Revista
Geama
www.geama.ufrpe.br

Hydrological Processes Simulation at Plot Scale Using the Smap Model in the Semiarid

Iug Lopes[1*] and Abelardo A. A. Montenegro[2]

Artigo recebido em 15/05/2017 e aceito em 18/06/2017

ABSTRACT
Vegetation cover plays an important role on overland flow generation and erosion, directly impacting infiltration and soil water storage. The objective of this study was to investigate hydrological processes and soil moisture dynamics through conceptual modelling in intensively monitored experimental plots under natural rainfall with different soil cover conditions, in the Brazilian semiarid. Soil moisture was monthly monitored using a CPN 503 DR Neutron Probe device. Calibration curves previously defined were adopted for moisture assessment. Four experimental soil cover treatment were established: Cactus "Palma" barriers (PB); mulching (MC); Bare soil (BS) and natural vegetation cover (NC). Nash-Sutcliffe (ENS) coefficient and PBIAS index were adopted to assess hydrological processes analysis. The SMAP model successfully predicted the flow and humidity of the experimental plots for the natural cover and Mulching coverage, with a global ENS index of over 0.877. Scenarios of changes in soil cover have dramatically affected the modeling of water resources in the plots. The present study was important to improve the understanding and distinct hydrological processes relevance under different cover conditions in experimental plots in the semiarid.
Keywords: Modeling, Caatinga, natural rainfall, Soil moisture, mulching.

Simulação de Processos Hidrológicos em Escala de Parcela Utilizando o Modelo Smap no Semiárido

RESUMO
A cobertura vegetal tem papel relevante na geração de escoamento superficial e na erosão, impactando diretamente a infiltração e o armazenamento de água no solo. O objetivo deste estudo foi investigar processos hidrológicos e dinâmica de umidade do solo por meio de modelagem conceitual em parcelas experimentais intensivamente monitoradas sob chuvas naturais com diferentes condições de cobertura do solo na região semiárida brasileira. A umidade do solo foi monitorizada mensalmente utilizando uma sonda de nêutrons CPN 503 DR. As curvas de calibração previamente definidas foram adotadas para avaliação da umidade. Foram estabelecidos quatro tratamentos experimentais de cobertura do solo: Palma (PB); Cobertura morta (MC); Solo nu (BS) e cobertura natural da vegetação (NC). O coeficiente de Nash-Sutcliffe (ENS) e o índice PBIAS foram adotados para avaliar a análise de processos hidrológicos. O modelo SMAP previu com sucesso o fluxo e a umidade das parcelas experimentais para cobertura natural e cobertura morta, com um índice ENS global de mais de 0,877. Cenários de mudanças na cobertura do solo afetaram dramaticamente a modelagem de recursos hídricos em parcelas. O presente estudo foi importante para melhorar a compreensão e o conhecimento da relevância de distintos processos hidrológicos sob diferentes condições de cobertura em parcelas experimentais no semiárido.
Palavras-chave: Modelagem, Caatinga, chuva natural, umidade do solo, cobertura morta.

[1]Posgraduate Program in Agricultural Engineering, Universidade Federal Rural de Pernambuco – UFRPE, Recife, Pernambuco, iuglopes@hotmail.com;
[2]SeniorLecture- Agricultural Engineering Universidade Federal Rural de Pernambuco – UFRPE, Recife, Pernambuco, Brazil. Abelardo.montenegro@ufrpe.br.

Introduction

Hydrological modelling constitutes a relevant procedure for water resources planning and management, and for evaluation of hydrological processes (MARTINS FILHO et al., 2004). Hydrological processes at the soil zone can be addressed either by physical or by empirical models (BRANDÃO et al., 2006). Empirical models present as an advantage the possibility for representing soil hydraulic characteristics and soil hydrological components without requiring physical measurements of soil variables, (MIRZAEE et al., 2014).

According to Wenninger et al. (2008), hydrological processes in the semiarid are highly variable, and also intermittent. Thus, not only rainfall and runoff measurements should be carried out, but also state variables such as soil moisture must be monitored.

The Soil Moisture Accounting Procedure (SMAP) is largely applied to rainfall-runoff simulations in semiarid zones. It can be considered an empirical deterministic model (LOPES et al., 1981). According to Beven (2012), such conceptual models are still widely used in hydrological practices. The SMAP model consider a series of linear reservoirs to represent overland flow routing, soil water store, groundwater store, etc.

Soil cover conditions play an important role on the water balance at the soil zone, due to interception and to reduce overland flow (CECÍLIO et al., 2013). Montenegro et al. (2013) and Santos et al. (2014) verified the impact of mulching from crop residues on increasing soil water storage, mainly during the raining season.

Several studies have been conducted to investigate rainfall-runoff processes in different scales, but there is still a lack of information on the main hydrological components and runoff generation in semiarid environments over different soil cover conditions (ROCHA et al., 2005; CANTON et al., 2011). Nowadays, due to severe and frequent droughts, and also considering climate change future scenarios of water scarcity, there is an increasing interest on studies addressing soil moisture temporal dynamics.

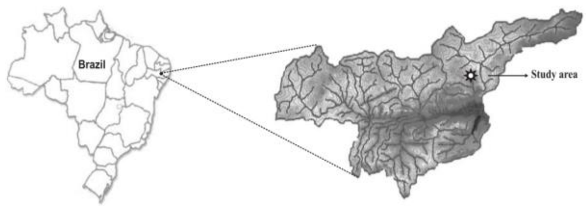
The objective of this study is to investigate hydrological processes and soil moisture dynamics through conceptual modelling in intensively monitored experimental plots under natural rainfall with different soil cover conditions, in the Brazilian semiarid.

Material and Methods

This study was developed at the Mimoso Representative Catchment, in the semiarid region of Pernambuco State, in Pesqueira municipality (Figure 1). The coordinates for the region are 8 ° 34 ' 17 "e 8 ° 18 '11" S, 37 ° 1' 35 "e 36 ° 47 '20" W).

According to Montenegro and Montenegro (2006), mean annual rainfall is 600 mm, with mean temperature of 23 °C, and mean potential evapotranspiration of 2.000 mm. The main vegetation cover is the shrubby Caatinga, and the Litholic Neosol is the predominant soil type (EMBRAPA, 2013). More details about the area description can be found in Montenegro & Ragab (2010).

Figure 1- Location of the study area, Mimoso Representative Catchment, Pesqueira, PE.



Experimental plots were installed at the catchment hillslopes, with 5%. Typical soil characteristics are presented in Table 1.

Table 1. Soil physical characteristics for the 0- 60 cm layer, at the experimental plots.

Sand	Silt	Clay	Ds	Dp	Porosity
	g kg-1		kg dm-3		m3 m-3
630	150	220	1.43	2.76	0.48

Ds- soil density; Dp- particle density

Four experimental plots 4.0 m wide and 11.0 m long were installed with bricked walls (Figure 2). Each plot had eight access tubes, 60 cm deep, and 2.0 m apart for soil moisture assessment.

Soil moisture was monthly monitored using a CPN 503 DR neutron probe device. Calibration curves previously defined were adopted for moisture assessment, according to Melo and Montenegro (2015). Four experimental soil cover treatment were established: Cactus "Palma" barriers (PB); mulching (MC); bare soil (BS) and natural vegetation cover (NC).

Figure 2. Experimental plots with different soil cover treatments: (A) "Palma" barriers (PB); (B) mulching cover (MC); (C) Bare soil (BS); (D) Natural vegetation cover (NC).

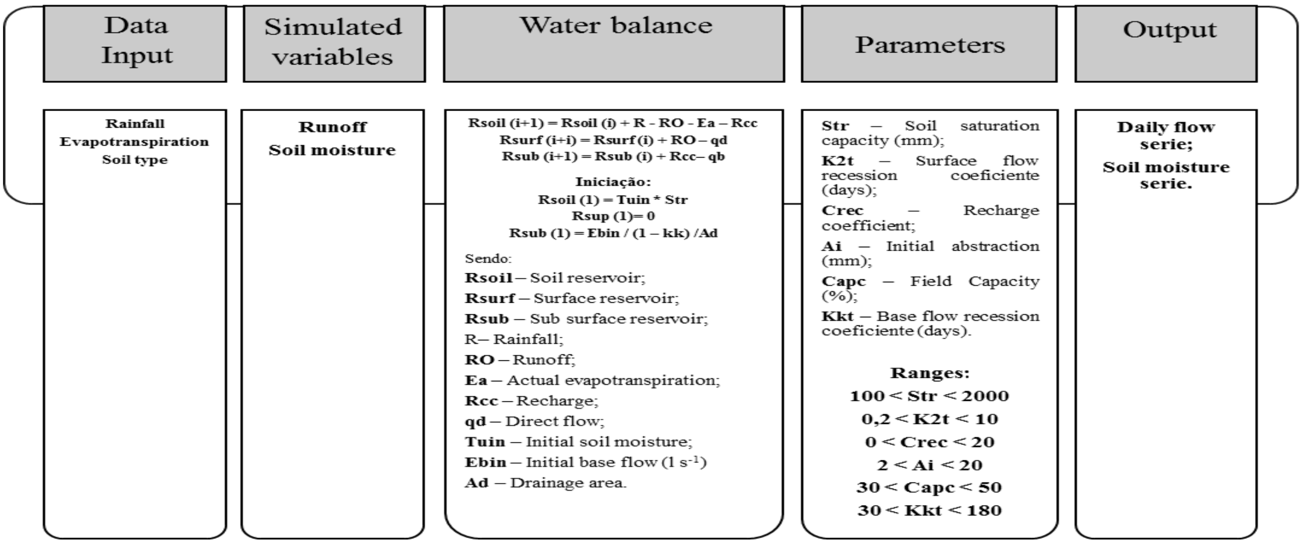
A B

C

D

Hydrological simulation for each soil cover condition was conducted using the SMAP model.

Figure 3. SMAP model representation: water balance equations and parameters.



Shallow soils dominate in the catchment hillslope, and recharge is usually negligible. Nevertheless, perched watertable could occur, contributing for lateral fast flow above bedrock. This concept was also analyzed during simulation. Hence, in addition to the usual SMAP model conceptualization, the conceptual model proposed by Wenninger et al. (2008) was also applied, adopting Darcy Law along the slope (Figure 4).

Figure 4. Conceptual model proposed by Wenninger et al. (2008) for shallow soils above fractured bedrocks, being (1) perched water table; (2) impediments; (3) slow infiltration; (4) local recharge; (5) fractured bedrocks; (6) lateral quick flow; (7) percolation; (8) groundwater; (9) stream contribution; (10) surface water. Source: Wenninger et al. (2008).

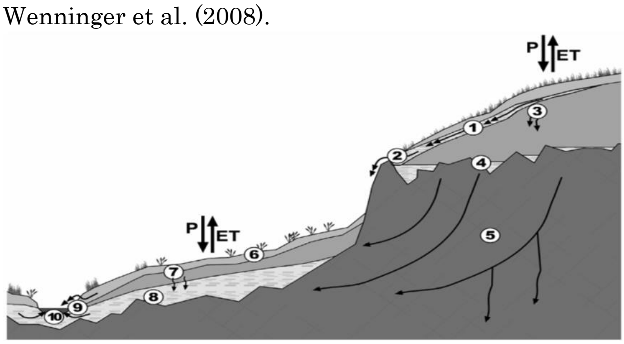


Figure 3 presents the main steps of the conceptual model, and model parameters, accounting for time variation of overland flow and soil moisture. Runoff was modelled based on the Soil Conservation Service Soil Number model. Instead of using CN values from literature, saturation capacity concept was adopted, consideration soil porosity and effective soil depth to impediment layer.

Calibration was carried out for a set of overland flow events in conjunction with soil moisture readings. Validation was then analyzed for another set of overland flow and soil moisture monitoring periods. The whole simulation period was from 01/01/2017 until 04/30/2017. Parameters were adjusted for each soil cover condition.

Visual joint analyses between measured and simulated values for both runoff and soil moisture allowed consistent estimation of hydrological components, and also state variables.

In addition, regression analyses were performed, the Nash-Sutcliffe Efficiency coefficient ENS calculated, and also the bias calculated (P_{BIAS}).

The ENS (Eq. 1) evaluates the model efficiency in reproducing observed data. Santhi et al. (2001) proposed the following classification: for ENS > 0.65, the simulation is considered very good; for 0.54 < ENS <= 0.65, the simulation is considered good; and between 0.5 and 0.54, regular.

$$ENS = 1 - \frac{\sum_{i=1}^{N}(z_{sim(i)} - z_{obs(i)})^2}{\sum_{i=1}^{N}(z_{obs(i)} - \bar{z}_{obs(i)})^2}$$

(Eq. 1)

The PBIAS (Eq. 2) allows the bias evaluation for the simulated variables against the observed values. Estimates close to zero mean that simulation represents well observed values (Moriasi et al., 2007).

Liew et al. (2007) presented the following classification: $|P_{BIAS}|$ <10%, very good; 10% < $|P_{BIAS}|$ < 15%, good; 15% < $|P_{BIAS}|$ < 25%, regular and $|P_{BIAS}|$ > 25%, the simulation is not adequate. The PBIAS for the z variable may be calculated as:

$$P_{BIAS} = 100 * \left(\frac{\bar{z}_{sim} - \bar{z}_{obs}}{\bar{z}_{obs}}\right) \quad \text{(Eq. 2)}$$

With the prospect of providing support to the management of water resources, daily series of data were computed for the period under study, with the parameters calibrated of flow and moisture soil for each scenario each type of vegetal cover, and bare soil condition.

Results and Discussion

Calibrated parameters for both overland flow and soil moisture are presented in Table 2, for each soil cover condition. The most sensitive parameters were the soil saturation capacity, the initial abstraction, and surface flow recession constant, associated with overland flow resistance at the soil surface.

Table 2. Data used for the SMAP model calibration.

	Units	Ground coverings			
		NC	BS	PB	MC
Soil saturation capacity (Str)	mm	300	150	200	300
Surface flow recession constant (K2t)	days	0.3	0.15	0.22	0.25
Underground recharge parameter (Crec)	%	0.10	0.10	0.10	0.10
Initial Abstraction (Ai)	mm	5	2	3	4
Field Capacity (Capc)	%	0.35	0.35	0.35	0.35
Basic flow recession constant (Kkt)	%	0.5	0.5	0.5	0.5

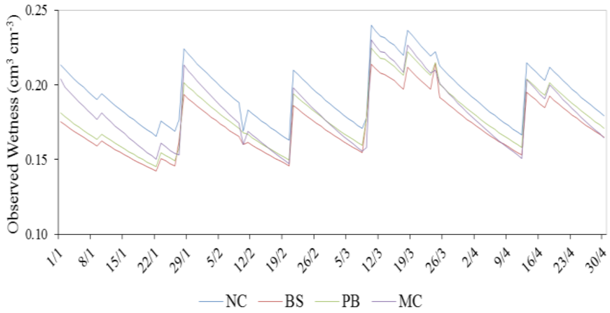
It can be observed that the soil physical parameters are similar, because the experimental plots are at the same pedological unit (distance 0.5 m from each other). These parameters are: Groundwater recharge parameter (Crec); and Field Capacity.

Initially the Str values for all plots were set at 300 mm, but conceptually it was adjusted to account for the impediment layers due to compaction formed at the bare soil plot and at palm bush plots. Thus, it was considered that in BS there was a reduction of 50% and for PB a reduction of 33.33% in the Str value.

The largest changes for the calibration parameters for the different plots were verified for the recession constant of the surface flow (K2t) and for the initial Abstraction (Ai).

For the study period it was observed a cumulative rainfall of 207 mm, producing a soil moisture dynamics for the experimental plots, which can be observed in Figure 5, with larger moistures values verified for the NC and MC plots.

Figure5. Variation of humidity in the studied period, for the plots of natural cover - NC, Bare Soil - BS, Palma Barriers- PB and Mulching cover – MC.

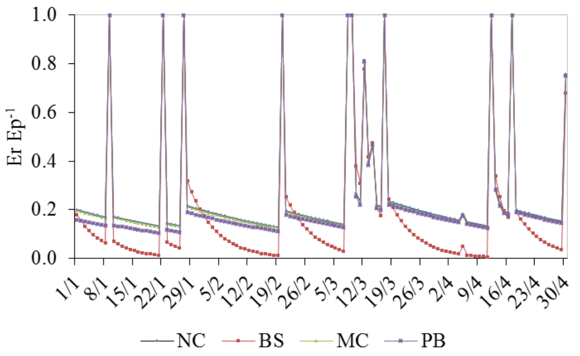


Sensitivity of soil moisture, in response to rainfall events, was influenced by its soil cover condition. Experimental plots with the highest cover index presented the highest soil moisture content. According to Buckman and Brady (1979), water retention capacity is improved by the formation of porous spaces, favoring the rapid water flow. In addition, covering reduces water application rates, enhancing infiltration, and the opportunity interval to infiltration.

The lowest moisture values for the bare soil plot are again observed when actual

Evapotranspiration (Ea) obtained by the SMAP model is related to the potential evapotranspiration (Ep) data measured at the local automatic agrometeorological station. The Ea by Ep ratio is much lower for the BS treatment, as presented in Figure 6.

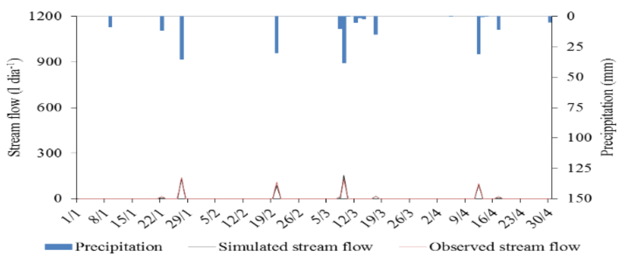
Figure 6. Variation of the relation between actual (Er) and the potential (Ep) evapotranspiration in the studied period, for the natural cover - NC, Bare Soil - BS, Palma Barriers- PB and Mulching cover – MC.



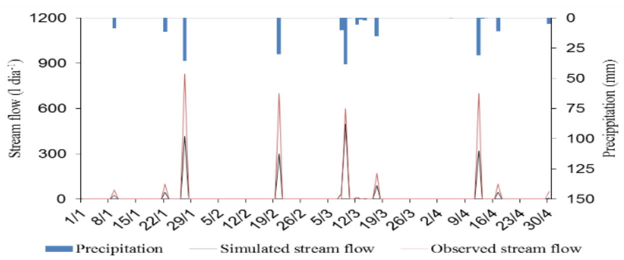
The purpose for adopting a conceptual hydrological simulation tool is to investigate and to compare the relative importance of distinct hydrological components towards a catchment response, aiming to validate the simulated behavior against the observed flows and water storage. It can be observed in Figures 7 (A, B, C and D) modeled and observed overland flows, and the impact of vegetal cover changes onto runoff peaks.

Figure 7. Observed and simulated hydrographs for plots for the natural cover - NC, Bare Soil - BS, Palma Barriers- PB and Mulching cover – MC. 2017 year.

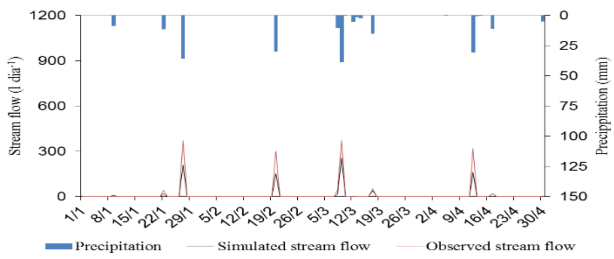
A



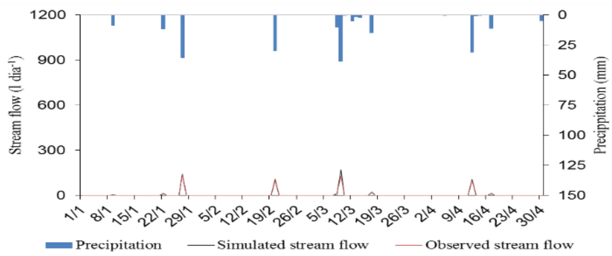
B



C



D



The visual analysis of the simulated and observed hydrographs indicated a good SMAP model performance. It was possible to observe the similarity of flow values for the natural cover and the mulching plots, and also lower peaks than at the bare soil plot.

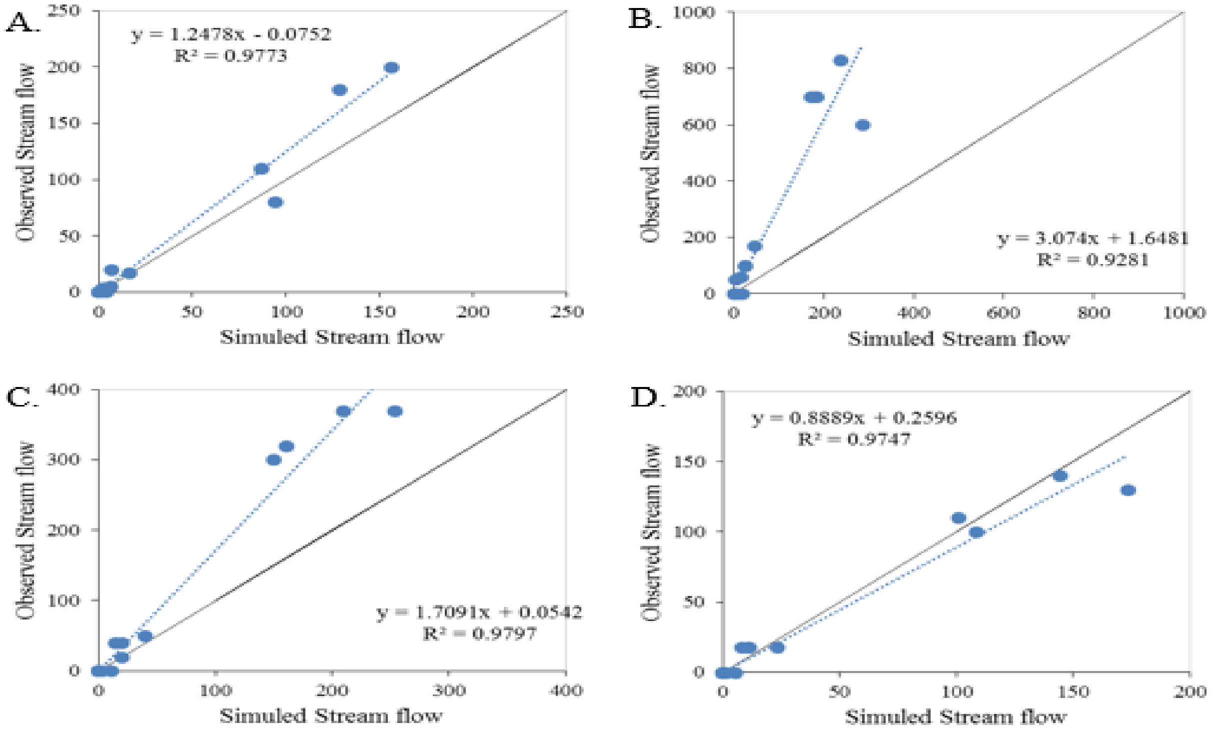
During the studied period (rainy season of 2017), there was a strong variation in rainfall concentrations and intensities and, consequently, variations in the flow peaks. The SMAP model simulated well both low and high peaks, raising the calibration/ validation quality, and enhancing performance indexes.

With the precipitation events that occurred, it was possible to model overland flow and thus to calibrate and validate the model parameters. Regression analysis between the estimated and observed flows in the four plots studied was carried out, which can be observed in Figure 8.

Simulated and observed flow rates for the different soil cover conditions presented linear correlation, and determination coefficients r^2 above 92%. However, for BS and PB, there was an underestimation of the flow peaks by the model. Nevertheless, through linear adjustments, it is possible to assess flows at the experimental plots, constituting an alternative planning tool (CRUZ and TUCCI, 2008).

For PB and mainly for BS, natural compaction may have occurred, causing soil saturation capacity to be reduced. This explanation is consistent to the observations of Melo and Montenegro (2015), to which under natural conditions, compaction at uncovered soils might occur as a result of the wetting and drying cycles in the semiarid.

Figure 8. Correlation between simulated and observed flow for plots of Natural cover - NC, Bare soil - BS, Palma barriers- PB and Mulching cover – MC.



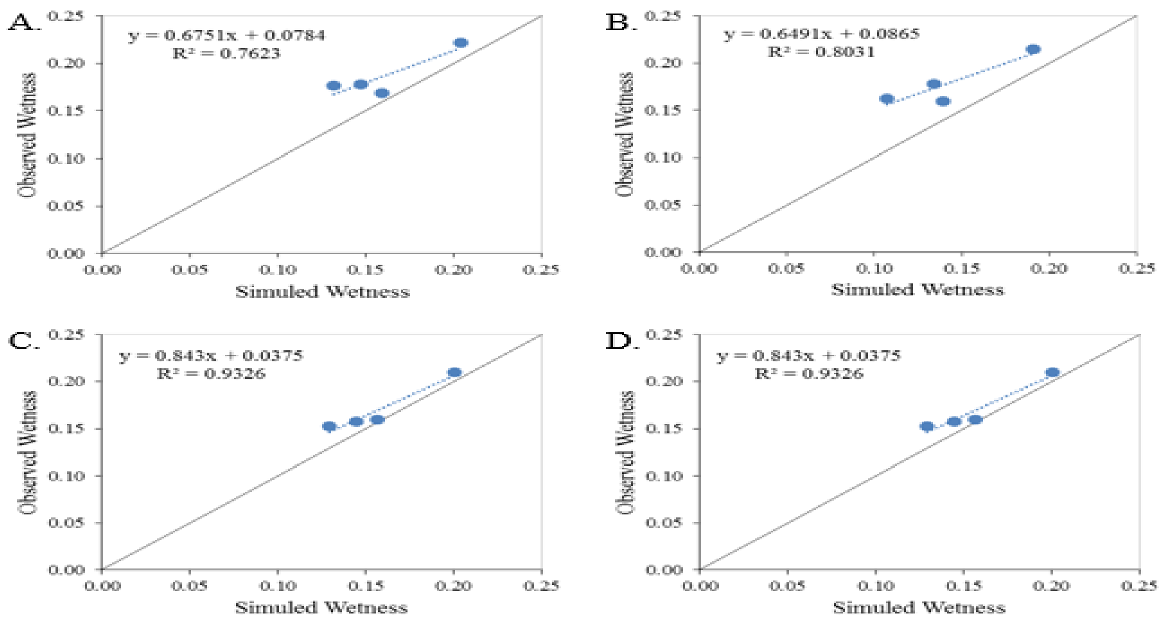
Montenegro and Ragab (2010), studying the Mimoso catchment response for different land uses and climate change scenarios, obtained a Nash-Sutcliffe coefficient (NS) of 0.73 for streamflow in natural Caatinga conditions.

Simulation of soil moisture was compared to data readings from neutron probe. A good correlation between the estimated and observed values was obtained (Figure 9), with R^2 values higher than 76%.

For the natural cover, SMAP simulations produced similar results as those observed by Montenegro & Ragab (2010) for catchment scale (150 km^2), that obtained a correlation coefficient of 0.70 between the simulated and observed soil moisture values.

.

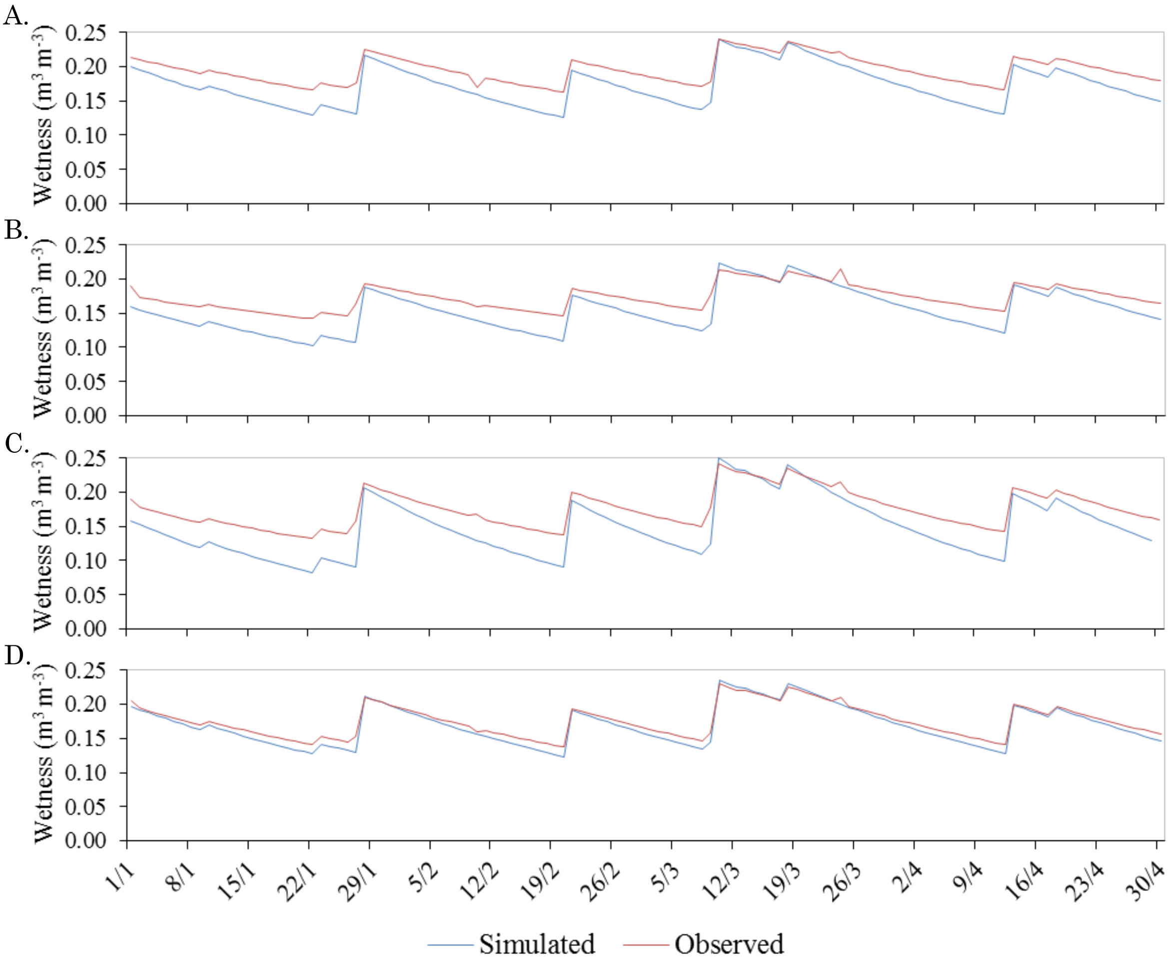
Figure 9. Correlation between simulated and observed soil moisture for the plots of (A) Natural cover - NC, (B) Bare soil - BS, (C) Palma barriers- PB and (D) Mulching cover – MC.



The applicability of the SMAP model is emphasized, not only for flow values, but also applied to parameters of the water balance that can be measured and then compared and calibrated for another independent variable, namely the soil moisture. The model performance for soil moisture and for the application in historical series analysis for semiarid regions is shown in Figure 10, for the different plots and soil cover conditions. Even more, it can be observed that both Caatinga cover and mulching cover presented higher moisture peaks than bare soil plot.

Bezerra et al. (2013) point out that information on soil water dynamics under different cover conditions is highly relevant, particularly in the semiarid region of Brazil, where little attention is still been paid to the Caatinga conservation, and consequently to better conditions for water storage.

Figure 10. Temporal variation of the simulated and observed moisture for the plots of (A) Natural cover - NC, (B) Bare soil - BS, (C) Palma barriers- PB and (D) Mulching cover – MC.



The SMAP model successfully reproduced trends for the soil moisture time series, for each cover type. The model considers the variation of humidity within the soil profile which can be computed through the water balance explicit equations for the domain. It is worth to note that availability of observed soil moisture values allowed the SMAP model to be applicable more efficiently, accounting for both water storage and overland flow, ensuring a more meaningful assessment of hydrological components.

The values of Nash-Sutcliffe Efficiency (ENS) and Minimization of bias percentage (P_{BIAS}), for the estimation of flows and soil moisture, are shown in Table 3.

Table 3. Statistical SMAP model performance for Stream flow and Wetness.

	ENS		I P_{BIAS} I	
	Streamflow	Wetness	Streamflow	Wetness
NC	0,895	0,879	19,34	11,04
BS	0,354	-0,239	24,8	15,2
PB	0,642	-0,828	21,08	15,35
MC	0,895	0,877	4,04	3,54

There are a number of studies in the literature that have used the ENS to test the hydrological simulation efficiency for river basins, such as Montenegro & Ragab (2010), Pinto et al. (2013) and Sexton et al. (2010). However, the major part of the applications addresses catchment scales, which are not suitable for a detailed analysis of the hydrological impact of a specific soil cover. For such analysis, a plot scale experiment is more suitable. Adopting the Hydrus-1D model, Silva et al. (2015) simulated soil moisture dynamics at plot scale in the semiarid. Similar ENS values were observed, and the model satisfactorily calibrated for the soil moisture dynamics over time, for natural and soil cover conditions, with the use measured moistures from TDR device.

The ENS results showed a very good adjustment for both flow and moisture, for the NC and MC plots. For PB plot, the model performance was good for overland flow, and for BS the model performance was lower than regular, according to the classification proposed by Santhi et al. (2001).When the values of P_{BIAS} were observed, interesting results occurred, which again tend to represent a good calibration.

Conclusions

The present study was important to improve the understanding of main hydrological processes under different cover conditions in experimental plots in the semiarid.

Most of the observed and simulated effects were properly correlated and fitted, exhibiting high performance statistical values, allowing precise quantification of the hydrological components for the experimental plots, and providing insights about the role of mulching and natural Caatinga cover for soil moisture conservation.

The SMAP model properly simulated hydrological processes in the experimental scale. Observed dataset for both overland flow and soil moisture were crucial for meaningful analysis, and to provide reliable parameterization for the model.

The SMAP model successfully predicted the overland flow and humidity at the experimental plots for the natural cover and mulching coverage, with a global ENS index of over 0.877. Scenarios for changes in soil cover have dramatically affected the water resources modeling in the plots.

Acknowledgments

The authors would like to acknowledge the financial support from the Brazilian Innovation Agency (FINEP). The authors would also like to express their gratitude to the FACEPE (Foundation for Science and Technology of Pernambuco State), CNPq (Brazilian National Council for Scientific and Technological Development), and CAPES (Coordination for the Improvement of Higher Education and Personnel) for the research and postgraduate fellowships.

References

BEVEN, K. J. *Rainfall-runoff modelling: the Primer.* John Wiley & Sons, Ltd Publication. Chichester, 2nd ed. 2012. 449 p.

BEZERRA, J. M.; MOURA, G. B. A.; SILVA, B. B. DA; LOPES, P. M. O.; SILVA, E. F. F. Parâmetros biofísicos obtidos por sensoriamento remoto em região semiárida do Estado do Rio Grande do Norte, Brasil. *Revista Brasileira de Engenharia Agrícola e Ambiental,* v.18, n.1, p.73-84, 2014.

BRANDÃO, V. S.; CECÍLIO, R. A.; PRUSKI, F. F.; DILVA, D. D. *Infltração da água no solo.* 3.ed. Viçosa: UFV, 2006, 120p.

BUCKMAN, H. O. & BRADY, N. C. *Natureza e propriedade dos solos.* 5 ed. Trad. A. B. N. Figueiredo Filho. Rio de Janeiro: Biblioteca Universitária Freitas Bastos, p. 647, 1979.

CANTÓN, Y.,SOLÉ-BENET, A.; DE VENTE, J.; BOIX-FAYOS, C.; CALVO-CASES, A.; ASENSIO, C.; PUIGDEFÁBREGAS, J. A review of runoff generation and soil erosion across scales in semiarid south-eastern Spain. *Journal of Arid Environments,* v.75, p1254-1261, 2011

CECÍLIO, R. A.; MARTINEZ, M. A.; PRUSKI, F. F.; SILVA, D. D. Modelo para estimativa da infltração de água e perfl de umidade do solo. *Revista Brasileira de Ciência do Solo,* v.37, p.411-421, 2013.

CRUZ, J. C.; TUCCI, C. E. M. Estimativa da disponibilidade hídrica através da curva de permanência. *Revista Brasileira de Recursos Hídricos,* v.13, p.111-124, 2008.

LIEW, M. W.; VEITH, T. L.; BOSCH, D. D.; ARNOLD, J. G. Suitability of SWAT for the Conservation effects assessment project: A comparison on USDA-ARS watersheds. *Journal of Hydrological Research,* v.12, p.173-189, 2007.

LOPES, J.E.G.; BRAGA JR.; B.P.F.; CONEJO, J.G.L. Simulação hidrológica: aplicações de um modelo simplificado. In: SIMPÓSIO BRASILEIRO DE RECURSOS HÍDRICOS, 3., 1981, Fortaleza. *Anais...*Porto Alegre: ABRH, 1981 (v. 2, p. 42-62).

MARTINS FILHO, M. V.; ENGLER, M. P. C.; IZIDORIO, R.; COTRIN, F. B.; SERRA, E. A.; AMARAL, N. S.; SOUZA, Z. M. Modelos para estimativa do subfator cobertura-manejo (CiII) relativo à erosão entressulcos. *Engenharia Agrícola,* v.24, p.603-611, 2004.

MELO, R. O.; MONTENEGRO, A. A. A. Dinâmica temporal da umidade do solo em uma bacia hidrográfica no semiárido Pernambucano. *Revista Brasileira de Recursos Hídricos,* v.20, p.430-441, 2015.

MIRZAEE, S.; ZOLFAGHAR, A. A.; GORJI, M.; DYCK, M.; GHORBANI DASHTAKI, S. Evaluation of infltration models with different numbers of fitting parameters in different soil texture classes. *Archives of Agronomy and Soil Science,* v.60, p.681-693, 2014.

MONTENEGRO, A. A. A.; MONTENEGRO, S. M. G. L. Variabilidade espacial de classes de textura, salinidade e condutividade hidráulica de solos em planície aluvial. *Revista Brasileira de Engenharia Agrícola e Ambiental,* Campipna Grande, v. 10, n.1, p. 30-37, 2006.

MONTENEGRO, A. A. A.; RAGAB, R. Hydrological response of a Brazilian semi-arid catchment to different land use and climate change scenarios: a modelling study. *Hydrological Processes,* v.24, n.19, p.2705-2723, 2010.

PINTO, D. B. F.; SILVA, A. M. ; BESKOW, S. ; MELLO, C. R. ; COELHO, G. . Application of the Soil and Water Assessment Tool (SWAT) for Sediment Transport Simulation at a Headwater Watershed in Minas Gerais State, Brazil. *Transactions of the ASABE,* v. 56, p. 697-709, 2013.

ROCHA, G.C.; LIBARDI, P.L.; CARVALHO, L.A. & CRUZ, A.C.R. Estabilidade temporal da distribuição espacial da armazenagem de água em um solo cultivado com citros. *Revista Brasileira de Ciência do Solo,* 29:41-50, 2005.

SANTHI, C.; ARNOLD, J. G.; WILLIAMS, J. R.; DUGAS, W. A.; SIRINIVASAN, R.; HAUCK, L. M. Validation of the SWAT model on a large river basin with point and nonpoint sources. *Journal of the American Water Resources Association*, v.37, p.1169-1188, 2001.

SANTOS, T. E. M.; SOUZA, E. R.; MONTENEGRO, A. A. A. Modeling of soil water infiltration with rainfall simulator in different agricultural systems. *Revista Brasileira de EngenhariaAgrícola e Ambiental,* v.20, p.513-518, 2016.

SEXTON, A. M.; SADEGHI, A. M.; ZHANG X.; SRINIVASAN, R.; SHIRMOHAMMADI, A. Using NEXRAD and rain-gauge precipitation data for hydrologic calibration of SWAT in northeastern watershed. *Transactions of the ASABE,* v.53, p.1501-1510, 2010.

SILVA, J.R.L.; MONTENEGRO, A.A.A.; MONTEIRO, A.L.N.; SILVA JUNIOR, V.P. Modelagem da dinâmica de umidade do solo em diferentes condições de cobertura no semiárido pernambucano. *Revista Brasileira de Ciência Agrária,* v. 10, p. 293-303, 2015.

WENNINGER, J.; UHLENBROOK, S.; LORENTZ, S.; LEIBUNDGUT, C. Identification of runoff generation processes using combined hydrometric, tracer and geophysical methods in a headwater catchment in South Africa. *Hydrological Sciences Journal,* v.53, n.1, p.65-80, 2010.