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Overland flow generation mechanisms in the Concórdia River basin, in southern Brazil

Mecanismos de geração de escoamento superficial na bacia do ribeirão Concórdia, Santa Catarina, sul do Brasil

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ABSTRACT

Overland flow in watersheds is responsible for the occurrence of various environmental problems, including flood formation, erosion and the transportation of sediment, and the addition of pollutants to the soil. Additionally, understanding this hydrological process is fundamental to improving knowledge regarding individual interest factors in a region, since it interferes with agricultural productivity and water supply for both the population and industry, among other contributions. Two principal theorists have described the overland flow generation processes: Horton (1933) and Dunne (1978). The TOPMODEL (a topography-based hydrological model) approach represents the overland flow by variable contribution areas, which develop along the watercourses following the concept of Dunne's overland flow. Thus, this study aimed to evaluate the mechanisms of overland flow generated in the Concórdia River basin based on the application of the TOPMODEL, using measured hydrological data obtained from a high frequency installed monitoring network. Discharge data series were performed for three sub-basins: SF3 (29.74 km^2), SF2 (5.81 km^2), and SF1 (2.36 km^2). In these sub-basins, the flood hydrograph were separated and its response conditions were verified in the TOPMODEL. Rainfall, discharge, and potential evapotranspiration data were used in an hourly scale for the three sub-basins. In general, the model showed adequate efficiency for the SF3 sub-basin; however, the SF2 and SF1 sub-basins showed distortion in its parameters, thereby delaying the simulated hydrograph in terms of time. Accordingly, the results corroborate the more frequent appearance of Dunnian overland flow in the SF3 sub-basin, where the topography is smoother and features large areas with a low slope, which serve as variable saturation areas. The SF2 and SF1 sub-basins present characteristics that strongly reflect Hortonian overland flow, with slopes in the topography that do not allow the frequent formation of variable contribution areas.

Keywords: Hydrological processes in watersheds; Variable contribution area; Hydrologic model of physical based.

RESUMO

Em uma bacia hidrográfica o escoamento superficial é responsável pela ocorrência de diversos problemas ambientais, como formação de ondas de cheias, erosão e transporte de sedimentos e de poluentes nas vertentes. Além disto, entender este processo hidrológico é de fundamental importância para aprimorar o conhecimento sobre fatores de interesse próprios de determinada região, pois interfere na produtividade agrícola e abastecimento de água para população e indústria, entre outras contribuições. Dois conceitos têm sido utilizados para descrever os processos de geração de escoamento superficial: (i) Horton (1933); e (ii) Dunne (1978). O modelo TOPMODEL representa o escoamento superficial pelas áreas de contribuição variável, que se desenvolvem ao longo dos cursos de água, seguindo o conceito de escoamento superficial de Dunne. Assim, este trabalho visou à avaliação dos mecanismos de geração de escoamento superficial da bacia do ribeirão Concórdia a partir da aplicação do modelo hidrológico TOPMODEL, utilizando-se dados hidrológicos medidos com rede de monitoramento de alta frequência instalada. Foram analisadas séries de dados de escoamentos fluviais para três sub-bacias: SF3 (29,74 km^2), SF2 (5,81 km^2) e SF1 (2,36 km^2). Nestas, foram separados os hidrogramas de cheias e verificadas as condições de resposta do modelo hidrológico TOPMODEL. Foram utilizados dados de precipitação, vazão e evapotranspiração potencial, em escala horária, para as três sub-bacias. Em geral, o modelo mostrou adequada eficiência para a sub-bacia SF3, contudo, as sub-bacias SF2 e SF1 apresentaram distorção em seus parâmetros, atrasando o hidrograma simulado. Neste sentido, os resultados corroboram com o aparecimento mais frequente do escoamento dunniano na sub-bacia SF3, onde a topografia é mais suave e apresenta grandes áreas com baixa declividade, passíveis de contribuição em forma de área de saturação variável. As sub-bacias SF2 e SF1 apresentam características que refletem fortemente o escoamento superficial hortoniano, onde a topografia é declivosa e não permite de maneira frequente a formação de áreas de contribuição variável.

Palavras-chave: Processos hidrológicos em bacias; Área de contribuição variável; Modelo hidrológico de base física.

INTRODUCTION

Hydrological processes involve a number of phenomena associated with the natural circulation of water. Among these phenomena is the separation of precipitated water into either infiltration into the soil or the generation of runoff.

In a watershed, runoff is responsible for the occurrence of many environmental problems, including the formation of flood waves, erosion and the transportation of sediment, and the entry of pollutants into the soil. Thus, identifying the mechanism that promotes the generation of runoff could help to minimize the resultant environmental damage.

Several concepts have been used to describe the generation of runoff. Horton (1933) established that runoff occurs when the intensity of precipitation exceeds the water infiltration rate of the soil. Hewlett and Hibbert (1967) improved this idea by including the soil moisture as a variable because Hortonian flow does not take into account the water content of the soil prior to the precipitation. This new understanding of runoff is known as Hewlettian flow. Dunne (1978) refined the concept of Hewlettian flow generation, thereby establishing the Dunnian surface flow, which is generated due to the saturation of the topsoil. This often occurs in areas close to streams, which evolve over time.

Additionally, runoff can be studied by contrasting two of the mechanisms, namely Hortonian flow and Dunnian flow (GIESEN et al., 2011).

An important relationship can be seen in the interaction between the Hortonian and Dunnian flows when compared in terms of land use. Pérez et al. (2011) determined that for the Lerma River basin in Spain, the change in land use to agriculture with irrigation that took place between 2006 and 2009 generated an increase in the Dunnian flow over the Hortonian flow due to changing their interaction with the aquifer. This means that the land use can interfere in the interaction between surface water and groundwater. Further, if the relationship between the surface runoff mechanisms and the predominant land use is established, that relationship can also be used to define the appropriate land uses in the basin.

Hydrological modelling has been used to understand the different hydrological processes. When simulating different events in different basins, it is possible to understand some of the hydrological phenomena that influence the results. According to Grayson and Blöschl (2001), understanding a particular process is of fundamental importance to the statement of a model. However, the process may not be fully understood without first being modelled in some way, since modelling always complements the understanding of a process.

Modelling is therefore an important tool for understanding hydrological processes. It assists in the extrapolation of hydrological phenomena from the junction of all available data and knowledge. This extrapolation in both space and time fulfills the need to improve limited knowledge about a phenomenon, including being able to predict the future impacts of a possible change in some of those hydrological phenomena (BEVEN, 2012).

In terms of the runoff process, hydrologic models are designed to represent their generation based on both the Hortonian and Dunnian concepts. Most models consider the concept posited by Horton. The TOPMODEL (a topography-based hydrological model) approach represents runoff by variable contribution areas that develop along a river.

In this way, over time, TOPMODEL has been used to achieve a better understanding of the hydrological processes involved in watersheds.

It has shown results consistent with the reality of the basin; however, it strongly points to more efficient Nash-Sutcliff rates in basins that generate Dunnian surface runoff.

Hollanda et al. (2015) conducted a study in a conservationist watershed near to the municipality of Alegre, Espírito Santo, which aimed to evaluate the use of the TOPMODEL in estimating runoff in a sloping watershed with deep soils. They observed that although the model presented promising results, it underestimated the surface runoff.

Nourani, Roughani and Gebremichael (2011) used the TOPMODEL in the Ammameh watershed in Iran, which is characterized by very shallow soils that convert up to 60% of all rainfall into runoff. They concluded that the model is very good at simulating the peaks of the hydrograph and hence produces very satisfactory results. Given that the model generates the Dunnian runoff hypothesis, this directly depends on the amount of saturated area in the basin, which varies according to the simulation interval.

Gumindoga, Rwasoka and Murwira (2011) used the TOPMODEL to simulate the flow in a basin in Zimbabwe. They concluded that the model infers a direct relationship between the topographic index and the generation of flows. Thus, the distributed topographic index is important when separating the flow and, hence, it can be used to improve the results generated by the model.

Therefore, TOPMODEL can be used to define the generation method of the runoff in a watershed. It responds in a particular manner in flatter river basins and shallow soils, where the Dunnian surface flow is dominant, while responding differently in river basins with higher average slopes and deeper soils, where the Hortonian surface flow prevails.

The present study aims to implement the TOPMODEL in the Concórdia River basin, which is located in the municipality of Lontras, in order to better understand the mechanisms of runoff generation in a small watershed characterized by predominantly rural use.

METHODOLOGY

Study area

The study area is the Concórdia River basin, which is located in the city of Lontras in the state of Santa Catarina, southern Brazil. It has 30.93 km^2 of drainage area. Its physiographic is variable, featuring steep slopes in sections upstream and smaller slopes downstream, with altitudes ranging from 340-891 m.

The basin of the Concórdia River is one of seven basins monitored by the Environmental Recovery Project and Support for Small Rural Producers (PRAPEM/MICROBASINS) program developed by the Ministry of Agriculture and Rural Development of Santa Catarina (PINHEIRO et al. 2013). The basin has a monitoring network, which was introduced in 2006, wherein eight pluviometric stations, four fluviometric stations, and an automatic weather station have been installed. In this work, three fluviometric sections were used for studies in the basin, with those stations being considers the exits from the SF3, SF2, and SF1 sub-basins, as shown in Table 1.

The data for the study were collected from six Waterlog© rainfall stations (Waterlog Series H-340, Model 2-SDI-08) and three level sensor Thalimedes stations (OTT Hidromet®) with a linimetric strip that records information every 5 min, as shown in Table 2. These data were superimposed in order to generate a single series of rainfall data, where the overlap criterion was the priority of the stations with the highest amount of data to those stations with more limited data. In this way, the resulting time series was used as the input for the three simulated sub-basins.

Figure 1 shows the characteristics of land use and occupation, as well as the slopes map, for the Concórdia River basin.

From the historical series obtained from the Concórdia River basin stations, hydrological data for the period April 21, 2010, to July 28, 2012, were used on an hourly scale. This collection of continuous data presented the highest number of working pluviographs and, throughout almost the entire period of rainfall, it presented working data from all six pluviographs, which calculated the precipitation compensation in heavy rain.

Events were selected from the hydrographs, wherein there was a historical series of 1008 consecutive days on an hourly scale for the three fluviometric stations. The selected hydrographs were those that exceeded the flow in 0.25 m^3.s^{-1} for the SF1 fluviometric section and 0.5 m^3.s^{-1} for the SF2 fluviometric section, having obtained 38 hydrographs suitable for potential use in the model. From this, the hydrographs that exhibited well-defined peaks during the floods were selected in order to reduce the errors in the estimates of the total runoff for each event. 26 well-defined hydrograms were obtained for use in the model.

The hydrographs derived from the fluviometric data were separated so as to quantitatively express both the surface and subterranean flows. Using a flow separation tool, namely Hydraccess© software version 4.6, a line is drawn between the starting points of the rise and the end of the recession of the hydrographs for each event and, considering the hydrograph above the surface runoff, the remainder of the volume is considered to be subterranean flow (TUCCI, 1997). For the application of these data in the simulation of the TOPMODEL, the input hydrogram was set as the sum of those hydrograms that comprise the runoff,

Table 1. Physical characteristics of the three studied sub-basins.

Section		SF3	SF2	SF1
Drainage area (km^2)		29.74	5.81	2.36
Length of the main river (km)		13.53	5.48	3.05
Mean slope of the main river (m.km^{-1})		1.30	3.92	10.77
Mean slope of the basin (m.km^{-1})		14.07	13.74	13.46
Drainage network length (km)		172.05	31.35	12.25
Form factor		0.47	0.53	0.43
Drainage index		0.57	0.53	0.51
Altitude variation (m)	Minimum	340	350	390
	Maximum	891	821	821

Table 2. Pluviometric and fluviometric gauge stations.

	Station nº	Name	Coordinates UTM (m)		Altitude (m)
			West	South	
Pluviometric station	1	3026	651575	6994203	651
	2	Serra	652146	6990005	726
	3	3023	652207	6992408	486
	4	3027	649556	6994434	421
	5	pII	648720	6993423	344
	6	Lis3	648432	6993505	360
Fluviometric station	1	SF3	646467	6992845	330
	2	SF2	648645	6993359	342
	3	SF1	649626	6994285	382

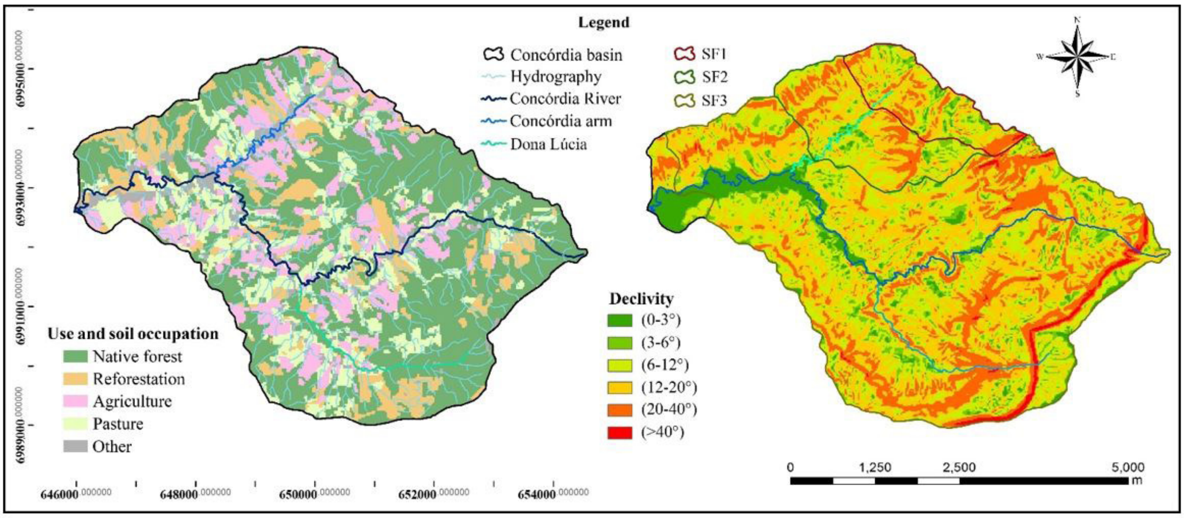

Figure 1. Maps of use and occupation of the soil and slopes of the basin of Concórdia River.

plus 24 hourly time intervals prior to the beginning of runoff and 24 hourly time intervals after the end of runoff.

The potential evapotranspiration was calculated using the FAO-modified Penman-Monteith equation (ALLEN et al., 1998). In the application of this potential evapotranspiration equation, data from the Lontras meteorological station, which is located at an altitude of 560 m and maintained by EPAGRI/FURB, were used.

The daily evapotranspiration was distributed at hourly intervals using the radiation data measured at the Salto Pilão plant's meteorological station. Hourly radiation values were used throughout the day in relation to the evapotranspiration distribution, with higher evapotranspiration values being seen at higher radiation times.

The topographic index map was generated using ArcGIS© software (ArcMap extension) version 10.1. The file used in the ArcGIS software was the numerical terrain model (NTM), which was generated by the Secretariat of Sustainable Development of the State of Santa Catarina (SDS-SC) through an aerial photogrammetric survey. The data presented the radiometric adjustment, levels of contrast and tone, homogenization of images, color balance, orthorectification, and mosaic. These data were made available by Lontras City Hall.

TOPMODEL application

For the application of the TOPMODEL, some input information is required, which must be configured every time the model is executed.

TOPMODEL version 97.01 was used, as elaborated by the University of Lancaster (BEVEN, 1997). In this case, the model depends on five parameters that should be calibrated as the average values of the watershed, in addition to data concerning the fixed topographic indexes distributed in the basin and data regarding the precipitation, potential evapotranspiration, and observed flow.

The parameters required for the model are:

- m: a function of the exponential transmissivity and recession curve, which describes the decay in the hydraulic conductivity varying with soil depth (m);
- ln(T0): the effective transmissivity of the saturated soil profile ($m^2.h^{-1}$);
- SRmax: the maximum capacity of the available water in the root zone (m);
- SRinit: the initial storage deficit in the root zone proportional to the SRmax (m) and;
- ChVel: the velocity of the surface proportion, assuming linear propagation ($m.h^{-1}$).

The calibration was performed separately for each event, generating different parameter values each time. For the calibration of the parameters, the approximation of the simulated hydrograms with the measured hydrograms was sought. The quality of this process was measured using the Nash-Sutcliff index generated by the model.

The calibration of the parameters of the hydrological TOPMODEL was a complex process due to the lack of a single optimal set of values.

The Monte Carlo method was used, which randomly simulates all five parameters a large number of times and also provides the efficiency response of the model. Each parameter had its own range of maximum and minimum values established manually, which guaranteed the physical integrity of the results. However, the resultant values do not necessarily represent the physics of the watershed.

For each event, the Monte Carlo simulation was run at least 90,000 times. The number of simulations reached 240,000 when the model was very sensitive to the parameters.

RESULTS AND DISCUSSIONS

Following the application of the TOPMODEL, an analysis of the results generated using both the observed and simulated hydrograms was performed. For the analysis of the parameters simulated by the model, only the events that corresponded best in terms of efficiency (equal to or greater than 0.75) were selected. This efficiency is given as the model's own answer and it represents the E index of Nash and Sutcliffe (NS). According to Santos and Celeste (2014), indexes where $E = 0$ indicate that the predictions are as accurate as the mean of the observed data, while indexes where $E < 0$ indicate that the observed mean is a better indicator than the model.

When calibrating the parameters of the model in the SF3 fluviometric section, the NS indexes exhibited good efficiency. However, for the SF2 and SF1 sections, while the simulated hydrograms adequately represented the observed hydrograms, the NS efficiency of the model was low. This was due to the delay in the simulated hydrograms, since the model cannot anticipate the simulated flow rate. This problem was solved by advancing the precipitations over time. As the hydrological data inserted in the model feature an hourly time scale, postponing the rainfall in one time interval means that the information arriving at the model is that the rain occurred 1 hour before it actually did. In this way, the simulated hydrogram could be anticipated, thereby increasing its efficiency.

For the SF2 and SF1 fluviometric sections, the precipitation was anticipated on average in three to four time intervals.

Surface flow analysis

The analysis of the SF3, SF2, and SF1 fluviometric stations is detailed in Table 3. For the SF3 sub-basin, the flow coefficients presented higher amplitudes and a higher average saturation index due to their higher average saturation area. The SF2 and SF1 sub-basins, with their smaller drainage areas, exhibited lower average runoff coefficients. The analysis of variance showed that the SF2 and SF1 stations did not present a significant difference ($p < 0.06$) between their means. However, when comparing the coefficients of these smaller basins with those of SF3, a statistically significant difference was observed. This difference may be associated with the topographic index, since the SF3 sub-basin presents a larger area with higher topographic indexes and less sloping regions.

Sensitivity of the model to the parameters

The sensitivity of the model to the different parameters varied between the three fluviometric sections studied, which influenced both the results and the efficiency of the model in the simulation of the exit hydrograms.

The SF3 section was the section featuring less events with high efficiencies. We selected 11 events from this section that had an efficiency equal to or greater than 0.75. For the SF2 section, 19 events were selected. The SF1 section presented similar efficiency results to those of the SF2 section, and 18 events with an efficiency equal to or greater than 0.75 were selected.

Table 3. Coefficients of the maximum, minimum, and average surface flow for the three studied sections.

	Coefficient of surface flow		
	SF3	SF2	SF1
Maximum	0.45	0.28	0.36
Minimum	0.01	0.02	0.02
Average	0.18[a]	0.11[b]	0.13[b]

Note: Equal letters indicate statistical similarity according to the analysis of variance ($p < 0.06$).

In relation to the m parameter, the results verified that it generated the greatest sensitivity to the model, thereby strongly influencing its results. The simulations in the SF3 section showed that for the reality of that sub-basin, the values of m should preferably remain between 0.006 and 0.015. Events with an m parameter calibrated with values less than 0.006 presented difficulties in terms of simulating the hydrograph recession due to accentuating the reduction of the recession flows to benefit the model's efficiency; however, they did not adequately represent the physical reality of the hydrograph. This is because the m parameter represents the decay of the water storage in the soil and therefore acts as a controller of the effective depth of the soil profile. The lower the value of m, the lower the layer and the shallower the soil, which contributes to the sub-superficial flow regime. Yet, the deeper the soil, the slower the flow generation process and the smoother the recession curve (SCHULER et al., 2000).

Nourani, Roughani and Gebremichael (2011) performed a study using the TOPMODEL and obtained a similar result to those found in the SF3 fluviometric section in relation to the m parameter. As in the SF3 fluviometric section, their study also indicated the greater sensitivity of the model to the m parameter, which, according to the authors, is directly related to the peak of the simulated hydrogram. They noted that as the value of the m parameter decreases, the peak of the hydrograph increases and, as a result, the m parameter becomes an indicator of the total flow volume in the exit of the basin.

For the SF2 and SF1 fluviometric sections, the values of m do not present preferred values, instead exhibiting high variations. Although the simulations have shown that the values for these two sections are lower than those found in the SF3section, the model also exhibited high sensitivity to this parameter.

The model presented low sensitivity to the ln(T0) parameter in all three fluviometric sections. The lateral subsurface flow is directly correlated with T0, meaning that a low value of m associated with a high T0 value could generate an abrupt recession in the hydrograms. The explanation for the low sensitivity of the model to this parameter may therefore be associated with the high sensitivity of the model to the m parameter, which significantly alters the recession, leaving little room for the T0 to modify it.

The SRinit parameter exhibited a direct relation with the m parameter. By adopting a very low SRinit value, the hydrograph tended to ascend immediately following the precipitation, thus presenting a well-defined ascent. Interactively with the m parameter, we can hence represent the rise, recession, and peak of the hydrograph. However, the calibration of only these two parameters is generally insufficient to adjust the rise, recession, and peak of the hydrograph altogether.

The SRinit represents the conditions of soil saturation in the basin at the beginning of the event. Its maximum value is controlled by the SRmax. However, once the SRmax is established, this value easily controls the start of the hydrograph's rise. The SRinit parameter tended to more strongly influence the hydrograph in the SF2 and SF1 sections, meaning that it showed greater influence in smaller basins.

The SRmax parameter displayed an interaction with the SRinit parameter, since if the SRmax was calibrated first, it was possible to calibrate the SRinit more accurately. Similar to the SRinit, the model presented greater sensitivity in the SF2 and SF1 sections for the SRmax parameter. It is possible to notice an inversion in the sensitivity of the model between the m parameter and the SRinit and SRmax parameters. The SRinit and SRmax tend to have a greater influence in smaller basins, while the m parameter loses influence in such conditions.

The SRmax is the available water capacity in the root zone, so the higher its value, the greater the amount of rain needed to completely fill it. This reservoir is emptied by evapotranspiration. When an event occurs following a long period of drought, rain must first completely fill the reservoir before beginning to contribute to the river flow. Conversely, when an event occurs after a few days of rainfall and the soil presents a high moisture content, the reservoir is already close to its maximum value, and the hydrograph can thus ascend immediately after precipitation begins. At the start of the event, this value is given by the SRinit.

The ChVel parameter presented a moderate influence on the efficiency of the model. In the SF3 section, the mean value was 2,234 $m.h^{-1}$; however, it had little influence on the efficiency of the model in the SF2 and SF1 sections, where its mean values were 4,658 and 5,143 $m.h^{-1}$, respectively. This parameter showed the ability to slightly delay or advance the hydrograph's peak by respectively decreasing or increasing its value.

It is important to emphasize that the TOPMODEL considers the spatial distribution of the topographic index, although the other parameters are adopted as a concentrated type. This implies that the spatial variability of the soil is not represented by parameters with unique values for the simulated contributory sub-basin. This leads to the obtained values exhibiting high variation among the events and contradictory physical representativeness between the sub-basins, even if they are located one inside the other.

Mechanism of generation of surface runoff

The objective of this work was to evaluate the mechanisms of surface flow generation of the Concórdia River basin based on the application of the TOPMODEL. From the present study, it was possible to arrive at some considerations regarding the use of the TOPMODEL for this purpose.

The evaluation of the various factors that influence the hydrodynamics in the Concórdia River basin involved three selected sub-basins: SF3, SF2, and SF1. In general, as seen in the analysis of the results of the parameters, the SF3 fluviometric station behaved differently to the other two stations. This indicates a physical difference between the sub-basins, whether it be related to the drainage area, length of the main river, or the mean slope of the main river. The mean slopes of the contributing basins, the shape factors, and the drainage rates were similar (Table 1). The use and occupation of the soil, while highly variable, presents high homogeneity among the contributing basins. It was therefore difficult to associate the model's operation with the type of soil use, as verified by Pérez et al. (2011).

First, the delay in the hydrographs of the SF2 and SF1 sub-basins occurred due to the inability of the parameters to adequately represent the physical mechanisms that occur inside the basin. Among these parameters, the SRinit parameter is principally responsible for the delay in the hydrographs, which was calibrated in order to reproduce the observed hydrographs. Ferreira (2004) obtained similar results and concluded that the delay in the hydrograms had a strong correlation with the values of the SRinit parameter. The mean values of the SRinit for the SF2 and SF1 sub-basins were 53 mm and 66 mm, respectively, which can be considered high when compared to the mean value of 5 mm that was determined for the SF3 sub-basin. These high SRinit values demonstrate a high storage deficit in the root zone, which must be completely filled by rainfall before contributing to the subsurface and superficial flows, therefore delaying the hydrograph in terms of time.

The high SRinit values ended up maintaining the average saturation of the basin at a very low level, which is around 2% of the average saturation during the events for the SF2 and SF1 sub-basins, unlike the 6% found for the SF3 sub-basin. In this sense, the model estimates that the Dunnian surface runoff is almost non-existent for the SF2 and SF1 sub-basins, while it becomes significant in the SF3 sub-basin.

The maximum saturation of the basin exhibits a good correlation with the coefficient of runoff in the SF3 sub-basin, reaching an R^2 correlation of approximately 52%. Hence, the maximum saturation index generated by the model corresponds to the values found for the coefficient of the surface flow. The events that present higher saturation indexes for the basin also present higher surface runoff coefficients.

In the SF2 sub-basin, this correlation does not exist. This fluviometric section presents variable maximum saturation values when compared to the surface flow coefficients, which implies poor simulation of the saturated regions for this sub-basin.

In the SF1 sub-basin, the correlation results between the maximum basin saturation and the runoff coefficients were similar to those found for the SF2 sub-basin.

Table 4 displays the coefficients of determination R^2 obtained from the relations between the coefficients of surface flow and different variables. Likewise, the coefficients of determination are presented in relation to the values of the coefficient of efficiency NS of the model, as obtained for each event. A higher correlation between the runoff coefficient and the total flow volumes of the three sections under analysis can be seen. For the SF3 fluvial station, the total flow volume of the event explains 87.5% of the variance of the coefficient of surface runoff. Although lower in the SF2 and SF1 fluviometric stations, these correlations can also be considered significant, reaching values of 51.7% and 69.7%, respectively. These values demonstrate the improved accuracy of the runoff coefficients as the contribution area of the fluviometric sections increases. This is due to the fact that the rainfall is considered to be the same over the whole basin, while the sections with the lowest correlations are located in a region with different characteristics to the others, namely higher slopes of the main river and higher elevations.

The watercourse flow rate at the beginning of the event and the NS efficiency of the model presented mean correlation values with the surface flow coefficient for the SF3 fluviometric section of 43.5% and 47.9%, respectively (Table 4). This correlation value between the watercourse flow rate at the beginning of the event and the runoff coefficient shows the importance of the initial moisture content of the soil, as well as the antecedent precipitation.

Table 4. Table of correlations R^2 between the runoff coefficient and the Nash-Sutcliff efficiency of the model versus other parameters from each event.

Sub-basin		Coefficient of surface runoff	Efficiency NS of the model
SF3	Watercourse flow at the beginning of the event	0.435	0.482
	Efficiency NS of the model	0.479	-
	Total flow volume	0.875	0.447
	Average precipitation	0.082	0.179
	Maximum precipitation intensity	0.009	0.000
	Total rainfall	0.025	0.004
	Coefficient of surface runoff	-	0.479
SF2	Watercourse flow at the beginning of the event	0.149	0.234
	Efficiency NS of the model	0.054	-
	Total flow volume	0.517	0.079
	Average precipitation	0.008	0.096
	Maximum precipitation intensity	0.012	0.025
	Total rainfall	0.023	0.291
	Coefficient of surface runoff	-	0.054
SF1	Watercourse flow at the beginning of the event	0.252	0.054
	Efficiency NS of the model	0.044	-
	Total flow volume	0.697	0.117
	Average precipitation	0.036	0.047
	Maximum precipitation intensity	0.006	0.045
	Total rainfall	0.000	0.147
	Coefficient of surface runoff	-	0.044

Figure 2 shows the saturation maps for the SF3, SF2, and SF1 sub-basins. These saturation maps indicate the variable contribution areas, which contribute to the generation of Dunnian surface flow. The tendency of the model to generate saturated cells in regions with a higher topographic index can be observed where the terrains show less slope. Beven and Kirkby (1979) used this index in the TOPMODEL to enable the simulation of the variable contribution areas, concluding that this saturation mainly occurs in areas near the drainage channel. This is because the variable contribution areas depend on the depth of the water table, which in the vicinity of the drainage channel is close to the surface.

Rennó and Soares (2003) conducted a study on the use of the topographic index as an estimator of the water table depth. They found higher topographic index values in regions associated with the drainage network, thereby obtaining good estimates of the depth of the water table in naturally saturated regions.

In Figure 2, the SF3 sub-basin features a larger contribution area, unlike the SF2 and SF1 sub-basins, which only present saturated areas in the convergence regions of the terrain directly associated with the watercourse. In the SF3 basin, the areas close to the watercourse, especially in regions with a low slope near the basin exit, also present areas of affluence, which contribute to the generation of Dunnian surface runoff. This higher occurrence of saturated areas in the SF3 basin occurs for two main reasons: (i) less sloping land and a higher topographic index; and (ii) the lower value of the SRinit parameter, which is associated with a water deficit in the root zone.

Thus, it is suggested that the TOPMODEL cannot adequately simulate the hydrographs for the SF2 and SF1 fluviometric sections, which both have characteristics that make it impossible to simulate the Dunnian surface flow. Therefore, it is understood that flow of this type does not prevail in these sub-basins.

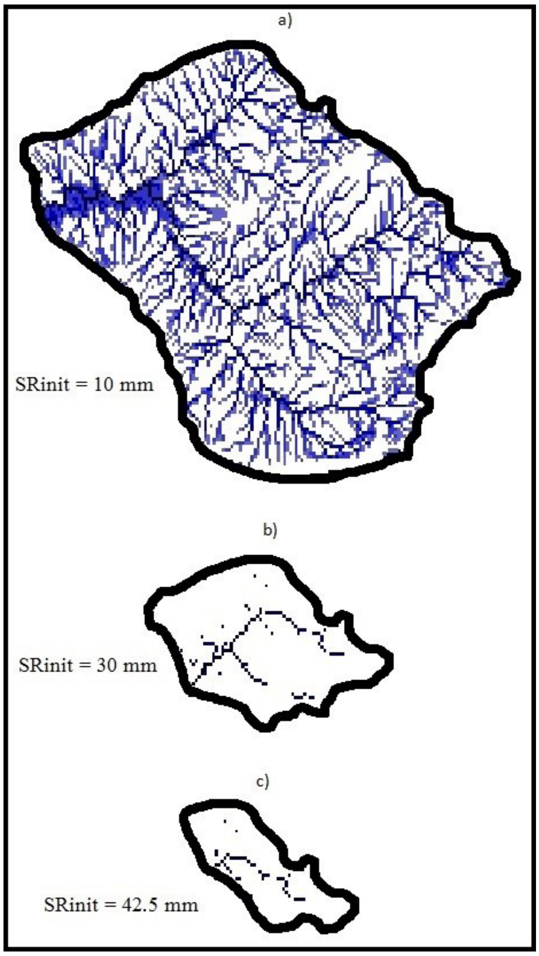

Figure 2. Map of the maximum saturation generated by the TOPMODEL and its SRinit values during an event for the sub-basins: (a) SF3; (b) SF2 and (c) SF1.

In relation to the SF3 sub-basin, due to its less sloping topography, it is understood that the model shows positive results, which point to a significant and present variable contribution area. This implies the most frequent generation of Dunnian surface flow.

CONCLUSION

The results obtained using the TOPMODEL corroborate the more frequent appearance of Dunnian flow in the SF3 sub-basin, where the topography is smoother and features only a low slope, which can contribute in the form of an affluence area.

The SF2 and SF1 sub-basins feature characteristics that strongly reflect the Hortonian surface flow, where the topography is sloping and does not frequently allow for the formation of areas of affluence.

In general, the efficiencies obtained in the SF3 fluviometric section can be considered good, which validates the use of the TOPMODEL in this sub-basin. Its results are consistent with reality, since it presented both medium and strong correlations between its parameters.

However, the SF2 and SF1 fluviometric sections presented a distortion in their parameters, which generates a hydrograph delay in terms of time. The only parameter that seems to behave appropriately is the m parameter, which displays strong correlations with the total flow volume in the basin exit at the end of the event. Therefore, in order to better understand the behavior of the surface flows of these two sub-basins, it is necessary to adopt another technique, in addition to perfecting the scales adopted for the data obtained from such small sub-basins.

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André Ricardo Loewen: Paper conception, definition and implementation of the methodology, bibliographical research, analysis and conclusions from the results, writing and preparation of figures and tables.

Adilson Pinheiro: Research coordinator, contribution in the paper conception, analysis and completion of results.