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Scenarios Simulation of the Runoff Response for a Peri-Urban Watershed in the Atlantic Forest Biome, Southern Brazil

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Abstract. *Simulating the hydrologic response of a watershed for different scenarios is an important tool for assessing the rational use of the land and natural resources, especially in environments where urbanization is not ever an organized procedure. This study used the Kineros2 event oriented hydrological model to simulate the runoff response of a 4.9 km² urban basin located in the Atlantic Forest biome in Southern Brazil, with 35% of the area being impermeable. The goal of the study was to estimate the characteristic parameters of soils and land cover for the watershed to enable the evaluation of basin response for different land uses. To achieve this objective, the responses of ten measured rainfall-runoff events were used to calibrate five parameters of the model. Two of these events were then used to simulate several scenarios. Using 100% forest land cover as reference, a scenario of 100% pasture land use increases runoff volume by 20% and peak flow by 50%. For the current land use (35% impermeable), the runoff volume is 78% higher and the peak 145% higher than the reference. For a scenario with 57% impermeable area, the runoff volume increases in average 124% and the peak 231%. For the most urbanized condition, with 78% impermeable area, the runoff volume increases in average 214% and the peak flow rate 470%.*

Keywords. Runoff Simulation, Kineros2 model, Scenarios, Atlantic Forest.

Introduction

Simulating the hydrologic response of a watershed for different scenarios is an important tool for assessing the rational use of the land and natural resources, especially in environments where urbanization is not an organized process. Among the many ways to do this task, the use of distributed hydrological models, such as Kineros2 (Kinematic Runoff and Erosion Model), Woolhiser *et al.* (1990), is one possibility. The Kineros2 model is intended for modeling small watersheds, with the area represented by a set of planes and channels (Smith *et al.*, 1995). More details about algorithms in the model can be found in Semmens *et al.* (2008).

In this paper, Kineros2 was applied to a small peri-urban watershed in Southern Brazil, characteristic of the Atlantic Forest Biome, and data from 10 observed rainfall-runoff events was used to calibrate parameters and validate the model. The goal was to estimate characteristic parameters of soils and land cover for the watershed, to then enable the evaluation of basin runoff response for different land use scenarios.

Study Area

The Cancela Creek watershed is located in the city of Santa Maria, in Rio Grande do Sul (RS) state, Southern Brazil, in the Atlantic Forest Biome, and has an area of 4.9 km². The watershed has one pluviometric station and one fluviometric station that registered the 10 rainfall-runoff events used in this study. More details about the monitoring program in Cancela Creek are described by Garcia and Paiva (2006).

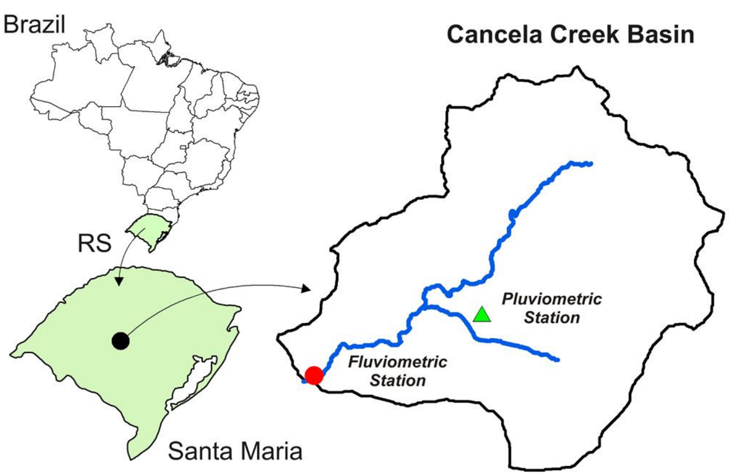


Figure 1. Cancela Creek Basin.

The physical characteristics of the basin are presented in Table 1. The land cover and uses are presented in Table 2. Maciel Filho (1990) classified 67% of the soils of the region as belonging to the Santa Maria Alemoa formation which is characterized by very low permeability. The next largest soil type, at 24% of the area, is the Caturrita formation which has a greater permeability due to higher silt and sand fractions.

Table 1.Cancela Creek basin physiography.

Parameter	Value
Area (km^2)	4.95
Perimeter (km)	10.29
Maximum elevation (m)	240.0
Minimum elevation (m)	76.0
Length of main river (km)	3.74
Slope of the main river (m/m)	0.013
Average slope of the basin	0.11
Impervious areas (%)	35

Table 2. Land cover and uses in the basin.

Land Cover	%
Forest	27
Roofs and Sidewalks	24
Gardens	18
Pasture	17
Roads	11
Bare Soil	3

Material and Methods

To represent the watershed in the Kineros2 model, the area was divided into 8 planes and 3 channels as depicted in Figure 2. Each of these elements needs at least 16 parameters.

The characterization of the geometric parameters of the basin (area, length and slope) was developed through the AGWA (The Automated Geospatial Watershed Assessment Tool) tool which runs as an extension inside ArcGIS and allows a discretization of the basin in planes and channels based on a digital elevation model (DEM). More details about AGWA can be found in Semmens *et al.* (2000). Cross-sections of the channels were obtained from topographic surveys (Garcia, 2005).

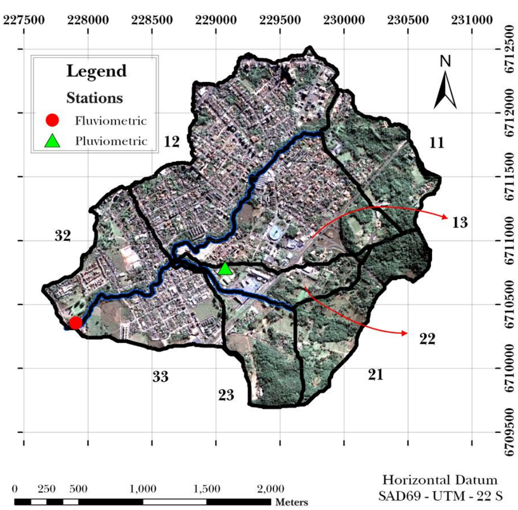


Figure 2. Basin discretization (planes with codes) used in Kineros2.

Initial parameter values for soil capillarity, porosity, and pore size distribution index were correlated with the correspondent soil textures in accordance with Rawls (1982) and Woolhiser *et al.* (1990). Saturated hydraulic conductivity (KSat) and textural soil classification was taken from Rauber (2008) who conducted *in loco* soil sampling in Santa Maria urban areas, some inside the Cancela Creek watershed, with analysis which included permeability and particle size analysis. The advice from Woolhiser *et al.* (1990) was followed in selecting the land use parameters, and Manning's roughness coefficients for planes and channels was based on recommendations of Shen and Julien (1992, p. 12-15).

With all initial parameters characterized for each soil type and land use, weighted parameters were obtained for each discretized plane and channel. Computational routines developed by Beling (2010) were used to generate the data inputs and process model outputs.

Despite the fact that Kineros2 can model each impermeable area individually (roofs and roads, for example), the present study considered the impermeable urban areas in a lumped way, assuming that these areas have no infiltration during storms (KSat = 0). Also, Kineros2 neglects evapotranspiration in its formulation, but this simplification is acceptable when rainfall-runoff events of less than one day are modeled.

Five parameters were selected for calibration: Manning's n, interception, saturated hydraulic conductivity (KSat), capillarity, and the variation coefficient of KSat. Parameter calibration was accomplished with the PEST package (independent model for parameter estimation and uncertainty analysis) using as objective function the weighted sum of squared differences between the observed runoff data and simulated runoff (PEST, 2010). A calibrated parameter set was developed for each of the 10 events. These same events were then used to assess model performance using the Nash-Sutcliffe index in a cross-validation approach. For each event, the parameter set for the validation simulation was based on an average of the best sets of parameters calibrated for all events excluding those parameters for the event under consideration. After the validation, one representative event of a wet antecedent moisture condition and another of a dry condition were used to evaluate distinct scenarios of land cover, with comparison to the current situation (35% imperviousness), and using a 100% forested condition as a reference.

The scenarios were defined by weighting the average parameters calibrated and validated over each discretized plane. The first scenario corresponds to a watershed entirely forested (pre-occupation). The second considers the basin covered by pasture. The third scenario considers the entire basin having a degree of impermeability similar to that of the current most urbanized plane (plane 12, Figure 2), which is 57% impervious. Finally, the fourth scenario considers the basin entirely urbanized, resulting in 77.5% imperviousness. A summary of the scenarios is shown in Table 4.

Table 4. Analyzed scenarios and characteristic land uses.

		Land Use																													
		Gardens (%)					Roofs and Sidewalks (%)					Forest (%)					Roads (%)					Pasture (%)					Bare Soil (%)				
Scen.*		a	b	c	d	e	a	b	c	d	e	a	b	c	d	e	a	b	c	d	e	a	b	c	d	e	a	b	c	d	e
Planes	11	9	-	-	29	23	9	-	-	40	60	62	100	-	12	-	4	-	-	17	17	13	-	100	-	-	4	-	-	2	-
	12	29	-	-	29	23	40	-	-	40	60	12	100	-	12	-	17	-	-	17	17	-	-	100	-	-	2	-	-	2	-
	13	20	-	-	29	23	29	-	-	40	60	19	100	-	12	-	15	-	-	17	17	14	-	100	-	-	4	-	-	2	-
	21	-	-	-	29	23	-	-	-	40	60	68	100	-	12	-	1	-	-	17	17	28	-	100	-	-	2	-	-	2	-
	22	9	-	-	29	23	24	-	-	40	60	25	100	-	12	-	7	-	-	17	17	31	-	100	-	-	4	-	-	2	-
	23	7	-	-	29	23	11	-	-	40	60	37	100	-	12	-	3	-	-	17	17	37	-	100	-	-	4	-	-	2	-
	32	24	-	-	29	23	24	-	-	40	60	13	100	-	12	-	12	-	-	17	17	26	-	100	-	-	2	-	-	2	-
	33	25	-	-	29	23	29	-	-	40	60	6	100	-	12	-	11	-	-	17	17	26	-	100	-	-	3	-	-	2	-

* Scenarios: a) Current --35% imperv.; b) Forested; c) Pasture; d) 57% imperv.; e) 77.5% imperv.

Results and Discussion

Calibration and Validation

The model performance statistics obtained in validation and calibration can be seen in Table 5, and some of the predicted and observed hydrographs are shown in Figures 3 to 8.

Table 5. Calibration and validation results.

Storm Date (D/M/Y)	Nash Sutcliffe		Error Peak Flow (%)		Error Volume (%)	
	Cal.	**Val.**	**Cal.**	**Val.**	**Cal.**	**Val.**
31/1/2004	0.95	0.26	0.8	94.9	-24.9	34.0
7/5/2004	0.86	0.81	1.4	1.0	-30.9	-28.3
10/6/2004	0.96	0.92	11.0	16.7	-17.4	-19.7
10/9/2004	0.94	0.93	11.0	1.3	12.4	11.0
22/9/2004	0.64	0.53	-5.7	-5.8	-26.0	-32.3
12/10/2004	0.94	0.86	-2.3	3.0	4.3	19.5
16/10/2004	0.84	0.72	1.0	11.3	-29.7	-21.7
3/11/2004	0.84	0.78	1.8	32.9	-34.2	-23.3
9/11/2004	0.87	0.87	9.6	3.9	-22.7	-28.6
6/12/2004	0.98	0.59	0.0	55.9	-4.9	37.9
Average	**0.88**	**0.73**	**4.5**	**22.7**	**20.7**	**25.6**

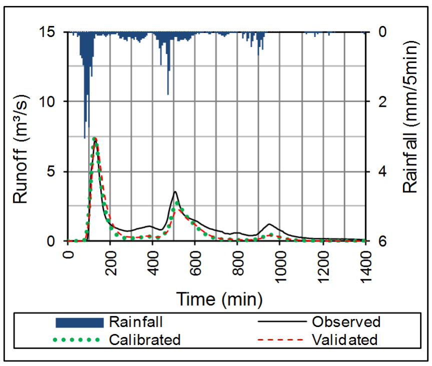
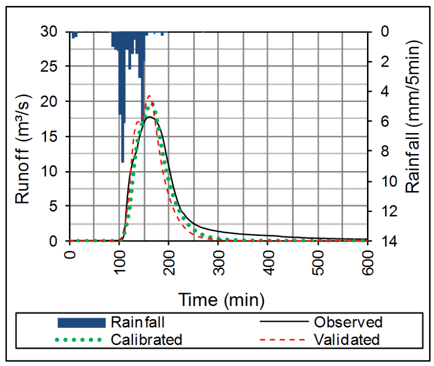


Figure 3. Event of day 07/05/2004



. Figure 4. Event of day 10/06/2004

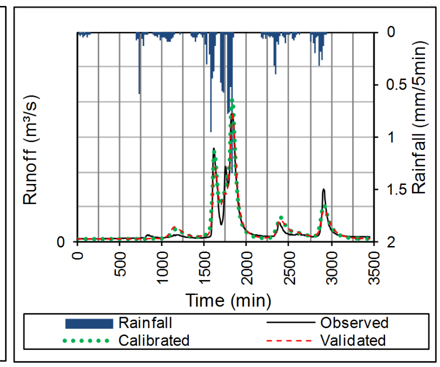


Figure 5. Event of day 10/09/2004..

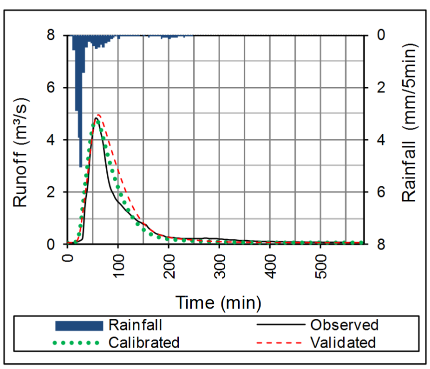


Figure 6. Event of day 12/10/2004.

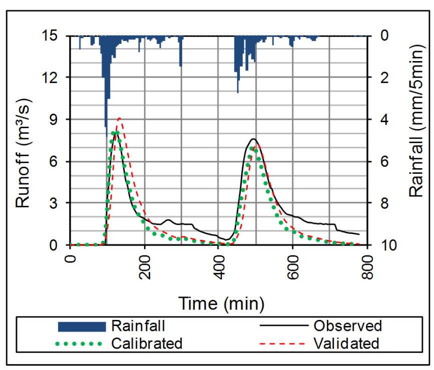


Figure 7. Event of day 16/10/2004.

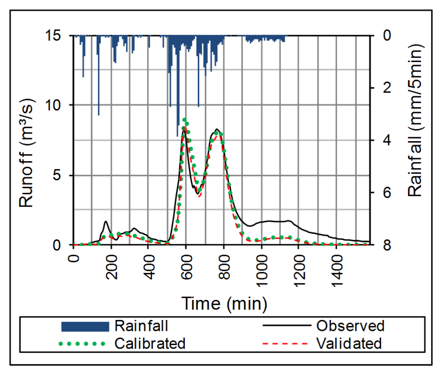


Figure 8. Event of day 09/11/2004.

Overall, goodness of fit of hydrographs, in calibration, ranged from a Nash-Sutcliffe of 0.64 to 0.98, with an average value of 0.88. In validation, these indexes decreased, with an average Nash-Sutcliffe of 0.73. It can be seen that the model underestimates runoff volume, with an absolute average error of 20.7% in calibration and 25.7% in validation. Also, it is important to note that baseflow in all simulations was considered constant and equal to the observed flow at the beginning of the storm. For the peak flow rate, average absolute error was about 4.5% in calibration, but over 22% in validation, although much of this error is from 2 storms.

Table 6 presents the main parameters found in calibration and used in validation. The Manning's roughness of planes (overland flow) found in calibration was an average of 0.058 which is much lower than a value of 0.19 found when calibrating Kineros2 to a watershed predominantly in forest land cover (Beling, 2010; p. 51). This is a reasonable result since we expect surface runoff to encounter smoother surfaces in the urban environment. Similar values were found by Hernandez *et al.* (2000). A similar comparison of values was also observed for the Manning's roughness for discretized channels found in this study.

Table 6. Average parameters used in calibration and validation.

Storm Date (D/M/Y)	Manning Channels		Manning Planes		Interception (mm)		Saturation (%)		CV		KSat (mm/h)	
	Cal.	Val.	Cal.	Val.	Cal.	Val.	Cal.	Val.	Cal.	Val.	Cal.	Val.
31/1/2004	0.040	0.034	0.062	0.057	1.2	1.0	0.20	0.05	0.33	0.54	5.3	3.3
7/5/2004	0.031	0.035	0.047	0.059	1.2	1.0	0.10	0.71	0.80	0.49	1.8	3.7
10/6/2004	0.045	0.033	0.069	0.056	1.1	1.0	0.22	0.12	0.47	0.53	3.2	3.5
10/9/2004	0.028	0.035	0.043	0.059	1.1	1.0	0.70	0.68	0.50	0.53	3.7	3.5
22/9/2004	0.037	0.034	0.057	0.058	1.2	1.0	0.88	0.89	0.44	0.53	1.7	3.7
12/10/2004	0.033	0.035	0.051	0.058	1.1	1.0	0.55	0.68	0.48	0.53	3.7	3.5
16/10/2004	0.010	0.037	0.062	0.057	1.1	1.0	0.27	0.67	0.43	0.53	2.4	3.6
3/11/2004	0.042	0.034	0.065	0.057	0.0	1.1	0.14	0.05	0.52	0.52	4.9	3.3
9/11/2004	0.040	0.034	0.061	0.057	1.1	1.0	0.81	0.68	1.01	0.47	3.9	3.4
6/12/2004	0.039	0.034	0.061	0.057	1.1	1.0	0.20	0.05	0.24	0.55	4.2	3.4
Average	**0.035**	**0.035**	**0.058**	**0.058**	**1.0**	**1.0**	**0.41**	**0.46**	**0.52**	**0.52**	**3.5**	**3.5**
Std. Dev.	**0.010**	**0.001**	**0.008**	**0.001**	**0.4**	**-**	**0.30**	**0.34**	**0.22**	**0.02**	**1.2**	**0.1**

Interception values also revealed differences between urban and forested applications. The average value found in the present study, 1mm, represents a very low interception, a quarter of the average value estimated by Beling (2010, p.51) for a forested basin.

The saturated hydraulic conductivity (KSat) showed a low average value in the calibrations. This is expected due to the soil type present in the region which has a very low permeability (0.08 mm/s) as determined by soil analyses (Rauber, 2008). Also, an important factor is the reduction caused by considering impermeable urban zones with null KSat.

When the initial saturation pattern is observed in both calibration and validation stages, it is possible to notice a considerable discrepancy between some events, especially in the events of 07/05/2004 and 16/10/2004. This effect is a result of the distinct KSat values used in the two stages, so that lower values of KSat generate greater runoff volumes which are balanced by lower initial saturations. This effect is not desirable, because it results in two patterns for initial soil conditions. While not applied in the present study, this problem could be avoided by correlating the five day antecedent cumulative rainfall with initial soil moisture conditions, as is considered in the curve number method (USDA, 1997). This correlation could allow greater confidence in the specification of a range of values for the saturation parameter in calibrations. These results show that sensitivity of the Kineros2 model is greatest to the KSat and initial saturation parameters as has been noted previously (Beling, 2010).

Scenario Analysis

After obtaining representative parameters for the watershed, the proposed scenarios for evaluating land use impacts were simulated. To simplify the comparison of the scenarios, they were identified as a, b, c, d and e (Table 4, 8). The events of day 07/05/2004 and 10/06/2004 were used for the predictions because they demonstrated best fits in calibration and validation for larger storms with peak flows greater than 5 m^3/s. Also, the event of day 07/05/2004 represents a wet initial condition, while the second represents a dry initial condition.

Results can be evaluated through the hydrographs depicted in Figure 9. Figure 10 and Table 7 summarize the differences in peak flow and volume between current land use (scenario a) and the other scenarios.

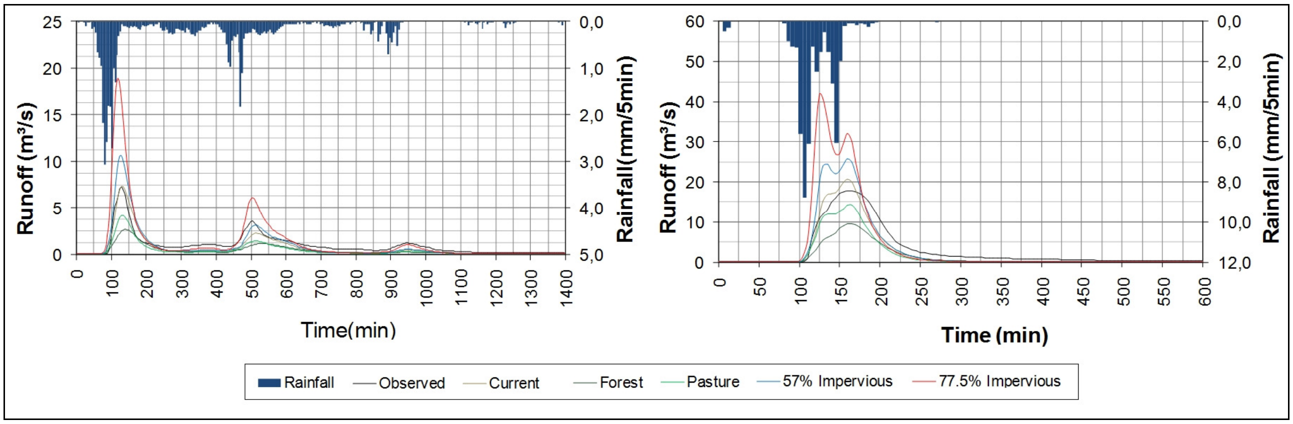


Figure 9. Event of day 07/05/2004 (wet initial cond) and day 10/06/2004 (dry initial cond).

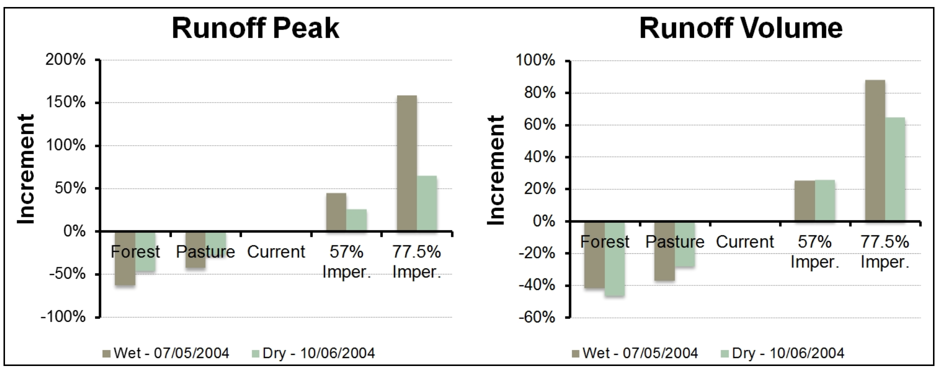


Figure 10. Differences between scenarios for runoff peak and volume.

Table 7. Scenarios for wet and dry conditions.

	Dry Condition					Wet Condition				
Scenario	**a**	**b**	**c**	**d**	**e**	**a**	**b**	**c**	**d**	**e**
Volume (%)	-	-46%	-28%	26%	65%	-	-42%	-37%	25%	88%
Peak(%)	-	-54%	-32%	24%	101%	-	-63%	-43%	44%	158%
Time to Peak	-	5	5	0	-35	-	10	0	0	-10

When runoff generation is analyzed, it is noted that the pre-occupation (100% forested) scenario shows a reduction greater than 50% in the peak flow, besides delaying it in time from 5 to 10 minutes. In case of runoff volume, this reduction is near 40%. In the pasture scenario, reductions could also be found both in volume and in peak flow when the current scenario is the reference.

Overall, when urban scenarios are analyzed, it is possible to highlight a non-linear relationship between progressive imperviousness of the basin and runoff generation. In this way, scenario “d” has 20.5% more impervious areas than scenario “e”, but the former produces peaks 3 times greater than the second one. These results illustrate the reasons why urban areas are more susceptible to floods and reinforce the conclusion that in these environments the presence of green areas is essential as they promote rainfall infiltration into the soil. Also, time to runoff peak in dry conditions is advanced 35 minutes, reflecting a smooth surface that does not offer much resistance to runoff.

Table 8 shows average values of the most affected parameters due to the changes in land use during the simulations. It can be noted that in the current scenario, Manning's roughness is 1.6 times greater than in a 100% forested scenario. This difference increases up to 3.5 times when the most impervious scenario (e) is compared with the pre-occupation land use (a).

Table 8. Average values of parameters for different scenarios.

Scenario	Manning Planes	Interception (mm)	Ksat (mm/h)
a. Current	0.058	1.00	3.6
b. Forested	0.094	1.85	4.5
c. Pasture	0.056	1.39	4.5
d. 57% Impervious	0.043	0.50	1.9
e. 77.5% Impervious	0.027	0.21	1.0

For the interception parameter, the forested scenario values are 8.8 times greater than those used in the high urbanized scenario (e). This increase represents the effect that vegetal cover has in hydrological processes in retaining part of the rainfall. It is important to point out that the interception in urban areas is considered in this study for the gardens land use class.

While soil type does not change from one scenario to another, KSat varies due to the consideration of impervious urban surfaces with KSat=0.0 in the weighting process to determine an average parameter for the flow plane. Also, due to the low permeability of soil types belonging to Santa Maria Alemoa formation, it is expected that water retention is greater in soils with higher KSat values, an effect that reduces runoff peak flows and volumes during storms.

Finally, the presented results compared the basin response to generate runoff in different land use scenarios. However, it is important to consider that the changes in land cover also impacts long term hydrological processes (not considered in Kineros2), such as evapotranspiration and groundwater flow, for example. In this sense, it is expected that a forested region retains more water in soil and that this water is slowly released to the streams and creeks through the groundwater flow or to the atmosphere by evapotranspiration. This process does not occur in the same way in urban areas highly impervious where a low part of the water remains in soil.

Conclusions

The use of Kineros2 distributed model allowed the definition of average parameters representative of the Cancela Creek basin. Nash-Sutcliffe indexes averaged over 10 rainfall/runoff events reached values of 0.88 in calibration and 0.73 in validation. The use of PEST ensured more agility in calibration tasks when compared to the trial and error method.

The distinct scenarios simulated confirmed that forested land cover directly reduces runoff peaks and volumes during storms. This analysis also confirmed that highly impervious areas significantly impact runoff, increasing and advancing peak flows.

Results showed that, if the pre-occupation scenario (100% forested) is taken as reference, a 100% pasture land use increases the runoff volume on average 20% and the peak flow 50%. For the current land use, the increase in runoff volume is 78% and 145% for the peak. For a scenario with 57% impermeable area, the runoff volume increases in average 124% and the peak 231%. And for the intense urbanization scenario, with 78% impermeable area, the runoff volume increases in average 214% and the peak 470%.

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