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## Article

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## Urban sustainability: Analyzing the water-energy nexus in the Guandu river basin, Rio de Janeiro, Brazil

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### Abstract

Urban sustainability has been one of the most important issues in the last decades. The modification of watercourses and their integration to power production facilities have resulted in severe environmental impacts around the globe. This study presents a sustainability analysis to examine the current state of the Guandu river basin Brazil. The approach includes the development of a hydrological model to simulate the stream flow, and an evaluation of the impacts of potential scenarios projected for 2035. Future scenarios included climate and land use change, and water transfers from surrounding basins. The results show that future scenarios might distress the total volume of water naturally captured in the basin mainly because of significant changes in precipitation patterns. Such changes could reduce the amount of water and electricity supply in the region, as well as the sustainability of water resources. The proposed model can be used as a decision making support tool to search for sustainable strategies for water and electricity distribution in highly urbanized systems.

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*Keywords:* Water-energy nexus; Hydrological model; Sustainable cities; Climate change

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### 1. Introduction

Over half of the world's population lives in cities and roughly 6.4 billion people will live in urban areas by 2050 [1]. Such an urbanization process has led to critical and irreversible changes in natural ecosystems [2]. This tendency pressures water resources considerably at national and regional levels worldwide and has significant implications for the water-energy nexus. Energy and water resources are intrinsically connected and are both

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important for economic development [3]. The management of environmental systems to accommodate the urban water-energy needs has been increasingly complex due to several unprecedented challenges including the rapid population growth and land use change, increasing welfare, industrialization, climate change, and expansion of infrastructure. In developing countries, in particular, water and energy supply has been considered “the big challenge” for the upcoming years because of the growth of megacities, with extremely large populations [4]. The metropolitan region of Rio de Janeiro (Brazil), with over 15 million inhabitants [5], is one of the most important megacities in the world with a strong dependency on water resources from one single basin, the Guandu watershed. This basin has a total area of 3500 km<sup>2</sup>, encompassing 15 municipalities in the state of Rio de Janeiro and homes the main industrial center of the State of Rio. It supplies water for approximately 10 million residents of the Rio de Janeiro metropolitan area, attending 85% of the total urban water demand, and is a key provider of energy to the integrated electric system in Brazil. Such water-energy capacity is a result of a series of engineering modifications that started in the '30s that culminated in five reservoirs (Lajes, Santana, Tocos, Vigarão and Pereira Passos); three hydroelectric plants (UHE Fontes-Lajes, UHE Vigarão, UHE Pereira Passos); one water treatment plant (ETA-Guandu) and two water transfers by pumping from Paraíba do Sul river basin (Fig. 1) [6,7]. Given the socio-economic importance of the Guandu basin, conservation strategies are fundamental to support the water resources needed to attend the water and energy demands from this basin. The main purpose of this study is to analyze the current hydrologic state of the Guandu river basin and to evaluate the impacts of different scenarios (climate and land use change, and water transfer) and their interactions on water supply. Also, a preliminary analysis of the interrelationship between water and energy is presented. We hope that this research can inform local stakeholders on water and energy security from the Guandu river basin for Rio de Janeiro, which may help to develop appropriate mitigation strategies.

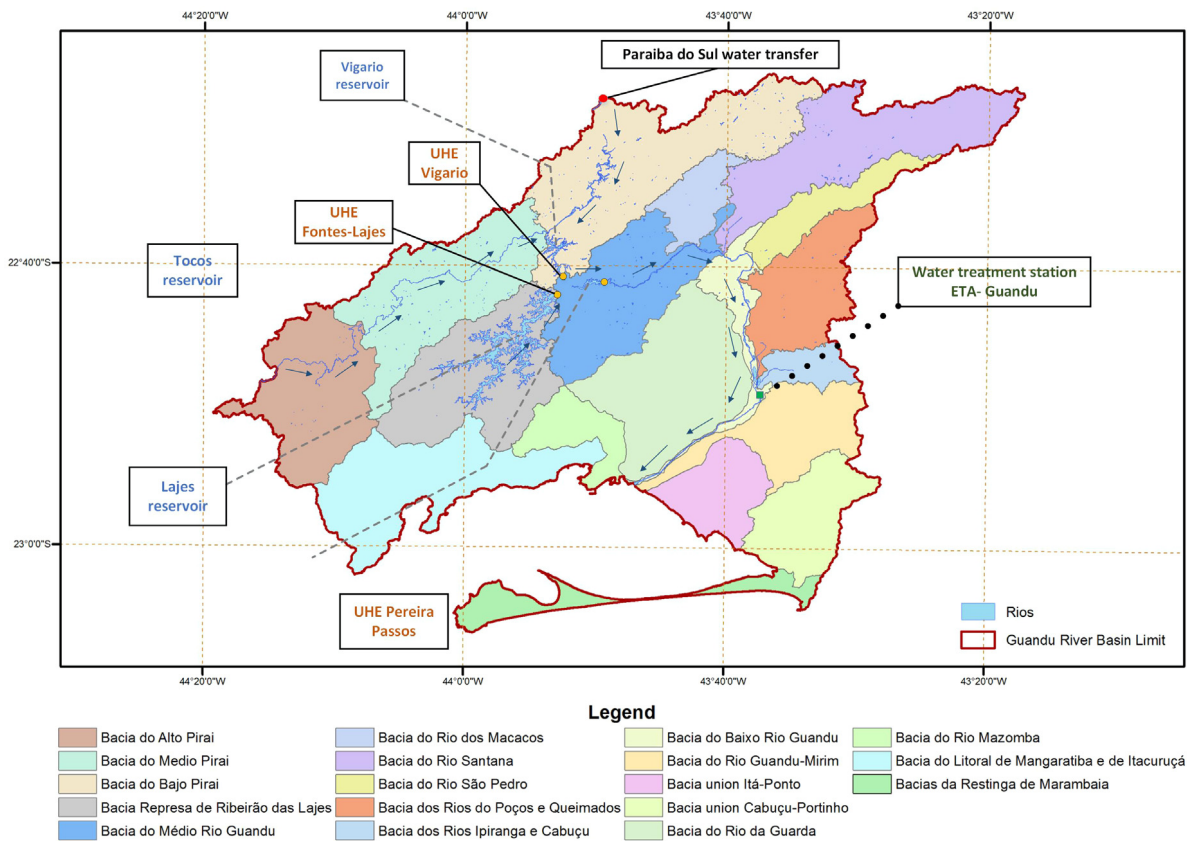


Fig. 1. General overview of the Guandu basin and its 17 sub-basins used in this research.

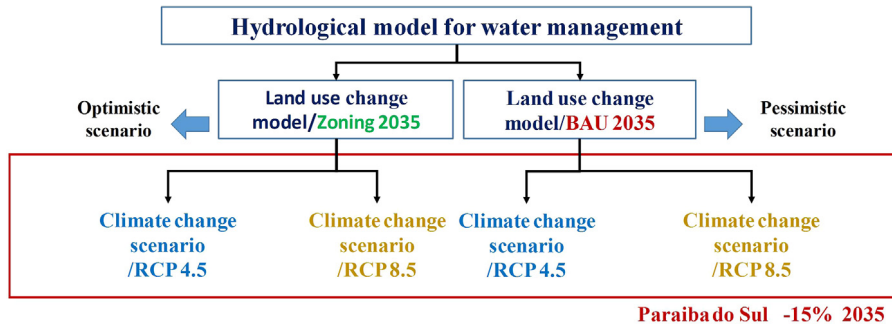


Fig. 2. A general framework for the analysis of water resource management in Guandu basin.

## 2. Methods

The general framework for the sustainability analysis of water resource management in the Guandu basin is presented in Fig. 2. The main components of this approach include a hydrological model, water transfer model, climate change (representative concentration pathways, RCP 4.5 and RCP 8.5) and land use scenarios (Business as usual, BAU and Zoning). These components were integrated to generate streamflow to describe the responses under various potential future scenarios while assessing water security in the Guandu basin.

### 2.1. Hydrological model development

The hydrological model for the Guandu basin was developed using Aquatool software [8] to reproduce the observed annual stream flows. It includes precipitation, evapotranspiration, and average air temperature as input data. Also, the simulation platform allows to include parameters related to the vegetation coverage, such as maximum soil moisture capacity ( $H_{max}$ ) and maximum infiltration ( $I_{max}$ ) that are parameters regulating the distribution of excess water between surface runoff and infiltration into the aquifer [9,10]. For Guandu, the model was calibrated using observed daily precipitation and air temperature for the period from 1990 to 2018 (28 years) data from official Brazilian databases [11–13]. From 119 pluviometry stations that were available only 14 had sufficient data for model calibration. Similarly, eight (out of 12) meteorological stations had the required temperature data for the analysis. The daily precipitation and the mean air temperature data were averaged for each sub-basin (Fig. 1) using the Thiessen polygon method [14]. Potential deviation of model input due to spatial averaging of precipitation was corrected with a constant multiplicative factor estimated in the calibration process. The calibration was performed using the automatic Aquatool calibration module [15]. The model included the 17 sub-basins described in Fig. 1, the modeled water-power system (considering two water transfers from surrounding basins, 5 reservoirs, and 3 hydropower plants). The comparison of observed versus simulated historical monthly precipitation for the Guandu river basin gave a coefficient of determination ( $R^2$ ) between 0.71 and 0.93 considering the results for each sub-basin, and a Nash Sutcliffe efficiency coefficient which varies from 0.70 to 0.91. The mean absolute error, calculated between the time series and the simulated streamflow, varied between 0.08–0.13.

### 2.2. Climate change scenarios

The CSIRO-Mk3.6.0 climate system model (GCM) for Guandu was downscaled [16] through the Statistical Downscaling Model (SDSM) [17] using historical datasets, global land data assimilation system (GLDAS) [18] and re-analysis (ERA-Interim) [19]. The projected daily future climate variables (air temperature and precipitation) were downscaled for a 2.5 km<sup>2</sup> grid point. The training dataset for the period 1981–2010 was applied to GCM projections (2011–2035) using two commonly used Representative Concentration Pathways (RCPs) to represent an optimistic and a pessimistic future: RCP4.5 (greenhouse gas emissions peak around 2040, then decline) and RCP8.5 (greenhouse gas emissions continue to rise throughout the 21st century).

### 2.3. Land use scenarios

The land use change scenarios for the Guandu basin were simulated using the GIS IDRISI Land Change Modeler [20] using as input available land use data sets for the years 2007 and 2015 [21]. Areas such as “clouds” or “shadows” were reclassified based on their predominant class of surrounding land cover to reach 11 total classes. The two sets of data determined the “demand” for different land uses between 2007–2015. To assess the geographical factors that influenced the change in land use during the period, we used data on the road network [5], slope and elevation [5] and proximity to urban and degraded land. Two scenarios were projected to 2035: Business as usual (BAU) where there is no special consideration to conservation environmental restoration measures; and Zoning scenario, based on the assumption that existing conservation and environmental restoration plans might restrict urbanization.

### 2.4. Trans-basin scenario

An additional scenario was included to assess the implications of the transferred flow from surroundings basins. A possible 15% reduction is expected in the volume of water transferred from other basins, according to the projection made by the Brazilian Panel on Climate Change and the Intergovernmental Panel on Climate Change [7].

## 3. Results and discussion

### 3.1. Simulated monthly averaged streamflow

Streamflow for the 17 watershed included in the analysis clustered into two regions (Fig. 3). One region including discharge from watersheds that presented accumulated discharge volumes above 200 hm<sup>3</sup>, these basins were those receiving flows from the Paraíba do Sul basin, and a second one corresponding to watershed with discharge volumes below 100 hm<sup>3</sup>. The basins in the group do not receive flows from any transposition systems, thus represent the natural runoff of those catchments. This finding is critical for the Guandu basin given the implications for the average water availability through the year (see Table 1). It can be observed that flows transferred from the Paraíba do Sul river basin represents ~80.6% of the total volume in the Guandu river and the volume transferred from the

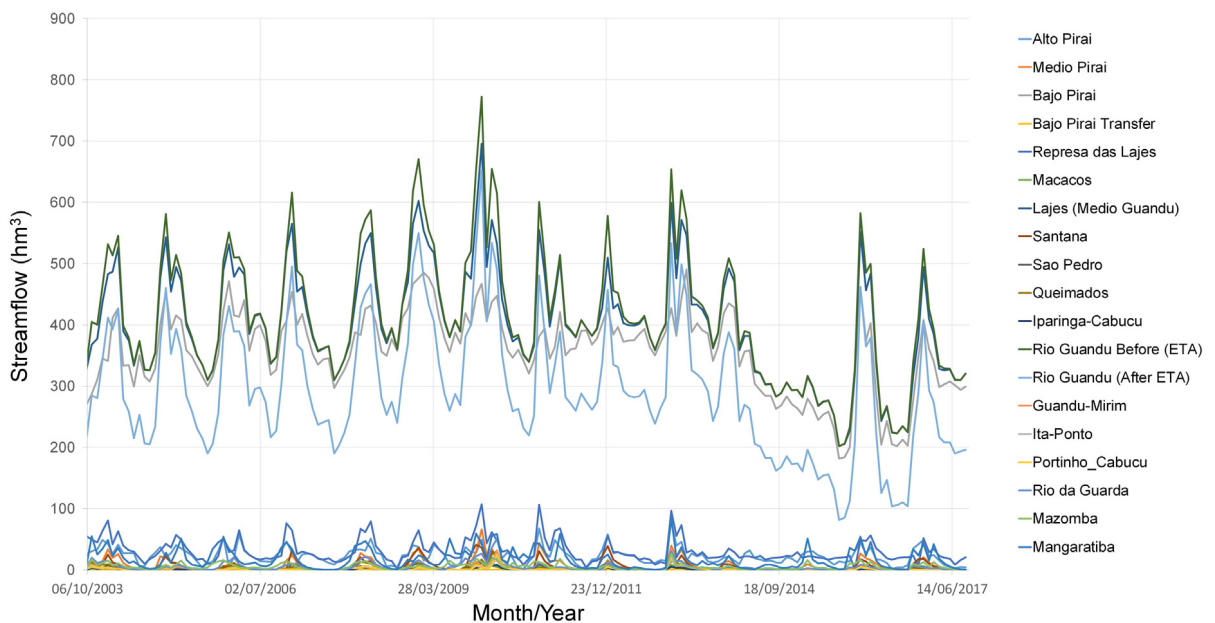


Fig. 3. Monthly streamflow in the Guandu river basin.

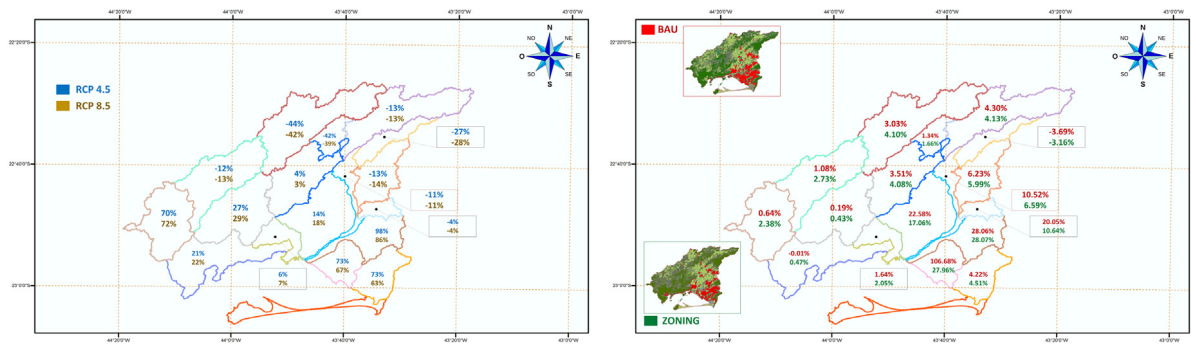
**Table 1.** Annual averaged water availability in the Guandu river basin.

Water source	Averaged streamflow (m <sup>3</sup> /s)	%
Transfer from Paraíba do Sul river	119.00	80.6
Transfer from Rio Pirai	20.00	13.5
Ribeirão das Lajes sub-basin contribution	5.50	3.7
Rio Guandu contribution	3.18	2.2
Total	147.68	100

Pirai river represents ~13.5%, whereas the natural flow represents only ~6% of the total volume of water. This corroborates the high hydrologic engineering state of the Guandu basin and its high dependence on the surrounding basins, particularly the Paraíba do Sul.

### 3.2. Streamflow sensitivity to climate change

The results related to the integration of climate change scenarios into the hydrological model revealed a generalized decrease in the total volume of water for the North and Northeast (NE) sub-basins. In contrast, there was an increasing trend for the Southwest (SW) region. This behavior is similar for both climate scenarios (RCP 4.5 and RCP 8.5) as seen in Fig. 4a showing the estimated variation in projected flows with respect to the historical data for each sub-basin. According to these calculations, the lowest volumes of water occur in the lower Pirai basin with possible flow reductions of up to 44% and 42% for the RCP 4.5 and RCP 8.5 scenarios, respectively. In contrast, the Guandu-Mirim sub-basin shows possible flow increases of 98% and 86%, corresponding to RCP 4.5 and RCP 8.5 respectively.



**Fig. 4.** Modeled streamflow deviations from baseline considering (a) climate change and (b) land use change scenarios.

### 3.3. Streamflow sensitivity to land use change

The projections obtained from the integration of land use change scenarios are presented in Fig. 4b, showing the percentages of change with respect to the historical data (2001–2018). The variations suggest possible increases in the total accumulated volume, mainly in the basins in the south, which are affected by urban expansion (Ita-Ponto, Canal do Guandu and Rio da Guarda).

### 3.4. Streamflow sensitivity to water transfers

Given the dependence of the Guandu basin on flows from the Paraíba do Sul, the most significant result from a management perspective is the potential reduction of the flows transferred from the Paraíba do Sul basin due to climate change in the coming years. The model indicates that such reductions could occur from 2019 onwards and that the magnitude of the reduction is greater for the period between 2025 and 2035. These results can inform the development of mitigation strategies and sustainable water management policies promoting the conservation and restoration of natural areas in the basin.



### 3.5. The water-energy nexus

The results indicated a strong link between the energy sector and the water transfer, which is mainly used to produce energy in the hydropower complex. This can be concluded because the average water transfer from Paraíba do Sul river basin is 139 m<sup>3</sup>/s and the natural flows from Guandu river basin contributes with just 9 m<sup>3</sup>/s, totaling 148 m<sup>3</sup>/s. The water concession from the water treatment plant is 45 m<sup>3</sup>/s, 57 m<sup>3</sup>/s are used to supply the natural water demand of the basin itself, and there are 46 m<sup>3</sup>/s, which represent non-accountable demand. It means that the amount of water transferred from Paraíba do Sul it is not just to satisfy the demand for water in Rio de Janeiro (which is 45 m<sup>3</sup>/s), in fact, it has a first purpose to generate enough power to provide electricity the state of Rio de Janeiro and to run the total nominal capacity of 612 MW installed in Lajes complex [6]. Recent studies in the US and Australia show that the net freshwater needed to produce energy in hydropower plants is in the range of 11 m<sup>3</sup>/GW to 17 m<sup>3</sup>/GW [22]. In the case of the Lajes complex, the averaged value is 13.5 m<sup>3</sup>/GW. Therefore, this is clear evidence that there is an amount of water that can be optimized to guarantee the water supply in the city of Rio de Janeiro and the metropolitan area.

## 4. Conclusion

This study described the development of a hydrological model for the Guandu basin and involved the simultaneous analysis of climate and land use change scenarios, as well as the integration of the water transfers from surrounding basins. The main contribution of this study is that it uncovers the high dependency of the transferred water from the Paraíba do Sul. This is because the most significant changes in flow were associated with alteration of precipitation patterns that might reduce available water in the Paraíba do Sul, consequently, to the Guandu basin. This calls the attention of government agencies and the private sector to prevent a water-energy crisis in the upcoming years as 85% of the water for the metropolitan region of Rio de Janeiro comes from Guandu. The results also implicate to the energy sector due to the hydroelectric system located in the watershed that represents the priority actor in water transfer from Paraíba do Sul as there is a potential to optimize and develop water management strategies in the Guandu basin. Future work includes the development of optimization methodologies that visualize optimal strategies for water resources management taking into account the electricity sector, water users, and the sustainability of the region's natural resources.

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