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Joint calibration of a hydrological model and rating curve parameters for simulation of flash flood in urban areas

Calibração conjunta de um modelo hidrológico com parâmetros de curva-chave para simulações de inundações bruscas em áreas urbanas

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ABSTRACT

Calibration process is usually time demanding and as much streamflow information as possible in rainfall-runoff models. Nevertheless, from a practical point of view, the available information is measurement of water level, which is essential to design rating curves. This manuscript proposes a set of joint calibration of hydrological model parameters with a range of rating curves, developed for the main channel of the catchment in a crowded urban area. As an alternative of free calibration, the simulations were carried out based on a list of proficient parameters. Four streamflow gauging stations were analysed and used to subdivide the basin. The hourly lumped rainfall-runoff model GR4H was applied to four critical flash flood events to create a rank of Nash-Sutcliffe efficiency criteria (NSE) applying the best set of parameters. The results indicated that the hydrological model errors were compensated by hydraulics errors and they presented an equifinality in the process.

Keywords: Rainfall-runoff model; Flash floods; Rating curves; Urban hydrology; Hydrological and environmental modelling.

RESUMO

Nos modelos chuva-vazão, a etapa de calibração geralmente exige tempo e grande quantidade de informação das vazões. No entanto, do ponto de vista prático, a informação usualmente disponível é o nível d'água medido, este, por sua vez, utilizado na construção das curvas-chave. Este artigo propõe uma calibração conjunta dos parâmetros de um modelo hidrológico com uma gama de curvas-chave, as quais foram desenvolvidas para o canal principal da bacia em estudo em uma área altamente ocupada e urbanizada. Como alternativa a uma calibração livre, as simulações foram realizadas com base em uma lista de parâmetros previamente testados. Quatro estações limimétricas foram analisadas e utilizadas para subdividir a área da bacia. O modelo concentrado horário de chuva-vazão GR4H foi utilizado com quatro eventos críticos de inundações bruscas com o intuito de criar uma classificação de critérios de eficiência de *Nash-Sutcliffe* aplicando o melhor conjunto de parâmetros. Os resultados indicam que os erros do modelo hidrológico foram compensados pelos erros hidráulicos e apresentaram uma equifinalidade no processo.

Palavras-chave: Modelo chuva-vazão; Inundações bruscas; Curvas-chave; Hidrologia urbana; Modelagem hidrológica e ambiental.

INTRODUCTION

Hydrological modelling uncertainties

Several hydrological and hydraulic models have been proposed over the years to simulate the variety of streamflow conditions of river catchments all over the world. They are mathematical representations of physical processes observed in a diverse local climatological, meteorological and geological conditions, as well as land use and occupation. Over the years, these models have taken advantage from increased computational power and observational datasets from local and remote networks. The spatial and temporal scales of the processes they simulate have increased and the modellers have also improved their knowledge about the behavior of hydrological systems. Despite these improvements, model predictions remain uncertain. Imperfect knowledge and errors from different data sources spread through the modelling components and affects the models' outputs. The level of uncertainty can be high, especially when considering extreme hydrometeorological events, complex river basin systems and urban catchments.

In urban areas, flow simulation often involves the use of hydrological and hydraulic or rating curve models to simulate flow rates and water levels along the channels and drainage systems. These models usually have parameters that need to be calibrated against observed data. However, the major challenge for monitoring and collecting data in urban catchments is high flow velocities, short response times during flood events and channelled streams of difficult access for gauging and installation of measurement devices. Although on-site and remote monitoring systems have advanced considerably and made available some important variables for set up and calibration of models, such as flow velocity, continuous measurements of water level and high resolution rainfall data from radar. The high costs of installation, maintenance and operation of advanced equipment may constrain their widespread use, particularly in emerging and developing economies.

Uncertainties from the observed flow and water level data can intensely affect flow simulation in urban areas. They complement other sources of uncertainty such as: i) parametric uncertainty of hydrological models, ii) model structural errors, i.e., approximation of hydrological processes, and iii) model input errors (rainfall, temperature, and evapotranspiration) (KUCZERA et al., 2010). Particularly, in relation to parametric uncertainties, the lack of long lasting series of observations can be a challenge for model calibration. Brigode, Oudin and Perrin (2013), for instance, investigated the hydrological predictions of a rainfall-runoff model when affected by uncertainties from the setup of parameters using subsets of data from a calibration period. Their results showed the lack of strength in calibration was a major source of variability in streamflow predictions.

In the case of model structural errors, Refsgaard et al. (2006) reviewed the strategies to manage them and outlined a framework to handle the effects of the model structure errors of predictive uncertainty, in particular for extrapolations of uncovered

situations by calibration data. Gupta et al. (2012) presented a discussion about model structural adequacy at different levels (groundwater, unsaturated zone, terrestrial hydrometeorology and surface water) aiming to detect, characterize and resolve models structural inadequacies

Andréassian et al. (2001) proposed a sensitivity analysis of a rainfall-runoff model in face of poor rainfall input to evaluate if hydrological models were reliable by comparing efficiency ratings by reproducing the rainfall-runoff processes. Their results showed two different behaviours: models unable to take advantage from improvement of rainfall data, and the models benefited from this improvement producing more consistent results in terms of efficiency.

Less attention has been given to errors from output uncertainty (SIKORSKA; RENARD, 2017). In fact, many modellers face lack of streamflow information (difficulties for measurements and not enough data information), consequently the rating curves may be a useful tool to manage this type of constraint. While there are rating-curve-related errors, discharge series transformed by rating curve are often communicated to modellers without any uncertainty (PETERSEN-ØVERLEIR; SOOT; REITAN, 2009).

Di Baldassarre and Claps (2011) emphasises that the uncertainties under rating curves are greater when the curves are extrapolated, particularly for flooding. These 3-6% average errors in discharge measurements can reach 20% in poor conditions. Lima et al. (2007) reported that a $\pm 5\%$ error in flow measurement results in a deviation of approximately $\pm 15\%$ in flow estimation in a case study of an urban channel located in São Carlos, São Paulo. Petersen-Øverleir, Soot and Reitan (2009) assert that some reasons lead the uncertainty in streamflow data, not often addressed in hydrological modelling: a) lack of knowledge by engineers about hydrometric data production and inaccuracies; b) the quality of collected streamflow data is questionable; in general, the hydrometric offices are not suitable to provide this kind of information; c) few research studies have been done in order to quantify the uncertainties in the streamflow data. In urban area, several streams are engineered and have stable and geometrically well-defined beds, more often, high flow velocities and floating objects during medium to high flows prevent the use of techniques for discharge measurements, such as current meters or Acoustic Doppler Current Profilers (ADCP). It makes difficult the development of proper rating curves, hence, the discharge estimations from water level time series which is more typical in urban areas of developing countries where investment in hydrologic monitoring is not enough to a broader use of fixed acoustic Doppler sensors to measure the stream sections.

When the stream water level time series are not available, an alternative to deal with this lack of information is to integrate the estimation of the rating curve parameters in the model calibration process. This is possibly easier to be done for stream reaches which are not subjected to downstream controls (e.g. gates, dams, river junctions) and where kinematic wave propagation prevails.

A relevant scientific issue is whether a joint calibration of hydrological and hydraulic parameters (rating curve) can

improve rainfall-runoff modelling and make possible the use of stream water level time series for hydrologic modelling in urban contexts.

Can the parameters of a hydrological model and a rating curve be calibrated simultaneously?

The challenge of carrying out a hydrological and hydraulic joint calibration is huge due to the previously discussed errors and uncertainties. However, the likelihood to perform a simultaneous calibration can bring an equifinality to the process. The term equifinality was first used in geomorphology to indicate that similar landforms might arise as a result of quite different sets of processes and histories (BEVEN, 2006).

Regarding hydrological modelling, the equifinality refers to the ability of the model to represent different hypotheses on the hydrological system processes with a different set of parameters or conditions. This statement leads to the non-uniqueness concept, a terminology used to specify that multiple sets of parameters can lead to equivalent model responses concomitantly with the series of the analysed data. As an alternative of one fit, a range of parameters to be equally efficient for modelling can be set.

The rating curves which are usually established by means of several discharge measurements within a range of water levels are supposed to have an equal weight in parameter estimation (PETERSEN-ØVERLEIR, 2004). Initial uncertainty occurs at the establishment of the rating curve, either by randomness of natural processes or inaccurate measurement of stage (JALBERT; MATHEVET; FAVRE, 2011). In addition, there is a temporal uncertainty related to the increased erosion and deposition that can modify the geometry of the river bed and, as a result, the relationship between the stage and streamflow.

Therefore, in the literature, there are some techniques to tackle this type of constraint. One of them is the NLS, Non-linear Least Squares, frequently used to design rating curves. Although Petersen-Øverleir (2004) showed that this method can model only a few classes of heterogeneous variance, and this constraint could lead to uncertain values for the rating curve parameters (LE COZ et al., 2014). There is also a technique called Dynamic Identifiability Analysis (DYNIA) proposed by Wagener et al. (2003) which identifies the hydrological parameters in a multi-objective calibration by calculating separately an objective function for each data set in the model.

Nevertheless, all the previously mentioned techniques aim to reduce the hydrological and hydraulic uncertainties independently. Our proposal is the combination of the uncertainties by comparing the outputs from both hydrological and hydraulic models to find pre-set hydrological parameters to be the best solution for a set of rating curves. It is expected the reduction of constraint in the process by limiting the parameter search in hydrological modelling.

As a matter of fact, there is a difficulty in simultaneous calibration due to the uncertainties of the complex hydrological processes in the basin area where the models are simulated. A free simulation from a hydrological or a hydraulic point of view can lead to satisfactory results in terms of efficiency but not in physical terms which requires the limitation of a range of possible parameter values.

Scope of the manuscript

The aim of this manuscript is to answer the following questions: a) why is it so difficult to calibrate the parameters of a hydrological model and rating curve simultaneously? b) Is there an equifinality, i.e., can a set of parameters from a hydrological model compensate the parameters of rating curve or vice versa? c) What can be done when not enough data is available (streamflow observations)?

This work is arranged by a brief introduction followed by the description of the site and the available hydrological data. Next, an explanation about the model and the methodology used with the suitable application particularities, the tools and considerations for uncertainties reduction in hydrological modelling, the construction of modelling scenarios and the dimensionality of rating curve reduction. Subsequently, the results and discussions are presented and finally the conclusions and perspectives.

ANALYSIS OF THE AREA AND CRITICAL EVENT DESCRIPTION

Arrudas catchment is located in Belo Horizonte, southeast Brazil, with 207 km² of area (Figure 1). This crowded urban basin with a high-density occupation (about 1.5 million inhabitants) is also steep (from 1,500 to 600 meters of altimetry) and has a main channel lined since the 1920's and designed for peak flows of about 1,000 m³/s, although, during dry periods it drains less than 6 m³/s in the same reach. During heavy convective rains, peak flows can be reached in less than one hour after the rain starts.

Four critical events were chosen for analysis of the purpose of flash flood warnings and each of them caused at least one negative impact in the catchment (flooding, car damages and traffic problems)(Event A to Event D – Figure 2). Collecting data from 13 rain gauging and 4 both stream and rain gauging stations for each one. Station 35 (Figure 1) is a gauging station and was not used due to insufficient data.

The stations are managed by Belo Horizonte's city hall, responsible to define the criteria for flood warning based on the flow levels in the channel cross-sections at each flow gauging station, as follow: red warning – 100% (full section), orange – 80% and yellow – 50%.

Table 1 shows the warnings colours of each gauging station by events, with fixed three-day duration (one day before and one day after the peak). It is seen that event D did not issue a warning at the stations located in the main channel, however, the stations located along the river tributaries issued some type of warning.

Since there was no rating curve available, the proposal was to simulate different flow rates and roughness coefficients to obtain

Table 1. Event date with colors of warning.

Station	A	B	C	D
	11/15/12	12/03/12	12/12/12	01/07/13
24	Red	Yellow	Yellow	No warning
30	Yellow	Yellow	Yellow	No warning
32	Yellow	Yellow	Yellow	No warning
33	Yellow	No warning	No warning	No warning

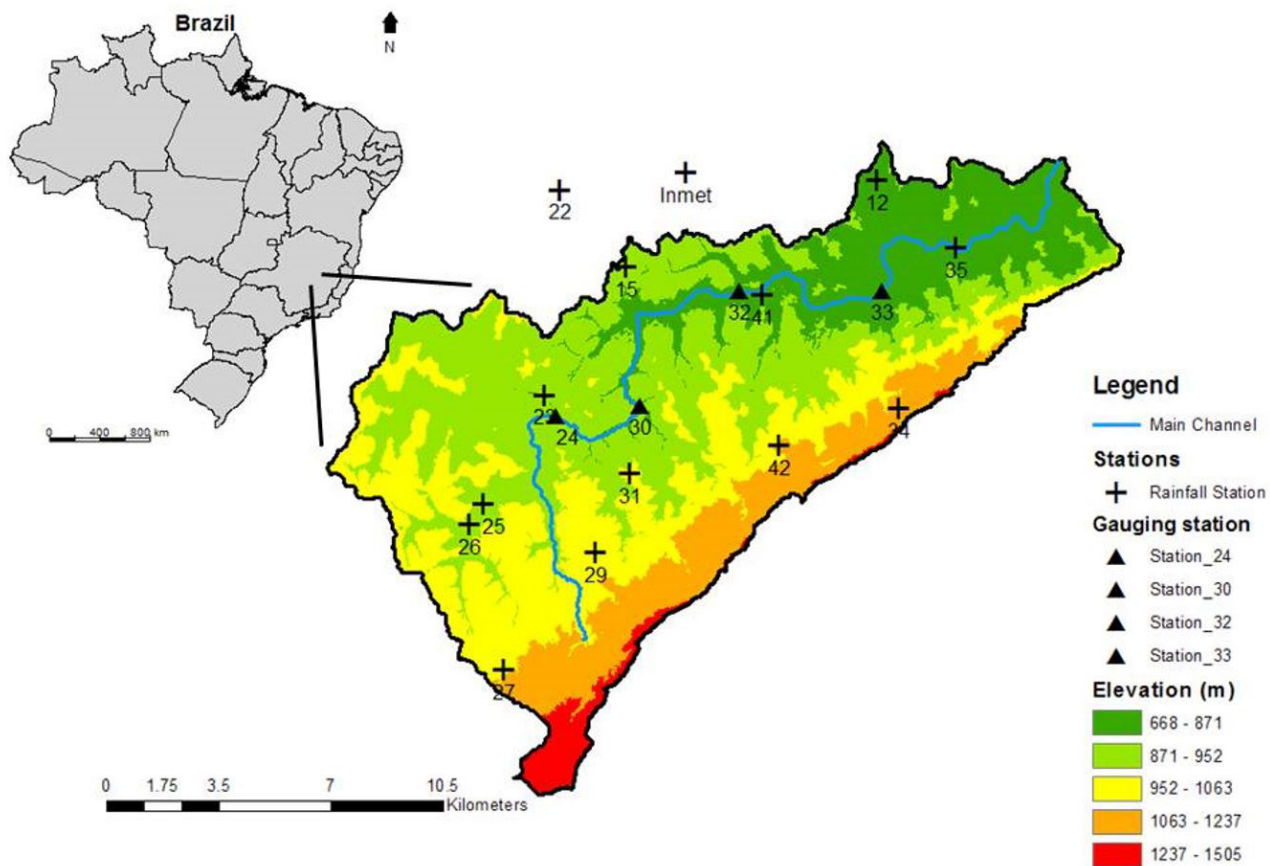


Figure 1. Catchment location and overview of all stations and main channel.

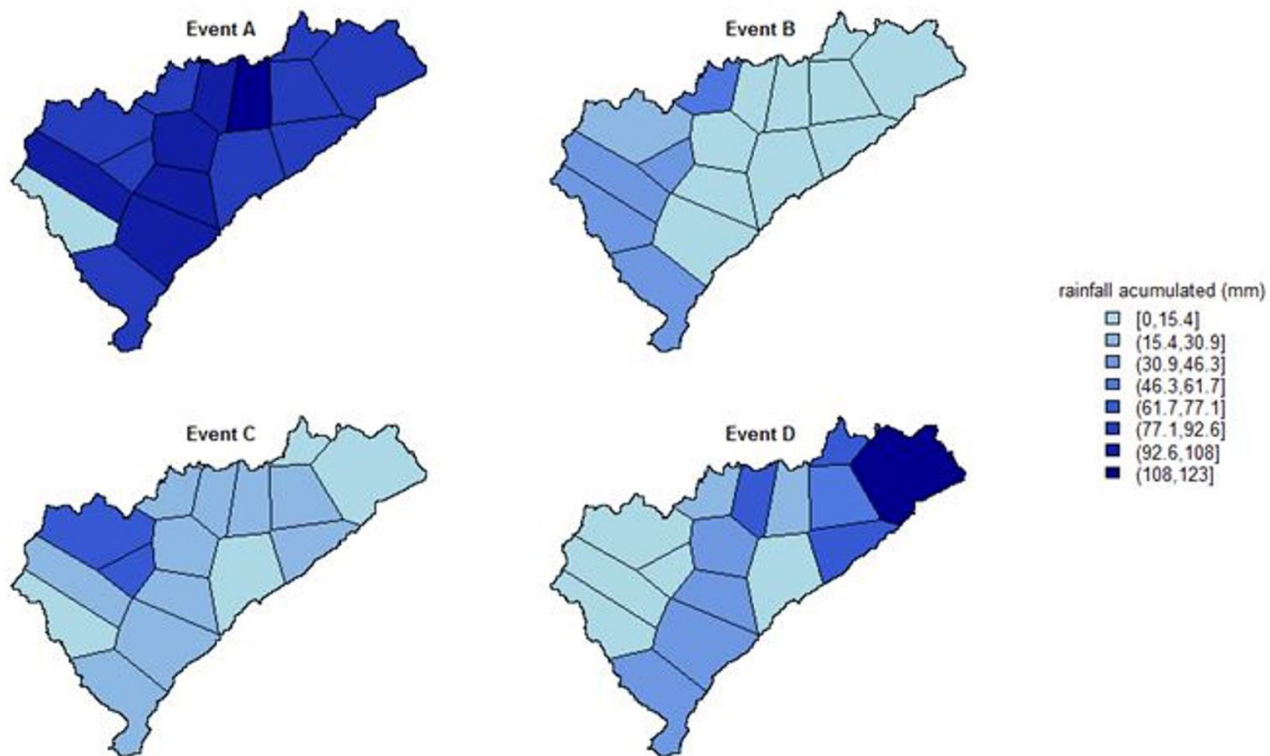


Figure 2. Accumulated rainfall in critical events at catchment distributed by Thiessen polygon.

a set of rating curves through a hydraulic model. Additionally, the event-based data, precipitation data from one Brazilian National Institute of Meteorology (INMET, 2017) station was collected. It was available from 2007 to 2015.

METHODOLOGY

GR4H Hydrological model and initial states

This manuscript proposed a methodology which combines a simulation with different sources of input data (rainfall), parametric (hydrological model) and output (rating curve) uncertainties.

The GR4H model which was used, an adaptation of GR4J (which stands for modèle du Génie Rural à 4 paramètres Journalier, a daily lumped model) was proposed by Perrin, Michel and Andréassian (2003). It has got four parameters: maximum capacity of the production store X_1 (mm), groundwater exchange coefficient X_2 (mm), maximum capacity of the routing store X_3 (mm) and time base of the unit hydrograph X_4 (hours). The structure of the model is shown in Figure 3.

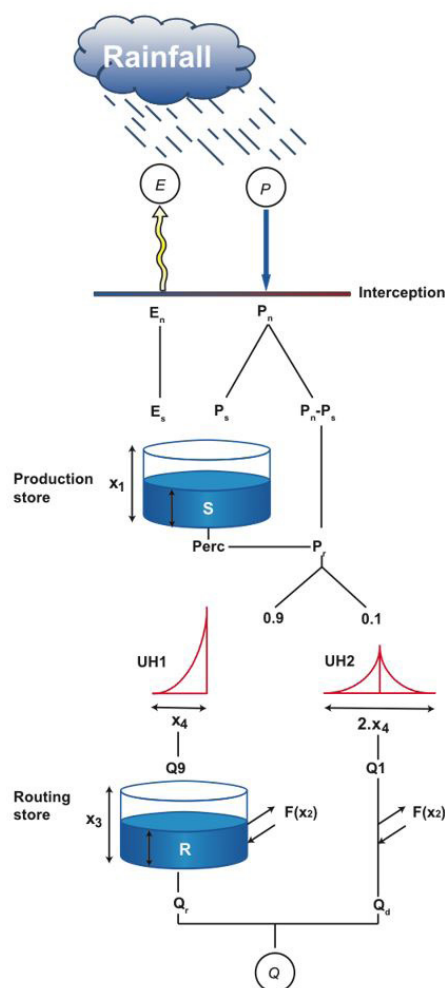


Figure 3. Diagram of GR4H (X_1 – X_4 are model parameters; E: evapotranspiration, P: rainfall, Q: streamflow, UH: unit hydrograph, R: level in the routing storage and S: level in the production storage). Source: (PERRIN; MICHEL; ANDRÉASSIAN, 2003).

The GR4H model has also two state variables, R and S, which correspond respectively to the levels in the routing and production reservoirs. The INMET station was used to start our application, the only one that has a continuous hourly data base (precipitation and evaporation) from 2007 to 2015. The first two years were used to warm-up the model and the rest of the observation period (2009-2015) was used to generate the initial states of each event, i.e., the relation between the S state variable and X_1 parameter, and the relation between R and X_3 . All GR4H simulations used the R environment package airGr (CORON et al., 2017). Clearly, some changes were made due to the case study and the initialization characteristics of the model.

Once, working with flash floods, i.e. short and intense events, it seems reasonable setting up the initial states to describe the previous conditions (e.g. soil moisture) in an attempt to achieve an “optimal” state for complete use of the available data, not enough to prompt a continuous simulation. Thereby, one day before the event (e.g. Event A started on 14 November 2012), the values from the relations (S/X_1 and R/X_3) were collected and introduced as the levels of reservoirs.

After the definition of the initial conditions, two modelling scenarios were created: MS1 and MS2. The first scenario was built with a set of GR4H parameters (X_1, X_2 and X_3) and X_4 fixed, the second scenario consists in a set of X_1 and X_3 with X_4 fixed and X_2 equal to zero including a rainfall multiplier (Initial States Level - Figure 4). The next step is on the catchment level using nested catchments limited by gauging stations and all the upstream information, which accounts to an event input with an hourly rainfall observation specialized by Thiessen polygons and evaporation data measured by Piché evaprimeter.

Next, a set of rating curves using the water depth observation of each event was designed by varying the roughness coefficient in a steady flow simulation. This information was compared with the GR4H outputs and an objective function Nash-Sutcliffe criteria (NASH; SUTCLIFFE, 1970) was calculated.

The number of simulations was the result between the outputs from GR4H and the total of rating curves for each gauging station. For every single scenario and each subcatchment, a rank of Nash-Sutcliffe (NSE) values was defined by event and an average value for all events indicated the “best” combination of parameters (hydrological from GR4H and hydraulic from the roughness coefficient of rating curve). The first positions in these rankings were selected reducing the parameters variability and the constraints of lack of information from data.

Reducing the dimensionality of parameter search in hydrological model

The application of the GR4H model in an urban area including flash flood events requires a special attention to boundary conditions. Consequently, this approach is based on reducing the parameter search by limiting the possible paths to a range of solutions.

Instead of a traditional free calibration, a simulation was proposed with a set of parameters (ANDRÉASSIAN et al., 2014), a short list of generic 27 parameters was tested and accepted along 202 catchments in France representing various hydrological

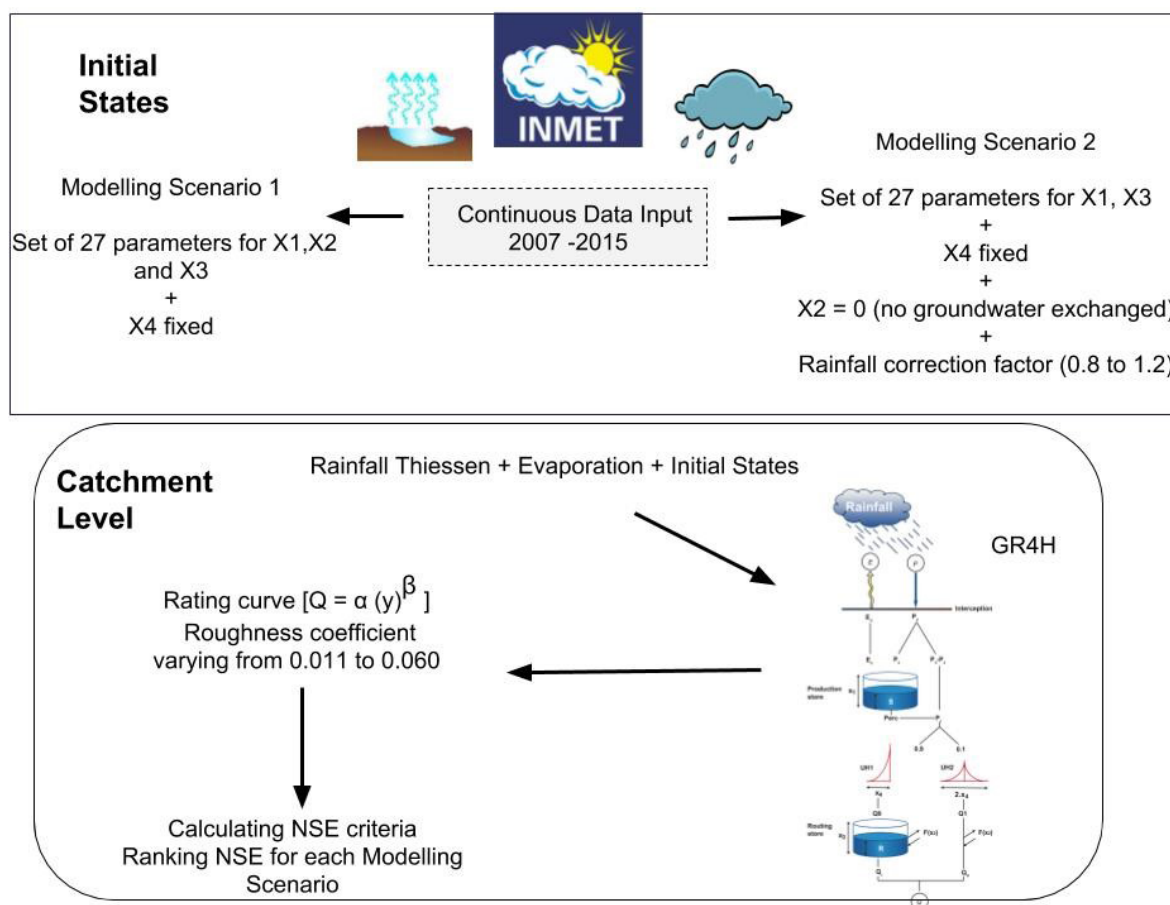


Figure 4. Scope of proposed methodology (INMET, 2017).

conditions according to the variability in climate, topography, and geology in the country with a high level of efficiency. The use of this method promoted an attempt to reduce the dependence on classical model calibration while avoiding over calibration, i.e., when a parameterization has an optimum result from a mathematical point of view for one period but it does not work for another one.

Therefore, there was an attempted to set the parameters which describe the behaviour of the catchment in relation to all critical events using the list of generic parameters with the previously described INMET data based to generate the initial states for each critical event.

Implementing complex versions of hydrological model

“Champions” parameters and X4 fixed – Modelling Scenario 1

As discussed before, the proposal is to carry out simulations through a list of “champions” parameters instead of free calibration. Moreover, flash floods indicates that the length of time is short and influences the time base of unit hydrograph (the X4 parameter). Various X4 values were analysed (0.5 to 3 hours) to compose the solution, and the coefficient of determination R^2 between GR4H

output and rating curve was calculated. Afterwards, X4 values with higher R^2 values in all the simulations were selected and fixed to reduce the time influence constraint. This first modelling scenario was built using the preset initial states for each event constraints by adding X4 value to X1, X2 and X3 from a list of expertise.

Introducing a rainfall multiplicative factor and neutralizing the groundwater exchange coefficient X2 – Modelling Scenario 2

The second modelling scenario was defined by using the same set of parameters for X1 and X3 fixing X4 again and neutralizing the groundwater exchange coefficient by reducing the X2 parameter to zero and adding a rainfall multiplicative factor.

The assumption of no groundwater exchange is valid because the site is an urban catchment and during extreme events the groundwater flow can be considered insignificant in comparison with the total volume of runoff.

Also, the multiplicative factor (0.80 to 1.20 by 0.05) in a rainfall observation was added to insert a 20% error in order to analyse if the measures were over or underestimated and the consequences of this type of error. From this approach, we expect to compare the input errors (rainfall observation) with the parametric error (parameters from GR4H) and the outputs errors (rating curve variation).

Reducing the dimensionality of rating curve

The water level data of each event was applied for the work with hydraulics parameters once there was no streamflow information. Then, a parameterization of rating curve was defined based on steady and uniform flow in the main channel simulation by River Analysis System developed by HEC – Hydrologic Engineering Center (BRUNNER, 2010). At each gauging station, a range of roughness coefficient was simulated, varying from 0.011 to 0.060 (ARCEMENT; SCHNEIDER, 1989; CHOW, 1959; WEBBER et al., 2018) and obtained a standard equation, it was adapted from Manning-Strickler equation:

$$Q = \alpha(y)^\beta \quad (1)$$

Q is the flow in m^3/s and y is the water level in meters, α and β are dependent coefficients on hydraulics characteristics (slope, section shape and roughness). Whereas the shape of cross section (see Figure 5) and the slope of the channel are known, the rating curve becomes exclusively dependent on the roughness and is reduced to one dimension. There is α and β related value for each Manning coefficient value.

From this information 50 different rating curves were obtained, each one to be compared with 27 outputs from the hydrological model simulation, a total of 1,350 simulations per event for each subcatchment.

RESULTS AND DISCUSSIONS

Precomputation of the initial states

For the first modelling scenario, 27 simulations with the set of parameters were done from 2009 to 2015, while the two first year's data (2007-2009) from INMET were used to warm up the model. The $X4$ parameter was fixed since the coefficients of determination for different $X4$ values were analysed. For the analysed events, the value of 1.5 hour was the most recurrent, which was reasonable because of the urbanized basin, as McCuen, Wong and Rawls (1984) showed by using eleven concentration time equations in 48 urban catchments and finding 1.49 hour as mean time of concentration.

Figure 6 represents the production and routing reservoir levels over the time, and the seasonality in the initial states has

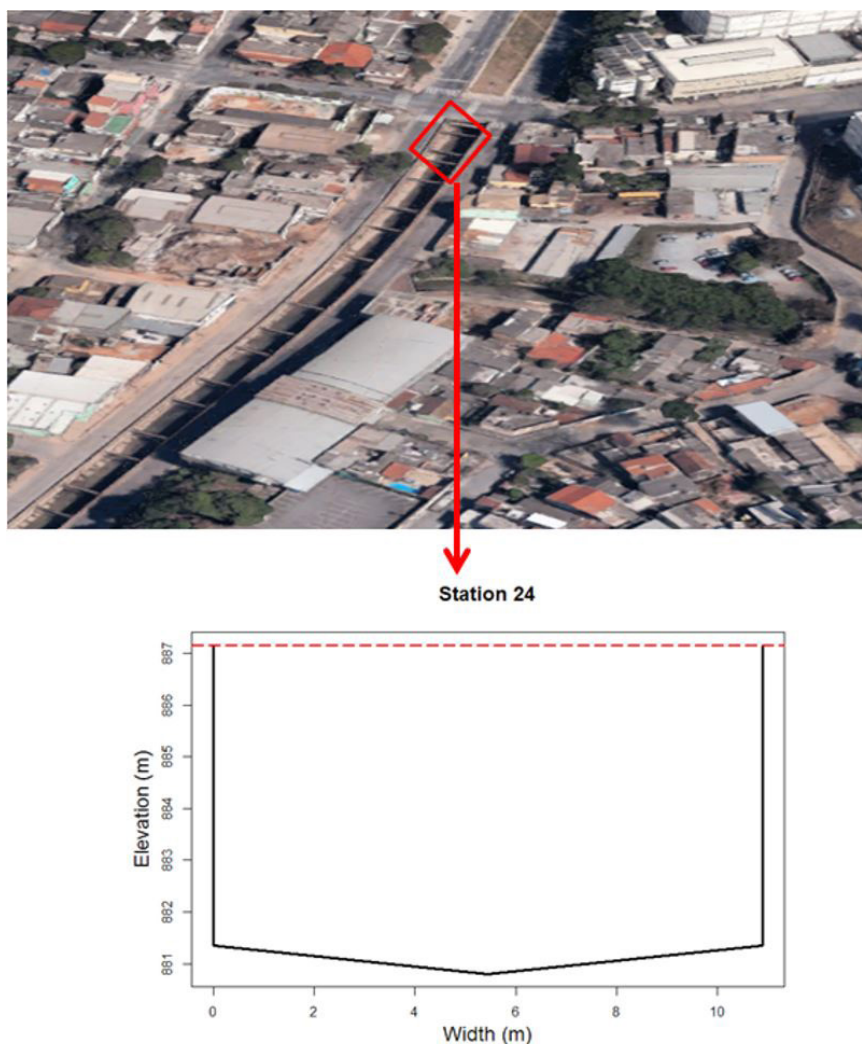


Figure 5. Position of the gauging station 24 (GOOGLE EARTH, 2018) and its cross section.

been perceived since the model inputs (rainfall and evaporation) also have such characteristic.

In fact, one of parameters sets presented a smaller variation in the reservoir production in comparison with the others as a result of a high X1 parameter value (4006 mm), i.e., it is a large reservoir which demands greater volume to produce minimum variation. On the other hand, all curves from the reservoir production obtained the same shape, but some of parameters sets reached near zero values (the relation between R and X3).

The second scenario (Figure 7) did not change in relation to the first one regarding the production reservoir and there was also a different result in the initial reservoir production due to a great X1 value (4006 mm) creating a smoother curve. By analysing the routing reservoir, a slight difference between modelling scenarios can be seen as shown in Figure 8, R/X3 values were nearer zero

than MS1 due to the fact that the X2 parameter was neutralized and had influence under X3 parameter. 27 simulations were also performed and their results were held for modelling scenario 2 applications (MS2).

Nash – Sutcliffe efficiency criteria ranking

The evaluation of the scenarios was carried out by ranking the Nash-Sutcliffe criteria values. In summary, from 1,350 simulations (27 simulations from hydrological model x 50 rating curves), the 30 best results were selected and a box-plot was designed for each scenario (Figure 9). The box-plot width represents the fit quality variability of the model for each event, in each subcatchment, and for each set of parameters. Thus, the larger the box-plot

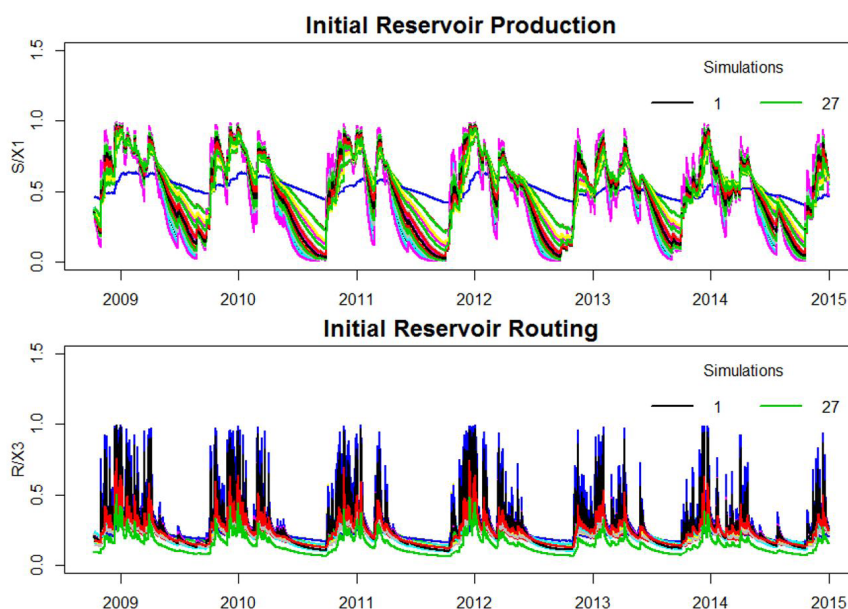


Figure 6. Initial states for Modelling Scenario 1.

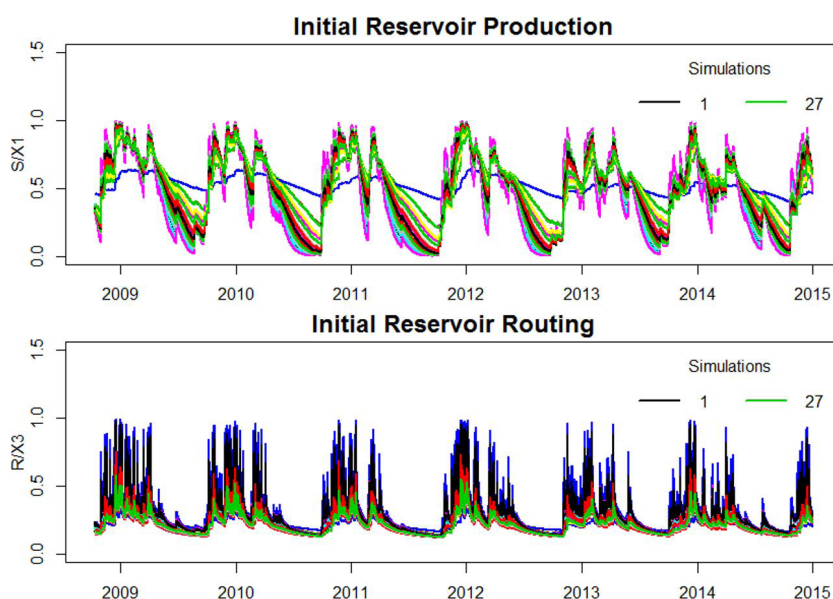


Figure 7. Initial states for Modelling Scenario 2.

width the greater the uncertainty in modelling. Considering the subcatchment 30 (red box-plots in Figure 9), for example, and only the event A (first box-plot in each column), it is concluded that scenario 2 provides more reliable estimates than scenario 1.

For each box-plot line there was a simulated subcatchment, the procedure was the independent running of 1,350 simulations for each subcatchment and then computation of the NSE values. There was no significant difference between the scenarios, except in the fact that the NSE variance was lower for most of the cases in the second scenario.

On the other hand, by analyzing each event, it was possible to perceive a difference among them; this can be explained by the difficulty to find an optimal solution for the characteristics of each event (intensity, volume). Event C is exemplified since it was the most difficult to obtain suitable objective function values especially for subcatchment 24 and 30.

By working with nested catchments, the results converged and became more uniform downstreamward, since more information was added and the subcatchment areas became greater i.e., the subcatchment 33 (last basin) presented more stable results in terms of efficiency than subcatchment 24 (the first upstream subcatchment) even in event C.

Ranking roughness coefficient

The initial choice of Manning coefficient of roughness was based on the specialized literature (CHOW, 1959). Both scenarios started with the range from 0.011 to 0.060 and this interval was reduced after the simulations and selection of the best NSE values.

The scenario 2 showed more plausible results from the physical point of view (material and section conditions) and presented smaller variance, as seen in the second column in Figure 10, thus reducing the hydraulic parameter uncertainty. The only exception is the subcatchment 32, the most urbanized area of the site in which the modelling scenario 2 was not able to reduce the n variance.

Although the main channel was entirely built in concrete, the construction techniques and period of construction are different along its parts. As demonstrated by Chow (1959), the variation of n depends on several factors, including surface roughness, vegetation, channel irregularity and alignment.

In this study, the influence on the results was caused by obstructions, beams in cross sections, especially in higher water level, another factor to influence the Manning coefficient once the events were extreme.

A discrepancy in values of roughness coefficient could be seen when comparing the results of the two first gauging stations (upstream) with the last two (downstream). The values at stations

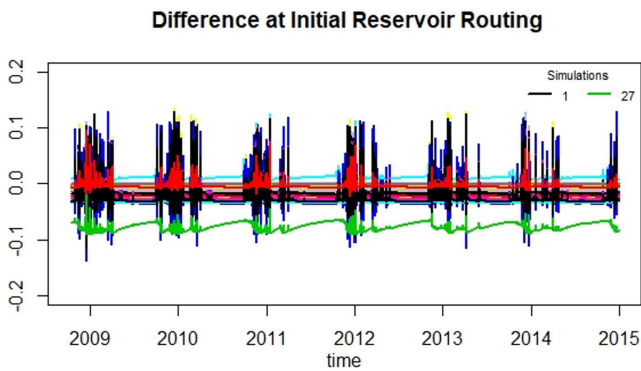


Figure 8. Difference at initial reservoir routing between modelling scenarios.



Figure 9. The best NSE result box-plot for modelling scenarios.

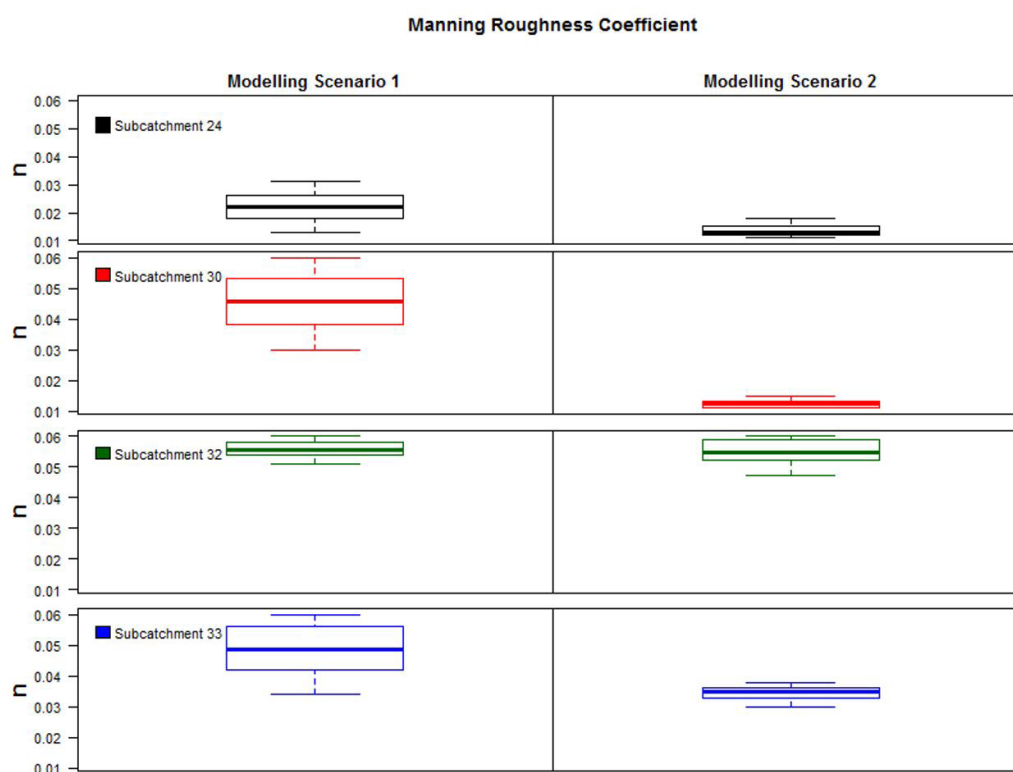


Figure 10. The best values box-plot of Manning coefficient of roughness.

24 and 30 demonstrated smoother lining, while the values at station 32 and 33, where roughness was higher, were suitable considering the site characteristic.

These differences in surface roughness can lead to large differences in the observed flow, especially when it comes to urban channel subject to rapid levels changes.

In an artificial channel study with a hydrodynamic model, Oliveira et al. (2016) identified a variation of 150% for the same level when comparing the rating curve to the model and using a multiobjective evaluation in the hydrodynamic model. The outcome presents a reduction of this discrepancy by assuming a possible set of roughness.

Roughness difference between the stations was expected due to the different channel conditions in each section. Identifying these differences is essential, especially in a hydraulic propagation which the response time is short. Siqueira et al. (2016) also found different roughness coefficients along the channel in their study by estimating them via optimization algorithm taking into account lateral contributions.

Rating curve variations

A steady flow simulation in HEC-RAS was required to create a set of rating curves, each one associated with a roughness coefficient. In fact, the aim was to start from a large array of roughness values into a smaller range of physically possible responses and assess the impact on the events. As seen in Figure 11 the modelling scenario 2 was efficient to reduce the possible paths given the boundary conditions. The initial range was reduced for

each scenario with a variance for each subcatchment for different conditions of roughness, as described before.

Instead of varying n from 0.011 to 0.060 at station 24, the method of ranking NSE values with the best parameters allowed the roughness coefficient to remain between 0.013 and 0.031 in MS1, and, for MS2 the interval for n was between 0.011 and 0.018. This implies that the flow rates which could initially vary between 68 and 304 m^3/s were between 127 and 268 m^3/s for MS1 and between 204 and 304 m^3/s for MS2.

Similarly, for stations 30, 32 and 33 the roughness coefficient range was also reduced in comparison to the initial range. However, the station 32 presented a smaller interval of possible values for n in MS1 in contrast to MS2 (Figure 12). Although there is still a possible arrangement of rating curves in the final response, the approach created possible ways to solve the initial lack of information reducing the uncertainty both in the flows and in the conditions of the channel.

These intervals are due to the uncertainties also present in the parameterization of the rating curve. Fenton (2018) discussed the type of the rating curve equation (power function or polynomial) by using two distinct methods (least-squares approximation and piecewise-continuous splines) to automatically calculate the rating curves: in both methods it was possible to define a rating envelope and not only a single curve which is according with the results obtained in this manuscript. In this study, as previously discussed, the power equation was used because the slope of the channel was known, making possible an equation with different coefficients for each roughness value.

Flows in situations of extreme events are more difficult to be measured, hence the importance of the methodology applied, the reduction of uncertainties once there is not enough information during the floods.

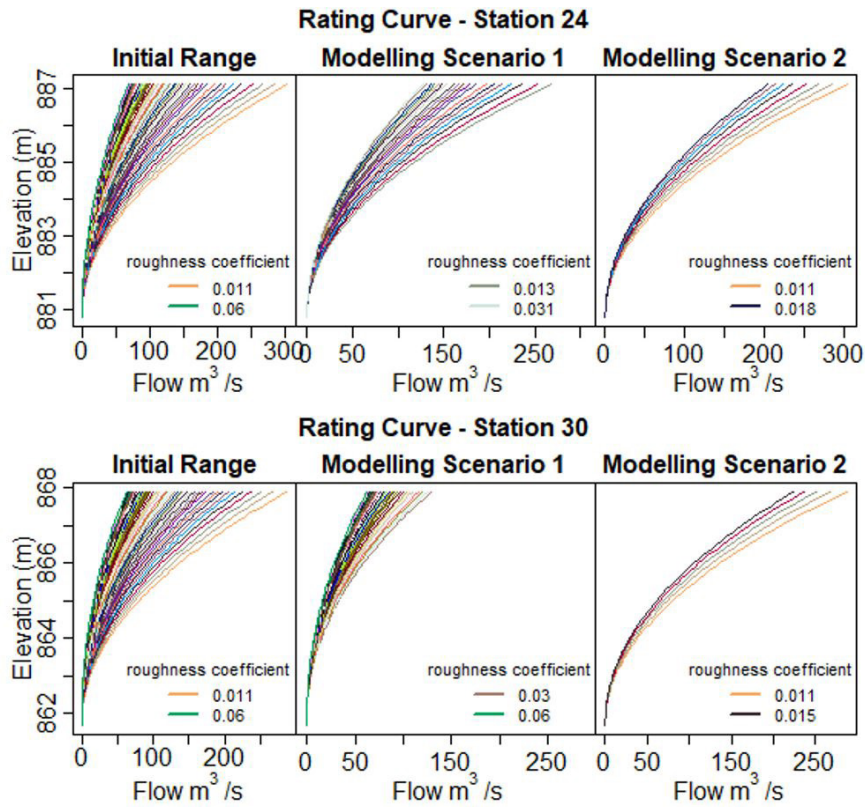


Figure 11. Rating curves for each scenario for stations 24 and 30. Each curve represents a parametric set in two modeling scenarios. The difference between the two scenarios exemplifies the variability reduction of the estimated flows in the second case.

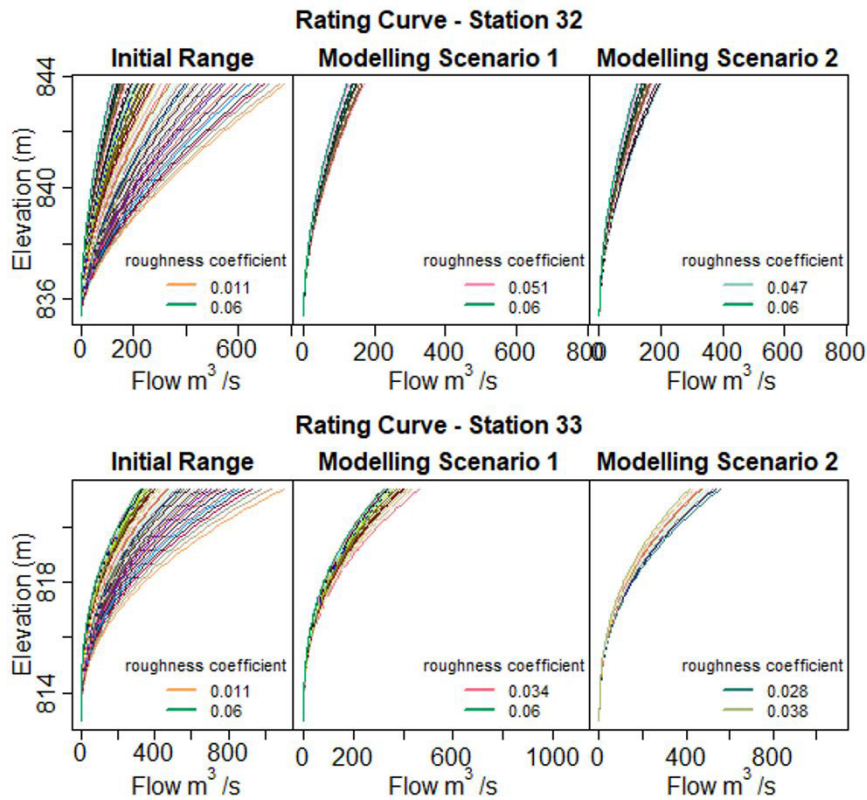


Figure 12. Rating curves for each scenario for stations 32 and 33. Each curve represents a parametric set in two modeling scenarios. The difference between the two scenarios exemplifies the variability reduction of the estimated flows in the second case.

The insertion of a rainfall multiplier, i.e., a hydrologic uncertainty, compensated the hydraulic uncertainty variance, Manning coefficient of roughness. Regarding the warnings, they did not change once they were given in terms of the stage (water level) and this information was respected but the flow rate could also vary according to the event.

In this study, only the flows inside the channel were simulated and the wave propagation was not simulated in case of overflow which implies that the areas affected by the floods were not calculated and therefore the consequences, in terms of loss of life and materials, were not evaluated since it was not the objective of this study and such analysis would require another approach from the hydraulic point of view.

Parameters and modeling scenarios

In general, the results were satisfactory and the combined methodology proved to be effective despite the lack of data (observed floods). As it can be seen in Table 2, the best 30 results

for station 33, which is the last station and therefore with the most stable results in the first scenario is more robust from the NSE values point of view and for X1 parameters (with 837 mm predominance) and X3 (with 151 mm).

However, it was noticed that X2 ranged from -0.7 to -36.4 mm demonstrating a high degree of uncertainty in the response to the groundwater exchange coefficient. There was also a great reduction in roughness as discussed before but the range of values (0.034 to 0.060) was still high.

In the case of MS2, even smaller NSE values were observed in relation to MS1, n values were much more stable (lower variance - 0.028 to 0.038). As an additional and intrinsic information to this scenario, the coefficient of rain correction and rainfall multiplier was above 1 for the entire rank (the first 30 results), which highlighted a case of underestimation by rain gauges in flash flood events (Table 3). This issue can be explained by two factors: a) the amount of rain lost during the tipping movement of the bucket, the systematic mechanical error, which increases with the intensity of rainfall and b) by the rainfall runoff process which was defined in the methodology.

Table 2. Rank of parameters at MS1 for Subcatchment 33.

X1 (mm)	X2 (mm)	X3 (mm)	n	NSE				
				Event A	Event B	Event C	Event D	Average
837	-2.3	151	0.049	0.65	0.71	0.63	0.68	0.67
837	-2.3	151	0.053	0.67	0.67	0.61	0.72	0.67
837	-2.3	151	0.050	0.65	0.70	0.63	0.69	0.67
837	-2.3	151	0.051	0.66	0.69	0.62	0.70	0.67
837	-2.3	151	0.054	0.68	0.66	0.61	0.73	0.67
837	-2.3	151	0.052	0.67	0.68	0.62	0.71	0.67
837	-2.3	151	0.048	0.64	0.71	0.63	0.67	0.66
837	-2.3	151	0.055	0.68	0.65	0.60	0.73	0.66
837	-2.3	151	0.047	0.63	0.72	0.62	0.66	0.66
837	-2.3	151	0.057	0.69	0.62	0.58	0.74	0.66
837	-2.3	151	0.056	0.68	0.64	0.59	0.74	0.66
837	-2.3	151	0.046	0.62	0.72	0.62	0.64	0.65
837	-2.3	151	0.058	0.69	0.60	0.56	0.75	0.65
837	-2.3	151	0.045	0.61	0.72	0.62	0.63	0.64
837	-2.3	151	0.044	0.60	0.72	0.61	0.61	0.64
837	-2.3	151	0.059	0.69	0.59	0.55	0.75	0.64
837	-2.3	151	0.060	0.69	0.58	0.54	0.75	0.64
453	-36.4	332	0.060	0.76	0.76	0.44	0.55	0.63
347	-3.7	136	0.037	0.62	0.73	0.65	0.49	0.62
347	-3.7	136	0.036	0.63	0.74	0.65	0.47	0.62
347	-3.7	136	0.039	0.60	0.69	0.65	0.53	0.62
347	-3.7	136	0.035	0.64	0.75	0.64	0.44	0.62
837	-2.3	151	0.042	0.57	0.72	0.59	0.58	0.62
347	-3.7	136	0.038	0.61	0.71	0.65	0.51	0.62
837	-2.3	151	0.043	0.58	0.72	0.60	0.59	0.62
453	-36.4	332	0.058	0.76	0.75	0.42	0.54	0.62
453	-36.4	332	0.059	0.75	0.76	0.43	0.54	0.62
347	-3.7	136	0.041	0.57	0.65	0.64	0.57	0.61
347	-3.7	136	0.034	0.64	0.76	0.63	0.42	0.61
827	-0.7	200	0.043	0.61	0.60	0.56	0.66	0.61

Table 3. Rank of parameters at MS2 for Subcatchment 33.

X1 (mm)	X3 (mm)	n	Rainfall Multiplier	NSE				Average
				Event A	Event B	Event C	Event D	
827	200	0.036	1.20	0.63	0.63	0.58	0.67	0.63
587	342	0.032	1.20	0.60	0.66	0.61	0.64	0.63
587	342	0.031	1.20	0.59	0.68	0.62	0.62	0.63
587	342	0.033	1.20	0.62	0.64	0.59	0.66	0.63
827	200	0.037	1.15	0.62	0.61	0.57	0.66	0.62
827	200	0.034	1.20	0.60	0.65	0.60	0.64	0.62
837	151	0.035	1.20	0.61	0.65	0.59	0.65	0.62
827	200	0.035	1.15	0.59	0.64	0.59	0.64	0.62
837	151	0.037	1.15	0.62	0.62	0.56	0.66	0.62
837	151	0.036	1.15	0.61	0.64	0.58	0.65	0.62
827	200	0.036	1.15	0.61	0.63	0.58	0.65	0.62
837	151	0.034	1.15	0.59	0.66	0.59	0.62	0.62
837	151	0.035	1.15	0.60	0.65	0.59	0.63	0.62
587	342	0.033	1.15	0.60	0.64	0.59	0.64	0.62
837	151	0.037	1.20	0.63	0.62	0.55	0.68	0.62
837	151	0.033	1.20	0.59	0.67	0.60	0.62	0.62
827	200	0.035	1.20	0.62	0.64	0.59	0.65	0.62
827	200	0.038	1.20	0.66	0.58	0.54	0.69	0.62
453	332	0.028	1.20	0.64	0.63	0.60	0.59	0.62
837	151	0.032	1.20	0.58	0.68	0.60	0.60	0.62
587	342	0.030	1.20	0.57	0.69	0.62	0.60	0.62
827	200	0.033	1.20	0.59	0.67	0.61	0.62	0.62
587	342	0.035	1.20	0.66	0.58	0.54	0.68	0.62
827	200	0.037	1.20	0.64	0.61	0.56	0.68	0.62
837	151	0.034	1.20	0.60	0.66	0.60	0.63	0.62
837	151	0.036	1.20	0.62	0.64	0.57	0.67	0.62
587	342	0.034	1.20	0.64	0.62	0.57	0.67	0.62
837	151	0.038	1.10	0.61	0.61	0.55	0.66	0.61
837	151	0.036	1.10	0.59	0.64	0.58	0.63	0.61
837	151	0.033	1.15	0.58	0.67	0.60	0.60	0.61

CONCLUSION

A methodology for joint calibration of hydrological model parameters and a range of rating curves was proposed in this article. The addition of the Manning coefficient to the parameter set allowed a balanced solution for the flash floods events.

The optimum parameter search was reduced to focus on multi-objective criteria and reduce the simulation time to achieve satisfactory Nash-Sutcliffe efficiency criteria (NSE) levels using the “champions” parameters set instead of a free calibration.

Two distinct results were obtained: in the first modelling scenario (MS1), NSE values were suitable but the range of parameters was still large, especially roughness; in MS2, NSE values were also high, however with a smaller variance and this fact contributed to the choice of the second modelling scenario even if when requiring a rainfall multiplier.

This method allowed the reduction of hydraulic modelling uncertainty, introduced by the lack of flow data. For instance, for MS2 in subcatchment 24, the modeller is responsible for the decision making process and a more or less conservative choice between an n (Manning coefficient of roughness) equal to 0.011 resulting in higher flows and consequently issuing a false warning, or an n equal to 0.018 at risk of issuing a late warning.

For future applications, either for un-occurred or forecasting events, the idea is to use the parameter rank to find

a response arrangement for the decision-making process for extreme event. Nonetheless, since they are short length events and there is no continuous simulation, the initial states are key in this methodology and they can be rejected in case of continuous applications. However, it is required to identify the prior conditions in an event analysis.

Finally, an equifinality was found between the hydrological and hydraulic parameters through the analysis of the rainfall multiplier and the roughness coefficient for MS2 and the analysis of MS1 between n (Manning coefficient of roughness), X1 (maximum capacity of the production storage) and X3 (maximum capacity of the routing storage). Although developed for rural areas, the GR4H model had an outstanding performance for the application in the urban basin, despite of the limited initial conditions.

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