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DETECTING HYDROCLIMATIC CHANGES USING SPATIO-TEMPORAL ANALYSIS IN THE SUB-MEDIUM SÃO FRANCISCO-PE BASIN, BRAZIL

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The São Francisco river basin is the third largest drainage basin of Brazil and the only one entirely within its frontiers. To estimate and generate surface runoff values of the Sub-medium São Francisco Valley basin, a model was developed based on the identification and quantification of the main hydrologic processes. This model was used to create scenarios of the climatic change impacts on the surface runoff. The model simulated the water balance and estimated the surface runoff considering the precipitation variation and the potential evapotranspiration, and taking into account the soil depth, the physiographic characteristics, and the plant cover of the drainage basin. In general, when considering precipitation variability, evapotranspiration, plant cover and soil depth, porosity and hydraulic conductivity, the developed model showed a good response to the spatio-temporal variability of the surface runoff. The model was shown to effectively simulate scenarios of climate change impacts on the surface runoff of the basin. The sub-medium São Francisco Valley drainage basin does not show any trend of increase or reduction of the surface runoff between 1963 and 1988.

INTRODUCTION

The burning of fossil fuels due to human activities is responsible for an increase of carbon dioxide (CO_2) and other greenhouse gases (GHG) emissions (IPCC, 2007). High concentration of greenhouse gases that enhances radiative forcing contributes to global warming (Kalnay and Cai, 2003). Based on the scenarios presented by IPCC (Intergovernmental Panel on Climate Change) (IPCC, 2007), carbon dioxide concentrations may increase from the present 330 ppm to approximately 550 and 970 ppm. The magnitude of that increase depends on human activities, on new and advanced technologies applied, and on the kind of economic development adopted by societies. According to the Fourth Assessment Report (AR4), the increase in global average temperatures is unequivocal and is very likely due to the observed increase in anthropogenic GHG concentrations (IPCC, 2007). Those changes will probably disturb the local hydrologic cycle.

According to the 21st century global changes projected by IPCC, global average temperatures will increase up to 6.4 ^oC and changes in precipitation quantity and intensity will lead to changes in runoff and water availability (IPCC, 2007). In other words, regional and seasonal changes in the temperatures and precipitation patterns are expected, which will affect the hydrologic cycle. Even so, in order to study the real impacts of climate changes in the hydrologic cycle, it is necessary to know how the water balance responds to natural phenomena and human activities.

Changes in the plant cover strongly influence earth's energy and water balance (Mão and Cherkauer, 2009), resulting in effects essentially over plant transpiration, rainfall interception by plant canopy, and evaporation surface. Soil physical properties are very important and have strong influences on the nature of hydrologic responses (Dunn and Mackey, 1995).

Those influences have significant effect over the duration and the magnitude of water evaporation to the atmosphere, over the amount of water stored in the soil, over the surface and subsurface runoff and, consequently, over the hydrologic response pattern (Hender-Sem-Sellers et al., 1993; Niehoff et al., 2002; Jones and Post, 2004).

The water balance model developed by Galvíncio (2005) for the Epitácio Pessoa basin (semiarid region in the Paraíba state) and the performance of the water balance model for the Caraúbas sub-drainage basin (Galvíncio et al., 2007), in El Niño and La Niña years, clearly showed that the soil physical property variations greatly influence the hydrologic response of drainage basins in these semiarid regions.

Mão and Cherkauer (2009), analyzing the impacts of land use changes in the hydrologic response of Grandes Lagos region, concluded that vegetation interference occurs through changes in the leaf area index and presence or absence of canopy roughness. According to these authors, great scale deforestation or changes in land use, common in agriculture practice, provokes an increase in surface runoff.

According to Palacios-Vélez et al. (1998), demand for models that allow a better hydrologic prediction increases when flooding and other related damages occur. However, developing improved models requires a continuous effort by research and the academic community. Besides, those models need consistent long-term data of precipitation, runoff, topography, and soil.

The São Francisco river drainage basin presents diverse problems that need to be characterized and quantified in order to obtain a better management of the drainage basin. One of the biggest problems for human survival in the semiarid regions is the water supply limitation, regarding quality, quantity, spatial distribution and permanence or reliability. In addition to the existing adversities in the sub-medium São Francisco valley, the climatic changes are another factor of great concern towards the challenges for a better management of water resources. It is necessary to know the distribution and water supplies in terms of quantity and quality. Fechine and Galvíncio (2008) analyzed monthly precipitation of the Brígida river drainage basin, in the semiarid region of Pernambuco, which is one of the biggest sub-drainage basin of the São Francisco Valley sub-medium, and identified three homogeneous pluviometric regions.

Considering the optimized exploitation of water resources as an essential part of the correct management of drainage basins, the main objective of this study was to create an adequate hydrologic model for the sub-medium São Francisco Valley drainage basin, considering physical processes. This model is able to generate scenarios for the climate change on water resources.

DATA AND STUDY AREA

The drainage basin of the sub-medium São Francisco Valley is the third major area of the São Francisco basin and contains the largest portion of land for irrigated agriculture. This zone of the basin is located in the semiarid region where the precipitation is physically and temporally erratically distributed.

Figure 1 shows the spatial distribution of the sub-drainage basins analyzed in the present study - Pajeú and Pontal, with the precipitation and fluviometric stations located in the inclusion area of each sub-basin.

Characteristics of the studied sub-basins

Pontal sub-drainage basin

The Pontal sub-basin has an area of 6,023 km² and includes Petrolina, Afrânio, Dormentes and Lagoa Grande municipalities in Pernambuco state. In this study, precipitation data of Petrolina, Dormentes and Lagoa Grande were used to develop the model for the period 1963-1988. Due to inconsistent data, the Afrânio precipitation series was ignored. To calibrate the model, fluid flow data obtained in the transversal section of Lagoa Grande were used.

Pajéu sub-drainage basin

Pajéu sub-basin is the major sub-basin of the sub-medium São Francisco and has an area of 16,582 km² and a principal river length of 279 km. For that reason, to calculate the water balance, the basin was divided in two parts and the flow observed in the transversal section of Flores and Floresta was used.

For this research, existing data was made available by CODEVASF (São Francisco Valley Development Company), ANEEL (National Agency of Electric Energy), ANA (National Agency of Water), DCA/UFCG (Atmospheric Science Department of Campina Grande Federal University) and Embrapa Semiarid, for the period 1963-1988.

METHODS

Water balance model

To estimate or create the surface runoff values of the Sub-medium São Francisco Valley drainage basin, a model was developed based in the identification and quantification of the principal

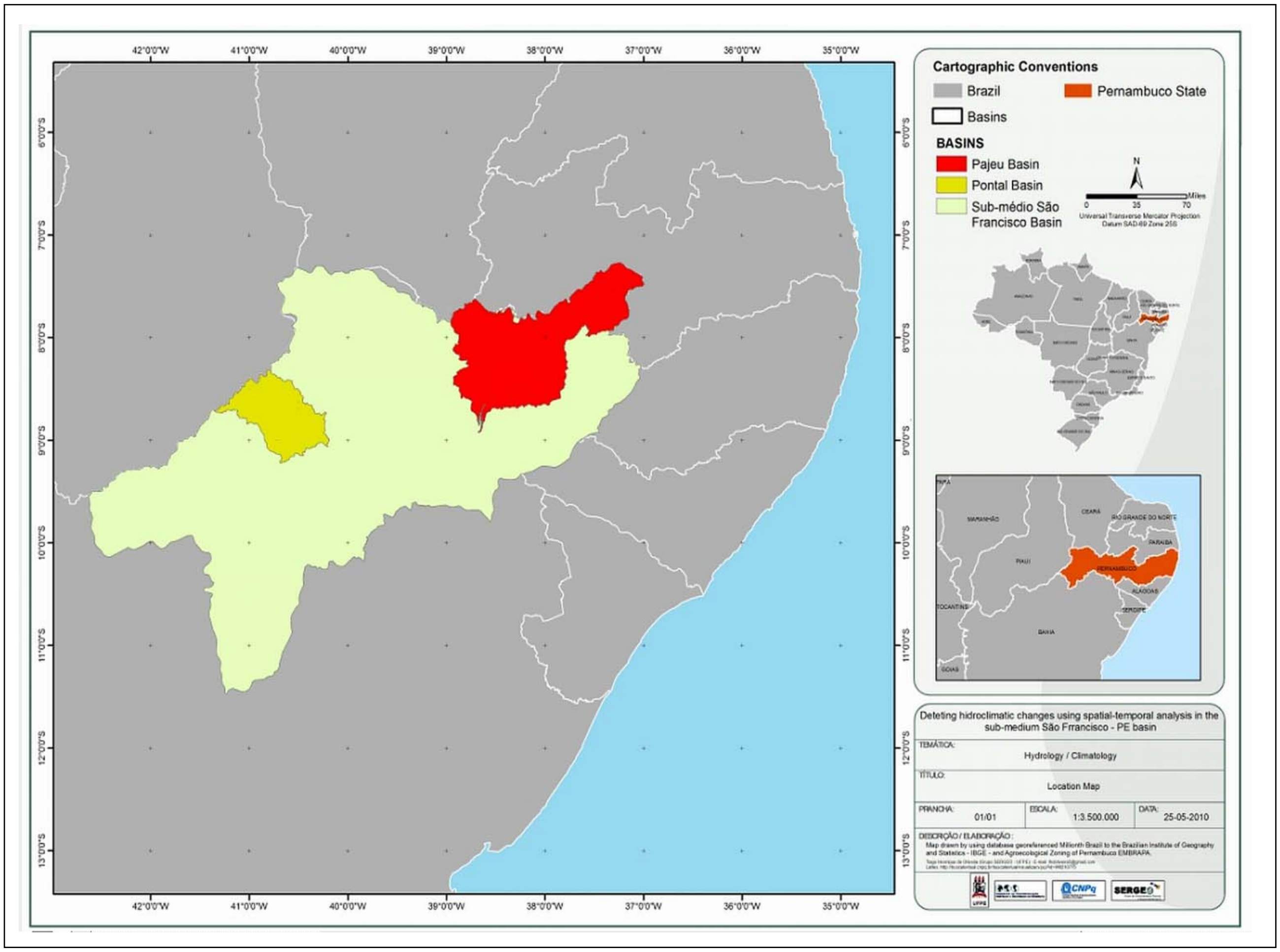

Figure 1. Spatial representation of the precipitation and fluviometric stations located in the sub-medium São Francisco Valley sub-basins - Pajeú and Pontal – analyzed in this study.

hydrologic processes. The model outlined here follows the same methodology proposed by Jothityangkoon et al. (2001), Galvíncio (2005), and Galvíncio et al. (2006). In this study, the water balance components were estimated in a daily scale.

The model establishes the water balance and an estimate of the surface runoff, considering the precipitation variations and potential evapotranspiration, and taking into account the influences of the soil depth variations, physiographic characteristics and plant cover. The developed model responds to the precipitation variability and to the potential evapotranspiration and follows the methodology adopted by Manabe (1969), Milly (1994), Jothityangkoon et al. (2001), and Galvíncio (2005).

The model represents the basin response in terms of a unique underground reservoir, with a finite capacity for soil water storage. The intent behind this choice was to represent the surface runoff with minimal complexity in order to evaluate the plant cover impacts. The observed precipitation is divided in evapotranspiration and surface runoff. The water interception by plant cover, the soil evapotranspiration, the plant transpiration, and the water extraction by roots from the underground reservoir are considered as losses. The surface runoff is considered when the water storage in the underground reservoir exceeds its capacity.

In the first simulation, it is necessary to specify an initial condition of soil humidity. After several interactions, it is assumed that the final storage value is equivalent to the initial one. This is because the humidity value of the initial soil or the water storage volume in the underground affects the other components of the water balance.

Water balance equation

The simplified water balance equation by unit of area is given by:

$$\frac{ds(t)}{dt} = p(t) - q_{se}(t) - e(t) \tag{1}$$

where $p(t)$ is the precipitation intensity (mm), $q_{se}(t)$ is the surface runoff rate or water excess after soil saturation (mm), $e(t)$ is the evaporation rate (mm) and $ds(t)/d(t)$ is the water volume variation stored in the soil (mm).

The variables $q_{se}(t)$ and $e(t)$ presented in Equation 1 are the underground reservoir discharges and are described as a function of the soil water storage, $s(t)$.

$$q_{se} = (s - S_b)/\Delta t \quad \text{if} \quad s > S_b \tag{2a}$$

$$q_{se} \quad 0 \quad \text{if} \quad s \quad S_b \tag{2b}$$

$$e = \frac{s}{S_b} e_p \tag{3}$$

where $S_b = D\phi$ is the storage capacity of soil humidity, D is the average soil depth (mm), ϕ is the average porosity (dimensionless), and Δt is time duration, considered 1 day. The water balance models, given by the Equations (1), (2a), (2b) and (3), use historical series of the daily totals precipitated and evaporated.

Input data

The input data necessary for the development of the water balance model are: soil depth (D) and porosity (ϕ), precipitation (p) and potential evapotranspiration (e_p).

It was assumed that the interception (i) would be 5% of the precipitation in all cases. The value of 5% was selected based on the fact that the savanna steppe vegetation has low interception by the canopy. The criterion developed here follows the same methodology proposed by Jothityangkoon et al. (2001), Galvíncio (2005), and Galvíncio et al. (2006).

In order to evaluate the plant cover influences in the water balance estimates, the following equation was used:

$$\frac{ds(t)}{dt} = p(t) - q_{se}(t) - e_b(t) - e_v(t) \tag{4}$$

where $e_b(t)$ is the evaporation rate in the soil without vegetation and $e_v(t)$ is the plant transpiration rate.

The evaporation estimate for the soil without vegetation was given by:

$$e_b = \frac{s}{t_e} \tag{5a}$$

$$t_e = \frac{S_b}{(1-M)e_p} \tag{5b}$$

where t_e is the temporal scale associated to the evaporation of the soil without vegetation and is given by Equation (5b), *M* is the plant cover fraction of the basin, which varies between zero and one.

The plant transpiration estimate was computed by the following equations:

$$e_v = Mk_v e_p \quad \text{if} \quad s > s_f \tag{6a}$$

$$e_v = \frac{s}{t_g} \quad \text{if} \quad s < s_f \tag{6b}$$

$$t_g = \frac{s_f}{Mk_v e_p} \tag{7}$$

where S_f is the soil water storage, considering a certain field capacity. $S_f = f_c D$ is assumed where f_c is the field capacity predominant in the basin, and *D* is the average soil depth. The reason for the use of the field capacity is that frequently, when the humidity content is smaller than the field capacity, the capillary force is greater than gravity, and drainage is slowed. t_g is the temporal scale associated to the transpiration and k_v is the plant transpiration efficiency. According to Eagleson (1978), k_v is equal to one.

The *M* parameter is used to divide the evapotranspiration into evaporation from the soil without vegetation and plant transpiration. The evaporation from the soil without vegetation is a proportion of e_p that depends on the *s* and S_b relation. When *s* is larger than S_f the transpiration is maximum and equivalent to e_p. When *s* is smaller than S_f the transpiration is given by a fraction of e_p.

Model parameters

The parameters for the monthly scale, are classified in the following categories: topographic (D, ϕ, f_c, L, K_s) and vegetation (M, k_v).

Evaluation criterion of the model

In this research, two criteria were used to select the best estimate. The first criterion adopted was the evaluation of the model response using the NASH coefficient. The second criterion consisted in evaluating how much the model explained the observed flow variability, using a determination coefficient.

RESULTS AND DISCUSSION

The water balance results adjusted to the sub-basins that drain to the transversal sections of Lagoa Grande-PE, Flores-PE, Floresta–PE and Inajá are presented next. Variations in precipitation, physiographic characteristics, plant cover and soil depth and porosity were considered for each sub-basin.

Climatologic and hydrologic analysis

Figures 2, 3 and 4 show the monthly precipitation variation, the average evapotranspiration, and the temperature of the Sub-medium São Francisco basin. The rainiest four-month period occurs

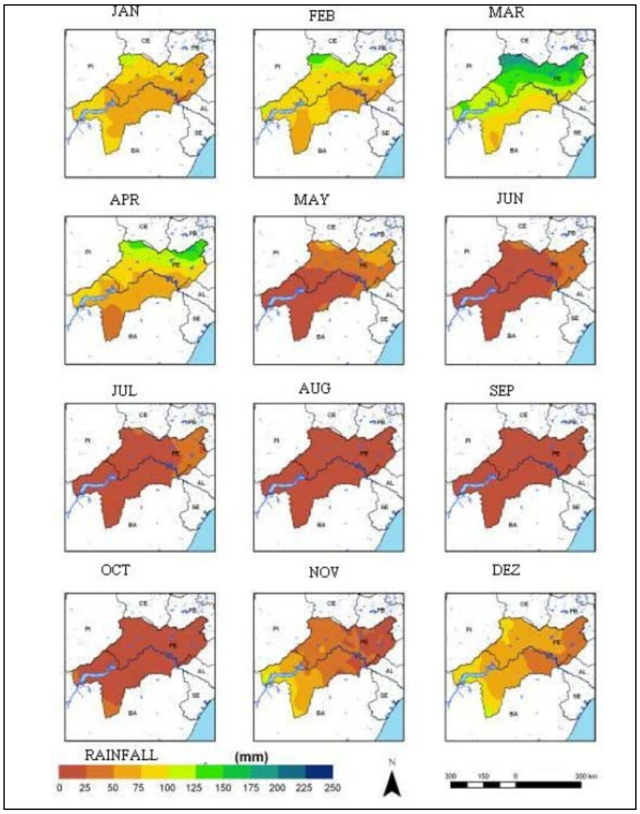

Figure 2. Monthly precipitation distribution of the sub-medium São Francisco basin.

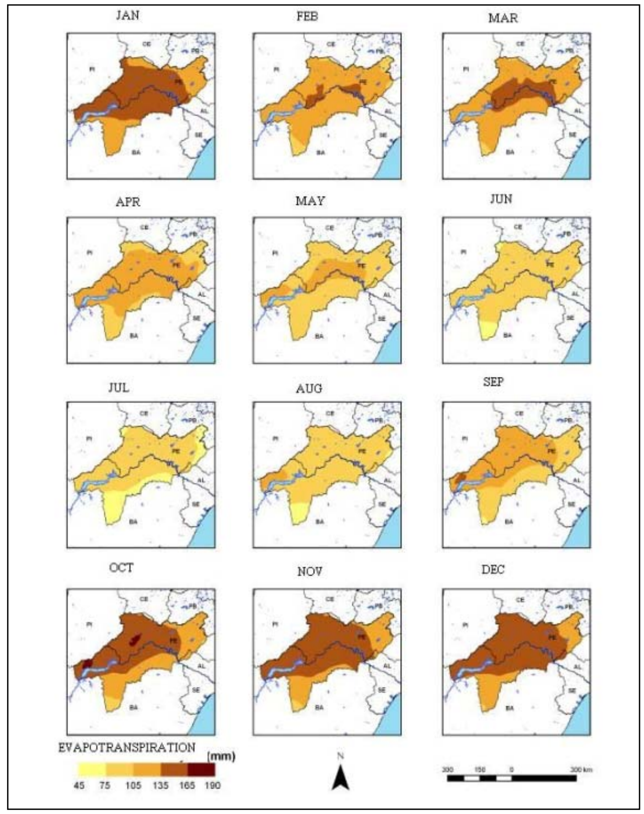

Figure 3. Monthly evapotranspiration distribution of the sub-medium São Francisco basin.

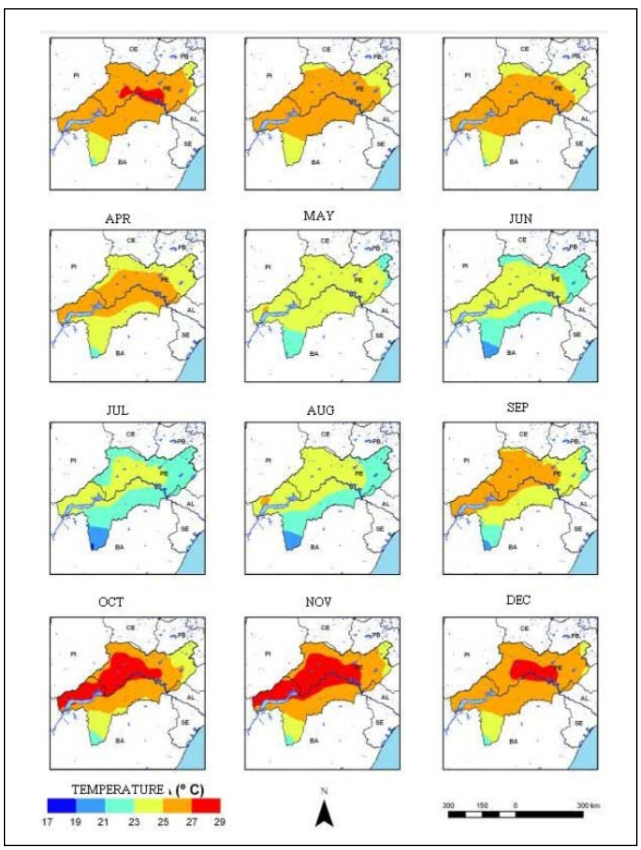

Figure 4. Spatial representation of the Sub-medium São Francisco basin temperature.

between January and April, and March is the rainiest month. This pattern occurs because of the Intertropical Convergence Zone (ITCZ), which is positioned closer to the Southern Hemisphere at this time of the year, resulting in an increase of precipitation in the Sub-medium São Francisco, in normal years. It is also clear that the north zone of the basin receives more rain than the south zone. According to Galvíncio and Sousa (2002), the Sub-medium São Francisco suffers a decrease in total precipitation during El Niño years, while during La Ninã years, the precipitation totals increase.

According to Da Silva et al., (2009a) and DaSilva and Galvíncio (2009), besides the ITCZ, the Pacific Decadal Oscillation (PDO), when associated with the ENSO phases (El Niño-Southern Oscillation), interferes in the Sub-medium São Francisco precipitation anomalies.

During annual cycles, the climatic conditions of the region can be divided in two defined periods: a dry season, with larger duration, and an irregular and short rainy season. In regular years, the dry season (with no rain) lasts roughly eight months but may last more to years of drought.

The basin has a climatologic regime with low precipitation and high evapotranspiration. The evapotranspiration largest values occurred in the central zone of the basin (Figure 3). One of the reasons for this pattern is the larger temperature values found in this area (Figure 4). Other factors may contribute to this pattern, like for instance the atmospheric pressure and the wind, which were not analyzed in this study.

The model results are presented fallowing the sub-basins order: Pontal and Pajéu. A comparison between the results and their respective tests of performance, applied during the verification period, are also presented.

Pontal sub-drainage basin

Figure 5 shows the relation between the estimated and observed surface runoff of the Pontal sub-basin. The model overestimated the surface runoff of April (rainiest month) and underestimated during the period from the dry season to the rainy preseason (December and January). The evaluation criterion for NASH was 0.99 and the determination coefficient was 97%. With this calibration, Pontal river basin can be presented in the hydrology with soil physical characteristics and plant cover of: medium soil depth of 40 cm, porosity 0.33, hydraulic conductivity of 13 mm/m, and 54% plant cover. The results were considered satisfactory. The results support those of

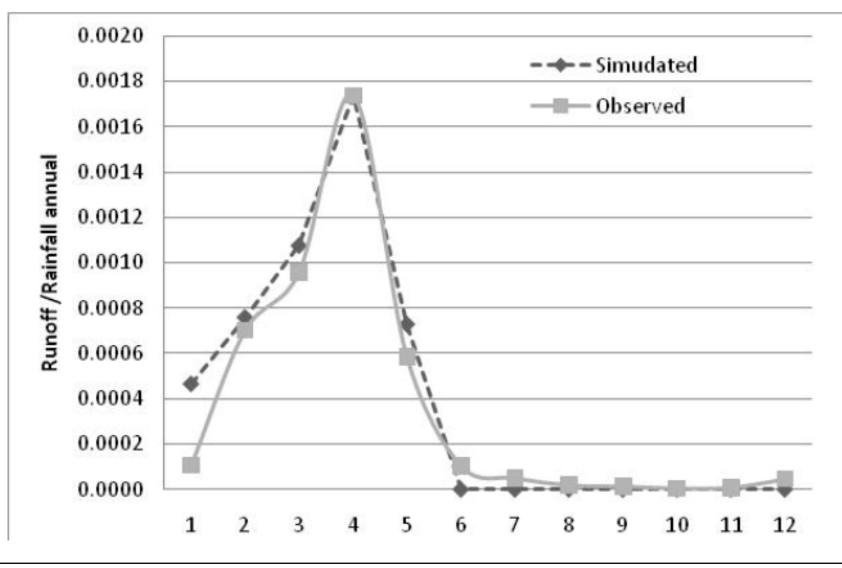

Figure 5. Comparison between the estimated and observed surface runoff of the Pontal-PE sub-basin.

Lacroix et al. (2002) and Galvíncio et al. (2007a). The water balance for the Epitácio Pessoa basin in the semiarid region of Paraíba state by Galvíncio et al. (2007b) used the same methodology adopted here when NASH and the determination coefficient values were around 0.95 and 93% respectively.

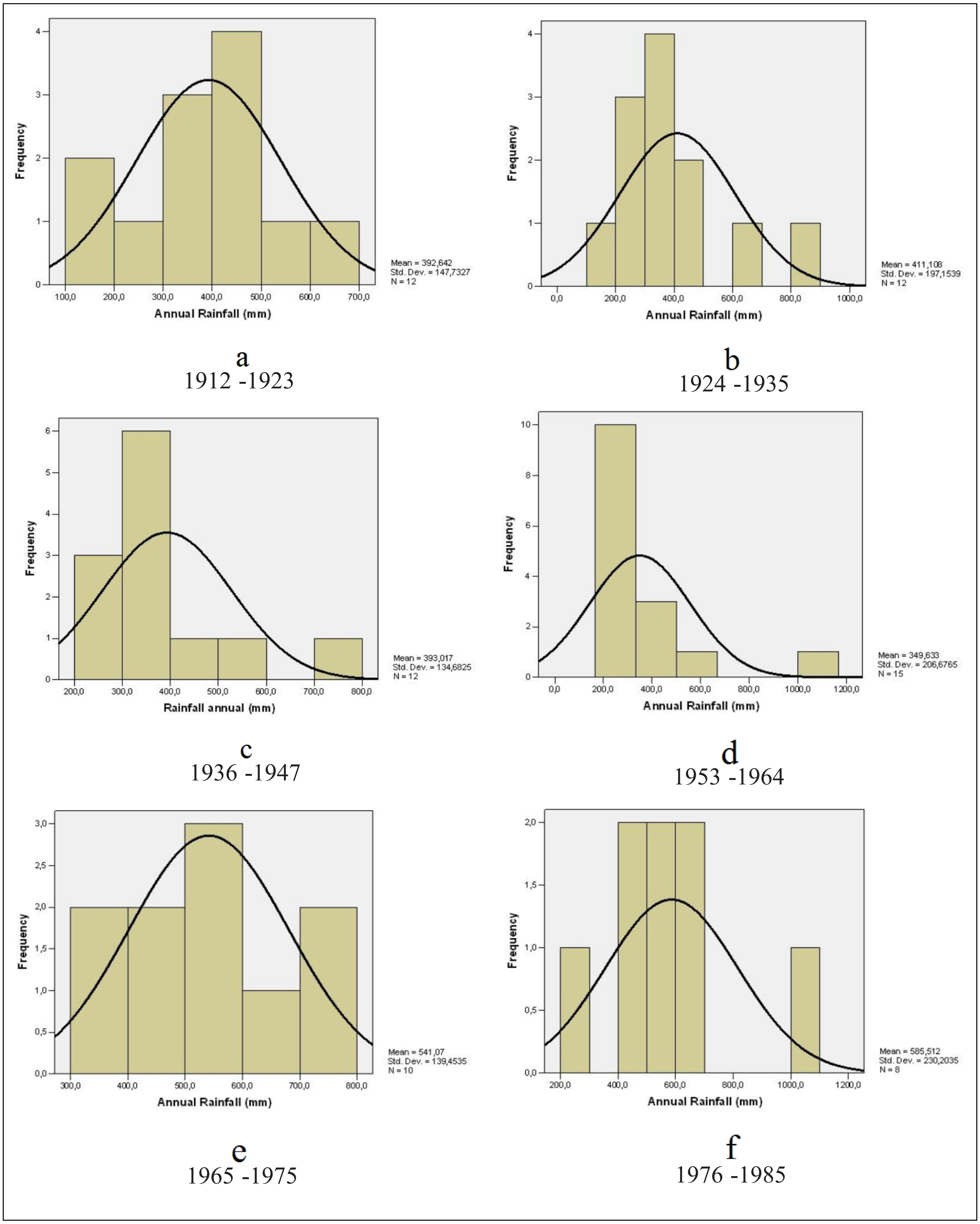

Figure 6. Histograms of the annual rainfall for different periods in the Pontal-PE river basin.

Figure 6 represents annual rainfall tendencies of the Pontal river basin. It is clear that the annual rainfall variations between 1912 and 1985 did not show any trends. It was not possible to identify trends in continuous temporal variability of rainfall. Other studies have been developed by Fechine and Galvíncio in the basin of the São Francisco river-Brazil, (FECHINE & GALVÍNCIO, 2009).

Pajéu sub-drainage basin

Figure 7 shows the comparison between the estimated and the observed surface runoff in the transversal section of Flores. It is clear that the model underestimated the surface runoff of January and February. The evaluation criterion for NASH was 0.60 and the determination coefficient was 76%. These coefficients were obtained when using an average depth of 20 cm, porosity of 0.30, hydraulic conductivity of 140 mm/m, and 38% plant cover.

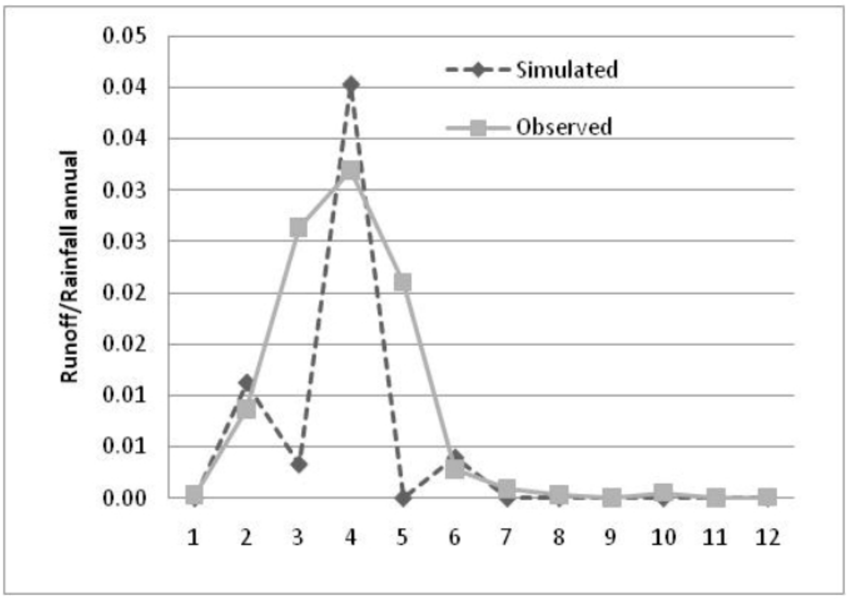

Figure 7. Estimated and observed surface runoff in the transversal section of Flores (Pajéu basin).

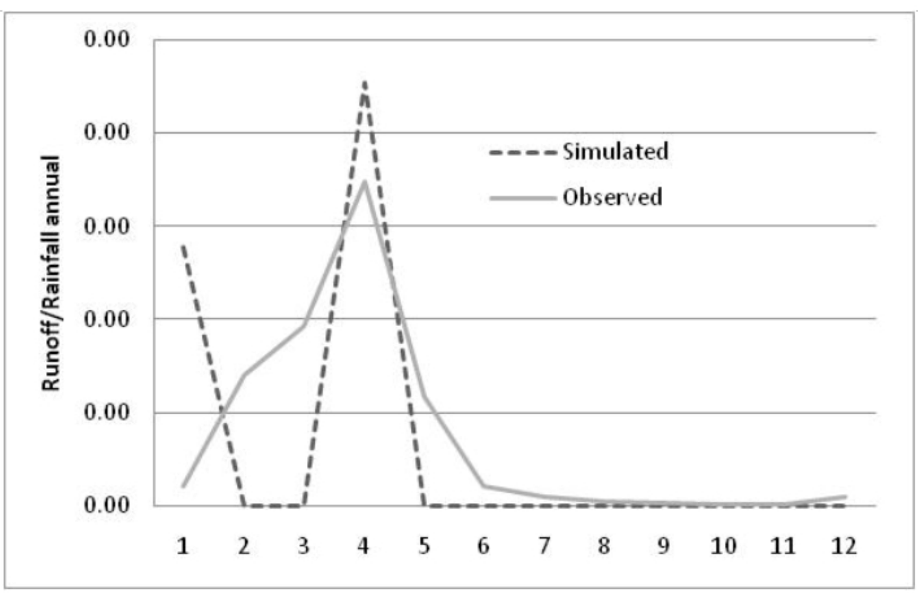

Figure 8. Comparison between the estimated and observed surface runoff in the transversal section of Floresta.

For the transversal section of Floresta, Figure 8, the determination coefficient was $R^2 = 0.86$ and NASH was 0.67. This adjustment occurred using a soil depth of 24 cm, porosity of 0.42, hydraulic conductivity of 110 mm/m, and 40% plant cover.

Guo et al. (2002) state that the surface runoff is very sensitive to the precipitation variation, which is typical of semiarid regions. Braga and Fuguierede (2003) by studying the influence of the climatic variability in the surface runoff in semiarid regions of the Northeast Brazil, showed that their effects in the simulations have great influence on runoff peaks.

Santos et al. (2009), using the same physical processes of the model presented here, has achieved good results. In this study, the developed model showed itself to be sufficiently feasible to be used in the planning and management of the basin Goina-PE-Brazil, especially for simulation of the impacts of climatic change.

CONCLUSION

In general, the developed model demonstrated a good response to the runoff spatio-temporal variability, when considering the variation of several factors, such as precipitation, evapotranspiration, soil depth and porosity, plant cover and hydraulic conductivity.

No hydroclimatic tendencies were observed in the sub-medium São Francisco for the period of this study.

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