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Determination of hydrological stress in a river basin in northeastern Brazil

Determinação do estresse hidrológico em uma bacia hidrográfica no nordeste do Brasil

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ABSTRACT

This study determines the degree of hydrological stress (HS) on the Goiana River basin in Pernambuco, a state in northeastern Brazil. The hydrological stress index is obtained by comparing the values of the surface permits with the limits granted by the managers. The results pointed to a situation of "High" hydrological stress (HS) in the Nazaré da Mata sub-basin, with approximately 94.76% of the grantable flow being used. In the Caricé sub-basin, the degree of hydrological stress was considered "Medium," with about 31.77% of available flow being granted. The other sub-basins had results considered to be "Low" hydrological stress (between 0% and 25%). Given these results, this study emphasizes the importance of constantly monitoring data on the demand for water use in the region and improving the criteria management bodies follow when granting permits.

Keywords: Permanence curve; Water resources management; River ecosystem; Hydrological stress.

RESUMO

Este estudo determina o grau de estresse hidrológico (HS) na bacia do rio Goiana em Pernambuco, um estado do nordeste do Brasil. O índice de estresse hidrológico é obtido comparando-se os valores das licenças superficiais com os limites concedidos pelos gestores. Os resultados apontaram para uma situação de "Alto" estresse hidrológico (HS) na sub-bacia da Nazaré da Mata, com aproximadamente 94,76% da vazão outorgável sendo utilizada. Na sub-bacia do Caricé, o grau de estresse hidrológico foi considerado "Médio", sendo concedido cerca de 31,77% da vazão disponível. As demais sub-bacias tiveram resultados considerados como "Baixo" estresse hidrológico (entre 0% e 25%). Com os resultados, o estudo ressalta a importância do constante monitoramento dos dados de demanda por usos de água na região e o aperfeiçoamento dos critérios para concessão de outorga pelos órgãos gestores.

Palavras-chave: Curva de permanência; Gestão dos recursos hídricos; Ecossistema fluvial; Estresse hidrológico.

INTRODUCTION

The efficient allocation of water among the usage demands required by the various economic sectors, as well as the maintenance of necessary minimum flows in the watercourses to protection the river ecosystems are tasks frequently required of water resource managers and governmental agencies (Durães et al., 2015). According to Harris et al. (2006), hydrological stress (HS) is an index that determines the amount of discharge reduced from a watercourse due to concessions to meet the various water usage demands.

The process of urbanization, the expansion of agriculture, and industrialization have all increased the demand for water resources in Brazil since the second half of the 20th century (Setti et al., 2001). The minimum reference flows adopted by management bodies for the granting of water use permits directly influence the availability of water that can be granted to users (Silva et al., 2015). The Q90 flow rate, which is exceeded or equaled 90% of the time, is used as a reference for legislation in the area of Environment and Water Resources in many Brazilian states (Collischonn & Dornelles, 2015). In Pernambuco, the permit granting criteria for the derivation and abstraction of surface water also use the Q90 value as a reference (Agência Pernambucana de Águas e Clima, 2021).

Permission to use surface water and groundwater is required in order to comply with Laws Nº 9,433/97 and Nº 12,984/05, the National Water Resources Policy (Brasil, 1997) and the State Water Resources Policy (Pernambuco, 2005), respectively, as they guarantee the right to access water and adequately manage it, both quantitatively and qualitatively. Permits are an instrument based on the application of specific legislation, that enable the advancement and improvement of the management of water resources (Ramos, 2005).

The framing of watercourses is directly linked to the process of granting permits for water resources, as different types of permits are allowed for the predominant uses of water. The incentive to rationalize volumes, purposes, and periods of water abstraction in a basin is essential for the maintenance of ecosystems. The improvement of legislation and the compliance with water resource plans and river basin committee guidelines play an important role in this dynamic.

Vestena et al. (2012) state that the prevention and minimization of environmental impacts related to river ecosystems is closely linked to the planning and management of water resources. The indices that assess the ecological health of watercourses and the level of disturbance caused by an operational policy are indispensable for the establishment of rules for granting water use permits (Gao et al., 2008).

|It is necessary to assess the degree of commitment of rivers, using indices that describe the current and future situation of water resources. The creation of limits and criteria for framing water bodies, similar to those for quality, which are based on availability and demand, improves water allocation among the various uses and users, according to Durães et al. (2015).

A methodology adopted by the Department of Natural Resources of New South Wales (2006), called Macro Water Sharing Plans (MWSP), determines the degree of hydrological stress (HS) on a basin or sub-basin, based on the climatic vulnerability and use of water resources in the basin. This methodology was also applied in Brazil by Galvão (2008) and Durães et al. (2015).

Durães et al. (2015) pointed out that determining hydrological stress provides water resources management agencies with a tool that assists in decision-making with regard to future permits to be granted, in the assessment of the impact of current demands, and in rational water management. The same authors studied the hydrological stress in Minas Gerais, considering a reference flow determined from the entire series of available flow data as a discharge corresponding to 90% of permanence (Q90). Therefore, the reference flow becomes a tool in the management of future demands and becomes an upper limit to warn the management bodies of critical levels of hydrological stress in a given sub-basin and of the future allocation of required flows.

\The main objective of this study is to evaluate the degree of hydrological stress on a hydrographic basin in Northeastern Brazil, namely, the Goiana River basin in the state of Pernambuco. To achieve this objective, permanence curves were drawn for all fluviometric stations present in the basin, comparing the Q90 with the granting of permits for the various uses in the region. Previous studies showed increasing data on water use for public and industrial supply and irrigation, a relevant factor in choosing the basin (Agência Nacional das Águas, 2013; Agência Estadual de Planejamento e Pesquisa de Pernambuco, 2005). Hydrological stress (HS) is numerically portrayed by sub-basins and provides an important input for decision-making related to future permit grants by water resources management bodies.

MATERIALS AND METHODS

The methodological strategy used to achieve the study's objectives involves the following steps: (1) Definition of the permanence curves for the fluviometric stations; (2) Determination of the Q90 which, in Pernambuco, serves as a parameter for granting a permit; (3) Survey of current and valid permits within each sub-basin; and (4) Calculation of the hydrological stress on each sub-basin.

Study area

The hydrographic basin studied was that of the Goiana River, located in northeastern Brazil in the state of Pernambuco, between 07º22'20" and 07º54'47" south latitude, and between 34º49'06" and 35º41'43" west longitude (Figure 1). The Goiana River basin has an area of 2,866.52 km^2, which is equivalent to 2.90% of the state's total area. The main rivers found within the basin are the Capibaribe-Mirim, Siriji, Tracunhaém and Goiana Rivers, with approximate lengths of 93 km, 74 km, 127 km, and 18 km, respectively. The Capibaribe-Mirim river drains most of the basin and the Goiana river is the stretch from the confluence of the Tracunhaém and Capibaribe-Mirim rivers that drains directly into the Atlantic Ocean.

The middle and lower courses of the basin lie in the semi-arid region of the state of Pernambuco. This region's main characteristic is that it lies between the regions of dry climate (*sertão*) and humid climate (*zona da mata*). Therefore, rainfall

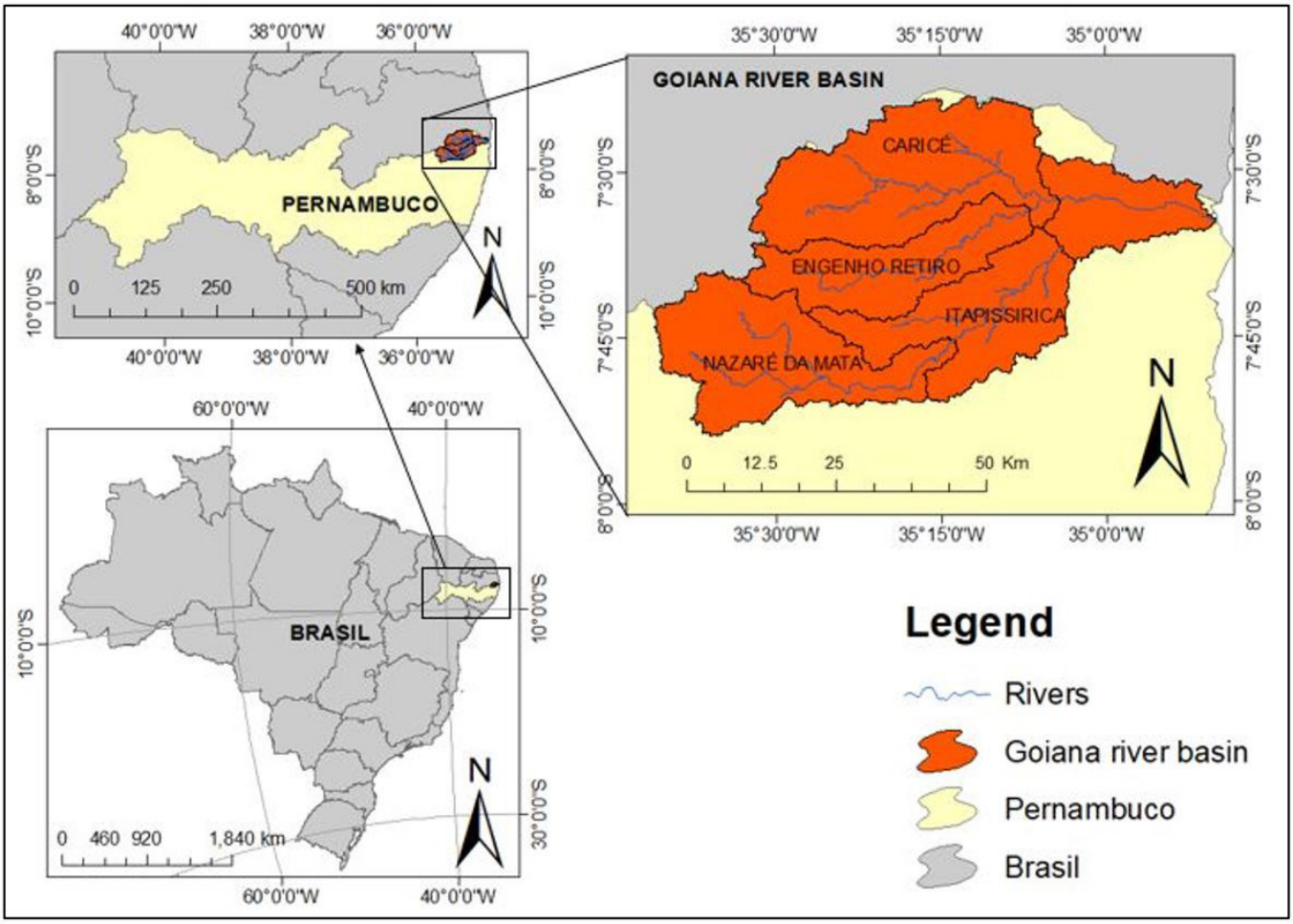

Figure 1. Location of the hydrographic basin of the Goiana River and fluviometric stations.

distribution in the basin alternates between the region surrounding the lower course, with a rainy season between March and July, and the region closest to the arid hinterland known as the *sertão*, with its rainiest period between February and June (Agência Estadual de Planejamento e Pesquisa de Pernambuco, 2005). The average annual rainfall, according to the records of rainfall stations in the region, is between 700 mm in the interior of the basin and 2000 mm in the portion nearest the coast (Pernambuco, 1998).

The vegetation of the basin has, for the most part, phytogeographic characteristics of the *zona da mata*, with species of perennial vegetation in the east part of of the basin and in the areas of greater quota to the west. There is a predominance of deciduous species in the central region (Aprile and Farias, 2001). There are five areas of environmental protection in the basin: the Mata do Siriji Wild Life Refuge, the Acaú Goiana Extractive Reserve, Mata de Água Azul, and the Environmental Protection Areas of the Goiana and Megaó Rivers Estuaries (Agência Estadual de Meio Ambiente de Pernambuco, 2003).

Within the basin, five types of land use can be found: urban and industrial use; cultivated areas; polyculture agriculture and livestock; Atlantic Forest areas; and mangrove and aquaculture near the coast. In the basin, there are concessions for the use of water for public supply; reception of domestic effluents; reception of agro-industrial, industrial, and agricultural effluents; and irrigation of crops, all of which are relevant to classes 2 and 3 of the watercourses.

This study focused on sub-basins drained by rivers which had available fluviometric data with consistency level 2, and current surface permit data. Thus, the study covers: a sub-basin drained by the Capibaribe-Mirim river (P1), the sub-basin of the Siriji River (P2), and two sub-basins of the Tracunhaém River (P3 and P4). Together, the aforementioned sub-basins correspond to approximately 89% of the total area of the Goiana River basin. The sub-basin of the final section of the Goiana River was not considered, because it does not have permit concession points.

Fluviometry of the region

In total, the basin contains 4 fluviometric stations with consistent data (level 2 consistency), all operated by the ANA (National Water Agency), (Table 1).

In this study, the Goiana River basin was subdivided into five sub-basins, with four of these having outlets at the fluviometric posts (control points). The last sub-basin, at the river's mouth, corresponded to the Goiana River, which does not have fluviometric data.

For the purposes of this study, the sub-basins were named after the fluviometric stations located at their outlets (Figure 2).

Methodology for estimating hydrological stress (HS)

Hydrological stress was estimated based on the methodology proposed by Durães (2010), who formulated it by studying the water use permit granting criteria of the states of Bahia, Ceará, and Espírito Santo, determining a limit discharge value that could be granted. By comparing the three states studied, the one with the most rigid legislation for permit granting is Espírito Santo, where the total flow granted cannot exceed 50% of the Q90, with this value being chosen to classify the highest degree of stress in the analyzed section. For qualitative analysis, the average value of the most rigorous class was considered to be the limit between the Low and Medium classes.

According to Durães et al. (2015), this methodology takes into account the analysis of the permanence curve, which reflects seasonality, physiographic characteristics of the sub-basins, location, and geology. It therefore provides management bodies with a hydrological stress assessment tool.

A survey of all fluviometric stations in the Goiana river basin was first carried out, and those with data of consistency level 2, sufficient to construct the permanence curve, were selected.

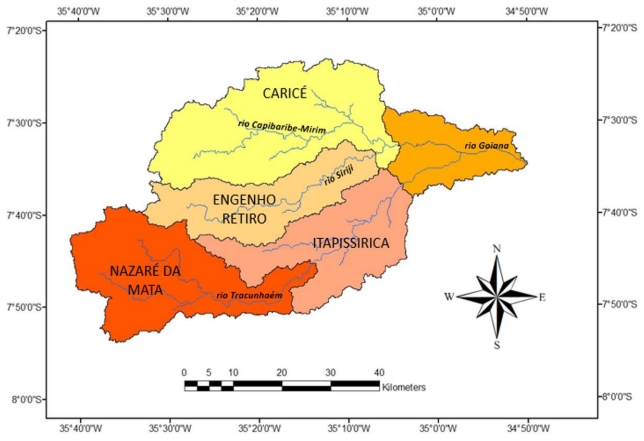

Figure 2. Sub-basins and watercourses in the Goiana River basin.

The data from the fluviometric stations were obtained from the HidroWeb/ANA website, as listed in Table 1.

The effects of seasonality on the hydrological regime of the basin can be evaluated through analysis of the permanence curves, and the minimum reference flows according to the criteria established by water use management bodies can be determined.

Hydrological stress (HS) is calculated from the ratio between the sum of the flow rates allotted to water use permits granted for each sub-basin and the corresponding flow limit that can be granted according to the criteria established by the state, which in Pernambuco corresponds to a flow with 90% permanence (Q90), according to Equation 1.

$$HS_i = \frac{\sum_{j=1}^{n} Q_{permit_j}}{Q_{90}} \times 100 \quad (1)$$

Where HS_i is the hydrological stress in sub-basin i as a percentage; Q_{permit_j} is the total flow of water use permit j; n is the total number of water use permits in sub-basin i, and Q_{90} is the flow with 90% permanence.

In each sub-basin, the level of hydrological stress was evaluated from the control points in Table 1, as shown in Table 2.

Data on superficial water use permits from the Pernambuco state water management body, the Agência Pernambucana de Águas e Clima (APAC), responsible for issuing water use concessions, were considered to determine the flow demand. Valid processes related to permits issued up to October 2020 were analyzed. The data used in the study comes from the cadastral base of the concession granting sector of the Agência Pernambucana de Águas e Clima (APAC), the agency responsible for registering all requests for the right to use water.

Considering valid surface water uses, there are currently 38 water abstractions in the Goiana River basin, distributed across all four sub-basins analyzed. Among the main uses are crop irrigation, industrial activities, and public supply, which are detailed by sub-basin in Table 3. These uses were spatially distributed to determine water stress by sub-basin, as shown in Figure 3.

RESULTS AND DISCUSSION

Table 4 shows the results for the permanence curves, the water demand for sub-basins and the level of hydrological

Table 1. Fluviometric stations and corresponding basins.

Code	Name	Latitude	Longitude	Area drained (km²)	River	Post	Observation period
39084000	Caricé	-7,5432	-35,0689	849,22	Capibaribe-Mirim	P1	1999 - 2014
39083000	Engenho Retiro	-7,5578	-35,1175	472,93	Siriji	P2	1977 - 2014
39084010	Nazaré da Mata	-7,7542	-35,2331	692,11	Tracunhaém	P3	1973 - 2014
39084020	Engenho Itapissirica	-7,6131	-35,0647	542,70	Tracunhaém	P4	1967 - 2014

Table 2. Classification of hydrological stress levels (adapted from Durães et al., 2015).

Stress Level	Criterion
Low	The sum of the flow rates of permits granted is below 25% of Q_{90}
Medium	The sum of the flow rates of permits granted is between 25 and 50% of Q_{90}.
High	The sum of the flow rates of permits granted exceeds 50% of Q_{90}.

Table 3. Water use permits granted for each sub-basin.

Sub-Basin	Irrigation	Industrial	Public supply	Others	Total
Caricé	10	1	2	0	13
Engenho Retiro	3	0	5	0	8
Nazaré da Mata	5	1	1	2	9
Itapissirica	5	0	3	0	8

Table 4. Information on reference flow, demand, and hydrological stress index (HS).

Control Point	Q_{90} (m^3/s)	Q(permit) (m^3/s)	$\frac{Q_{permit}}{Q_{90}} * 100$	HS
P1	1.121	0.356	31.77%	Medium
P2	0.731	0.147	20.14%	Low
P3	0.052	0.049	94.76%	High
P4	0.539	0.120	22.23%	Low

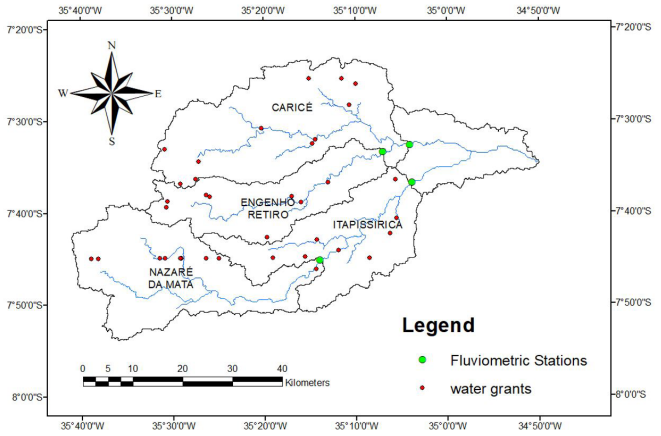

Figure 3. Spatial distribution of water uses granted in the Goiana river basin and the fluviometric stations considered in the study.

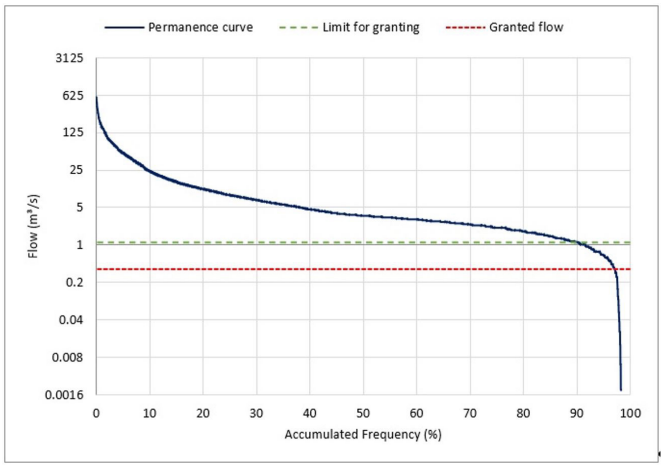

Figure 4. Permanence Curve at Caricé.

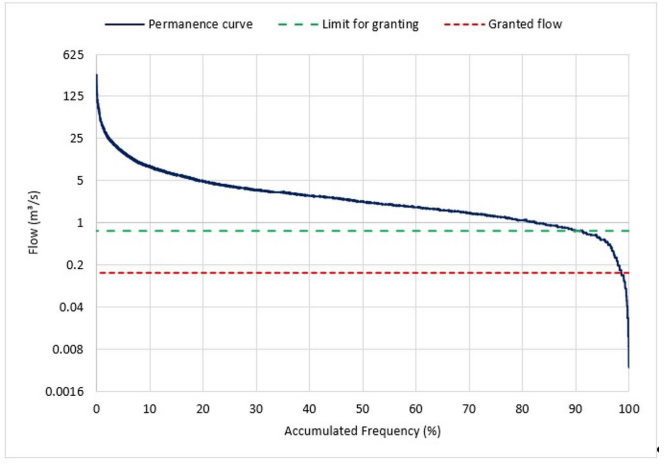

Figure 5. Permanence Curve at Engenho Retiro.

stress for each, according to the classification mentioned above. Figures 4 through 7 show the permanence curves for the four control points studied, Figure 8 shows the water consumption by use type at the control points, and Figure 9 maps the hydrological stress in the analyzed sub-basins. One important fact to highlight is the constant updating of the database of the Agência Pernambucana de Águas e Clima (APAC), which makes it possible to accurately assess the flow granted in water use permits, making it easier to manage water resources in the state.

In the Capibaribe-Mirim river sub-basin, with a control section at the Caricé station (P1), equivalent to approximately 29.62% of the Goiana basin, there was a total water demand of 0.356 m^3/s, approximately 31.77% of the discharge available for concession, classifying it as having a "Medium" hydrological stress level. The largest water use permit in this sub-basin, around 0.155 m^3/s, was granted to the Companhia Pernambucana de Saneamento (COMPESA) for the purpose of public water supply. This value corresponds to approximately 43.57% of the total flow of all permits granted. Considering current permits for public supply, the Caricé sub-basin has the highest percentage granted for this purpose, mainly due to the greater number of urban centers within the basin. Although the region has a "Medium" level of hydrological stress, it is suggested that future concessions of water use permits should be carefully evaluated for the socioeconomic benefit of the region. Silva & Galvíncio (2011), in a study of the Ipojuca river basin, also in the state of Pernambuco, obtained results for the commitment of water resources. This region also has a high consumption of water for crop irrigation, mainly driven by banana production.

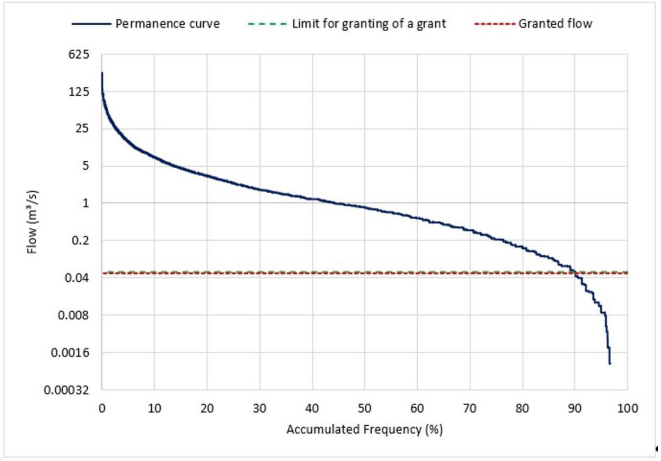

Figure 6. Permanence Curve at Nazaré da Mata.

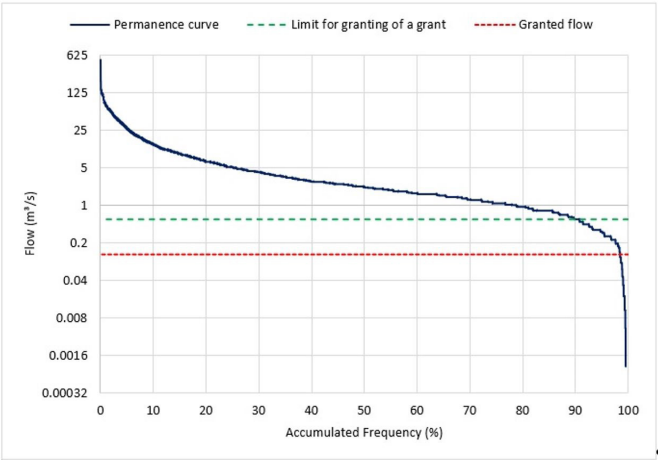

Figure 7. Permanence Curve at Engenho Itapissirica.

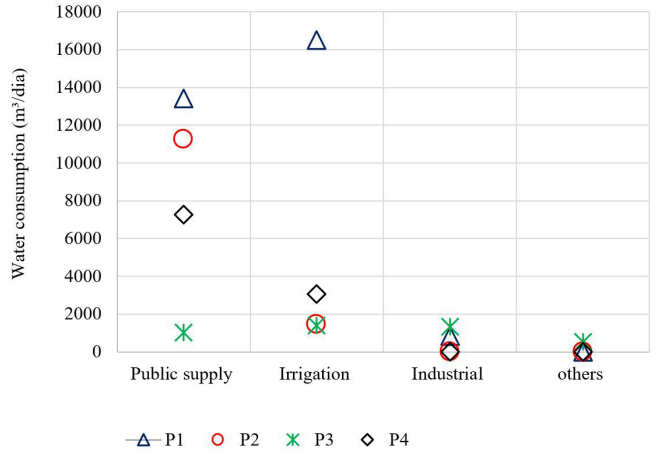

Figure 8. Water consumption at control points.

The Tracunhaém River tributary was divided into two sub-basins with outlets at the Nazaré da Mata (P3) and Engenho Itapissirica (P4) control points. Water consumption in the two sub-basins corresponds to 0.049 m^3/s and 0.120 m^3/s, respectively.

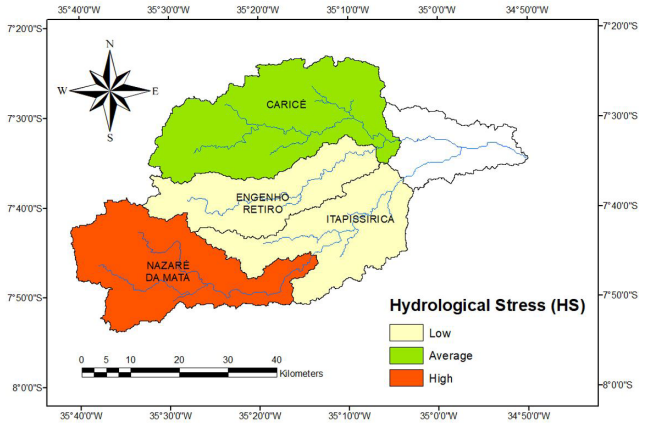

Figure 9. Mapping of Hydrological Stress by sub-basin.

In the Nazaré da Mata sub-basin, the degree of hydrological stress reached 94.76% and is considered "High." This is caused mainly by the consumption of water for industrial activities in the region and irrigation for the cultivation of sugarcane. Similar results, also with a high degree of hydrological stress, were found by Durães et al. (2015) in river basins in the state of Minas Gerais.

The sum of the discharge flows in the Nazaré da Mata sub-basin corresponds to only 7% of the water use permit concessions in the entire Goiana river basin, however, it has low water availability when compared to the other sub-basins. Industrial activity is known to be of high economic importance for this sub-basin region, but the impacts caused by these excessive demands must be taken into account to properly manage the water resources of this river stretch. For issuing future permits, the environmental impacts on the river's ecosystem should be analyzed and the establishment of a maximum percentage in relation to the 90% permanence over time discharge (Q90) should be considered.

The sub-basin with a control section at Engenho Itapissirica station (P4), on the Tracunhaém river, has a hydrological stress level classified as "Low," which indicates it is a reasonably secure region. The total discharge flow of granted water use permits is estimated at 0.539 m^3/s, which is equivalent to approximately 22% of the total discharge available for concession in all analyzed sub-basins. The largest demand in permits granted for this stretch is public supply, approximately 70% of total concessions in the sub-basin.

A total hydrological demand of 0.147 m^3/s was observed for the sub-basin with its control section at Engenho Retiro station (P2), on the Siriji River, corresponding to approximately 22% of the total consumption permitted for the sub-basins analyzed. This stretch has a hydrological stress level classified as "Low," with approximately 20% of the discharge limit (Q90) granted for use. The predominant use is public supply with a total grant of 0.130 m^3/s, equivalent to approximately 89% of the total flow granted for the stretch, being the largest proportion for this purpose out of all of the sub-basins.

Durães et al. (2015) emphasized that there was an increase in the level of hydrological stress for one of the studied basins when compared with the results for the same basin from Durães (2010). The authors argue that this increase in hydrological stress is related to the addition of insignificant users to the database,

which improves the process of assessing the degree of water resource impairment. The present study did not take into account insignificant usage values due to the unavailability of these data, which is important to note, because even without this information, one sub-basin was already at a high level of hydrological stress. The permanence curves (Figures 4 to 7) have high determination coefficients with a mean value of 0.8253, which shows that the curves have a good fit to their respective regression curves.

Water resource managers must pay attention to the uses considered insignificant, which, in Pernambuco, are the derivations and abstractions of surface waters with an average flow rate below 0.5 L/s and the damming of intermittent rivers, which has a maximum accumulation volume of 200,000 m^3 (Agência Pernambucana de Águas e Clima, 2021). The results indicate that the concessions of water for this type of use need better discussion, especially in the sub-basins with greater hydrological stress, because, in large numbers, they can compromise future demand and increase the possibility of conflicts over water use. Harris et al. (2006), using a methodology similar to the one presented in this study, were able to identify regions within Australia's hydrographic basins that are more susceptible to conflicts over water use. Lima et al. (2019) evaluated hydrological stress and the coverage of sewage systems in the Sergipe River basin, with the results indicating that 80% of the water sources in the basin studied were classified as having a "very critical" hydrological stress level.

The results of this study demonstrate the importance of determining the degree of hydrological stress for the management of water resources, as it helps to identify the most critical regions in terms of water availability, even within the same basin. This methodology can be used as a complementary resource for water concession management, in addition to those currently used, providing greater security for users and for the environment.

CONCLUSIONS

This article evaluated the degree of hydrological stress on the sub-basins of the Goiana River, in the state of Pernambuco. An analysis was performed on the current flow rates in granted water use permits, registered up to October 2020, and the 90% permanace flows over time (Q90), extracted from the permanence curves recorded at the fluviometric stations, which defines the upper limit for granting water use permits in Pernambuco.

The results indicated a "High" level of hydrological stress (HS) in the Nazaré da Mata sub-basin, with approximately 94.76% of the grantable flow being used. The predominant water use permits granted in this sub-basin are for industrial purposes and for public supply, equivalent to 55% of the total. The high level of hydrological stress in this stretch must be viewed with attention by water resources managers.

In the Caricé sub-basin, the degree of hydrological stress was considered "Medium," with about 31.77% of available flow granted for use. The largest portion in this stretch is allocated to the Companhia Pernambucana de Saneamento (COMPESA) for the purpose of public supply, equivalent to approximately 43.57% of the consumption granted through permits. This is the highest value for water allocated to public supply in the entire Goiana basin. |The region's crop irrigation demands also contribute to the level of stress. The "Medium" water stress level for the stretch should be regarded as an alert for future permits. The other sub-basins presented a result considered to be "Low" hydrological stress (between 0% and 25%).

Two Sources of information were absolutely essential for the development of the study: the database of surface water use permits, provided by the Agência Pernambucana de Águas e Clima (APAC), and the historical flow series from the fluviometric stations, operated by the geological service of Brazil. This demonstrates the importance of routinely updating information on permitted discharges and hydrological monitoring in the basins. Another point that should be highlighted is the need to improve the granting of water use permits for uses classified as insignificant, because the ease in obtaining these concessions can put even more pressure on the surface water consumption in the sub-basins, increasing the areas that have a "High" hydrological stress index. The assessment of the degree of hydrological stress can assist in the management of water resources and help decision makers in northeastern Brazil to issue future permits with greater security for both river ecosystems and water resource users.

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