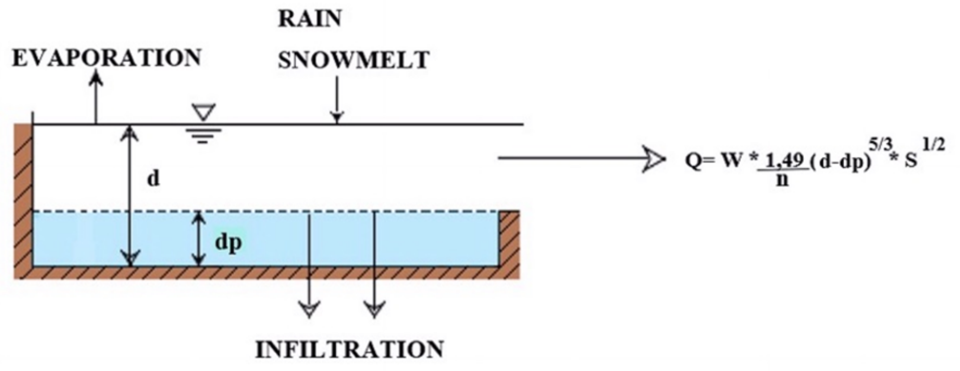

Figure 2. Non-linear deposit, Conceptual view of the runoff phenomenon in SWMM

Source: Adapted from: Storm Water Management Model, Version 4: User's Manual pg. 115.

EXTRAN transport model

SWMM's EXTRAN transport model (Extended Transport Module) is a dynamic flow model that routes inflow hydrographs through an open channel and/or closed conduit system. It calculates the flow and water depth throughout the sewer network, including ducts, nodes, and reservoirs, for the simulation of the hydraulics of the urban drainage system. EXTRAN is considered one of the most sophisticated models available in the public domain and is designed for application in systems where the constant flow assumption cannot be made, allowing for the calculation of backwater profiles.

In unsteady open-channel flows, the depth and velocities of the water vary with time and longitudinal position. The program solves the complete dynamic equations for gradually varied flows (Saint. Venant equations) (15). These differential equations model the variation of discharge and flow depth in a one-dimensional space and time in a non-steady way for open channels (17).

Therefore, EXTRAN allows the modeling of weirs, manholes, pumps, sluicegates, tanks, sewer networks, and discharges, using the desired boundary conditions. EXTRAN combines the continuity and momentum conservation equations into one, which it solves for all the ducts at each instant of time (16), see Equation 4:

$$\frac{\partial Q}{\partial t} - 2V\frac{\partial A}{\partial t} - V^2\frac{\partial A}{\partial x} + gA\frac{\partial H}{\partial x} + g \cdot A \cdot S_f = 0 \quad (4)$$

Where:

- Q: Discharge through the duct

- t: Time
- V: Flow velocity in the duct
- A: Flow cross-sectional area
- x: Distance along the duct
- g: Gravity
- H: Piezometric head (invert elevation plus depth of water)
- S_f: Friction slope, according to the Manning equation

Flow dividers node

Flow dividers are nodes within the drainage system that divert incoming flows to a specific conduit. A flow divider may not have more than two conduits connected at its outlet. Flow dividers are only active in Kinematic Wave routing and are treated as single junctions in the dynamic wave model via a flow through / flow rate ratio (inflow / outflow in m^3/s), that is, using flow regulators between two nodes ("outlets"), characterized through hydraulic load / captured flow tables. Four types of flow dividers are defined according to how inputs are diverted:

- Overflow Divider. Diverts all inlet flow above the flow capacity of the undiverted duct.
- Tabular Divider: Uses data in a table that expresses the diverted flow as a function of the total flow.
- Weir: Uses a weir equation to calculate diverted flow, diverting inlet flow above a minimum Qmin as flow over a full-height weir hW with discharge coefficient cW. This is difficult to estimate if experimental data regarding the hydraulic behavior of the grids under discharge conditions is not available. In addition, the pouring length must be calculated, an approximation of the sum of the length and width of the grate.
- Cutoff: Diverts all input flow above a user-defined cutoff value Qmin.

Results and Discussion

The findings presented here build upon previous research conducted by the authors in the framework of the Master's program in Civil Engineering with an emphasis in Hydro-environmental studies at Santo Tomás University, Tunja. Amaya Tequia (18), carried out the

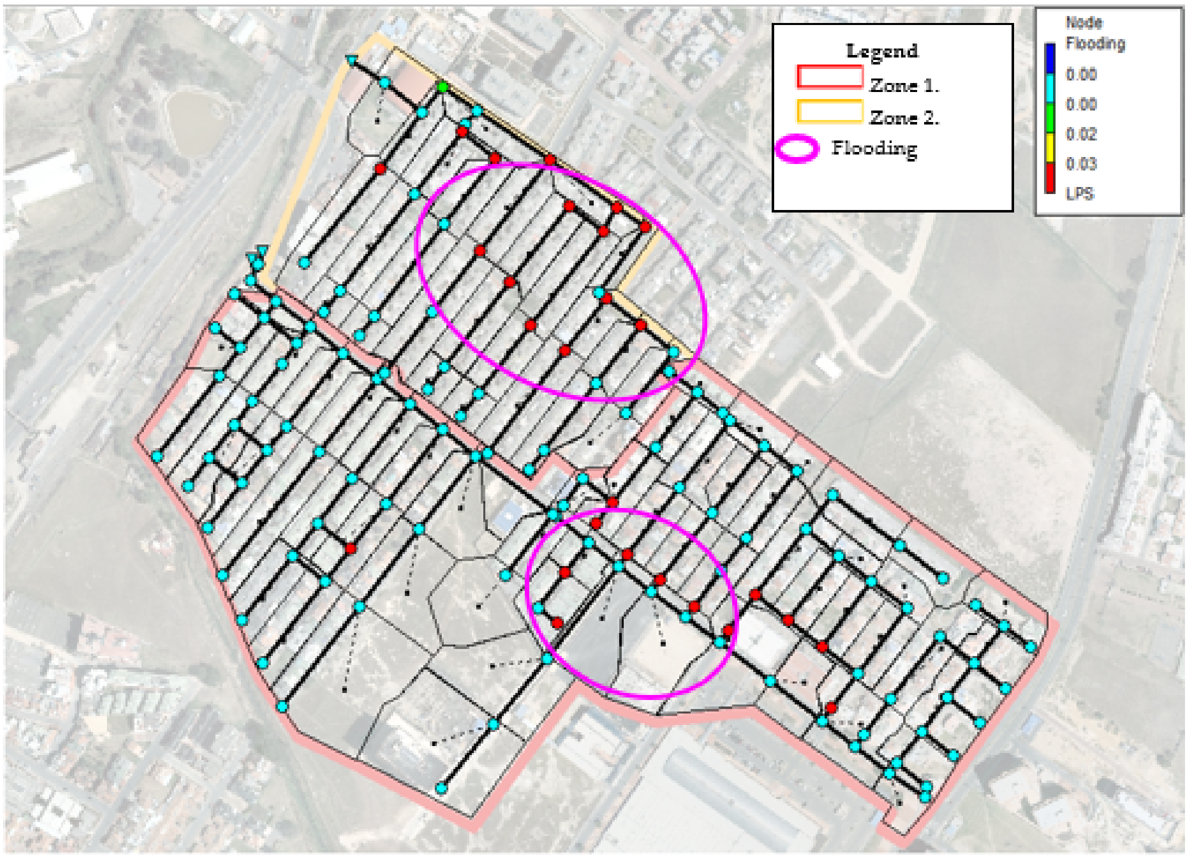

Figure 3. Santa Inés district Zone 1 and 2. Return period 10 years, minute 40. Wells with overflow SWMM 5.1

Source: Author.

hydrodynamic modeling of the sewage system in the North-eastern sector of Santa Inés District, Tunja. He conducted the instrumentation of the area with precipitation and flow measurement equipment. The peak flow of the discharges, or relief chambers, was simulated by configuring the inlet and outlet water levels of the basin in SWMM. At the manhole node output, the basin was disaggregated at a detailed scale, obtaining 56 drainage sub-basins for Zone 1 and 26 sub-basins for Zone 2. For each sub-basin, hydrological parameters were determined, including slope, average basin width according to physical and drainage conditions, percentage of impervious area, curve number, and directly connected area (see Figure **3**).

This research was based on real sewage hydrographs measured at the main discharge of the urban basin. Parameters associated with initial hydrological losses and roughness coefficients were calibrated. A calibrated and validated model of urban drainage was built using SWMM 5.1. Calibration was carried out using the rainfall event of July 15, 2018, with a total rainfall of 28.4 mm in 85 minutes. The final calibrated parameters were: Manning's roughness coefficient = 0.016 for streets, depression storage = 1.5 mm, and average basin width = 35 m. The correlation between observed and simulated hydrographs reached $R^2 = 0.89$, demonstrating adequate model performance. The temporary hydrodynamic modeling of the system was obtained under real rainfall events and significant flows of generated runoff.

The model adequately reproduces the real evolution of the system and was subsequently used to run predictions under a designed maximum rainfall event. The duration of the design hyetograph was 60 minutes, considering that the general delay time of the urban basin ranges between 20 and 25 minutes. Precipitation events recorded in the monitoring time generally exhibited the largest pulses in the middle of the rain duration, therefore, this form was adjusted to the design storm. In addition, an exploratory analysis was carried out. It was possible to statistically establish the presence of a correlation between the precipitation data series observed for the month of July 2018 between the Santa Inés pluviometer and the UPTC main climatological station pluviometer. Therefore, the adoption of intensity duration and frequency curves was considered to be valid. These were provided by the UPTC station of the Institute of Hydrology, Meteorology, and Environmental Studies (IDEAM) for the construction of the design hyetograph through the alternate block methodology (11).

The calibrated and validated hydrodynamic model managed to determine 2 zones vulnerable to flooding. Under a rainfall scenario with a magnitude associated with a return period of 10 years, hydraulic incapacity was presented for drainage in pipes. 94.87 % of all collectors in the system operated at or exceeded 93hydraulic capacity at the peak of the hydrograph. Moreover, 27 manholes were recorded to overflow during the 35th and 40th minute of the simulation. Namely, the water flowed from the minor drainage system into the major drainage system. During this period, the hydraulic load of the collector (minor drainage system) was higher than the free surface of the water in the street, causing the conduits to act as flow sources (see Figures **4** and **5**). As a result, it could be concluded that the disaggregation of the hydrodynamic model at a detailed scale reduced the degree of uncertainty in the evolution of the flow.

However, this model did not include the hydraulic structures that form part of the surface system or street model, which is made up of roads and grids. As such, the limits of the drainage areas will be determined by the location of the existing sinks. The initial conditions in the model assumed dry weather conditions prior to the rainfall event, with no stored volume in the conduits. Boundary conditions were defined as free outflow at the outlet node connected to the main collector of Tunja's combined sewer system. The study area was discretized into 82 subcatchments, 94 conduits, and 206 inlets, according to street layout and topography. Hydraulic structures considered in the model included manholes, relief chambers, and street inlets of dif-

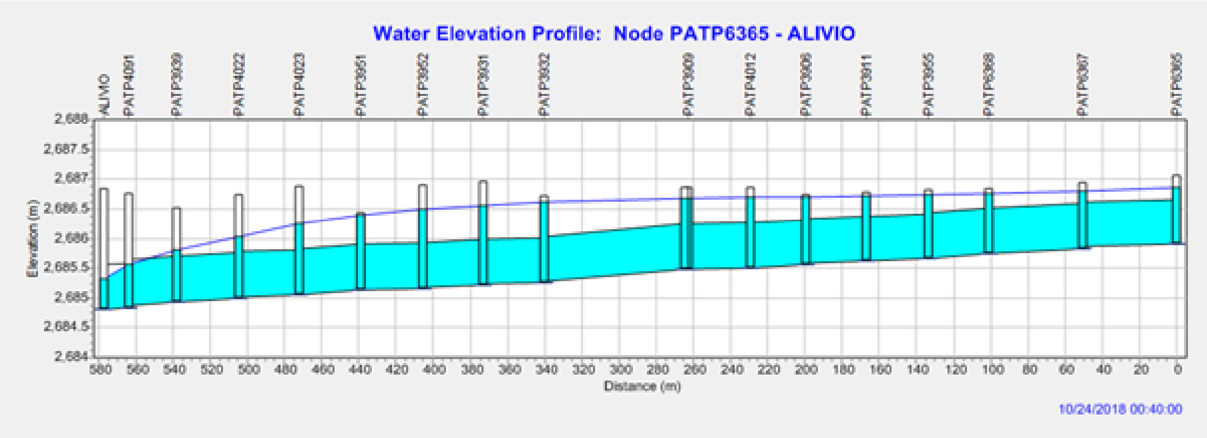

Figure 4. General hydraulic profile Santa Inés District Zone 1. SWMM 5.1

Source: Author.

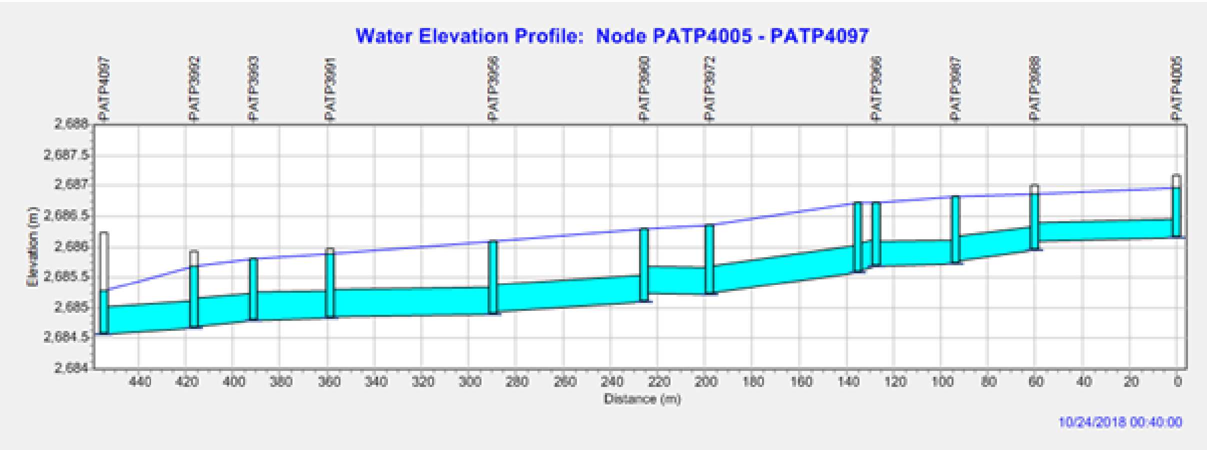

Figure 5. General hydraulic profile Santa Inés District Zone 2. SWMM 5.1

Source: Author.

ferent typologies, whose efficiency was introduced using cutoff flow values. Manning's roughness coefficients, depression storage values, and slopes were assigned based on field surveys and laboratory data. To overcome these limitations, three simulation scenarios were defined: (i) without inlets, (ii) inlets with ideal efficiency (100 %), and (iii) inlets with real efficiency measured in laboratory tests. In the third scenario, hydrological coupling was achieved through cutoff nodes, where the excess flow not captured by the grid was routed to the street model until reaching downstream sinks. The integrated model considered 271 sub-basins and 206 inlets connected to 94 conduits, thus allowing differences between scenarios to be quantified in terms of peak flow, hydrograph base time, and volume distribution. The comparison between the three scenarios revealed that assuming ideal inlet efficiency leads to an underestimation of surface storage volumes by up to 25 %. In contrast, the real-efficiency scenario showed delayed concentration times of about 15–20 minutes and peak flows up to 12 % lower than those obtained with the ideal-efficiency assumption. These results demonstrate the relevance of explicitly considering inlet performance in drainage design, since it directly influences flood-risk assessment and the identification of critical points in the urban network.

There are many different types of grids and sinks with distinct characteristics. Some of these capture more flow than others or have a larger free areas. In the design of catchment structures, the elements functioning as sinks (grilles or storm drains) should be approached from a hydraulic perspective. However, in practice, these designs are often determined by their dimensions, shapes, aesthetics, and their integration within the broader context of urban infrastructure. For this reason, manufacturers typically disclose data on the structural behavior of these elements but rarely on their water capture efficiency. (10) Building on this gap, the present study used a previous study as a starting point. This work characterized and classified the existing sinks of the Santa Inés district, North-eastern sector, and developed a hydraulic street model (superficial system) using SWMM 5.1. This model included physical and hydrological parameters of the 271 sub-basins, such as road and sidewalk area, basin width, surface slope, contour lines, percentage of impermeability of sub-basins (100 %), and the directly connected area (% zero-imperv). The basin width was calculated as an inclined rectangular plane whose surface flow travels downslope; thus, the width of the sub-basin is the physical width of the level runoff. The surface slope was calculated using a digital elevation model (DEM). The contour lines were built from the ground levels of the manholes, platforms, and urban planning, with an average slope of 0.4 %. The percentage of the directly connected impervious area, without depression storage related to directly generated runoff, was 100 % (19).

Parameters such as depression storage (Dstore) for permeable and impermeable surfaces were assumed to have a value of 0 without storage. According to the literature, for rough asphalt and brick-paver in cement mortar, the Manning roughness coefficient is 0.016, a value adopted in the model. In order to establish the connection between the street and the sink, the splitter node tool Cutoff or flow dividers were used. These are transport system nodes that are used to divide the flow into two user-defined outlet conduits. They are active only when the phenomenon is analyzed using the Kinematic Wave model. The roadway was simulated as an irregular section, with an average width of 2.8 meters and a curb height of 0.15 m, values typical of the study area (see Figure **6**).

Finally, the present study also builds on the work repotted in [20], which carried out the hydraulic evaluation of 11 types of lateral bottom grids through three-dimensional analysis, high-performance computing to numerically solve the fluid motion equations. The FLOW-3D®

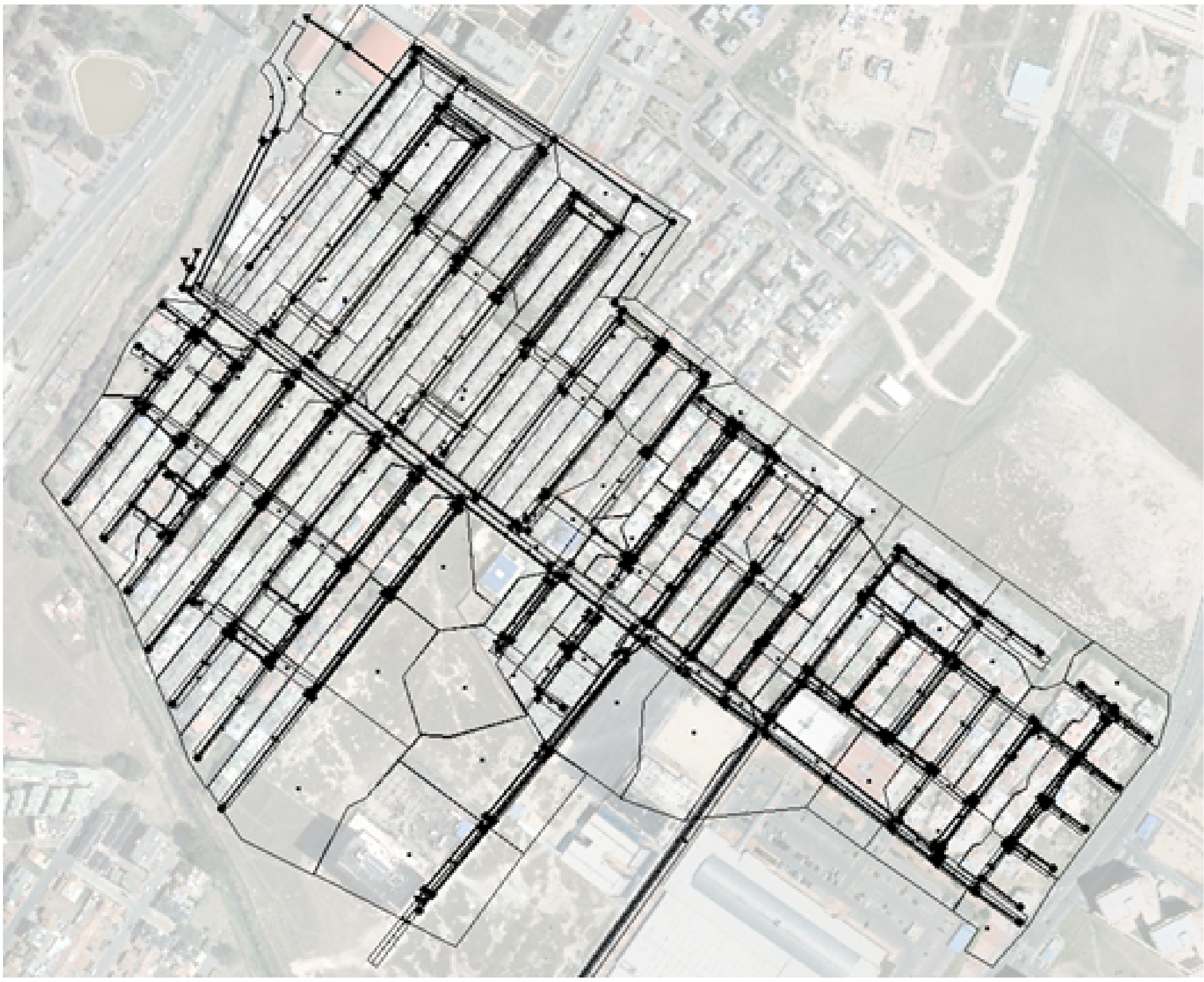

Figure 6. Overview of the integrated hydrodynamic model Santa Inés District Zone 1 and 2. SWMM 5.1

Source: Adapted from (18) and (19).

version 12 solver was used for numerical simulations, with full-scale digital models being created. The typologies of grids found by (19) in the urban drainage system of the area of study were considered. The configuration of the physical experimental model was maintained, and grid typologies were tested for combinations of longitudinal slopes of 1.0 %, 1.5 %, and 2.0 %, with the transverse slope fixed at 1.0 %. Collection efficiencies were determined based on the results of the CFD model, using the flow captured by the grid and the flow that circulates through the street. Table 1 shows the classification of grids and their corresponding collection efficiencies. The hydraulic efficiency ranged between 36 % and 44 %, depending on the grid type, with an average close to 40 %. For example, grid type 6 reached an efficiency of 44 %, while grids 2 and 4 had lower efficiencies of 38 % and 36 %, respectively. These results confirm that inlet typology significantly conditions its capture capacity.

Table 1. Classification and catchment efficiencies of existing grids in the Santa Inés, North-eastern sector

Grid #	Existing Grids a	Efficiency [E] % b
Grid 1		40.00
Grid 2		38.00
Grid 3		39.00
Grid 4		36.00

Grid #	Existing Grids a	Efficiency [E] % b
Grid 5		40.00
Grid 6		44.00
Grid 7		38.00
Grid 8		42.00
Grid 9		39.00

Grid #	Existing Grids a	Efficiency [E] % b
Grid 10		42.00
Grid 11		41.00

Source: Adapted from: a) Abaunza Tabares, K., & Chaparro Andrade, F. (2020), b) Monroy González, H.E. (2021).

Some adjustments were made during the verification process of the original street model. To obtain more reliable numerical results, the area of the holes was adjusted to 3 decimal places and losses due to evaporation were included. The multiannual monthly total average evaporation record of the local UPTC climatological station determined a constant rate equal to 3.18mm/d. Although infiltration losses are negligible, the infiltration model was also adjusted to the curve number method, CN 89. In addition, the Manning coefficient of the pathway was rectified to 0.016. Likewise, each divider node, a description was added indicating the type of Grid according to classification.

The cutoff divider node was used to represent the sinks in the hydrodynamic model. By including a cutoff of 0 l/s, the node is configured in such a way that any flower greater than 0 l/s is diverted and consequently captured through the sink, simulating a grid capture efficiency of 100 %. As the present study seeks to analyze the hydraulic behavior of the surface system (street model); therefore, the following activities and modeling scenarios were carried out:

- Identify type of grid according to database in the database ArcGIS.
- 0 l/s cutoff scenario: Using the modeling report, the peak flow at the splitter node discharge was extracted, keeping in mind that the 0 l/s cutoff configuration simulates 100 % of the sink catchment.

- Calculated cutoff scenario: In this scenario, the cutoff to be included in the hydrodynamic model was calculated with the Equation 5:

$$Q_{cc} = Q_{c0} \cdot (1 - E) \tag{5}$$

Where:

- Q_{cc} = Calculated cutoff flow. Flow that runs along the road or flow that is not captured by the grid (l/s)
- Q_{c0} = Flow cutoff 0. Maximum flow with capture efficiency $E = 100\,\%$ (l/s)
- E = Sink collection efficiency for a road lane and cross slope of 1.0 %
- **Hypothetical cutoff scenario:** For this modeling scenario, a hypothetical cutoff flow was included in the splitter node configuration to simulate the non-existence of sinks

Node configuration in order to simulate the non-existence of sinks: In the calculated cutoff scenario, the catchment efficiency of the sinks was incorporated into the SWMM 5.1 model, based on Equation 5. The model results made it possible to reproduce the flow movement on the road until it reached the sink. This will allow the entry of water flow according to its collection capacity. Subsequently, a spatial analysis of the study area was conducted to identify flood zones where the collectors operate at full flow and the flow ascends through the manholes of the subsurface system towards the street. In addition, streets longer than the 300 meters, draining in a single direction toward a discharge point, were identified. This allows for a varied number of sinkholes to be included in the analysis of the area.

Integrating the characteristics indicated above, through spatial analysis, 7 zones of interest were established (see Figure **6**). They were named according to the ID of the main conduit (subsurface system), PATLAL4785, PATLAL4766, PATLAL10448, PATLAL7609, PATLAL7624, PATLAL4750, PATLAL4719.

For these areas, an integrated numerical modeling of urban drainage was developed to analyze flow behavior within the conduits of the subsurface (minor) drainage system. It was assumed that the entire contribution area drains directly to the manholes, in accordance with the traditional methodology for sewerage design. This condition assumes that collector flow results from the combined contributions of residential connections and surface runoff later captured by sinks. The analysis also included both the total flow that was captured by existing sinks in the area and the surface flow that travelled along the street toward the outlet area without being intercepted by upstream sinks.

The base time of the sink hydrographs was short, since the cutoff flow setting is activated only when the surrounding flow by the road or direct contribution of the basin exceeds the predetermined value. Therefore, a numerical approximation of the hydraulic operation of a sink is achieved; however, the inflow below the maximum capture efficiency of the grid cannot be represented. Under this configuration, it is not possible to numerically represent the flow input to the sink from the beginning the transit of surface runoff, this is only carried out until the instant in which the generated runoff exceeds the cut-off flow configured in the divider node. Through street modeling, we managed to adequately represent the surface flow circulation. The resulting hydrological response scheme differs from the traditional design method: depending on each grid's efficiency, part of the runoff produced within the area is not immediately captured downstream by the sink and continues flowing along the street, modifying the limits of the sub-basins.

As can be seen in hydrographs 1–6 (see Figure **7**), the flow that travels over the street surface to the outlet area without being captured by sinks upstream has a general base time of 100 minutes, with a sustained hydrograph peak. This effectively reproduces the flow behavior over the street surface without rapid drainage, as expected under 1D numerical modeling. This is the case in hydrograph 7, PATLAL4719 Zone, where it is identified that the volume of the installed drains is insufficient. This is because the volume stored in the street and not conducted to the subsurface system is equivalent to 28 % of the volume that passed through the sewerage collector. A base time of 110 minutes with a peak flow of 21.78 l/s in the 40th minute of simulation was observed.

Through the 1D numerical modeling of the urban drainage processes, it was possible to identify traffic and flow accumulation patterns on the streets of the Santa Inés district. Specifically, water depths ranging from 2 to 5 cm were observed between minutes 100 and 110, with localized accumulations in the PATLAL4719 zone. These values were obtained directly from the SWMM model and correspond to the interaction between insufficient inlets and streets with low longitudinal slopes (see Figure **8**).

In the calculated cutoff and hypothetical cutoff scenarios, a flow risk assessment was performed. Considering the maximum water depth criterion, as established in the *Urban Drainage Manual* of Denver, Colorado, USA, and for the city of Mendoza, Argentina. Using the above criteria as a reference, the maximum permissible water depth in the street was defined for the city of Tunja. To prevent water from entering homes and buildings, this value was set at 25 cm, considering the characteristics of the urbanization of the area.

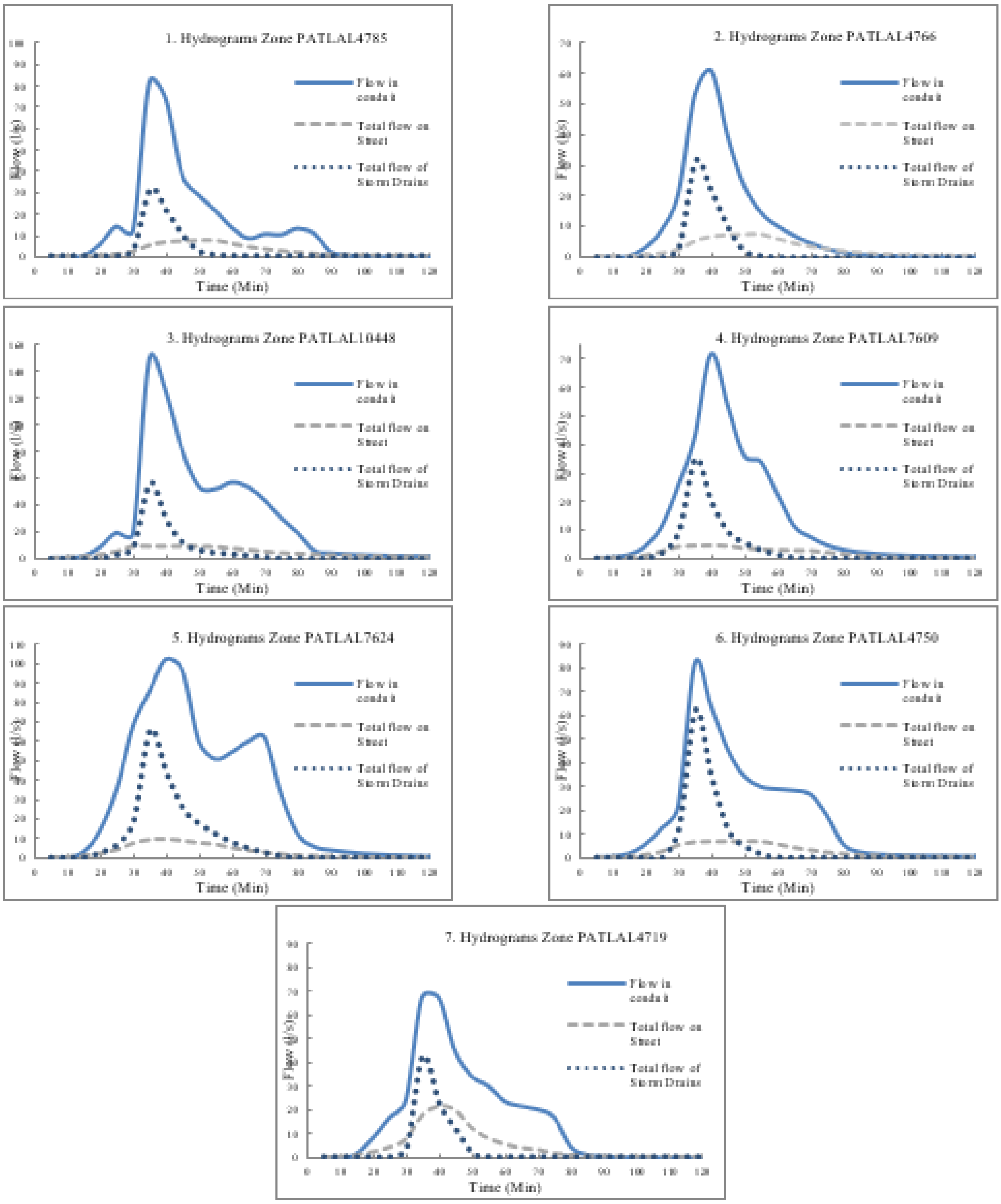

Figure 7. Hydrographs integrated numerical modeling of urban drainage district Santa Inés Northeast sector. Note: In simulations with real inlet efficiency, a cutoff flow of 0.24 L/s per inlet was used, determined experimentally from a triangular weir calibrated in laboratory conditions. This value was included in each hydrograph to indicate the threshold for surface-to-subsurface flow transfer

Source: Author.

Figure 8. Depth of water on roads in the Santa Inés district, Northeast sector Zone 1 and 2. SWMM5.1

Source: Author.

Furthermore, the landslide stability criterion proposed by Nanía Escobar (21) was adopted. It contemplates parameters such as velocity and water depth in the streets. The slip stability of an individual was considered when subjected to the drag forced caused by the water flow to determine this criterion. A threshold was established with a maximum V2 product of 1.23 m^3/s^2. Additionally, to include criteria considering velocity, the approach by Témez (22) was used, which sets a maximum allowable velocity of 1 m/s (see Figure **9** and **10**).

Conclusions

The streets in the study area sector exhibit varying levels of deterioration on the pavement surface, particularly in flexible pavements. It is common to observe subsidence and depressions that facilitate the accumulation of rainwater. The water that, through retention and infiltration, is stored on the surface promotes loss of structural stability. This may be due to the increased humidity in the pavement or foundation layers (23). Consequently, this study successfully numerically represented the inadequate drainage performance of the streets in the analyzed area. It was determined that in Zone 2 there is surface storage represented in a water layer from 2 to 5 cm in the 40th minute of simulation. Thus, we can conclude that the existing system does not have enough installed drains to capture as much water as is produced by the streets and sidewalks.

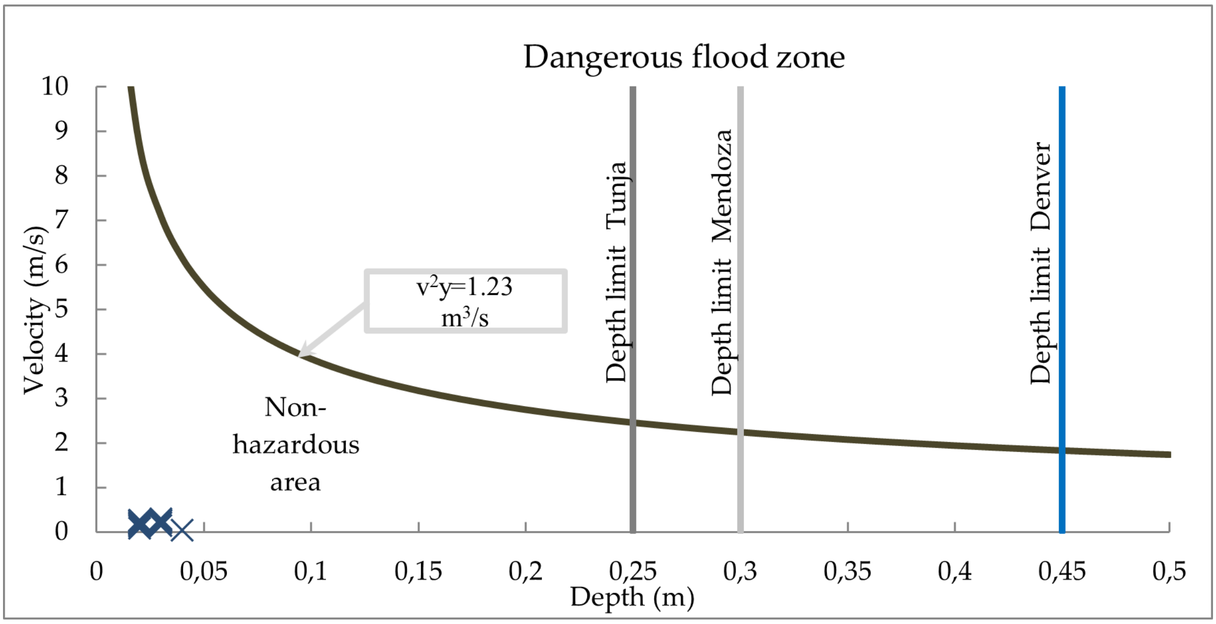

Figure 9. Criteria for the delimitation of the zone of dangerous flooding and landslide stability scenario with sinks

Source: Author.

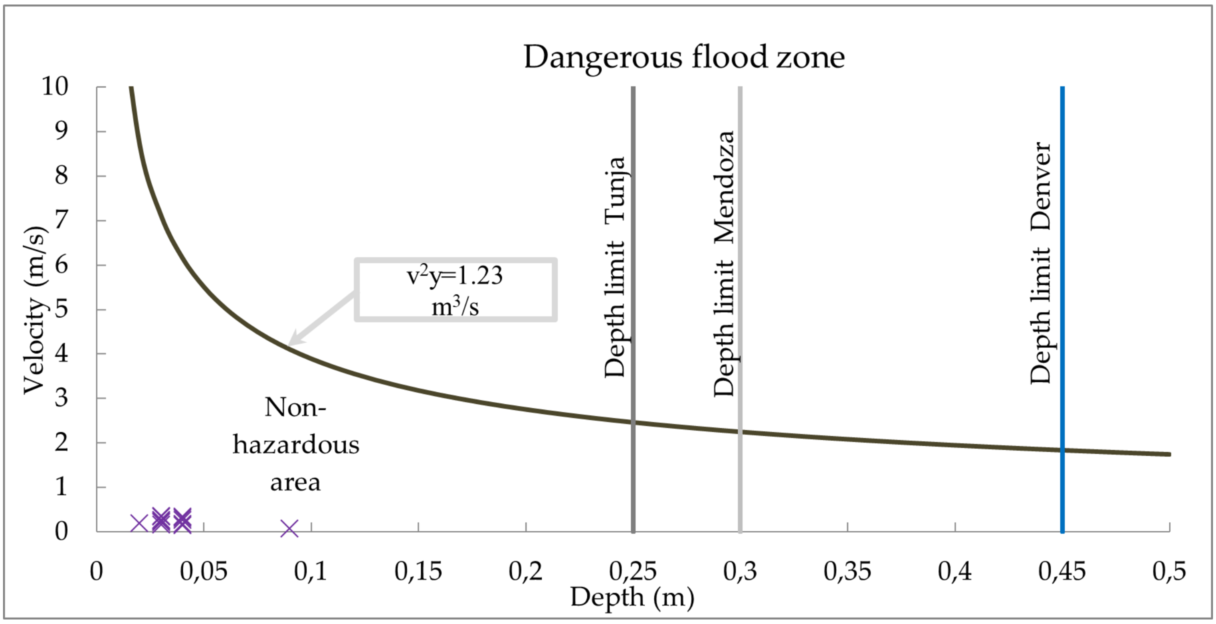

Figure 10. Criteria for the delimitation of the dangerous flood zone and landslide stability scenario without sinks

Source: Author.

The one-dimension numerical modeling of the drainage system under study enabled us to determine the evolution of the velocity and water depth over time, through simulation scenarios with a designed storm associated with a return period of 10 years. It is necessary to mention that the maximum velocity and water depth occur at different moments of time during the simulation. The maximum flow velocity in the study area streets did not exceed the value of 1 m/s; therefore, following Témez's criterion, we can conclude that there is no danger stemming from flow velocity in the study area. However, it is recommended that street flow hazard criteria be evaluated for the historic center of the city of Tunja. This is because the streets in this area act as drainage channels for rainwater due to the inadequate location or absence of sinks, steep slopes, and the limited capacity of the existing drainage system.

Ensuring the correct functioning of urban drainage infrastructure is essential. It should be highlighted that one of the main benefits of this is the social impact in the study area. Adequate operation, planning, and provision of public services mitigates urban development risks, such as flooding, overflows, and network clogging, while improving the quality of life of residents and contributing to the sustainable development of cities.

The aforementioned preliminary studies have shown that the problem of flooding in the city is not solely caused by overflow of the Jordan River and the Vega Stream, but is also associated with the low efficiency of the constituent elements of the conventional combined sewerage network. From an academic perspective, we propose to contribute to the development of new methodologies and the construction of tools that promote hydraulic study and knowledge, as well as the understanding of urban drainage structures. In doing so, we can continue to lay the groundwork for the future formulation of technical regulations in the water management sector.

Author contributions

Melquisedec Cortés Zambrano. Wrote the paper, simulated scenarios of drainage, designed the analysis, hydraulic analysis. Carlos Andrés Caro. Conceptualization, Formal analysis, Methodology, Drafting - original draft Monica Lara. hydraulic analysis, methodology, advice.

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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.

Institutional Review Board Statement

Not applicable for studies not involving humans or animals.

Informed Consent Statement

Not applicable for studies not involving humans. You might also choose to exclude this statement if the study did not involve humans.

Data Availability Statement

In the next link are the data supporting reported results can be found, and datasets analyzed or generated during the study.
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Conflicts of Interest

The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

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