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Integrated management of groundwater and surface water under climate change scenarios

Gestão integrada de águas subterrâneas e superficiais em cenários de mudanças climáticas

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ABSTRACT

This study aimed to simulate the joint use of surface water and groundwater in the urban-rural basins of the municipality of São Carlos and evaluated the impact of climate change scenarios in the system. A calibrated WEAP model is employed with 5 km resolution climate model data from the CPTEC - PROJETA project with the future scenario of RCP85 and RCP45 from 2007 to 2050. This system is utilized to create various future scenarios of groundwater and surface-water abstraction of public water supply, industrial and private demands, with combination of conjunctive use 50-50% of both type of resources and 100% from one them. Results were assessed by analyzing the flow duration curves and the level of the aquifer for the 2007-2050 period. The simulated climatic scenarios indicate that the pressure over groundwater in the area could represent a challenge due to the progressive depletion of the resources affecting the system sustainability, the flow of the main rivers with the 95% percentile presents a reduction of 20% in some cases. This modelling approach can be used in other river basins to manage scenarios of supply and demand.

Keywords: Water allocation; WEAP; Water balance; Demands scenarios.

RESUMO

O objetivo deste trabalho foi simular o uso conjunto de águas superficiais e subterrâneas nas bacias hidrográficas que abastecem o sistema urbano-rural do município de São Carlos no Brasil e avaliar o impacto de cenários de mudanças climáticas. O modelo WEAP foi simulado e calibrado para simular o uso integrado dos dois tipos de recursos nas bacias. Os resultados do modelo foram usados para avaliar seis cenários futuros e estimar o impacto na disponibilidade de água para atender às demandas de água do sistema. Foram utilizados dados do modelo climático regional da Eta e o resultado foi avaliado por meio da análise das curvas de duração do fluxo e do nível do aquífero para o período 2007-2050. Os cenários climáticos simulados indicam que a pressão sobre as águas subterrâneas na área pode representar um desafio devido ao esgotamento progressivo dos recursos, afetando a sustentabilidade do sistema.

Palavras chave: Alocação de água; WEAP; Balanço hídrico; Cenários de demanda.

INTRODUCTION

The pressure on water resources makes their integrated management a topic of great relevance (Birhanu et al., 2018). Surface and groundwater resources have been managed separately, even when it is known that these systems interact in a variety of geological, topographical, hydrological and climatic configurations (Ehtiat et al., 2018). However, with the increasing demand for water resources and the impacts of climate change, the topic of groundwater-surface water interaction became of interest and has become a challenge for managers (Fathy et al., 2021; Fuchs et al., 2018). Several studies were performed to evaluate conjunctive use of surface and groundwater (SW -GW) and improve water management in basins with irrigated areas (Dehghanipour et al., 2019).

In general, hydrological models have been applied to surface water management without considering groundwater in detail, while groundwater models generally do not consider properly surface water in modelling (Singh, 2014). Nevertheless, attempts to integrate both systems into the modelling are found in the literature, so some models integrate hydrological models with groundwater models, e.g., the SWAT-MODFLOW model (Sophocleous et al., 1999) and the GSFLOW model (Markstrom et al., 2005). Besides these systems, some models integrate hydraulic and groundwater models, such as MODBRANCH (Swain & Wexler, 1996), and DAFLOW (Jobson & Harbaugh, 1999). Soleimani et al. (2021) summarize the models that simulate groundwater and surface water interaction.

In addition to the mentioned models, Decision Support Systems (DSS) are now available for simulations and strategies selection, including groundwater processes (Aliyari et al., 2018). One of them is WEAP-DSS developed by the Stockholm Environment Institute (Yates et al., 2005), a tool that, besides modelling the surface water resource, integrates the interactions of surface and groundwater, analyzing the demands of both resources.

Despite the water availability in Brazil being considered abundant, there are current problems for water users due to disorderly concentrations of demands, low efficiency in water supply and enormous degradation of the quality of water bodies (Schneider et al., 2021). Furthermore, climate projections estimate a reduction in annual rainfall between 40 and 45% in the state of São Paulo (Lyra et al., 2018). This study aims to simulate the behavior of the water resources of the basins that supply the urban-rural municipality of São Carlos, Brazil, in the face of optimistic and pessimistic climate scenarios. The study area is located in the Aquifer Guarani, the largest groundwater reservoir in Brazil. There is a concern about the over-exploitation of the aquifer since in cities like São Carlos, the water from the aquifer is a source for public supply and is combined with surface water. WEAP tool was used to simulate the hydrology, including the river-aquifer interactions, and to estimate the impacts on six future scenarios with variations in the water demands and climate projections for IPCC scenarios RCP4.5 and RCP8.5.

CASE STUDY

The city of São Carlos is located in the central region of the State of São Paulo in southeastern Brazil. The zone used for this study has an area of approximately 515 km^2 (Figure 1), covering the Monjolinho and Feijão rivers basins, which serve as sources for the city's water supply system. Irrigated cultures are a significative portion of the total area, the sub-basins include crops such as sugar cane (29% of the area), citrus (6% of the area) eucalyptus (6% of the area) and other cultures (2%). The area has a warm and humid climate, with a dry winter and a rainy season from October to March and a dry season from April to September, with an average precipitation of 1,300 mm/year. The region is in a recharge zone of the Guarani aquifer, the largest source of groundwater in the world, which is widely exploited. According to the water resources report for the baseline year 2020, the per capita availability of water in the municipality is in a state of attention, and the demand for groundwater in relation to the exploitable reserve is critical (the GW use represents over 80% of the exploitable reserve). In addition, Perroni &Wendland (2008) evaluated the state of the supply system of the city of São Carlos, finding static water level declines of up to 32 m in the supply wells.

MATERIAL AND METHODS

WEAP model application, calibration, and validation

WEAP model integrates a series of physical hydrological processes with the management of the demand and infrastructure installed continuously and coherently. The soil moisture method was considered for the root zone, where two layers of soil (Z_1 and Z_2) in a one-dimensional form represent the basin (Figure 2); with aquifer connection, the flow between the river and the aquifer must be computed, where the aquifer is considered a stylized wedge that is assumed to be symmetrical to the course of the river. For details see Yates et al. (2005).

The rainfall (P) database was made up of historical monthly rainfall series available by National Water Agency (ANA) (Figure 1). The climate data for evapotranspiration calculation, based on

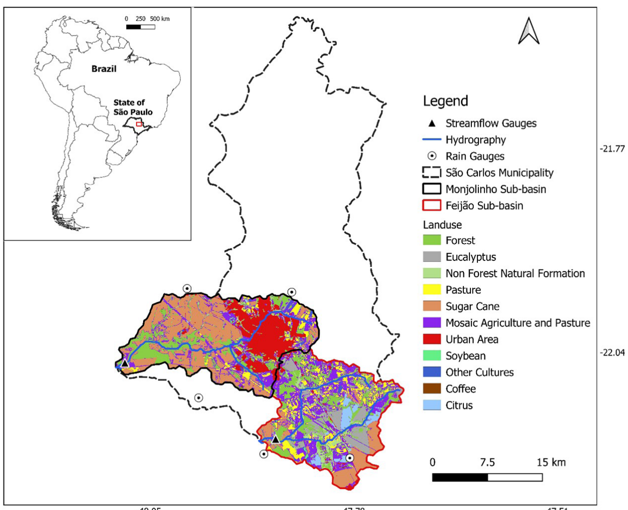

Figure 1. Location of study basins, landuse and gauge stations.

the Penman-Montieth method (*PET*) was obtained from two meteorological stations. For the flow calibration and validation stages, 10-year historical series (1997-2007) were obtained from two ANA stream gauges (Figure 1). From the total of the historical series, seven years were used for calibration (1997-2004) and three years for validation (2005-2007). For the groundwater calibration process, static water level data from different wells located in the study area were used. Also, all the water demands, based on water users data from the Department of Water and Electric Energy - DAEE (96 000 m^3/day) were introduced in the model, highlighting the demand for public supply, which represents 77% of the total. The calibrated parameters were S_w (water storage capacity in the root zone), D_w (water storage capacity in the deep zone), *RRF* (flow resistance factor), k and k_2 (Conductivities of root and deep zone), f (partition coefficient), and the aquifer geometry characteristics. The calibration was performed for the average monthly streamflow and was performed by trial and error by changing one parameter at a time and then analyzing the results. The Nash-Sutcliffe coefficient and bias percentage (Moriasi et al., 2007) were used to evaluate the fit between simulated and observed flow rates. WEAP was validated by carrying out the Split Sample Test (Klemes, 1986) by the application of the previously calibrated model for a given period to another unknown period.

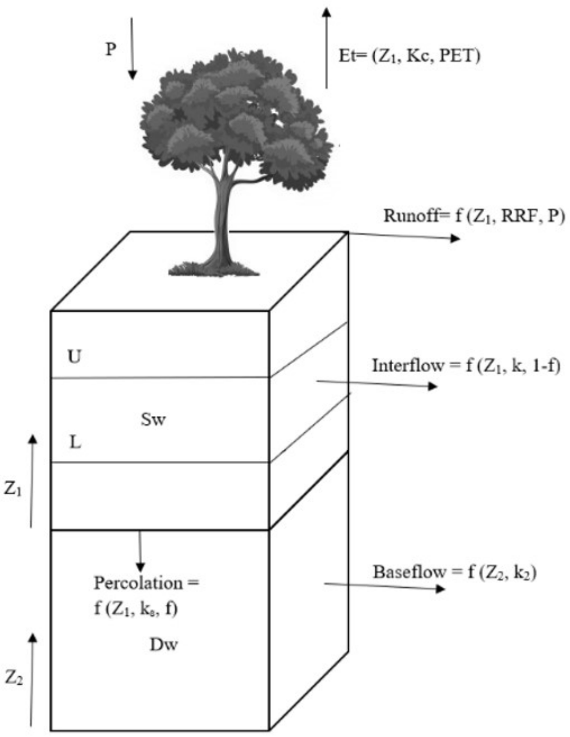

Figure 2. Schematic of the two-layer soil moisture method.

Climate projections and demand increase

To evaluate the possible future impacts caused by changes in water demand and climate, six scenarios were generated from the combination of three alternatives of changes in the demands of both resources and two scenarios of greenhouse concentration or Representative Concentration Pathway-RCP4.5 and RCP8.5 (Pachauri et al., 2014). For the construction of the water demand scenarios, data from Costa et al. (2013) were used. The demands for public water supply system, industrial and private residential supply (77%, 8% and 12% of the total water use in the area respectively) were increased in all scenarios, described below and resume in Table 1.

D1 scenario: The demand for urban water supply will grow in line with population growth and current per capita consumption, with 50% coming from surface sources and 50% from underground sources from 2007 to 2050. Industrial and sanitary demand will grow by 10% and 20% respectively, continuing with current sources (SW or GW).

D2 scenario: The demand for water for public supply will grow in line with population growth and current per capita consumption. Industrial and sanitary demand will grow by 10% and 20% respectively. In all cases, preference will be given to underground sources from the 2007 to 2050.

D3 scenario: The demand for water for public supply will grow in line with population growth and current per capita consumption. Industrial and sanitary demand will grow by 10% and 20% respectively. In all cases, preference will be given to surface sources from 2007 to 2050.

Climate projections from the Centre for Weather Forecasting and Climate Studies - CPTEC (Chou et al., 2014) were considered. The climatic scenarios were generated from the regional climatic model Eta with a resolution of 5 km. The downscaling by CPTEC was produced from HadGEM2-ES model (Collins et al., 2011). Values from the gridded data (2008-2050, temperature, humidity, and precipitation) were obtained for the location of the rain gauge stations used for the historical period (Figure 1).

For the evaluation of the scenarios, the flow duration curves, and the results simulated by WEAP of demand and reliability coverage were generated, the latter representing the percentage of times when demand is fully satisfied.

Table 1. Evaluated Scenarios of demand and climate projection.

Scenarios of demand	**Climate Projection**	
	RCP4.5	**RCP8.5**
D1	RCP4.5_D1	RCP8.5_D1
The increase in public demand will be supplied by 50%-50% proportions of both sources		
D2	RCP4.5_D2	RCP8.5_D2
Increase in all demand will be supplied by groundwater.		
D3	RCP4.5_D3	RCP8.5_D3
The increase in all demand will be supplied by surface water.		

RESULTS AND DISCUSSIONS

To analyse the water demand and supply on the catchment level, it was necessary to disaggregate the available information to achieve a manageable amount of data. Figure 3 shows the system that was represented in WEAP interface. The three principal rivers, Monjolinho, Feijão and Laranja (Feijão tributary) were represented as subbasins, and each one were subdivided in, upper sub-basins without connection with the aquifer and lower sub-basins with connection, totalizing six subbasins (green nodes in Figure 3). An important abstraction of surface water in the Feijão river is released in Monjolinho River after its use and treatment in a wastewater plant and due to the number of water users (more than 200), the information for the demands (Red nodes in Figure 3) was grouped, considering the use of the water (irrigation, public urban supply, industrial, private residential attend, etc.) and the resource used (surface or groundwater).

The fits of the simulated hydrographs to the observed ones are shown in Figures 4 and 5. Overall, the streamflow simulated by the WEAP model fits the observed ones well, albeit with some difficulties in simulating some streamflow peaks both in the calibration and validation. The statistical indices used to evaluate the performance of the calibration are shown in Table 2. Failures in the rating curve of the Monjolinho River station led to a change in the validation period for the 2004-2007 period. The performance of the model was evaluated with and without the identified outliers.

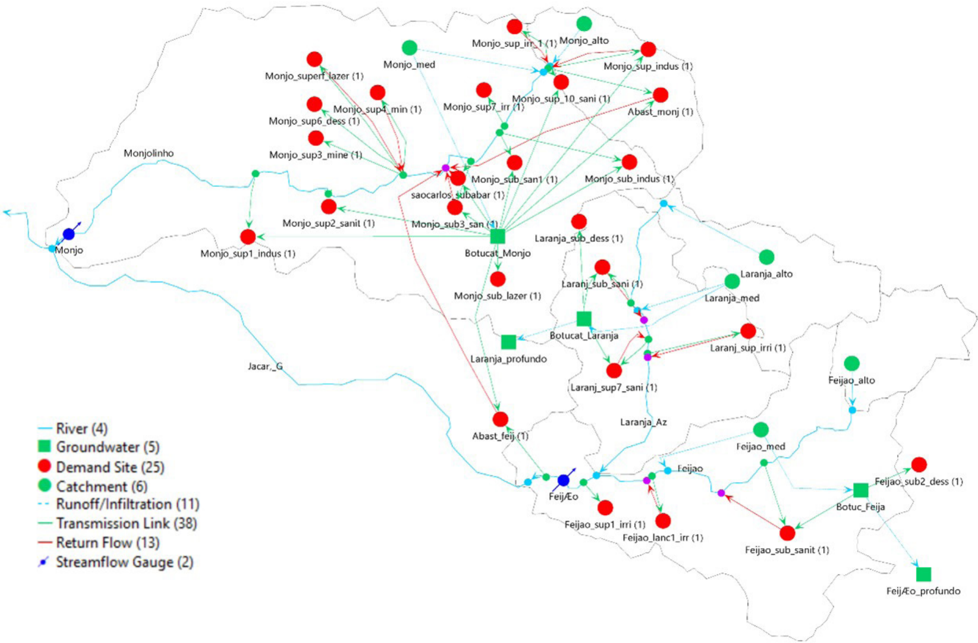

Figure 3. Conceptual model of the System in WEAP.

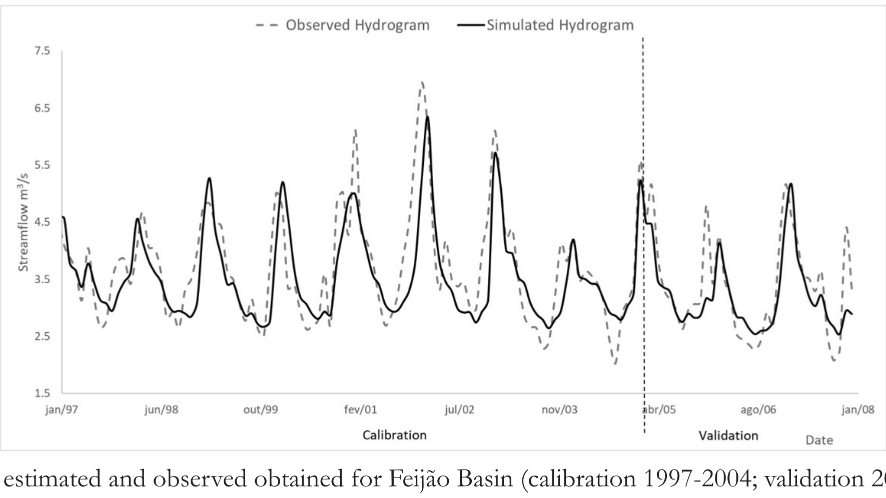

Figure 4. Hydrograph estimated and observed obtained for Feijão Basin (calibration 1997-2004; validation 2005-2007).

Table 2. Statistic index of simulation performance

Indicators	Monjolinho Basin			Feijão Basin	
	Calibration	Validation		Calibration	Validation
		without outliers	with outliers		
Nash-Sutcliffe (-)	0.76	0.81	0.57	0.67	0.7
BIAS (%)	7.97	2.35	12.16	-4.13	-3.33

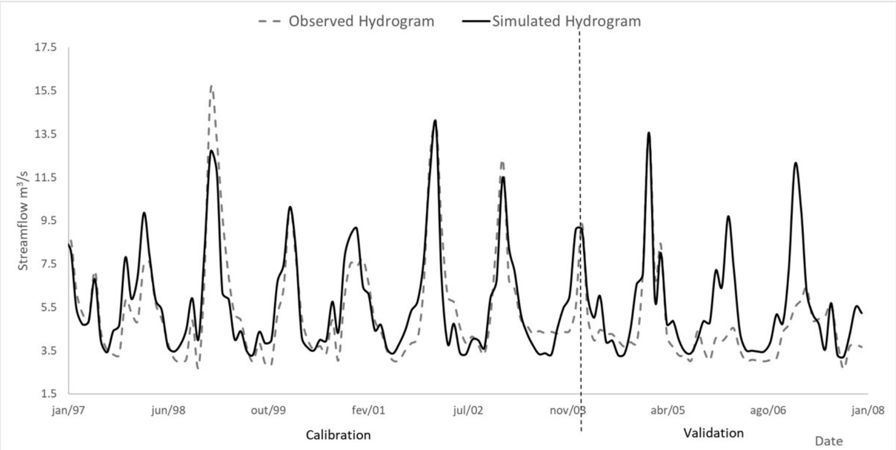

Figure 5. Hydrograph (estimated and observed) obtained for Monjolinho Basin (calibration 1997-2003; validation 2004-2007).

The model showed a satisfactory performance. Bias percentage values between ± 10% are reported by Moriasi et al. (2007) as a very good fit. The Nash-Sutcliffe values, also according to the same author, showed a very good performance for the Monjolinho River (0.75 <Nash <1.00 for the evaluation without outliers) and good for the Feijão (0.65 <Nash≤ 0.75). The Nash-Sutcliffe index is significantly influenced by peak and drought flows (McCuen et al., 2006), resulting in better performance in the validation dataset that in the calibration dataset, where the flow was closed to an average value.

The simulation of the groundwater was evaluated by comparing the results obtained with the water level data from different wells in the study area. It is expected that if the model can adequately represent the use of surface and groundwater, it should be able to track the trends in groundwater well observations. A set of three wells named Tramer, Industrial District, and Fehr Park was selected to estimate the fluctuations because of their location in the outcrop Guarani aquifer and the higher number of level records. The simulation of groundwater elevation in WEAP is stylized, so a one-to-one comparison of observed versus simulated values was considered inadequate. Instead, the standard normal variation of the observed and simulated water levels was calculated as $z = (x-\mu) / \sigma$, where x is the observed or simulated water surface elevation, μ is the mean and σ is the standard deviation of the static water level data from each well. Figure 6 shows the comparison for the aquifer belonging to the Monjolinho basin. The results show coherence even with the poor hydrogeological monitoring, usual in tropical countries.

The data generated by the WEAP model follow the measured data and the progressive decrease in static levels (Figure 6) already identified by Perroni & Wendland (2008) for the case of

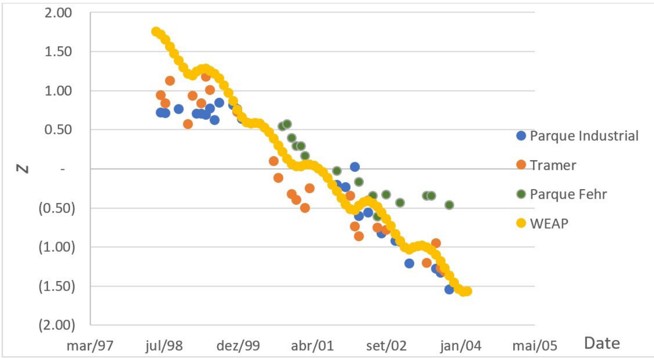

Figure 6. Standardized variation in groundwater level rise observed from three wells and simulated by WEAP in the Monjolinho basin.

the Monjolinho River. The monthly variation is still in the order of magnitude of less than one meter found in other areas of the Guarani aquifer, near São Carlos (Arantes et al., 2006). Additionally, the accuracy of the model was verified by analysing the results of the annual simulated water balance components for the basins. The calculated values for evapotranspiration and recharge are close to those estimated in other studies in the same area, such as annual evapotranspiration of 914 mm (Barreto et al., 2010) and annual recharge reported by other authors in the area (from 215 mm to 465) (Rabelo & Wendland 2010).

Regarding the Feijão basin, it was not possible to obtain static water level measurements for wells in the sub-basin area in the experimental period. However, it was admitted as suitable the estimated values for WEAP; the demand for groundwater in the basin corresponds to less than 0.05% of the recharge. In addition, it has already been established that exploitation in the Guarani aquifer system has not yet significantly affected upwelling areas with the same recharge and demand characteristics (Barreto et al., 2010). All the calibrated parameters are shown in Table 3.

The calibration and validation processes show uncertainties and constraints concerning the model and input data. These uncertainties have already been pointed out by Yates et al. (2005) and Dehghanipour et al. (2019). The WEAP integrated groundwater model considers only alluvial aquifers and the assumption that each sub-catchment has its own groundwater aquifer neglects the connectivity of the groundwater aquifers. However, the model does show realistic trends of the groundwater dynamic in the study area. A challenge of many studies in which WEAP was applied is the validation of the model at different spatial and temporal scales, although there are different studies with satisfactory results (Balambal & Mudgal, 2014; Majedi et al., 2021). It can be said that WEAP results offer a solid basis to assist planners and can be a useful tool linking supply and demand site requirements.

Evaluation scenarios of demand

The flow duration curves to fully meet demand (Figures 7 and 8) were used to evaluate each scenario. The impact of the conjunctive use (D1) has different results for each sub-basin analysed. The interconnection between basins and the priority use of groundwater (D2) or surface water (D3) have diverse consequences on the river's flow and water levels of the aquifer.

In this study, it was decided not to adopt bias correction (BC) for projected rainfall data and preserve the original Eta result. Ehret et al. (2012) comment that BC methods generally change the consistency of the spatio-temporal field and impair the relationships between the variables adopted by the global climatic models, violating conservation principles. The flow curve for 1997-2005 period from HadGEM2-ES (historical) shows that in case of Feijão basin the flow calculated by WEAP using the precipitation data from Eta is close to the observed data, and for Monjolinho there is an overestimation of the values. As Eta model data were used as option for climatic scenarios based on literature availability, it was considered suitable data to be used for this purpose.

In the case of Feijão basin, all the scenarios showed a decrease in the flow values. Table 4 shows the differences in the percentage of supply flow with 95% percentile (Q_{95}) between demand scenarios and historical series (1997-2018). The variation was negative in all cases for Feijão basin. Scenarios RCP4.5_D1 and RCP4.5_D2 were the least affected since the pressure on the water resource, which is mostly represented by the demand for public water supply, was transferred to groundwater. As the figure shows, the variation of the historical data compared to the same period of the Eta data was not significant.

Table 3. Model calibrated parameters.

Parameter	Units	Range	Categories	Monjolinho	Feijão
Deep zone storage Capacity	mm	15000-35000		20000	20000
Deep zone Conductivity (k_2)	mm/month	150-600		500	500
Z_2 Initial	%	30-70		20	28
Soil Storage Capacity (Sw)	mm	500-7000	Other cultures	900	900
			Pasture	1500	1500
			Eucalyptus	5000	5000
			Citrus	1500	1500
			Sugar Cane	1500	1500
			Forest	8000	8000
			Urban	1500	1500
Root zone conductivity (k)	mm/ month	100-500	Oxisols	150	250
			Entisols	200	400
	mm/ month		Ultisols	-	300
			Urban	100	250
Preferred flow direction (f)	-	0-1	Oxisols	0.2	0.2
			Entisols	0.2	0.2
			Ultisols	0.3	0.2
			Urban	0.3	0.2
Z_1 Inicial	%	30-70		30	35
Runoff resistance factor (RRF)	-	1-10	Other cultures	5	6
			Pasture	3	6
			Eucalyptus	6	7
			Citrus	4	5
			Sugar Cane	4	6
			Forest	6	8
			Urban	0.5	0.5
Conductivity	m/day			19	20
Specific yield	-	0.1-0.25		0.15	0.18

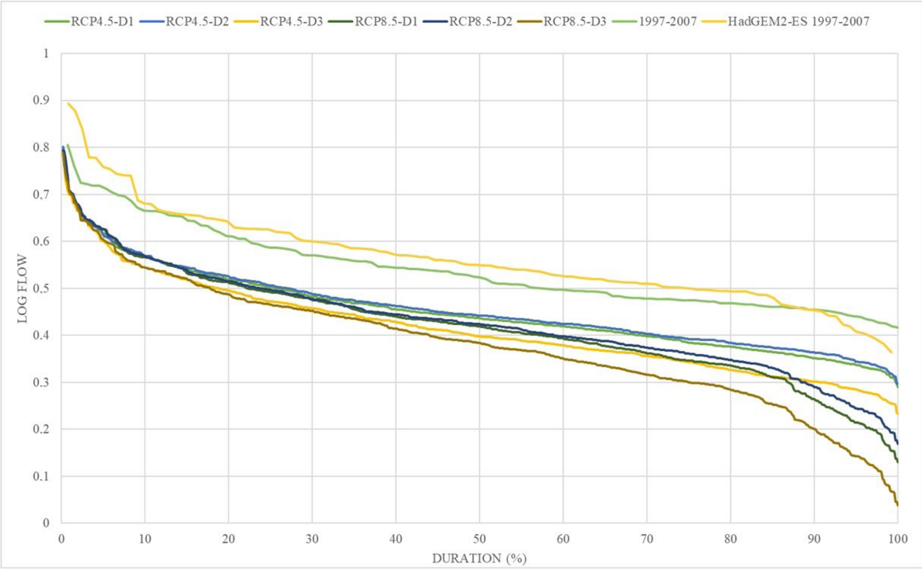

Figure 7. Flow duration curves for Feijão basin Scenarios.

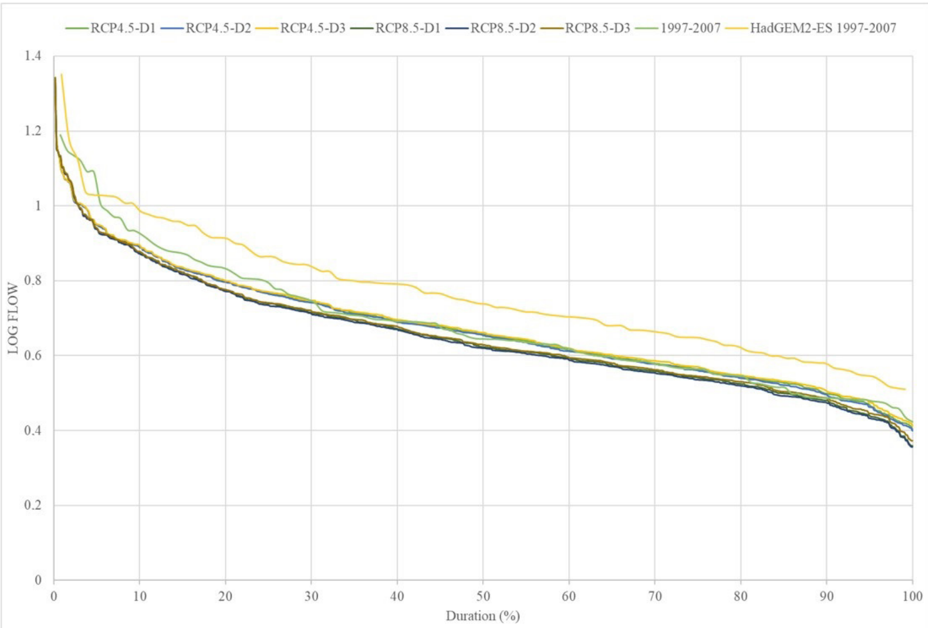

Figure 8. Flow duration curves for Monjolinho basin scenarios.

Table 4. Comparison of the flow of the main rivers with the 95% percentile (Q95) between demand scenarios and historical series (1997-2018).

Scenario	Feijão		Monjolinho	
	Q_{95} (m^3/s)	Difference to Q_{95} 1997-2018 series (%)	Q_{95} (m^3/s)	Difference to Q_{95} 1997-2018 series (%)
1997-2007	1.47	-	2.86	-
Eta 1997-2007	1.44	-2.04	3.03	5.59
RCP4.5_D1	1.4	-4.7	2.93	2.3
RCP4.5_D2	1.41	-4	2.9	1.33
RCP4.5_D3	1.33	-9.5	2.98	4.24
RCP8.5_D1	1.24	-15.7	2.74	-4.32
RCP8.5_D2	1.27	-13.1	2.71	-5.38
RCP8.5_D3	1.15	-21.5	2.78	-2.7

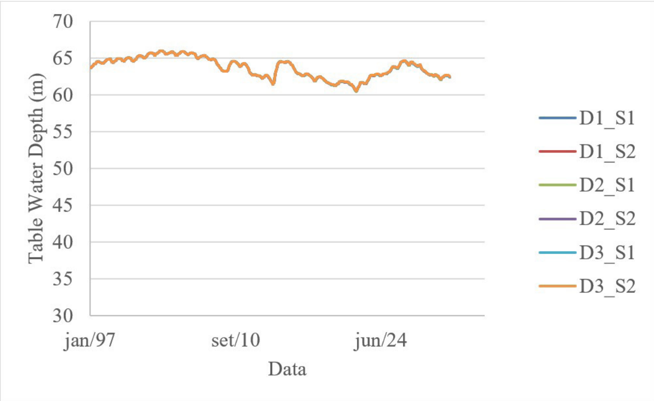

Figure 9. Variation of the static level for each scenario in the Ribeirão do Feijão basin.

For Monjolinho, the Figure 8 and Table 4 show an overestimation of the rainfall by the Eta model (curve above of historic period with observed data). The biases of the Eta model on streamflow (dQ_{95} ~ 5.6%) are higher than the projected changes given by the RCP4.5 scenario ($dQ_{95} < 4.3\%$). Therefore, although RCP4.5 curves are above the curve of the 1997-2018 series, the projections do not indicate an increase of streamflow for this scenario. On the other hand, for RCP8.5 scenarios the signals are clearer. Lower precipitation and the overexploitation of the resources generate a decrease in the minimum flows compare to observed historic. Table 4 shows that the low precipitation (RCP8.5) resulted in a decrease in surface water. The dynamic of the connection between the resources reveals that groundwater has an important influence in the area, where over-exploitation will impact all the systems.

The evaluation of the scenarios also involved some changes in the levels of the aquifer, which for the case of the Feijão basin did not have representative variations between scenarios and along the analyzed period (Figure 9). The use of groundwater in the Feijão basin in the historic scenario (therefore in the future scenarios) is significantly lower than in Monjolinho basin, then, the affection on water level is expected to be low as calculated for WEAP. The water level in Feijão basin shows periods of decrease and increase as it naturally happens, corresponding with the results of areas of the Guarani aquifer in the region where the resource demand is not representative and where the geological formation (Botucatu Formation) has a considerably storage capacity (Barreto et al., 2010).

For the Monjolinho basin, although the scenarios showed a small difference in the Q_{95} flows (Table 4), there is a great difference in the affectation of the static water levels. Table 5 presents the time variations of the levels, showing that for all scenarios, the differences between levels in 1997 and the horizon 2050 are higher than 50 meters, which follows the results of Perroni & Wendland (2008). It is expected that this situation continues due to the decision of the municipality to increase the number of wells for public supply.

Finally, the reliability (percentage of times demand is fully satisfied) for all scenarios had a value of 100%. In each case, the demands are satisfied throughout the period, showing that the basins have a water production that could sustain the progressive increase in the demands. The panorama in the basin is already considered by the authorities as worrying, the results show that the pressure on São Carlos's water resources will increase, leading to greater competition for groundwater. The progressive reduction of the water levels of the aquifer can increase the risk of shallow wells running dry and decreasing inflows and groundwater recharge due to climate change can aggravate this situation. Besides, the reduction in the minimum flows can make the system unsustainable. Kundzewicz & Döll (2009) and Dehghanipour et al. (2019) identified this tendency in Brazil and other basins.

Table 5. Variation of the static level (measured from the bottom of the aquifer) at the beginning (Jan/1997) and end (Dec/2050) of the simulation for each scenario in the Monjolinho basin.

Scenarios	Static level		Difference (m)
	jan/1997 (m)	dec/2050 (m)	
RCP4.5-D1	138.68	70.38	68.3
RCP4.5-D2	138.68	67.54	71.14
RCP4.5-D3	138.68	79.72	58.96
RCP8.5-D1	138.68	63.52	75.16
RCP8.5-D2	138.68	60.67	78.01
RCP8.5-D3	138.68	72.85	65.83

CONCLUSIONS

The results for the climate change scenarios show that it is challenging for the city of São Carlos to maintain the sustainability of its water resources. Thus, reuse and efficient use of the water programs should be a priority for the authorities to control the depletion on the water table, which has already been identified due to the exploitation of the aquifer. Proper management on the demands, recharge areas and water quality should be considered for granting the availability of the hydric sources.

The Feijão basin showed the greatest flow reductions for all scenarios to supply demand. The supply of surface water demand (D3) showed a greater reduction in flows for both scenarios of global climate change. The largest impact was for the RCP8.5 scenario, which decreased 21.5% in Q95. In the Monjolinho basin, only the RCP8.5 scenario presented a reduction in flow, where the most critical situation was the supply of demand for groundwater (D2) with a reduction of 5.38% in Q95 and a decrease in the static level of 78 m.

WEAP model has potential to be used in integrated hydrological studies in areas with scarcity data and it is a tool to consider the interaction of all elements to achieve effective results for decision-making in basin management.

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Lina Maria Osorio Olivos: Data collection, model simulation and calibration, analysis of the results, paper writing.

Arisvaldo Vieira Méllo Jr: Conceptualization, analysis of the results, paper review.

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