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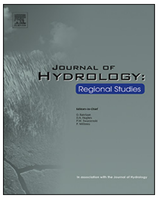

Water resources sustainability index for a water-stressed basin in Brazil

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ABSTRACT

Study region: Rio Verde Grande Basin, Brazil.
Study Focus: Extensive regional development, mainly expansion of irrigated areas and urban population, has resulted in low water availability and caused water conflicts since the 1980s. Therefore, it was necessary to enact the Water Resources Plan of the Rio Verde Grande in 2011. The plan provided actions to improve water availability and meet increased water demand but there have been no studies on the sustainability of these policies. It was evaluated the future of the water management and calculate the sustainability index for water resources in the Rio Verde Grande Basin (RVGB), Brazil.
New hydrological insights for the region: The water demand and available water have been compared and evaluated for activities in the Water Resources Plan (WRP) based on three different improvement of available water scenarios. These scenarios include water imports and the construction of channels and reservoirs. A sustainability index was used to evaluate and compare alternative plans for future water availability and water supply in these scenarios, considering measures of reliability, resilience, vulnerability and maximum deficit. The SI has identified the best scenario foreseen in the WRP for the RVGB that will improve the availability of water through 2030 having positive impact to water users of the basin. The results also indicate that the increase in available water will not result in significant improvements of sustainability of water resources by the implementation of the policies proposed in the WRP for the RVGB.

1. Introduction

The Rio Verde Grande Basin (RVGB) provides significant agricultural production for important cities, such as Montes Claros (400,000 inhabitants), primary through irrigation. Extensive regional development and urban expansion have caused low water availability in regional rivers, causing water conflicts that have been recorded since the 1980s. RVGB presents several problems of water resources as a high variability in time and space of water resources (Many years of the drought), activities that demand a lot of water (as irrigation with 90% of water consuption) and there is almost no infrastructure for water resources. To solve these problems, in 2011, the "Water Resources Plan for the Verde Grande River Basin (WRP)" was approved, which aimed to articulate the instruments of the National Water Resources Policy and propose a series of actions to improve available water in the basin (ANA, 2016a,b). In the Water Resources Plan of the Rio Verde Grande, three scenarios were envisaged for implementing action. Interventions that were already underway, to increase water supply were considered in the Trend Scenario. Based on the Trend Scenario, two other

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scenarios were developed, Normative 1 and 2, in which water management leads to successive efficiencies that both increase available water and efficiency of use. However, there have been no studies in the RVGB that evaluate and compare the sustainability of different actions or methods for water management in these scenarios proposed on WRP.

Recently, other countries have placed great emphasis on the adaptability of water resources using measures that reduce the vulnerability of these systems in proposed future scenarios (Cerón et al., 2011; Sandoval-Solis et al., 2011; Cerón et al., 2012; Cortés et al., 2012; Koop and van Leeuwen, 2015; Loucks and Van Beek, 2005). The vulnerability is the magnitude of an adverse impact on a system. The objective is to seek ways to reduce the negative impacts of actual and expected events, and meet the water requirements for various human activities and the environment, considering various future scenarios. To achieve this target, performance measures or indices are required that can be used to evaluate and compare water resources, subject to varying actions and policies under different scenarios (Sandoval-Solis et al., 2011). The sustainability index (SI) identifies policies that preserve or improve the desired water management characteristics of the basin in the future. Thus, SI of water resources is an index that provides a mechanism for evaluating and comparing different methods of management and water uses with regard to sustainability. If proposed policy or action of the water plan make the system more sustainable, the SI will show that the system will have a larger adaptive capacity. Thus, given the increasing conflicts between water users in the RVGB, the can SI be applied to assess the various actions proposed in the WRP with regard to the various sectoral demands and future scenarios proposed in the WRP? Could SI to be used to evaluate and compare policies proposed in water plan of others basin in the region? SI used in this study was developed by Loucks (1997), adapted by Sandoval-Solis et al (2011) and recently extended by Srdjevic and Srdjevic (2017).

The objective of this work is to calculate the SI of water resources in the Rio Verde Grande Basin, Brazil, evaluating and comparing water demand and available water for activities foreseen in the WRP for three water availability future scenarios.

2. Methodology

2.1. Study area and model geography

The Rio Verde Grande is a major tributary to the east side of São Francisco River, and forms the boundary between the states of Bahia and Minas Gerais along part of its course. The Rio Verde Grande Basin has an area of 31,410 km^2 covering eight municipalities in Bahia (13% of the total area) and 27 municipalities in Minas Gerais (87% of the total area). The population was 768,000 inhabitants as of 2011, which corresponds to about 5% of the total population of the São Francisco River Basin (ANA, 2016a,b). The headwaters of the Rio Verde Grande are at an elevation of 1256 m in Minas Gerais, and travels 577 km to join the São Francisco River, at an elevation of 431 m. The segmentation of the Rio Verde Grande Basin (RVGB) into smaller subcatchments was proposed in the WRP for the basin; the intention was to obtain a spatial structure of the basin to analyze information, from diagnosis to future scenarios phase. The eight RVGB subcatchments are defined as follows:

Alto Verde Grande (AVG) – This region contains the highest elevations of the RVGB, and has a watershed area of 3098 Km^2. The AVG sub basin contains about 48% of the population and most of the industries in the RVGB.

Medio Verde Grande-Trecho Alto (MVG_TA) – This region is located downstream of the AVG and has a watershed area of 7102 km^2. It contains most of the cattle operations in the RVGB.

Médio Verde Grande – Trecho Baixo (MVG_TB) – This region contains the Verde Grande River from the end of the MVG_TA and goes to mouth of Verde Pequeno River. The area is 3161 km^2.

Alto Gorutuba – (AG) – The largest reservoir in the RVGB is in AG sub basin. The area is 2133 km^2.

Médio Baixo Gorutuba – (MBG) – This region is the largest subcatchment of the RVGB at 7715 km^2. It has the second largest population of the entire basin.

Alto Verde Pequeno – (AVP) – The area is 2899 km^2.

Baixo Verde Pequeno – (BVP) –The area is 3368 km^2

Baixo Verde Grande – (BVG) – This region is the smallest sub basin of the RVGB at 1934 km^2. It has the smallest population of the entire basin, but has the largest irrigated area; more than 21,000 ha is irrigated. That sub basin stretches from the confluence of Verde Pequeno and Verde Grande Rivers to the confluence with the São Francisco River.

In the upper RVGB, the prevailing climate is semi-humid and warm with mean annual rainfall around 1100 mm, occurring mostly between November and February (Summer); the mean annual rainfall in the lower basin is around 700 mm. The mean annual potential evapotranspiration is around 2000 mm considering whole basin (ANA, 2016a,b).

2.2. Model description

A model for the RVGB was built using the Water Evaluation and Planning System (WEAP), an Integrated Water Resource Management (IWRM) model developed by the Stockholm Environment Institute (Yates et al., 2005a). The soil moisture method in WEAP was used to model the hydrologic response of the basin. This method is based on empirical functions that describe the behavior of surface runoff, interflow, baseflow evapotranspiration, and deep percolation for a basin (Yates et al., 2005a, b). As in the WRP for the RVGB (ANA, 2016a,b), the Rio Verde Grande Basin was subdivided into eight sub catchments with the same water users and connected to a network of rivers (see Fig. 1). The water user withdraws this resource from various water sources (e.g. rivers, groundwater and reservoirs) and for its demands. The water users were divided into the four largest groups: irrigation, livestock, urban population, and rural population. The RVGB map (Fig. 1) includes the upper and lower catchment and schematic diagram that shows six control points (CP) and all catchments contributing to the Rio Verde Grande.

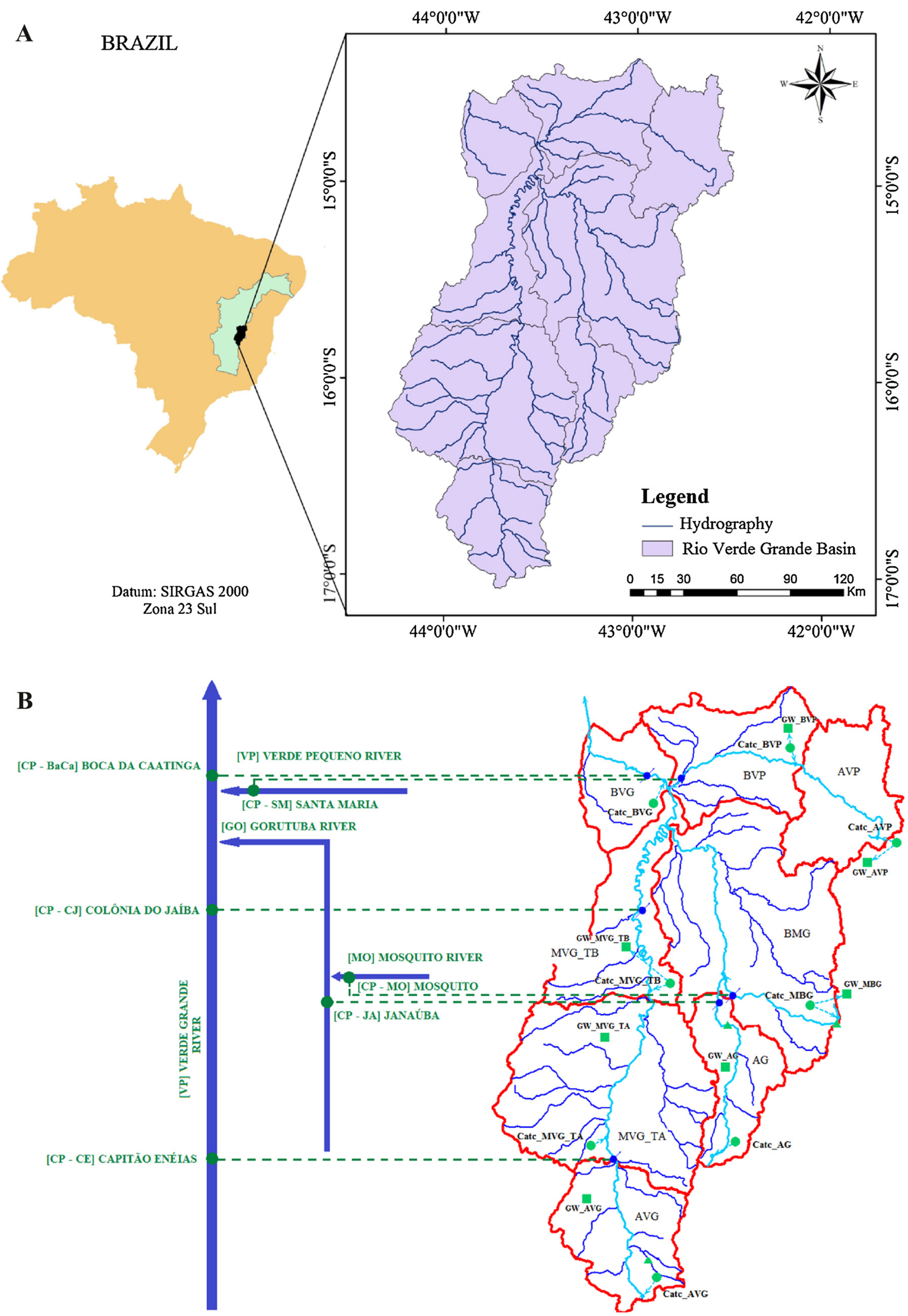

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Fig. 1. Location and schematic representation of the Rio Verde Grande Basin (A) for WEAP analysis showing sub-divisions catchments, rivers and Control-points (B).

2.3. Data source

Monthly data for precipitation, surface air temperature, relative humidity, and wind velocity were obtained from the Instituto Nacional de Meteorologia (INMET, 2015) for 2000–2014. The historic climate conditions were repeated from 2015 to 2030 because this period of record includes drought and wet years necessary to evaluate the different strategies proposed in the WRP. Monthly streamflow data were obtained from HIDROWEB (ANA, 2016a,b) at six control points: CE – Capitão Enéias, CJ – Colônia do Jaíba, and BoCa – Boca da Caatinga on the Verde Grande River; JA – Janaúba on the Gorutuba River; MO – Mosquito on the Mosquito River, and SM – Santa Maria on the Verde Pequeno River.

2.4. Scenarios

The purpose of this study is to evaluate three possible scenarios and a baseline scenario (Table 1):

- Baseline scenario: no action taken.
- Trend Scenario: Interventions that were already underway to increase water supply. The scenario proposes importing water from the Congonhas River to the AVG at 2 m^3/s starting in 2018.
- Normative 1 scenario: The water management increases water supply using the same intervention as in the Trend Scenario, plus two additional water diversions. The first is from the São Francisco River to the city of Jaiba, 1.5 m^3/s to the MVG_TB, starting in 2020. The second is from the São Francisco River to the city of Verdelandia, an additional 1.5 m^3/s to the MVG_TB, starting in 2025.
- Normative 2: The water management increases water supply using the Normative 1 plan, with an additional water diversion from the São Francisco River, 1.5 m^3/s to the AG and resulting in a total of 4.5 m^3/s diverted, starting in 2028, and construction of five dams, two in the AVG, one in the MBG, and two in the AVP.

These scenarios are developed for the period from 2015 to 2030.

2.5. Performance criteria and sustainability index

Four performance criteria were used to evaluate the model results and compare alternative management policies under the three scenarios for increasing available water in the RVGB WRP (ANA, 2016a,b): volumetric reliability; resilience; vulnerability, and maximum deficit. These performance criteria quantify the SI of the water resources system in the RVGB. All performance criteria are based on a water supplied deficit (D_t^i) (Eq. (1)), which is the difference between water demand ($X^i_{Target,t}$) and water supplied ($X^i_{Supplied,t}$) for each time period t for a determined ith water user, defined in this work as irrigated area, livestock, urban population and rural population:

$$D_t^i = \begin{cases} X^i_{Target,t} - X^i_{Supplied,t}\ , & \text{If} X^i_{Target,t} > X^i_{Supplied,t} \\ 0\ , & If\ X^i_{Target,t} = X^i_{Supplied,t} \end{cases} \tag{1}$$

Deficits D_t^i are positive when the water demand $X^i_{Target,t}$ is more than the water supplied $X^i_{Supplied,t}$, and $D_t^i = 0$ if the water supplied is equal to water demand ($X^i_{Supplied,t} = X^i_{Target,t}$) (Loucks, 1997).

Volumetric reliability (Rel^i) is the total volume of water supplied divided by the total water demand for the ith water user during the simulation period (Hashimoto et al., 1982; Sandoval-Solis et al., 2011; Lane et al., 2015) (Eq. (2)):

Table 1
Possible available water scenarios for the Rio Verde Grande Basin (ANA, 2016a,b).

Scenarios			ACTION	Additional Supply Rate (m^3/s)	Cumulative Additional Supply (m^3/s)	Nº	Start Year
Baseline			No action taken			0	2015
T	N1	N2	Import water from Congonhas River	2		1	2018
–	N1	N2	Water Diversion From São Francisco River	1.5		2	2020
–	N1	N2	Water Diversion From São Francisco River	1.5	3	3	2025
–	–	N2	Water Diversion From São Francisco River	1.5	4.5	4	2028
–	–	N2	Rio Verde Dam	0.15		5	2025
–	–	N2	Cocos Dam	0.05		6	2025
–	–	N2	Pedras Dam	0.04		7	2028
–	–	N2	Mamonas Dam	0.05		8	2028
–	–	N2	São Domingos Dam	0.42		9	2028

T = Trend Scenario; N1 = Normative 1; N2 = Normative 2.

$$Rel^i = \frac{\sum_{t=1}^{t=n} X^i_{Supplied,t}}{\sum_{t=1}^{t=n} X^i_{Target,t}} \tag{2}$$

Resilience (Res^i) is a measure of the system capacity to adapt to changing conditions, defined as the probability that the system will remain in a non-failure state (Moy et al., 1986; Sandoval-Solis et al., 2011; Lane et al., 2015; Safavi et al., 2015) (Eq. (3)):

$$Res^i = \frac{No.\ timesD^i_t = 0\,followsD^i_t > 0}{No.\ timesD^i_t > 0\,ocurred} \tag{3}$$

Vulnerability (Vul^i) represents the average severity of a deficit during the total number of months simulated or, in others words, the likely damage from a failure event (Kjeldsen and Rosbjerg, 2004; Sandoval-Solis et al., 2011; Asefa et al., 2014) (Eq. (4)):

$$Vul^i = \frac{\left(\frac{\sum_{t=1}^{t=n} D^i_t}{No\,.\,oftimesD^i_t > 0\,ocurred}\right)}{X^i_{Target}} \tag{4}$$

The maximum deficit ($Max\ Def^i$), if deficits occur, is the worst-case annual deficit ($MaxDef^i_{annual}$), for the ith water user (Moy et al., 1986). A dimensionless maximum deficit is calculated by dividing the maximum annual deficit by the annual water demand, $Waterdemand^i$ (Sandoval-Solis et al., 2011) (Eq. (5)):

$$Max\ Def^i = \frac{\max(D^i_{annual})}{Water\ demand^i} \tag{5}$$

The sustainability index (SI^i) is an index that measures the sustainability of water resources systems and can be used to estimate and compare the sustainability among water users or/and water policies proposed (Sandoval-Solis et al., 2011). Sandoval-Solis et al. (2011) proposed a variation of Loucks' SI where the index is defined as a geometric average of M performance criteria (C^i_m) for the ith water user (Eq. (6)):

$$SI^i = \left[\prod_{m=1}^{M} C^i_m\right]^{\frac{1}{M}} \tag{6}$$

For this work, the sustainability index proposed for water users in the RVGB is (Eq. (7)):

$$SI^i = [Rel^i * Res^i * (1-Vul^i)*(1-Max\ Def^i)]^{1/4} \tag{7}$$

The sustainability by group (SG) is a combination of SIs of a group k, with ith to jth water users belonging to this group, into one value using a weighted average of SI; this helps identify water management improvements in basin (Sandoval-Solis et al., 2011, 2013) (Eq. (8)):

$$SG_{GroupK} = \sum_{i=1\in k}^{i=j=k} W_{user\ i}\ x\ SI_{User\ i} \tag{8}$$

2.6. Statistics for model calibration and validation

The WEAP model was calibrated and validated using monthly flows from the six control points (gauging stations) in the basin and monthly climate data based on precipitation, temperature, relative humidity, and wind speed. The flow data for the period 2000–2009 was used for calibration and 2010–2014 for validation (Fig. 2). The calibration parameters were: Deep Water Capacity (DWC) varying from 15 to 3000 mm, Runoff Resistance Factor (RRF) from 1 to 10, Preferred Flow Direction (PFD) from 0,1 to 1, Root Zone Conductivity (RZC) from 5 to 30, and Soil Water Capacity (SWC) varying from 100 to 3000 mm. The trial-and-error approach that was applied in this research involved a process wherein the model parameters were altered systematically and then the model was ran several times until the solution matched observed values within an acceptable level of accuracy.

The coefficient of Efficiency Nash-Sutclifffe (NSE) and Index of Agreement Willmott (IA) (Eq. (9) and (10)) were calculated to evaluate the performance of the WEAP model (Nash and Sutcliffe, 1970; Legates and McCabe, 1999; Coffey et al., 2004; Gupta and Kling, 2011; Ewen, 2011; Bren and Lane, 2014). The model calibration was accomplished manually using trial and error and maximizing NSE and IA. Parameters, such as soil water capacity (SWC), root zone conductivity (RZC), runoff resistance factor (RRF), and preferred flow direction (PFD) were adjusted so that the predicted flow from WEAP fit the observed flow. Table 2 shows a summary of the NSE, IA and R2 values for the calibration and validation period for each control point. Relationships between monthly observed and predicted streamflows show a strong correlation, indicating good model performance, which is supported by an NSE above 0.69 and IA above 0.92. The validation period showed a decreasing performance, however, with an NSE and IA above 0.7 and 0.8, respectively. The alternating between the NSE values for the calibration and validation period can be explained by many gaps in the streamflow data provided in the calibration period for some gauging stations. In the validation period, the gauging stations used in this work presented data more consistent with smaller number of failures. Some gauging stations (in AG, MBG and BVP) in this work, were used the monthly average due to the large number of failures. Drought periods also influenced the variation of NSE in the calibration and validation periods for some control points. Fig. 2 shows the streamflow time series data of observed and predicted flows for control point Boca da Caatinga at the outlet of the basin. Similar goodness of fit results were obtained for the rest

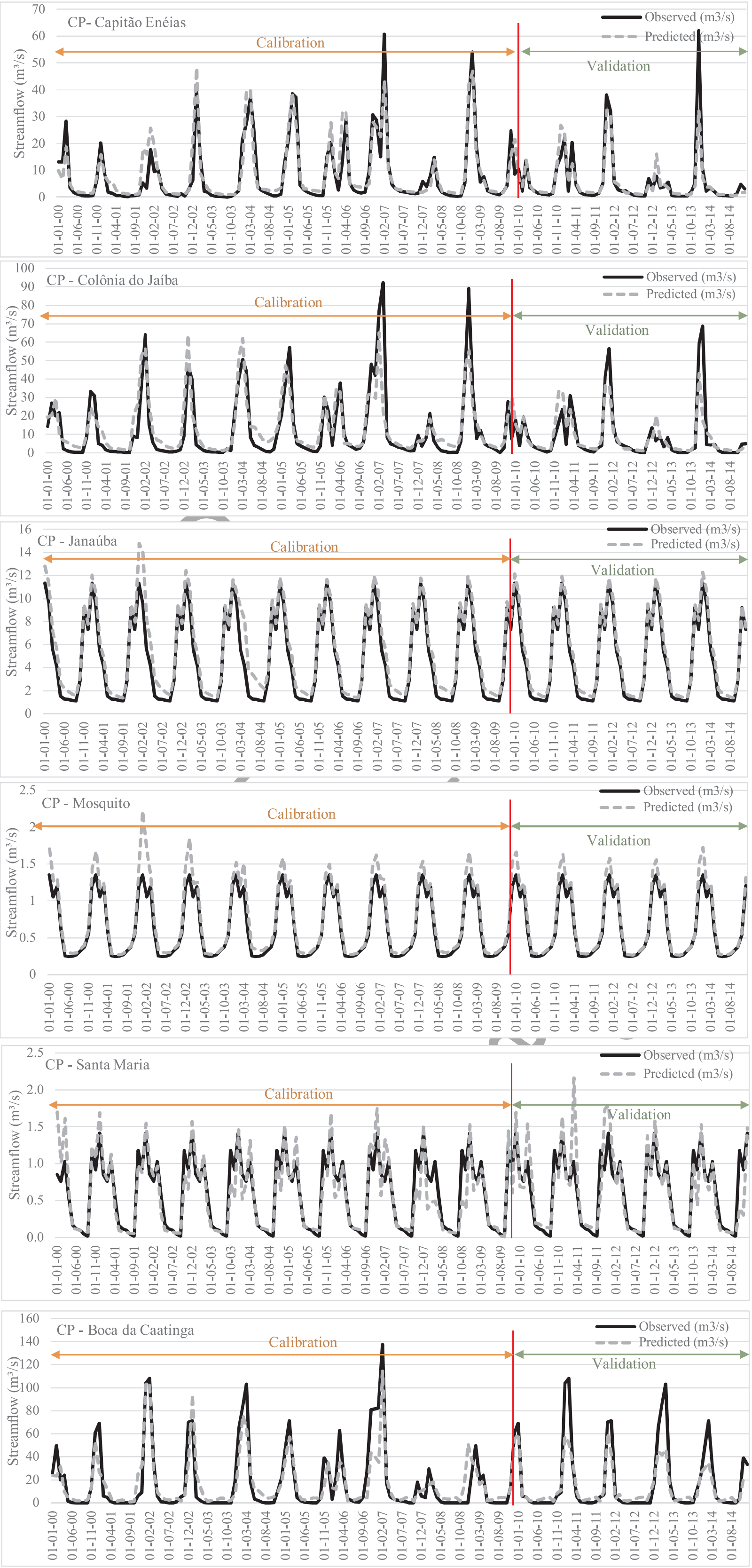

Fig. 2. Monthly observed and predicted streamflow for the calibration and validation period of six control-points of RVGB.

Table 2
Evaluation of the results by indicator.

Control Point	Subcatchment	Calibration			Validation		
		NSE	IA	R^2	NSE	IA	R^2
Cap. Enéias	AVG	0.814	0.951	0.826	0.828	0.945	0.842
Colônia do Jaíba	MVG_TB	0.693	0.902	0.701	0.692	0.885	0.715
Janaúba	AG	0.898	0.975	0.959	0.976	0.994	0.997
Mosquito	MBG	0.841	0.968	0.902	0.920	0.983	0.986
Santa Maria	BVP	0.779	0.947	0.813	0.694	0.931	0.796
Boca da Caatinga	BVG	0.776	0.926	0.788	0.736	0.895	0.879

of the control points. The model didn't reproduce well the flows for season period of some control points.

$$SE = 1.0 - \frac{\sum_{i=1}^{N} (Q_i^o - Q_i^p)^2}{\sum_{i=1}^{N} (Q_i^o - \overline{Q}^o)^2} \tag{9}$$

$$IA = 1.0 - \frac{\sum_{i=1}^{N} (Q_i^o - Q_i^p)^2}{\sum_{i=1}^{N} [|Q_i^p - \overline{Q}^o| - |Q_i^o - \overline{Q}^o|]^2} \tag{10}$$

3. Results and discussions

The Rio Verde Grande is a water-stressed basin in the northern part of the state of Minas Gerais, Brazil. The high water demand from many water users has resulted in low water availability in regional rivers, and caused water conflicts since the 1980s. Therefore, an evaluation and comparison, using the SI, is required for the various actions proposed in WRP for the RVGB; to address this need, the various sectoral demands and future scenarios proposed in the plan are evaluated using the WEAP model.

3.1. Analyses of the performance criteria for basin water resources

Although the RVGB was segmented into eight Subcatchments, only AVG, MVG_TB, and BVG along the main stream of the basin are shown as examples in this work, because AVG represents almost 50% of the water demand for the urban population of the whole basin; MVG_TB will receive the largest available water intervention with 3 m^3/s and the BVG represents the highest water demand for irrigated areas throughout RVGB. Table 3 and Figs. 3–5 show the performance criteria, reliability, resilience, vulnerability and maximum deficient, for irrigation area, livestock, and urban and rural population in those subcatchments.

In AVG, both livestock and rural population showed high resilience and reliability and zero vulnerability and max deficit. This result is due to the current low activity of water users, and even an increase proposed in the WRP of RVGB (ANA, 2016a,b) does not compromise the future availability of water in this subcatchment. In AVG, urban population is the largest consumer of water, surpassing irrigation area. Urban population shows a significant improvement in resilience and reliability only in the Trend scenario, when the water supply to the basin increases by 2 m^3/s from the Congonhas dam. In addition, neither of the Normative 1 and Normative 2 scenarios results in improvements in the performance criteria for reliability and shows only a small change in resilience. The vulnerability is halved, but remains stable in the Trend scenario. Similarly of the study of Safavi et al. (2015) that after assessing some interventions found very low reliability and resilience, and high vulnerability of the Zayandehrud Dam, located at center of Iran, in very critical conditions period after withdrawing of water to irrigation, industries, animal farming and municipal supply.

The maximum deficit remains high for all scenarios, despite the increase in water supply proposed in the WRP. The irrigation area in the AVG is the smallest in the entire basin, and shows small improvements in all the criteria analyzed, but has high vulnerability values and maximum deficit.

In the MVG_TB basin, high reliability and resilience values are found for livestock and available water for rural and urban populations. Because the MVG_TB has a low population density, the water demand also remains low. However, irrigation area is low in all performance criteria; reliability and resilience do not exceed the thresholds of 66.1% and 22.5%, respectively (Fig. 4). The vulnerability and maximum deficit have values of 42.3% and 77.1%, respectively. Those values are considered high, even though the MVG_TB basin receives two-thirds of the water diversion from the São Francisco River, 3.0 m^3/s. If the irrigation area growth rate remains as proposed in the WRP, it will be a high-risk activity.

There is no urban population in the BVG because the municipalities are located outside the boundaries of the subcatchment; therefore, this water user does not appear in Fig. 5. The BVG has the largest irrigated area in the entire basin, so the irrigation area also shows relatively high reliability values but low resilience values for all scenarios proposed in the water plan. Once all proposals for water development in the basin are implemented the vulnerability falls from 63.5% to 49.3%, and the max deficit remains above 80%.

Table 3

Performance criteria results by sub-basin and type of use.

		Reliability (Volume)				Vulnerability				Resilience				Max Deficit			
		Irrig	Liv	RurP	UrbP	Irrig	Liv	RurP	UrbP	Irrig	Liv	RurP	UrbP	Irrig	Liv	RurP	UrbP
Baseline	AVG	59.2	100.0	100.0	23.3	56.2	0.0	0.0	76.8	21.6	100.0	100.0	0.0	95.4	0.0	0.0	84.2
	MVG_TA	58.2	100.0	31.4	100.0	50.8	0.0	68.6	0.0	19.3	100.0	0.0	100.0	91.2	0.0	69.1	0.0
	MVG_TB	56.1	100.0	100.0	100.0	49.8	0.0	0.0	0.0	19.5	100.0	100.0	100.0	90.1	0.0	0.0	0.0
	AG	56.7	100.0	100.0	100.0	79.7	0.0	0.0	0.0	30.8	100.0	100.0	100.0	95.3	0.0	0.0	0.0
	MBG	62.5	100.0	100.0	100.0	68.9	0.0	0.0	0.0	31.4	100.0	100.0	100.0	96.2	0.0	0.0	0.0
	AVP	10.6	75.5	92.5	92.3	78.0	69.0	45.5	45.5	9.1	24.2	50.0	50.0	100.0	100.0	75.9	75.9
	BVP	19.2	92.0	100.0	100.0	71.9	32.3	0.0	0.0	14.2	29.5	100.0	100.0	100.0	71.0	0.0	0.0
	BVG	68.4	100.0	100.0		63.5	0.0	0.0		32.6	100.0	100.0		95.4	0.0	0.0	
Trend Scenario	AVG	620	100.0	100.0	65.1	51.8	0.0	0.0	36.2	22.5	100.0	100.0	35.2	92.8	0.0	0.0	77.2
	MVG_TA	61.0	100.0	31.4	100.0	48.6	0.0	68.6	0.0	20.3	100.0	0.0	100.0	88.8	0.0	69.1	0.0
	MVG_TB	56.1	100.0	100.0	100.0	46.9	0.0	0.0	0.0	20.3	100.0	100.0	100.0	87.7	0.0	0.0	0.0
	AG	56.9	100.0	100.0	100.0	79.3	0.0	0.0	0.0	30.8	100.0	100.0	100.0	95.3	0.0	0.0	0.0
	MBG	62.5	100.0	100.0	100.0	68.9	0.0	0.0	0.0	31.4	100.0	100.0	100.0	96.2	0.0	0.0	0.0
	AVP	10.6	75.5	92.5	92.3	78.0	69.0	45.5	45.5	9.1	24.2	50.0	50.0	100.0	100.0	75.9	75.9
	BVP	19.2	92.0	100.0	100.0	71.9	32.3	0.0	0.0	14.2	29.5	100.0	100.0	100.0	71.0	0.0	0.0
	BVG	69.4	100.0	100.0		62.3	0.0	0.0		33.3	100.0	100.0		93.0	0.0	0.0	
Normative 1 Scenario	AVG	68.5	100.0	100.0	65.1	42.9	0.0	0.0	36.2	23.9	100.0	100.0	51.2	82.3	0.0	0.0	77.2
	MVG_TA	67.2	100.0	31.4	100.0	42.5	0.0	68.6	0.0	21.9	100.0	0.0	100.0	80.4	0.0	69.1	0.0
	MVG_TB	66.1	100.0	100.0	100.0	42.4	0.0	0.0	0.0	22.5	100.0	100.0	100.0	77.1	0.0	0.0	0.0
	AG	58.1	100.0	100.0	100.0	78.3	0.0	0.0	0.0	31.4	100.0	100.0	100.0	95.3	0.0	0.0	0.0
	MBG	65.3	100.0	100.0	100.0	66.1	0.0	0.0	0.0	32.7	100.0	100.0	100.0	96.2	0.0	0.0	0.0
	AVP	10.6	75.5	92.5	92.3	78.0	69.0	45.5	45.5	9.1	24.2	50.0	50.0	100.0	100.0	75.9	75.9
	BVP	19.5	92.0	100.0	100.0	71.9	32.3	0.0	0.0	14.9	29.5	100.0	100.0	100.0	71.0	0.0	0.0
	BVG	75.4	100.0	100.0		49.3	0.0	0.0		35.0	100.0	100.0		84.4	0.0	0.0	
Normative 2 Scenario	AVG	68.6	100.0	100.0	65.1	42.8	0.0	0.0	36.2	23.9	100.0	100.0	56.1	82.3	0.0	0.0	77.2
	MVG_TA	67.3	100.0	31.4	100.0	42.4	0.0	68.6	0.0	21.9	100.0	0.0	100.0	80.4	0.0	69.1	0.0
	MVG_TB	66.1	100.0	100.0	100.0	42.3	0.0	0.0	0.0	22.5	100.0	100.0	100.0	77.1	0.0	0.0	0.0
	AG	61.1	100.0	100.0	100.0	77.3	0.0	0.0	0.0	33.3	100.0	100.0	100.0	95.0	0.0	0.0	0.0
	MBG	68.5	100.0	100.0	100.0	63.2	0.0	0.0	0.0	34.8	100.0	100.0	100.0	95.9	0.0	0.0	0.0
	AVP	10.6	75.5	92.5	92.3	78.0	69.0	45.5	45.5	9.1	24.2	50.0	50.0	100.0	100.0	75.9	75.9
	BVP	19.5	92.0	100.0	100.0	71.9	32.3	0.0	0.0	14.9	29.5	100.0	100.0	100.0	71.0	0.0	0.0
	BVG	77.2	100.0	100.0		49.3	0.0	0.0		37.8	100.0	100.0		84.4	0.0	0.0	

Irrig – Irrigation; Liv – Livestock; RurP – Rural Population; UrbP – Urban Population.

3.2. Sustainability index and sustainability by group for basin water resources

Because the RVGB has high water demand and low water availability, it is challenging to identify actions that can improve the management of its water resources when evaluating performance criteria in isolation. Lèvite et al. (2003) testing water demand management scenarios in water-stressed basin in South Africa demonstrated that even in normal hydrological years, but no water demand management efforts, just 10% of the water reserve targets could all be achieved.

The SI and SG are tools that can evaluate and compare actions to improve the management of water resources in a basin by integrating multiple performance criteria. Table 4 and Figs. 6–8 show the variations in the SI for a subcatchment with reference to the baseline scenario, in which no action had been implemented.

Fig. 6 shows a comparison of the baseline with the Trend scenario, whose only structural action was to increase water available by importing water from the Congonhas River to the Juramento dam to meet the demands of urban population growth in the AVG, specifically Montes Claros city. This action has a significantly positive impact, resulting in a SI $>$ 30%. Subcatchments in the same watercourse, MVG_TA, MVG_TB and BVG showed changes in their SI of 1.9%, 2.4%, and 2.2%, respectively. The slight increase in SI for the subcatchments is due to 50% of the imported water being allocated for environmental flow. However, these increases in SI are not enough to change the classification range (10%), as shown in Fig. 6.

Fig. 7 shows the comparison between the baseline and Normative 1 scenarios. As indicated previously, the Normative 1 scenario has the same criteria as the Trend scenario with the addition of water diversions of 1.5 m^3/s to Jaíba and 1.5 m^3/s to Verdelândia. From these additional diversions, there is a significant improvement in the SI throughout the main channel of the Rio Verde Grande. All subcatchments located in the main river channel showed meaningful changes in the SI classification, 35.3%, 7.3%, 9.6%, and 13.1% for the AVG, MVG_TA, MVG_TB, and BVG, respectively.

Fig. 8 shows the comparison between the baseline and Normative 2 scenarios. As indicated previously, the Normative 2 scenario has the same criteria as the Normative 1 scenario with the addition of construction of five dams and an increase in flow, around 0.71 m^3/s (Table 1). Two dams are added to the AVG, with a flow increase of around 0.04 m^3/s. One dam is added to the AG, with a flow increase of around 0.05 m^3/s, and two dams are added to the AVP. In addition, the Normative 2 scenario provides for the establishment of another water diversion from the São Francisco River reaching the Bico da Pedra dam in Nova Porteirinha city, with a

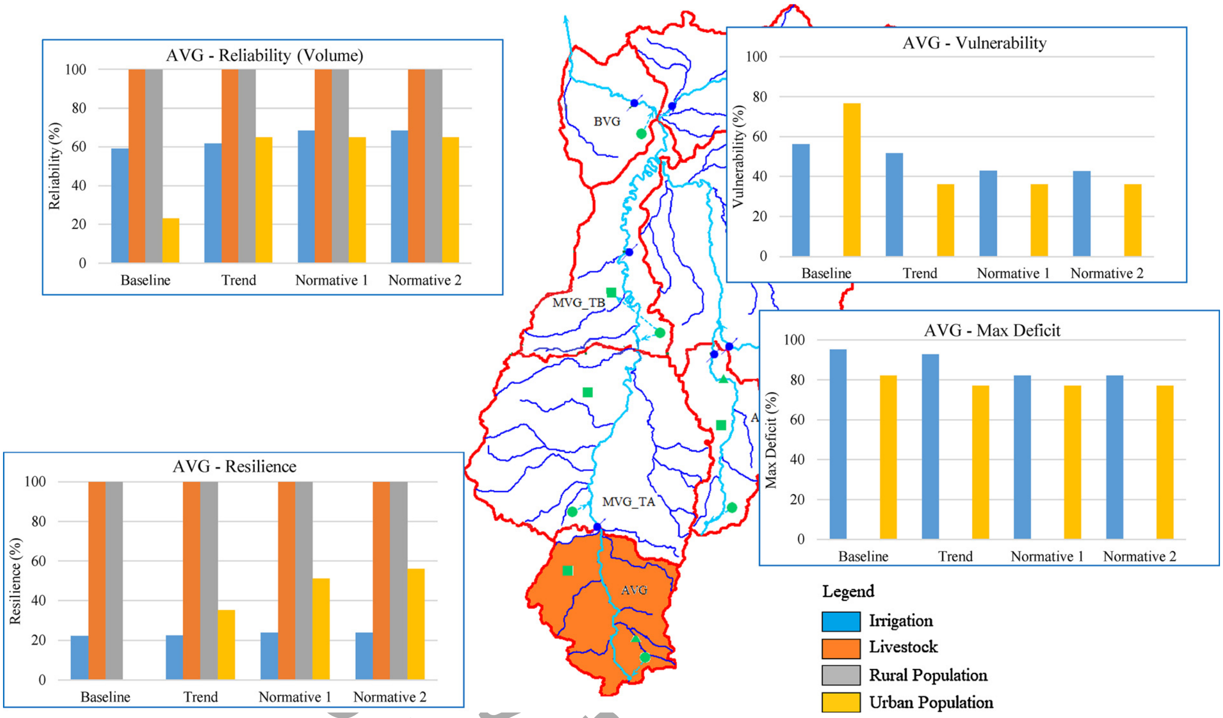

Fig. 3. Performance criteria of water resources in the Alto Verde Grande (AVG) subcatchment.

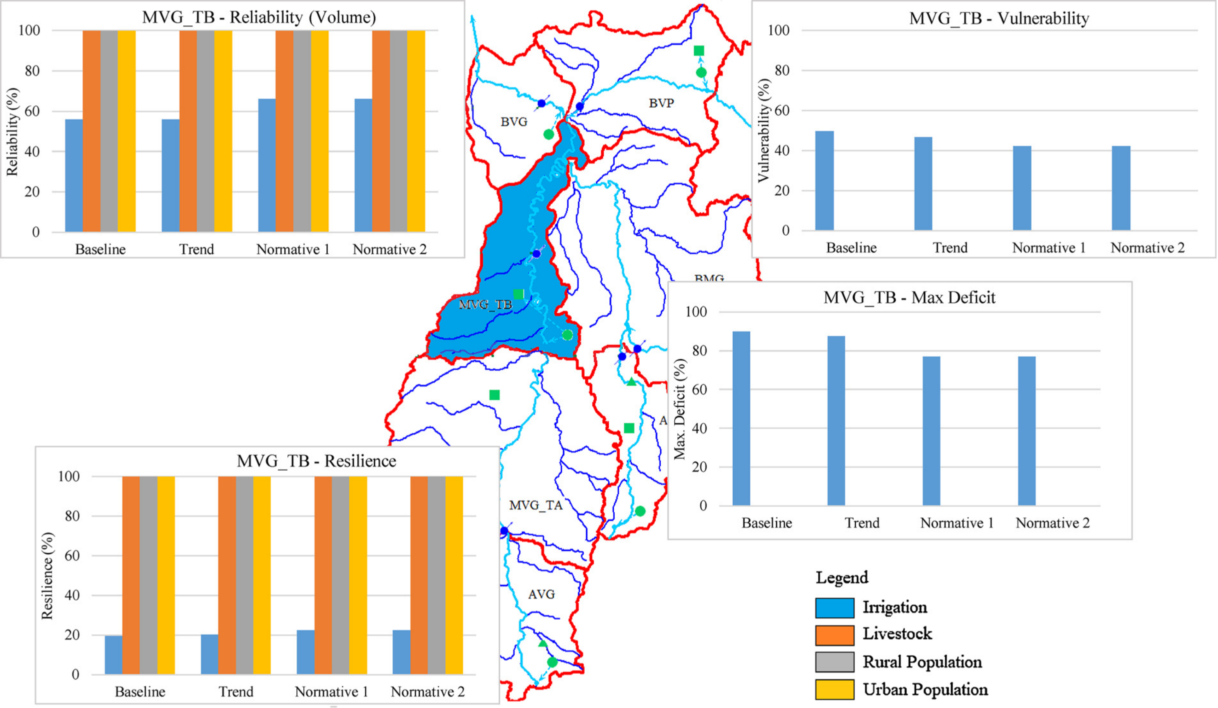

Fig. 4. Performance criteria of water resources in the Médio Verde Grande (MVG_TB) subcatchment.

flow of 1.5 m^3/s. These actions result in an improvement to the SIs for almost the entire RVGB, except for the AVP and BVP. These two subcatchments have two proposed dams: the Santo Domingo dam, with a regulated flow of 0.42 m^3/s, and the Mamonas dam, with a flow rate of 0.05 m^3/s. Despite the increase in water availability in both subcatchments, the demand will grow outweighing supply, which leads to very low sustainability. These low SI values for AVP and BVP can be modified based on the implementation

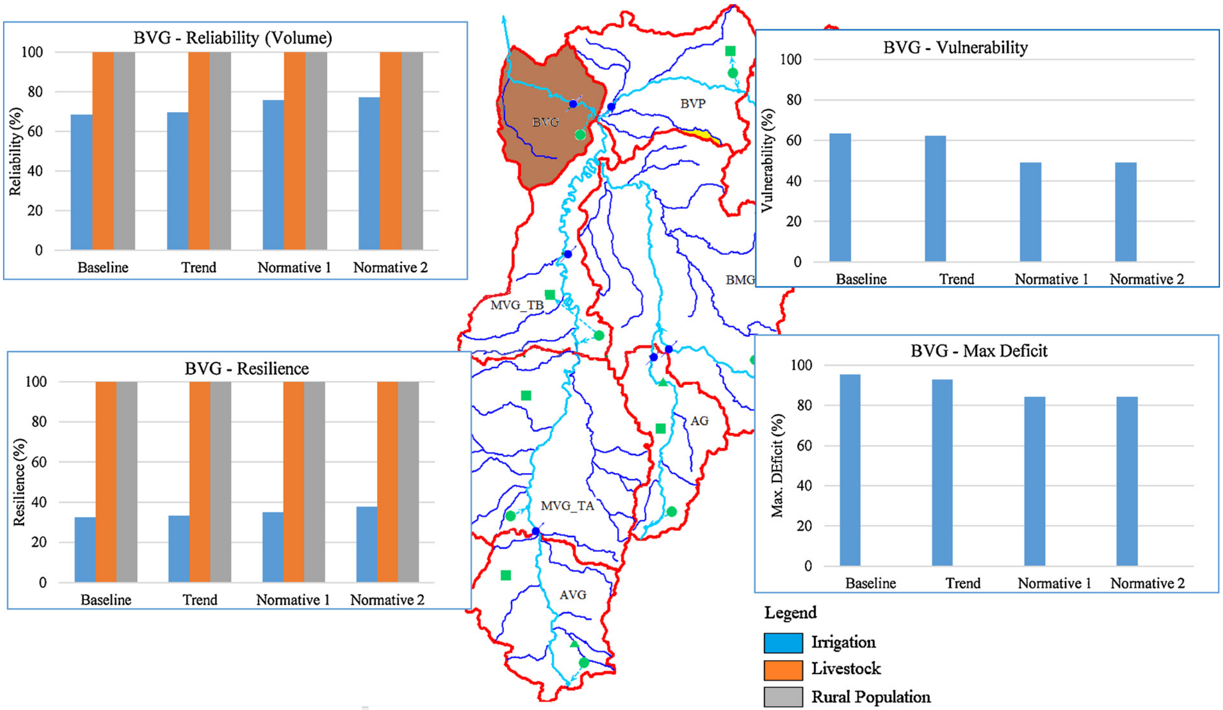

Fig. 5. Performance criteria of water resources in the Baixo Verde Grande (BVG) subcatchment.

Table 4
Sustainability index (%) by subcatchment and scenario.

	Baseline	Trend	Normative 1	Normative 2
AVG	19.4	50.6	54.7	55.5
MVG_TA	48.3	50.2	55.6	55.6
MVG_TB	31.8	34.2	41.4	41.5
AG	29.9	30.0	30.4	31.5
MBG	28.0	28.0	29.0	30.3
AVP	1.1	1.1	1.1	1.1
BVP	6.5	6.5	6.5	6.5
BVG	25.5	28.7	39.6	40.5

date for the actions proposed in those subcatchments.

The SG was calculated to analyze the activities by sustainability of each activity and assess the improvement due to the proposed in the WRP (Fig. 9). Comparing the four water users analyzed in this work, the livestock has the highest SG (above 90%) followed by rural population (approximately 80%). However, the available water to the basin through importing water, water diversions, and reservoirs results in a small increase in the SG for irrigation, compared with the reference scenario (Baseline). This result shows that irrigated area growth will result a water demand always below available water, assuming the growth rate proposed in the WRP is maintained. Therefore, irrigated area has low sustainability. The water activity for urban population shows a considerable increase in SG because the Trend scenario results in a large import of water supply from the Congonhas River, with a flow of 2 m^3/s. This action results in more than 30% increase in SG, but the other actions do not result in significant improvements to SG. Thus, urban population reaches a plateau at approximately 60% SG (Fig. 9). Whereas water supply for population is the top priority provided for in the WRP, this activity still has a high vulnerability value.

As shown in Fig. 10, all scenarios compared to the baseline scenario provide an improvement in the SI; however, the SI remains at low levels throughout the basin. After the implementation of the policies, the SI in the RVGB only increased 7.7%, which is little considering the increasing water demand from growth proposed by the RVGB.

4. Summary and conclusions

The increasing economic activity and growing population of the RVGB resulted in conflicts over the use of water that led in the elaboration of a water resources plan. Several actions of improvements in the available water were proposed in the plan, however, without an evaluation if these actions would result in the sustainability of the water resources. Thus, the SI was used to evaluate and

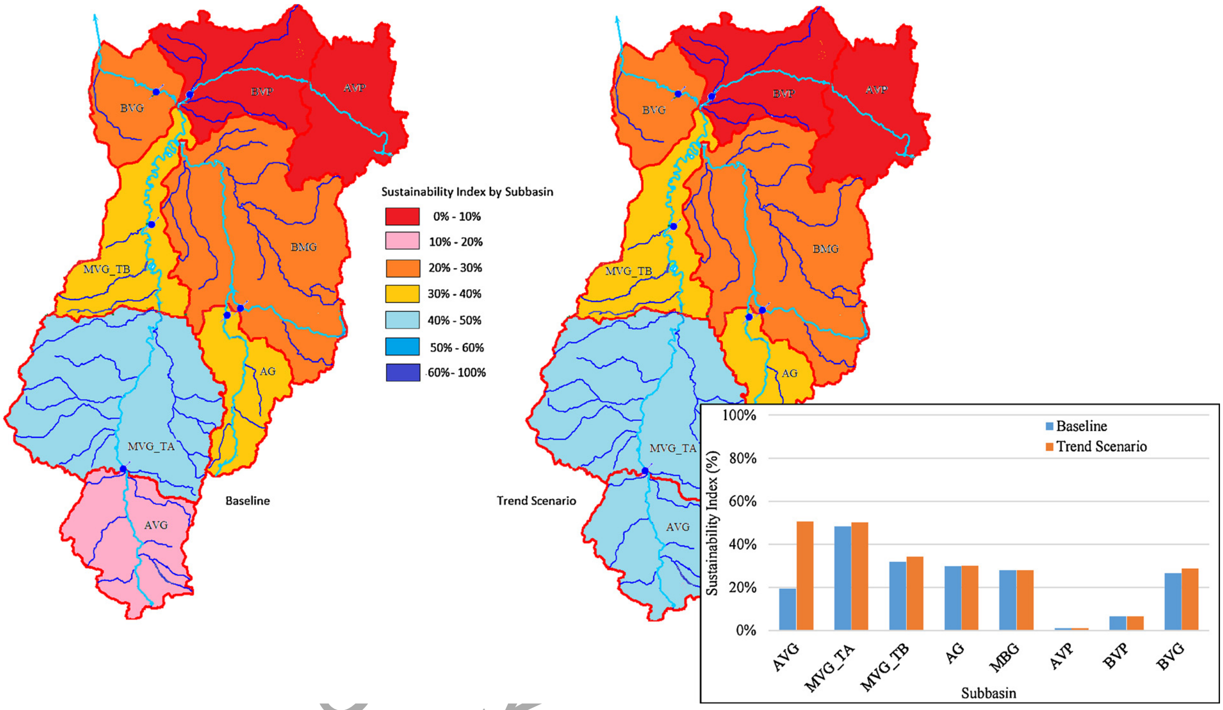

Fig. 6. Change in the sustainability index between Baseline and Trend scenarios by subcatchment considering period from 2015 to 2030.

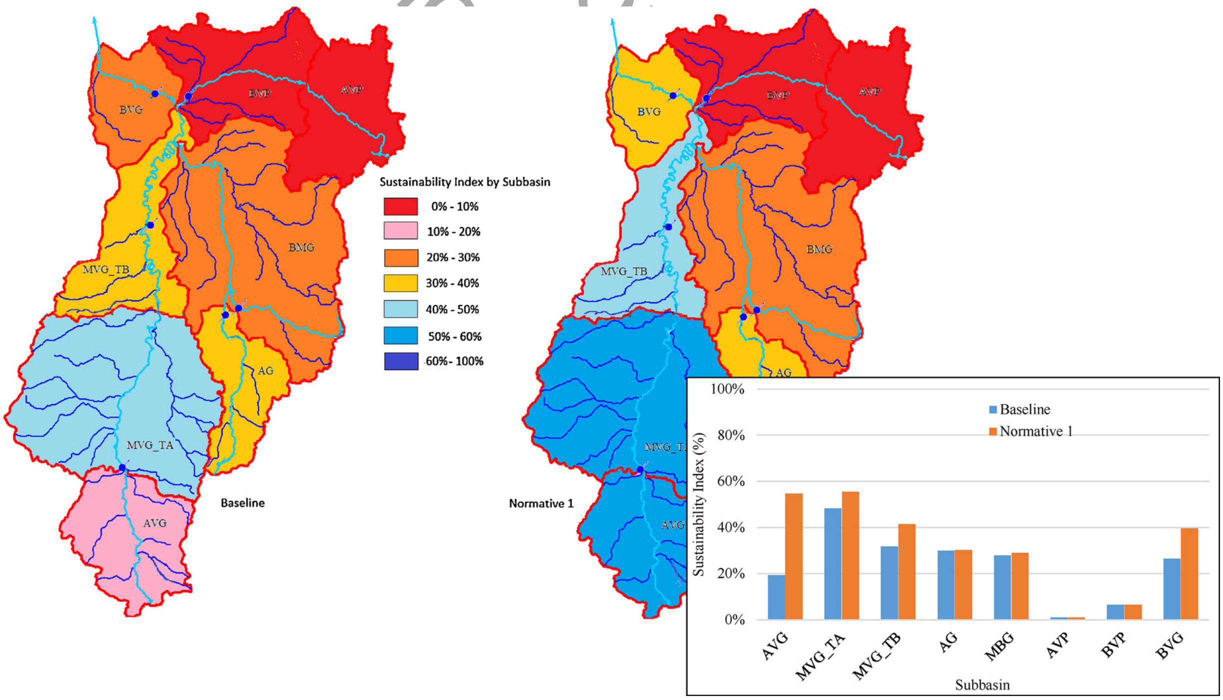

Fig. 7. Change in the sustainability index between Baseline and Normative 1 scenarios by subcatchment considering period from 2015 to 2030.

compare the increasing demand for water and the improvement of the available water available with the implementation of several actions proposed in the basin water plan.

The SI has identified the best scenario foreseen in the WRP for the RVGB that will improve the availability of water through 2030 having positive impact to water users of the basin. However, the water availability has improved for some activities in the proposed scenarios, but the water resources remains unsustainable and has a high maximum deficit in all subcatchments.

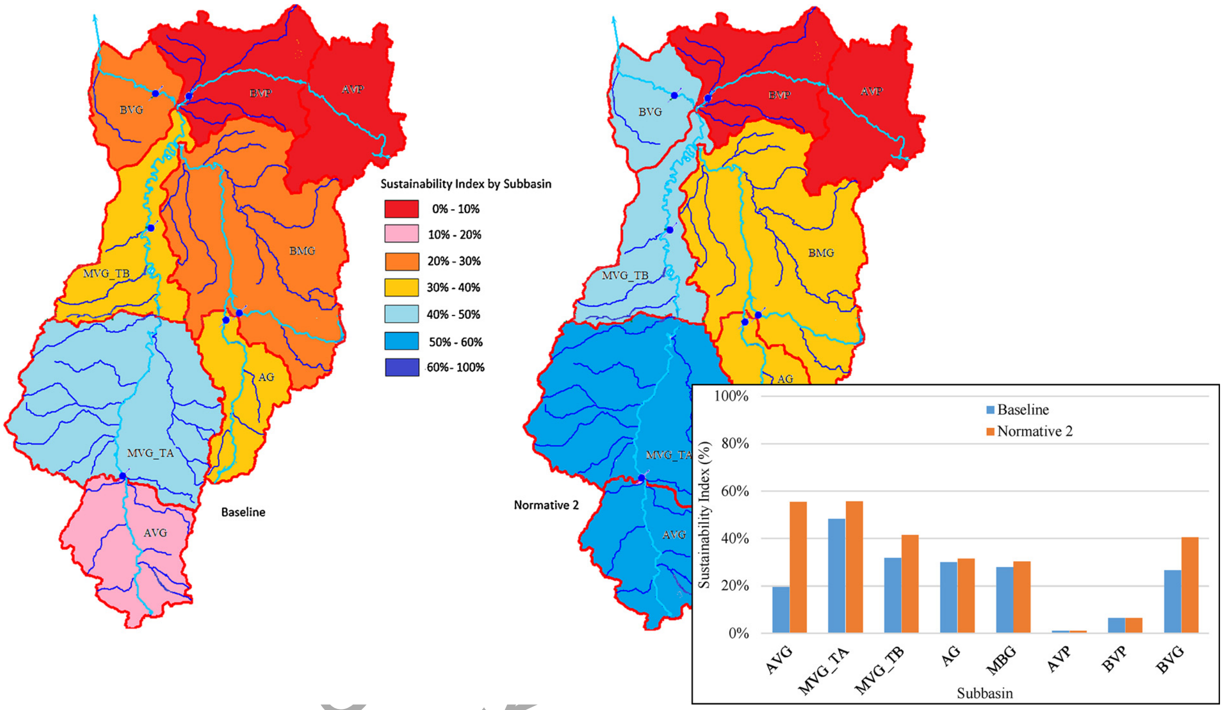

Fig. 8. Change in the sustainability index between Baseline and Normative2 scenarios by subcatchment considering period from 2015 to 2030.

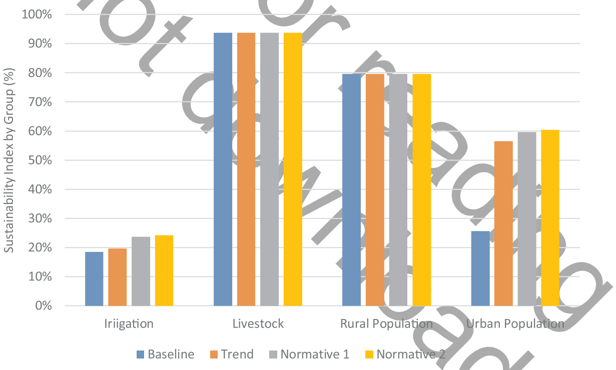

Fig. 9. Sustainability for each group of water users in the Rio Verde Grande Basin.

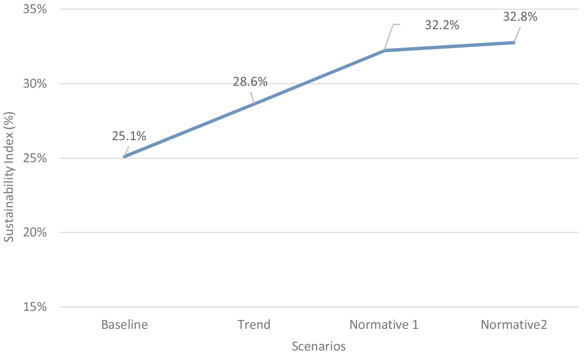

Fig. 10. Sustainability Index for the entire Rio Verde Grande Basin.

The comparison of the SG between different water users indicated that the actions proposed in the RVGB significantly improved the water supply for urban population in the AVG subcatchment.

Considering the entire RVGB, there were no significant improvements in sustainability of water resources with the implementation of the policies proposed in WRP, even considering the best scenario.

The SI has a limitation when the water required by the system is not well calculated, especially when it comes to estimating future scenarios. The quality of data (in terms of availability and reliability) also is very important and must be dealt with common sense. Even thus, SI is a tool that can be used by decision makers and stakeholders in the water resource management process to evaluate and compare proposed actions in a basin water plan, avoiding unnecessary financial resources expenditures in actions that will not result in significant improvements in the available water for water users, environmental and system requirements.

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