SUSTAINABILITY INDEX AND INTEGRATED WATER RESOURCES MANAGEMENT OF THE RIO VERDE GRANDE BASIN IN BRAZIL

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Abstract - Rio Verde Grande basin (RVGB) is an important basin in Brazil. The extensive regional development, have resulted in low water availability and have been causing conflicts of water user since the 1980's. The objective of this work is to evaluate the water management by sustainability index of water resources in the RVGB, Brazil, evaluating and comparing water demand and water supply for activities of the Water Resources Plan of RVGB in three different scenarios of water supply. The sustainability index identified policies that improved the water availability of the RVGB for the future and considering the whole basin, there are no significant improvements in water supply with the implementation of these policies proposed by the Water Resources Plan for the RVGB.

Keywords: Hydrologic model, Integrated water resources management, Water-Stressed Basin

1. INTRODUCTION

The Rio Verde Grande basin stands out for its agricultural production, accomplished mainly with irrigation, for important cities like Montes Claros (400.000 inhabitants). Extensive regional development and urban expansion have caused low water availability in regional rivers, causing use of water conflicts that have been recorded since the 1980's.

In PRHVG, three scenarios were envisaged for implementation of actions. Interventions that were already planned or underway in relation to the increase in water supply were considered in the Trend Scenario. From the trend scenario, two other scenarios were developed, called Normative 1 and 2 in which performance of water management is present with successive efficiencies both increase the water supply and efficient use. However, in Rio Verde Grande Basin there are no studies that allow to evaluate and compare the sustainability of different actions or methods of water management in different scenarios.

Recently, in other countries, great emphasis has been given the adaptability of water resources to measures that reduce the vulnerability of these systems for a proposed

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future scenario (Ceron *et al.,* 2011; Sandoval-Solis *et al.,* 2011; Ceron *et al.,* 2012; Cortés *et al.,* 2012; Koop and van Leeuwen, 2015). 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 humans in their various activities and the environment, considering various future scenarios. To accomplish this goal, it is must have performance measures or indexes that allow the evaluation and comparison of water resources subject to these actions under different scenarios (Sandoval-Solis et al, 2011)

Sustainability index (SI) of water resources is one of those indexes that enables to evaluate and compare different methods of management and water uses with regard to its sustainability. Sustainability index (SI) identifies the methods and water uses that preserve or improved water management in the basin in a future scenario.

Thus, given the increasing conflicts between water users in the basin of the Rio Verde Grande becomes necessary evaluation and comparison through sustainability index for the various actions proposed in PRH Verde Grande regard the various sectoral demands and future scenarios proposed in the plan. The sustainability index that will be used in this study was developed by Loucks (1997) and adapted by SANDOVAL-SOLIS et al (2011).

The objective of this work was to calculate the sustainability index of water resources in the Rio Verde Grande basin, Minas Gerais State, Brazil, using WEAP model, evaluating and comparing water demand and water supply for activities of the PRH Verde Grande in three scenarios of water availability.

2. METHODOLOGY

2.1. Characterization of the study area

The Rio Verde Grande is a major tributary of the right side of the São Francisco river which is in part of its course, in the boundary between the states of Bahia and Minas Gerais. Its basin has an area of 31,410 km² covering 8 municipalities in Bahia (13% of total area) and 27 municipalities in Minas Gerais (87% of total area). The population is 768,000 inhabitants (2009), which corresponds to about 5% of the total population of the São Francisco River Basin (ANA, 2011).

The segmentation of Verde Grande Basin (VGB) into smaller areas as subbasin, had the intention to get the spatial structure of whole basin to analyze of informations, from diagnosis phase until future scenarios phase. This segmentation was proposed by water plan of Rio Verde Grande Basin.

2.2. Case of study: Rio Verde Grande Basin

2.2.1. Geography of the model

The previously proposed hydrologic Two-bucket model is applied to Rio Verde Grande basin in north of Minas Gerais State in Brazil. Part of Rio Verde Grande Basin (VGB) is located in Minas Gerais state (87%) and part in Bahia State (13%). The VGB is the one of main tributary flowing into the São Francisco River. The Rio Verde Grande arises at roughly 1,256 m from the hills of headwaters, In Minas Gerais state, following more than 577 Km to join the São Francisco river, 431m of altitude, at border between the states of Minas Gerais and Bahia.

2.3. Model Description

A model for Rio Verde Grande Basin was built using the Water Evaluation and Planning (WEAP), a Integrated Water Resource Management (IWRM) model developed by Stockholm Environment Institute (Yates *et al.* 2005a). The soil moisture method of 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, Yates et al. 2005b) . Following the Water Resource Plan of Rio Verde Grande (PRHVG, ANA, 2011), the Rio Verde Grande Basin was subdivided into 8 subcatchments with same water users and connected to a network of rivers (see Fig. 1). The water user represents the system in terms of its various sources of water supply (e.g. rivers, groundwater and reservoirs), withdrawals and water demands. The water users were divided into 4 biggest group: Irrigation; Livestock; Urban Population and Rural Population.

The VGB map (Figure 1) include the upper and lower catchment and schematic diagram that shows six control points (CP) and all the catchments contributing to the VG.

2.4. Data Source

Monthly data as precipitation, surface air temperature, relative humidity, and wind velocity data were obtained from the Instituto Nacional de Meteorologia (INMET, 2015) for 2000 to 2014. Monthly data of streamflow were obtained from HIDROWEB (ANA, 2015) for six control point: CE – Capitão Enéias, CJ – Colônia do Jaíba, and BoCa – Boca da Caatinga on Rio Verde Grande; JA – Janaúba on Gorutuba river; MO – Mosquito on Mosquito river and SM – Santa Maria on Verde Pequeno river.

2.5. Scenarios

The purpose of this study is to evaluate three scenarios foreseen in plus a baseline scenario (Table 1):

- Baseline scenario: no actions;
- Trend Scenario: Interventions that were already planned or underway in relation to the increase in water supply as the Import Water from Congonhas river with 2m³/s to AVG Subbasin with start year in 2018;
- Normative 1: in which performance of water management is present with increase the water supply as the same interventions of Trend Scenario plus water diversion from São Francisco river to city of Jaiba (1.5m³/s to MVG_TB) start year in 2020 and same channel with water diversion from São Francisco river to city of Verdelandia (plus 1.5m³/s to MVG_TB) with star year in 2025;

- Normative 2: same interventions of Normative 1 plus water diversion from São Francisco river (plus 1,5m³/s to AG and 4.5m³/s total) with starting in 2028 and construction of the five dams (2 to AVG; 1 to MBG and 2 to AVP)

These scenarios are developed for period from 2015 to 2030.

Table 1 – Scenarios of water supply foreseen in PRHVG (ANA, 2011).

Scenarios			ACTIONS	Nº	Start Year
Baseline			No actions	0	2015
T	N1	N2	Import water from Congonhas river 2m³/s	1	2018
__	N1	N2	Water Diversion From São Francisco River 1.5m³/s	2	2020
__	N1	N2	Water Diversion From São Francisco River 1.5 m³/s (3m³/s Total)	3	2025
__	__	N2	Water Diversion From São Francisco River 1.5 m³/s (4.5m³/s Total)	4	2028
__	__	N2	Rio Verde Dam 0.15m³/s	5	2025
__	__	N2	Cocos Dam 0.05m³/s	6	2025
__	__	N2	Pedras Dam 0.04m³/s	7	2028
__	__	N2	Mamonas Dam 0.05m³/s	8	2028
__	__	N2	São Domingos Dam 0.42m³/s	9	2028

T = Trend Scenario; N1 = Normative1; Normative 2

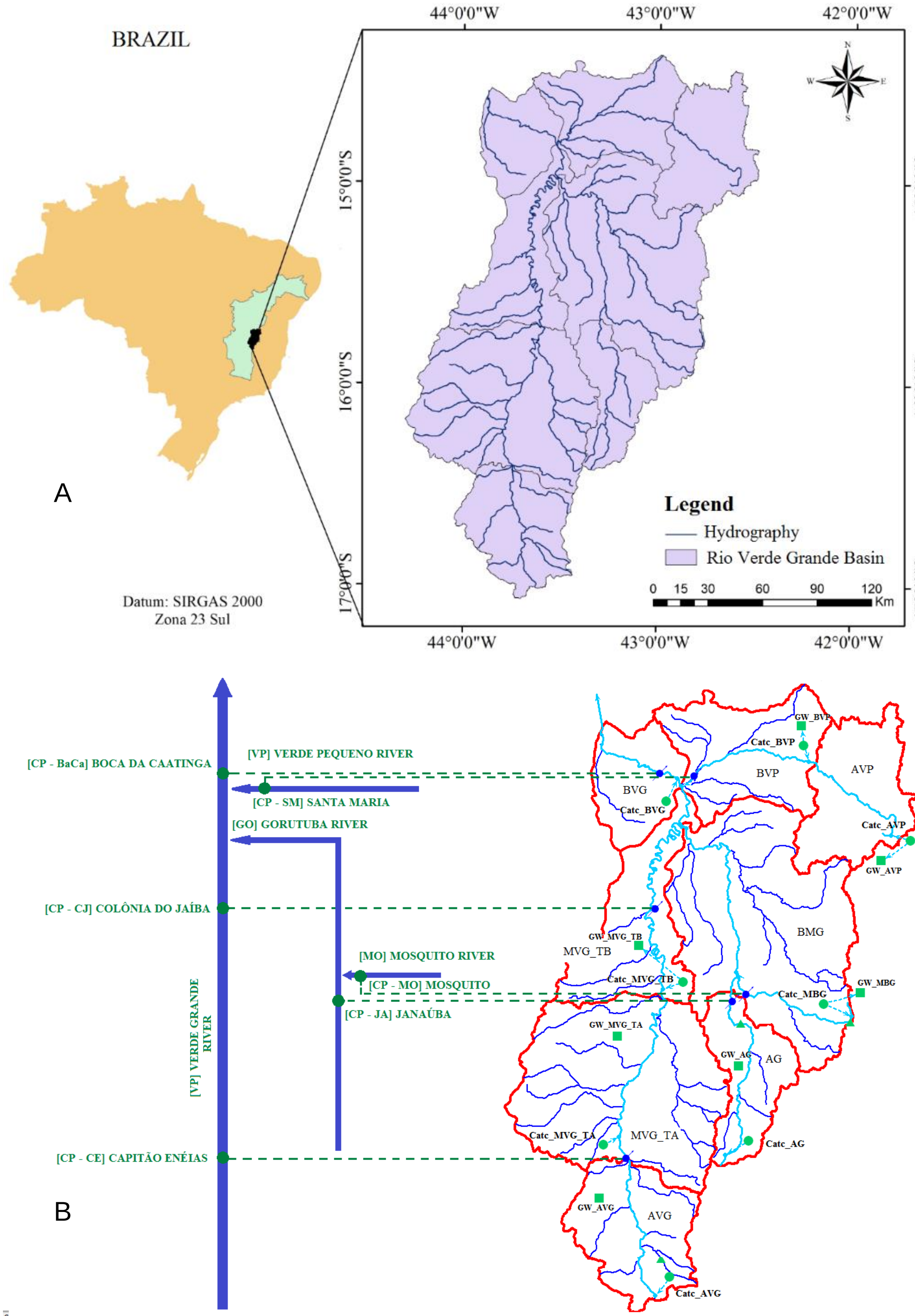

Figure 1 – Location of the Verde Grande Basin (A) and the schematic representation of the Rio Verde Grande Basin (B) for WEAP analysis showing sub-divisions catchments and rivers

2.6. Performance Criteria and Sustainability index

Four performance criteria were used to evaluate model results and to compare alternative management policies under three scenarios of incremental water supply foreseen in PRHVG (ANA, 2011): volumetric reliability; resilience; vulnerability and maximum deficit. With those performance criteria became possible to quantify the sustainability index of water resources system of Rio Verde Grande Basin. All performance criteria former mentioned relate with water supplied deficit (D_t^i) (Eq. 1) that is the difference between water demand ($X_{Target,t}^i$) and water supplied ($X_{Supplied,t}^i$) for each time period *t* for a determined *i*th water user, defined in this work as Irrigated Area, Livestock, Urban Population and Rural Population:

$$D_t^i = \begin{cases} X_{Target,t}^i - X_{Supplied,t}^i , & If\ X_{Target,t}^i > X_{Supplied,t}^i \\ 0 , & If\ X_{Target,t}^i = X_{Supplied,t}^i \end{cases} \quad (1)$$

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

Volumetric reliability (Rel^i) is the total volume of water supplied divided by the total water demand for ith water user during the simulation period (Hashimoto *et al.,* 1982; Sandoval-Solis *et al.,* 2011; Lane *et al.,* 2014) (Eq. 2):

$$Rel^i = \frac{\sum_{t=1}^{t=n} X_{Supplied,t}^i}{\sum_{t=1}^{t=n} X_{Target,t}^i} \quad (2)$$

Resilience (Res^i) is a measure of a system's 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.,* 2014, Safavi *et al.,* 2015) (Eq. 3):

$$Res^i = \frac{No.\ times\ D_t^i = 0\ follows\ D_t^i > 0}{No.\ times\ D_t^i > 0\ ocorred} \quad (3)$$

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

$$Vul^i = \frac{\left(\frac{\sum_{t=1}^{t=n} D_t^i}{No.\ \ of\ times\ D_t^i > 0\ ocorred}\right)}{X_{Target}^i} \quad (4)$$

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

$$Max\ Def^{i} = \frac{\max\left(D^{i}_{annual}\right)}{Water\ demand^{i}} \qquad (5)$$

Sustainability index (SI^{i}) is an index that measures the sustainability of water resources systems and can be used to estimate and to 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 was defined as a geometric average of *M* performance criteria (C^{i}_{m}) for the *i*th water users (Eq. 6):

$$SI^{i} = \left[\prod_{m=1}^{M} C^{i}_{m}\right]^{\frac{1}{M}} \qquad (6)$$

For this work, the sustainability index proposed for water users at Rio Verde Grande Basin is (Eq. 7):

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

The sustainability by group is a combination of Sis of a group k with *i*th to *j*th water users belonging to this group into one value using a weighted average of SI and it helps to identify water management improvements in basin (Sandoval-Solis *et al.,* 2011; Sandoval-Solis *et al.,* 2013) (Eq. 8):

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

2.7. Statistics of model calibration and validation

The coefficient of Efficiency Nash-Sutclifffe (NSE) (Nash; Sutcliffe, 1970) and the Index of Agreement Willmott (IA) were calculated to evaluate the performance of WEAP model. Model calibration was done manually via trial and error seeking to maximize NASH and IA. Parameters as Soil Water Capacity (SWC); Root Zone Conductivity (RZC); Runoff Resistance Factor (RRF) and Preferred Flow Direction (PFD) have been adjusted so that the WEAP fitted the predicted flow with observed flow.

$$NSE = 1.0 - \frac{\sum_{i=1}^{N}\left(Q^{o}_{i} - Q^{p}_{i}\right)^{2}}{\sum_{i=1}^{N}\left(Q^{o}_{i} - \overline{Q^{o}}\right)^{2}} \qquad (9)$$

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

For equation 9 and 10, Q_i^o= observed streamflow; Q_i^p = predict streamflow; and $\overline{Q^o}$ = average streamflow. The Nash-Sutcliffe coefficient (NSE) can range from minus infinity to 1.0. The numerical value of NSE increases with performance and it reaches its maximum value (1.0) when there is a perfect match between predicted and observed streamflows (Nash and Sutcliffe 1970, Legates and McCabe 1999, Coffey et al. 2004, Gupta and Kling 2009, Ewen 2011, Bren and Lane 2014). The Index of agreement (IA) is the ratio of the square error to the squared absolute differences of the predicted and observed values and their averages. Values of IA range from 0 to 1, with high values indicating better agreement between predicted and observed streamflows (Ingol-Blanco and McKinney 2013).

3. RESULTS AND DISCUSSIONS

Analyses of the performance criteria of water resources of basin

Although the basin has been segmented into 8 subbasin only AVG, MVG_TB, and BVG in main course of Rio Verde Grande basin are analysed as a exemple in this work (Figure 2). This analysis refers to Normative 2 scenario, considering implemented all infrastructures policies foreseen in water plan of Rio Verde grande. In AVG subbasin, both Livestock and Rural Pop showed high resilience and reliability and zero vulnerability and max deficit. This can be explained by the low activity of these water users and even with the increase foreseen by PRHVG (ANA, 2011) does not compromise the future availability of water in this subbasin. Specifically in this subbasin, Urban Pop is the largest consumer of water surpassing Irrigated Area. Even though all infrastructures implemented for Normative 2 scenario, those did not result in improvements in the performance criteria as reliability and did only a small change in the resilience. The vulnerability has halved but remains stable for Normative 2 scenario. The max deficit remains high, despite of the increment of water proposed in PRHVG for all scenarios. The Irrigation area in AVG subbasin is the smallest in the entire basin of the Rio Verde Grande, but still showed small improvements in all the criteria analyzed, but remaining with high vulnerability values and max deficit.

In MVG-TB showed high reliability and resilience values for livestock and water supply of rural and urban population. It is noteworthy that in MVG-TB subbasin has low population density as well, the water demand also remained low. However, irrigation showed low in all performance criteria. For irrigation area in MVG-TB subbasin, reliability and resilience did not exceed the threshold of 66% and 22%, respectively. The vulnerability and max decifit remain values of 42% and 78% respectively. Those values are considered high whereas the MVG-TB receives two of the three sections of the water diversion from San Francisco river with a total flow of 3.0 m³/s. If the growth rate of irrigation area remains as proposed in PRHVG it will perform as a high-risk activity.

There is no urban population on BVG subbasin because the municipalities are located outside the boundaries of the subbasin, because of this, this water user does not appear in Figure 2. The BVG has the largest irrigated area in entire Rio Verde Grande basin, so the irrigation area also showed relatively high reliability values but low resilience values for all scenarios proposed in the water plan. Once implemented all proposals for water development in the basin, the vulnerability fell from 65.6% to 51.4% and max deficit remained above 80%.

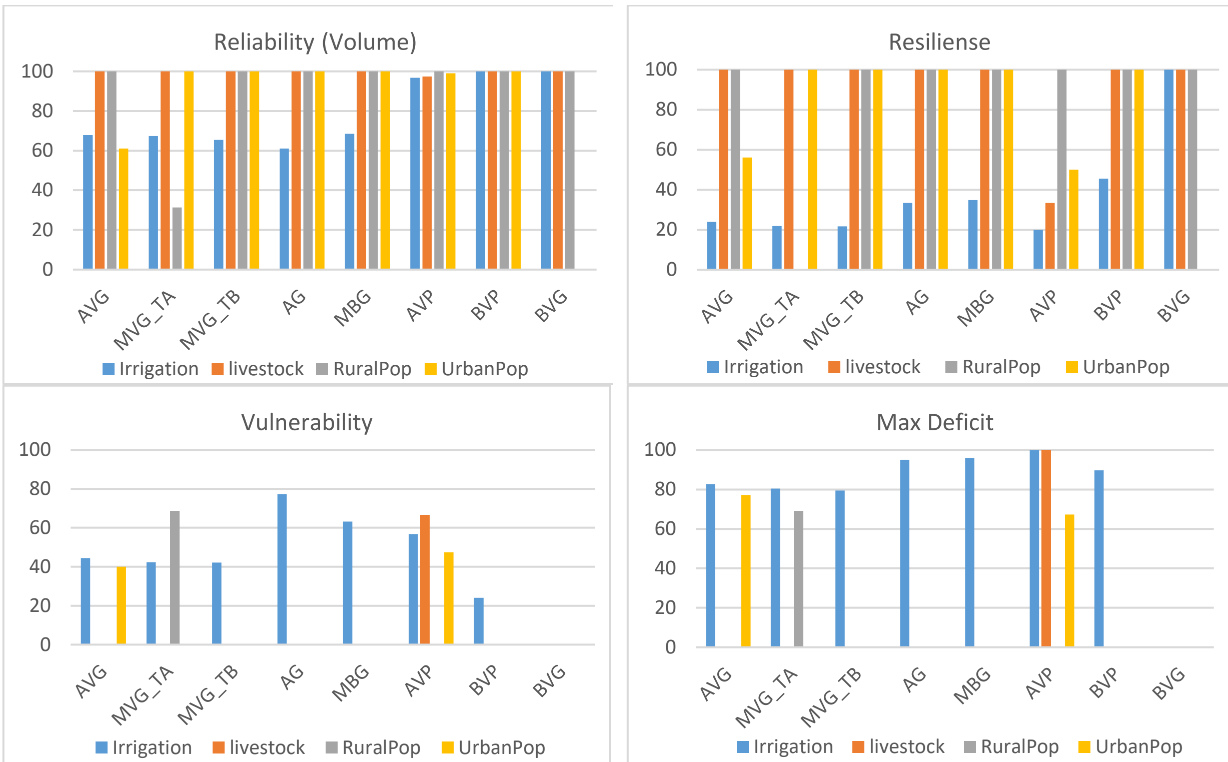

Figure 2. Performance criteria for Rio Verde Grande in Normative 2 scenario.

Sustainability index and sustainability by group of water resources of basin

A river basin as the Rio Verde Grande basin, with high demand and low water availability, it becomes difficult to identify actions that allow an improvement in the management of its water resources when evaluating performance criteria in isolation. Thus, SI and SG are tools that allow evaluation and comparison of actions to improve the management of water resources in a basin integrating multiple performance criteria.

It was calculated the Sustainability Index by group (SG) in order to analyze which activities are less sustainable and how the increase of water proposed by PRHVG contributes to improve this index (Figure 3). It can be seen that the four water users analyzed, the livestock presented the highest SG (above 90%) followed by the rural population (approximately 80% in Normative 2 scenario). However, the water supply to the basin through imports water, water diversions and reservoirs resulted in a small increase in the SG for irrigation, comparing with the reference scenario (Baseline). This shows that the growth of the irrigated area will result, if kept the growth of the rate activity in the basin as provided for in PRHVG, a water demand just a little below the water supply. Thus, irrigated area has low sustainability. The water activity for the urban population showed a considerable increase in the SG, as the Trend scenario, result of the large water supply from the import water of the Congonhas river with a flow of 2 m³/s. This action resulted in a 33.8% increase in SG, but the other actions did not result improvements in SG, significantly. Thus, irrigated area reaches a plateau of approximately 35% in SG (Figure 3). Whereas water supply for population is the top priority provided for in the PRHVG, the achieved value still retains this activity with a high value of vulnerability.

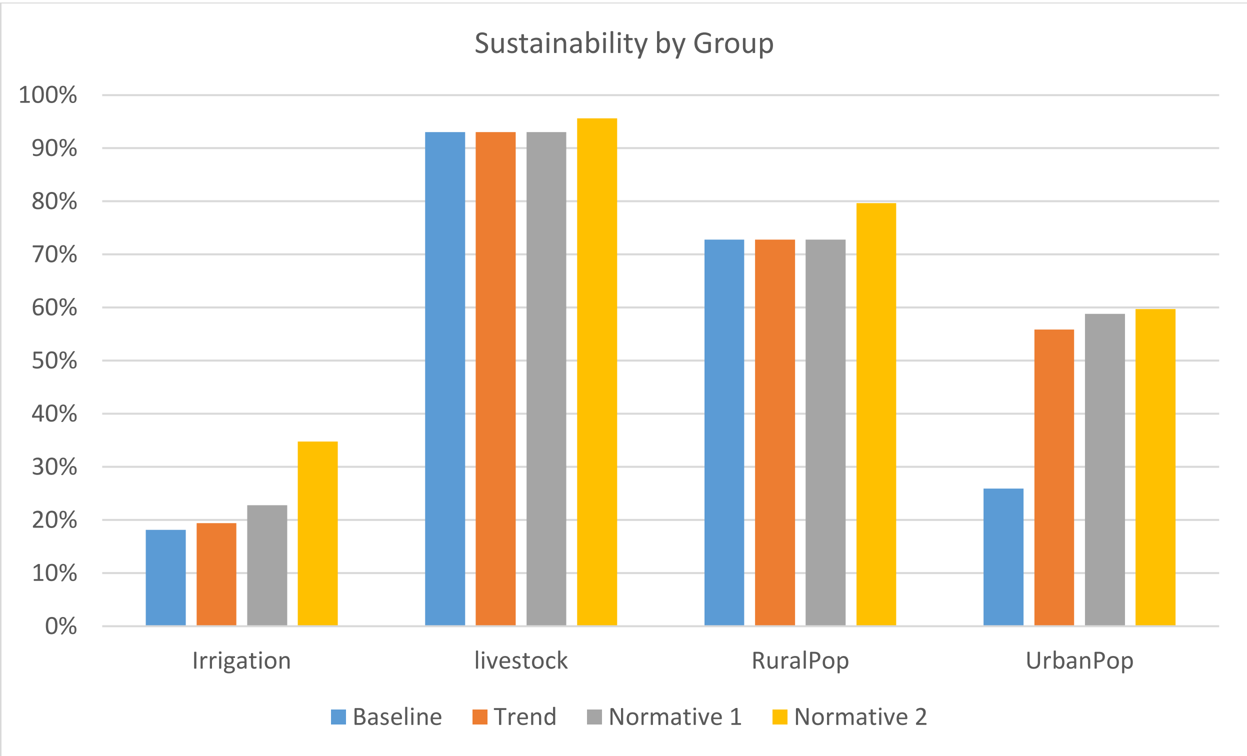

Figure 3 – Sustainability by group by water users

Figure 9 presents the Sustainability Index (SI) considering the entire basin without distinction of water users.

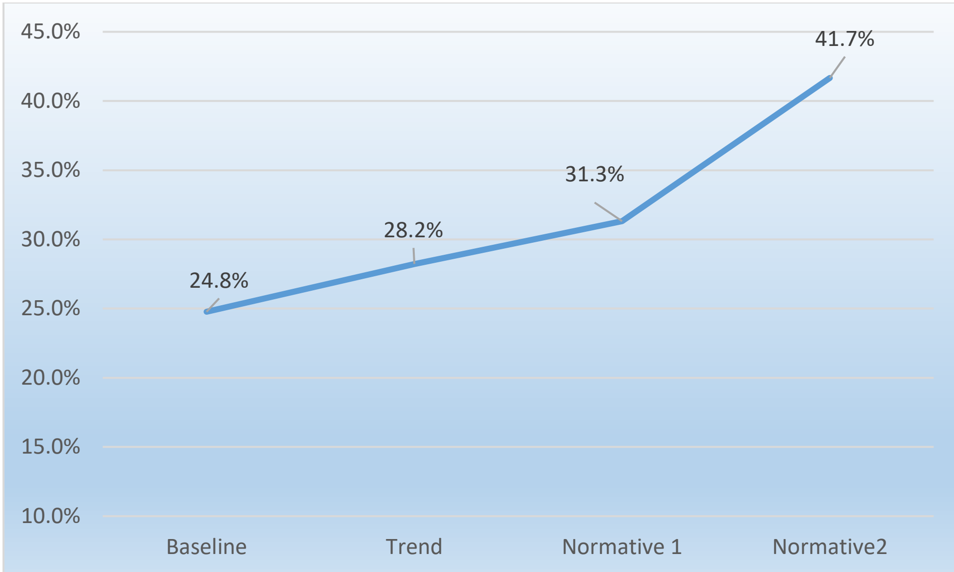

Figure 4 - Sustainability Index for entire Rio Verde Grande Basin

Figure 4 shows that compared to the baseline scenario there was an improvement in the SI, however, maintaining at low levels the sustainability of the entire water system of the basin. The Rio Verde Grande basin, after the implementation of the policies, changed SI only 16.9%, which is little in view of the increasing water demand considering the growth proposed by the PRHVG.

According SANDOVAL-SOLIS *et al.* (2011), the sustainability index of water resources does not replace any performance criteria and its goal is to make it easier to quantify and identify policies that provide improved water resources management process.

4. CONCLUSIONS

- The Sustainability Index (SI) has identified the actions of the Water Plan of water resources of the Rio Verde Grande Basin (PRHVG) that have improved the availability of water as expected until 2030.
- The Sustainability Index (SI) showed that the water available, although it has some improvements for some activities after the analysis of scenarios remains unsustainable presenting the Maximum Deficit still high.
- Comparison of the Sustainability by Group (SG) between different water users found that the actions foreseen in PRHVG improved the increase of water to the Urban Population in Alto Verde Grande subbasin (AVG)
- Considering the entire Rio Verde Grande basin, there were no significant improvements in water increase with the implementation of the policies proposed in PRHVG.

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