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SENSITIVITY ANALYSIS OF THE WATER BALANCE COMPONENTS OF THE WEAP MODEL FOR THE HIGH RIO VERDE GRANDE BASIN/MG

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ABSTRACT: The Water Evaluation and Planning system (WEAP) allows the integrated analyze of a series of hydrological processes of a physical nature with the water resources management, along with the installed infrastructure. Given the importance that the hydrological models have currently received by the scientific community and decision makers working with water resources, knowledge of the parameters that most interfere with their results is of great importance. In this sense, the objective of the present work was to perform a sensitivity analysis to identify the parameters that most influence the water balance of the WEAP model and, consequently, its importance in the results generated in the Alto Verde Grande (AVG) sub-basin. The results show that the flow estimated by the WEAP model is influenced especially by the resistance factor to the flow (RRF), followed by water capacity in the soil (SWC),. For a minimum variation, equivalent to -30% of the RRF default value, a simulated flow increase of 51% was observed, considering the simulated flow based on the standard condition. The conductivity of the lower layer (DC) was not sensitive to the data simulated by the model for the AVG sub-basin.

KEYWORDS: Hydrological modeling, calibrated parameters, water resources management.

ANÁLISE DE SENSIBILIDADE DOS COMPONENTES DO BALANÇO HÍDRICO DO MODELO WEAP PARA A BACIA DO ALTO RIO VERDE GRANDE/MG

RESUMO: O modelo Water Evaluation And Planning System (WEAP) permite a analise integrada de uma série processos hidrológicos de natureza física com a gestão dos recursos hídricos, juntamente com a infra-estrutura instalada. Dada a importância que os modelos hidrológicos têm recebido atualmente pela comunidade científica e pelos tomadores de decisão que atuam na área de recursos hídricos, o conhecimento dos parâmetros que mais interferem

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nos seus resultados é de grande importância. Nesse sentido, o objetivo do presente trabalho foi realizar uma análise de sensibilidade para identificação dos parâmetros que mais influenciam no balanço hídrico do modelo WEAP e, consequentemente, sua importância nos resultados gerados na sub-bacia do Alto Verde Grande (AVG). Os resultados apresentados evidenciam que a vazão estimada pelo Modelo WEAP é influenciada especialmente pelo fator de resistência ao escoamento (RRF), seguido pelo, ou capacidade de água no solo (SWC). Para uma variação mínima, equivalente a -30% do valor padrão de RRF, notou-se um aumento de 51% na vazão simulada, considerando a vazão simulada com base na condição padrão. O parâmetro condutividade da camada inferior (DC) não foi sensível em relação aos dados simulados pelo modelo para a sub-bacia do AVG.

PALAVRAS - CHAVE: Modelagem hidrológica, parâmetros calibráveis, gestão de recursos hídricos.

INTRODUCTION

The WEAP model allows the integrated analyze of a series of hydrological processes of a physical nature with a management of water resources, together with an installed infrastructure. It is possible to analyze multiple scenarios, with a possibility of applying a section of climatic order, changes in water consumption patterns through population or industries, adoption of new technologies, alteration of land use and occupation, increase of irrigated areas, increased irrigation efficiency, among others (YATES et al., 2005).

The availability of water in WEAP is modeled by the physical factors that involve the hydrological cycle, that’s, climate, topography, soil cover, surface hydrology, underground hydrology, soil and water quality, considering the a watershed as a management unit. The demand for water use depends on the type and level of economic activity in the basin. It is worth mentioning that the hydrographic basin itself will be the first point of withdrawal through the interactions between the atmosphere and the surface (evapotranspiration) (MAHMOOD and HUBBARD, 2002). After the withdrawals of natural order, the residual supply is the one that will be available for the management system. Given the importance of hydrological models currently received by the scientific community and decision makers working water resources management, knowledge of the parameters that most interfere with their results is of great importance. In this context, the sensitivity analysis becomes essential, one that allows the identification of the parameters that most influence the model and, consequently, its importance in the generated results, directing the focus to acquisition and refinement of those that have more weight in the result of the hydrological model (ADRIOLO et al., 2008; JHA, 2009). Therefore, the objective of the present work was to perform the sensitivity analysis of the water balance components of the WEAP model for the Alto Verde Grande sub-basin.

MATERIAL AND METHODS

The study site of the present study was the AVG sub-basin, whose drainage area is 3,098 km², located in the northern of Minas Gerais state. As its name indicates, this hydrographic basin is formed by the upper stretch of the rio Verde Grande, comprising the municipal headquarters of Montes Claros, Glaucilândia, Guaraciama and Juramento. The Figure 1 shows the AVG sub-basin and its location.

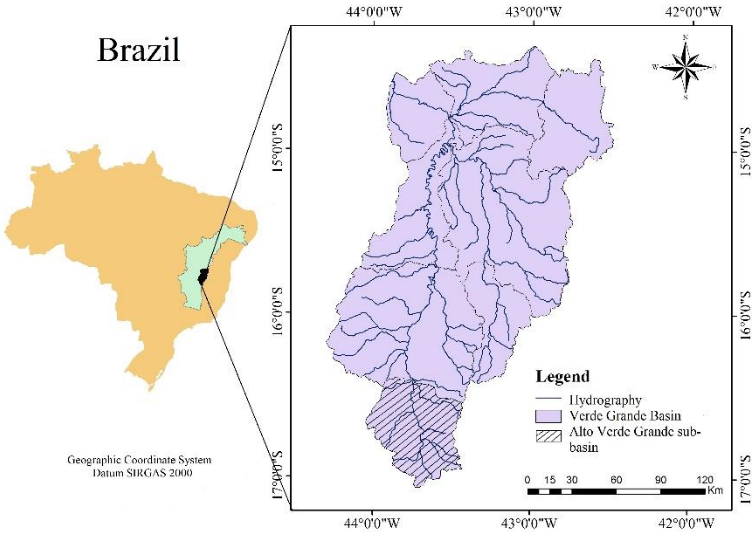

Figure 1. Location of the Alto Verde Grande sub-basin.

The sensitivity analysis was performed in the Rainfall Runoff method (Soil Moisture Method), considered the most complex method to perform the water balance, representing the basin in two layers of soil. In the upper (superficial) layer, the model simulates evapotranspiration, considering rainfall and irrigation in agricultural and non-agricultural lands, surface and subsurface flows and changes in soil moisture. The use of this method allows the characterization of land use, soil type and its impacts on these processes. In the lower layer, simulations are performed for the river runoff routines and changes in soil moisture. The great difficulty in using the method lies in the need for greater parameterization of the soil and climate. For the application of the model for the AVG sub-basin, the balance was calculated considering each fraction of area j, depending on the type of soil cover or type of crop. In each fraction of area j was assumed a uniform climate, where the mass balance equation is written according to Equation 1.

$$SWC_j \frac{dz_{1,j}}{dt} = Pe(t) - PET(T)K_{c,j}(t)\left(\frac{5z_{1,j} - 2{z_1^2}_{,j}}{3}\right) - Pe(t){z_1^2}_{,j}^{\frac{RRF_j}{2}} - PFD_j RZC_j {z_1^2}_{,j} - (1 - PFD_j)RZC_1 {z_1^2}_{,j} \quad (1)$$

where, $Z_{1,j}$ is the relative storage given as a fraction of the total effective storage in the root zone, SWC_j represents the effective total storage of the top layer (mm).

The value of $Z_{1,j}$ ranges from 0 to 1, with 0 being the permanent wilting point and 1 being the field capacity, and the SWC_j value corresponds to an estimate of the water retention capacity of the soil for each soil cover fraction j .

The first term of Equation 1 is defined as precipitation. The second term refers to the evapotranspiration of each fraction of area, where PET is the potential evapotranspiration of the reference crop (Penman-Montieth) in mm day^{-1}, and $K_{c,j}$ is the crop / plant coefficient for each fraction of soil cover.

The third term represents the surface runoff, where *Pe* is the effective precipitation and the RRF (Runoff Resistance Factor) is the resistance factor to the flow, in which lower values of RRF_j refer to the class of soil cover that will promote the greater response to surface runoff, in order words, uncovered soils. It has a direct relationship with the leaf area index and soil slope, with a range between 0 and 10, where higher values provide a decrease in flow.

The subsurface flow and percolation are represented by the fourth and fifth terms of equation 1, respectively, where the RZC_j (Root Zone Conductivity) parameter is an estimate of the conductivity of the upper storage layer (mm h-^{1}) and PFD_j (Preferred Flow Direction) is an adjustment parameter related to soil, topography, soil cover type, it is possible to fractionate the water both horizontally, PFD_j, and vertical (1 - PFD_j), where 1.0 = 100% horizontal, 0 = 100% vertical flow.

The mass balance for the second layer ($z_{2,j}$) is obtained according to Equation 2.

$$DWC_j \frac{dz_{2,j}}{dt} = (1 - PFD_j)RZC_j {z_1^2}_{,j} - DC{z_2^2}_{,j} \quad (2)$$

Where the inflow to the bottom layer is the deep percolation from the upper storage, obtained in Equation 1, DC (Deep Conductivity) is the conductivity of the lower layer (mm h^{-1}), represented as a single value for each Sub-basin and DWC_j (Deep Water Capacity) is the storage capacity of water in the bottom layer (mm).

The sensitivity analysis of the WEAP model was performed manually, varying each input parameter individually, while the others were kept constant. Silva et al. (2009) presented a Relative Sensitivity Index (SI), according to Equation 3.

$$IS = \frac{\frac{R_1 - R_2}{R_{12}}}{\frac{E_1 - E_2}{E_{12}}} \qquad (3)$$

Where IS is the sensitivity index of the model to the input parameters; R_1 is the result obtained by the model in response to the lowest input value used in the sensitivity analysis, R_2 is the result obtained by the models in response to the highest input value used in the sensitivity analysis, R_{12} is the mean of the results obtained with the highest and lower input value; E_1 is the smallest input value, E_2 is the largest input value; and finally, E_{12}, the mean values of the input values.

The results obtained by Equation 3 indicate that the larger the value of IS (in module) the more sensitive the parameter will be the model. However, values close to zero indicate that the model does not represent parameter sensitivity (LELIS et al., 2012).

The parameters used in the sensitivity analysis of the WEAP model were SWC Soil Water Capacity (SWC), Deep Water Capacity (DWC), Root Conductivity (RZC), Runoff Resistance Factor (RRF), Preferred Flow Direction PFD). The variation of the parameters was - 30%, -20%, -10%, 10%, 20%, 30%, and the standard was based on the parameters of the calibrated model. The values of the calibrated parameters used as standard can be seen in Table 1.

Table 1. Calibrated parameters of the WEAP model for the Alto Verde Grande sub-basin.

Parameters	
Soil Water Capacity (SWC)	1000 (mm)
Deep Water Capacity (DWC)	100 (mm)
Deep Conductivity (DC)	20 (mm s^{-1})
Root Zone Conductivity (RZC)	20 (mm s^{-1})
Runoff Resistance Factor médio (RRF)	6.40
Preferred Flow Direction médio (PFD)	0.55

In order to verify the perturbation that the variation of the parameters promoted in the results simulated by the model in detriment to the observed data, the accuracy of the results of the model was verified in relation to the historical data series observed in Capitão Enéas (44630000) streamflow gauge station by the coefficient of efficiency Nash-Sutcliffe (ENS), calculated using Equation 4.

$$E_{NS} = 1 - \frac{\sum_{i=1}^{n}\left(O_i - P_i\right)^2}{\sum_{i=1}^{n}\left(O_i - \hat{O}\right)^2} \tag{4}$$

Where is the mean of the observed data, O_i is the observed data, P_i is the predicted data and n is the number of observations in a given time interval. When the E_{NS} value is greater than 0.75, the model performance is considered good. For E_{NS} values between 0.36 and 0.75 the performance is considered acceptable, while E_{NS} values lower than 0.36 the model is considered unacceptable (BALTOKOSKI *et al*., 2010).

For the WEAP sensitivity analysis, the calibrated model was used, and for the calibration eight years of flow data were used in the monthly scale, using data from the Capitão Enéas (44630000) streamflow gauge station, considering the monthly flow data From January 2000 to December 2008.

RESULTS

The Figure 2 shows the average monthly flows observed and estimated by the WEAP model for the AVG sub-basin for the years 2000 to 2008, and the adjustment by the Nash and Sutcliffe Coefficient for this situation was 0.81, classified as good.

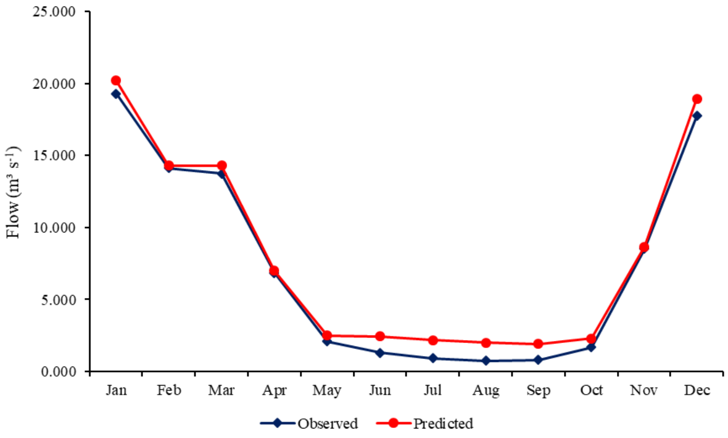

Figure 2. Observed and estimated monthly average flows for the AVG sub-basin.

Table 2 presents the results of the Sensitivity Index (IS) of the WEAP model for the Alto Verde Grande (AVG) basin.

Table 2. Sensitivity analysis of the WEAP model for the AVGsub-basin.

Parameters	E1	E2	R1	R2	IS	Ranking
SWC	700.0	1300.0	11.332	7.809	-0.614	2
DWC	70.0	130.0	8.966	8.986	0.004	5
DC	14.0	26.0	8.059	8.059	0.000	-
RZC	14.0	26.0	8.140	9.791	0.307	3
RRF	4.47	7.30	13.612	6.658	-1.427	1
PFD	0.39	0.66	8.940	9.035	0.021	4

The results show that the flow estimated by the WEAP model is influenced especially by the RRF, followed by the SWC, RZC, PFD and DWC, and observed that the DC or the conductivity in the lower layer did not show sensitivity to the model.

As described by Silva et al. (2009), the IS is the normalized difference obtained from the model output data for a normalized difference in relation to the model input data. The same author comments that the IS signal represents a relation between the input value and the model result, with negative values indicating that the input value and the result are inversely proportional.

Therefore, since the IS value for the RRF was -1.427, it means that the lower the IS value, the higher the simulated flow rates will be. From this result, it is possible to state that in the calibration process of the WEAP model special attention must be given to this parameter.

According to Seibt (2013), if the sensitivity analysis shows that a small variation in the input data promotes large variation in the output data, greater efforts should be directed at the reliable determination of this parameter. As the flow resistance factor is directly related to the use and occupation of the soil, greater detailing of the surfaces must be performed to supply the model, making the simulation of the model consistent with reality.

The second parameter that presented the highest sensitivity to the model was the SWC, also presenting an inverse relation, that is, as the SWC value increases, the lower the output value of the model.

The third factor to have a higher sensitivity to WEAP model was RZC, or hydraulic conductivity in the root zone, however, unlike the SWC and RRF, this parameter showed a directly proportional relation to the output values of the model.

The PFD was the fourth parameter in the sensitivity ranking, however, its value was very low when compared to the RRF, SWC and RZC, which makes it little influential in the model response. This can also be observed in the DWC parameter or water storage capacity in the lower layer.

The DC parameter was not sensitive in relation to the data simulated by the model. Figure 3 presents the results of the sensitivity analysis of the water balance parameters of the WEAP model.

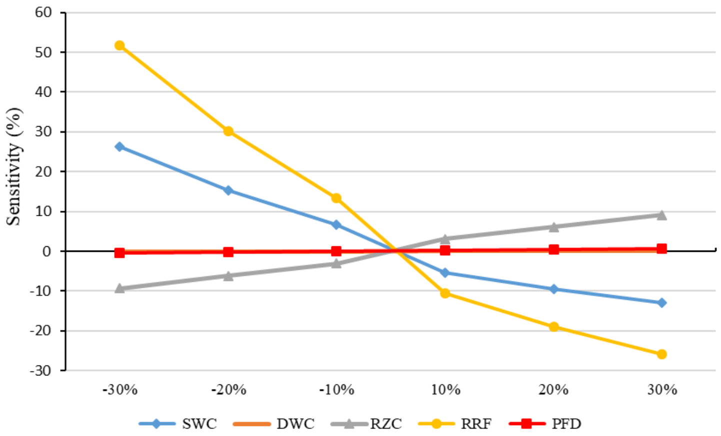

Figure 3. Sensitivity of WEAP balance parameters.

In the above figure, we can see the sensitivity dimension of the parameter RRF in relation to the average flow. For the minimum variation, equivalent to -30% of the RRF standard value, a simulated flow increase of 51% is observed, considering the simulated flow rate based on the standard condition. Whereas, for the maximum variation, 30% of the RRF value, provided a reduction in average flow around 25%.

Another observation that can be made in relation to figure 5 is the fact that values smaller than the standard condition, considering the parameter RRF, promote larger changes in the output of the model than when compared to the standard condition. This behavior can be observed in Figure 6, where we have the Nash-Sutcliffe Efficiency perturbation as a function of the variations in the parameter values.

The SWC parameter presented the same RRF behavior, however with a smaller variation. Corroborating with Table 2, the variation of the behavior of the RZC parameter, in Figure 4, shows that increases in the value of this parameter proportionally increase the results of the model.

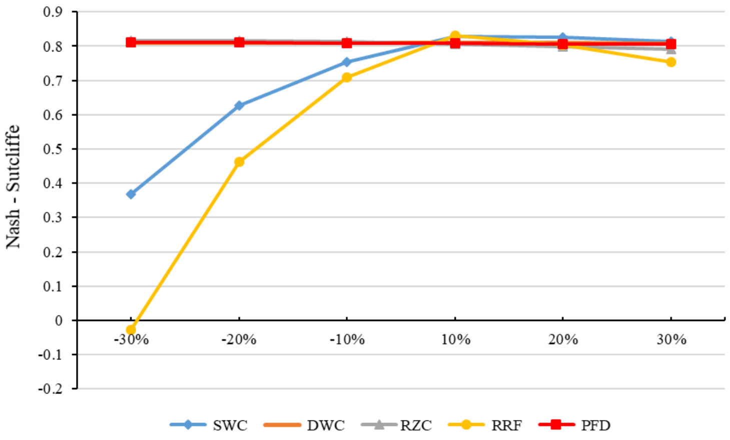

Figure 4. Deformation in Nash-Sutcliffe Efficiency as a function of parameter variation.

The deformation caused by the Nash-Sutcliffe Efficiency is observed mainly for the smallest variations, and a Nash-Sutcliffe coefficient of -0.027 was observed for the simulation with -30% of the RRF value.

It is important to note that the variations in the parameter RZC didn’t promote relevant changes in the Nash-Sutcliffe coefficient, even though this parameter was the third most sensitive among the evaluated parameters.

CONCLUSION

It is concluded that the most sensitive parameter in the water balance equation of the WEAP model for the Alto Verde Grande (AVG) sub-basin was a *Runoff Resistance Factor* (RRF), followed by *Soil Water Capacity* (SWC) and by *Root Zone Conductivity* (RZC).

The Root Zone Conductivity (RZC) and Preferred Flow Direction (PFD) parameters showed such low Sensitivity Index values that they were virtually unresponsive to model outputs.

The Deep Capacity was not sensitive to the water balance equation of the WEAP model for the AVG sub-basin.

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