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EFFECT OF URBAN GROWTH ON THE HYDROLOGY OF THE URBAN SPOT IN THE MUNICIPALITY OF TARIJA, BOLIVIA

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Hydrological abstractions are fundamental variables for the hydrological simulation of a basin. Infiltration is one of them and allows determining the amount of water lost by the natural process of the soil. However, the anthropogenic alteration of the soil structure generates an adverse effect in urban areas if the drainage systems are not correctly designed. In recent years, the urban area of Tarija, Bolivia, has had a substantial population and real estate growth, which caused the growth of impermeable areas. The waterproofing of the soil due to the real estate and road process has caused the city to suffer flooding and problems due to flows generated by the rains in recent years. This work shows the results of the simulation carried out on flows generated as a result of urban growth in the next 15 years and how this affects the urban area of Tarija. The simulation considers the possible growth of impervious areas based on the historical growth of the municipality and identifies the areas at risk of flooding

Keywords: urban hydrology; infiltration; impermeable soils; floods

EFECTO DEL CRECIMIENTO URBANO EN LA HIDROLOGÍA DE LA MANCHA URBANA DEL MUNICIPIO DE TARIJA, BOLIVIA

Las abstracciones hidrológicas son variables fundamentales para la simulación hidrológica de una cuenca. La infiltración es una de ellas y permite determinar la cantidad de agua perdida por el proceso natural del suelo. Sin embargo, la alteración antropogénica de la estructura del suelo genera un efecto adverso en las zonas urbanas si los sistemas de drenaje no están correctamente diseñados. En los últimos años, el casco urbano de Tarija, Bolivia, ha tenido un importante crecimiento poblacional e inmobiliario, lo que provocó el incremento de área impermeables. La impermeabilización del suelo por el proceso inmobiliario y vial ha provocado que la ciudad sufra inundaciones y problemas por los caudales generados por las lluvias de los últimos años. Este trabajo muestra los resultados de la simulación realizada sobre los flujos generados como consecuencia del crecimiento urbano en los próximos 15 años y como este afecta la zona urbana de Tarija. La simulación considera el posible crecimiento de áreas impermeables con base en el crecimiento histórico del municipio e identifica las áreas en riesgo de inundación

Palabras clave: hidrologia urbana; infiltración; suelos impermeables; inundaciones

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1. Introduction

Urbanization is an expanding global trend, more than 50% of the world's population currently lives in cities and there are more than 500 cities that now have more than 1 million inhabitants (UN, 2010). This growth, accompanied by the rapid increase in urban areas, has dramatic impacts on the basin's hydrology. It generates higher runoff rates and volumes, infiltration losses, and higher base flow. One of the factors that causes faster runoff is the increase in impervious areas in urban areas and the construction of very simple storm drainage systems. The concentration times are shorter, and the recession times are much reduced. Urban hydrology is also affected by sanitary sewer systems not separated from the storm sewer system (Buettner, 2015).

Fletcher et al. 2013, finds that urban hydrology has evolved to improve the way urban runoff is managed for flood protection, public health, and environmental protection. This study points out that the ability to predict urban hydrology has evolved to provide models suitable for the small temporal and spatial scales typical of urban and peri-urban applications. Fletcher et al. 2013 also points out that although urban hydrology is not so different from 'natural' hydrology, the plurality of objectives and interactions with other parts of the urban water system results in the importance of urban hydrology. This is further complicated by the mosaic nature of developed, undeveloped, and agricultural lands, crossing watershed boundaries accompanying urbanization. For his part, Leopold (1968) indicates that impermeable surfaces and built drainage systems are fundamental drivers of change in hydrology, with increases in peak flows, annual runoff volumes, and flow variability, together with other factors such as decreased infiltration and shorter lag times.

Jennings et al. (2010) detected the influence of cities on precipitation. For their part, Burian, S., and Shepher, J. (2005), Krajewski et al. (2011), and Niyogi et al. (2011) detected the influence of urbanizations on rainfall and climatology. Miao et al. (2011) and Shem and Shepherd (2009) confirm the observational evidence of the significant effect of urban land cover on rainfall variability.

In their investigation of water flows in residential areas, Ragab et al. (2003) found significant differences in runoff and evaporation depending on the slope of the roof, the type of material, and the height. Impervious surfaces profoundly impact hydrology, eliminating infiltration and thus dramatically increasing the volume of surface runoff. Streets and sidewalks are usually considered impermeable, but in reality, their hydrological behavior varies with the intensity and duration of the rains.

Regarding the influence of urban areas on the flow, Dotto et al. (2011), Smith et al. (2005), Villarini et al. (2009), and Hawley and Bledsoe (2011) confirm that urbanization and the nature and layout of the drainage network play a dominant role in the hydrology of the basin. The influence of urban areas on the peaks and duration of flows has a significant effect, especially in times of higher precipitation.

Konrad (2005), Bledsloe (2006), and Nelson et al. (2006) state that hydrological changes due to impermeable surfaces also lead to significant geomorphic changes, including habitat simplification, erosion, and the creation of larger and deeper channels. In addition, mobilization, and transport of fine sediments to the detriment of coarse ones significantly affect drainage systems.

Le Coustumer, S. et al. (2009), Mikkelsen et al. (1996), Hatt et al. (2009), Gonzalez-Merchan et al. (2010), and Fletcher et al. (2013) point out that the hydrological simulation with infiltration techniques depends more firmly on the site conditions, the permeability of the soil together with the possible evolution of the obstruction. The latter depends on poorly specified infiltration media, excessive sediment disposal, and hydraulic compaction. They also demonstrated the role of vegetation in reducing the probability of obstruction Archer et al. (2002).

For Elliot and Trowsdale (2007), urban hydrological simulation can be carried out from clustered or spatially distributed models and continuous simulation. Continuous models use historical series that represent long-term behavior. They analyze various rainfall events in wet and dry weather periods and thus have a broader potential application. McGuire et al. (2007) point out that hydrological models bring uncertainty related to the input data. The critical calibration data for the solidity and precision of the simulation results is the case of soil properties, among others.

Khu et al. (2006), Thorndahl et al. (2008), and Han (2009), as a result of their investigations, conclude that the estimation of the effective impermeable area is the most significant parameter to predict and simulate runoff in urban basins.

In essence, the fundamental objective of urban hydrology is to adequately manage the behavior of water, reducing the problems of flooding, erosion, and environmental degradation. Attempt to maintain the flow regime as close to natural, restore water quality, restore receiving water health, conserve water resources, and improve the urban landscape, Fletcher et al. (2013), Wong, (2007) and Coffman (2002).

Infiltration is a critical process in aspects of hydrology; it is a phenomenon that is defined as the maximum rate at which soil in certain conditions absorbs the rain that falls. This varies over time, especially during the initial period of rain, reaching a minimum infiltration capacity at the end of it (Horton, 1940). The process depends on the soil properties and the initial and boundary conditions within the flow domain (Assouline, 2013).

Maktav et al. (2006) indicate that remote sensing and GIS are the new technologies that can help solve the planning and administration of resources in urban areas with updated spatial information. Likewise, Jürgens (2001) points out that the strong tendency to seal the ground surface with roads and buildings results in less groundwater recharge because stormwater sewer lines drain sealed surfaces in urban areas. Remote sensing can help quantify the proportion of sealed surfaces, which can be used in hydrological models.

For Murillo (2011), the Témez model, which is of a general, semi-distributed, and monthly nature, can be applied to any basin, although it must be verified that the periods used to give a response consistent with the physical reality of the hydrological system under study . It is integrated into the method called Hydrometeorological Calculation of Inflows and Floods (Cálculo Hidrológico de Aportes y Crecidas [CHAC], 2013), developed at the Center for Hydrographic Studies of Spain (CEDEX) and allows hydrological modeling and simulation in basins.

The urban sprawl of the municipality of Tarija is located within the Guadalquivir River basin in the Department of Tarija, Bolivia. The study area represents the largest population in the department, generating the most important environmental and water impacts in the basin (Copa and Villena, 2016).

1.1. Goals

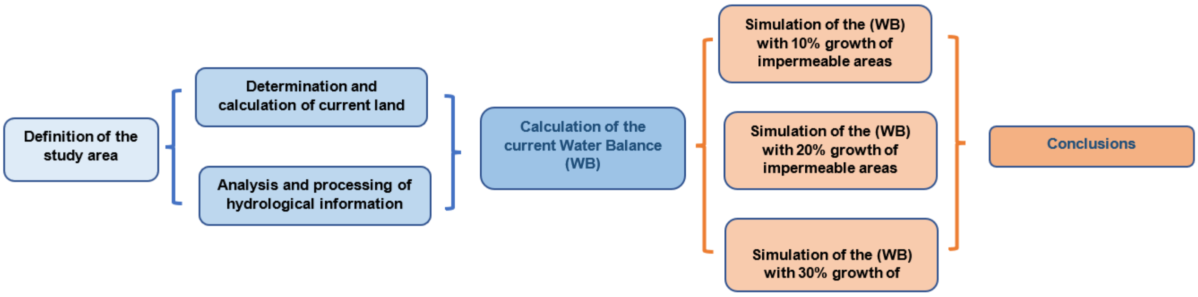
This paper aims to show the results of the hydrological simulation of the municipality of Tarija under scenarios of future growth of the impermeable area and its impact on the urban area in the next 20 years.

- The realization of a water balance in the urban area in real conditions is proposed.
- The current areas of land use in the urban area of Tarija are calculated
- The growth of impermeable areas is simulated in the order of 10, 20 and 30%
- The water balance of each simulation is determined in order to analyze its variation

2. Methodology

This section describes the methodology used for the hydrological simulation carried out in the study basin. The figure 1 outlines the development phases of the work.

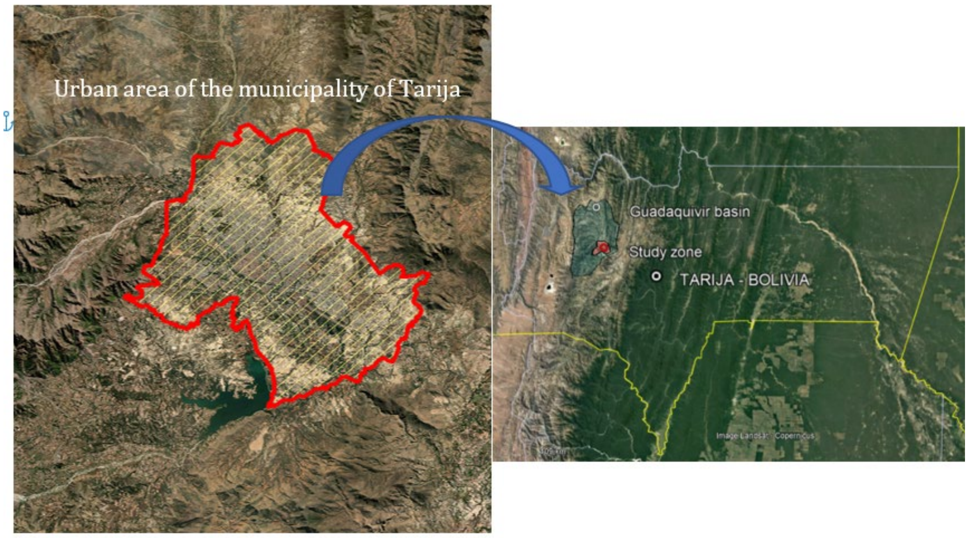
Figure 1: Project development scheme



2.1. Study area

The project was carried out in the urban area of the Municipality of Tarija, located within the Guadalquivir basin in the department of Tarija, Bolivia. Figure 2 shows the location of the study area. The study area has an extension of 11,846 Ha.

Figure 2: Location of the urban area of the municipality of Tarija



2.2. Hydrometeorological information of the basin and morphometric characteristics

The hydrometeorological information collected from the (Servicio Nacional de Meteorología e Hidrología [SENAMHI], 2019) of Bolivia was used for the modeling of flows. The calculation of the morphometric parameters and generation of soil maps of the basin was carried out with ArcGIS 10.4. The processing of satellite images and generation of land use areas was carried out by remote sensing. To determine runoff coefficients, infiltration parameters, land use, remote sensing data, were used.

2.2.1. Complementation of missing data and homogeneity test using the double accumulation curve

For the complementation of missing data and consistency analysis, the CHAC computer system [Cálculo Hidrometeorológico de Aportes y Crecidas [CHAC], 2013) was used. The software uses a bivariate regression model with a monthly data series for the first calculation. In contrast, the evaluation of the consistency of the precipitation time series uses the analysis of the double accumulation curve.

2.2.2. Analysis period and hydrological year

The use of 40 years of continuous data has been defined with a period from 1980 to 2020, with monthly data series, whose hydrological year has been determined from January to December.

2.3. Hydrological Modeling

For modeling the water balance, the sim distributed model of Temez, Jorquera et al. (2012). The model operates by making moisture balances between the different processes in a hydrological system from the moment it begins to rain until the moment in which runoff is generated and the subsequent discharge of the aquifers into the rivers. The model is integrated into the CHAC, which allowed the hydrological simulation of the basin to be carried out and its monthly contributions to be calculated.

2.3.1. Potential Evapotranspiration

The CHAC allows the calculation of the potential evapotranspiration using the Penman-Monteith method (FAO, 1990), which relates the Potential Evapotranspiration (ETP) with climatic factors such as precipitation, temperature, wind speed, sunshine hours, and relative humidity.

2.3.2. Determination of impervious areas and soil characterization

To estimate the regions and their permeability characteristics, the information provided by the Municipality of Tarija was used. Land use and permeability maps were worked from remote sensing data and ArcGIS.

3. Results and discussion

The results of modeling the basin's water balance are detailed below.

3.1. Determination of the land-use area in the basin

The study area has an area of 11,846 Ha. Based on urban cadastre maps from the mayor's office and using the capture of territorial information through remote sensing and digital processing of satellite images of the study basin, the map of land use has allowed the quantification of permeable, impermeable areas in the urban area of Tarija. Figure 3 shows the land use map.

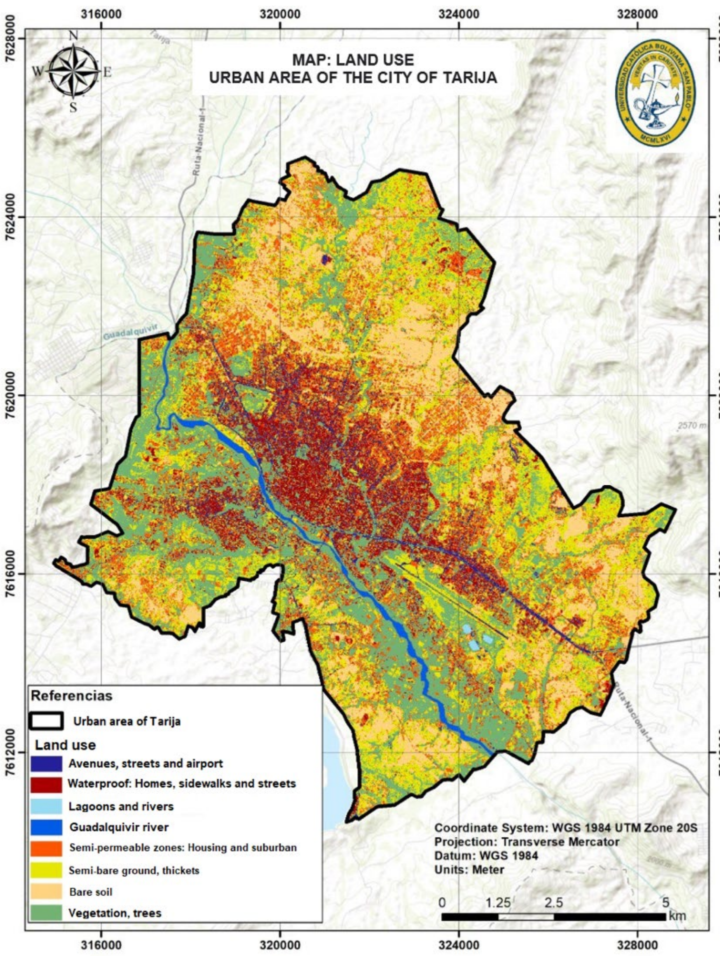
3.2. Quantification of land use areas

With the land use map and the support of ArcGIS 10.4 (2016) ArcGIS 10.4 (2016) support, the land use areas were quantified. Table 1 shows this calculation.

Table 1. land-use area in the urban basin of Tarija

Land use	Area (Ha)
Avenues, streets and airport	927.5
Homes, sidewalks and streets	1074.4
Lagoons and rivers	10.7
River banks	125.6
Homes in peri-urban areas (semi-impervious)	1845.6
Semi-bare soils, thickets	3305.0
Bare soils	1682.1
Vegetation	2875.0
Total	**11.846**

Figure 3: Map of land uses in the urban basin of the municipality of Tarija



3.3. Determination of the runoff coefficient

The runoff coefficient "C" is a calibration parameter that allows evaluation the infiltration potential of a soil. From the areas of land use and the Curve Number methodology, the locations and characteristics of the grounds were weighted to determine the coefficient. Coefficients close to 1 mean that everything runs off and, therefore a more significant contribution to the flow, while close to 0, all the runoff infiltrates. Equation 1 details the calculation method.

$$C = \frac{\sum Ci * Ai}{\sum Ai} \quad (1)$$

Where:

C = Basin Weighted Runoff Coefficient

Ci = Runoff coefficient of each partial area

Ai = Partial regions of the basin

Table 2. Calculation of the weighted runoff coefficient

Land use	Area (Ha)	C
Avenues, streets and airport	927.5	0.90
Homes, sidewalks, and streets	1074.4	0.85
Lagoons and rivers	10.7	1.0
Riverbanks	125.6	0.25
Homes in peri-urban areas (semi-impervious)	1845.6	0.65
Semi-bare soils, thickets	3305.0	0.50
Bare soils	1682.1	0.55
Vegetation	2875.0	0.25
$C_{ponderated}$		**0.53**

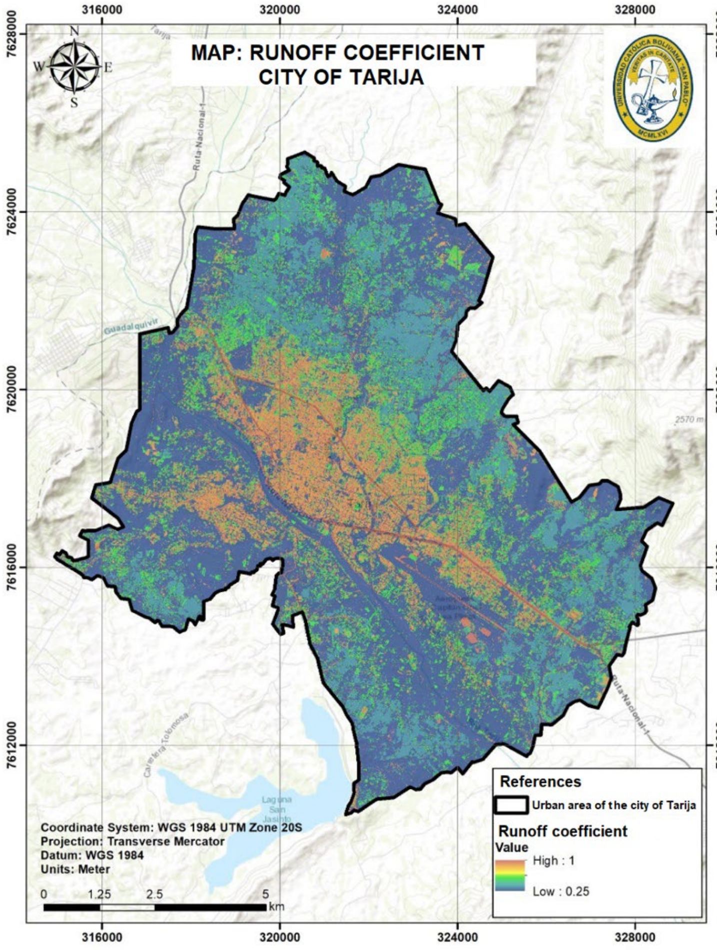
The table shows us that the weighted runoff coefficient for the urban area is 0.53, corresponding to soil with a moderate runoff potential. Figure 4 illustrates the runoff map generated for the study basin.

More significant potential for runoff is observed in the central zone due to a more excellent impermeability of the soil due to the process of urban and real estate expansion.

3.4. Hydric balance

For the hydrological simulation, six hydrological stations close to the study area were used, and the process of complementation and data consistency analysis was carried out with the CHAC software. Potential evapotranspiration was calculated with the same software, using the Penman-Monteith model. At the same time, the areal weighting of precipitation and evapotranspiration has been carried out with the support of ArcGIS.

Figure 4: Runoff map of the basin of the municipality of Tarija



3.4.1. Model calibration

The Tolomosa hydrometric station was used for the calibration because it contains a more extended period of registration and more reliable information. Table 3 details the gauges used for calibration.

Table 3. Hydrometric station

Station	Number of years – historical series	Average monthly flow (m^3/seg)
Tolomosa	7 (1978-1984)	22.44

3.4.2. Calibration parameters

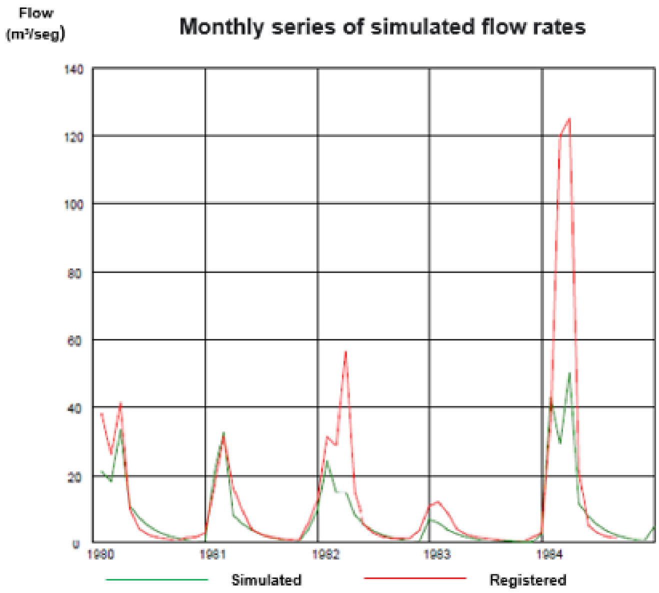
The calibration parameters have been determined from the analysis of land use and infiltration data in the basin, Table 4 details them.

Table 4. Calibration parameters

Basin	Area (Ha)	Leave C	Maximun humidity H_{max} (mm)	Number of rainy days	Maximun infiltration I	Descarga α
Cuenca urbana de Tarija	11.85	0.53	20	10	26.61	0.013

Figure 5 show the calibration and comparison curves between simulated and observed in the Tolomosa stations.

Figure 5: Observed Vs. simulated flows: Obrajes Station



A similar trend is observed in the behavior of the flows, both in the dry season and in the rainy season; this indicates that the calibration parameters are adjusted to the hydrological conditions and characteristics of the basin.

3.5. Analysis of future scenarios in impermeable areas in the basin

Data from the INE census (2012) shows that the city of Tarija has had a population growth of close to 2% per year, with similar urban and real estate development. These data have made it possible to analyze future urban growth scenarios that lead to an increase in impervious areas in the city of Tarija. New streets, avenues, and houses increase the impermeability of the soil and decrease the areas of most excellent infiltration. Under this scenario, it is estimated that, in the next 20 years, the city could increase up to 30% of urban growth, which entails a similar increase in impervious areas. Table 4 shows the variation of land use areas and the weighted runoff coefficients under the different scenarios, and table 5 shows the calibration data for the three impervious area growth scenarios.

Table 4. land-use area in the urban basin of Tarija – future scenarios

Land use	Increase 10%		Increase 20%		Increase 30%	
	Area (Ha)	C	Area (Ha)	C	Area (Ha)	C
Avenues, streets, and airport	927,5	0,9	927,5	0,9	927,5	0,9
Homes, sidewalks, and streets	1182,2	0,85	1290,0	0,87	1397,8	0,88
Lagoons and rivers	10,7	1	10,7	1	10,7	1
Riverbanks	125,6	0,25	125,6	0,25	125,6	0,25
Homes in peri-urban areas (semi-impervious)	2318,3	0,65	2790,9	0,70	3262,4	0,72
Semi-bare soils, thickets	3305,0	0,5	3305,1	0,5	3305,0	0,5
Bare soils	1389,5	0,55	1096,9	0,54	805,5	0,50
Vegetation	2587,2	0,25	2300,5	0,24	2012,6	0,20
$C_{ponderated}$		**0.54**		**0.56**		**0.57**

Table 5. Calibration parameters – future scenarios

Basin/scenario	Area (Ha)	Leave C	Maximun humidity H_{max} (mm)	Number of rainy days	Maximun infiltration I	Descarga α
Tarija urban basin – current	11.85	0.53	20	10	26.61	0.013
Tarija urban basin – 10% increse	11.85	0.54	18	10	23.95	0.012
Tarija urban basin – 20% increse	11.85	0.56	16	10	21.29	0.010
Tarija urban basin – 30% increse	11.85	0.57	14	10	18.63	0.009

3.6. Water balance simulation for different scenarios

Figure 6 shows the monthly behavior of the contributions in the current situation and the variation of the flows simulated under the various scenarios of growth of impermeable areas. Figure 7 illustrates the multi-year simulation.

Figure 6. Contributions to current situation and. the growth scenarios of impervious areas at a monthly level

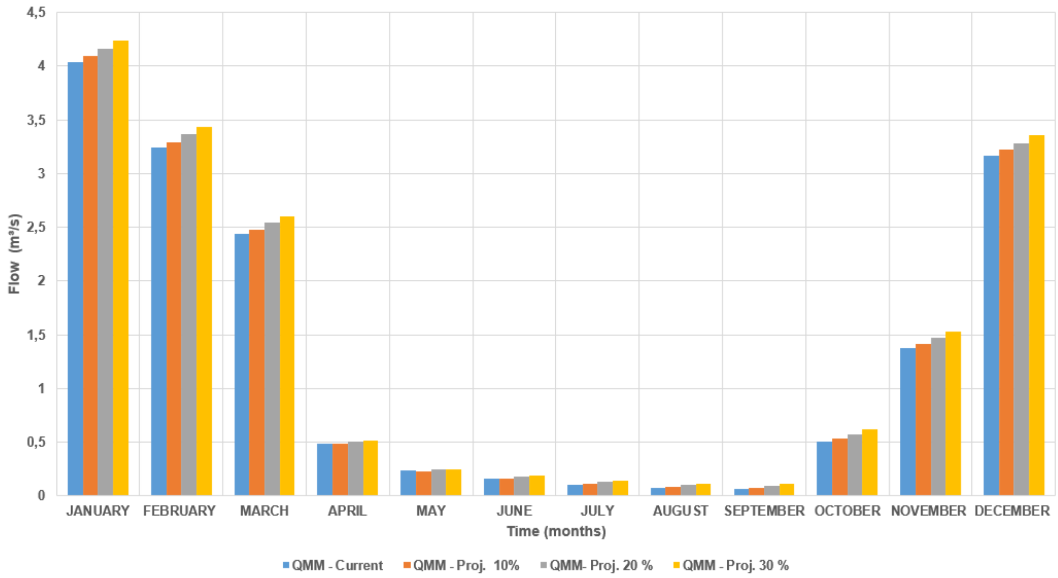
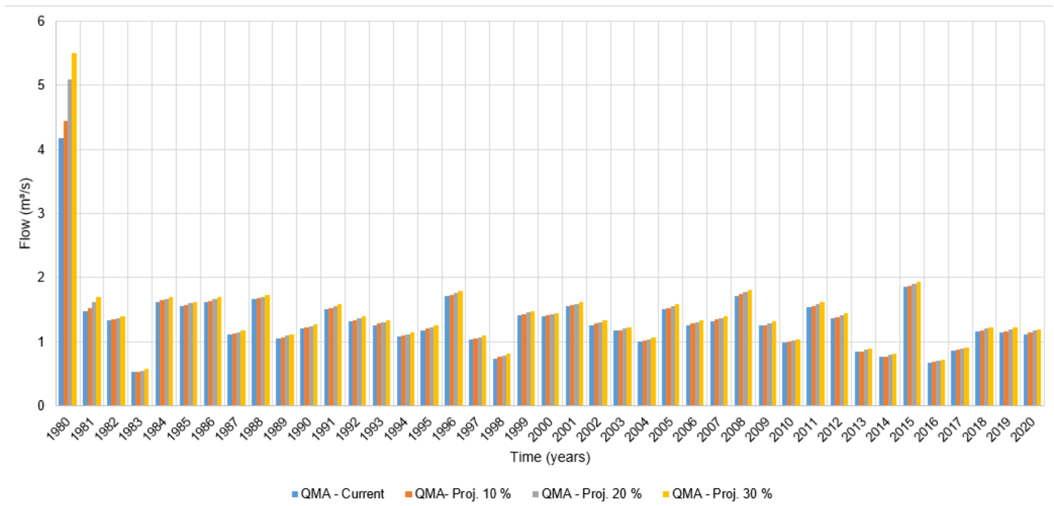


Figure 7. Contributions to current situation and. the growth scenarios of impervious areas at a multiannual level

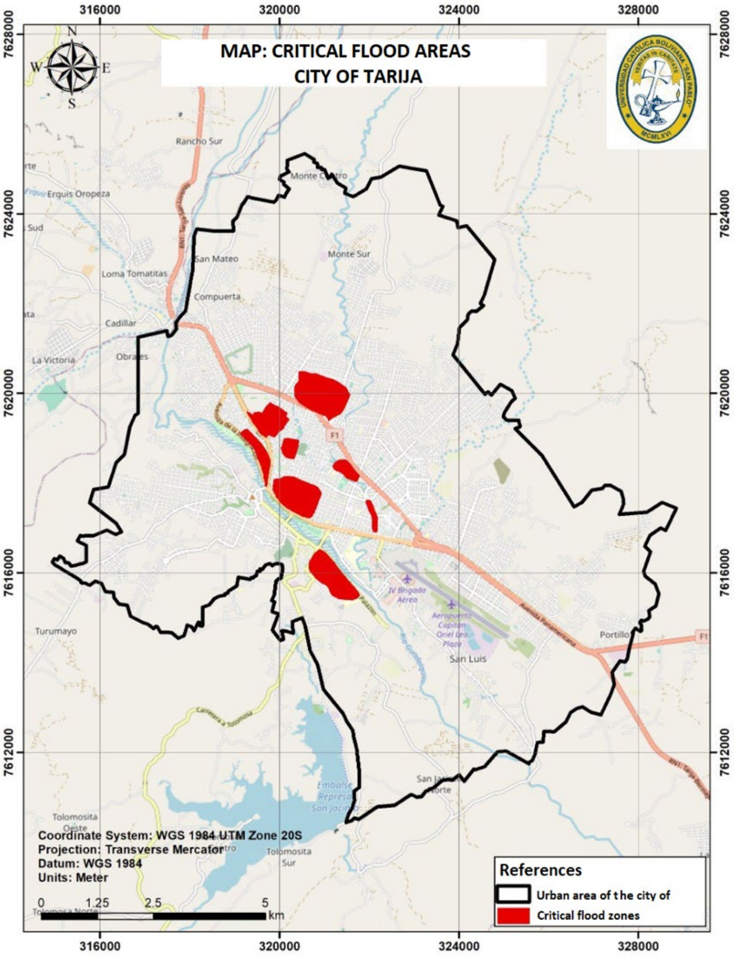


The figures show that the variation of impervious areas and land uses considerably impacts the generation of contributions within the basin.

Under the possible scenario of a 10% increase in impervious areas, the flow increases by 3% compared to the current situation; however, for a 20% future scenario, the flow increases by 13%, and for a 30% increase of impervious areas the contribution increases up to 19%.

Regarding hydrological risk, the contribution of flows in deficient pluvial drainage systems can cause severe flooding problems, especially in low-lying areas or areas with steep slopes. Figure 8 shows the critical and high-risk areas for flooding in the urban area in the simulation scenarios.

Figure 8. Risk areas



The simulation maps show the risk areas in the event of simulated events; this is somehow confirmed because in recent years, these areas have been affected by precipitation produced in the rainy season. Figure 9 illustrates the problems generated by the latest rainfall recorded in the study area.

Figure 9. Floods in the study area during 2021

4. Conclusions

The urban area of the municipality of Tarija is in constant and sustained real estate growth, observing a solid investment in road infrastructure, housing, and public spaces that have replaced natural soil with another impermeable characteristic.

Regarding the limitation of the study, the hydrological information in the study area is limited, especially about the characterization and use of the soil. The hydrological abstractions considered in the project have been determined using remote sensing. However, it is necessary to have data that allows adequate verification.

The current climatological events have shown the high risk that several areas of the municipality have, particularly the lowest and steepest, flood events, waterlogging and problems generated by the rains were observed.
The simulated scenarios regarding the increase in impervious areas show a significant increase in the contributions under the same rainfall. This allows locating risk zones and neighborhoods critical to flooding and other weather effects if adequate drainage systems and sustainable urban planning are not considered.
Under an urban growth scenario of 10%, the contribution of flows in the urban area grows by 3%, however, for larger scenarios the contribution grows considerably, for 20% the flows increase to 13% and for 30% of increase of impervious areas the flows go up to 19%.

The Bolivian Catholic University is carrying out a research study intended to know the properties of soils in the urban area of the Municipality of Tarija. This research will allow characterizing and defining hydrological calibration parameters.

In future lines of research, it is proposed to incorporate the infiltration data obtained into this study and adjust the simulations carried out. Additionally, it is intended to extend the analysis to higher-risk areas after knowing the characteristics of the soils.

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