Exploring an Approach to Estimate Runoff in an Ungauged Mixed Urban Micro Catchment - A Case Study, Pune, India

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Abstract

Sustainable and integrated water resource management needs an hour, and achieving accurate estimation of runoff is key. The decision-making on urban landscaping planning for low-impact development techniques depends largely on the accuracy of rainfall. The haphazardly developed cities in India are encountering flooding crises due to the unexpected expansion. These mixed urban catchments comprise a muddle of residential, commercial, urban-rural, and industrial zones in any combination. Due to this change in urban catchments, the hydrological cycle gets affected and results in elevated runoff volume. The solutions to these are therefore necessary to be planned at a micro catchment level. This paper aims to explore an approach to calculate the runoff of such a micro mixed urban catchment. The geographical scope of this study is the fringe boundary of Pune city. For this ungauged basin, the basic mass balance equation was used to estimate runoff values compared with the runoff values calculated from empirical equations previously developed. From this comparison, it is observed that runoff values obtained from empirical equations were underestimated, which may be due to rapid land-use caused by urbanization. Hence, a need was felt to re-evaluate the coefficients of these empirical models, which take into cognizance the current scenario and its allied changes over the years.

An attempt is made to modify the coefficients of empirical equations considering precipitation as the primary parameter. These modified coefficients fetched better runoff results than the runoff results obtained from the coefficients of previously established empirical equations. However, even with these modified coefficients, the runoff results were underestimated, which may be because of not considering the physical characteristics of the catchment in these equations. Therefore, to increase the accuracy of these results, a numerical model that considers these catchment characteristics was chosen. In the present study, a dynamic rainfall-runoff model - stormwater management models (SWMM) is used and compared to assess runoff for an ungauged micro-catchment. The runoff results achieved from these SWMM models better reproduced the hydrologic and hydraulic behavior of the study area (with RMSE

of 2.51) by considering detailed catchment characteristics compared to those obtained from all the other empirical models.

1. Introduction

The world's thirst for water is one of the significant resource issues of this Century. Water is a lifeline for humanity and is a vital requirement for the sustainable growth of society. Precipitation forms a crucial fraction of the hydrological cycle, directly affected by urbanization and climate change. India is a developing country and urbanizes at a rapid rate [1]. The level of urbanization in India increased from 10.8% to 31.1% from 1901 to 2011. India ranks in the second position in urban population, followed by China. From 1947 to 2011, the Indian urban population increased by 317 million. Due to the rise in urban population, the average size of towns (and cities) in India has increased from 33,624 in 1961 to 61,159 in 2011 [2].

Urbanization is transforming the previous green cover into impervious areas like concrete roads, parking spaces, and building rooftops. Urban areas started in the 1960s when various hydrological problems popped out due to accelerating urbanization. Urban stormwater runoff is of significant environmental concern as the cities are experiencing contrast water-stressed and flooding situations [3]. Appropriate assessment of the runoff volume in an urban area is essential for designing, planning, and managing water resources. These solutions will be effective and efficient if they are planned at micro catchment levels. Accurate runoff determination is a significant factor in analyzing and managing water resources [4].

Major catchments or river basins in India are gauged to calculate hydrological variables. However, medium-sized and microsized areas are not gauged. The transformation of rainfall to runoff for an urbanized area is an abstruse process. The distribution is spatial and nonlinear. Models can be developed if the long-range of data is available [5]. Rainfall-runoff simulation employs several different methods. These models have shown their success in determining the runoff for large catchment areas. This paper explores to find a method to calculate the runoff for an ungauged micro mixed urbanized area in a developing country [6].

2. Study Area

Pune city is booming exponentially over its longitudinal scope as new neighboring fringe areas were taken under its sphere with time [7]. "The developed space at Pune Municipal Corporation (PMC) has grown from 18.3 km^2 in 1973 to 139.4 km^2 in 2013 by a medium growth rate of 3 km^2 per year, around 7.5 times. If this urban sprawl persists, by 2030 the built-up area will increase by 206,4 km^2", Location Sketch is indicated in Figure 1.

For the last two decades, the growth of the Pune city has remained on a circle and spoked design. An increase in migration rate and haphazard growth resulting in unauthorized construction on a wide scale and independent property uses leads to mixing urban land use [8].

Pune district is divided into 23 basins based on geography by Pune Municipal Corporation. For this study, the "G basin" is considered, located on the fringe limit of the city of Pune, as shown in Figure 2. With urbanization, a significant increase in impervious areas is observed, which results in elevated runoff volume. Due to these impervious lands such as paved grounds, concrete roads, roofs of the buildings result in the quick flow of runoff and, in turn, reduced loss due to evaporation as of decreased contact time along with low infiltration rates, causing the increased peak in a short duration also referred as flash floods [9]. Thus, with the shift in land-use form, the influence the rainfall-runoff process of the catchments. Figures 3 and Figure 4 depict the quick modifications in the build-up area due to the urbanization of the G basin in 12 years, from the year 2004 to 2018. This study attempts to understand the adequacy of existing models to cope with the dynamics of catchment and rainfall characteristics for a small catchment area [10].

Figure 1 - Location Sketch
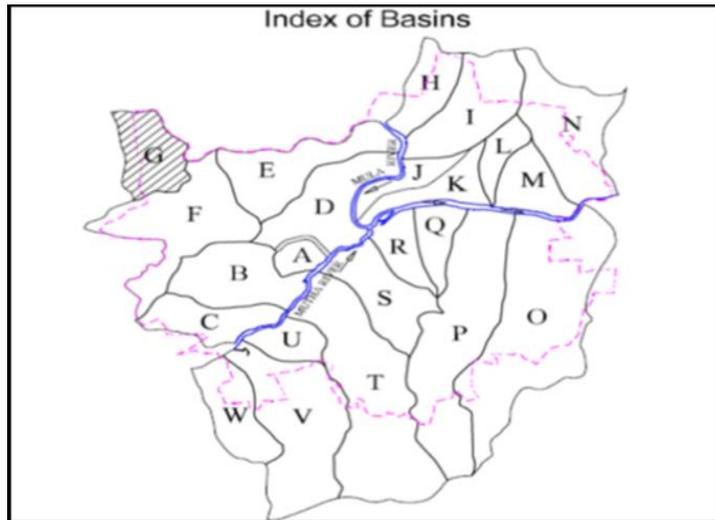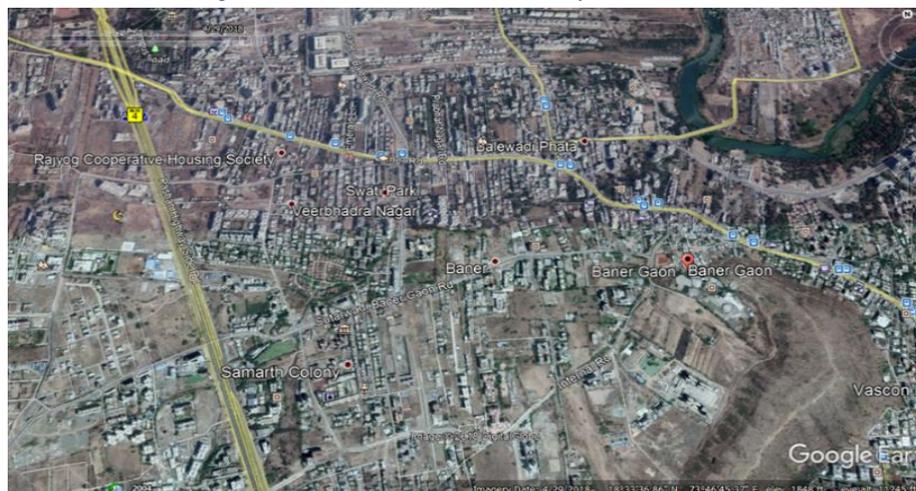
Figure 2 - Study area: highlighted g basin (PMC)

Figure 3 - Satellite view of the Study Area in 2004

Figure 4 - Satellite view of the Study Area in 2018

3. Results and Discussion

3.1. Estimation of Runoff Using Empirical Models

Empirical equations have also been known as data-driven sets. They implement nonlinear numerical relationships between input parameters and the results obtained. These analytical equations vary considerably with the precision of input. Most empirical versions are black-box patterns, implying less knowledge of intricacies involved that influence the runoff as output [11]. Empirical runoff models are used when another form of output is not required, such as the distribution of runoff in a basin. Implementation simplicity, quicker processing, and economy are reasons for using empirical models for modeling.

Several empirical relationships developed between precipitation and annual surface runoff, such as Inglis and D'Souza formula, Khosla's equation, the Irrigation Department of India, Coutagine relationship, etc. The empirical models are employed for several catchments, such as "Chaskaman and NiraDeoghar Catchment of Pune." The conclusions demonstrated the considerable deviations between the measured and estimated values of runoff. Also, the accuracy and efficiency of each model are required to be tested before using it in other watersheds [12]. The empirical interactions are essentially relevant for a specific region, where relationships are developed by considering that region's information. Topographical conditions of the area are dynamic, immensely changed with the years, lowering the efficiency of these empirical equations. Hence, modifying these empirical equations for the micro-catchments that are not gauged is necessary. The existing geographical environments and associated changes are taken into consideration.

In this research, an effort is done to modify the empirical equation concerning the changes in the current scenario due to rapid urbanization. G basin is an ungauged catchment and has four main streams, which meets Mule River at four outfall station [13]. Being an ungauged catchment, hydrological variables such as runoff volume is not available. For runoff volume calculations, the basic water balance equation is used from the year 1982 to 2018. Out of which, from 1982 to 2011, an annual runoff was taken to train the model. Precipitation is considered as the crucial parameter for the enhancement of the modified model. Equation 1 is a governing equation taken from the base equation derived from Inglis and DeSouza equation for the Deccan plateau. G basin falls in this area [14].

$$R = aP^2 - bP \qquad (1)$$

Where,

R= Runoff from water balance equation in cm/yr.

P= Rainfall in cm/yr.

By using the Gaussian elimination method, MATLAB gives output coefficients as a =0.0038 and b=-0.4025.

The final equation is as follows:

$$R = 0.0038 * P^2 + 0.4025 * P \qquad (2)$$

Using the above-modified Equation 2, runoff is calculated and compared with Inglis and DeSouza, Department of irrigation, India, and rational formula, where values C are taken from PMC.

Figure 5 - Comparison of Runoff Values with Modified Equation (Satpute et al.)
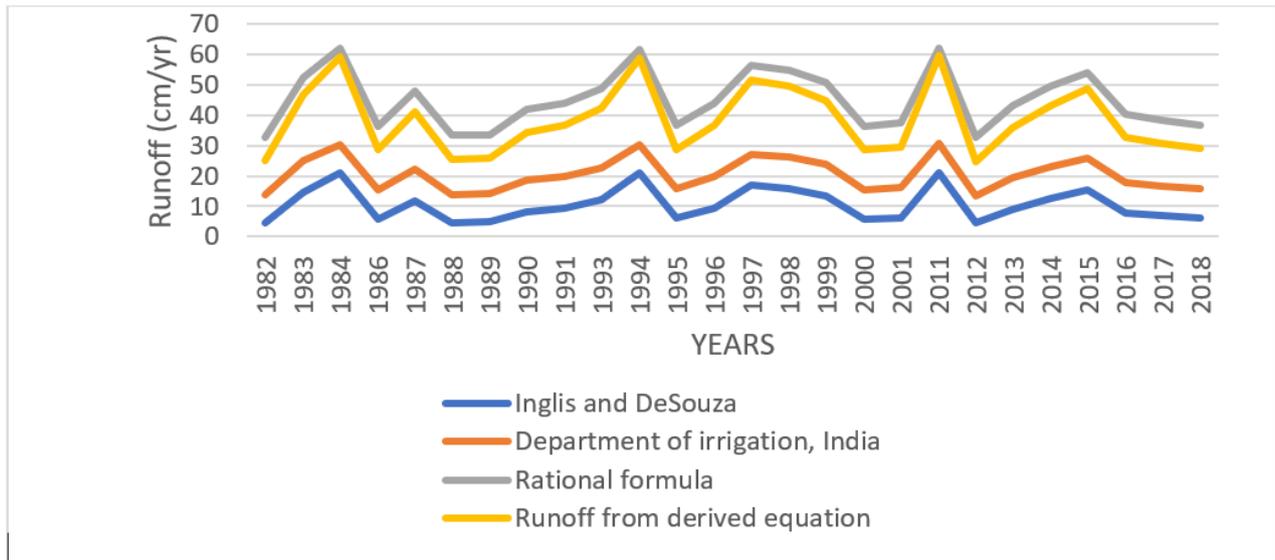
From Figure 5, it was observed that empirical equations undervalued runoff values. Thus, it can be concluded that when these empirical models have developed, the geographical advancement at that period was distinct from the existing urbanized scenario. Modified equation is simple to use as it requires only precipitation as input. From the statistical report of the study, in present RMSE of the modified equation are 6.79, which show the least error than other empirical equations. These empirical equations are reliable but are quite sensitive to the input parameters and possess a high degree of subjectivity in their application. Numerical models were explored further for micro ungauged mixed urban catchment to consider the catchment characteristics [12].

## 3.2. Estimation of Runoff using Numerical Model

Numerical models appeared to be simplified hydrological equations to give you a general understanding of what is happening and the performances in a catchment. Such models require a

long-range of parameters and input meteorological data to calibrate and validate the models. In recent years, numerical models have earned acceptance because they are easy to use and calibrate.

At present, many numerical models are available, out of which the stormwater management model (SWMM) is utilized for rainfall-runoff modeling and conveyed through the drainage system. The EPA Storm Water Management Model (SWMM) is a complex rainfall-runoff model used to simulate runoff quantities. It performs better, predominantly for urban areas. A research was done by Waikar et al. in SGGSIE&T located in Vishnupuri, Nanded, using SWMM. The catchment area, with 31 junction nodes and conduits, is distributed into 98 small sub-catchments. The simulation is performed for 30 events: rainfall data from 1983-2014 as extreme events every year and compared to the rational approach. The cumulative runoff from the catchment using SWMM and rational approach is 2.177m3 / sec and 1.109m3/sec, respectively. The SWMM model to study the overflow attributes of Centennial Park catchments in Sydney [13]. Surface runoff varies with the catchment characteristics to minimize prediction error, and model control parameters required adjustments. The optimization algorithm in MATLAB was developed to find out optimum values of control parameters and used to develop a model to improve the efficiency of the catchment modeling system calibration process. The hydrological processes of stormwater runoff were examined by Kong et al. about land-use changes at Bazhong, China, utilizing the GIS-based Stormwater Management Model (SWMM). The modeling parameters required were extracted from the existing GIS information and then directly linked with the SWMM. Simulation results showed that a reduction of 33.3% in a percentage region raises runoff 92.9%, runoff coefficients 90.9%, and peak runoff time 35 min earlier.

G basin contains four naturally occurring streams to which the stormwater drains are connected in the present case study. The mainstream of this micro catchment is selected, which is about 3.5 km in length and catchment delineated using global mapper in 20 sub-catchments as presented in Figure 7., and the area of each sub-catchment was calculated. The imperviousness area is one important parameter for numerical modeling. The percentage of impervious areas is calculated for each sub-basin from 2011 to 2018 using GIS bases for accounting for urbanization [14]. From Figure 6, it is observed that urbanization increases with time. Suppose we consider sub-catchment number 4, the percentage of impervious increases from 46.63 to 84.60 in 7 years, almost 40% increment in impervious area. It is observed that the trend is of an increase in the impervious area for all 20 delineated catchments. There is no specific growth pattern observed, which may be due to uncontrolled haphazard growth resulting from the formation of mixed land use. For the current case study, two numerical models, SWMM (Horton equation), SWMM (SCS-CN Method), were developed.

Figure 6 - % of Impervious of Each -Sub-catchment from 2011 to 2018
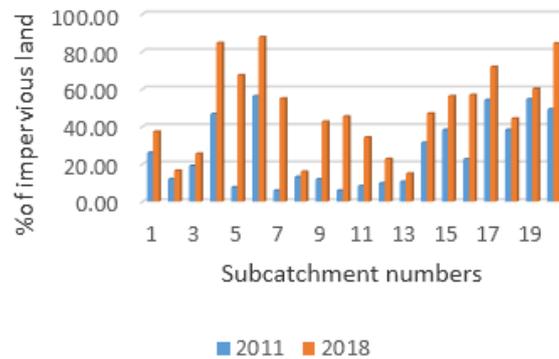
In SWMM, for the Horton equation for the present study maximum and minimum infiltration rate was taken as 2 in/hr and 0.1 in/hr obtained from laboratory permeability tests. Impervious manning's 'n' was taken as 0.01 and pervious 0.1 for mix urban catchment from data provided by PMC. Global mapper is used and DEM as an input layer to calculate the slope of each sub-catchment [15].

In the present study, 22 nodes and one outfall node were selected on the stream, where one drain meets another stream or stormwater drains change their shape. The outfall node is of free type, which means it discharges stormwater freely in the Mula River. The basic input parameter is an inverted level of each node. Invert level and details of a section of each node were taken from the PMC datasheet. The model created is shown in Figure 7; one rain gauge is assigned to all sub-catchments. Daily rainfall and evaporation time series is created from 2011 to 2018.

Figure 7 - Structure of the SWMM Model
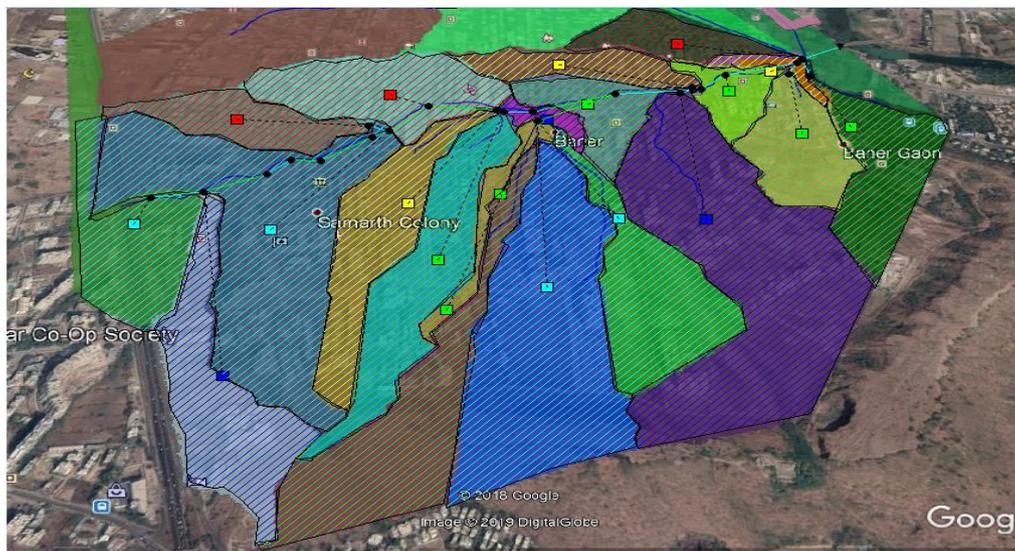
The routing time step was set to 30 sec. The design was reproduced with rainfall information daily for the duration from 1 January 2018 to 31 December 2018 with 2011 to 2018 [16].The status report shows total precipitation and surface runoff of a simulation result of the year 2018, as shown in Table 1.

The Curve Number infiltration method in SWMM is an extensively used SCS Curve Number Method for calculating runoff. The curve number method, also known as a mixed loss method, collects the damages due to interference, depression storage, and intrusion. The CN is a role of land usage, soil group, and precursor damp states. The SWMM uses an updated, incremental method that relies only on infiltration losses, as the other abstractions are modelled separately. The expressions used in the modified curve number method are given below in Equations 3 & 4.

$$CN1= (4.2\ CN2)/ (10-0.058\ CN2) \qquad (3)$$
$$CN3= (23\ CN2)/ (10-0.13\ CN2) \qquad (4)$$

In this study for the G basin, the Equation 3 condition was adopted due to long-term simulation. The soil can reach its maximum possible moisture retention capacity during the expanded dry period. A CN values, rainfall, and evaporation time series data from 1 January 2018 to 31 December 2018 are entered into the SWMM 5.1 and simulated. The reporting step and routing step were set at 30 minutes and 30 seconds, respectively. As a total output runoff, and runoff coefficients were determined and further analyzed. The results of SWMM Horton overpowered SWMM (SCS_CN); therefore, further Horton results are compared.

Table 1 - Results of Runoff Quantity using SWMM

Parameter	SWMM Horton Depth (mm)	SWMM SCS CN Depth (mm)
Total precipitation	490.00	490.50
Surface runoff	410.07	396.64

Table 2 - Equivalent Runoff Coefficient

YEAR	Equivalent runoff coefficients derived from SWMM
2011	0.723131
2012	0.741881
2013	0.748067
2014	0.784311
2015	0.788177
2016	0.798679
2017	0.805219
2018	0.816978

The value of C increases as the impervious area increases due to urbanization, which increases runoff volume for the same rainfall intensity, which observed from Table 2. From the equivalent runoff coefficients obtained from the SWMM models, the peak runoff derived from rational models is compared as in Figure 8. The under prediction and over prediction of runoff are observed comparing the empirical and numerical models for the area. Table 3 represents the statistical results, RMSE for annual runoff values of empirical models, and the numerical model; numerical models give better results than empirical models [17].
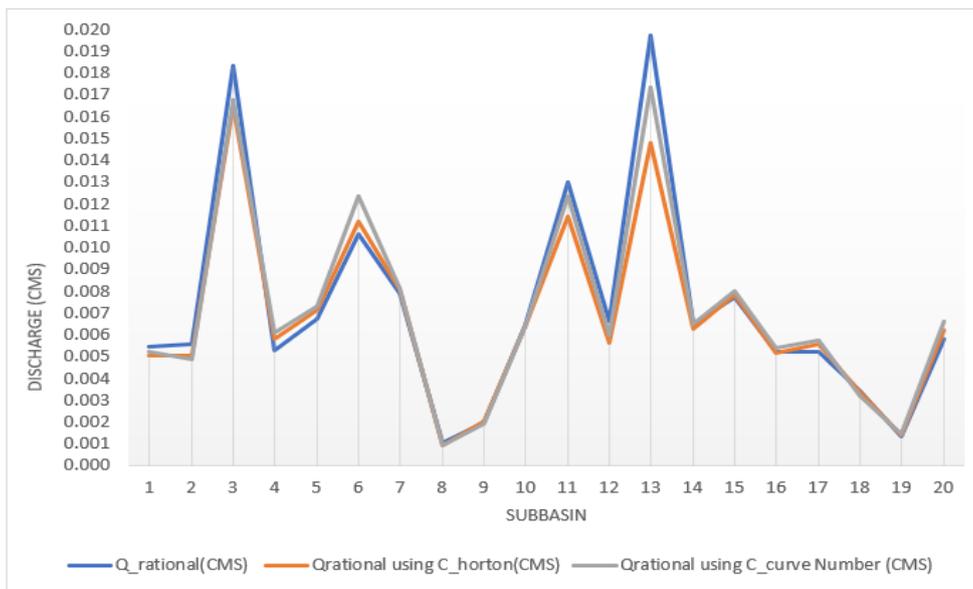
Figure 8 - Comparison of Peak Discharge Values

Table 3 - Statistical Results of Empirical Models and Numerical Model in G Basin (Satpute et al., 2019)

METHOD	MAD	MSE	RMSE	MAPE
Inglis and DeSouza	34.40	1200.72	34.65	77.86
Department of irrigation, India	24.46	613.80	24.77	54.91
Runoff from derived equation	6.58	46.13	6.79	15.94
SWMM	2.13	6.31	2.51	4.87

It can be concluded that the modified empirical equation provides an improved result than the department of irrigation and Inglis and De Souza formula [18].The change in characteristics of the catchment is not considered in the previously developed empirical equations. The modified coefficients of these existing equations fetch better results. The successful rational approach depends on the calculations of the coefficient of runoff. Numerical models developed using SWMM are more accurate for micro mixed-urban catchments as compared with the modified equation [19].

4. Conclusion

The rational approach assumes a homogeneous catchment, which has runoff coefficient as a single value as in PMC datasheet, is considered one value. The area under consideration is micro ungauged catchment. SWMM is considered a non-homogeneous catchment and divides into 20 sub-catchments. Each sub-catchment weighted equivalent runoff coefficient calculated from 2011 to 2018 is derived from both SWMM models. This study shows how for three research catchments with differing urban densities, spatial resolution was established; The runoff results were compared to those of a series of models developed for the same catchments but with progressively lower spatial resolution. High-quality data from the three instrumented research catchments are used to enable a quantitative review of the spatial resolution impacts on model parameters and efficiency. In all three catchments, for the same surfaces, HR model calibration provided identical parameter values. Although there was no influence of spatial rainfall variability on parameters, this variability did impact model results. The model efficiency degraded for distances greater than 2 km between the rainfall gauge and the flow measurement stations. These results explicitly demonstrate that the rainfall gauge must be positioned near the catchment if the aim is to replicate the patterns of urban runoff determined at a high temporal resolution.

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