XXVI SIMPÓSIO BRASILEIRO DE RECURSOS HIDRÍCOS

# POINT AND NON-POINT POLLUTION: MANAGING THEM IN THE WATERSHED

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**Abstract:** Reservoirs are fundamental to the water supply, and high levels of incoming load can lead to eutrophic environments and algal blooms, compromising water quality and use. The decontamination of water bodies depends on controlling the input load. This article aims to demonstrate a new approach to pollutant load modelling techniques, improving watershed management, and highlighting the separate roles of point and non-point pollution. A hydrological and load model was applied to describe watershed flow and load production. The developed tool showed good performance, providing flow throughout the year, and separating it into total flow, superficial flow, and base flow. Related to the incoming load, the model was able to describe the BOD, Total Phosphorus, and Total Nitrogen concentrations, showing that the dry season accumulates pollutants and elevates concentrations, whereas in the wet season, washes them off and decreases pollutant concentrations, like January 2022. Allied with load model coefficients, EMC values for BOD and TP are like previous work, but for TN values are 3 times higher. Regarding the wash-off parameter, the nonpoint pollution has multiple sources for each constituent. As a result, the reservoir has a trophic state that varies from Eutrophic to Hypereutrophic. This research demonstrates that effective basin management is essential for water bodies. Therefore, it's crucial to remove nutrients from sewage and manage agricultural land effectively.

**Resumo:** Reservatórios são fundamentais para o abastecimento de água, e altos níveis de carga de entrada criam a ambientes eutróficos e florações de algas, que comprometem o uso da água. A despoluição dos corpos d'água depende do controle da carga de entrada. O objetivo foi demonstrar uma abordagem para modelagem de carga poluente que destaca os papéis da poluição pontual e difusa. Um modelo hidrológico e de carga foi aplicado para descrever a vazão e a produção de carga na bacia hidrográfica. A ferramenta desenvolvida apresentou bom desempenho, fornecendo vazão ao longo do ano e separando-a em três classes. Em relação à carga de entrada, o modelo descreveu as concentrações de DBO, Fósforo Total e Nitrogênio Total, mostrando que a estação seca acumula poluentes e eleva as concentrações, enquanto na estação chuvosa, os lava e diminui as concentrações. Os coeficientes do modelo de carga tiveram valores de EMC para DBO e TP similares à trabalhos anteriores, mas para TN, os valores foram 3 vezes maiores. Em relação ao parâmetro de lavagem, a poluição difusa tem múltiplas fontes para cada constituinte. Como resultado, o reservatório tem um estado trófico que varia de Eutrófico a Hipereutrófico. Esta pesquisa reforça os impactos do gerenciamento de bacias em corpos d'água, indicando a importância de remover nutrientes do esgoto e gerenciar áreas agrícolas adequadamente.

**Palavras-Chave** – Non-point Pollution; Watershed's Management, Water Quality; Urban and rural watersheds, Hydrological and Load Modeling.

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## INTRODUCTION

Reservoirs are fundamental in water supply, and their water quality is harmed by the poor management practiced in the watersheds. The high levels of incoming load, especially organic matter and nutrients can lead to eutrophic environments and algal bloom events. Those events compromise water use, such as water supply (ANA, 2018).

The incoming loads are a combination of point and non-point sources, such as sewage and industrial discharges and the surfaces wash off, which are fundamental to describing the reservoir's water quality condition. The load continuously received due to point sources, such as sewage, and the one carried during rain events, will be drained by the rivers to the reservoirs, where it will have more time of detention to interact with the environment and minor advective transportation, which propitiates sedimentation. Making these environments the load accumulation points (Magalhães A. , 2023).

Developed countries have point sources controlled and nowadays the challenges are mainly in the non-point sources, in the other hand, developing countries like Brazil, have point pollution as recurrent problem, and the new sanitation federal guideline aims to achieve the goal of 90% of the population with sewage collection and treatment (BRASIL, 2020).

With that in perspective new plans to recover watersheds are being developed and some questions come up: How much of the incoming load should be removed? Which loads have more impact on the watershed water bodies considering seasonal variations? Will the problem of water quality be solved once the point source pollution is removed?

The interactions between basins and water bodies reinforce the concept of integrated management between them. While efforts can be made and new technologies tested to clean up rivers or reservoirs, if the incoming load is not controlled, the problem will persist.

Coupled mathematical models are often used to develop studies on the relation between basin's wash off, hydrodynamic behaviour and water quality conditions, but its application and performance are dependent on the time series of field measures (Brooks, et al., 2016) (Plec D. , Silva, Vinçon-Leite, & Nascimento, 2021) (Ji Z.-G. , 2008) (Liu, Benoit, Liu, Liu, & Guo, 2015).

This article aims to demonstrate a new approach in terms of pollutant load modelling techniques to improve watershed management efficiency in terms of controlling the organic matter and nutrients incoming load in a reservoir, highlighting separately the role of point and non-point pollution.

## METHODS

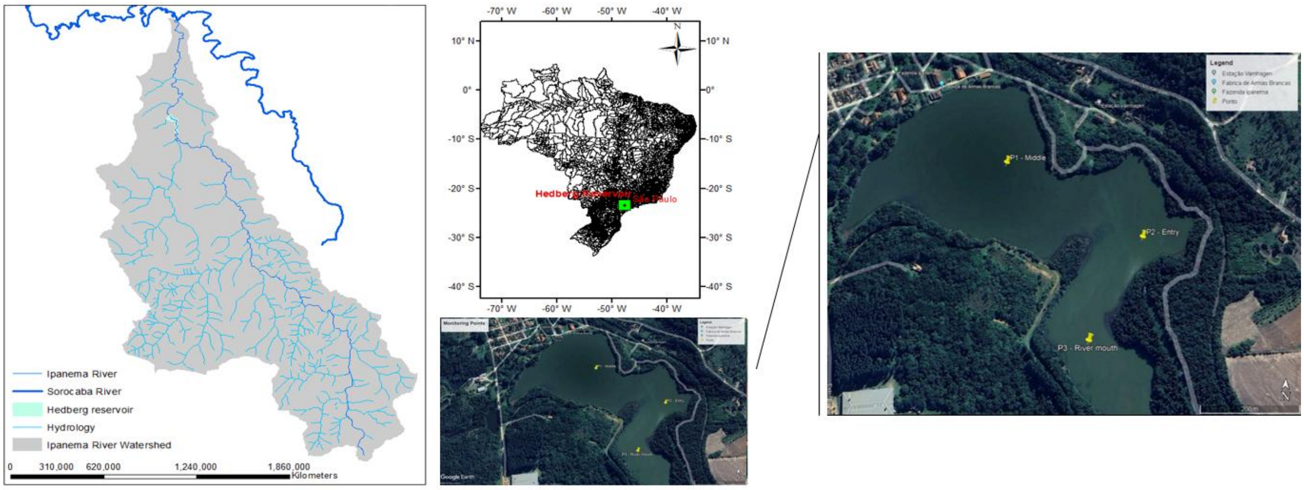
Here are presented the characteristics of the study site, its monitoring system and mathematical models applied in the study.

### Study Site

The studied site was the Hedberg reservoir (23°25'39" S, 47°35'39" W), located in the state of São Paulo, in Brazil's southeast region (Figure 1). It is a small-tropical reservoir enclosed in the Ipanema River basin, a catchment area of 235 km², where urban (9.8%), forest and natural vegetation (21.5%), and rural (68.2%) land uses are found. Situated in the tropical zone, has a temperature range between 15°C and 35°C and an annual precipitation rate of 1500 mm (Magalhães A. , 2023).

The reservoir has a 0.26 km² surface area, an approximate volume of 1.5 hm³, and a detention period of 2 to 10 days. Its maximum depth is 5 m and the mean depth is 4.5 m. In relation to its thermal regime, the Hedberg reservoir presents a polymictic behavior, with several stratification and mixing events observed throughout the year (Amorim L. , 2020).

Figure 1. The catchment from Hedberg Reservoir and monitoring points




## Monitoring

The monitoring system include a set of thermistors and a meteorological station. This last one was placed on the reservoirs' banks, recording the variables: air temperature, solar radiation, wind's velocity and direction (10m heigh), atmospheric pressure, relative humidity, and precipitation. The measurement frequency is every 10 minutes for all variables, except for radiation, which is measured within a 5 min interval.

The set of thermistors have probes fixed to a rope and plummet, with a float in the upper end, they are distributed as showed in Figure 1. The bouys P1 and P2 are equipped with thermistors and are point of water quality samples, while P3 has it temperature measure with hand sensor during water quality samples collection.

The thermistors are positioned in a space step that could reproduce the temperature profile along the water column, and well characterize the moments of stratification and mixing. The time between measurement is the 1 min, with the absolute accuracy of the equipment is ±0.2°C and the relative accuracy, verified in the laboratory, is of 0.17 °C.

Water quality monitoring count with data from different variables to characterize nutrients, algal biomass, organic matter, and gases in the study areas. The choose of the indicators considered the capacities of the university's laboratory and the data available on the government reports. The used variables were: Biochemical Oxygen Demand – BOD; Dissolved Oxygen - DO; Nitrate – NO3; Nitrite – NO2; Ammonia - NH; Total Phosphorus - TP; Chlorophyll-a – Chla-a; Total Suspended Soils – SST; Secchi depth.

## Hydrological and Load modeling

In this study was applied the CAbc (Software for Hydrological Simulation of Complex Basins), developed by the Center for Hydraulic Technology at the University of Sao Paulo (USP) and funded by Fundação Centro Tecnológico de Hidráulica (FCTH, 2002). It is a system of models intended for hydrological simulation to flow generation in catchments using Soil Conservation Service (SCS), and Unit Hydrograph or the SMAP method (LOPES; BRAGA JR; CONEJO, 1982).

The CAbc model applies to urban and rural drainage problems, especially macro drainage. It models complex and a wide variety of types of watersheds, small or large: urban, mixed, rural, etc. The diversity obtained from rain distribution and land occupation can also be considered. Those were the reasons to choose CAbc to be adapted for nonpoint pollution analysis (FCTH, 2002).

SMAP model was chosen as the mathematical model of the rain-flow transformation type. As advantages, CAbc and its SMAP method allow the separation of base flows and runoff that will generate, respectively, the endemic or base loads and the wash off loads. In addition, it can be simulated for a continuous series and not only for a given precipitation event (LOPES; BRAGA; CONEJO, 1982).

The CAbc **Quality Module** has 3 components. The first consists in hydrology and rainfall-flow transformation. Using SMAP method and radar rainfall, the hydrologic model generates, for each sub-basin: QT: Total Flow; Qs: Superficial Flow; Qb: Base Flow (Magalhães A. , 2023).

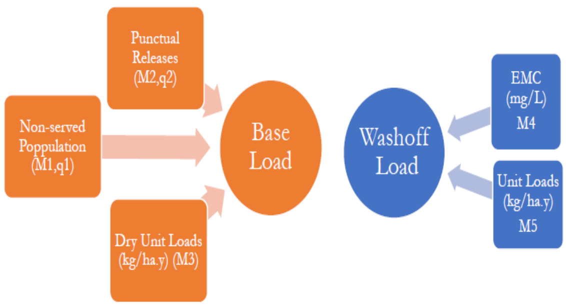
For loads, the model is divided into 2 major parts, and each has its own particularities. One part is when there is no rainfall and generates Base Loads and the other is when there is rainfall and it generates Wash Off Loads (Magalhães A. , 2023).

Non-served population is the part of releases that are not treated, so the releases are incorporated through its *per-capita* flow – q - (L/inh.day) and mass -m - (g/inh.day) of each pollutant (BOD, TN and TP). The product of the multiplication of each by the population provides water (q1) and mass (M1) flow respectively. That flow is added into the existing flow (natural provided by rainfall) and the mass is divided by total flow giving, concentrations, as described by Equations (1), (2) and (3).

The point releases must provide flow - q2 - ($m^3/s$) and concentration - C2 - (mg/L). The point release flow is also added into the existing flow and the concentration is turned into a mass. The final base release is diffuse given by dry weather unit loads (kg/ha.y). These unit loads can be calculated or calibrated using literature values. Later, those coefficients are multiplied by its area and gives a mass flow (M3) for each time step of the model, as described in Equation (4).

Finally, each concentration and/or mass calculated (M1, M2 and M3) are summed and divided by Total Flow (in this case, base flow produced in each sub-basin) (Eq. (5) and (6)). It is important to state that, while CAbc-QUAL does not specify if BOD is the ultimate or the 5-day type, the user can decide which one to use according to the field data.

Figure 2 – Load Model in CAbc Qual




$$q_1 = \frac{C\ x\ q\ x\ P}{86400} \quad (1)$$

$$M_1 = \frac{m\ x\ P}{86400} \quad (2)$$

$$C_1 = \frac{M_1}{q_1} \quad (3)$$

$$M_3 = \frac{EC_s\ x\ A}{365\ x\ 86400} \quad (4)$$

$$Q_{b_{i+1}} = Q_{b_i} + q_1 + q_2 + q_{imp} \quad (5)$$

$$C_{b_{i+1}} = \frac{C_{b_i} + Q_{b_i} + C_1 + Q_1 + C_2 + q_2 + M_3}{Q_{b_{i+1}}} \quad (6)$$

In the above equations, P is the non-served population (inh); C is the water/sewage rate; q is the *per-capita* water consumption (L/inh.day); q1 is non-served population release ($m^3/s$); m is the sanitary sewage *per-capita* contribution (g/inh.day); M1 is total mass injected by non-served population (g/s); ECs is the unit load(Export Coefficient) in dry weather (kg/ha.y); A is the sub-basin area (ha); M3 is the mass given by diffuse contributions (g/s); C2 is the point release concentration (mg/L); q2 is point release flow ($m^3/s$); qimp is the imported flow ($m^3/s$); Qbi+1 is total base flow ($m^3/s$); Cbi+1 is total base concentration ($g/m^3$ or mg/L).

The inputs required are: EMC (mg/L) and Wet Season Unit Loads (UL) (kg/ha.yr). The model allows the user to insert both at the same time, although it is important to remember that they have different roles, and each are interpreted differently. Usually, EMC (mg/L) values are obtained with monitoring, with automatic sampling and Unit Loads usually calibrated when there are no data for rain events. So, when using both EMC and UL for rain events, there is a duplicity, because they have the exact same purpose (providing wash off load), only the math is done differently.

When there is rain the model calculates all surface volume (Ves) for each time step (Δt) based on a hydrological model to generate runoff. Then based on EMC and/or Wet Season Unit Loads it generates wash off loads, as described by Equations (8) and (9), respectively. Then, as Equation (10) shows, final surface mass (M0) is obtained for modeling through Equation (11).

$$q_w = \frac{V_{es}}{\Delta t} \quad (7)$$

$$M_4 = EMC \ x \ V_{es} \quad (8)$$

$$M_5 = \frac{EC_w \ x \ A}{86400 \ x \ 365} \quad (9)$$

$$M_0 = M_4 + M_5 \quad (10)$$

$$M_{es}(t) = M_0 x \left\{1 - exp\left[-\frac{k}{A} \ x \ V_{es}(t)\right]\right\} \quad (11)$$

The variables in the above equations are: Ves is the surface volume (m³); Δt is time step (daily, hourly, etc); EMC is the Event Mean Concentration informed (mg/L); M4 is the washed mass obtained by EMC (kg); ECw is the wet season Export Coefficient /Unit Load informed (kg/ha.y); M5 is the washed mass obtained by EC (kg); k is the wash off constant; A is the sub-basin area (ha).

The results to be obtained are a series of concentrations along the intended time window. One can clearly see that in terms of loads, there are two important characteristics to notice: when it rains, the wash off process removes pollutants from the watershed surface, resulting in a quickly descending line and, during dry periods, pollutants build up on the surface, giving an ascending line. For concentration, the opposite occurs.

**Impacts on the reservoir's trophic state**

After modeling the incoming load from the basin to the reservoir, the Trophic State Index (IET) was calculated to categorize reservoir into its trophic state. IET is calculated through a set of equations for the variables of Secchi Depth, Chlorophyll-a and Phosphorus. The final result is compared with the classification on Table 1 (Lamparelli, 2004).

Table 1. Trophic State Index – IET reference values

| Trophic level | Total Phosphorus (mg/L) | Chlorophyll-a (µg/L) | Secchi depth (m) | IET |
|---|---|---|---|---|
| ultraoligotrophic | ≤0.008 | ≤1.17 | ≤2.4 | ≤47 |
| oligotrophic | 0.008< TP ≤0.019 | 1.17< Chla-a ≤3.24 | 2.4< S ≤1.7 | 47< IET ≤52 |
| mesotrophic | 0.019< TP ≤0.052 | 3.24< Chla-a ≤11.03 | 1.7< S ≤1.1 | 52< IET ≤59 |
| eutrophic | 0.052< TP ≤0.120 | 11.03< Chla-a ≤30.55 | 1.1< S ≤0.8 | 59< IET ≤63 |
| super eutrophic | 0.120< TP ≤0.233 | 30.55< Chla-a ≤69.05 | 0.8< S ≤0.6 | 63< IET ≤67 |
| hypereutrophic | >0.233 | >69.05 | >0.6 | >67 |

## RESULTS AND DISCUSSIONS

The following item presents the hydrological and load model results and discuss the impacts of incoming load on the reservoir trophic state.

**Hydrological model calibration**

The Ipanema River's watershed was divided into 13 sub-basins using the criteria of land use homogeneity, natural drainage network and the location of the WWTP and/or industrial disposals. The model's calibration and validation steps used the monitoring point: Entry (Figure 1).

The calibration and the validation in SMAP model produced the simulated flow shown in Figure 3 and Table 2. It is possible to observe that calibration presented a very good result in terms of flow when compared to the observed series. Some peaks of the observed data were not possible to be replicated for three reasons: (1st) observed flow, as mentioned before, is obtained in a 10-minute step and then an average is made from the series, and accumulated rain is obtained in daily time step which makes hard to reproduce peaks; (2nd) convective rains that act locally sometimes are not well represented only with daily rain amount, and; (3rd) possible errors in the flow station.

To analyze the model performance, Nash and Sutcliffe Efficiency (NSE); Root Mean Square Error (RMSE); and Standardized RMSE (RSR) were applied (Table 3). From that it is possible to see that, despite RMSE value being far from the performance rate, it can be considered satisfactory for RSR and NSE, when compared to the values on literature (REUSSER; BLUME; SCHAEFLI; ZEHE, 2009; RITTER; MUÑOZ-CARPENA, 2013; WASEEM; MANI; ANDIEGO; USMAN, 2017).

Figure 3 – Hydrologic model calibration and validation

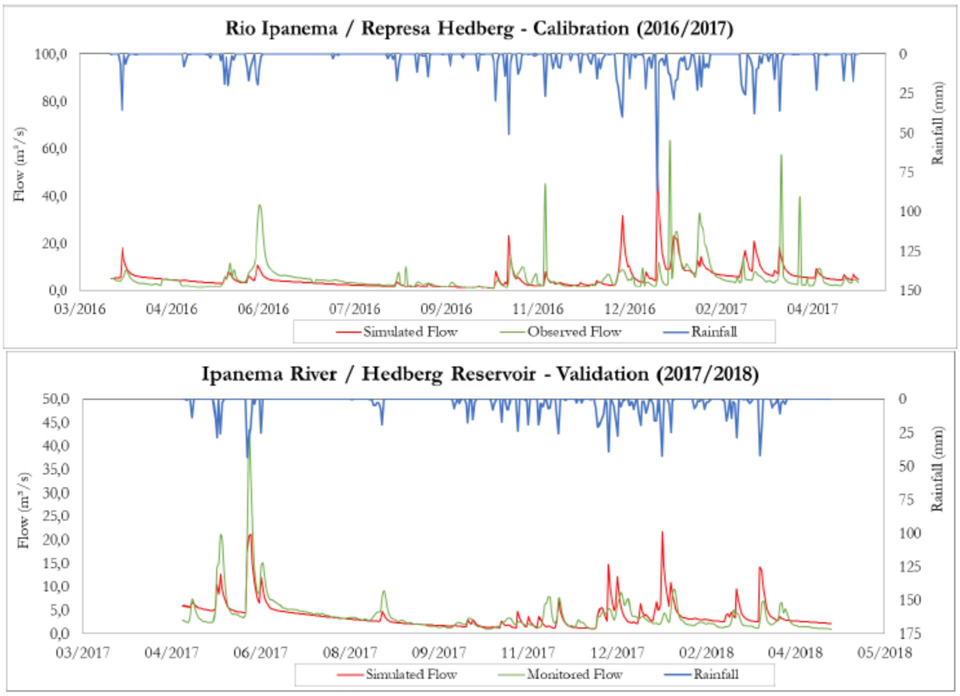



Table 2. SMAP parameters

| Parameters | |
|---|---|
| **Sat**: soil saturation capacity (mm) | 150 |
| **K2t** - runoff constant recession (days) | 1,5 |
| **Crec** - groundwater recharge parameter (%) | 11 |
| **Ai** - initial abstraction (mm) | 2 |
| **Capc** - field capacity (%) | 40 |
| **Kkt** - basic outflow constant of recession (days) | 60 |

Table 3. Hydrological model's index errors

| Index / Criteria | |
|---|---|
| RMSE | 2,74 |
| NSE | 0,53 |
| RSR | 0,69 |

## Load model calibration

From the calibrated hidroloical model, the CAbc-Qual was simulated, the show Figure 4, Figure 5, Figure 6, the curve behavior for BOD, Total Phosphorus (TP), Total Nitrogen (TN) concentrations respectively. And from those, one can see that: first, BOD concentrations are always lower than quantification limits (2 mg/L), which suggests a good data input from WWTP and EMC values, and second, BOD concentration is not the best parameter to quantify organic matter in this watershed because it cannot exhibit its variations in detail.

Phosphorus was the hardest constituent to calibrate. Using concentrations presented in the informed discharges by the WWTPs (Vacariú and Ipaneminha), computed concentrations yielded much higher than the monitored. There are two assumptions here that can be made: (1st) the actual average phosphorus concentrations are lower than the ones used for statistics; (2nd) Hedberg Reservoir is well known for a high population of macrophytes, therefore some phosphorus near the reservoir would be imprisoned by algae and then driven outside of the reservoir by the flux. Also, some part could be adhered to sediments. For that reason, proper calibration resulted in the reduction of some of the phosphorus entering the reservoir.

On the other hand, Total Nitrogen simulation reproduced adequate concentrations for almost the entire time series. However, EMC releases were higher than the values expected in literature.

From all the pollutant simulations (lines) it is also possible to observe each seasonal behavior, as this research intends to. In other words, the dry season (from May to October) accumulates pollutants and elevates concentrations, whereas in the wet season we have a great wash off and decrease of pollutant concentrations, as can be clearly observed in January 2022.

Figure 4 – Simulated BOD, along with field measurements of BOD and precipitation

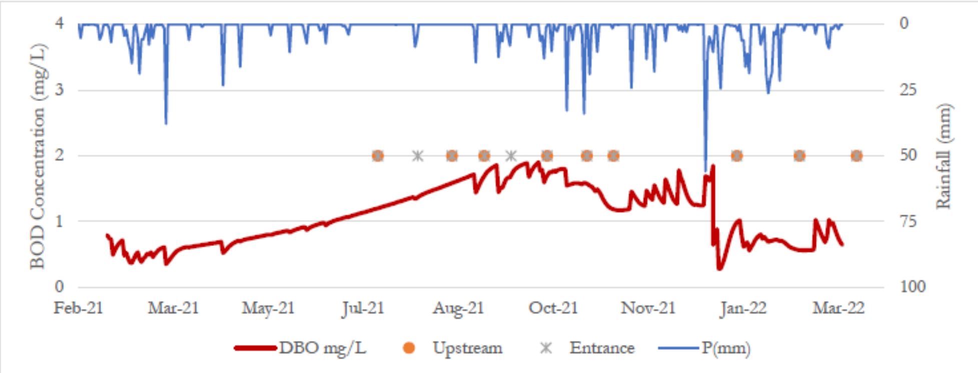



Figure 5 – Simulated PT, along with field measurements of PT and precipitation

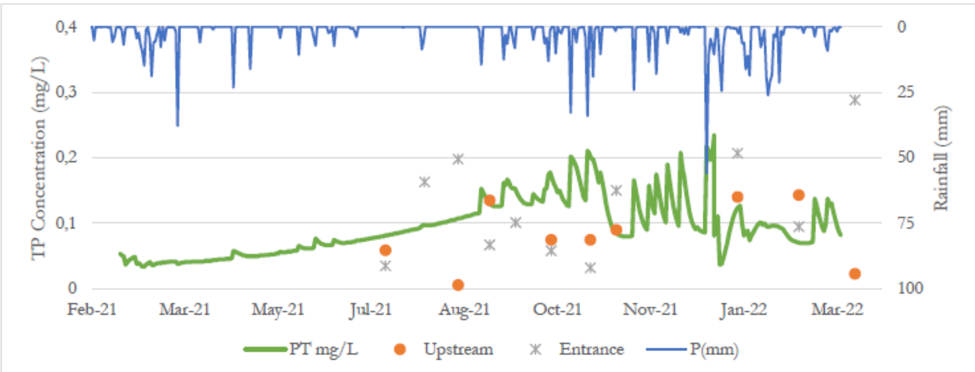


Figure 6 – Simulated NT, along with field measurements of NT and precipitation

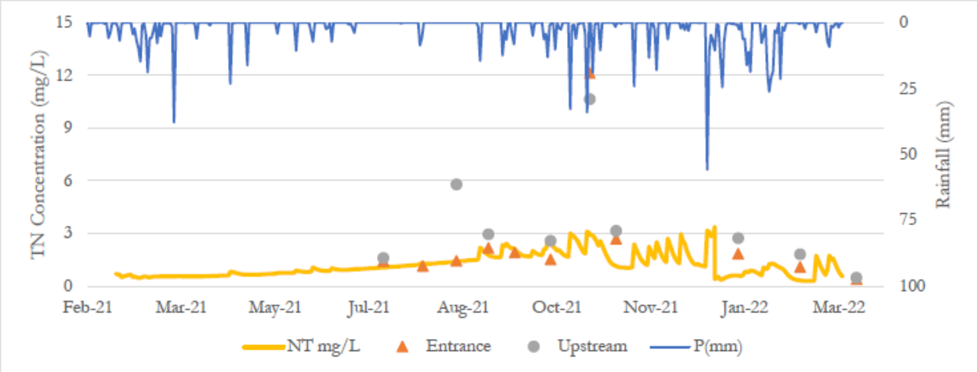



Table 4 summarize the coefficients calibrated on the CAbc-Qual. As can be seen, base loads are still accountable for the largest pollution by BOD in Ipanema Watershed. BOD base loads are explained by the WWTP in operation. As for TN and TP, both nonpoint pollution and base loads are characterized by agriculture areas filled with pesticides, which are rich in nutrients and sewage. For EMC values, by simply pondering by each land type, the obtained results have almost the same BOD and TP values as in the work from SPAT (SSRH, 2016). But, for TN, EMC values are 3 times higher than expected. Whereas it was observed before that concentrations for WWTP releases were high for this preserved watershed, indicating the use of nitrogen fertilizers.

The wash off parameters represents the response to the rainfall events. It is possible to see and infer that, for Ipanema, the wash off process differs from each constituent, in other words, nonpoint pollution in this watershed comes from many possible sources and intensity for each constituent.

Table 4. CAbc-Qual coefficients

| Coefficient | BOD | TN | TP |
|---|---|---|---|
| Unit Load Total (kg/km².day) | 1,15 | 1,46 | 0,11 |
| Unit Load Dry Weather (kg/km².day) | 0,7 | 0,76 | 0,06 |
| Unit Load Wet Weather (kg/km².day) | 0,45 | 0,71 | 0,05 |
| EMC (mg/L) | 17,85 | 24,5 | 2,45 |
| **Wash off parameter: K** | 1,00 | 1,50 | 1,00 |
| **Wash off parameter: M0 (%)** | 5,00 | 10,00 | 50,00 |

## Reservoir's eutrophic state

As presented in the methods and materials, the Trophic State Index (IET) is an important tool to evaluate the changes in the reservoir's conditions over the years and comparison to other water bodies. It combines the values of TP, Chla-a, and Secchi Depth concentrations, and as was demonstrated in Oliviera (2023), those constituents have a positive correlation along the year in the Hedberg Reservoir, strengthening the IET meaning in reservoir's environmental analysis.

Over the years, Hedberg Reservoir has been classified as Hypereutrophic, Super eutrophic, and Eutrophic, with being 2021 the year with the lower indication of nutrient accumulation and 2017 with the highest (Figure 7).

This behavior may indicate that the sewer contributions removal reduces the TP load in the reservoir, regulating the algal blooms, but still susceptible to the load amount of the basin's wash-off. Once

2022, which was a rainy year, reach the same classification as earlier years, which had the sewer contributions, indicating that wash-off load can be as important as the point sources in this basin.

The monthly analysis (Figure 8) shows that, except for two months (June and November), all the other indices vary between Eutrophic and Super eutrophic for almost all the months, confirming the recent years' trend. The reservoir's entry has a bigger amount of nutrient loads and is more affected by the basin's wash-off, given the greater IET values in this point.

Figure 7. Hedberg Reservoir Annual Trophic Index

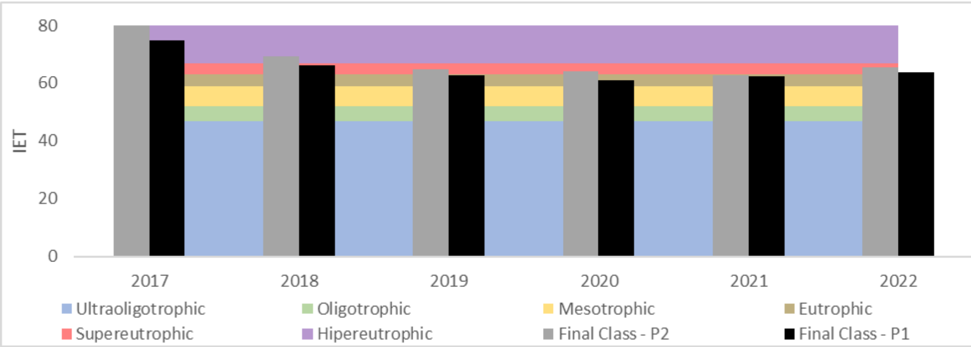
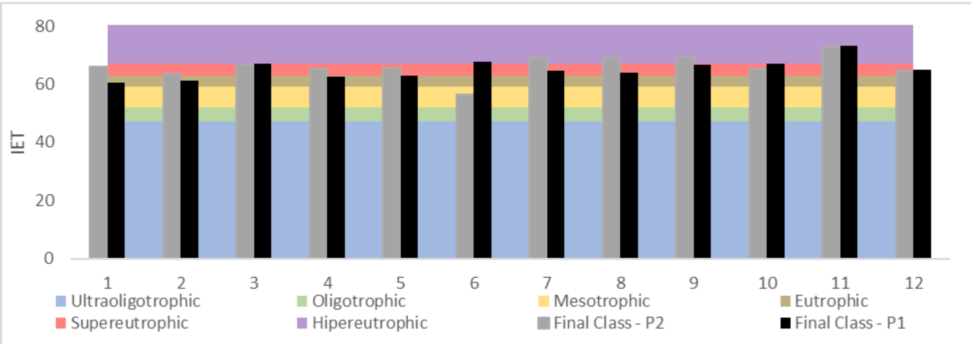



Figure 8. Hedberg Reservoir Monthly Trophic Index




## CONCLUSION

The reservoir here studied represents an artificial reservoir in a government-protected area, that had different uses over the years, located in a basin with mixed land use and changes in its environmental management during time.

The monitoring of the basin has a reliable 26-year time-series of historical data. However, this data has been interrupted and is no longer publicly accessible, which makes it difficult to compare the data of the reservoirs with that of the basin.

It is apparent that Hedberg's reservoir and basin have elevated levels of Phosphorus concentration, which changed depending on the sanitation infrastructure implemented. After the implementation of sewage treatment plants, there has been a decrease in pollution from domestic sewage, but there are still high nutrient concentrations due to the basic treatment methods.

The quality of water bodies is directly affected by basin management. Sewage and agricultural runoff contribute to eutrophication in reservoirs, which fosters the growth of algae, indicating the importance of removing nutrients from sewage and managing agricultural areas properly.

In addition, autumn and spring are critical periods for water quality. During these seasons, there is a high load of pollutants entering the reservoir, the temperature is mild, the flow is slow, and the water is transparent, which allows light to penetrate. These conditions create an ideal environment for microorganisms to thrive, leading to increased organic matter degradation and algal growth, altering the trophic state of the reservoir.

This work makes significant contributions to the field of understanding and model nonpoint pollution along the year, as long as it's coefficients in mixed basins. The role of sanitation infrastructure in the water bodies quality and the necessity of improvement in managing the loads throughout the basin.

## ACKNOWLEGEMENTS

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