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TOTAL MAXIMUM DAILY LOADS: A PERSPECTIVE FOCUSED ON RESERVOIR WATER QUALITY PLANNING AND MANAGEMENT

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ABSTRACT

Considering the the Brazilian Law nº 9.433/1997 (BRASIL, 1997) recommendation that the water quality and quantity should not be dissociated, this research presents the Total Maximum Daily Loads (TMDLs) calculation as an important tool to better assess and equilibrate both aspects in the context of the Brazillian Water Quality Classification Framework. The objective of this research is to determine the loading rate that would be consistent with meeting the Water Quality Criteria (WQC) to the case study reservoirs in Paranapanema watershed, which is known as the Total Maximum Daily Load (TMDL) calculation, in order to answer the question: "How much pollution is the reservoir capable of receive without compromising the reservoir planning and management?". In order to find out the acceptable load limits, the corresponding load compatible with the water quality standards from CONAMA 357/2005 resolution was calculated. The results showed the estimated phosphorus concentrations in the case study of the Paranapanema watershed were superior to the TMDL limits in the most of the future loading scenarios.

INTRODUCTION

In order to maintain the designated uses of a water body, the governmental agencies around the world provide regulation aiming to guarantee the best strategies for water quality planning and management. In Brazil, for instance, the Brazilian Law nº 9.433/1997 (BRASIL, 1997), also known as National Policy of Water Resources, defines five instruments for the water planning and management. One of them is called "Water Quality Classification Framework", that establishes the overall framework considering the future plans for the watershed, main water uses and the overall reference for future scenarios development. This system states that water uses are conditioned by its quality. Higher quality waters allow more demanding uses, while lower quality waters allow only less demanding uses. These procedures are regulated by CNRH resolution nº 91/2008 (BRASIL, 2008).

This instrument defines the class of a waterbody based on the most restrictive designated use. The CONAMA 357/2005 resolution (BRASIL, 2005) establishes concentration standards for each class of waterbodies, classified according to the formal legal instrument to date. However, there is no specific methodology for reservoirs water quality classification in the framework context considering that, according to the CNRH resolution nº 91/2008, the procedure should consider the specificities of the waterbodies, with emphasis on the lentic environments and the stretches with artificial reservoirs,

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flow seasonal periods and intermittent regime. Besides, the general overview of waterbodies based on concentration limits does not allow adequate conditions for analysis considering the dynamics of the water system.

A limitation to the adequate assessment of the reservoir environment is that CONAMA 357/2005 Brazilian resolution focus on concentration standards. However, this approach provides a limited understanding of the waterbody behavior, since the same amount of pollution, in mass, may provide different effects on water quality in different flow situations, because the concentration changes as a function of the flow. The United States Environmental Protection Agency (USEPA) provide a different perspective of this problem, determining the calculation of Total Maximum Daily Loads (TMDLs) for impaired waters (USEPA, 2020a). Other regulations indicate following the load analysis tendency, such as Canadian Water Quality Guidelines (CCME, 2021), Australian and New Zealand Guidelines for Fresh and Marine Water Quality (ANZEEC; ARMCANZ, 2000) and European Union Water Framework Directive (EC, 2000).

This research proposes the aforementioned TMDL perspective to improve the reservoir planning and management in the case study of the Paranapanema watershed cascade reservoirs, using the TMDLs aiming to contribute to the Water Quality Classification Framework management recommendations. The phosphorus was chosen as model variable since its important behavior limiting the primary productivity of the reservoirs (ANA/UFPR, 2019).

This kind of analysis will be relevant to understand the limitations of the reservoir in terms of capability of receiving load and how such limitations should be reflected in the regulatory legislation. The TMDL analysis can be helpful to understand the cascade reservoirs capability of receiving load. The main goal is to determine the loading rate that would be consistent with meeting the Water Quality Criteria (WQC) to the case study reservoirs, which is known as the Total Maximum Daily Load (TMDL) calculation, in order to answer the question: “How much pollution is the reservoir capable of receive without compromising the reservoir planning and management?”.

THEORETHICAL BACKGROUND

According to USEPA (2020a), a Total Maximum Daily Load (TMDL) is the maximum amount of a pollutant allowed to enter a waterbody so that it will still respect the water quality standards for that particular pollutant. The TMDL was established by the Clean Water Act. The Federal Water Pollution Control Act was created in 1948 and was reorganized and expanded in 1972, when it became known as the “Clean Water Act”. This regulation establishes how to plan actions aiming the restoration of impaired waters. When the water is recognized as “impaired”, it is required to the relevant entity to access and allocate pollutant loads in a manner that the Water Quality Standards are attained (USEPA, 2020b).

USEPA (2020b) explains that the TMDL process is divided into two main steps: the first one is quantifying existing pollutant loads and the second is calculating the load reductions needed to meet the Water Quality Standards. Besides, the aforementioned report also highlights three elements of a TMDL:

a) **Acceptable load (pollutant cap):** is the loading rate that would meet the Water Quality Criteria.

b) **Margin of Safety (MOS):** is an extra measure of protection, which takes into account the uncertainties of the loading rate calculation.

c) **Allocation of the acceptable load among sources:** is the distribution of the loading rate between the sources in a manner that Water Quality Standards are achieved.

Table 1 shows examples of how TMDL has been explored in literature.

Table 1 – Total Maximum Daily Load (TMDL) applications

Article	What did they do?	What's the conclusion?
Fernandez; McGarvey (2019)	They develop and apply a dynamic game model with economic, hydrologic, environmental and institutional components for interdependent states to reach the Total Maximum Daily Load (TMDL) water quality goals either jointly or separately. It´s an economic tool for P abatement across transboundary emitters at least coast to meet a TMDL water quality goal.	Comparing noncooperation and cooperation based on three different sector's abatement cost functions in different states, helps to delineate key differences in the amount of P reduction and the frequency in meeting water quality goals of total P load reduction to accomplish the water quality regulation goal for the time horizon.
Conroy (2018)	This paper uses the state of Ohio as a case study to explore the role of planning and planners with respect to nonpoint source water quality mitigation, specifically related to the Section 319 grant related funding, through watershed planning efforts. Section 319 directed watershed planning are focused on TMDL guidelines to combat nonpoint source pollution levels.	Planners are not involved enough in water decisions, because of the lack of integration between water quality and TMDL goals and the other government plans, such as land use
Lemly (2002)	There is no technical guidance from EPA or elsewhere that deals exclusively with selenium. This article provides guidance by laying out an assessment method that links the basic components of EPA's TMDL process to the contaminant-specific information required for selenium.	The HU (hydrological unit) approach provides the contaminant-specific site characterization that is necessary for selenium. Proper application of this TMDL technique will ensure compliance with EPA regulatory requirements and also protect fish and wildlife resources.
Gulati *et al.* (2014)	The objective was to compare the accuracy of five load estimation methods to calculate pollutant loads from agricultural watersheds	The results show that parametric methods are surprisingly accurate, even for data that have starkly non-normal distributions and are highly skewed
Wang *et al.* (2015)	A site specific empirical model is developed and linked to a general, mechanistic model of water quality.	The model performs satisfactorily for prediction of pollutant fate and evaluation of various modeling scenarious to meet the target TMDL condition. The calculated TMDL reductions can provide a scientific basis for the authority to make water pollution management decisions.
Fakhraei *et al.* (2014)	A biogeochemical model was used to relate decreases in atmospheric sulfur and nitrogen deposition to changes in lake water chemistry.	The TMDL of acidity corresponding to a moderate control scenario was estimated, including a 10% MOS.
Havens; Schelske (2001)	Considers how biological processes can influence the ability of lakes to assimilate P, and in turn the ability of managers to select appropriate TMDLs.	If some biological changes can be reversed in a rehabilitation program then the lake may be able to support a higher TMDL.
Cho; Lee (2015)	A calibration framework is developed using an influence coefficient algorithm and genetic algorithm to calibrate the models. The pollution discharges from the watershed were estimated for each land-use type, and the seasonal variation of the pollution loads were analyzed. The exceedance frequency of the water quality standard was calculated for each hydrologic condition class, and the percent reduction required to achieve the water quality standard was estimated.	The critical conditions for TP occur under high-flow conditions, wherein a 66% loading reduction is required to meet the WQS. These reductions could represent goals to work towards in the implementation phase of the TMDL process.
Zhang *et al.* (2015)	An Environment Decision Support System (EDSS) was developed to establish a daily water quality simulation, maximum daily load calculation and pollutant load reduction measures simulation using water environment management based on TMDL.	The integration is easy to implement and enables different development languages and reuse of existing models.
Kang *et al.* (2006)	Apply the soil and water assessment tool (SWAT) to develop TMDL programs.	The total maximum daily load system (TOLOS) appears to be a useful tool for planning TMDL for a small watershed.
Chen *et al.* (2000)	The Watershed Analisys Risk Management Framework (WARMF) was applied to calculate the TMDL of total phosphorus discharged to a reservoir without violating the water quality criteria of chlorophyll-a.	The TMDL of phosphorus was higher with a thermal power plant than without. Policy makers can learn, through this type of scientific analysis, about the impacts of a thermal power plant and make rational decisions about phosphorus TMDL.
Ahmadisharaf; Benham (2020)	Presents a risk-based framework for evaluating alternative pollutant allocation scenarios considering reliability in achieving water quality goals.	Achieving water quality goals with very high reliability was not possible, even with extreme levels of pollutant reduction.

Article	What did they do?	What's the conclusion?
Zhao *et al.* (2012)	The TMDL was calculated using two interpretations of the water quality standards for Class I of the China National Water Quality Standard (CNWQS) based on the maximum instantaneous surface and annual average surface water concentrations.	The model results show that, under the existing conditions, the average water quality meets the Class I standard and therefore load reduction is unnecessary.

Some other authors present alternatives for the margin of safety (MOS) determination, such as Patil; Deng (2011), Liang et al. (2016) and Camacho et al. (2018).

There is no doubt of the relevance of TMDL concept and its understanding as tool for water resources planning and management strategies. Additionally, the use of modelling tools is consolidated as well using the same approach. This research establishes the first element (acceptable load) and compares with the results of zero-dimensional model developed by Becker (2021) and applied to three main reservoirs of the Paranapanema basin: Jurumirim, Chavantes and Capivara.

MATERIAL AND METHODS

The Paranapanema basin (Figure 1) is located in the States of São Paulo (47% of the basin) and Paraná (53%). The Paranapanema river rises in the Serra de Agudos Grandes, in São Paulo State, and has its mouth at Paraná River, after covering about 930 km. The headspring region is surrounded by intense native forest. Other data on vegetation cover and land use throughout the watershed can be consulted at ANA/UFPR (2019). The Paranapanema river was considered unsuitable for navigation due to the waterfalls along its course. From the 20th century onwards the energetic potential was discovered. Therefore, the greatest use today is power generation (IGIA, 2013). This research focused on the three biggest reservoirs of the Paranapanema River: Jurumirim, Chavantes and Capivara. Their main characteristics are described in Table 2.

Figure 1 – Cascade reservoirs on Paranapanema watershed

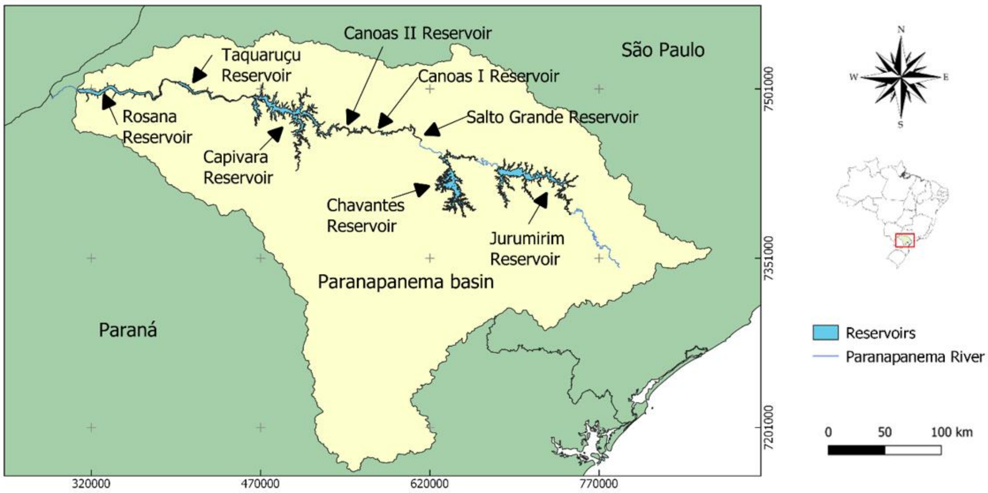


Table 2 – Reservoir's characteristics

Power plant →	Jurumirim	Chavantes	Capivara
Inauguration year	1956	1959	1978
Power (MW)	98	414	619
Reservoir surface area (km²) [a]	449	400	576
Residence Time (days) [a]	392	322	128
Average flow (m³/s) [b]	263	394	1191
Volume ($10^6 m^3$) [a]	7107	8963	11623

(a) IGIA (2013); (b) Considering the year 2012.

The Total Maximum Daily Loads are the maximum amount of a pollutant allowed to enter a waterbody so that it will still respect the water quality standards for that particular pollutant. A possible way to estimate the acceptable load (pollutant cap) is calculating the corresponding load compatible with the water quality standards. Therefore, the TMDLs were calculated based on the daily flows of the year 2012 (which was selected for the reference scenario due to the availability of flow and concentration data) and the phosphorus concentration limits for lentic environments from CONAMA 357/2005 resolution.

The first step was to integrate the limit daily loads through the year and get to the Total Maximum Annual Load (TMAL), in ton/year, according to Equation 1, in which i represents the day of the year, Q_i is the flow registered in the respective day (m³/s), CL is the concentration limit from CONAMA 357/2005 resolution (mg/L) and 86,4 is a factor for transformation of units.

$$TMAL = \sum_{i=1}^{366} \frac{Q_i \times CL}{86{,}4} \qquad (1)$$

The TMAL divided by the 366 days of the year represents the TMDL (ton/day), according to Equation 2.

$$TMDL = \frac{TMAL}{366} = \sum \frac{Q_i \times CL}{31622{,}4} \qquad (2)$$

The zero-dimensional model developed by Becker (2021) was based on an unsteady Continuously Stirred Tank Reactor (CSTR) model. For each day, there was a value of inflow, outflow, volume, area and input concentration. The flows, areas and volumes came from the Brazilian reservoir tracking system (SAR). The daily input concentrations are the results from the synthetic series of ANA/UFPR (2020). The simulations were made for a base scenario and four future scenarios: B12, T25, T35, A25 and A35, as described in Table 3. Those scenarios were defined by ANA/UFPR (2020), based in economic scenarios shown in Integrated Water Resources Plan of the Paranapanema Water Resources Management Unit (ANA/CBH PARANAPANEMA, 2016). In the tendential scenarios, public policies and the cultural socioeconomic arrangement will not differ radically from current ones. Brazil's short-term trend scenario brings stagnation to this basin until 2020, a moderate increasing in the economy until 2025 and a large increase until 2035. The accelerated scenarios represent the hypothesis of a series of positive factors joined, creating favorable conditions to economic growth. In this scenario, the wide increase in the economy starts from the year 2025 and it is maintained until 2035.

Table 3 – Future scenarios

B12	Baseline scenario - 2012	The year 2012 was selected for the reference scenario due to the availability of flow and concentration data.
T25	Tendential scenario - 2025	Brazil's short-term trend economic scenario for the year 2025, considering a moderate increment in the economic situation.
T35	Tendential scenario - 2035	Brazil's long-term trend economic scenario for the year 2035, considering a moderate increment in the economic situation.
A25	Accelerated scenario - 2025	Brazil's short-term trend economic scenario for the year 2025, considering a wide increment in the economic situation.
A35	Accelerated scenario - 2035	Brazil's long-term trend economic scenario for the year 2035, considering a wide increment in the economic situation.

RESULTS AND DISCUSSION

Considering the daily time series of inflows and outflows for the year 2012, the limit loads were calculated for each day, according to the procedure previously expressed. This calculation was made by multiplying the daily flow per the limit concentration of each water quality class of CONAMA

357/2005 resolution. The sum of this daily values represents the TMAL and the mean represents the TMDL. The TMALs and the TMDLs are shown in Table 4, as well as the phosphorus concentration limits for lentic environments.

Table 4 – Phosphorus limits, TMAL and TMDL

Phosphorus limits for lentic environment (mg/L)			TMAL (ton/year)			TMDL (ton/day)		
			Jurumirim	**Chavantes**	**Capivara**	**Jurumirim**	**Chavantes**	**Capivara**
Inflow	**Class 1**	0.02	291 727	441 102	291 727	399	603	399
	Class 2	0.03	437 591	661 653	437 591	599	905	599
	Class 3	0.05	583 454	882 205	583 454	798	1207	798
Outflow	**Class 1**	0.02	306 967	453 768	1 499 208	420	621	2 051
	Class 2	0.03	460 451	680 651	2 248 811	630	931	3 076
	Class 3	0.05	613 934	907 535	2 998 415	840	1241	4 102

Therefore, Table 4 answers the question: “How much pollution is the reservoir capable of receive without compromising the reservoir planning and management?” for each one of the Water Quality Framework class. Figure 2 and Figure 3 show the load duration curves in the entry and in the exit of the reservoir, respectively. As can be seen in the y axis, the magnitude of the values are reduced considerably in the outlet. These values were compared to the TMDLs correspondent to the same flow (input limit and output limit).The shape of the outlet load duration curves was defined by the pattern of the regulated flow considering the reservoir operation.

Figure 2– Load duration curves in the reservoir’s inlet

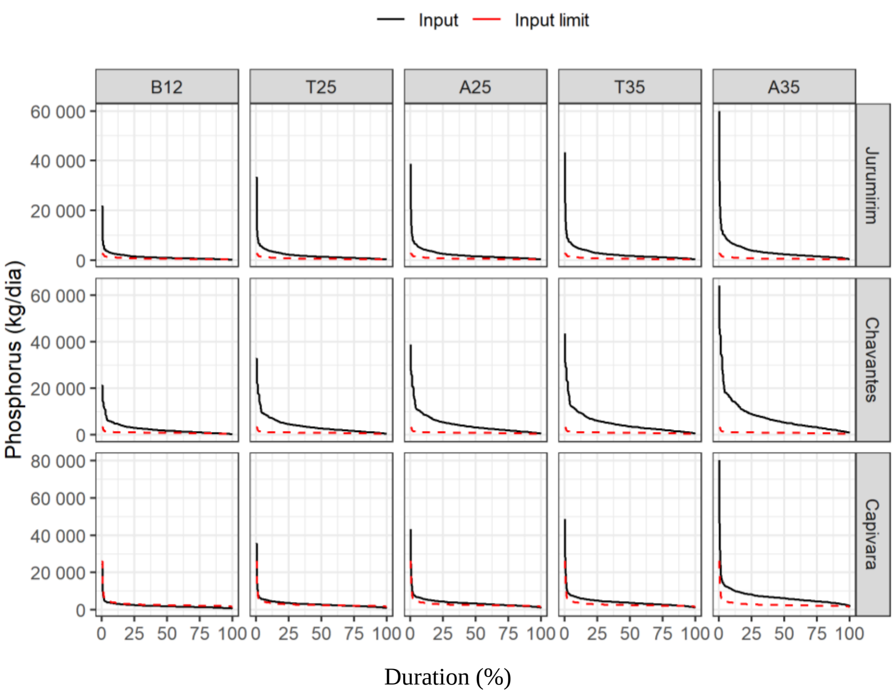
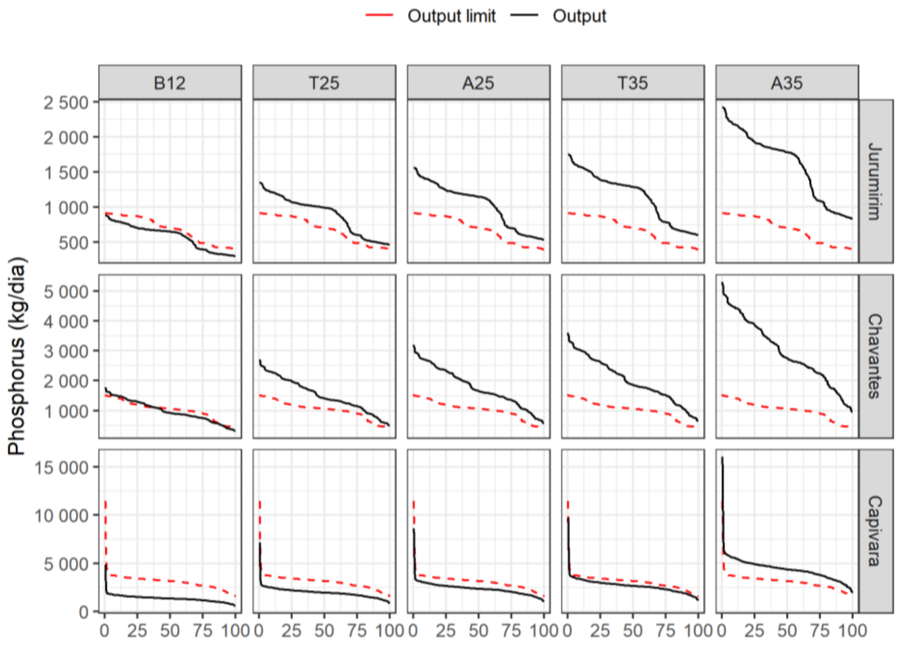


Figure 3 – Load duration curves in the reservoir's outlet



Duration (%)

The Total Maximum Daily Loads were calculated as the mean of the daily load results of the model. Figure 4 indicated that the input TMDLs are above the class 2 input limit in all economic scenarios, except for Capivara (B12). The output TMDLs are showed in Figure 5, that showed that in Jurumirim and Chavantes reservoirs the TMDLs exceeded the output limit load in the future scenarios. In Capivara reservoir, the exceedance occurred only for A35 scenario.

Figure 4 – Total Maximum Daily Loads for Class 2 limits (inputs)

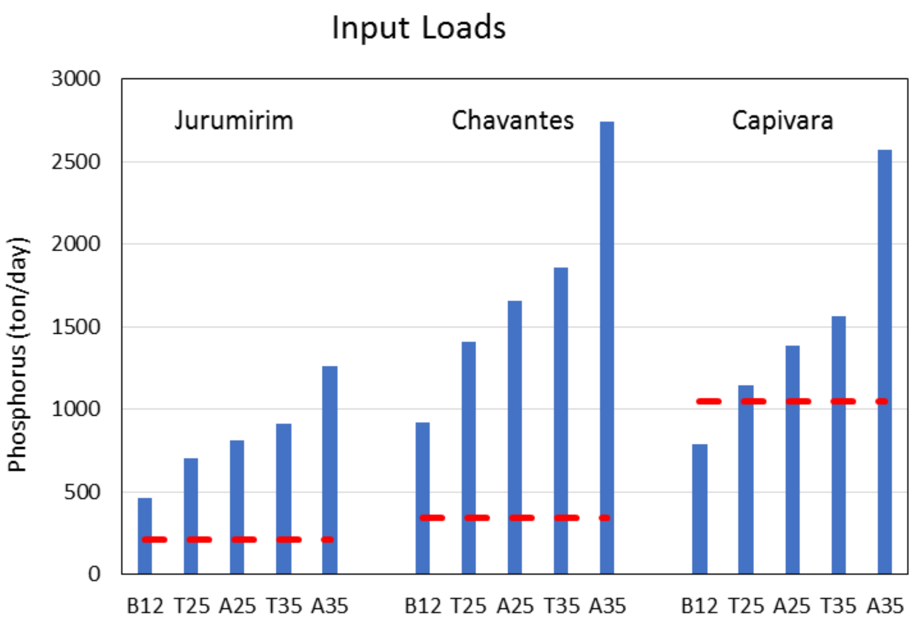
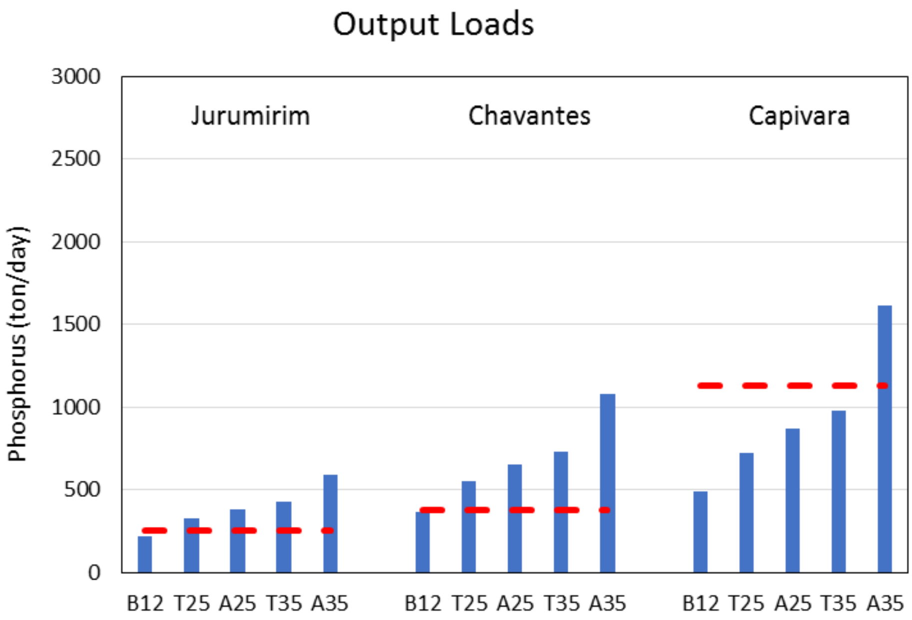


Figure 5 – Total Maximum Daily Loads for Class 2 limits (outputs)



The analysis showed the input (estimated by synthetic series) and output (estimated by the zero-dimensional model) reservoir loads exceeded the TMDL limits in the most of the evaluated scenarios. It points out the urgent need of new policies and tools of planning and management for Paranapenema basin, such as the Water Quality Classification Framework process.

The input and output load results reinforce the reservoir role in decreasing the pollutants concentrations downstream. The reason for that is that the decrease in water velocity and increase in retention time favor the occurrence of chemical and biological oxidation and decantation of various elements in the sediments, of which phosphorus is one of the most susceptible, as stated by Cunha-Santino et al. (2017). Zubala (2009) also points out the reservoir role in the processes of self-purification that improves the quality of waters flowing out of anthropogenically transformed areas.

FINAL REMARKS

This research provided an overview on the Total Maximum Daily Loads use for planning and management despite the Brazilian regulations only focus on concentration standards. Considering the use of synthetic series, the chronological gaps can be fulfilled and the loadings calculation can provide a general indication of the reservoir condition. The results showed the estimated phosphorus concentrations were superior to the TMDL limits in the most of the future loading scenarios. It points out the urgent need of new policies and tools of planning and management for Paranapenema basin, such as the Water Quality Classification Framework process. During this process, the special condition of the reservoir dynamics should be taken into account, since they have an important role on decreasing the pollutants concentrations downstream.

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