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WATER SCARCITY IN AREAS WITH HIGH DENSITIES IN THE GUADALAJARA METROPOLITAN AREA, A CHALLENGE FOR THE YEAR 2050

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Abstract: The Metropolitan Area of Guadalajara (AMG) has experienced a remarkable development since the 90's and an accelerated growth since 2015, leading to a change and use of soil that has caused significant alterations to runoff, as well as a decrease in infiltration to the subsoil causing crop losses as a result of erosion. Among the factors contributing to the serious water crisis we can mention the following: non-compliance with water security plans, inadequate Integrated Water Management, in addition to an extreme concentration of water by a few. The objective then is to determine the magnitude of rainfall runoff in the lower part of the basin, as well as the hydrographs before and after urbanization through the collection of information on physiographic and climatological characteristics of the watersheds: Real del Valle, Santa Fe, Chulavista and Unión del Cuatro, as well as to determine the peak flows with return periods up to 100 years. The methodology used was the application of the American rational formula using probabilistic and statistical models and using log normal, Gumbel and Pearson distribution functions. These values of average precipitation and rainfall intensity were obtained with information from the Tlajomulco climatological station. The solution would be for the information generated with metadata to be conclusive, indicating the existence or modification of the natural channels through hydraulic works that alter the regimes of the currents, for which reason it is recommended that the data sample be ample and if it is small it is convenient to carry out additional studies, such as rainfall-runoff.
Keywords: Erosion, runoff, hydrographs, urbanization, watersheds.

INTRODUCTION

Water is a universal right for all living beings on the planet, but today it has become a commodity that costs us more and more to extract it from more distant sources, for these reasons and many more exposed in this article, the struggles for water are increasingly complex, as has been documented since 2004 by the construction of La Parota Dam in the state of Guerrero by the Federal Electricity Commission (CFE), affecting the municipalities of Acapulco, Juan R. Escudero and San Marcos.

In addition to being a right, water is the most important natural resource for human subsistence, which is why people's quality of life is directly affected by the lack of access to this resource. Despite the fact that 70% of the planet's land surface is covered with water, only 2.53% of this vital resource is suitable for human consumption, to cite just one case the situation in our country is not only critical but unfavorable, since only less than 1500 m^3/inhab/year is available (Virtual Water Information Center, 2017) what considered by the UN as a strong pressure of closed areas, it should be noted that a closed area are aquifers, where additional water uses are not authorized to those legally established (CONAGUA, 2014).

The water crisis is directly related to the adverse effects of Global Climate Change (GCC) (UN-Water, 2001). We know that the increase in the variability of the hydrological cycle has catastrophic effects, most of the time due to anthropogenic effects, as we can document in publications and written press: floods in urban areas, prolonged droughts in most of the Mexican territory, forest fires with losses of large extensions of land, just to mention a few, as a consequence, the challenges are increasingly greater (Taiba, 2021).

Within this context, Guadalajara, Jalisco, the second most densely populated city in the country, is no exception due to its vulnerability to both water shortages and its own excesses in the form of extreme hydrometeorological events. Two thirds of the country suffers from water shortages of good quality, and most homes in the suburban areas of the Guadalajara Metropolitan Area (AMG) do not have efficient water systems.

The lack of water is a much more difficult situation than the 2020 pandemic itself, the lack of sanitation in urban type basins affects the vast majority of the population in Mexico (González Villareal, 2017), as they are closely linked to technological development and the inordinate policies of privatizing the water resource, it has undoubtedly increased the quality of life of a good part of the population.

Cases such as La Parota dam, Guerrero, is not the only one in the issue of environmental and ecological fragmentation, due to megaprojects, the state of Jalisco is in the sights of international agencies, projects such as El Zapotillo dam for more than 15 years, is an issue that is becoming increasingly complex, due to population growth in the Metropolitan Area of Guadalajara (AMG).

The positive and negative effects are sides of the same coin, whose impact affects the poorest population, on the one hand, the lack of commitments in a society of great imbalances and injustices where a minority concentrates the greatest wealth on the planet and a large majority concentrates the crudest misery (Martinez, 2010).

One of the challenges facing humanity is the construction of an efficient water infrastructure with drinking water, sewage and sanitation services, especially for the most vulnerable sectors of the population with scarce resources (Duran-Juárez, 2005).

Precisely, an alternative to avoid more construction of dams or multipurpose dams is the implementation of public policies with actions focused on the integral solution of water, that is, that it be distributed fairly and equitably to all users, avoiding more concessions to large industries such as soft drinks or breweries, which are the main consumers and demanders of water (Vázquez, 2023).

The water supply problem will not end with the construction of more dams but with the creation of a water culture among citizens, local actions such as the control of household leaks, rational use of supply sources, as well as alternative methods such as rainwater harvesting, better operation of wastewater treatment plants, it should be noted that Jalisco is the state with the largest number of non-operational plants (CONAGUA, 2022), but above all, priority should be given to comprehensive management of groundwater and aquifers (Duran, 2006).

In this context, we analyze vulnerability through different variables, from its distribution and variability, presenting as a case study the municipality of Tlajomulco de Zúñiga and its neighborhoods that compose it, taking as a starting point: floods, water scarcity, elements of vulnerability, such as: risks, threats and insecurity, to name a few.

On the other hand, extreme hydrometeorological events, such as climate change, together with urban expansion without any Urban and Territorial Management Plan, have caused considerable damage in recent years, mainly in the southern area of the AMG, which has caused a high increase in points vulnerable to flooding, as well as heat islands, increasing the temperature increase year after year, resulting in greater vulnerability to the population (Das *et al*, 2023; Darabi *et al*, 2019).

As well as the damages described above, the water crisis is directly related to the adverse effects of the GCC. The increase in the variability of the hydrological cycle has caused catastrophic consequences, prolonged droughts in the center and north of the country, forest fires with loss of large areas of forests, as a consequence, the challenges are increasingly greater, to ensure that all humanity by 2030 has basic drinking water supply services, in addition to making communities more resilient and sustainable, as mitigation strategies.

BACKGROUND

Mexico is one of the 12 countries with the greatest diversity in the world, occupying fourth place in biotic richness, manifested by the large number of plant and animal species in its diverse ecosystems. The municipality Tlajomulco de Zúñiga presents the confluence of two large biogeographic regions: the Nearctic and the Neotropical, which allows it to have excellent conditions for a great faunal and floristic biodiversity (Michel, 2017).

The fauna of our country is one of the richest in the world, for example, Canada and the United States together register 2187 species of terrestrial vertebrates, while in Mexico there are about 3032 species (Flores, 1994).

For these and other reasons, Mexican soil gathers a high proportion of flora and fauna worldwide, only 1.3% of the land emerged from the sea, concentrates between 10 and 15% of terrestrial species, occupies the first place in the world in reptile species (717), the tenth first in birds (1150) and possibly the fourth place in angiosperms (flowering plants). These and other reasons place us, as noted above, among the twelve countries with the highest diversity (Jiménez, *et al.,* 2014).

However, the municipality of Tlajomulco may lose its biological richness if the instruments of the Land Use, Territorial and Ecological Management Program (POTE) are not put into practice, because the Metropolitan Area of Guadalajara (AMG) has experienced significant development and growth since the 1990's and accelerated after 2010, This has led to changes in land use, which was originally intended for agriculture with high yields and dense vegetation of some forests, now urbanized and paved (Torres, 2013).

These dynamics of population growth and urbanization in the Tlajomulco valley have characterized the basin in recent decades to face severe problems caused by the degradation and deterioration of the environment (Nápoles, 2022), constituting an indiscriminate use and exploitation of its natural resources, today more than an opportunity for the most vulnerable population of Tlajomulco is a constraint for development.

Tlajomulco de Zúñiga is one of the municipalities with the highest real estate growth, but also one of the areas with the highest risk of extreme hydrometeorological phenomena: droughts, floods, sinkholes, subsidence, etc. It should be noted that the Tlajomulco watershed, together with the El Ahogado watershed, has been characterized in recent years by the fact that only a rainfall intensity of 15 mm/hr is enough to cause waterlogging and flooding of considerable heights (Valdivia, 2022).

The El Ahogado watershed, located in an environment of extrusive volcanic origin, presents climatic variations that influence the presence of numerous plant communities arranged in contrasting soil types. As a result, biodiversity is extensive and offers numerous environmental services to the population (Chávez 2009). It should be noted that most of the territory of the El Ahogado watershed belongs to the municipality of Tlajomulco, its surface area occupies approximately 48% of its territory and its use for housing is 25%, but the authorized by the development plans gives it the possibility of increasing up to 35% (De Anda, 2022).

In addition to the natural reserves, the situation of the settlements indicates that in the medium term 50% of the area will be urbanized. Currently, the forested area is 60%, but this could be reduced to 40% based on the partial urban development plans that are implemented (Inegi, 2020). In addition, the intense agricultural activity and, in recent years, technified agriculture for agave production have resulted in a constant loss of vegetation cover and degradation, which has caused irreversible damage, such as soil impoverishment and erosion.

The aforementioned changes in land use can be seen throughout the valley zone, which is predominantly agricultural and is now totally urbanized (without any urban development plan), since the infrastructure for rainwater collection and absorption wells for groundwater recharge is not capable of removing the volumes precipitated by torrential storms (Valdivia, 2000).

These transformations and alterations in the hydrological water cycle, mainly the decrease in natural infiltration of rainwater into the subsoil, have resulted in the identification of about 350 points vulnerable to flooding in the AMG, as shown in Figure 1 (*ibid,* 2020), of which 100 points have occurred in the municipality of Tlajomulco. Consequently, hydrological problems occur in the lower part of the watershed, mostly covered by housing developments since many natural watercourses or streams have been modified, invaded or even disappeared (Ramirez, 2012).

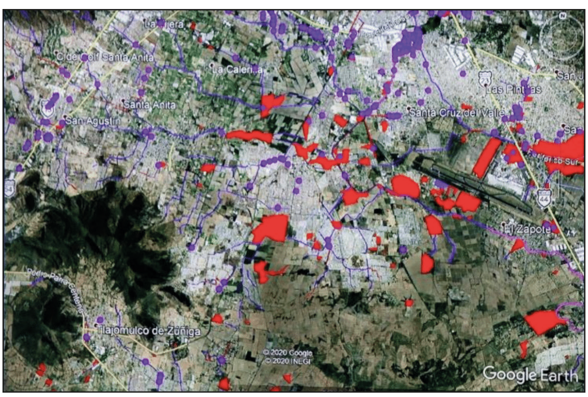

Figure 1. Flood vulnerable points in the Guadalajara Metropolitan Area

Source: Google Earth, 2022

PROBLEM STATEMENT

Urban growth without a Land Use and Ecological Management Plan is the real cause and consequence of natural disasters, in other words, the public policies that have been implemented have not been of much use, since the real problem lies in the lack of maintenance and operation of the Wastewater Treatment Plants (Tucci, 2006).

Of the centralities proposed by Imeplan in its POTMet for the determination of risk and disaster management, it emphasizes that despite the rainwater infrastructure built in the south of the AMG, flood risk points continue to increase year after year.

Regarding areas vulnerable to flooding (Valdivia, 2021) has identified at least 100 points, among them: Villas de la Hacienda, Jardines del Edén, Geovillas, La Arbolada and Villa Fontana, Real del Valle, Santa Fe, Chulavista, Unión del Cuatro, to name just a few, since one of the scopes of this work is to determine peak costs with return periods Tr from 2 to 100 years, based on probabilistic and statistical models, in order to identify flood plains.

The real causes and consequences of flooding have been practically due to a bad GIA, in short, a drainage and sewage network built in the 80's. As a consequence, the drainage network is already obsolete; what we are looking to achieve in the short and medium term is to implement a much more efficient hydraulic and sanitary infrastructure free of household leaks.

On the other hand, an insufficient design of storm drains, as well as their location, as a consequence of an accelerated and poorly planned growth without any Urban Development Plan, as mentioned above. In addition, there is a total lack of knowledge of the topography of the Valles de Tlajomulco area (areas invaded by irregular properties that originally belonged to the streams and creeks).

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PROBLEM

The Ahogado watershed is located southeast of the MGA (20° 38'N and 103° 15'W), where it extends along the Santiago River (at an altitude of 1550 meters above sea level) with an area of 520 km². It covers portions of five of the 12 municipalities of the AMG, which are divided into: 48% of the territory for Tlajomulco de Zúñiga, 21% Tlaquepaque, 13% El Salto, 13% Zapopan, 5% Tonalá, in addition to 30 ha for Guadalajara (De Anda, 2022).

This basin is divided into 13 sub-basins according to their importance and magnitude: Arroyo de en Medio, El Maleno, El Cuervo, El Mulato, El Guayabo, La Teja, Arroyo Seco, La Rusia, El Cuervo de Abajo and three portions of the territory belonging to the El Ahogado dam (Aguilar, 2005), among them the Presa El Guayabo sub-basin, where about 50 points vulnerable to flooding have been fully identified, for which reason a series of hydraulic works have been proposed as flood control works mainly regulating vessels in the lower part of the basin.

The El Guayabo dam sub-basin is part of the El Ahogado watershed and is located in the municipality of Tlajomulco de Zúñiga, Jalisco, between the geographical coordinates 103° 25' longitude and 20° 31' latitude at an average altitude of 1555 meters above sea level (Chávez, 2015) and crosses as its most important social and economic points the town of San Sebastián El Grande, In terms of basic services, 90% of the population has water infrastructure and sanitary and storm sewage services. The most important watercourses and streams are San Juanate and Arroyo Seco, both of which are treated at the El Ahogado Wastewater Treatment Plant (PTAR El Ahogado).

Faced with the extreme hydrometeorological events presented in recent years and the consequences they have caused in the AMG, the authorities have implemented instruments such as: Metropolitan Land Management Plan (POTMet, 2016), Action Plan for Climate Change in the AMG, Metropolitan Risk Atlas, as well as the Water Agenda for the AMG (Imeplan 2016 and Imeplan-UNAM, 2021). These instruments were developed and implemented between 2015 and 2021 and show a commitment to risk management associated with the climate crisis, but especially with urban and disorderly growth.

These Urban and Territorial Management plans mentioned above, have led us to seek paradigm shifts in watershed management, which has led us to introduce the concept of Zero Hydrological Impact (IHC), which takes the idea that the increase of impervious areas within cities should not increase peak flows within the allowed, estimated by *rainfall-runoff* hydrological models, so that if these are controlled, flooding in vulnerable areas can be avoided.

The IHC should be applied when executing a development project, whether urban, industrial, agricultural, infrastructure, transportation, or a combination of these, and if there is no modification to the hydrological cycle of water in its natural state or generating the least possible impact, then the goals and objectives of the IHC are being met (USGS, 2019).

NATURAL ASPECTS

The Guayabo sub-basin is divided into two micro-basins, according to the Local Ecological Management Program of Tlajomulco, these are: Arroyo Seco-San Juanate with an area of 49.37 km² and Culebra-Colorado with an area of 39.57 km². The former collects runoff from the streams that give it the same name and ends at the confluence with the Seco stream and its tributaries, integrates the waters from the micro-watershed and flows into the El Guayabo dam, while the Culebra-Colorado micro-watershed contains a significant portion of undeveloped areas.

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The San Juanate stream micro-watershed as it has the lowest parts of the sub-watershed contains the localities of Santa Anita, San Agustín and San Sebastián, these three localities concentrate most of the population of the municipality of Tlajomulco de Zúñiga, Jalisco (Aguilera, 2015), as shown in Figure 2.

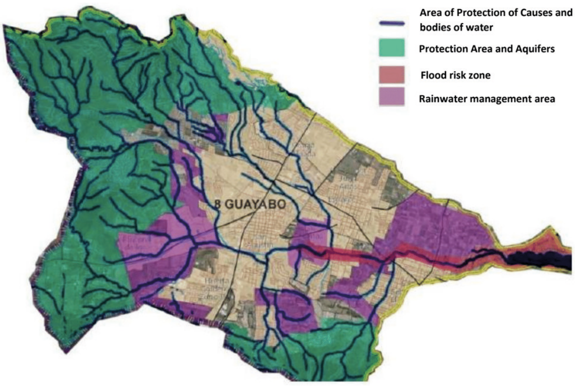

Figure 2. Physiographic characterization of the Guayabo dam basin

Source: Aguilera-Cortez, 2015

OBJECTIVES

One of the objectives of this work is to determine and estimate the physiographic characteristics of the Tlajomulco valley watershed, as well as the magnitude of rainfall runoff upstream and its peak discharge that accumulates downstream. These results will be obtained based on *rainfall-runoff* models with return periods Tr from 2 to 100, in order to have an optimal design of the hydraulic works to be implemented in the lower part of the basin.

Particular Objectives

As for the specific objectives to be achieved, the first is: to gather climatological and statistical information (Tlajomulco Climatological Station) which will have information on maximum rainfall in 24 hours, as well as to apply the American rational formula before and after urbanization, to have a better control of runoff, and finally to evaluate peak flows for return periods Tr from 2 to 100 years, due to changes and land use, in the aforementioned neighborhoods.

JUSTIFICATION

In recent years due to the consequences and adverse effects of the GCC, the topic has been taking more and more strength and interest by civil society the science of Hydrology especially in the management of stormwater, this is appreciated the clear advances that have presented both Mexico City and Guadalajara, the two most important metropolises in the country (Caro, 2018).

The initiative arises with the aim of achieving a better control of surface runoff, as well as acting jointly: society-government-entrepreneurs-university, in order to implement real-time runoff measurements, mainly in the lower part of the Tlajomulco-El Ahogado basin, which arises under the idea and implementation of the IHC as we pointed out above, that the peak flows Qp do not exceed both in quantity and magnitude to those estimated in the return periods, in other words if these are kept within a regime less than the critical, floods can be controlled in the lower parts of the basin.

STATE OF THE ART

Zero Impact Urbanization. The new paradigm

There are many ways to be able to control the effects of urbanization, it is only to think and there are many ways to carry out processes of Retention-Detection of rainwater, obviously all these valued from the technical aspect and go from a non-structural measure that is the correct planning of the system of evacuation of rainwater to structural measures consisting of control works, which are basically necessary even indispensable to reduce the peak flow of the hydrograph of the floods that occur and accumulate downstream (Caro, 2018).

However, in some places where long-lasting rainfall occurs, it is necessary to evaluate the volume of precipitation to know whether our work will lower the maximum peak of the hydrograph or only delay it, since the drainage works are designed to evacuate the maximum flow and if this is exceeded we would be having the already known consequences due to extreme hydrometeorological phenomena (Ponce, 2008).

Urbanization is a phenomenon that has accelerated in recent decades (it is predicted that in the coming years 90% of the population will be concentrated in medium-sized cities and metropolises) and this leads to an exacerbated concentration of the use of natural resources, fuels and raw materials, as well as the disposal of large amounts of solid waste and poor air quality due to the high emission of Greenhouse Gases (GHG), to name but a few (Bárcena, 2001).

On the other hand, the problem lies in the obsolete models of urban and territorial planning, since the changes in land use for low densities by creating buildings whose infrastructure in neighborhood areas are not designed for high population densities and the effects are noticed in an irreversible increase in traffic, decreased water pressure or that the buildings cause the loss of sight and the concealment of sunlight (Eibenschutz, 2022).

For example, in recent years at the international level and due to the effects of Climate Change (CCG) has caused innumerable floods around the planet (Olcina, 2008) and science of hydrology in the sustainable management of rainwater has been gaining strength and interest by civil society, as can be seen in the clear advances in this area both in Mexico City and in the city of Guadalajara, the two most important metropolises.

The purpose of the initiative is to achieve better management of surface runoff and thus control and mitigate flooding in the lower parts of the basin from upstream runoff caused by the sudden and irreversible increase in flood traffic.

The paradigm shift to follow seen from watershed management, is to modify anthropogenic actions in a rational way, prioritizing the conservation of the environment and its natural resources (Moreira, 2018), such is the case of the municipality of Tlajomulco de Zúñiga, which has been implemented under the idea that increases in impervious areas within the cities do not increase peak flows, i.e., if these are conserved, flooding can be controlled in the lower parts of the basin, which is where the greatest collateral effects occur.

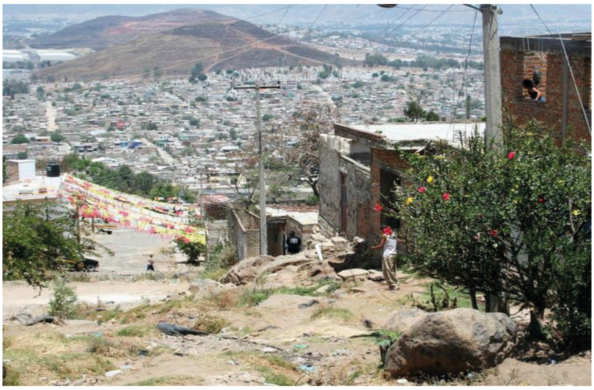

Figure 3. The effects of urbanization in high risk areas

Source: www.informador.com

The effects of accelerated urbanization without proper planning and resolution of problems, tends to increase environmental degradation and as a consequence greater vulnerability to natural disasters (Jordan, 2017), with terrible consequences for the population, so urbanization affects the hydrological cycle due to increases in expenditure and surface runoff velocities in the affected area, such increase causes greater intensity in receiving streams and downstream areas of the basin.

It is common that the development plans of a city are not linked to the results of a particular hydrological study in order to take measures concerning the problem of flooding, which is a warning situation. The problems that are presented to the observed changes are:

- An increase of 50% of the mean annual runoff
- An increase of a factor of almost 3 times the average annual flood (instantaneous peak).
- A 3-fold reduction in the delay time of the Triangular Unit Hydrograph.
- A 3.5-fold increase in peak spending, also from the HUT

The solution to the problem is a stormwater drainage system that integrally solves the possible contributions due to the increase of the city; the drainage subsystems are part of the great urban environmental system. Ideally, stormwater management and control of peak floods generated at El Guayabo Dam should take into consideration all the important interrelationships, as well as the quality and quantity of runoff.

Prior to urbanization, a large portion of the total rainfall contributes to soil moisture and groundwater recharge through infiltration and percolation, or is detained in the form of surface storage. Generally direct runoff accounts for 25% to 30% or less of the total storm in a natural area. After urbanization, both the volume and the velocity of runoff suddenly increase, resulting in irreversible damage to hydraulic infrastructure.

The Imeplan in its study (2021) in its study *"Characterization of the aquifers of the Metropolitan Area of Guadalajara"* mentions that the AMG is delimited seven aquifers, among which, the aquifers that cover the municipality of Tlajomulco are: Toluquilla and San Isidro, which shows no difference based on the different lithological units, geological structures, soil types, vegetation cover or soil and only mark a unit that agglutinates notable differences in the aforementioned parameters. However, Garnica (2017) in his master's thesis: *"Geological-Geophysical Analysis to determine the aquifer recharge zones in the AMG"*, mentions that there have been modifications both in land use and in the configuration of the drainage network, in addition to the fact that the emergence of new subdivisions has expanded the impervious area in the basin, particularly El Ahogado.

As a result, the natural flow network has been modified by drainage systems and sewage works, which have led to out-of-normal peak flows, causing increasingly sudden and intense flooding in the AMG.

On the other hand, in flood generation and control projects, the immediate concern is generally what to do with the water that generates local flooding in the lower parts, since the water comes to the surface and gushes through the sewers in a sudden way through the sanitary and storm drains; but in the end what is achieved is only to transfer the problem from one place to others downstream, which in a very short future will be in the same circumstances as the current one.

In practice, flooding conditions have worsened in the lower basin of the point of interest and have required the construction of costly subway conveyance systems. On the other hand, the control measures that have been used, such as infiltration zones, rooftop storage, parking lots and urban recreational lakes, have been insufficient because runoff in urbanized watersheds increases by up to 200%.

Effective flood control planning should be based on the watershed as a systemic unit, i.e., it should be studied from a watershed management approach, in other words, preparing the watershed for a master drainage project that incorporates the complete drainage system, This consists of a system of pipes of commercial and economic diameters and another that will consist of an urban drainage system consisting of a system of collectors, canals and emitters, either subway or surface, since the lack of coordination in urban planning and the change of land use forces many cities to undertake costly programs for flood control.

MATERIALS AND METHODS

Based on the rainfall-runoff methodology and the rational American formula, the following results were obtained: hydrology, vegetation cover, design costs and triangular unit hydrograph, which show the problems regarding water scarcity as a result of the levels of depletion of the Toluquilla aquifer, so that a spatial modeling and three-dimensional views were used with the QGIS 3 program (qGIS, 2024), from which clear maps and visual presentations were obtained that reflect the degree of overexploitation, as shown in Figure 4.38 (qgis, 2024), from which clear maps and visual presentations were obtained that reflect the degree of overexploitation, as shown in Figure 4.

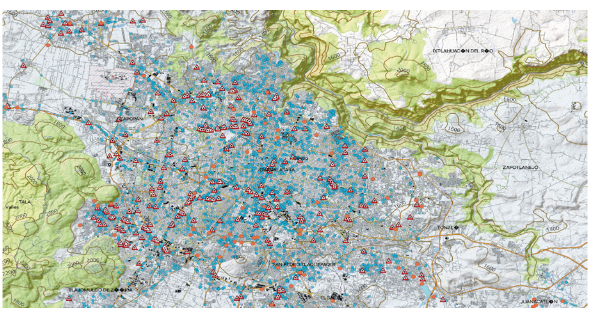

Figure 4. Vulnerable points to flooding in the Guadalajara Metropolitan Area

Source: Metropolitan Information and Management System, 2023

In this work, the methodology to be implemented proposes tools to integrate a mapping of historical events to know where flood risks have been recorded, in addition to identifying, describing and quantifying areas that may be affected in the future.

This method is based on the generation of new cartography of environmental variables susceptible to flooding and their spatial representation with the help of spatial interpolation procedures (Valdivia Ornelas, *et al.*, 2005):

a) Climatic: precipitation, evaporation and temperature

b) Hydrological: surface and groundwater runoffs

c) Relief: analysis of contour lines, slope orientation, topographical slope

To determine possible relationships between environmental attributes and water availability with vegetation distribution, arithmetic and algebraic operations were developed from LandSat images of various seasons, as shown in Figure 5.

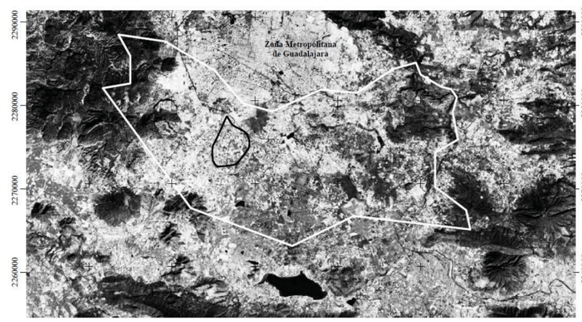

Figure 5. El Ahogado Basin in LandSat Image

Source: GEOEX, 2022

It is found that the factors that favor water retention for biological processes are the presence of gentle topographic slopes, high values in attributes and high values in attributes of relief surface (storage). The climate in this case exerts a great influence on the modifications that the relief undergoes in the conformation of the nature of the soil and in the spatial distribution of living beings.

The manifestations of climate are linked to the daily life of all living beings, so that activities such as technified agriculture, livestock, fishing, industry, commerce or transportation, have a strong relationship with the physiogra-

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phic characteristics of the terrain, especially the slope, which influences the vegetation or fauna, and also influences health, recreation, comfort, clothing and housing (Chávez Hernández, 2009).

Climatology describes statistically the average behavior of the main atmospheric variables such as temperature, precipitation, humidity and atmospheric pressure in a given place. The basic information for the climatological analysis consists of daily records obtained from the Tlajomulco climatological station, located within the municipal capital, which is shown below.

In order to achieve the specific and general objectives, a detailed investigation was made on the physiographic characterization of the basin based on AMG cartography, as shown in Figures 4 and 5, due to the involvement of several factors such as soil types, rocks, relief, slopes, vegetation, surface, length of the main channel, precipitation, time of concentration, dimensions of the channel due to both natural and urbanized conditions, these factors present variations along the channel.

For this reason, probability and statistical tools, such as the rainfall-runoff model, will be used to determine peak discharge Qp. To determine the discharge or flow that reaches an outlet point, it can be seen that during the first minutes of the storm the intensity is very high, but since the time of concentration is very short, the entire basin has not been drained, so the discharge that passes through an outlet point is not very large.

The American rational formula was used to determine the peak flow rate Qp, based on the runoff coefficient for both urban and non-urbanized areas. It is worth mentioning that these coefficients are extremely important in hydrology, since they determine the soil's capacity to retain, evaporate and infiltrate rainwater.

The runoff coefficient c is the ratio between the sheet of water precipitated on a surface and the sheet of water that drains superficially, this ratio can be obtained by experimental methods, however, there are runoff coefficients associated with the soil types indicated in Table 1 extracted from the Manual of Drinking Water, Sewerage and Sanitation (MAPAS; 2018).

TYPE OF DRAINED AREA		
	Minimum	Maximum
Commercial Zone	0.75	0.95
Neighborhood	0.50	0.70
RESIDENTIAL AREAS		
Single-family	0.30	0.50
Spaced multifamily	0.40	0.60
Compact multifamily	0.60	0.75
Semi-urban	0.25	0.40
Residential houses	0.50	0-70
INDUSTRIAL ZONES		
Spacing	0.50	0.80
Compacts	0.60	0.90
Cemeteries and parks	0.10	0.25
Playing fields	0.20	0.35
Suburban areas	0.10	0.30

Table 1. Runoff coefficients C, for different types of terrain.

Source: Drinking Water, Sewerage and Sanitation Manual (MAPAS) of the National Water Commission.

APPLICATION OF THE AMERICAN RATIONAL FORMULA

The rational method is one of the most widely used for estimating the maximum flow associated with a given design rainfall. It is normally used in the design of urban and rural drainage works, and has the advantage of not requiring hydrometric data for the determination of maximum peak flows (Breña, 2013).

Most empirical methods have been derived from the American rational method, the first to use it being Kuichling (1989). However, other authors cite that the basic principles of this method were developed by Mulvaney (1851).

The expression used by the rational method is:

$$Qp = 0.278\ c\ i\ A \qquad \text{ecn. 1}$$

where:

c = coefficient of runoff on heath = 0.20

c = runoff coefficient in urbanized area = 0.85

i = rainfall intensity with duration equal to the time of concentration of the basin and with frequency equal to the desired return period = 62 mm/hr.

A = area to be served 500 ha

tc = time of concentration = 15 min ~ 90 *seg*

APPLICATION OF THE RAINFALL-RUNOFF MODEL

The estimation of peak costs is too complex without hydrometric information, so tools such as probability and statistics are used to present alternative solutions through necessary hydraulic works, such as: rectification of riverbeds, streams and storm water channels.

The quantification of rainfall costs is commonly carried out with the rational method or, if additional data is available for the project, such as the runoff coefficient of the land in urbanized and undeveloped areas, the *rainfall-runoff* model is used.

The rainfall-runoff model was used to determine the peak discharge. This methodology consists of determining a base precipitation height, which will be associated with a storm duration of 1 hour and a return period of 10 years. From this, the specific design precipitation height is determined, for which the precipitation is affected by three factors that are related to the time of concentration tc, basin area Ac and return period Tr that has been chosen to interpolate the data.

These factors were estimated after several analyses such as: Log normal, Pearson III and Gumbel, whose purpose is to establish a congruent relationship between the amount of rainwater and runoff volumes, their values have been arranged in a practical range, as shown in Table 2.

Calculation of the peak expenditure for return periods Tr from 2 to 100 years

The estimation of natural runoff is very complex, due to the involvement of several factors such as soil types, rocks, relief, slopes, vegetation, catchment area or basin, length and dimensions of the main channel, precipitation, because being natural conditions, these factors present variations along their trajectory.

For this reason, in order to determine the peak discharge, it is necessary to plan the surface and subsurface runoffs to be analyzed, grouping sections that have a certain common behavior. To determine the discharge or flow that reaches an outlet point, it can be seen that, during the first minutes of rainfall, the intensity is very high, but as the time of concentration tc, has not reached to drain the entire surface of the basin, so the discharge that passes through the outlet point is not very large.

As the time of concentration elapses, the basin begins to contribute more water due to the fact that the area drained is greater, since the intensity of rainfall decreases.

The constant equivalent slope S of the El Ahogado watershed was obtained with the Taylor-Schwarz formula, which is as follows:

$$S = \left(\frac{\sum_1^n li}{\sum_i^n \frac{li}{\sqrt{Si}}}\right)^2 = \left(\frac{6051}{96761.91}\right)^2 = 0.0039 \qquad \text{eqn. 2}$$

To determine the peak discharge of maximum floods, the second step is to calculate the time of concentration, which is the travel time of the water from the beginning of the basin (upstream) to its own outlet (downstream). The time of concentration tc refers to the time it takes for the water to travel between two determined points, which are: the upper end

Storm duration (hr)	Recommended factor	Basin area km² (km²)	Recommended factor	Return Period (years)	Recommended factor
0.50	0.79	1.00	1.00	2	0.67
1.00	1.00	10.00	0.98	5	0.88
2.00	1.20	20.00	0.96	10	1.00
8.00	1.48	50.00	0.92	25	1.15
24.00	1.50	100.00	0.88	50	1.25

Table 2. Adjustment factors to determine the specific design precipitation

Source: Regional Water Management of the Valley of Mexico GRAVAMEX

Class interval dimensions msnm	Difference in dimensions m	Horizontal distance between contour lines m	Slope for each segment	$Si^{0.5}$	$\frac{li}{Si^{0.5}}$
1560 - 1550	10	676	0.0147	0.1212	5577.55
1550 - 1540	10	1900	0.0052	0.0721	26532.28
1540 - 1530	10	3475	0.0028	0.0536	64832.08
		Σ = 6051			Σ = 96761.91

Table 3. Slope data by segment of the El Ahogado watershed.

Source: Own elaboration

of the basin and the point where the rainfall runoff is measured, the time of concentration refers to the time it takes for the rainwater to travel from the entry point to the exit point, this only applies to exorheic basins. In the case of surface runoff, it is obtained using Kirpich's formula, which is as follows:

$$tc = 0.0003245 \left(\frac{lc}{S^{0.5}}\right)^{0.77} = 0.0003245 \left(\frac{6051}{0.0039^{0.5}}\right)^{0.77} = 2.24\ hr \qquad \text{ecn. 3}$$

Development of the hydrological study

This part of the study as a whole constitutes one of the core activities to conclude the research work, since it is here where the amount of rainwater produced in the entire basin and in the different sub-basins that comprise it is determined, as well as the magnitude of the volumes that flow through the channels of the main streams, for this purpose it is divided into three sections: physiographic characteristics of the basin, analysis of precipitation and return period.

Since the AMG has practically no hydrometric information, but does have climatological information, we estimate the peak discharge based on the rainfall-runoff model, taking into consideration the only climatological station within the municipality: Tlajomulco, which is shown below:

January	20.2	July	188.0
February	11.1	August	171.4
March	2.2	September	129.9
April	5.4	October	44.4
May	18.9	November	6.8
June	166.4	December	6.1

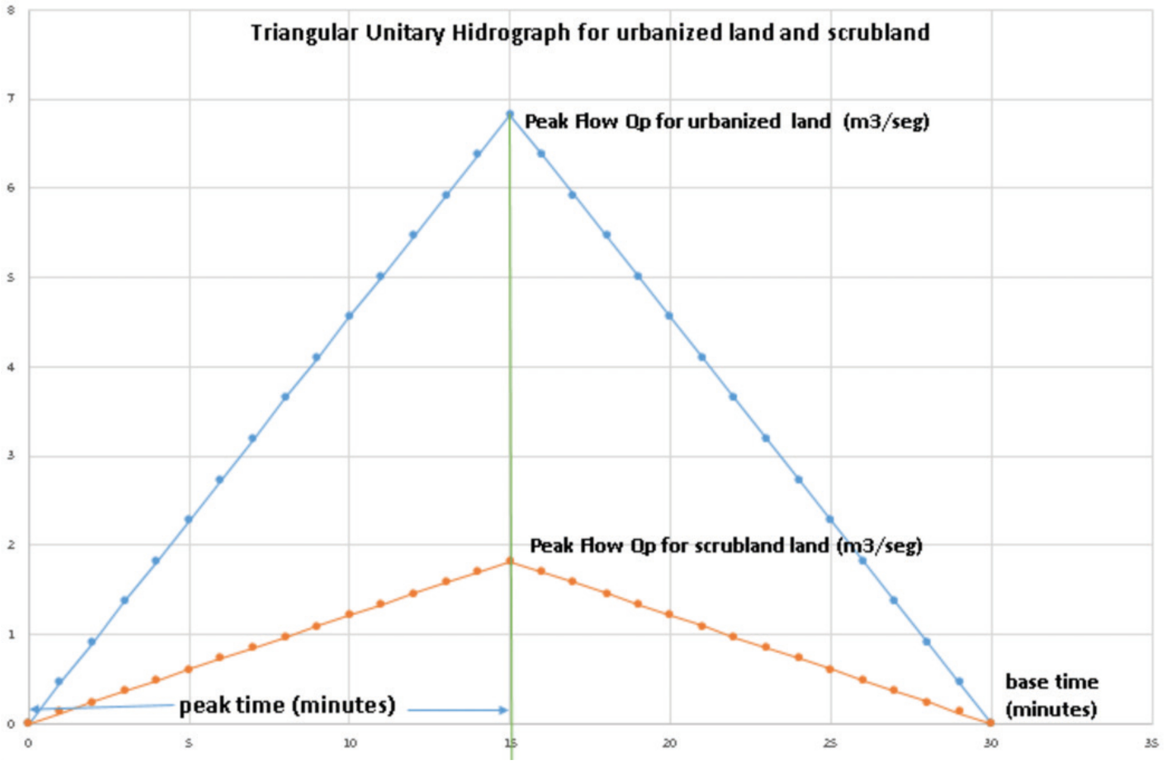
Climatological information of the Tlajomulco station for the period 1973-2011.

Source: National Weather Service

The average rainfall in 24 hr at the Tlajomulco station was 64.23 mm.

RESULTS AND DISCUSSION

Accelerated urbanization has significantly transformed runoff patterns in urban areas, as seen in the municipality of Tlajomulco de Zúñiga. This phenomenon has increased peak flows, exacerbating the risk of flooding, especially in the lower parts of the basin. In terms of vulnerability, around 700,000 inhabitants in the municipality are at risk of urban disasters.



Triangular Unitary Unitary Hidrograph for urbanized and scrubland land

Source: Caro 2025

Therefore, knowledge of the effects of a flood along a river flood allows us to take measures to adapt to climate change in the event of an extraordinary hydrological event that could cause flooding problems due to the overflowing of channels and streams, thus having the necessary elements to determine solutions to improve the hydraulic behavior of the San Juanate stream: peak expenditures for 50-year return periods limit, affected by adjustment factors such as: basin area, storm duration and return period, which are shown in Figure 1.

The results to be obtained are basically, as already mentioned, the obtaining of peak discharge before and after urbanization, as well as the Triangular Unitary Hydrograph (HUT) graphs, both for peak discharge and retained volumes.

To determine the peak discharge, the first step is to calculate the time of concentration *tc,* which is the travel time of the water from the beginning of the basin (upstream) to its own outlet (downstream). The time of concentration refers to the length of time it takes for the rainwater to travel from the inlet to its exit point.

$Qp = 0.28\ c\ i\ A = 0.28 * 0.20 * 65 * 0.50 = 1.82\ m^3/seg$ for soil in heath

$Qp = 0.28\ c\ i\ A = 0.28 * 0.75 * 65 * 0.50 = 6.826\ m^3/seg$ for soil in heath

$Vol.\ retenido = (6.826*900) - (1.82*900) = 4505.4\ m^3$

To mitigate these effects, it is necessary to implement both structural and non-structural measures. Structural measures, such as the construction of control and drainage works, are essential to reduce the peak flows of flood hydrographs (Ponce, 2008). However, it is also crucial to consider adequate urban planning, as well as the design of rainwater evacuation systems that integrate infrastructure such as green roofs and permeable pavements, in order to infiltrate larger volumes of water and thus reduce runoff from the upper part.

Urbanization not only affects local hydrology, but also contributes to broader environmental problems, such as the concentration of natural resources and the emission of greenhouse gases (Bárcena, 2001).

These problems are aggravated by obsolete urban planning models that do not adequately consider land use and changes, especially high population densities (Eibenschutz, 2022).

Global climate change has intensified the aforementioned challenges, causing increasingly frequent and severe flooding (Olcina, 2008). In response, there has been a growing interest in the science of hydrology to sustainably mitigate stormwater.

The achievement of the goals proposed by Mexico and the state of Jalisco, through management and Land and Ecological Planning in the fulfillment of the Sustainable Development Goals, in particular SDG 6 Clean Water and Sanitation and SDG 11 Sustainable Cities and Communities, will not be met by the year 2030. Because the socio-urban dynamics based on the free market and freedom of consumption, bring such complex challenges for the implementation of effective solutions in technical terms and thus the satisfactory fulfillment of the SDGs of the United Nations.

In Tlajomulco de Zúñiga, the Zero Hydrological Impact paradigm shift seeks to ensure that the increase in impervious areas does not increase peak flows, beyond allowable limits. By controlling these flows, flooding in the lower part of the watershed, where collateral effects are more severe, can be mitigated (Moreira, 2018).

Accelerated urbanization without controlled planning has intensified environmental degradation, increasing vulnerability to urban disasters such as floods (Jordan, 2017). This phenomenon affects the hydrological cycle of water, leading to higher intensities in receiving streams and in areas downstream of the basin (iAgua, 2023).

The lack of integration of hydrological studies in urban plans has increased the runoff coefficient by 50% as well as the peak flows of the triangular unit hydrograph (HUT) up to 3.5, as shown in Figure 1, reducing its delay times by up to a third and increasing the risk of flooding (Ferdowsi & Behzadian, 2024). Before urbanization, precipitation helped soil moisture and groundwater recharge. However, urbanization has increased the volume and velocity of runoff, causing irreversible damage to water infrastructure (GFDRR, 2017). Therefore, a greater focus on Integrated Water Management is required to mitigate these effects.

CONCLUSIONS

In order to solve the problems of a stream or riverbed, as well as to demarcate the federal zone of a specific stretch of stream, it is necessary to carefully analyze the available information, whether hydrometric or pluvial and physiographic, of the basin. The hydrometric or climatological information must be consistent at the time the relevant studies are carried out and, if necessary, the temperature and precipitation data must be duly adjusted.

The basis for determining the maximum flow was the American rational formula, which is the most appropriate method for areas smaller than 50 km² compared to the statistical methods of intensity-duration of the storm-return period, in order to assign a flow corresponding to the return period, which in practice has indicated 50 years as long as the current is perennial.

In areas with a natural regime of intermittent runoff, it is advisable that the sample of discharges be large for a better understanding of the behavior of the stream, since there may be large discharges and zero discharges. If the sample is small, it is convenient to make an additional study using *rainfall-runoff* models.

RECOMMENDATIONS

The municipality of Tlajomulco de Zúñiga has the potential to change the way its inhabitants live inside and outside the city; therefore, its inhabitants live in fragmented spaces due to the imposition of walls and fences caused by the residential planning model, which accentuates the levels of marginalization as an effect of capitalist progress.

It is recommended that in areas with natural and intermittent runoff, it is advisable that the expenditure sample be large with the best knowledge of the streams under study in the Tlajomulco-El Ahogado watershed, since there may be records of both large and null expenditures. If the sample is small, it is convenient to make an additional study using the rainfall-runoff model, as mentioned above.

As a second recommendation, *"buffer zones"* should be established, in other words, restrictions on grazing areas, in order to generate connectivity in watercourses and streams and to minimize risks and disasters in the event of natural disasters.

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