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Dynamic and maintenance of water purification ecosystem service in the Guandu River Hydrographic Region, Rio de Janeiro, Brazil

Dinâmica e manutenção do serviço ecossistêmico de manutenção da purificação da água na Região Hidrográfica do Rio Guandu, Rio de Janeiro, Brasil

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ABSTRACT

The present study aimed to develop a methodology for analyzing the dynamics and maintenance of the water purification ecosystem service in the water bodies of the Guandu River Hydrographic Region, responsible for water supplying the Rio de Janeiro Metropolitan Region, characterized by the presence of water transfers and low levels of effluent treatment. The dynamics of this service occurs through an ecosystem flow, influenced by the volume of water that moves from one region to another. The methodology consisted of reviewing studies of ecosystem flows, building a database, classifying impacts on water purification in hydrological planning units from a similarity dendrogram, analyzing indicators related to water demands and availability of these units, and developing an ecosystem flow diagram of water purification. The effects of transfers on the maintenance and flow of water purification were also analyzed from the comparison between the real scenario (which considers the presence of the existing hydraulic infrastructure) and the natural scenario (which disregards it). The results showed that the worst situation of maintenance of water purification is in the western part of the region, and the demands for it requires more than double the volume of withdrawn water to supply the local population and industry.

Keywords: Ecosystem service flow; Water pollution; Water quality maintenance.

RESUMO

O presente estudo teve como objetivo desenvolver uma metodologia para análise da dinâmica e manutenção do serviço ecossistêmico de purificação da água nos corpos hídricos da Região Hidrográfica do Rio Guandu, responsável pelo abastecimento de água da Região Metropolitana do Rio de Janeiro, caracterizada pela presença de baixos níveis de tratamento de efluentes. A dinâmica desse serviço ocorre por meio de um fluxo ecossistêmico, influenciado pelo volume de água que se desloca de uma região para outra. A metodologia consistiu em revisar estudos de fluxos ecossistêmicos, construir um banco de dados, classificar impactos na purificação de água em unidades de planejamento hidrológico a partir de um dendrograma de similaridade, analisar indicadores relacionados à demanda e disponibilidade hídrica dessas unidades e desenvolver um fluxograma ecossistêmico de purificação de água. Os efeitos das transposições na manutenção e no fluxo da purificação da água também foram analisados a partir da comparação entre o cenário real (que considera a presença da infraestrutura hidráulica existente) e o cenário natural (que a desconsidera). Os resultados mostraram que a pior situação de manutenção da purificação da água está na parte oeste da região, e que as demandas por este serviço ecossistêmico exigem mais que o dobro do volume de água captada para abastecer a população local e a indústria.

Palavras-chave: Fluxo de serviços ecossistêmicos; Poluição hídrica; Manutenção da qualidade da água.

INTRODUCTION

Access to clean water and sanitation is considered a fundamental right by United Nations and is directly related to Sustainable Development Goal (SDG) 6, Clean Water and Sanitation, and ODS 2, Zero Hunger, which composes the 2030 Agenda for Sustainable Development (Organização das Nações Unidas, 2016). Despite this, the universality of the water access is still far from being a global reality, especially in underdeveloped countries (Borja & Moraes, 2020). In Brazil, 35 million people don't have treated water and only 46% of the effluents generated are treated, as a consequence water pollution is one of the main socio-environmental problems of the country (Azevedo & La Poente, 2022; Brasil, 2019).

Ecosystem services (ES) are understood as "the benefits that people obtain from ecosystems", according to the definition of the Millennium Ecosystem Assessment (2005). Water or hydrologic ecosystem services are the benefits obtained by society related to water bodies, such as the water supply for nutrition, the support of aquatic life, and the regulation of the conditions of the aquatic environment (Brauman et al., 2007). The dilution of effluents by water bodies is another important water ecosystem service (WES), which counterbalances human impacts and prevents sanitary collapses in urban regions with low levels of effluent treatment (Tavares et al., 2019; La Notte & Dalmazzone, 2018).

Despite the growing interest in the topic of ecosystem services, and its importance for the development of Watershed Management Plans, the use of this approach for managing water resources has been hampered by the lack of practical definitions and methodologies (Mengist et al., 2020). Mengist et al. (2020) suggest the use of sustainability indicators, combining information on capacity and flows of ecosystem services, which has been a trend in the literature (Schirpke et al., 2019; Shi et al., 2020; Verhagen et al., 2017; Goldenberg et al., 2017).

The dynamic of ES, in general, can be synthesized by the interaction of three processes in ecosystems: production (of ES and benefits), use (by beneficiaries), and flow (transmission of nature benefits to society) (Bagstad et al., 2013). Production is widely addressed in studies that quantify the benefits obtained by societies, but they often do not reflect the location of beneficiaries or the spatial and temporal flow of services, which information is fundamental for the analysis of the security of populations about the benefits received.

The flow of an ES depends on an intermediate agent that carries the benefit, the corresponding provision or natural regulation, the physical attributes of the landscape, and the presence of natural features or anthropogenic changes. In the case of water supply and regulation services, the water is the intermediate agent of the flow. On the way between the ecosystems that produce these WES and the beneficiaries that consume them, there is a depletion in their availability, and the understanding of this flow is extremely important for the water security of populations (Villa et al., 2014).

Based on these concepts, the purpose of the present study was to develop a methodology for analyzing the dynamics and maintenance of the water purification ecosystem service (WPES) in the water bodies of the Guandu River Hydrographic Region. It is a region of fundamental importance for the water supply of the Metropolitan Region of Rio de Janeiro state, but it has suffered from the precariousness of the sewerage system. This fact justifies the search and compilation of information and advancement of knowledge to support the development of tools to facilitate decision-making regarding water resources in this region.

Analysis of the flow of ESs can provide very useful information, like the quantification of the difference between the benefits acquired by societies and the productive potential of an ecosystem, contributing to greater precision in the valuation of ESs, or by identifying patterns of distribution of ESs (Syrbe & Walz, 2012; Burkhard et al., 2012; Palomo et al., 2013). In the case of the study area, it is considered that the information obtained can be of great value to support decision-making, resource allocation, compensation measures, Payment for Environmental Service (PES) programs, among others, aimed at improving the socio-environmental conditions related to the HR-II water bodies.

More specifically, the WES studied and which to simplify understanding was called water purification ecosystem service (WPES) in the present study, in theory was the "regulation of the biochemical conditions of the water by diluting effluents in water bodies", within the regulation and maintenance (biotic) section, based on the most recent version (V5.1) of the Common Classification of Ecosystem Services (CICES). This is the most popular system used to classify ES, especially in Europe (Costanza et al., 2017; Haines-Young & Potschini, 2018). CICES is not intended to replace other classification systems, such as that proposed by Leemans & Groot (2003), in the "Millenium Ecosystem Assessment", but allowing studies to move more easily between them, and that people understand more clearly how measurements and analyzes are made. It presents broad equivalence with the main existing ES classification systems.

MATERIAL AND METHODS

Study area

The study area (HR-II) is one of the regions defined in the Resolution of the Rio de Janeiro State Water Resources Council, number 107, May 22, 2013 (Rio de Janeiro, 2013). It is located in the Southwest region of the state and covers the watersheds of the rivers Guandu, Guandu Mirim, and Guarda, besides two other watersheds, in the southeastern region of Brazil. The HR-II also comprises the state part of the Pirai River watershed, a tributary of Paraiba do Sul River. The hydraulic infrastructure of this region is characterized by the presence of the Lajes Hydroelectric Complex, which comprises seven power plants, three of which are generators, two are pumps, and six are water reservoirs. The pumps of Santa Cecília and Vigario are responsible for 155 $m^3.s^{-1}$ of water transfer from the Paraiba do Sul and the Piraí rivers in the Paraiba do Sul watershed to the Guandu River watershed (1,400 km^2) (Associação Pró-gestão das Águas da Bacia Hidrográfica do Rio Paraíba do Sul, 2018).

The map presented shows the distribution of the hydrological planning units (HPU) of the HR-II, which were defined according to the homogeneity of the physical, socioeconomic, cultural, political-administrative, and institutional conditions focused on water resources, following the Strategic Plan for Water Resources for the Guandu, Guarda and Guandu-Mirim River watersheds

(Associação Pró-gestão das Águas da Bacia Hidrográfica do Rio Paraíba do Sul, 2018) (Figure 1). HPU 13 – Islands and Restinga de Marambaia were not considered in this study because they are out of the continent part of the HR-II.

Methodological framework

The study methodology can be divided into five steps. Initially, a survey of HR-II data was carried out to characterize the HPUs and perform the proposed analyses. The second stage was the classification of HPUs according to the impact class of effluent release, based on a similarity dendrogram. The third stage was to calculate and analyze WPES maintenance based on indicators. Then, a comparison was made between the WPES demand and the ES water supply demand based on indicators (4th stage). Finally, a diagram of the flow of this ES was constructed and an analysis of the effects of transpositions on this flow was carried out (5th stage). Figure 2 presents the steps and methods applied in the current study.

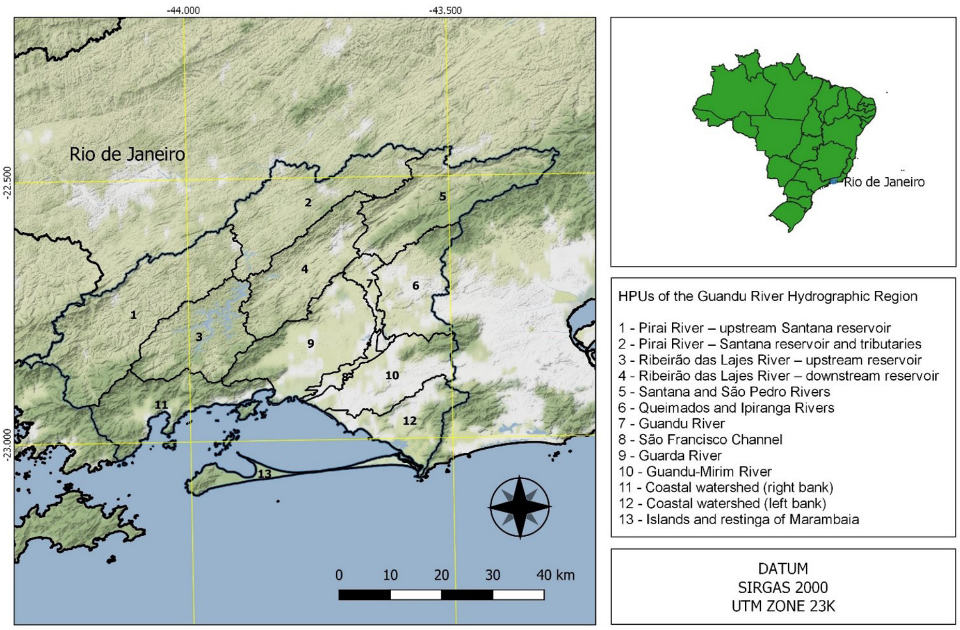

Figure 1. The HR-II subdivisions in hydrological planning units.

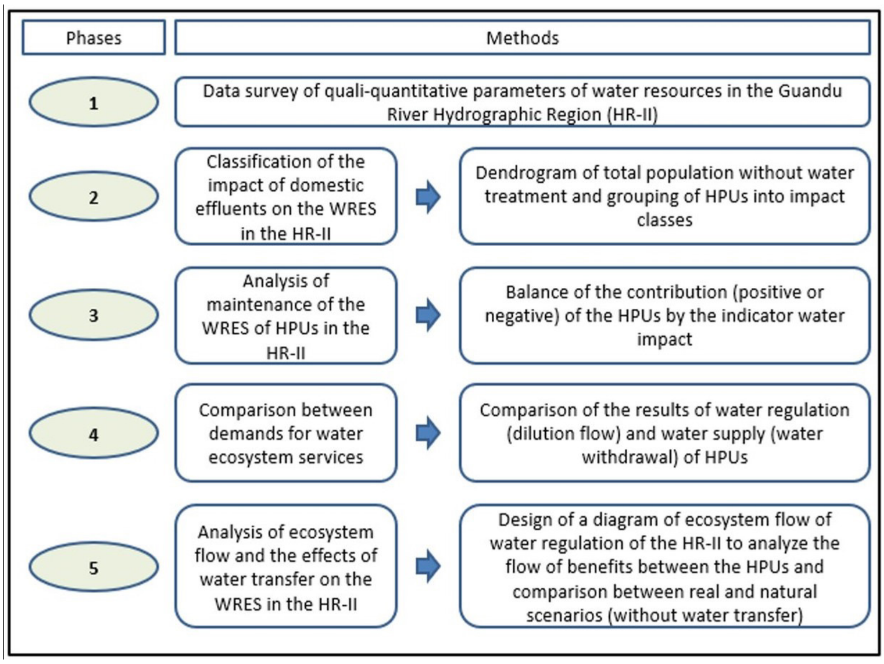

Figure 2. Methodological framework of the current study.

The analysis methodology focused on the ES of "regulation of the biochemical conditions of the water by diluting effluents in water bodies", based on the CICES classification, being named in the study as water purification ES (WPES). However, it is important to clarify that the ES of water purification, which is a ES of regulation, exerts and receives influence from other hydrological services, related to the demand and supply of water (water supply), for example. In this sense, the other water ES mentioned in the study were treated in a complementary way and to help in the discussion around the WPES.

Data survey

Initially, a database including was organized in an Excel spreadsheet to support the analyzes carried out in this study. The data were obtained from a variety of sources and can be found in the Strategic Water Resources Plan for the Guandu, Guarda and Guandu-Mirim River Basins (SWRP Guandu) (Associação Pró-gestão das Águas da Bacia Hidrográfica do Rio Paraíba do Sul, 2018). The data are and were related to. the general characterization of the HPUs (Rio de Janeiro, 2013; Agência Nacional de Águas e Saneamento Básico, 2006), demography (Instituto Brasileiro de Geografia e Estatística, 2010), sanitary sewage (Brasil, 2019; Agência Nacional de Águas e Saneamento Básico, 2006), water availability (Agência Nacional de Águas e Saneamento Básico, 2023; Agência Nacional de Águas e Saneamento Básico, 2006), water demands and framing of the rivers (Associação Pró-gestão das Águas da Bacia Hidrográfica do Rio Paraíba do Sul, 2018).

The data used to obtain the results of the HPUs impact classification and WPES maintenance are presented in Table 1.

A brief analysis of the data shows that HPU 7 and HPU 8 present the greatests water availability in terms of natural and modified flow (actual, altered by transfers), respectively. There is an increase in water availability due to water transfers when compared to their original situation in HPU 4, as well as in HPU 7 and HPU 8. Most of the water withdrawal to the Metropolitan Region of Rio de Janeiro State occurs in these three HPUs, whereas the main water abstraction for supplying the population is in HPUs 4 and 7, while HPU 8 is the main water abstraction for industries and thermoelectric supplies. Unlike the aforementioned HPUs, HPUs 1 and 2, in the headwaters of the Pirai River, present a modified water availability, lower than the natural one due to water transfers (Associação Pró-gestão das Águas da Bacia Hidrográfica do Rio Paraíba do Sul, 2018).

The effluent treatment index (ET%) of the HPUs presented in Table 1 varies between 2.8% (HPU 2) and 27.2% (HPU 11). And the largest total populations without effluent treatment are from the HPUs in the eastern portion of the HR-II: HPU 10, with 653,953 people without treatment, followed by HPUs 6 (295,259) and 12 (266,413). This low ET% in urban and populous regions such as these HPUs has a great impact on the quality of life of these populations, who are exposed to unhealthy conditions, in addition to other consequences, such as damage to wildlife, especially fish and other aquatic living beings, and increase of water treatment costs to make it fit for consumption, which become higher the worse the quality of the water that reaches the treatment plant.

Classification of the impact of domestic effluents on the water purification ecosystem service

The classification of the impacts of the release of domestic effluents on HPUs' water bodies was based on the methodology presented in Tavares et al. (2019), and it was developed using a similarity test for the total population without effluent treatment, which is proportional to the total domestic organic load released by HPU. For this, the free software Past (Paleontological-Statistics software package for education) was used, which is a dendrogram generator based on the similarity of elements used in Paleontology, but that can also be applied to other areas of knowledge. It allows the formation of clusters, using a data matrix entered by the user and multivariate classification techniques.

The sanitation data used are provided by HPU, and they are the estimated population (from IBGE census data) and effluent treatment index (Associação Pró-gestão das Águas da Bacia Hidrográfica do Rio Paraíba do Sul, 2018).

The euclidean distance among HPUs was applied as the similarity measure. The number of classes was defined based on the principle of balancing the highest possible level of similarity

Table 1. Water availability: modified ($Q_{av_{(mod)}}$) and natural ($Q_{av_{(nat)}}$), water withdrawal (Q_{wd}), effluent treatment index (ET%) and population without effluent treatment (PWET) from HPUs of the HR-II.

HPU	Name	$Q_{av_{(mod)}}$ (m³ s⁻¹)	$Q_{av_{(nat)}}$ (m³ s⁻¹)	Q_{wd} (m³ s⁻¹)	ET%	PWET
1	Pirai River – upstream Santana reservoir	2.21	5.79	0.116	5.3	22,253
2	Pirai River – Santana reservoir and tributaries	1.97	7.56	0.165	2.8	62,363
3	Ribeirão das Lajes River – upstream reservoir	10.03	2.54	0.233	7.2	1,324
4	Ribeirão das Lajes River – downstream reservoir	122.04	4.63	6.037	25.2	45,084
5	Santana and São Pedro Rivers	3.82	3.82	1.267	6.4	25,188
6	Queimados and Ipiranga Rivers	2.47	2.47	0.942	14.4	295,259
7	Guandu River	126.33	8.92	50.933	24.1	22,558
8	São Francisco Chanel	126.47	9.05	27.963	24.7	19,800
9	Guarda River	2.53	2.53	0.295	10.7	153,144
10	Guandu-Mirim River	1.49	1.49	0.507	21.5	653,953
11	Coastal watershed (right bank)	3.6	3.6	0.424	27.2	19,852
12	Coastal watershed (left bank)	1.15	1.15	0.178	20.1	266,413

within the classes, considering a practical and reasonable number of them, which resulted in four defined impact classes: low, medium, high, and very high.

Analysis of the maintenance of water purification ecosystem service

The capacity of maintenance of WPES was measured using the water impact indicator of HPUs, a parameter related to the self-purification capacity of water bodies, obtained from the integration of three sub-indicators: effluent dilution flow (Q_{dil}), water withdrawal (Q_{wd}), and water availability (Q_{av}) in the HR- II.The effluent dilution flow (Q_{dil}) is the flow required for the dilution of an effluent in a water body, depending on a certain parameter of water quality, such as the biochemical oxygen demand (BOD), and is based on the mixture equation (Equation 1), used by the National Water Agency for the management of water grants (Agência Nacional de Águas e Saneamento Básico, 2013). It is calculated based on the class in which the water body receiving the effluents falls according to CONAMA Resolution 357 (Brasil, 2005), and represents how much water a user appropriates to dilute their effluents (Agência Nacional de Águas e Saneamento Básico, 2013).

$$Q\,dil_x = \frac{Q_{eff} * C_{eff} - C_{max}}{C_{max} - C_{nat}} \tag{1}$$

Where:
Q_{dil_x} - effluent dilution flow of a pollutant "x" in a river stretch ($m^3\ s^{-1}$);
Q_{eff} – flow of the efluente released by user ($m^3\ s^{-1}$);
C_{eff} – concentration of the pollutant released in the local ($mg\ L^{-1}$);
C_{max} – maximum concentration of the pollutant allowed in the water body, according to the standard criteria ($mg\ L^{-1}$);
C_{nat} - natural concentration of the pollutant in the water body (considered equal to zero in this study) ($mg\ L^{-1}$).

Two types of water availability data were used in this study, corresponding to Q_{95}, which is the waterflow guaranteed to remain 95% of the time: modified Q_{av}, which considers the hydraulic infrastructure in the HR-II which changes the natural flow of the rivers; and natural Q_{av}, which disregards it, being the hypothetical natural flow, in case there had not been executed hydraulic interventions, especially the transfer of Piraí and Paraíba rivers.

HPUs water impact (WI%) quantifies in percentage terms the relationship between the water volume needed for HPUs effluent dilution (domestic and industry effluents) and the actual water volume for this dilution taking into account the existing water withdrawal, which reduces the water availability of the rivers (Agência Nacional de Águas e Saneamento Básico, 2013; Instituto Estadual do Ambiente, 2014) (Equation 2). This indicator was calculated for the real (taking into account the modified water availability) and natural (taking into account natural water availability) scenarios to assess the effect of transfers on the maintenance of WPES.

$$WI\% = \frac{Q_{dil_{tot}}}{Q_{av_{res}}} 100 \tag{2}$$

Where:
$WI\%$ - water impact (%);
$Q_{dil_{tot}}$ - total dilution flow ($m^3\ s^{-1}$);
$Q_{av_{res}}$ – resulting water availability (water availability minus water withdrawal) ($m^3\ s^{-1}$).

WI% values greater than 100 indicate that the resulting water availability of HPU is not able to dilute the effluents released by it. Values less than 100 denote a potential contribution to the dilution of effluents of external sources from HPU (Associação Pró-gestão das Águas da Bacia Hidrográfica do Rio Paraíba do Sul, 2015). The results of WI% of HPUs of the HR-II in both scenarios were used to classify them, in terms maintenance balance of WPES, being considered negative, when WI% is greater than 100; and positive, when WI% is less than 100.

Comparison between demands for water ecosystem services

A comparison was made between the demands for water purification, which refers to the benefit obtained from water bodies by diluting discharged effluents (represented by Q_{dil}), and water supply, understood as the total water abstracted for supply (Q_{wd}), ecosystem services. The sum of these demands composes the "total demands" (D_t) of HPUs, considering the volume of water needed to supply these services. Thus, the total demands were calculated (Equation 3), as well as the relative share of each water ecosystem service, in percentual terms (Equations 4 and 5)

$$Q_{dil} + Q_{wd} = D_t \tag{3}$$

$$D_r = \frac{Q_{dil}}{D_t} 100 \tag{4}$$

$$D_s = \frac{Q_{wd}}{D_t} 100 \tag{5}$$

Where:
Q_{dil} - dilution flow in a river stretch ($m^3\ s^{-1}$);
Q_{wd} - water withdrawal ($m^3\ s^{-1}$);
D_t - total demands for water ecosystem services ($m^3\ s^{-1}$);
D_r - relative demands for WPES ($m^3\ s^{-1}$);
D_s - relative demands for water supply ecosystem service ($m^3\ s^{-1}$).

This comparative analysis was applied only for the actual scenario, seeking to create subsidies for policies that aim to meet the demands for those water ecosystem services.

Analysis of water purification ecosystem service flow and the effects of the transfers

For the analysis of the WPES flow, and the effects of the transfers on it, the results of the indicator WI% were combined with the characteristics of the hydrography of the HR-II to build diagrams, from a base diagram, representing the transfers of the carrier agent (water) from one compartment (HPU) to the other, and the contribution of HPUs to the maintenance of the WPES, in a comparative way between the two scenarios: actual and natural.

RESULTS AND DISCUSSION

Classification of the impact of the release of domestic effluents on the water purification ecosystem service

The similarity dendrogram generated from the total population without access to effluent treatment data are presented in Figure 3 below, as well as the classification of HPUs by impact class of the release of domestic effluents (Table 2).

HPU 10 shows the greatest Euclidean distance (1,040) (Figure 3). This is because this HPU covers a large part of the Metropolitan Region of Rio de Janeiro, with a high population density, and an effluent treatment rate of 21.5%. Only this HPU integrates the impact class “very high”, according to this study criteria.

The impact class “high” (Euclidean distance = 420) was assigned to HPUs 6 and 12, both with more than 250,000 inhabitants without effluent treatment (Brasil, 2019; Instituto Brasileiro de Geografia e Estatística, 2010). HPU 6 is formed mainly by the Queimados, Ipiranga and Poços Rivers watersheds, and presents an intense urban occupation, industrial hubs, and a low level of effluent treatment efficiency (Associação Pró-gestão das Águas da Bacia Hidrográfica do Rio Paraíba do Sul, 2018). HPU 12’s main destination for effluents is the Cabuçu-Piraquê River, which has good water conditions at its source, where human occupation is rare, but its conditions are impaired after crossing the urban area of the West Zone of Rio de Janeiro.

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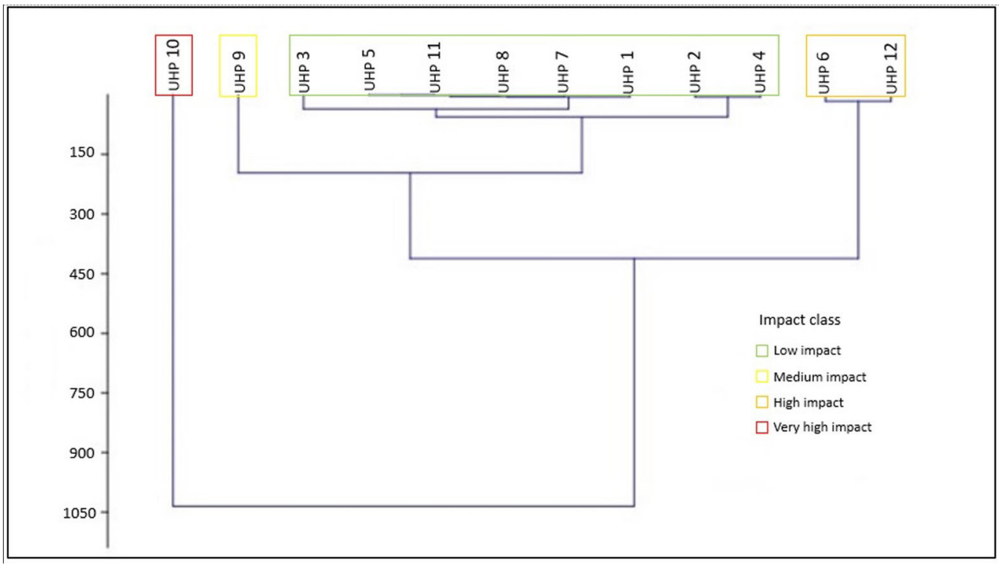

Figure 3. Similarity dendrogram of HPUs of the HR-II and impact classes of the release of domestic effluents.

Table 2. Impact classes of the release of domestic effluents of HPUs of the HR-II.

HPU	HPU name	Impact classes
1	Pirai River – upstream Santana reservoir	Low
2	Pirai River – Santana reservoir and tributaries	Low
3	Ribeirão das Lajes River – upstream reservoir	Low
4	Ribeirão das Lajes River – downstream reservoir	Low
5	Santana and São Pedro Rivers	Low
6	Queimados and Ipiranga Rivers	High
7	Guandu River	Low
8	São Francisco Channel	Low
9	Guarda River	Medium
10	Guandu-Mirim River	Very high
11	Coastal watershed (right bank)	Low
12	Coastal watershed (left bank)	High

effluents is the Cabuçu-Piraquê River, which has good water conditions at its source, where human occupation is rare, but its conditions are impaired after crossing the urban area of the West Zone of Rio de Janeiro.

The impact class "medium" (Euclidian distance = 200) was assigned only to HPU 9, a neighbor of the Guandu River watershed (HPU 8), with 153,144 inhabitants without effluent treatment. Is one HPU with a predominance of anthropized areas and with permanent protection areas (APPs) of watercourses in a situation considered "worrying", according to the SWRP Guandu.

The impact class "low" was assigned to HPUs with less than 70,000 inhabitants without effluent treatment (HPUs 1, 2, 3, 4, 5,7, 8 and 11). The predominant land cover of these HPUs is vegetation (forests and pasture), and they present a low urbanization rate. The exception is HPU 8, where 35% of its land cover is urban área, but it is the smallest HPU of the HR-II, which reflects its relatively low population.

Analysis of the capacity of maintenance of water purification ecosystem service

The parameters used and the results obtained for HPUs'water impact, which is used as an indicator of WPES maintenance, and its balance (positive or negative), in actual and natural scenarios are presented in Table 3.

HPU 10 presents the highest water impact, being necessary a water availability 74 times greater (WI = 7353%) than the actual would be needed for the adequate dilution of its effluents. It is followed by HPU 12 and HPU 6, with HPU 6 requiring the highest flow to dilute its industrial effluents (about 15% of its total demand for water ecosystem services, i.e. requires 5.49 $m^3 s^{-1}$ from 37.71 $m^3 s^{-1}$).

HPUs 10, 12 and 6 are the HR-II most populous, and they also have in common the fact that they do not have differences between their modified and natural water availability (as shown in Table 1), which means that the transfers do not alter the flows of their water bodies. The additional fact that their effluent treatment rates do not exceed 22% (as shown in Table 2), makes the water availability of these HPUs very insufficient for adequate effluent dilution. These characteristics place these three HPUs as the most impaired in terms of maintaining the WPES in the HR-II.

Considering HPUs that present negative balances of water shortage, HPU 9 (WI = 867%) and HPU 5 (WI = 101%), like the previous ones, do not present differences between modified and natural water availability (as shown in Table 1). HPU 1 (WI = 112%) and HPU 2 (WI = 606%) present lower modified water availability compared to the natural (as shown in Table 1). This is due to the volume lost by transfer from these HPUs to HPUs 3 and 4.

Considering HPUs with a positive balance, the ones which present better WPES maintenance are HPUs 4, 7 and 8, with Q_{av} higher than 120 m^3s^{-1} (Table 1), and water impact not exceeding 5%. It was due to the increase in water volume from the transfers. HPU 3 is also favored by transfers and contributes positively to the effluent dilution, but a lesser extent, with Q_{av} equal to 10 m^3s^{-1} (Table 1) and water impact equal to 2%.

Among HPUs with a positive balance of WPES maintenance, only HPU 11 does not present an increase in water availability in the actual scenario, being the one with the lowest Q_{av} (Table 1) and the highest *WI*% (Table 3). Its population, around 27,000 inhabitants, represents only 1.4% of the total HR-II population, and it has the best rate of effluent treatment (Table 2), factors that explain its situation of maintenance of the WPES. Even so, it has WI higher than 50%, which means that more than half of its water availability is required by its users for effluent dilution.

The industrial activities in the HR-II require a dilution flow of about 17 $m^3 s^{-1}$, corresponding to nearly 9% of total effluents released (188.41 $m^3 s^{-1}$), considering the water grants data of Instituto Estadual do Ambiente (2014), and disregarding possible clandestine releases. In HPU 2, which presents WI equal to 606%, the industrial effluents are responsible for 40% of the dilution flow demanded, i.e. requires 4.46 $m^3 s^{-1}$ from 11.11 $m^3 s^{-1}$.

Table 3. Results of dilution flow of domestic ($Q_{dil(dom)}$), industrial ($Q_{dil(indm)}$), and total ($Q_{dil(tot)}$), effluents, total demands (D_t) for ecosystem services, relative demands for water supply ecosystem service (D_s), relative demands for WPES (D_r), water impact (WI%), and maintenance balance in actual and natural scenarios, by HPU of the HR-II.

HPU	$Q_{dil\ (dom)}$ ($m^3 s^{-1}$)	$Q_{dil\ (ind)}$ ($m^3 s^{-1}$)	$Q_{dil(tot)}$ ($m^3 s^{-1}$)	D_t ($m^3 s^{-1}$)	D_s (%)	D_r (%)	Actual		Natural	
							WI%	**Balance**	***WI%***	**Balance**
1	2.34	0.00	2.34	2.45	5	95	112	Negative	41	Positive
2	6.48	4.46	10.94	11.11	1	99	606	Negative	148	Negative
3	0.23	0.00	0.23	0.46	50	50	2	Positive	9	Positive
4	4.92	1.34	6.26	12.30	49	51	5	Positive	148	Negative
5	2.57	0.00	2.57	3.84	33	67	101	Negative	69	Positive
6	31.28	5.49	36.77	37.71	2	98	2,406	Negative	2632	Negative
7	2.41	0.00	2.41	53.34	95	5	3	Positive	30	Positive
8	2.15	0.70	2.85	30.81	91	9	3	Positive	33	Positive
9	16.03	3.34	19.37	19.67	2	98	867	Negative	1,265	Negative
10	71.75	0.53	72.28	72.79	1	99	7,353	Negative	-6,395	Negative
11	1.90	0.00	1.90	2.33	18	82	60	Positive	54	Positive
12	29.19	1.30	30.49	30.67	1	99	3,137	Negative	10,328	Negative
Total	171.26	17.15	188.41	277.47	-	-	-	-	-	-

Comparison between demands for water ecosystem services

The water demands for effluent dilution are equivalent to approximately 68% of the total demands, 62% for domestic effluents, and 6% for industrial effluents (Figure 4). This represents little more than double the volume withdrawn by the HR-II. However, this demand is not fully met, given the conditions of the water that arrives at the Guandu water treatment plant (WTP Guandu) (Associação Pró-gestão das Águas da Bacia Hidrográfica do Rio Paraíba do Sul, 2018).

The percentage share of demands for the ecosystem services of water purification (dilution flow) and water supply (water withdrawal) in total demands in each HPU helps to understand this scenario in a more detailed way (Figure 5).

HPUs 7 and 8 present the highest total demands related to water supply withdrawal, followed by HPUs 3 and 4, where the demands for both water ecosystem services are balanced. The remaining HPUs have a much higher water demand for water purification than for water supply.

Analysis of water purification ecossistem service flow and the effects of the transfers (actual and natural scenario)

The diagram of the ecosystem flow of water purification in the HPUs of HR-II, built to represent the dynamic of this service, shows the transport of water between the HPUs and its contributions to the WPES, from the indicator *WI*%, used in the

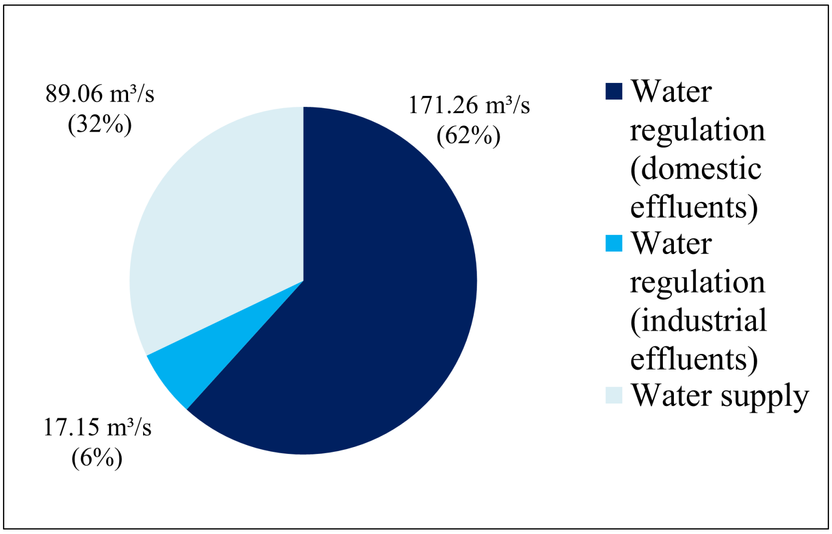

Figure 4. Demands for water use (in absolute and relative terms) for supply and purification of domestic and industrial effluents of the HR-II.

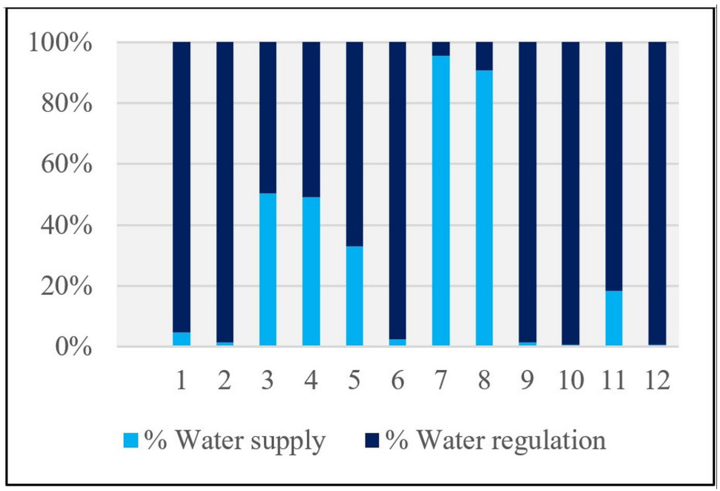

Figure 5. Percentages of total demands required for the water purification ecosystem services ($Q_{dil\,(tot)}$) and water supply (Q_{wd}) by HPU of the HR-II.

analysis of maintenance of water purification ES, in the actual (Figure 6) and natural (Figure 7) scenarios. It should be noted that HPUs 3, 4, 5, 6, 7 and 8 belong to the Guandu River Watershed (GRW), from where water is abstracted to supply the Metropolitan Region of Rio de Janeiro, and receive contributions of HPUs 1 and 2 through transpositions, in the real scenario, while in the natural scenario, they are disconnected from GRW. HPUs 9, 10, 11 and 12, despite belonging to the same Hydrographic Region (HR-II), are not connected to GRW and its water supply system.

HPUs 1 and 2, located in the highest portion of the HR-II, are in the Piraí River watershed, and they are connected to HPUs 3 and 4, located in the GRW, through dams and pumping stations. In the natural scenario, this connection would not occur, so its contributions to the ecosystem flow studied in the HR-II derives

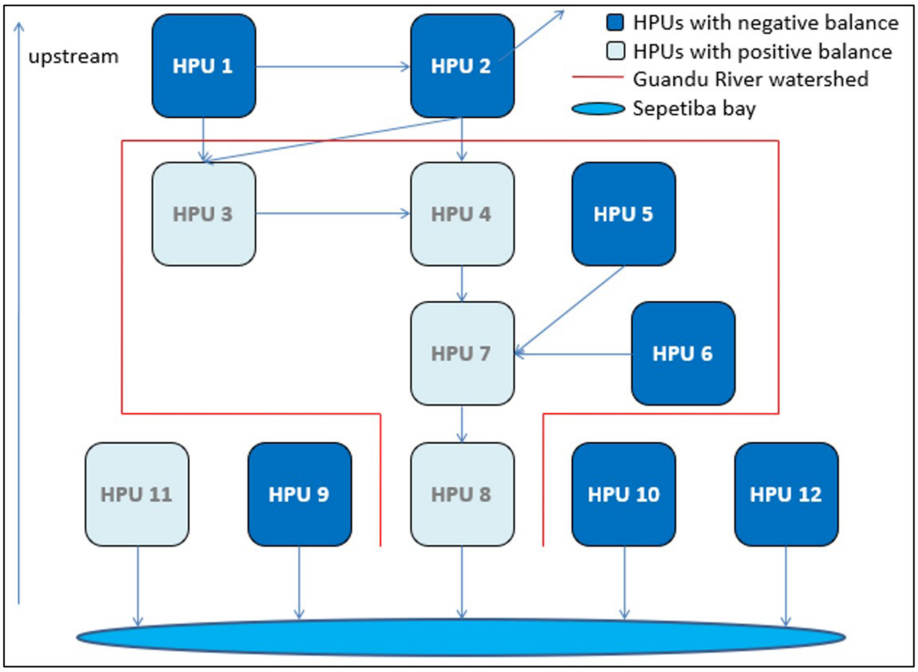

Figure 6. Balance for maintenance of HPUs of the HR-II represented in a flowchart, considering the actual scenario.

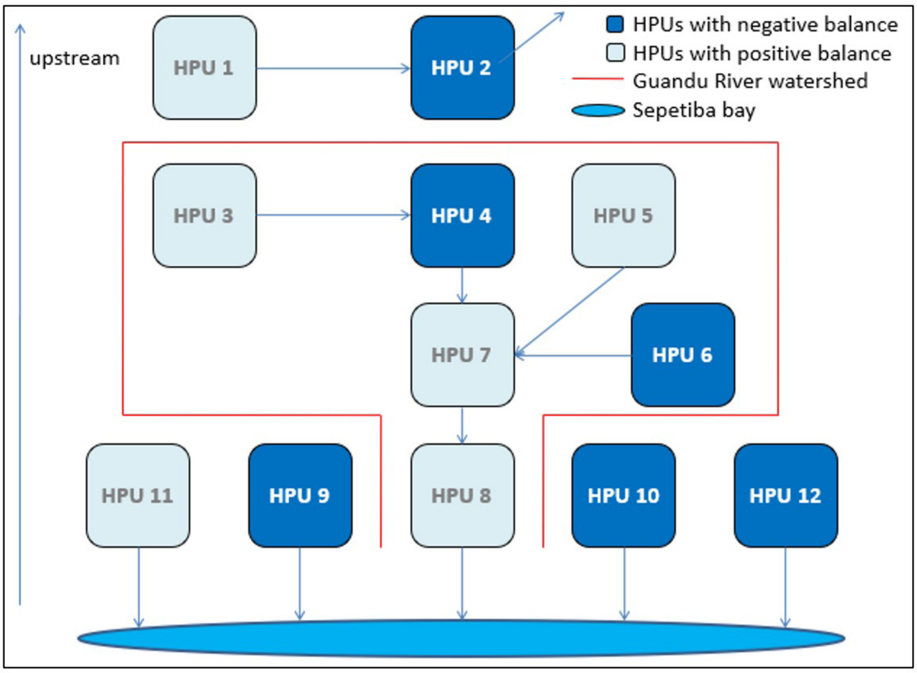

Figure 7. Balance for maintenance of HPUs of the HR-II represented in a flowchart, considering the natural scenario.

directly from the transfers. In the case of HPU 1, the negative balance of the maintenance results from the loss of water volume which is transferred to HPU 3, which differs from the natural scenario, in which it presents a positive balance. HPU 2 presents a positive balance in both scenarios, despite the differences in WI%.

HPU 3 has a positive balance in both scenarios, but its water availability is reduced by approximately 75% in the natural scenario. On the other hand, HPU 4 loses its positive balance in the natural scenario, with an increase of 143% compared to the actual scenario.

HPU 5 has a negative balance in the actual scenario due to the withdrawal of water for supply beyond its needs, exporting to the other HPUs. In the natural scenario, its balance becomes positive.

The main fluvial channel of the HR-II, related to the Guandu River, has a low ratio between the dilution flow required by its effluents and the water availability, with an extremely positive balance (WI = 3%). This is due to the high-water availability of HPUs 7 and 8, resulting from the natural contributions upstream and, mainly, the volume added by the transfers. This region, with a low number of inhabitants, has the greatest water availability in the HR-II. These HPUs lose a lot in dilution potential when considering the natural scenario but remain with a positive balance.

The ecosystem flow diagrams show the water impact of the entire eastern portion of the HR-II, the most urbanized and with the largest population, whose water availability is not affected by the transfers, which are insufficient for the dilution of its effluents. This portion has a high demand for WPES, and its impacts could be drastically reduced with better levels of effluent treatment. HPU 6, with extreme water shortage and a large demand for dilution flow, is the only HPU in the eastern portion connected to the Guandu River, with major impacts on the conditions of the water that reaches the WTP Guandu. The others, HPU 10 and 12, contribute directly to the Sepetiba Bay and do not suffer changes in water availability due to transfers. The differences found in WI% for both scenarios, natural and actual, occur due to the natural scenario considering that HPUs capture water from their rivers to meet their demands for water supply when in reality (actual scenario) these HPUs do not capture enough water to meet these demands.

HPU 11 and 9, from the western portion of the HR-II, also contribute directly to the Sepetiba Bay, not influencing the water conditions that reach WTP Guandu. These are HPUs that impact the water quality less than those in the eastern portion. HPU 9, which does not have water availability altered by the transfers, has an increase in WI% in the natural scenario as it depends on the withdrawal of other HPUs for its water supply, as well as HPUs in the eastern portion. HPU 11 shows little difference in WI% between scenarios, which denotes a low influence of transpositions on its balance of maintenance.

CONCLUSIONS

The results of the present study showed that deficiencies in the effluent treatment system in the area of the present study (HR-II) causes serious impacts on the water purification ecosystem service. This is evidenced by the results obtained that show that water demands for WPES are equivalent to twice the demands for water supply in the HR-II, even though it is a region of large withdrawals for supply, not only for its internal needs but also to meet the Metropolitan Region of Rio de Janeiro ones.

Regarding the maintenance of WPES, five of the evaluated HPUs had a positive balance, with water impact (WI%) below 100, and seven HPUs had a negative balance, with WI% above 100. This scenario would be much worse if it weren't for the transfers, that modify the WPES dynamics in the HR-II, by connecting the Piraí and Paraíba do Sul River watersheds to the Guandu River, giving it a great increase in water availability and the consequent improvement in the maintenance of water purification in HPUs 3, 4, 7 and 8, which are the HPUs with the most positive balance. In the natural scenario, without the transfers, these HPUs would have this maintenance extremely reduced, but they would still maintain a positive balance, except HPU 4. The effect of transfers on water availability of HPU 1 and 2, which belongs to the Piraí River watershed, is negative, due to the volume transferred to the Guandu River watershed. HPUs 9, 10, 11 and 12 contribute directly to the Sepetiba Bay, without connection with the fluvial channel of the Guandu River, and without alterations caused by the transfers.

From these WPES maintenance results obtained and the knowledge of the HR-II hydrology, it was possible to successfully represent the ecosystem flow of this ES in the form of a diagram, signaling the hydrographic connections between HPUs of the HR-II associated with the capacity of maintaining the WPES of these HPUs, making it possible to visualize the current panorama of the dynamics of this service, the most critical regions, the effects of transfers, among other relevant information for the population and the decision makers.

The improvement of the level of effluent treatment in the HR-II through basic sanitation policies is of fundamental importance for better maintenance of the WPES of HPUs, with effects on the water withdrawal for the supply of the population and industries, and on other water ecosystem services dependent on water quality. The perspective that is set of increased demands HPUs, making improvements in water management urgent. Currently, basic sewage projects are being prepared for the HR-II municipalities, with eight of those having already been delivered, with a potential positive impact on the WPES of HPUs 1, 2, 4, 5, 6, 7, 8, and 9.

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