Water Science & Technology

Water Science & Technology Vol 87 No 3, 783 doi: 10.2166/wst.2023.010

Modelling-based methodological approach to assess the effect of urbanization on hydrology and runoff water quality: a case of study for tropical and dry regions

Pascual Ferrans [a],* and Javier Temprano [b]

[a] Doctoral School, University of the Basque Country UPV/EHU, Leioa, 48940, Spain
[b] Department of Water and Environmental Sciences and Techniques, Cantabria University, Santander, 39005, Spain
*Corresponding author. E-mail: pferrans001@ikasle.ehu.eus

PF, 0000-0003-2905-0055; JT, 0000-0002-2294-6417

ABSTRACT

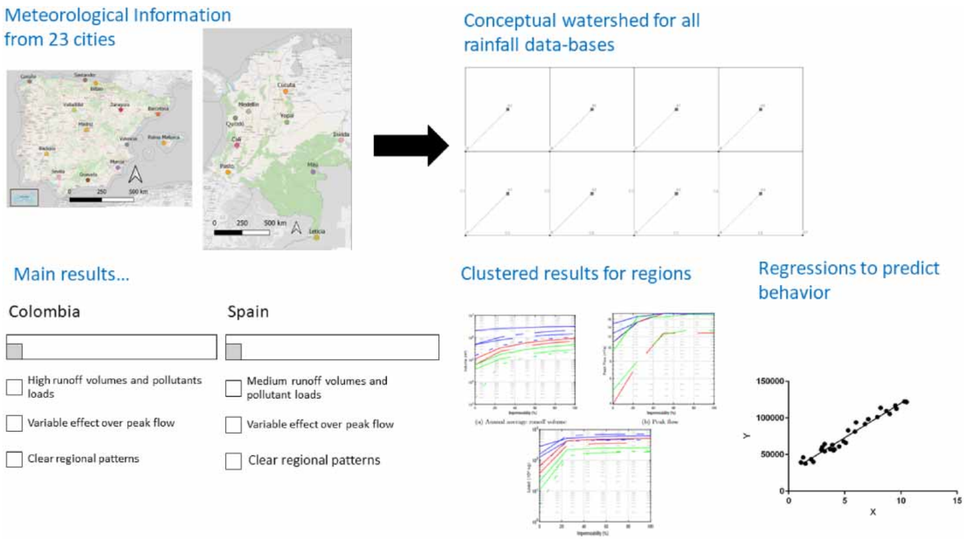
It is necessary to have unified tools and methodologies for the correct understanding and quantification of urbanization effects on watershed hydrology. This study presents a modelling-based methodology developed on EPA SWMM to evaluate the effect of urbanization in conceptual watersheds using meteorological data from cities in Spain and Colombia. Results show that the effect of urbanization is significant in variables such as runoff volume, peak flow and pollutant loads, increasing these indicators in all cases. Furthermore, this effect has different dynamics for the regions evaluated. Overall, Colombian cities presented higher runoff volumes, peak flows and pollutant loads, while Spanish cities presented higher variability in these variables due to urbanization. The analysis allowed to cluster the cities within each country, using as criteria the modelled hydrological behaviour. A curve fitting procedure presented high performance rates for all the variables studied.

Key words: environmental modelling, runoff quality, runoff quantity, urban drainage modelling, urban hydrology, urbanization

HIGHLIGHTS

- The proposed framework proved to be efficient for predicting the effect of urbanization.
- The effect of urbanization is highly variable depending on the region and hydrological variable assessed.
- Colombian cities presented higher runoff volumes, peak flows and pollutant loads.
- Spanish cities presented higher variability in the variables assessed.

GRAPHICAL ABSTRACT



1. INTRODUCTION

The development of industrialized economy and the social dynamics of the last decades have generated migration processes from rural to urban areas at an accelerated pace. Over the last 60 years, urbanization rates increased significantly (Srishantha & Rathnayake 2017) and for the first time in history, more than half of the world's population lives in urban areas (Beecham & Razzaghmanesh 2015).

The urbanization process brings significant challenges and environmental issues, such as air pollution, loss of natural ecosystems, heat island phenomena, contamination of natural water sources and alterations of the natural water cycle (Berndtsson 2010). Regarding the urban water cycle, the increase of impervious areas in urban watersheds substantially reduces water infiltration rates, causing more frequent floods. In addition, accelerated urbanization causes sewage systems overloads, increased water demand, water pollution, among some other problems (Berndtsson 2010).

Urbanization impacts not only the water flows and volumes at the catchment scale, but also the water quality. Runoff quality problems are caused by the wash-off of pollutants previously deposited in urban watersheds (Zafra *et al.* 2017a), such as suspended solids, heavy metals (Zafra *et al.* 2011), organic matter, nutrients and pathogens (Srishantha & Rathnayake 2017; Zafra *et al.* 2017b). As suggested by Powell *et al.* (2008), the presence of these pollutants is due to changes in land-use patterns (industrial, commercial and residential areas), as well as anthropogenic actions such as vehicle use and waste generation. Runoff quantity constitutes another source of issues; as previously stated by multiple authors, the reduction of permeable areas generates lower infiltration, storage and evapotranspiration rates, and in turn, this causes higher runoff volumes and increased peak flows (Brabec *et al.* 2002; Brattebo & Booth 2003; Jacobson 2011; Barbosa *et al.* 2012; Dotto *et al.* 2012; Fletcher *et al.* 2013, 2015; Salvadore *et al.* 2015; Oudin *et al.* 2018).

Different strategies have been developed to fully understand and quantify the issues caused by urbanization, and one of the most popular is the deployment of urban water models. Urban water modelling is widely used to understand various aspects related to the water resource management in cities, including the design of sewage systems, simulation of structures performance, scenarios analysis, among others (Jayasooriya & Ng 2014). These modelling tools take as input data the hydraulic, hydrological, climatic and land-use variables from the study site (Temprano *et al.* 2006) and offer as output hydrographs and pollutographs (Jayasooriya & Ng 2014).

Nowadays, modelling of urban systems is widely adapted in practice. However, these models and tools strongly rely on the study site variables and characteristics. The applicability of a model/tool to different hydroclimatic regions is a subject that has been studied by previous authors (Salvadore *et al.* 2015; Saadi *et al.* 2021), in which they found that there is still a gap regarding the study of tropical and dry areas, such as Colombia and Spain, respectively.

To address this last aspect, this article proposes a methodological approach that allows quantifying the effect of urbanization, depending on the meteorological conditions of two geographical regions. For this purpose, the same conceptual model was applied to 23 different case-studies, using meteorological information from cities located in Colombia and Spain. With these models, the effect of urbanization was assessed, using as evaluation variables the runoff volume, peak flow and pollutant loads. The software selected to develop the analysis was EPA SWMM (Rossman 2010), as it is publicly available and widely used by researchers in the area.

2. STUDY SITES AND DATA COLLECTION

To collect the meteorological data necessary to develop the models, two state agencies in Spain and Colombia were reached: the 'Agencia Estatal de Meteorología' (AEMET) in Spain and the 'Instituto de Hidrología, Meteorología y Estudios Ambientales' (IDEAM) in Colombia. Continuous rainfall databases with a temporal resolution of 10 min were obtained, in periods between 2009 and 2019 for 23 cities spread across these two countries. Additionally, monthly average evaporation series and intensity-duration-frequency (IDF) curves were collected for each city.

As the main objective of the study was to assess the effect of urbanization on watersheds with different hydroclimatic conditions (specifically tropical and deserted regions), a preliminary regional analysis was performed. Using the base scenario (see Section 3.1), a different model was developed for each city, and they were run and analysed. Consequently, each of the scenarios consisted of the same theoretical watershed (same parameters and configuration), developed using different meteorological information.

From each scenario, the average annual runoff volume, pollutant loads and peak flow were calculated. This process allowed to classify the cities according to their geographical location and the results' similarity.

As Colombia is a tropical country, rainfall regimes consist of events with high intensity and duration (Poveda 2004), while the geographical location of Spain constitutes it in a drier region with lower rainfall intensities and depths. Regarding the Spanish locations, it is worth clarifying that the cities assessed included islands with different geographic locations (Gran Canaria, from the Canary Islands, and Palma de Mallorca, from the Baleares Islands). Figure 1 presents the geographical location of the cities included in the analysis, and Table 1 presents a list of these cities, as well as the start and end date of the rainfall databases. Because the databases had different extensions, the information from the hydrological variables was calculated as annual averages.

Regarding the urban structure of the two regions, the cities in both Spain and Colombia are highly urbanized, with percentages of imperviousness in the watersheds of about 90% (Torres & Eljaiek 2012). The presence of green areas is usually low, although Spanish cities have a slightly higher index. Parking areas and road infrastructure consist mainly of paved areas. In all cases, the regions used for extracting the meteorological information consisted of regional capitals, so it is common to find varying land uses, but mainly residential and commercial; industrial land uses are usually located in specific and focused areas of the cities.

Another aspect to take into account when analysing the different regions is the type of sewage systems. On the one hand, most Colombian cities have combined sewage systems (Jiang 2017). Only a few cities (mainly large cities) have certain areas of the city with separate systems. Spanish cities also have mostly combined sewage systems, although new developments are expected to increasingly include separate systems (AEAS 2017).

In order to verify the quality of the rainfall information, distributions, descriptive statistics and outliers were calculated from the databases, identifying that the information for Spanish cities had no outliers or relevant missing data. However, when performing the same procedure for Colombian cities, anomalous values of rainfall depths of up to 200 mm in 10 min were found.

Consequently, the procedure followed to manipulate the databases was to allow certain rain intensity threshold. Maximum intensities reported for different Colombian regions were assessed from Jaramillo & Kogson (1994). This value was, on average, 20 mm/h for measuring time intervals of 10 min. Consequently, it was decided to discard all values that exceeded this threshold. The eliminated values were less than 5% of the total database in all cases.

3. METHODS

3.1. Base scenario layout

The software used was EPA SWMM, which was developed by the Environmental Protection Agency of the USA. It is a dynamic rainfall-runoff model that aims to simulate the process of runoff generation, mainly for urban areas (Rossman &

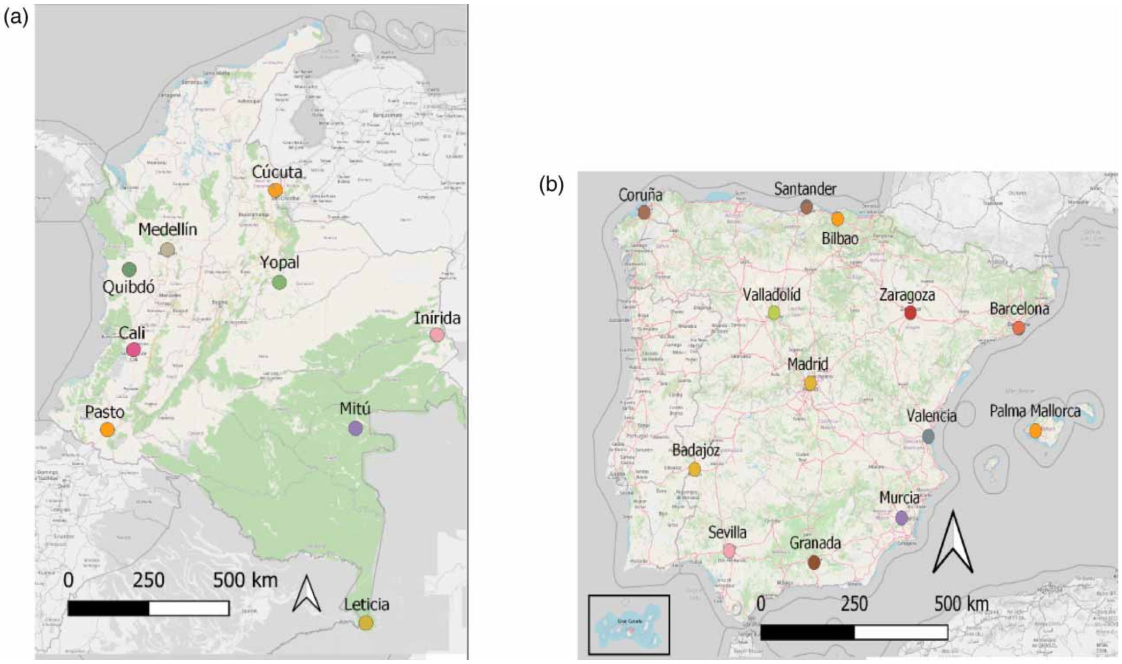


Figure 1 | Geographical location of cities in the analysis. (a) Colombian cities. (b) Spanish cities.

Table 1 | Cities and database extension for rainfall information

City	IATA code	Country	Data start date	Data end date
Badajóz	BJZ	Spain	07/10/2009	11/09/2019
Barcelona	BCN	Spain	09/10/2009	25/05/2019
Bilbao	BIO	Spain	07/10/2009	29/05/2019
Cali	CLO	Colombia	01/01/2009	30/10/2019
Canarias	LPA	Spain	09/09/2013	26/04/2019
Coruña	LCG	Spain	05/10/2009	27/05/2019
Cúcuta	CUC	Colombia	01/01/2009	12/01/2015
Granada	GRX	Spain	03/01/2010	02/05/2019
Inírida	PDA	Colombia	01/01/2009	22/05/2018
Leticia	LET	Colombia	31/07/2014	12/10/2018
Madrid	MAD	Spain	07/10/2009	16/05/2019
Medellín	MDE	Colombia	01/01/2009	30/11/2011
Mitú	MVP	Colombia	28/11/2016	31/10/2019
Murcia	RMU	Spain	08/10/2009	24/05/2019
Palma	PMI	Spain	10/10/2009	25/05/2019
Pasto	PSO	Colombia	01/01/2009	02/03/2010
Quibdó	UIB	Colombia	01/01/2009	27/01/2019
Santander	SDR	Spain	05/10/2009	28/05/2019
Sevilla	DVQ	Spain	20/10/2009	25/04/2019
Valencia	VLC	Spain	03/01/2009	02/02/2012
Valladolíd	VLL	Spain	06/10/2009	16/05/2019
Yopal	EYP	Colombia	02/11/2009	29/01/2013
Zaragoza	ZAZ	Spain	08/10/2009	19/07/2017

City codes obtained from the International Air Transport Association (IATA) database.

Huber 2015). It can operate under single events or under continuous modelling with long-term databases. It consists of three main components: The transport component of the model, which is based mainly on a collection of subcatchments with certain characteristics, which receive rainfall and consequently generate runoff and pollutants (Rossman & Huber 2015). Subsequently, the routing module simulates the transport of runoff water and pollutants through pipes, channels, treatment systems, pumps, among others. In parallel, the software allows monitoring the quality of runoff water during the simulation time, making use of the processes of build-up and wash-off of pollutants (Rossman & Huber 2015). Additionally, in its latest versions, it includes a specific sustainable urban drainage systems (SUDS) module, which allows the inclusion of this type of structures within the urban water management framework.

As the developed watershed was theoretical, all parameters of the model were defined based on previous studies (Temprano *et al.* 2006; Hood *et al.* 2007; Chen & Adams 2007; Chow *et al.* 2012; Hossain *et al.* 2012; Modugno *et al.* 2015; Rosa *et al.* 2015; Li *et al.* 2016; Tu & Smith 2018) and the user manual's recommendations by EPA SWMM (Rossman 2010). The watershed developed (Figure 2) consisted of a rectangular area of 80 ha, distributed in eight equal subcatchments (A1 to A8). Subcatchments A5 to A8 discharged to nodes J5 to J8, respectively, and runoff was transported to nodes J1 to J4 through conduits C1 to C4. At the same time, subcatchments A1 to A4 discharged to nodes J1 to J4, and runoff was then transported using pipes C5 to C8; the final outlet node was O1. All conduits of the sewer system consisted of circular pipelines dimensioned using the rational method and simulating a PVC material. The mean slope defined for the watershed was 1%, the impervious coverage was 50%, and the storage depths were 2.45 and 7.62 mm for impervious and pervious areas, respectively. As the watershed used in the study was a theoretical approximation, it is not expected that the model will reproduce the actual behaviour of the sewage systems from the different cities. On the contrary, the study proposes the same watershed for the different models, in order to exclusively assess the effect of the meteorological information.

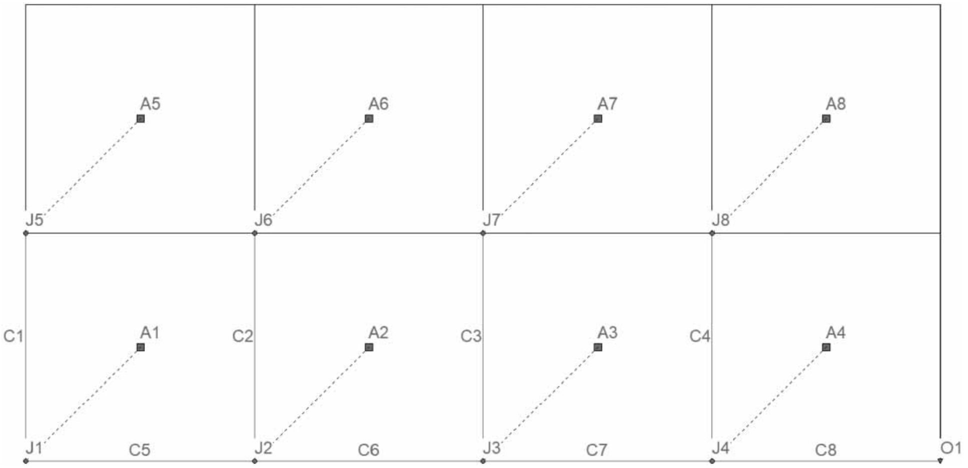


Figure 2 | Base watershed.

The routing method of the dynamic wave was used, and the infiltration method was the curve number. A total duration of 10 years was modelled, in the period comprehended between 2009 and 2019. The exponential function was selected to simulate the pollutant build-up and wash-off, using the parameters presented in Table 2.

3.2. Scenarios analysis

Five different aspects from the base scenario were selected, as those that could have potential modification due to urbanization processes. These aspects were (a) impervious coverage, (b) directly connected impervious area (DCIA), (c) land uses, (d) pipe material and (e) sewage system type. For the purpose of this article, it was decided to present only the information for scenario (a) impervious coverage, as it proved to replicate in an accurate and simplified manner the process of urbanization. The scenarios consisted of models with varying impervious coverage percentages, ranging from 0% to 100%, with increasing steps of 5%.

3.2.1. Sensitivity and statistical analysis

The sensitivity analysis consisted of performing iterative increments on the variable being analysed (impervious coverage), and subsequently, analysing the effect of these increments in the performance variables previously defined; these results were summarized in sensitivity graphs for the different performance variables.

In order to have a robust statistical analysis for the sensitivity curves, a fitting procedure was developed. Each curve was first adjusted using a linear regression; if the determination coefficient R^2 was higher than 0.9, it was accepted as a valid

Table 2 | SWMM parameters used for water quality modelling

Pollutant	Parameter	Selected value
Total suspended solids (TSS)	Max. build up	71.06
	Constant	0.74
	Coefficient	4.03
	Exponent	2.45
Total phosphorus (TP)	Max. build up	0.04
	Constant	0.16
	Coefficient	1.95
	Exponent	2.05
Total nitrogen (TN)	Max. build up	0.15
	Constant	2.02
	Coefficient	25.22
	Exponent	3.96

regression. Curves that did not meet this criteria were adjusted using a quadratic regression.

$$\mathrm{Vol(L)} = b + a * \mathrm{impermeability} \tag{1}$$

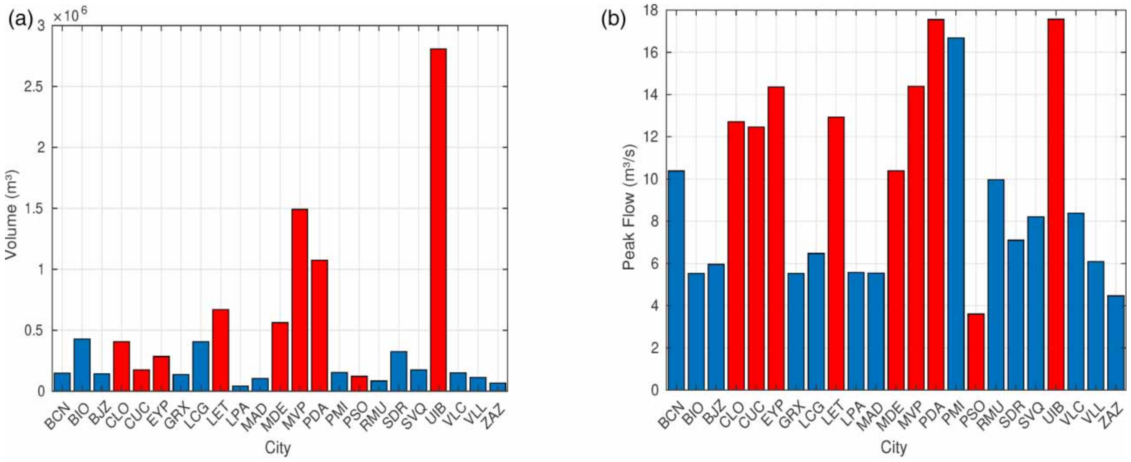
$$Q(\mathrm{L/s}) = c + b * \mathrm{impermeability} + a * \mathrm{impermeability}^2 \tag{2}$$

$$\mathrm{TSS\,load\,(kg)} = c + b * \mathrm{impermeability} + a * \mathrm{impermeability}^2 \tag{3}$$

4. RESULTS AND DISCUSSION

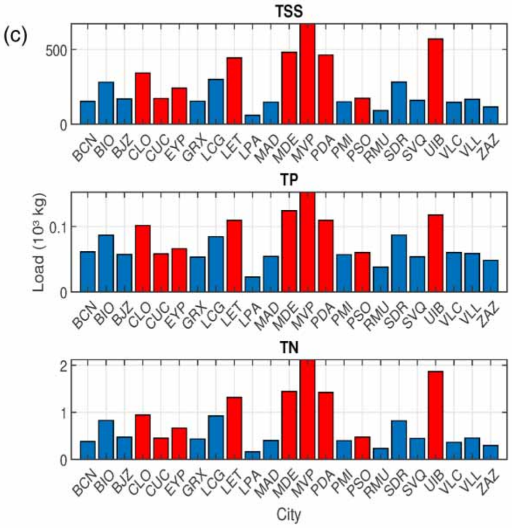
4.1. Preliminary geographical analysis

Figure 3(a) presents the average annual runoff volume by cities. Red bars represent the cities located in Colombia, and blue bars represent the Spanish cities. When conducting a trans-national analysis, it was identified that Colombian cities presented average annual runoff volumes much higher than Spanish cities.



Annual average runoff volume

Peak flow



Annual average pollutants load

Figure 3 | Runoff volume (a), peak flow (b) and pollutants loads (c) for Colombian (red bars) and Spanish cities (blue bars). Please refer to the online version of this paper to see this figure in colour: https://dx.doi.org/10.2166/wst.2023.010.

Regarding a national analysis, results for the Spanish cities allowed to identify that Bilbao (BIO), La Coruña (LCG) and Santander (SDR) were the cities with the highest runoff volumes, with values above 4,000 m^3 per year; these are all cities located in the oceanic coast of Spain, where precipitation events are quite recurrent. At a second level are the Mediterranean-weather cities of Badajoz (BJZ), Barcelona (BCN), Seville (DVQ), Granada (GRX) and Valencia (VLC) (values around 2,000 m^3 per year), which have similar hydroclimatic regimes, as they are all located in (or near) the south coastal part of the country. Finally, the cities with the lowest runoff volumes were Madrid (MAD), Murcia (RMU), Valladolid (VLL), Zaragoza (ZAZ) and Gran Canaria (LPA), with average yearly runoff values below 1,000 m^3; the first three cities have in common that they are all located in continental inner regions of Spain. Regarding Gran Canaria, it is located at a subtropical level, far away from the peninsular Spanish region, where the hydroclimatic conditions are completely different than the rest of Spain. The other island included in the analysis was Palma de Mallorca, which is located in the Baleares Islands, in the Mediterranean sea.

For Colombian cities, the variability found within the different cities was even higher. Quibdó (UIB), Mitú (MVP), Inírida (PDA) and Leticia (LET), located in rainy forest regions, were the cities with the highest average annual runoff, with values above 1,000,000 m^3 of yearly annual runoff. Subsequently, there were cities such as Cali (CLO) and Medellín (MDE), located in Andean regions with middle rainfall averages around 5,000 m^3. Finally, the cities with the lowest annual runoff rates were Yopal (EYP), Cúcuta (CUC) and Pasto (PSO), the first one being located in the eastern plains, and the other two in inner regions; these are all locations where the mean annual rainfall is lower than the rest of the regions (Poveda 2004).

Results for peak flow are presented in Figure 3(b). Quibdó (UIB), Inírida (PDA), Mitú (MVP) and Palma de Mallorca (PMI) presented the highest peak flows, with values of up to 16 m^3/s, which is a clear indicator of the high rainfall intensities that are common in these cities (Poveda 2004). Then, cities such as Cúcuta (CUC), Cali (CLO), Barcelona (BCN), Medellín (MDE), Murcia (RMU), Seville (DVQ) or Valladolid (VLL) presented peak flows between 10 and 14 m^3/s. The rest of the cities presented values close to 6 m^3/s, while Pasto (PSO) and Zaragoza (ZAZ) were the cities with the lowest peak flows, with values below 4.5 m^3/s. In this case, the regional and national patterns were not so evident as before, and the ranking of the peak flow from Spanish and Colombian was not so clear.

The dynamics for the pollutants loads (Figure 3(c)) presented a behaviour similar to the runoff volume. In general, Colombian cities showed higher loads of pollutants, with a clear correlation between the quantity of runoff and the pollutants loads. Understanding that the parameters used for washing-off and building-up of pollutants were the same for all cities, these differences can be directly attributed to the effect of the rainfall regimes. It is worth mentioning that Figure 3(c) allowed to identify that the dynamics for the three pollutants modelled (total suspended solids (TSS), total nitrogen (TN) and total phosphorus (TP)) were similar, reason why it was decided to present results only for TSS from this point forward.

After this preliminary analysis, the cities were classified in different groups. The criteria used to make this classification consisted of the similarity in results found in this analysis, which coincided with the geographical location of the cities (see Table 3).

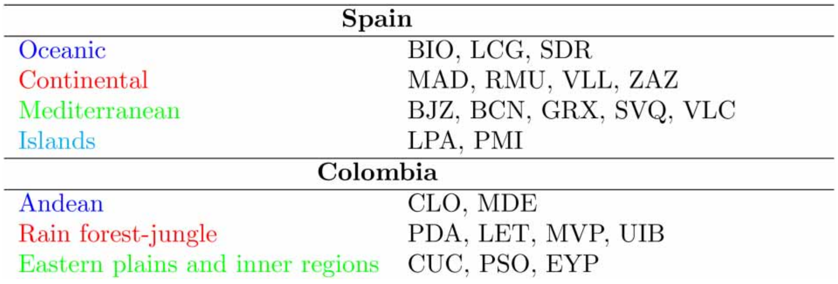
4.2. Urbanization effect

4.2.1. National scale

Acknowledging that the national scale had a representative effect on the hydrological values assessed, it was decided to perform a sensitivity analysis for the impervious areas grouping the cities into Colombian and Spanish cities. Figure 4(a) presents the sensitivity analysis results for the average annual runoff volume for the 23 different cities, classifying the cities in Colombian (red curves) and Spanish cities (blue curves). The model used for the present, and the subsequent analyses consisted of the same theoretical base catchment (Figure 2), with an area of 80 ha.

As expected, increases in the impervious coverages led to higher runoff volumes, confirming one of the negative effects of urbanization stated by numerous authors (Brattebo & Booth 2003; Barbosa *et al.* 2012). Figure 4(a) allowed to identify substantial differences between the cities analysed; at a broad scale, it could be noticed that for low levels of impermeability (below 20%), the majority of Colombian cities presented higher runoff volumes, with values of up to three orders of magnitude higher than the Spanish cities. Furthermore, the effect of increasing the impervious coverage was different for the different scenarios; cities with lower initial runoff volumes presented higher increase ratios, and consequently, cities with higher initial runoff volumes were not so sensitive to changes in the impervious coverage. For high impermeability coverage (higher than 80%), the difference between the Spanish and the Colombian cities was less perceptible, with differences of up to one order of magnitude (comparing them with the initial three levels of magnitude differences). It is clear that the magnitude

Table 3 | Climatic classification for Spanish and Colombian cities



Spain	
Oceanic	BIO, LCG, SDR
Continental	MAD, RMU, VLL, ZAZ
Mediterranean	BJZ, BCN, GRX, SVQ, VLC
Islands	LPA, PMI
Colombia	
Andean	CLO, MDE
Rain forest-jungle	PDA, LET, MVP, UIB
Eastern plains and inner regions	CUC, PSO, EYP

The color of the text of each group indicates the legend in Figures 5 and 6.

of the urbanization effect is different for the two countries analysed; regions with water scarcity, such as the Spanish cities, presented higher sensitivity to the urbanization processes. In turn, cities with higher initial runoff volumes also proved to be sensitive to changes in the impervious coverages, but in lower magnitude. Overall, it could be identified that the most sensitive range was for values from 0 to 30% of impervious coverages.

Regarding the peak flow, Figure 4(b) allowed to identify that urbanization processes caused higher peak flows. In this case, the difference in sensitivity between Spanish and Colombian cities was sharper than the difference observed for the runoff volume. In most of the cases, Spanish cities presented initial peak flows of 2 m^3/s or lower, and consequently, they increased significantly, reaching levels above 10 m^3/s. At the same time, Colombian cities that had initial peak flows above 10 m^3/s did not suffer drastic changes due to urbanization. As a general fact, it could also be noticed that all curves tended to flatten, but at different impermeability values (varied from 20 to 60%) regardless of the country; this is a clear indicator that the sensitivity of the peak flow might be dealing with multiple other variables besides the region, such as the sewer system capacity and the study site characteristics.

Finally, the analysis for pollutant loads (Figure 4(c)) presented a similar behaviour than the runoff volume. In all cases, urbanization processes caused higher pollutant loads; for Spanish cities, the changes ranged from less than $10*10^3$ kg of TSS loads for low levels of impermeability to values up to $100*10^3$ kg. At the same time, Colombian cities with initial loads above $100*10^3$ kg presented increases of up to $400*10^3$ kg. In all cases, two different stages in the curves were identified: for impermeability coverages between 0 and 25%, the increases in the TSS load were sharp; from this point forward, the increase rates in the pollutant load decreased substantially, which was represented by the flattening of the curve.

As a general fact, it was possible to confirm some negative effects of urbanization stated by previous studies (Berndtsson 2010; Zafra *et al.* 2011; Barbosa *et al.* 2012; Srishantha & Rathnayake 2017), such as increased runoff volumes, peak flows and pollutants loads. These effects proved to have complex dynamics depending on the different regions assessed. For that reason, it was decided to perform a regional analysis in greater depth.

4.2.2. Regional scale

In order to include a smaller geographical scale on the analysis, different colour labels were used to cluster regions described in Table 3. The objective of this analysis was to evaluate the hydrological similarities within the cities that were located in the same region, in order to count with solid evidence to differentiate the effect of urbanization depending on the region. Figure 5(a) presents the total runoff volume for the 14 Spanish cities, which allowed identifying similar patterns within the cities from each group; at the same time, differences between the groups could be clearly identified, leading to the conclusion that the regions were well defined, and that they are an important aspect to have under consideration when analysing the effect of urbanization.

A particular case occurred with the Spanish islands (cyan label); in this case, the two cities presented different behaviours; Palma de Mallorca (PMI) presented a behaviour similar to the Mediterranean group, as it is located in this region, while Gran Canaria's (LPA) behaviour is closer to the continental group. This fact can be attributed to the fact that the islands have unique and specific hydroclimatic conditions, which is why it is difficult to find similar patterns between them.

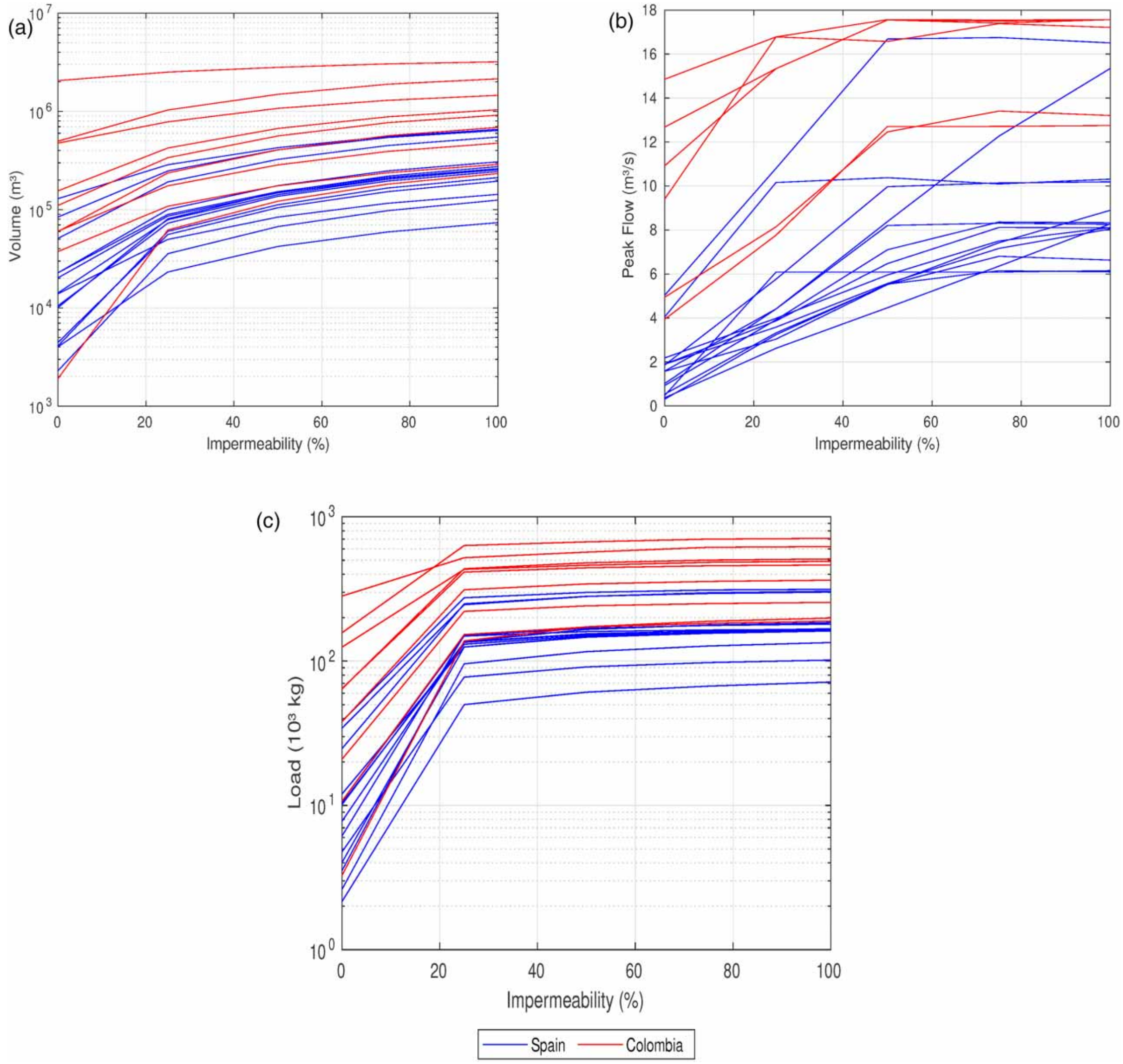


Figure 4 | National scale analysis of impervious coverage effect over runoff volume (a), peak flow (b) and TSS loads (c). Please refer to the online version of this paper to see this figure in colour: https://dx.doi.org/10.2166/wst.2023.010.

Furthermore, Figure 5(c) presents the results for TSS loads. The regional scale yielded a similar pattern than in Figure 5(a), with the exception that the differences between the Mediterranean and the continental cities is less perceptible. Regarding the peak flow analysis (Figure 5(b)), the regional differences are not evident, as it is not possible to identify clear patterns for each group of cities.

Figure 6 presents the results for the regional analysis in Colombia. The patterns identified are very similar to the analysis for Spanish cities. Runoff volume and TSS loads behaviour presented a high correlation with the region, with clear patterns identified along the different groups of cities. Similarly, this regional effect of the urbanization processes is neglected when analysing the peak flow.

Once again, the relevance of the region becomes evident when modelling the effect of urbanization in the watersheds. In this case, it was shown that, specifically for runoff volume and pollutant loads, the dynamics of variation largely depend on the region where the case study is located.

4.3. General dynamics for the hydrological variables assessed

Regardless of the regional scale of the meteorological information, it was found that, depending on the hydrological variable, there were more sensitive ranges to changes in the imperviousness. For runoff volumes and peak flows, this range was

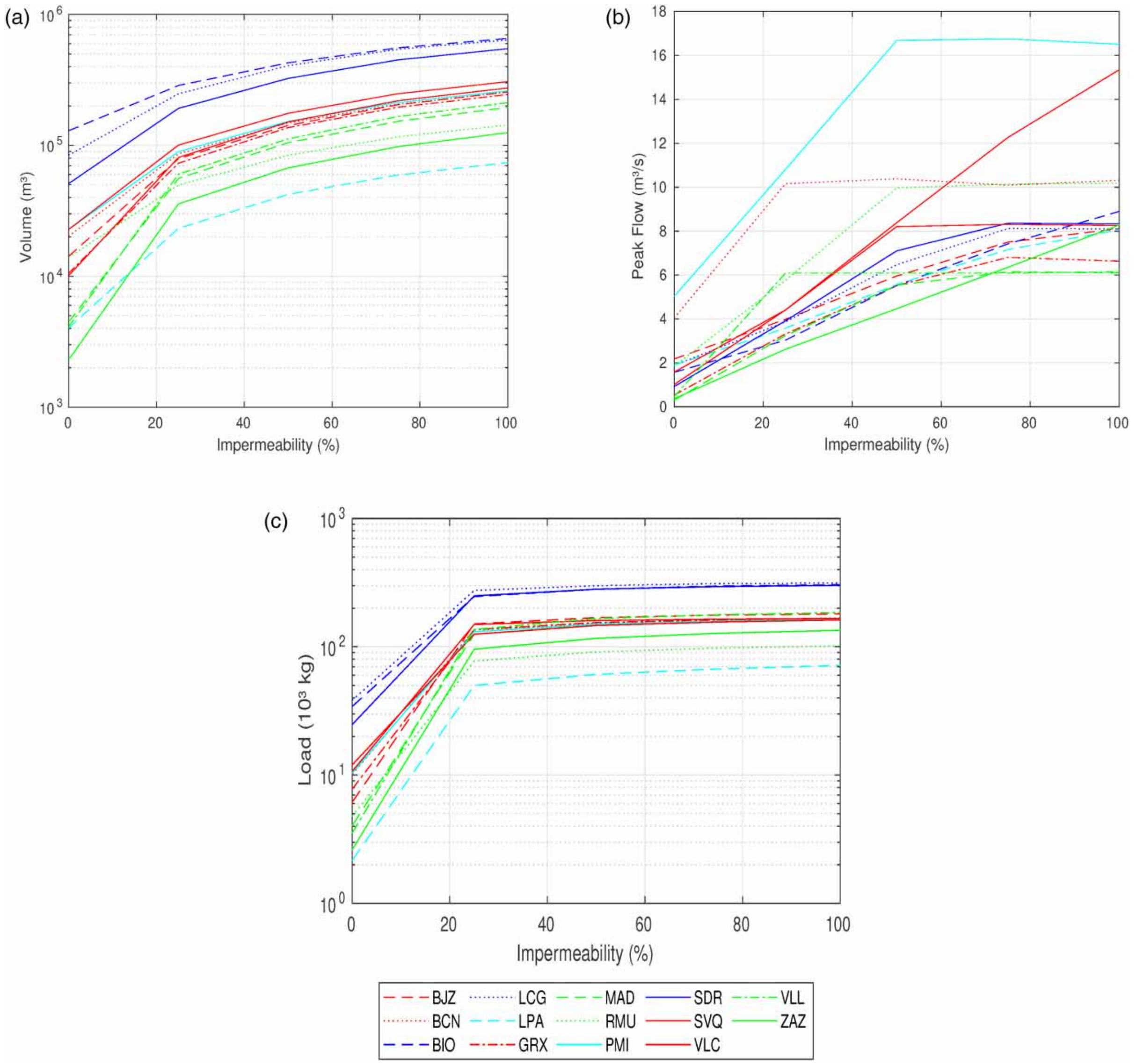


Figure 5 | Spanish Regional scale analysis of impervious coverage effect over runoff volume (a), peak flow (b) and TSS loads (c). Blue labels correspond to the Oceanic cities, red to Mediterranean, green to Continental and cyan to Islands. Please refer to the online version of this paper to see this figure in colour: https://dx.doi.org/10.2166/wst.2023.010.

between 0 and 50%, while for TSS pollutant loads, it was between 0 and 30%. Inquiring into the reasons for these dynamics, it is theorized that the reason behind each variable may be different, since the nature and structure of the watershed may affect each variable differently.

For peak flow and total volume, it is considered that these dynamics are mainly explained by the runoff conveyance infrastructure. For changes in the impervious cover between 0 and 50%, it is highly probable that the sewage system has not reached its maximum capacity, which is reflected in gradual increases in the flow that it transports, and consequently in the water flow and amount that is discharged into the outlet. When the capacity of the sewage system begins to be exceeded, it is likely that CSO events, or flooding (depending on the type of sewage system) will begin to occur (St-Hilaire *et al.* 2016). This means that part of the runoff does not reach the final outlet of the basin, which is reflected in the fact that the increases in peak flow and runoff volume are increasingly smaller.

In turn, the results indicate that the sensitivity range for TSS loads is up to 30%. The first reason attributable to this dynamic is the pattern of land use in the basin. As the watershed becomes impermeable, these are modified, which generates changes

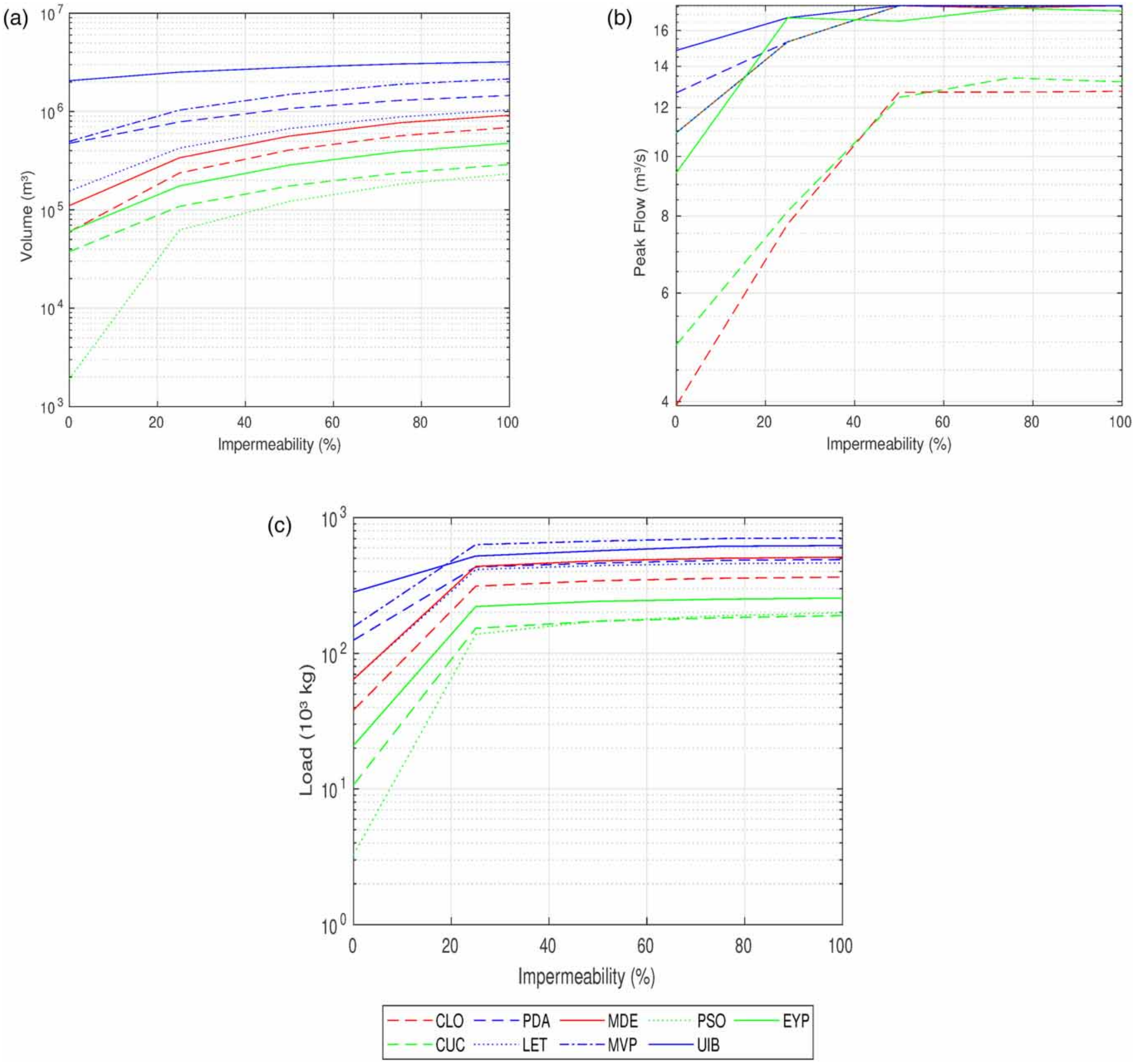


Figure 6 | Colombian Regional scale analysis of impervious coverage effect over runoff volume (a), peak flow (b) and TSS loads (c). Blue label corresponds to Rainy Forest-Jungle, red to Andean, and green to Eastern Plain and Inner Regions. Please refer to the online version of this paper to see this figure in colour: https://dx.doi.org/10.2166/wst.2023.010.

in the dynamics of surface build-up and wash-off. It is highly probable that the maximum accumulation and flushing rates of pollutants in rainfall events are reached when the watershed has percentages of imperviousness around 30%, which would explain why after this point the increases in pollutant loads are lower.

4.4. Proposed model

Regression and fitting models were developed for each curve, in order to propose a simplification that would allow to easily quantify the effect of urbanization on runoff volume, maximum flow and pollutants loads for each city analysed. All curves for runoff volumes presented a linear behaviour, following Equation (1), while peak flow and TSS loads presented a quadratic behaviour following Equations (2) and (3), respectively. In all cases, R^2 resulted to be higher than 0.95.

The coefficients *a*, *b* and *c* found for each curve are presented in Table 4. Although this information should not be considered as strictly predictive, it is worth presenting, in order to find expected reference values in each city for changes in the percentages of impermeability.

Table 4 | Regression coefficients for runoff volume (Equation (1)), peak flow (Equation (2)) and TSS loads (Equation (3)) by cities

	Volume (L)		**Peak flow (L/s)**			**TSS load (kg)**		
City	***a***	***b***	***a***	***b***	***c***	***a***	***b***	***c***
BJZ	2′436,776	17′384,296	−0.32	94	2,069	−33.30	4,830	19,974
BCN	2′360,175	25′246,789	−1.41	190	4,746	−28.38	4,207	21,789
BIO	5′297,336	146′470,418	−0.06	83	1,403	−48.86	7,255	53,175
LCG	5′620,179	103′120,956	−0.57	123	1,653	−54.80	7,836	61,411
LPA	703,594	5′380,462	−0.23	86	1,789	−10.46	1,670	6,078
GRX	2′364,105	13′905,122	−0.78	141	449	−29.84	4,346	19,666
MAD	1′911,626	6′981,428	−0.88	146	270	−27.88	4,190	14,578
RMU	1′300,124	16′460,510	−1.34	219	1,696	−16.53	2,509	11,101
PMI	2′398,369	27′814,280	−2.04	320	4,822	−27.63	4,100	21,328
SDR	5′009,518	62′685,176	−0.91	168	736	−51.94	7,586	45,766
SVQ	2′862,491	27′674,670	−1.08	177	1,352	−31.99	4,506	24,900
VLC	2′670,286	13′660,878	−0.08	154	879	−25.89	3,911	21,860
VLL	2′087,889	6′593,228	−1.27	172	1,116	−30.85	4,701	14,457
ZAZ	1′231,484	4′089,810	−0.07	85	419	−20.74	3,256	10,311
CLO	6′340,573	74′273,809	−1.43	233	3,672	−62.91	9,079	64,855
CUC	2′529,218	43′096,313	−1.16	204	4,617	−31.96	4,746	24,175
PDA	9′910,225	522′095,883	−0.85	133	12,673	−69.65	10,099	155,338
LET	8′907,696	189′175,992	−1.24	186	11,127	−80.28	11,396	100,144
MDE	8′161,506	131′029,965	−1.24	186	11,127	−85.65	12,395	100,188
MVP	16′623,972	581′318,950	−1.25	187	11,114	−107.76	15,464	205,133
PSO	2′328,292	3′861,111	−1.25	187	11,114	−30.65	4,835	13,654
UIB	11′237,499	2.162′218,963	−0.53	78	14,965	−53.15	8,410	300,868
EYP	4′189,073	68′256,260	−1.61	226	10,211	−46.01	6,593	40,847

Results found in this section allowed quantifying some of the dynamics identified in Figures 4 and 5. For example, the runoff volume base point (*b* in the regressions for Equation (1)) for Colombian cities was, on average, higher than for Spanish cities ($4.19*10^5$ m^3 and $3.41*10^4$ m^3, respectively), confirming that the runoff volume for low impermeability rates is higher for Colombian cities. Furthermore, when comparing the slope (coefficient *a*) of the two different curves, it could be noticed that, proportionally to the base point, the curves for Spanish cities presented higher slopes than Colombian cities. This finding confirms that these are more sensitive to changes in the impermeability coverage.

5. CONCLUSIONS, RECOMMENDATIONS AND LIMITATIONS

The regional analysis allowed identifying clear differences between the models with meteorological information from Spain and Colombia. Furthermore, each country presented differences between the cities, which allowed to cluster them based on their geographical location. The clusters defined proved to be adequate, as results confirmed the hydrological similarities for the cities in the same clusters, and at the same time, the differences for each cluster. The overall analysis allowed identifying that Colombian cities have higher rainfall depths, which in turn generates higher runoff volumes, and pollutant loads for these cities; regarding the peak flow, no clear differences could be noticed between the Colombian and the Spanish cities.

Regarding the effect of impermeability, the negative effect of urbanization over runoff volumes, peak flows and pollutant loads could be quantified. Furthermore, these effects were variable depending on the region and variables analysed. At a trans-national scale, cities with low rainfall averages (mostly Spanish cities) presented higher sensitivity, with increased rates in the hydrological variables between 10 and 30%. Colombian cities presented increase rates lower than 20%.

Curve fitting procedures allowed to quantify the behaviour of each hydrological variable analysed. The equations presented could be used as guidelines when predicting the potential effect that changes in the impervious coverages will have on the different regions analysed.

It is important to understand that the information presented in this manuscript is a discussion of the effect of meteorological information on the hydraulic and hydrological consequences of urbanization. As mentioned in the section on study sites, in real-life cases, there will be fundamental variables that mediate this process, such as urban structure, land uses or the type of sewage system in the cities. For future studies, it is proposed to adapt the models so that they work, not on a theoretical basin, but replicate as adequately as possible the dynamics that occur in the stormwater management system of the cities. However, it is considered that the present study is valuable as a first approximation, which evaluates at a detailed level and with real information the effect of rainfall regimes.

For future studies, is it highly recommendable to take into consideration the strong effect that the region has when studying and analysing the effect of urbanization on urban watersheds. As this was a study based on conceptual watersheds, it is highly recommendable to adopt the same methodology, using calibrated models with real watersheds. Also, more cities from different countries and regions should be included, in order to identify clear national, regional and global patterns. Furthermore, it is highly advisable to include other types of pollutants in the water quality analysis, which would allow to adequately assess the effect of chemical and biochemical processes and transformation that take place during the runoff transportation. Finally, the representation of urbanization in this study was modelled only by increments in the impervious coverage, but other parameters should also be taken into consideration to effectively model urbanization processes, such as changes in land-use patterns, infiltration rates and water quality parameters.

ACKNOWLEDGEMENTS

Rainfall and evaporation information used to develop the models was gathered thanks to the public state agencies of AEMET in Spain and IDEAM in Colombia.

FUNDING

This work was supported by the ‘Instituto Colombiano de Crédito Educativo y Estudios Técnicos en el Exterior’ (ICETEX) under the program ‘Pasaporte a la Ciencia’ granted to the first author under grant number 5334506.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

REFERENCES

AEAS 2017 *Informe sobre aguas residuales en España*.

Barbosa, A. E., Fernandes, J. N. & David, L. M. 2012 Key issues for sustainable urban stormwater management. *Water Research* **46**, 6787–6798.

Beecham, S. & Razzaghmanesh, M. 2015 Water quality and quantity investigation of green roofs in a dry climate. *Water Research* **70**, 370–384.

Berndtsson, J. C. 2010 Green roof performance towards management of runoff water quantity and quality: a review. *Ecological Engineering* **36**, 351–360.

Brabec, E., Schulte, S. & Richards, P. L. 2002 Impervious surfaces and water quality: a review of current literature and its implications for watershed planning. *Journal of Planning Literature* **16**, 499–514.

Brattebo, B. O. & Booth, D. B. 2003 Long-term stormwater quantity and quality performance of permeable pavement systems. *Water Research* **37**, 4369–4376.

Chen, J. & Adams, B. J. 2007 A derived probability distribution approach to stormwater quality modeling. *Advances in Water Resources* **30**, 80–100.

Chow, M. F., Yusop, Z. & Toriman, M. E. 2012 Modelling runoff quantity and quality in tropical urban catchments using storm water management model. *International Journal of Environmental Science and Technology* **9**, 737–748.

Dotto, C. B. S., McCarthy, D. T., Deletic, A., Mannina, G., Kleidorfer, M., Rauch, W., Vezzaro, L., Henrichs, M. & Freni, G. 2012 Comparison of different uncertainty techniques in urban stormwater quantity and quality modelling. *Water Research* **46**, 2545–2558.

Fletcher, T., Andrieu, H. & Hamel, P. 2013 Understanding, management and modelling of urban hydrology and its consequences for receiving waters: a state of the art. *Advances in Water Resources* **51**, 261–279. 35th Year Anniversary Issue. Available from: https://www.sciencedirect.com/science/article/pii/S0309170812002412.

Fletcher, T. D., Shuster, W., Hunt, W. F., Ashley, R., Butler, D., Arthur, S., Trowsdale, S., Barraud, S., Semadeni-Davies, A., Bertrand-Krajewski, J.-L., Mikkelsen, P. S., Rivard, G., Uhl, M., Dagenais, D. & Viklander, M. 2015 SUDS, LID, BMPs, WSUD and more – the evolution and application of terminology surrounding urban drainage. *Urban Water Journal* **12**, 525–542. arXiv: https://doi.org/10.1080/1573062X.2014.916314.

Hood, M., Reihan, A. & Loigu, E. 2007 Modeling urban stormwater runoff pollution in Tallinn, Estonia. In: *UWM, International Symposium on New Directions in Urban Water Management*, September, Paris, France, pp. 12–14.

Hossain, I., Imteaz, M. A. & Hossain, M. I. 2012 Application of a catchment water quality model for an East-Australian catchment. *International Journal of Global Environmental Issues* **12**, 242–255. PMID:49370.

Jacobson, C. R. 2011 Identification and quantification of the hydrological impacts of imperviousness in urban catchments: a review. *Journal of Environmental Management* **92**, 1438–1448. Available from: https://www.sciencedirect.com/science/article/pii/S0301479711000259.

Jaramillo, A. & Kogson, J. F. 1994 Características de las lluvias máximas en la zona cafetera colombiana. *Cenicafé* **45** (1), 25–34.

Jayasooriya, V. M. & Ng, A. W. 2014 Tools for modeling of stormwater management and economics of green infrastructure practices: a review. *Water, Air, and Soil Pollution* **225**, 1–20.

Jiang, S. S. S. 2017 *Åes posible la separación de los alcantarillados de aguas residuales y de aguas lluvia en ciudades colombianas?*

Li, J., Li, Y. & Li, Y. 2016 SWMM-based evaluation of the effect of rain gardens on urbanized areas. *Environmental Earth Sciences* **75**, 1–14.

Modugno, M. D., Gioia, A., Gorgoglione, A., Iacobellis, V., la Forgia, G., Piccinni, A. F. & Ranieri, E. 2015 Build-up/wash-off monitoring and assessment for sustainable management of first flush in an urban area. *Sustainability* **7**, 5050–5070.

Oudin, L., Salavati, B., Furusho-Percot, C., Ribstein, P. & Saadi, M. 2018 Hydrological impacts of urbanization at the catchment scale. *Journal of Hydrology* **559**, 774–786. Available from: https://www.sciencedirect.com/science/article/pii/S002216941830146X.

Poveda, G. 2004 La hidroclimatología de Colombia: una síntesis desde la escala inter-decadal hasta la escala diurna. *Revista de la Academia Colombiana de Ciencias Exactas* **28**, 201–222.

Powell, S. L., Cohen, W. B., Yang, Z., Pierce, J. D. & Alberti, M. 2008 Quantification of impervious surface in the Snohomish Water Resources Inventory Area of Western Washington from 1972-2006. *Remote Sensing of Environment* **112**, 1895–1908.

Rosa, D. J., Clausen, J. C. & Dietz, M. E. 2015 Calibration and verification of SWMM for low impact development. *Journal of the American Water Resources Association* **51**, 746–757.

Rossman, L. A. 2010 *Storm Water Management Model User's Manual, Version 5.0*. National Risk Management Research Laboratory, Office of Research, Environmental Protection Agency, Washington, DC, USA.

Rossman, L. A. & Huber, W. C. 2015 *Storm Water Management Model Reference Manual Volume Hydrology*. US Environmental Protection Agency, Washington, DC, USA, p. 3.

Saadi, M., Oudin, L. & Ribstein, P. 2021 Physically consistent conceptual rainfall-runoff model for urbanized catchments. *Journal of Hydrology* **599**, 126394. Available from: https://www.sciencedirect.com/science/article/pii/S0022169421004418.

Salvadore, E., Bronders, J. & Batelaan, O. 2015 Hydrological modelling of urbanized catchments: a review and future directions. *Journal of Hydrology* **529**, 62–81. Available from: https://www.sciencedirect.com/science/article/pii/S0022169415004412.

Srishantha, U. & Rathnayake, U. 2017 Sustainable urban drainage systems (SUDS) - what it is and where do we stand today? *Engineering and Applied Science Research* **44**, 235–241.

St-Hilaire, A., Duchesne, S. & Rousseau, A. N. 2016 Floods and water quality in Canada: a review of the interactions with urbanization, agriculture and forestry. *Canadian Water Resources Journal/Revue Canadienne des Ressources Hydriques* **41**, 273–287.

Temprano, J., Arango, Ó., Cagiao, J., Suárez, J. & Tejero, I. 2006 Stormwater quality calibration by SWMM: a case study in northern Spain. *Water SA* **32**, 55–63.

Torres, F. J. S. & Eljaiek, I. R. E. 2012 *Urbanización, desarrollo económico y pobreza en el sistema de ciudades colombianas 1951-2005*.

Tu, M. C. & Smith, P. 2018 Modeling pollutant buildup and washoff parameters for SWMM based on land use in a semiarid urban watershed. *Water, Air, & Soil Pollution* **229**, 1–15.

Zafra, C., Temprano, J. & Tejero, I. 2011 Distribution of the concentration of heavy metals associated with the sediment particles accumulated on road surfaces. *Environmental Technology* **32**, 997–1008.

Zafra, C., Temprano, J. & Suárez, J. 2017a A simplified method for determining potential heavy metal loads washed-off by stormwater runoff from road-deposited sediments. *Science of the Total Environment* **601–602**, 260–270.

Zafra, C., Temprano, J. & Tejero, I. 2017b The physical factors affecting heavy metals accumulated in the sediment deposited on road surfaces in dry weather: a review. *Urban Water Journal* **14**, 639–649.

First received 17 November 2022; accepted in revised form 9 January 2023. Available online 19 January 2023