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HYDRAULICS AND ENVIRONMENTAL ENGINEERING DEPARTMENT

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# The dynamic of seasonal nonpoint pollution in complex watersheds

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# The dynamic of seasonal nonpoint pollution in complex watersheds

**Revised Version**

Ph. D. Thesis presented to the School of Engineering at the University of Sao Paulo (EPUSP) to obtain the degree of Doctor of Science.

Concentration Area: Hydraulics Engineering

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# ABSTRACT

**MAGALHÃES, Ariel Ali Bento** The dynamic of seasonal nonpoint pollution in complex watersheds. PhD Thesis, Escola Politécnica - Universidade de São Paulo. São Paulo, 2023.

Periods of drought are impactful in terms of surface water quality, as there is less mass available to dilute the released contaminants. However, it has now been determined that the cause of substantial effects on water and aquatic habitat is surface runoff caused by rainfall-flow process. Although not receiving as much attention, diffuse pollution (runoff, deforestation, fertilizers from farmland, etc.) is just as harmful as point pollution (from treatment plants, industrial discharges, etc.). Thus, the coupling of hydrological, load and hydrodynamic models related to water quality is becoming increasingly important. The development of the CABC-QUAL model in this work was thought to help with these complex issues, which include the multiples uses of the watershed and the variability of precipitation itself, the different forms of sanitary systems and the seasonality of the constituents. In addition, a tool was included to manage Best Management Practices (BMP) through *in situ* Treatment Units, which proved to be a great helper for positioning these practices to reduce pollution in surface waters. In the two case studies used to validate the developed model, the CABC-QUAL demonstrated its ability to perform all its tasks accurately, quickly and completely. It also demonstrated results on an annual time scale, discussing all the complexity of the variation in constituent concentrations distributed across the basin. This tool will be essential to represent the complexity of water quality more accurately and will serve as support for depollution programs.

**Key-Words:** modelling; nonpoint pollution; best management practices.

# RESUMO

**MAGALHÃES, Ariel Ali Bento** A dinâmica sazonal da poluição difusa em bacias complexas. Tese de Doutorado, Escola Politécnica - Universidade de São Paulo. São Paulo, 2023.

Períodos de seca são impactantes em termos de qualidade das águas superficiais, pois há menos massa disponível para diluir os contaminantes lançados. No entanto, já foi determinado que a causa de efeitos substanciais na água e no habitat aquático é o escoamento superficial direto, causado pela precipitação. Embora não receba tanta atenção, a poluição difusa (escoamento superficial, desmatamento, fertilizantes de terras agrícolas, etc.) é tão prejudicial quanto a poluição pontual (de estações de tratamento de esgotos, descargas industriais, etc.). Dessa forma, o acoplamento de modelos hidrológicos, de carga e hidrodinâmicos relacionados à qualidade da água está se tornando cada vez mais importante. O desenvolvimento do modelo CABC-QUAL neste trabalho foi pensado para ajudar nessas questões complexas que, incluem a bacia hidrográfica e a variabilidade da precipitação em si, as diversas formas de sistemas sanitários e a sazonalidade dos constituintes. Além disso, incluiu-se uma ferramenta de gerenciar Melhores Práticas de Gestão (BMP) através de Unidades de Tratamento in situ, que se mostrou como grande auxiliador para posicionamento destas práticas a fim de reduzir a poluição nas águas superficiais. Nos dois estudos de caso utilizados para validação do modelo desenvolvido, o CABC-QUAL demonstrou sua capacidade de realizar todas as suas tarefas de forma precisa, rápida e completa. Também demonstrou resultados em uma escala de tempo anual, discorrendo toda a complexidade da variação das concentrações dos constituintes de forma distribuída na bacia. Esta ferramenta será essencial para representar com mais precisão a complexidade da qualidade da água e servirá como suporte para programas de despoluição.

**Palavras-chave:** modelagem; poluição difusa; melhores práticas de gestão.

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*(alphabetical order)*

ADP - ADENOSINE DIPHOSPHATE

ATM - ALTERNATIVE TREATMENT METHODS

ATP - ADENOSINE TRIPHOSPHATE

BMP – BEST MANAGEMENT PRACTICES

BOD/$BOD_5$ – BIOCHEMICAL OXYGEN DEMAND

DNA - DEOXYRIBONUCLEIC ACID MOLECULE

DO – DISSOLVED OXYGEN

EC – EXPORT COEFFICIENTS

EMC – EVENT MEAN CONCENTRATION

IEM - INTEGRATED ENVIRONMENTAL MODELING

LID – LOW IMPACT DEVELOPMENT

MAE - MEAN ABSOLUTE ERROR

NBS – NATURE BASED SOLUTIONS

NCS - NON-CONVENTIONAL SOLUTION

NPC – NITROGEN, PHOSPHORUS, CARBON

NPS – NONPOINT SOURCE

NWRP - NATIONAL WATER RESOURCES POLICY

RMSE - ROOT MEAN SQUARE ERROR

RU – RECOVERY UNIT

SPAT – SISTEMA PRODUTOR ALTO TIETÊ

SPMR - SÃO PAULO METROPOLITAN REGION

TN – TOTAL NITROGEN

TOC – TOTAL ORGANIC CARBON

TP – TOTAL PHOSPHORUS

UL – UNIT LOADS

WWTP – WASTEWATER TREATMENT PLANTS

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# CHAPTER 1

## INTRODUCTION

*"The deeper the waters are, the more still they run"*

Korean Proverb

People rely on surface waters for important aspects of their lives such as recreation, supply for consumption, fish production, among many other uses. They are also critical to the survival of many species (birds, mammals, fish, and other forms of life), which depend on water to live, feed and reproduce. Surface waters are both resilient and fragile and therefore quantity and quality are constantly changing as a result of natural and anthropogenic forces (JI, 2017). The economic use of water has made it recognized as a commodity, that is, it carries economic value.

The culture of water abundance has been progressively replaced by the idea of water as finite and endowed with economic value, making the analysis of the balance between uses and water supply increasingly important, by revealing regions with water access deficit and risks for productive sectors (ANA, 2019).

It is known that the exploitation of natural resources is a result of the increasing population, economy, and consumeristic urban lifestyles. The sustainability of the environment and the well-being of people are under increasing pressure as a result. In addition, it is urgently necessary to find ways to balance conflicting sectoral demands and municipality needs within a nation, plus human interests and the sustainability of nature. As global water stress rises dramatically as a result of rising demand, demographic and economic expansion, intersectoral competition for water resources is predicted to rise and lead to over exploitation (NIVA; CAI; TAKA; KUMMU *et al.*, 2020).

The growth of urban areas has as main result the waterproofing of the catchment area. This, along with the usually disorganized expansion and the incompatible use of ecosystem’s capacity, causes progressive degradation of the environment through changes in land use and occupation, inefficiency of adequate infrastructure and poor public cleaning. Figure 1 and Figure 2 show how urbanization around the world has been increasing at high rates since 1945 and will continue increasing up to 2050. One can infer by these two images that Brazil was one of the most affected by the transition from rural to urban areas, especially after World War II.

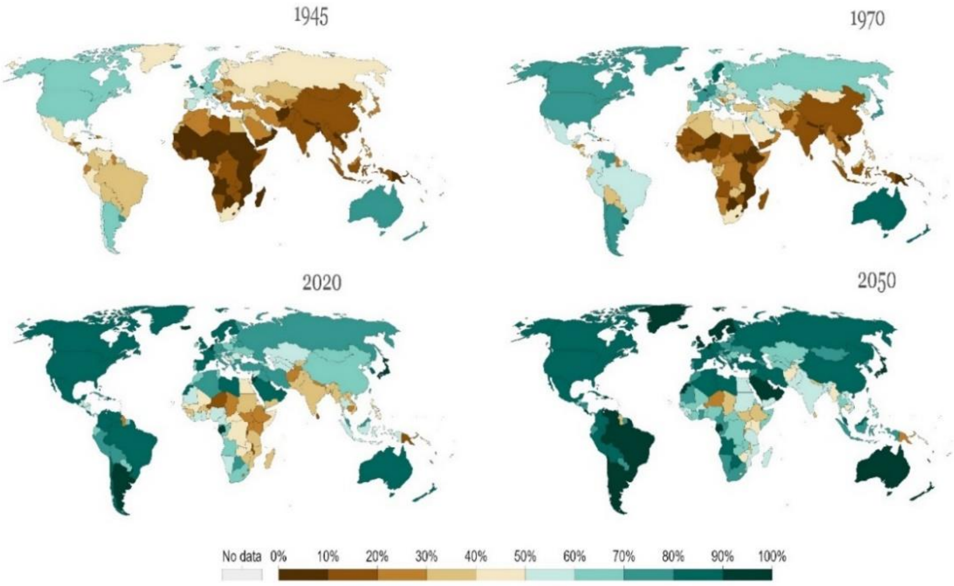



Figure 1 - Share of the population living in urban areas evolution (from 1945 - 2050)
Source: Adapted from OWID, 2022.

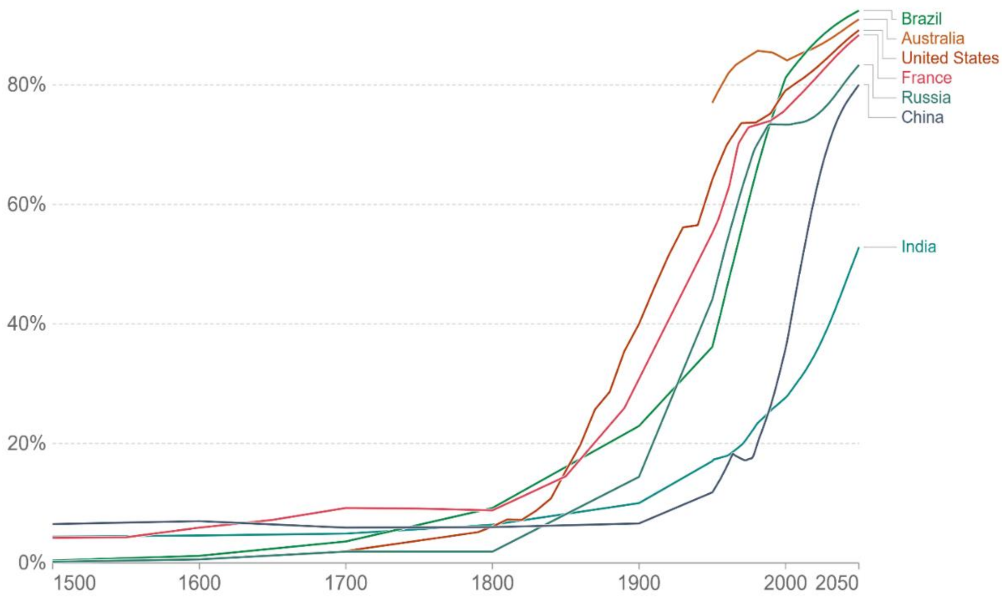



Figure 2 - Share of the population living in urban areas from 1500 to a 2050 prediction
Source: OWID, 2022

At the beginning of the twentieth century, the industrialization and the fast urbanization of São Paulo affected the physiography and river landscapes for energy production and urban sanitation. The main rivers were redirected and dammed for the purpose of generating hydropower and water supply, and their beds were canalized and corrected to increase the flow and to keep them off the cities. Rivers and streams were made into infrastructure elements (CASTRO; ALVIM, 2022).

From the 1930s onwards, the impairment of surface water quality in cities with high population density drove the emergence of the first models of water quality that, over time, became more complex. Currently, the water quality models with the highest acceptability are Qual2E and Qual2K (CHAPRA, 2008), Wasp (WOOL; AMBROSE; MARTIN; COMER, 2020), Aquatox (PARK; CLOUGH, 2014), DELFT-3D (HYDRAULICS, 1998), HEC-RAS (USACE, 2010), among others.

From the water quality point of view, periods of drought are considered critical because the volume available to dilute the mass of pollutants reaches a minimum during this period. However, surface runoff, streams of areas under construction and the (contaminated) base flow have been identified as the causes of significant impacts on water and the aquatic habitat (PRODANOFF, 2005). Of course, these effects are more severe for small water bodies in basins under intense development rates.

When relating water quality to hydrological behavior under critical conditions (such as in drought periods), the assumption of steady state is usually valid, as the variation of the components of the flow over time is very gradual. However, in urban environments, the discharge of pollutant loads is continuous and the hydrodynamics of the river is variable, resulting that steady-state water quality modeling may lead to imprecise results (GARCIA; TUCCI, 2000).

In this context, there is a trend to couple hydrological, load and hydrodynamic models to plan and forecast water quality. This tends to offer greater precision to the intended results, and may help the analysis of the uncertainty associated with model parameters, usually used in the calibration of water quality models (FERREIRA; FERNANDES; KAVISKI, 2016).

The aspect to be considered in this assessment is that the management of water resources can be more efficient if the quality of the river is considered during all the hydrological cycle (including storms and droughts), making mapping of nonpoint pollution impacts an evolution to the established technological approach. In addition, substantiate actions considering associations between concentration and reference flows at different times of the year, instead of launches as defined by Resolution 430 (CONAMA, 2011)

The impacts related to point pollution (from sewage treatment plants, industrial releases, etc.) are well known and usually they are easy to quantify, predict and locate. However, nonpoint pollution (surface runoff, forest cutting, fertilizers from crop lands, etc.) is just as important, although it is not given so much importance. Researches carried out around the world, including Brazil, show that diffuse pollution contributes to a considerable part of the total polluting load released in urban water bodies, reaching more than 30% of the total load (MORIHAMA; AMARO; TOMINAGA; YAZAKI *et al.*, 2012; MOURA; PELLEGRINO; MARTINS, 2013; NOVOTNY, 2002).

Nonpoint loads can be quantified and estimated by several methods, such as: Exports Coefficients (EC) or Unit Loads (UL); Event Mean Concentration (EMC); Mathematical Simulation Models, such as HSPF, STORM, SWMM, etc.; or even combinations, improving reliability (MAGALHAES; MARTINS; DA SILVA; AMORIM, 2019). Mainly, these methods are integrated with hydrological models, and their results only include the final loads that arrive at the water body. The hydrodynamics of the water body are not included, requiring a tool that couples the two models: hydrological and hydrodynamical and provides the water quality results aimed.

Xiang, Wang and Liu (2017) released a paper entitled "A *scientometrics* review on nonpoint source pollution research" in which they analyzed 3246 papers from 2001 to 2015 about the theme. They discovered that out of the top 10 subject categories, Agriculture had the highest centrality, which plays an important role in nonpoint source areas. In Figure 3, they illustrated how the research about nonpoint pollution is spatially distributed. We can notice that the greatest amount of work on this topic is divided between North America (USA and Canada), Europe, India, and China.

In addition, the study showed, as mentioned before, that agriculture is one of the main themes related to diffuse pollution, with the focus being almost always related to nutrients (Nitrogen and Phosphorus, mainly). The focus on urban areas, especially in areas that have already gone through the urbanization process and have a good municipality planning for the disposal of solid waste, sanitation, and etc., is often unnecessary, since most of the pollution on surface water bodies is expected to come from point sources (such as industries or effluents from sewage treatment plants) or deposition from atmospheric pollution (XIANG; WANG; LIU, 2017)

As seen, papers in this theme are few in Brazil and the research on the subject is still developing, as well as in several countries around the world. But, for Brazil and emerging countries, the available models need extensive information on flow and water quality, and their application can be complicated and expensive. Several water bodies are situated in areas where data are scarce, impossible, or otherwise impractical to collect. Since these models are potent instruments, there is a concern regarding the compatibility and application of these models (FERREIRA; MUHLENHOFF; FERNANDES, 2018).

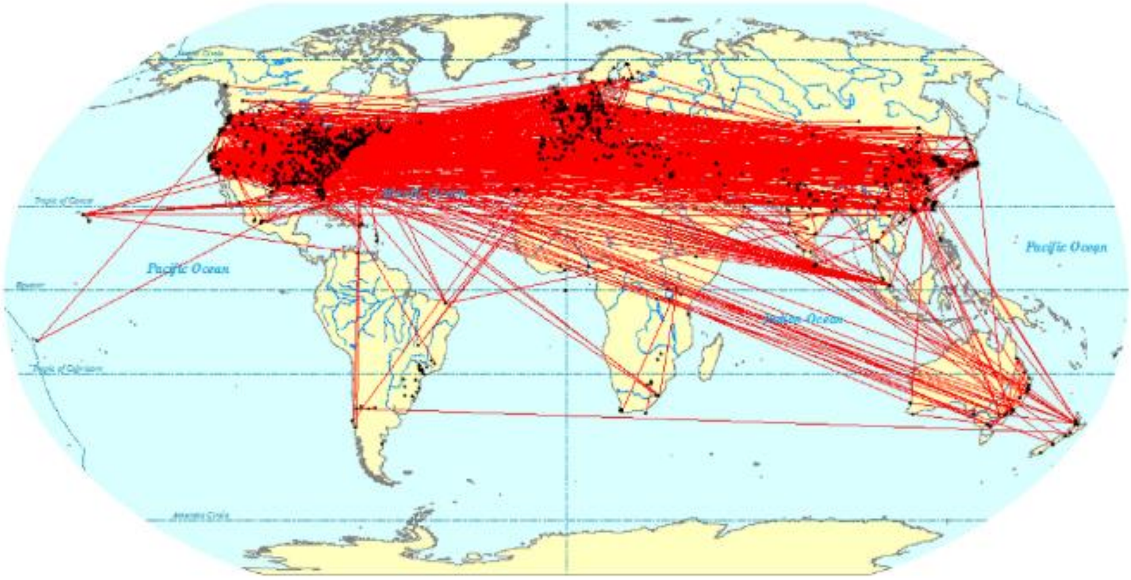



Figure 3 – World spatial distribution of the research on Nonpoint Pollution
Source: (XIANG; WANG; LIU, 2017)

In places that are still in the process of urbanization or with poor infrastructure, illegal or poorly conducted sewage loads, inadequate solid wastes management, construction sites, etc., lead to great degradation of surface water bodies, especially by BOD, ammonia, and orthophosphate, all contained in domestic sewage. For instance, Brazil, holds the famous Pinheiros and Tietê Rivers, in São Paulo. From time to time, water cleaning-up projects for these rivers are initiated but there is a stated sense that only with the control of these sources of pollution there will be possibilities for achieving the successes reached in the rivers around the world like Seine and Thames, for example (BAPTISTELLI, 2020).

Many water resources management programs involve upland watershed plus water body systems analysis. Usually, the two processes are made through a two stage analysis, taking longer to perform, and going back and forward to couple results from hydrological (and load) and hydrodynamical (and water quality) models. That said, computer simulation models that include all the processes (in terms of quantity and quality) beginning in the upland watershed and downstream water bodies are extremely necessary (DEBELE; SRINIVASAN; PARLANGE, 2008).

Thus, it is essential to develop methods to quantify the pollutant loads found in surface flows, to create projects and structures that reduce or prevent nonpoint pollution. Some measures for controlling diffuse pollution involve non-structural, administrative, and educational actions. It can also be said that diffuse pollution has cultural aspects that involve more complex factors like economic and social ones. That said, the will from the government and the engagement of the citizens in this process is extremely important, exhaustively discussing a problem that involves all departments of society (PARENTI; PEREIRA; FUNARI, 2016).

To manage the problem of diffuse pollution in large cities, it is necessary to rethink the role of urban engineering and the environmental approach. Historically, engineers and managers are used to leading and storing rainfall flows with a quantitative focus only, and now there has been an increasing need for a new concept, similar to the natural processes that happened previous to the human occupation. This process involves techniques of retention, filtration and infiltration of superficial flows, allowing the development of biological, physical and chemical processes that promote the treatment of contaminated rainwater (PARENTI; PEREIRA; FUNARI, 2016).

In this context, Best Managements Practices (BMP) and Low Impact Development (LID) fundaments are incorporated. BMP means a practice, or combination of practices, that is determined to be an effective and practicable means of preventing/reducing the amount of pollution generated by nonpoint sources (NPS) to a level compatible with water quality goals (JAIN; SINGH, 2019).

Deriving from that thought, in the watershed management, the basin can be divided into control units with the purpose of breaking complex water-environmental problems into simpler homogenous units (landscape, land use and occupation, etc.), so that specific environmental management measures and policies can be effectively implemented (DING; DONG; ZHAO; PENG *et al.*, 2020).

It is difficult to estimate the spatial and temporal distributions of agricultural nonpoint pollution loads precisely because of the interactions among surface conditions, pollution sources, and hydrological processes. Complex hydrological processes combined with the physical and biogeochemical processes of pollutants make it extremely difficult to predict pollution events (e.g., eutrophication). The interactions of underlying surface conditions, pollution sources, and hydrological process result directly in largely spatial and temporal variations (WANG; WANG; ZHANG; LIN, 2020).

All considered, the exposed arguments are the background and motivation to investigate and develop a modeling approach to the nonpoint pollution assessment in complex basins. To fulfill this goal, some questions must be addressed:

i. Is it possible and relevant to model pollutants according to their different sources and seasonal behavior?
ii. Is it feasible to consider different land uses and sanitation systems (infrastructures) to compute pollutant loads in a complex watershed?
iii. How striking is the rain spatial and time distribution when it comes to nonpoint pollution?
iv. Is it possible to calibrate the seasonal behavior of water quality in complex watersheds considering singular and sparse data and common variables?
v. Is it possible to evaluate structural and non-structural actions to reduce water pollution or improve water bodies quality status?
vi. Is it possible to evaluate the real effect of mitigation devices as the so-called Nature Based Solutions (NBS) as a tool to increase water quality conditions in different watersheds?

Possible answers and fundaments to the challenging questions above are explored in the next chapters.

# CHAPTER 2

## RESEARCH OBJECTIVES AND APPROACH

*"If you want to live a happy life, tie it to a goal, not to people or objects"*

Albert Einstein

To answer the questions mentioned in the previous chapter, the main objective was to develop and test modeling techniques (using real case studies) that allow prospective users (researchers, municipal managers, etc.) to assess nonpoint pollution in complex watersheds under a more realistic representation of the involved phenomena, e.g.: hydrological seasonal behavior, land use and occupation, culture and infrastructure, etc., with higher reliability.

To achieve this, differences between time and spatial distribution of rainfall were analyzed, as well differences between time steps in measuring flow and precipitation. Also, realistic, and precise surface and base flow determination to simulate base load and wash off load.

In this context, it is also mandatory to investigate and correctly assign sanitation systems and infrastructure to the watershed in order to adjust load generation in urban areas. With this, coupling the hydrological and the load model, using conceptual and practical techniques (Unit Loads – UL and Event Mean Concentration – EMC, respectively) shall present good results.

Finally, we have the importance of these assessments when applying Best Management Practices (BMP) in complex watersheds. Where to locate them? When are they necessary? What is the load or concentration that is expected at this point (or area)? These are questions that we aim to answer.

### *2.1 THESIS ORGANIZATION:*

The thesis is divided into 7 chapters. Chapter 1 describes the motivation and the context in which this thesis was planned and executed. It presents the main problems and challenges in the field of managing nonpoint pollution and our plans towards it. Chapter 2 presents the goals and the approach to develop this thesis.

Chapter 3 presents the fundamental bases for the development of the model, including nonpoint pollution characteristics, hydrological models, load estimation techniques and Best Management Practices. Chapter 4 shows the monitoring planning and campaigns developed for both study cases. Chapter 5 describes, precisely, how the model was developed and the software features.

In Chapter 6, model validation through two study cases is developed. The studies were chosen by their evident differences: one of them is in a mixed basin (mainly rural), but in an arising development environment (Ipanema) and the other is in a highly urbanized place (Jaguaré), inside the city of São Paulo.

Finally, Chapter 7 brings together the main discussions and recommendations for future projects involving nonpoint pollution modeling and forecasting.

## *2.2 APPROACH*

The approach to develop this thesis is divided into 3 grand parts. In Part 1 the literature review was made, and the investigation of the concepts involved. Firstly, reviewing all types and kinds of hydrological and stormwater concepts and modeling. Later, investigating existing load and nonpoint pollution models already available and in use (such as SWAT, SWWM, BASINS, etc.), as well as consolidating the knowledge about Export Coefficients (EC) Event Mean Concentration (EMC), and other concepts regarding nonpoint pollution modeling. Finally, how the coupling of the two models is performed and how sanitation systems and urban rivers are considered.

Part 2 consisted of investigating the study cases. Part of the nonpoint pollution dynamic is the watershed characteristics, such as land use, elevation, hydrography, and other elements in the study areas, as well as rainfall spatial and time distribution. So, exploring these attributes is fundamental in this process. The other part consists of field measurements (monitoring) at Floresta Nacional de Ipanema and Jaguaré.

The final grand part (Part 3) was developing modeling techniques and validating it for the studied cases. So, the first step was setting up, developing, calibrating, and validating the model to verify the thesis. Also, investigating the impacts on self-purification (fate and transport on water quality) and its possibilities to implement on the model. Thirdly, to simulate the watershed control and Best

Management Practices (BMP) to reduce nonpoint pollution. To sum up, this work was developed as shown in Figure 4.

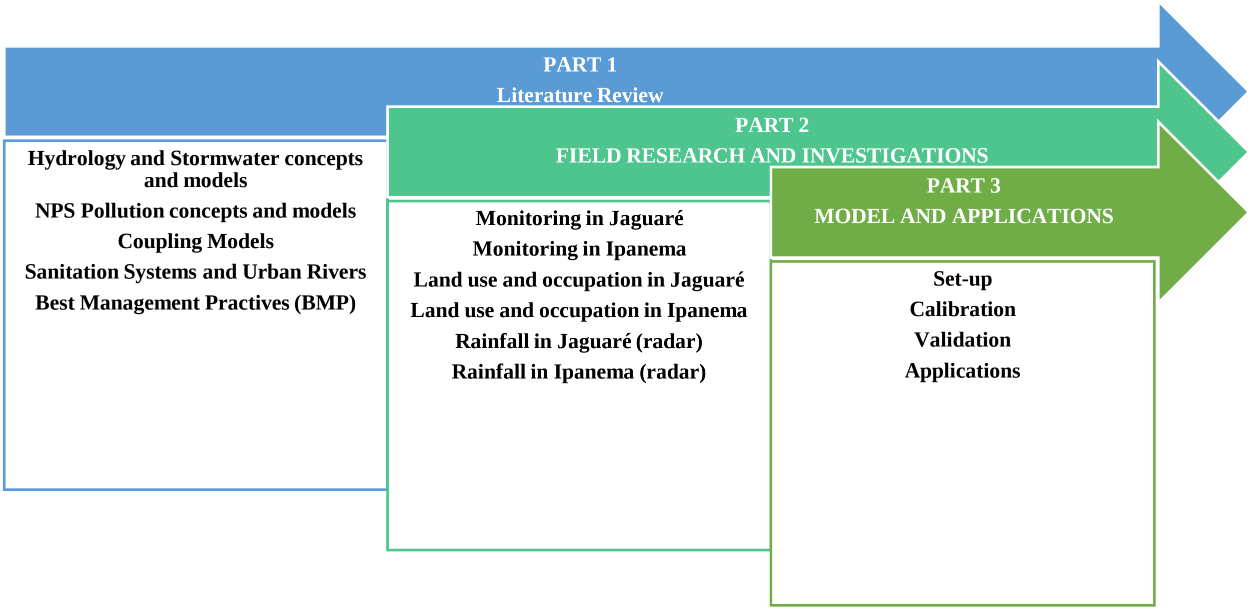



Figure 4 - Methodological Approach

# CHAPTER 3

## LITERATURE REVIEW

*"Water quality reflects the composition of water as affected by nature and human activities"*

Novotny and Olem, 1994

### *3.1 GENERAL CONCEPTS AND DEFINITIONS*

The management of natural resources is challenged by a variety of complex social-ecological interdependencies. To account for these complexities, several researchers highlight the need of an alignment of the governance system (institutional arrangements addressing environmental problems or resource uses) with the characteristics of the ecosystem (WIDMER; HERZOG; MOSER; INGOLD, 2019).

Water resources are considered a significant factor in economic and social growth for effective environmental management and planning. Water resources must be appropriately allocated, utilized to assess the impact on the environment, and poses a specific challenge in designing ecological systems (XIANG; LI; KHAN; KHALAF, 2021).

Water is so important because of its many uses. A use is considered consumptive when the withdrawn water is consumed, partially or totally, in the process for which it is intended, not returning directly to the water body. Consumption can occur through evaporation, incorporation into products, among others. Water uses such as navigation, fishing, and tourism, for instance, do not directly affect the amount of local water - although they depend on it - being considered non-consumptive uses. The main consumptive water uses in Brazil are human supply (urban and rural), animal supply, the processing industry, mining, thermoelectricity and irrigation (ANA, 2019).

To ensure water quality that is compatible with the most demanding uses for which they are intended and to reduce the costs of reducing water pollution, through permanent preventive actions, a classification of water bodies was established, according to the predominant uses of water. This is part of the instruments of the National Water Resources Policy (NWRP), instituted by Law No. 9,433, of January 8, 1997. Figure 5 illustrates NWRP water quality requirements according to classes framework and water uses.

The special class is the one in which the natural conditions of the water body must be maintained and is the most restrictive to human activities. The higher the number of the corresponding class, the less demanding the level of water quality necessary for water uses becomes, decreasing the restriction to activities that may impact the quality of these waters. Although, even in the lowest class there are conditions and standards for compliance with the class, such as: minimum Dissolved Oxygen (DO), acceptable pH range, odor restrictions, among others.

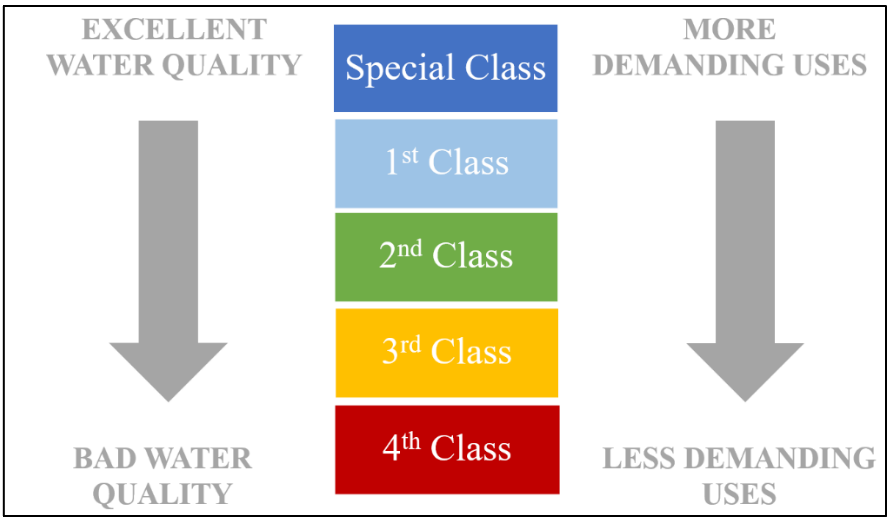



Figure 5 - Water quality requirements according to classes framework and uses
Source: Adapted from ANA (2019).

Water pollution is caused by the addition of substances or types of energy that directly or indirectly alter the physical and chemical characteristics of the water body so that its use for beneficial purposes is impaired. The first form of pollution, called point source, refers, as the name itself implies, to the pollution resulting from localized modifying actions. This is the case, for example, of the mouth of a river, effluent from a domestic or industrial sewage treatment plant, or the discharge of an underwater emissary into the sea (VON SPERLING, 2007).

Law 6.938, dated from August 31th 1981, which depicts the National Environmental Policy, among other considerations, defines pollution as:

> Degradation of environmental quality resulting from activities that directly or indirectly:
> (a) adversely affect the health, safety and well-being of the population;
> (b) create adverse conditions for social and economic activities;
> (c) adversely affect biota;
> (d) affect the aesthetic or sanitary conditions of the environment
> (e) release matter or energy in disagreement with established environmental standards.

The second type, diffuse pollution, is a process that starts with the washing and transport of air pollutants by rain, the formation of surface runoff that carries a great part of the pollutants deposited on the surface of the basin and then leads to its final destination: a stream. This type of eviction, unlike point releases, is a random phenomenon that is difficult to measure and whose magnitudes depend mainly on meteorological factors and the use and occupation of the land. Along this thesis, it will also be referred to as wash load or nonpoint pollution.

In Brazil, a significant part of the pollutant loads is generated by non-compliance with legislation, the inefficiency of public policies and, mainly, the lack of awareness of the population in order to prevent degradation (SOARES, 2003).

Nature is rather fragile, but very resilient. And this resilience comes in the form of self-purification in the waters. According to Von Sperling (2007), self-purification can be understood as a phenomenon of ecological succession, in which the restoration of balance in the aquatic environment (search for the initial stage found before the release of pollutants) is carried out by essentially natural mechanisms.

The association of various physical, chemical, and biological processes is responsible for self-purification. Dilution, sedimentation, oxidation, decomposition and atmospheric reaeration are the components and steps that integrate this process (HYNES, 1960). Its stages are physically identified by stretches, as shown in Figure 6.

For a better understanding of self-purification, it is necessary to know the main water quality constituents, such as Dissolved Oxygen (DO), organic matter (identified by the C-BOD parameter), nitrogen, phosphorus, among others. The aforementioned nutrients are available in the water column and are used at cellular level by microorganisms for essential metabolisms, which are susceptible to physical interference from the environment (FERREIRA, 2014).

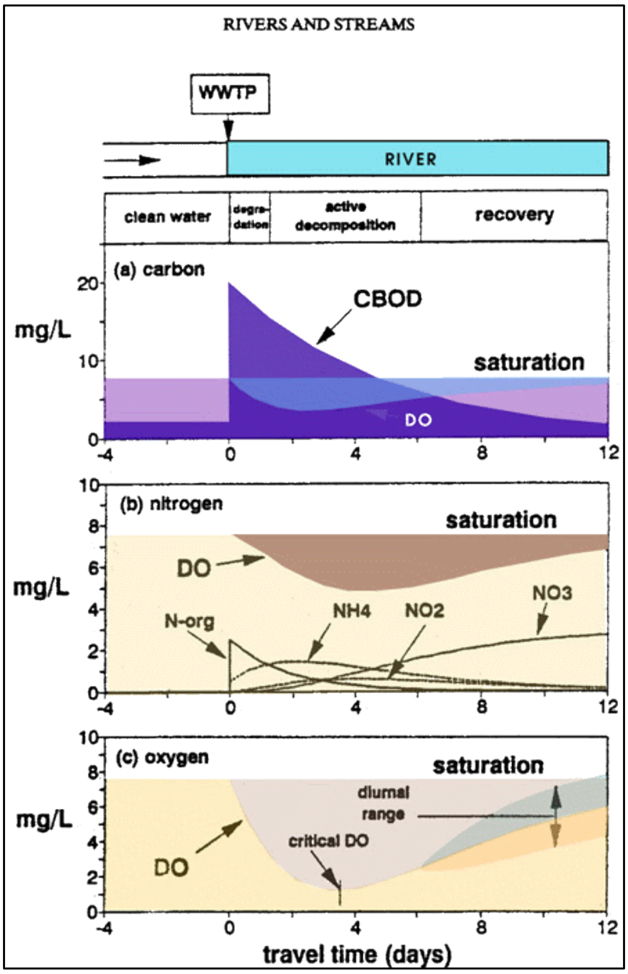



Figure 6 - Trends of (a) C-BOD, (b) nitrogen, and (c) oxygen below a wastewater treatment plant discharge into a river Source: Adapted from Chapra (1996).

The main processes (sedimentation, decomposition, etc.) that occur in the degradation of these parameters occur simultaneously and constantly in the liquid mass, however they are usually arranged separately due to the complexity of the interactions. Greater understanding of chemical, physical and biological processes enable the development of knowledge about the dynamics of nutrients in ecosystems.

The main processes and interactions in the Nitrogen, Phosphorus and Carbon (NPC) cycle are illustrated in Figure 7 and will be detailed in sequence.

### *3.1.1 Dissolved Oxygen (DO)*

Oxygen consumption can be described through the organic matter oxidation; nitrification; algae respiration and the benthic (bottom) demand. The oxygen main intakes can be through aeration and the algae photosynthesis.

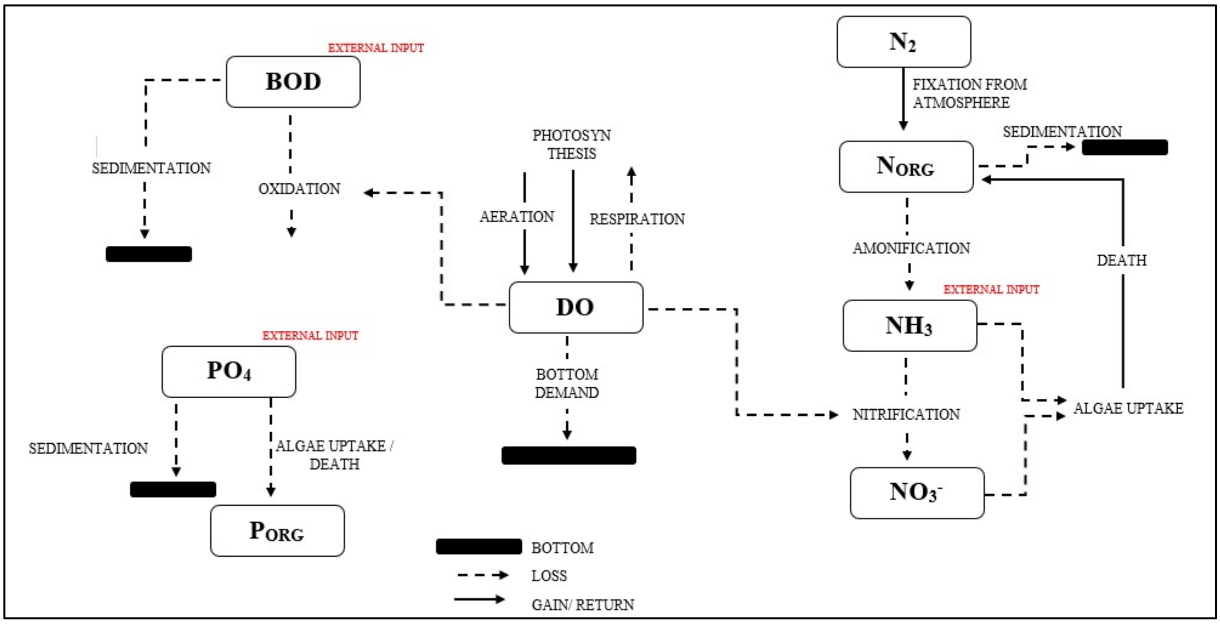



Figure 7 - Main process and interactions in the NPC cycles (Nutrients)

Oxidation is the process in which electrons are extracted from a substance, increasing its oxidation state, and transforming pollutants into compounds less undesirable to the environment. Total oxidation or mineralization results in simple and stable end products, such as $CO_2$, $H_2O$, $NO_3$, etc (VON SPERLING, 1995).

In nitrification, autotrophic bacteria use DO to modify ammoniacal nitrogen in nitrites and nitrates. The consumption of DO in these reactions is called nitrogen demand and it occurs at a later stage than the oxidation reactions of carbonaceous organic matter, due to the autotrophic nitrifying bacteria growing less than the heterotrophic bacteria. The benthic demand is the consumption of DO by organic matter in which the superficial layer of sludge undergoes aerobic decomposition, resulting in the use of oxygen.

For the oxygen intake, there is atmospheric aeration - the most frequent process and the main factor of introducing oxygen into the liquid through the gas-transfer. This generates an increase in the concentration of oxygen in the liquid phase, mainly through turbulent diffusion. Photosynthesis is the method used by autotrophic beings for the synthesis of organic matter (VON SPERLING, 2007).

*3.1.2 Biochemical Oxygen Demand (BOD and $BOD_5$)*

Carbon circulates in the aquatic environment naturally through three classes of processes: (1) assimilative and dissimilative reactions of carbon, mainly in photosynthesis and respiration; (2) exchange of carbon dioxide between the atmosphere and the oceans; and; (3) sedimentation of carbonates (RICKLEFS, 2003).

Anthropologically, carbon is released in water from domestic effluents, which is easily quantified indirectly by the BOD parameter. Another factor that can increase the suspended organic matter is called bottom turning, which consists of the reintroduction of the previously sedimented organic matter in the water column mainly because of a quick flow increase (FRAGOSO; FERREIRA; MARQUES, 2009).

Carbon or carbonaceous organic matter can be found in the non-biodegradable (suspended and dissolved) and biodegradable (suspended and dissolved) fractions. The biodegradable matter in suspension has larger dimensions and, due to its size, its sedimentation is faster than the dissolved matter. As an energy source, dissolved organic matter is more easily consumed.

The organic matter degradation process ends up consuming the DO present in the water, since the metabolic processes of the decomposing bacteria need oxygen for their functions (RICKLEFS, 2003). Usually BOD is called C-BOD when it is referring to carbonaceous organic matter oxygen demand and N-BOD when it refers to nitrogenous organic matter oxygen demand (organic fraction).

The $BOD_5$ indicates the amount of oxygen which bacteria and other microorganisms consume in a water sample during the period of 5 days at a temperature of 20 °C to degrade the water contents aerobically. It is widely used in laboratories to analyze samples from surface waters. In this paper, $BOD_5$ will be used when referring to carbonaceous organic matter and when results are compared to samples.

*3.1.3 Nitrogen and fractions*

The nitrogen cycle is one of the most important in the aquatic ecosystem, since through its assimilation and metabolism it is possible for living beings to produce essential molecules such as proteins, amino acids and nucleic acids (FRAGOSO; FERREIRA; MARQUES, 2009).

The primary source of molecular nitrogen ($N_2$) is the atmosphere. In addition to this source, nitrogen may come from anthropogenic sources such as industrial, domestic waste, animal droppings and fertilizers or from natural sources, since it is part of proteins and several biological compounds, in addition to nitrogen from cellular composition of microorganisms (VON SPERLING, 2007).

Also, according to Von Sperling (2007), nitrogen in the aquatic environment is found in the forms of organic nitrogen, ammoniacal nitrogen (ammonia), nitrite and nitrate. Along with the processes that convert nitrogenous matter, nitrification (oxidation of ammonia to nitrite and from this to nitrate) also consumes DO.

Another reaction of importance is the conversion of organic nitrogen to ammonia (ammonification), as the outcome potentially results in the nitrification process explained before. This reaction begins in the sewage collector network, progressing in the treatment units and eventually in the receiving watercourse. More common is that, at the end of the sewage treatment, the amount of organic nitrogen is already low (VON SPERLING, 2007).

### *3.1.4 Phosphorus and fractions*

Phosphorus is essential for plants and animals, since it is an essential component of the deoxyribonucleic acid (DNA) molecule, adenosine triphosphate (ATP), adenosine diphosphate (ADP) and lipid cell membranes. It comes from rocks, fossilized bones, fertilizers, detergents and sewage transported to the aquatic ecosystem through the sewage network (FRAGOSO; FERREIRA; MARQUES, 2009).

This nutrient is essential for the growth of microorganisms responsible for the stabilization of organic matter, but in high concentrations it is responsible, along with nitrogen, for the eutrophication process, since it is also indispensable for the growth of algae.

The runoff from agricultural areas (dragging the fertilizers) and urban areas (with the flow of chemicals, polluting loads of sewage and detergents) increases the presence of phosphorus contents in water courses.

### *3.2 HYDROLOGY AND STORMWATER CONCEPTS*

Hydrologic cycle is defined as water circulation through different paths and at different rates all over the globe. The cycle begins with precipitation which is either absorbed into the ground or travels as surface water. Water absorbed by soil and vegetation will percolate to the water table or return to the atmosphere through evaporation and evapotranspiration. The cycle completes when water evaporates into the atmosphere (KUANG, 2014).

The hydrologic cycle water balance equation can be presented as Equation (1)(1):

$$\begin{aligned} Total\ Precipitation \\ &= \text{Net change in surface water} + \text{Net change in ground water} \\ &+ \text{Evapotranspiration} + \text{Interceptions} \end{aligned} \tag{1}$$

Precipitation, land use, soil type in terms of water absorption and storage, groundwater table, climatology, and the meteorology of the area of interest are all hydrologic cycle elements used in stormwater modeling. Runoff is one of the most interesting aspects of stormwater modeling. Initial abstraction refers to the entire amount of water captured by evaporation and absorbed into groundwater before runoff begins. Water infiltrates into the soil until it becomes saturated when runoff (2) begins (KUANG, 2014).

$$\boldsymbol{Runoff} = Total\ precipitarion - Initial\ abstraction - Infiltration - Evaporation \tag{2}$$

> "Stormwater is an all-inclusive term that refers to any of the water running off the land's surface after a rainfall or snowmelt event. Prior to development, stormwater is a small component of the annual water balance. However, as development increases, the paving of pervious surfaces with new roads, driveways, rooftops, etc., reduces the water infiltration and more water runs off (MPCA, 2020)."

In a vegetated watershed, most of the rainfall infiltrates the soil and subsequently percolates deeper into groundwater or is sent back to the atmosphere by evaporation and vegetal transpiration processes. As urbanization arises and the percentage of impervious surface increases, an escalating amount of precipitation runs off the landscape and is eventually discharged into receiving waters (MPCA, 2020). Figure 8 illustrates differences in the water budget between natural forested and urban land use.


Figure 8 - Water balance for forested (left) and urban watersheds (right)
Source: University of Washington apud MPCA (2020)

As seen, urban development alters the hydrology of watersheds and streams by disrupting the natural water cycle. Similar changes can occur from intensive agricultural or foresting activities, mainly because of soil compression. The Georgia Stormwater Manual (2016) notes seven relevant impacts on hydrology caused by urban development:

i. ***Increased runoff volumes:*** *Land surface changes can dramatically increase the total runoff volume generated in a developed watershed through soil compression and impervious surfaces.*
ii. ***Increased peak runoff discharges:*** *Rainfall quickly runs off impervious surfaces instead of being released gradually as in more natural landscapes.*
iii. ***Greater runoff velocities:*** *Impervious surfaces and compressed soils, as well as improvements to the drainage system such as storm drains, pipes, and ditches, increase the speed at which rainfall runs off land surfaces within a watershed.*

iv. ***Shorter times of concentration:*** *As runoff velocities increase, it takes less time for water to run off the land and reach a stream or other water body.*

v. ***Increased frequency of bank-full and near bank-full events:*** *Increased runoff volumes and peak flows increase the frequency and duration of smaller bank-full and near bank-full events, which are the primary channel forming events.*

vi. ***Increased flooding:*** *Increased runoff volumes and peaks also increase the frequency, duration and severity of out-of-bank flooding.*

vii. ***Lower dry weather flows (Baseflow):*** *Reduced infiltration of stormwater runoff could cause streams to have less baseflow through shallow groundwater inflow during dry weather periods and reduces the amount of rainfall recharging groundwater aquifers.*

Figure 9 illustrates how changes in stream hydrology, as a result of urbanization, affect the hydrographs.

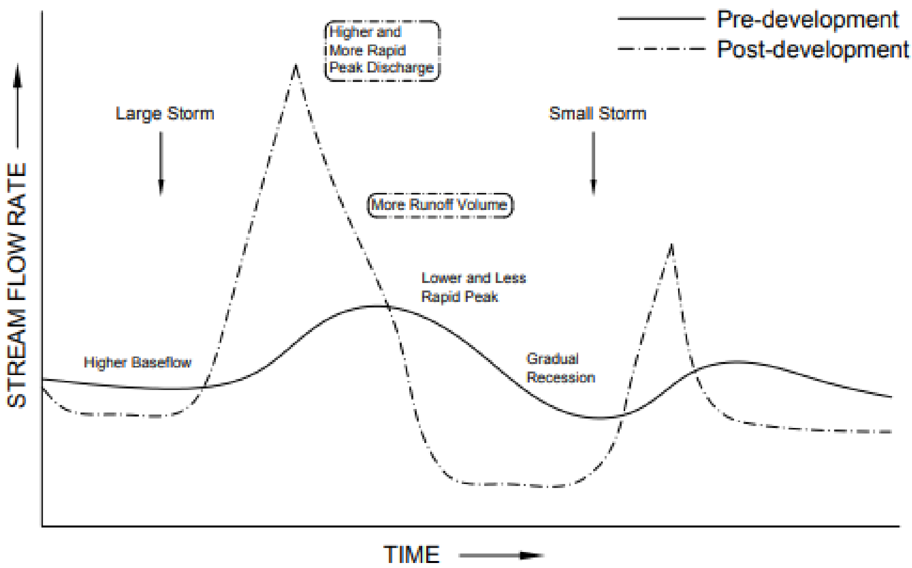



Figure 9 - Hydrograph under Pre- and Post-Development Conditions
Source: Schueler, 1992 Apud (ARC, 2016)

In quantitative terms, the changes in the rate and volume of runoff from developed watersheds directly affect the morphology, or physical shape and character, of urban streams, rivers and others. Some of the impacts due to urban development include stream widening and bank erosion; higher flow velocities; stream downcutting; loss of riparian vegetation; sedimentation; and increase in the floodplain elevation (ARC, 2016).

Different types of hydrological models are used for impact assessment (floods, climate changes, predictions for the future, etc.). Usually they are classified according to the type of variables used in the modeling (stochastic or deterministic), the type of relationships between these variables (empirical or conceptual), the arrangement of data representation (discrete or continuous), the existence (or not) of spatial relationships (concentrated or distributed) and the existence of temporal dependence (stationary or dynamic) (KRYSANOVA; DONNELLY; GELFAN; GERTEN *et al.*, 2018).

Empirically based models are developed by analyzing a large set of data and developing statistical relationships between the inputs and the outputs (WOOLHISER, 1982). Deterministic models are the ones that mathematically describe the modeled processes. As the processes are independent of geographic variations, deterministic models can be applied to a wider range of conditions than empirical models can. In some instances, however, it may not be possible to describe a process adequately. Besides, the excessive amount of data required to describe a process may restrict the use of the model (WARD; TRIMBLE, 2003).

Stochastic models seek to identify statistical probabilities of hydrologic events (WOOLHISER, 1982), like rainfall or flood flows, and to predict the probability of a given outcome. They also consider the natural variability that might occur in some model input parameters. As users become more acquainted with the statistical nature of hydrology, stochastic modeling increases.

SMAP (*Soil Moisture Accounting Procedure*) is a mathematical model for hydrological simulation that performs rainfall-flow transformation type considering different phases of the water cycle. It was initially presented at the International Symposium on Rainfall-Runoff Modeling held in Mississippi, U.S.A., and published by Water Resources Publications (LOPES; BRAGA; CONEJO, 1982). Even though it dates from 40 years ago, recent studies still use it for its high reliability (CAVALCANTE; DA CUNHA LUZ BARCELLOS; CATALDI, 2020; DA CUNHA LUZ BARCELLOS; CATALDI, 2020; MACIEL; CABRAL; MARCATO; JUNIOR *et al.*, 2020).

Because of its relevance and capabilities for this study SMAP fundaments will be detailed in CHAPTER 5 – Model and Software Development.

### *3.3 NONPOINT SOURCE (NPS) POLLUTION*

In qualitative terms, Nonpoint Source (NPS) pollution, which is the primary cause of polluted stormwater runoff and water quality impairment, comes from scattered sources — many of which are associated with human activities within a watershed. Development concentrates and increases the amount of nonpoint source pollutants. As stormwater runoff moves across the land, it picks up and carries away both natural and human-made pollutants, depositing them into streams, rivers, lakes, wetlands, coastal waters and marshes, and even underground aquifers.

Nonpoint pollution is a process that begins with washing and transporting air pollutants through rain, the formation of surface flow that carry a large part of the pollutants deposited on the basin surface and transport them to their destination in a receiving body. This type of dumping, unlike occasional releases, is a random phenomenon that is difficult to measure and whose magnitudes depend mainly on meteorological factors and the type of land use and occupation (RIGHETTO; GOMES; FREITAS, 2017).

The most noticeable characteristic of diffuse (nonpoint) pollution is the wide range of pollutant concentrations on surfaces captured by runoff. Concentrations differ by orders of magnitude between river basins, between precipitation events, and even within a single event (BAPTISTA; NASCIMENTO; BARRAUD, 2005). The graph that explains the behavior of the concentration of the pollutant in the storm event *versus* time is known as a pollutograph and it is essential for the studies of nonpoint pollution.

Novotny and Chester (1981) describe five conditions that characterize sources of diffuse pollution:

i. Intermittent polluting load that is related to precipitation.
ii. Pollutants are transported from extensive areas.
iii. Polluting loads cannot be monitored from their point of origin, even because their exact origin is hard to identify.

iv. Controlling pollution from diffuse sources must include actions on the pollution-generating area, rather than just controlling effluent at launch.

v. It is difficult to establish quality standards, since the pollutant load launched varies according to the intensity and duration of the meteorological event, the extension of the production area in that specific event and with other factors that make the flow x pollutant load correlation virtually impossible to establish.

The removal of the pollutants deposited during the dry period and the transport to the receiving areas during rainfall is called *wash off* or *washing load* (WL). This process encompasses the dissolution of possible soluble compounds in the first rainwater by surface wetting with sufficient turbulence for dissolution to occur, suggesting that the peak of the pollutograph occurs before the peak flow, as shown in Figure 10, curve **a**. The greater the intensity of the storm, the greater the occurrence of the process of dissolution and transportation (GOONETILLEKE; THOMAS, 2003).

The initial period of stormwater runoff during which the concentration of pollutants is substantially higher than later periods is called the **first flush phenomenon** (GUPTA; SAUL, 1996). During the first flush, an enormous quantity of pollutants is discharged into the receiving waters (LEE; BANG; KETCHUM; CHOE *et al.*, 2002).

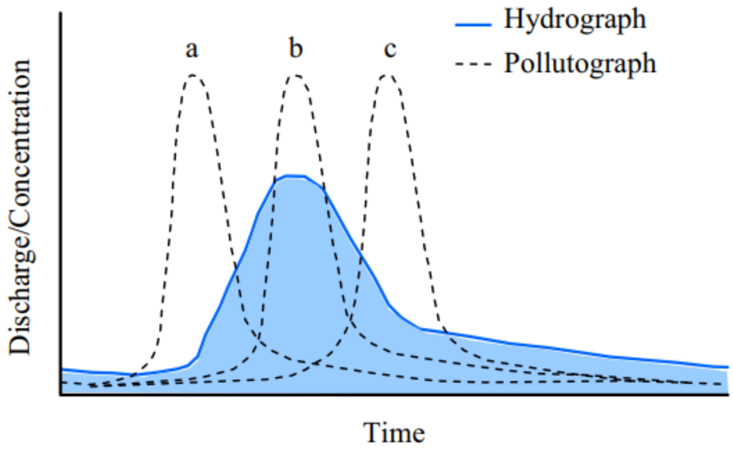



Figure 10 - First-Flush effect in the shape of the pollutographs curves
Source: (QIN; HE; FU, 2016)

In addition to the first flush, previous studies have found that some pollutants in some storm events exhibit a "middle flush" or "final flush" behavior (also known as "second flush," "end flush," or "last flush" in the literature), which means that the majority of pollutant loads are washed off by the middle or last proportion of runoff volume rather than the first (QIN; HE; FU, 2016), as seen in curves **b** and **c** of Figure 10.

To assess the first flush, researchers usually use curves of the cumulative fraction of total pollutant mass vs the fraction of total cumulative runoff volume for the event. Geiger (1987) defined a first flush as occurring when such curves have an initial slope greater than 45% (Figure 11) and used the point of maximum divergence from the 45º slope to quantify the first flush. Gupta and Saul (1996) used a remarkably similar definition.

Saget, Chebbo and Bertrand-Krajewski (1996) suggested a very strict definition of the phenomenon; they defined a first flush as occurring when at least 80% of the pollution load is transferred in the first 30% of the runoff volume. In the work published by Sansalone and Buchberger (1997) a non-restrictive criteria is used; the first flush is perceived if a mass cumulative curve of a pollutant is above the runoff volume curve.

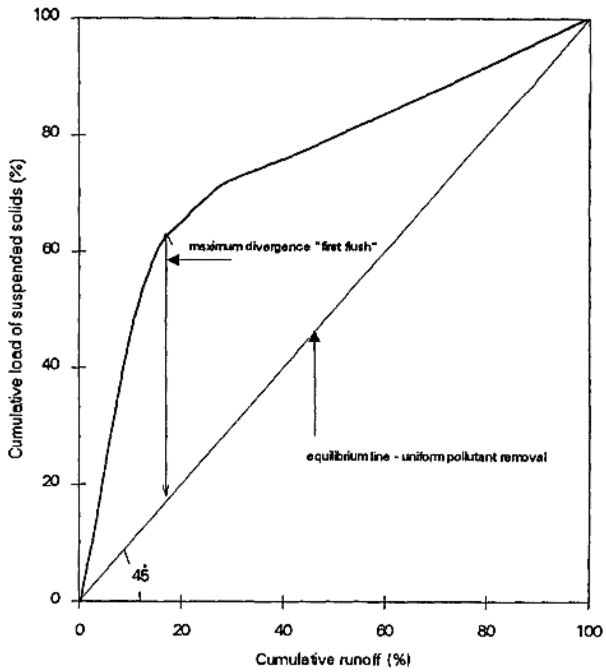



Figure 11 - First flush as defined by Geiger (1987)
Source: Geiger (1987)

In most of Brazil's urban watersheds, pollutograph or solid discharge curves are not available once automatic sampling is required. However, it is quite common to have measured hydrographs or synthetic hydrographs. That way, it is possible to proceed with the execution of several monitoring campaigns or perform the generation of a Synthetic Pollutograph (PRODANOFF, 2005).

Although numerous efforts have been made to investigate the flush effect of storm runoff pollution in urban catchments, there are very few studies reporting the flush characterization in undergoing urbanization catchments. Qin, Khu and Yu (2010) and Qin, He and Fu (2016) showed that in catchments with a low fraction of impervious surfaces, the first flush intensity is weak. The efficiency of urban runoff models based on the first flush theory may be hampered if first flush phenomena are not prevalent and second flush phenomena are important. As a result, all flush impacts must be characterized and investigated for the management and treatment of storm runoff pollution in urbanizing catchments.

Unlike sewage, which goes to treatment plants for contaminant removal, polluted stormwater runoff flows untreated into stormwater drainage where it is carried to the nearest stream, river, lake, estuary or coastal water. Figure 12 presents some major sources of stormwater pollution (NPS pollution). This type of water pollution might seem to be very small, but cumulatively for a large area or population, it has a significant impact into surface waters and many times can be the major source of pollution in watersheds (Figure 13) (ARC, 2016).

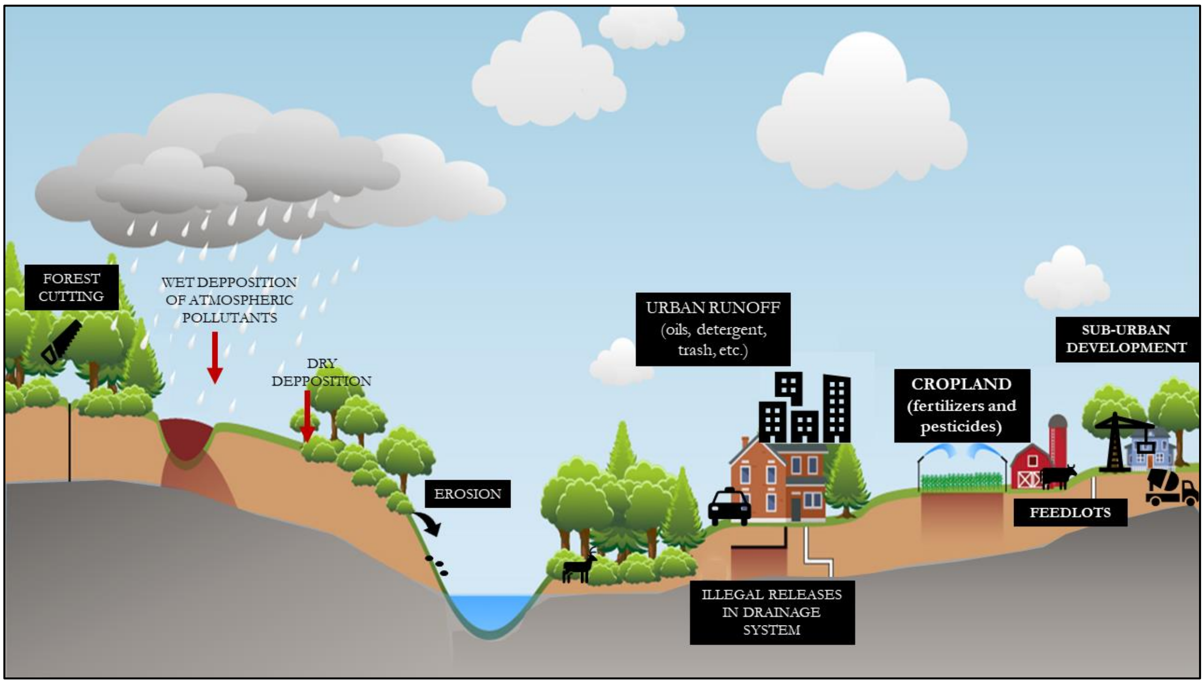



Figure 12 - NPS pollution

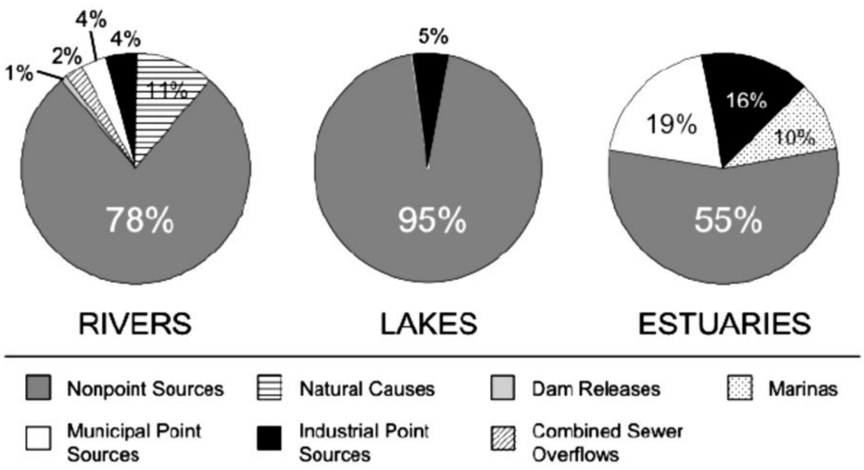



Figure 13 - Causes of Water Quality Impairment in Georgia

Source: State of Georgia 303(d) List of Impaired Waters (2001)

Diffuse pollution is generated by runoff in urban areas, resulting from the deposition of pollutants, in a distributed manner, over the watershed which is why urban drainage networks carry high pollutant loads, constituting one of the main sources of water bodies degradation (BRITES; GASTALDINI, 2005). This pollution presents itself in a very diversified form and depends on factors such as land use and occupation, population density, seasons, topography, geology and the characteristics and frequency of rainfall. Rural activities, atmospheric deposition, and urban runoff are examples of diffuse pollution activities. Cross-connections of sewers and effluents from septic tanks in the rainwater system are other examples of this type of pollution, but they are transmitted in a different way (PORTO, 1995); (SSRH, 2016)).

While diffuse pollution is typical from the washing off surfaces provided by direct runoff, whereas an intermittent flux, due to precipitation; point pollution encompasses releases already known - for example, the release of Wastewater Treatment Plants (WWTP) and industries. In this way, it can be considered that there is an endemic load, with a perennial flow over time, arising from sewers (CAMPBELL; D'ARCY; FROST; NOVOTNY *et al.*, 2005).

Currently in Brazil, CONAMA 430 establishes limits for effluent releasing conditions and standards, which can be applied to point source releases. Even though, currently there are not any laws or means to regulate nonpoint pollution on the water bodies and how to control it. In the

United States, The U.S. Clean Water Act (1972) established the term TMDL – Total Maximum Daily Loads for restoring impaired waters and it describes the maximum amount of a pollutant allowed to enter a water body so that the water body will meet and continue to meet water quality standards for that pollutant.

> *"Pollutant sources are characterized as either point sources or nonpoint sources. Point sources include all sources subject to regulation under the National Pollutant Discharge Elimination System (NPDES) program (wastewater treatment facilities, concentrated animal feeding operations, etc.). Nonpoint sources include all remaining sources of the pollutant as well as natural background sources. TMDLs must also account for seasonal variations in water quality and include a margin of safety to account for uncertainty in predicting how well pollutant reductions will result in meeting water quality standards." (USEPA, 2022)*

Expressed mathematically, the TMDL equation is presented in Equation (3), where WLA is the total of waste load allocations (point sources), LA is the sum of load allocations (nonpoint sources and background) and MOS is the margin of safety.

$$TMDL = \sum WLA + \sum LA + MOS \tag{3}$$

Each pollutant that causes a water body to be impaired or threatened is referred to as a water body/pollutant combination, and for each water body/pollutant combination, a TMDL is normally established. Three TMDLs might be created for a water body that is impaired or endangered by three contaminants, for example. In some circumstances, however, a single TMDL document can be created to handle several water body/pollutant combinations (USEPA, 2022).

### *3.4 METHODS TO ESTIMATE AND QUANTIFY DIFFUSE POLLUTION*

The quantification and prediction of diffuse pollution are characterized by the difficulty of collecting and analyzing data. Thus, according to Pessôa (2013), as this process does not occur directly, it is necessary that specific methodologies are applied, making it possible to estimate diffuse pollution and allowing the adoption of measures for the control and minimization of related negative impacts.

Therefore, this process must be done, according to Silva, Marti and Imberger (2014), in different hydrological periods (dry and wet weather), so that an adequate assessment of the influence of the diffuse load and characterization of the quality of the water body can be performed under analysis. According to the author, in dry weather there is a tendency to accumulate potential pollutants in the studied area (increase in the mass of pollutants to be carried by the runoff of rainwater).

Nonpoint loads can be quantified and estimated by several methods, such as: Exports Coefficients (EC) or Unit Loads, Event Mean Concentration (EMC) and Mathematical Simulation Models. However, some methods are used combined, due to the limitations of these methodologies in producing reliable and trustworthy results when applied alone.

### *3.4.1 Export Coefficients or Unit Loads Method*

In the Export Coefficients (EC) or Unit Loads (UL) methods, as the name implies, all runoff is assumed to have the same, constant concentration for a given pollutant. These are simple values or functions that express the generation of pollutants in dry weather per unit area and time for each type of land use, by the population and their sanitation infrastructure. The most common units of measure are mass / area-time and mass / inhabitants-time.

At its very simplest, an annual runoff volume can be multiplied by a concentration to produce an annual runoff load. However, this option may be coupled with a hydrologic model, wherein loads will vary if the model produces variable flows. This option may be quite useful because it may be used with any hydrologic or hydraulic model to produce loads, merely by multiplying it by the constant concentration (NOVOTNY, 2002).

The Export Coefficients (EC) or Unit Loads (UL) method, requires that these coefficients must be "characteristic" of a particular use and occupation of the soil. Its use has wide acceptance in planning studies but has the limitation of not explicitly describing the relationship between the diffuse loads and the hydrology of the watershed. It is undoubtedly a simple and easy to use practical application. The total affluent load (W) is the sum of the dry weather load (Wts) and the rainfall load (Wec) according to the basic Equation (4).

$$W = Wts + Wec \tag{4}$$

Wts being detailed on Equation (5):

$$Wts = ft \times \left[\sum_i (A_i \times c_i) + \sum_j (P_j \times e_j) + \sum_k B_k\right] \tag{5}$$

Wherein:

- $f_t$ is the transport coefficient of the basin; representing the processes of retention and self-purification between the generation points and the mouth of the stream that drains the basin;
- $A_i$ is the occupied area by the different categories of land use (i) in the basin, in $km^2$;
- $c_i$ is the load coefficient of the different categories of land use (i), in kg / $km^2$.day;
- $P_j$ is the resident population of the basin, under different conditions of sanitary infrastructure (j);
- $e_j$ is the sewage export coefficient generated by population under different conditions of sanitary infrastructure (j), in kg / inhab.day;
- $B_k$ are other point loads in the basin, in kg / day.

And Wec is calculated by Equation (6).

$$Wec = \sum_i [EMC \times A_i] \times q \times C_{es} \tag{6}$$

In which:

- EMC is the typical concentration of each parameter of rainfall events in the basin (mg/L);
- $A_i$ is the catchment area in each land use category (ha);
- q is the specific average long-term flow of each basin (L/s.$km^2$);
- $C_{es}$ is the coefficient of surface runoff (rate between average surface flow and average flow).

Previous research assumed that fixed EC results in huge inaccuracies in the assessment of NPS pollution because it is influenced by several factors with large geographic variability, especially for large-scale watersheds. The temporal stability of the fixed EC in a dynamical environment is also questioned. Therefore, there is a need to analyze the dynamics of the factors that have the greatest effect on the forecast of NPS contamination in watersheds in the context of continuing global climate change and large land use transitions. As a result, fixed EC would exhibit substantial inaccuracies (WANG; CHEN; SHEN, 2020).

Table 1 shows EC obtained for Guarapiranga Watershed (Brazil) and Table 2 shows the EC in Korea. Table 3 shows the range of export coefficients in the United States. It is possible to notice that for each location, the coefficients are considerably different. Studies show that this high variability is explained by differences between sanitation infrastructure, land use and occupation particularities and availability of data monitoring (MAGALHÃES; SILVA; NOGUEIRA; PEREIRA *et al.*, 2021).

Table 1 - Export Coefficients in Dry Weather in the Guarapiranga Watershed

| **Source** | **Unit** | **Total Phosphorus** | **Total Nitrogen** | **COD** | **BOD** | **TSS** |
|---|---|---|---|---|---|---|
| Agricultural activity | kg/ km².day | 0.066 | 0.227 | 4.917 | 0.933 | 10.455 |
| Reforestation | kg/ km².day | 0.002 | 0.060 | 1.172 | 0.247 | 2.500 |
| Tertiary shrub vegetation / Weald | kg/ km².day | 0.002 | 0.060 | 1.172 | 0.247 | 2.500 |
| Secondary shrub vegetation / Meadow | kg/ km².day | 0.001 | 0.050 | 1.079 | 0.206 | 3.750 |
| Farms | kg/ km².day ² | 0.005 | 0.090 | 3.800 | 0.370 | 8.000 |
| Urban areas – Upper standards | kg/ km².day | 0.136 | 0.951 | 16.000 | 3.913 | 0.600 |
| Urban areas – Inferior standards | kg/ km².day | 0.272 | 2.378 | 40.000 | 9.781 | 1.100 |
| Industrial and comercial areas | kg/ km².day | 0.190 | 1.665 | 32.000 | 6.847 | 0.800 |
| Population with direct sewage discharge into water streams | kg/inh.day | 0.00151 | 0.01190 | 0.05616 | 0.04896 | 0.05500 |
| Population of urbanized areas with individual sewerage system - High density | kg/inh.day | 0.00121 | 0.00952 | 0.05054 | 0.03917 | 0.03300 |
| Population of urbanized areas with individual sewerage system - Low density | kg/inh.day | 0.00076 | 0.00595 | 0.0337 | 0.02448 | 0.01650 |

Source: (PRIME ENGENHARIA, 2005)

Table 2 - Export coefficients in Korea in (kg / km².day)

| Use | BOD | Total Nitrogen | Total Phosphorus |
|---|---|---|---|
| Wet paddy fields | 2.3 | 6.56 | 0.61 |
| Dry paddy fields | 1.6 | 9.44 | 0.24 |
| Forest | 1.0 | 2.20 | 0.14 |
| Urban áreas | 85.9 | 13.69 | 2.10 |
| Prairies | 35.1 | 5.37 | 1.72 |
| Golf courses | 1.0 | 3.56 | 2.76 |
| Others | 1.0 | 0.06 | 0.03 |

Source: (MOE, 1999)

Table 3 - Range of export coefficients in the United States in (kg / km².day)

| Use | SS | Total Nitrogen | Total Phosphorus |
|---|---|---|---|
| General agriculture | 0.8-1534 | 0.2-12.0 | 0.03-2.50 |
| Cropland | 5.5-1397 | 1.2-8.5 | 0.05-1.26 |
| Improved pasture | 8.2-22.0 | 0.9-3.8 | 0.03-0.14 |
| Forest/wooded | 0.3-225 | 0.3-1.7 | 0.005-0.18 |
| Idle/perennial | 1.9-225 | 0.1-1.6 | 0.005-0.18 |
| General urban | 55-135 | 0.05-5.0 | 0.08-1.30 |
| Residential | 170-630 | 1.40-2.0 | 0.10-0.40 |
| Commercial | 14-227 | 0.50-3.0 | 0.03-0.25 |
| Industrial | 123-466 | 0.50-3.8 | 0.20-1.10 |
| Developing Urban | 7534 | 17.3 | 6.30 |

Source: (SONZOGNI; CHESTERS; COOTE; JEFFS *et al.*, 1980)

In fact, Magalhães, *et al* (2021) performed a compilation of the previously mentioned studies and others and compared the values obtained by each coverage type and by each constituent (Nitrogen, Phosphorus and BOD). As an example, results for agricultural use are illustrated in Figure 14, Figure 15 and Figure 16 for Total Phosphorus, Total Nitrogen and BOD respectively. Novotny (2002) maximum value was considerably higher than the other works shown. Also, it is possible to observe that export coefficients obtained in wet seasons are higher than in dry seasons, all due to the fact that rainfall washes off the nutrients from the watershed surface.

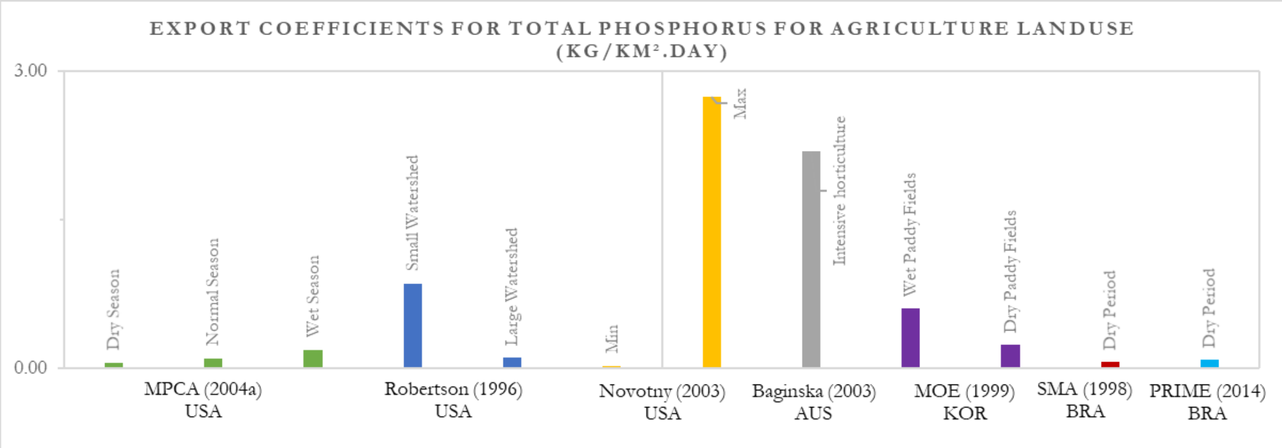



Figure 14 - Export Coefficients for Total Phosphorus for agriculture land use.

Source: Magalhães, et al (2021)

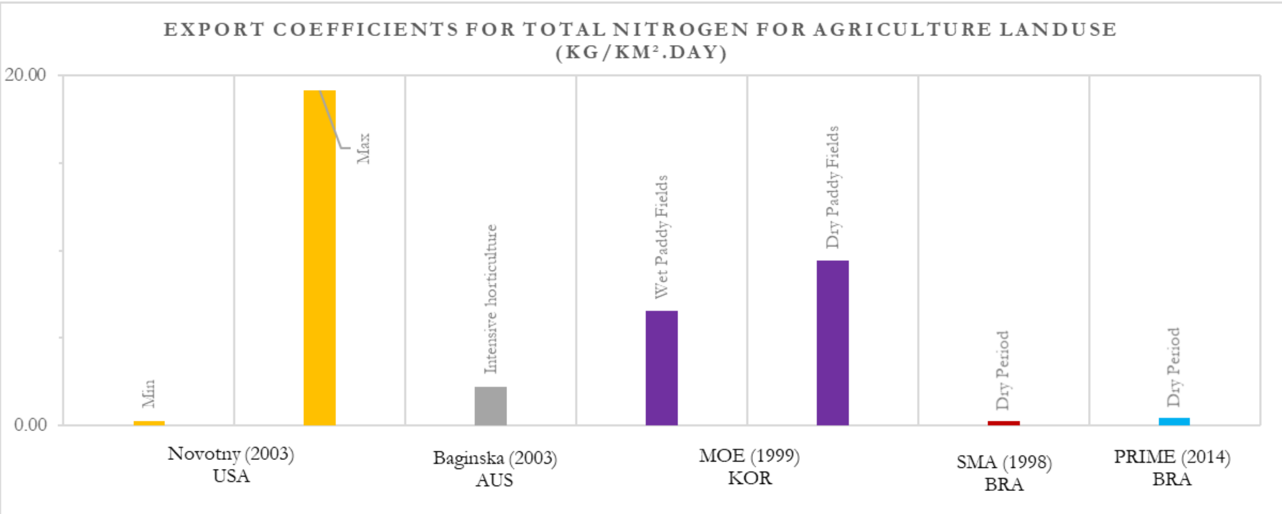



Figure 15 - Export Coefficients for Total Nitrogen for agriculture land use

Source: Magalhães, et al (2021)

Regarding BOD/$BOD_5$ export coefficients (Figure 16), studies originated in the USA and other developed countries usually do not research with this parameter. In fact, this water quality variable has progressively been replaced by more representative ones, like the Total Organic Carbon (TOC). $BOD_5$ is very sensitive to the presence of hindering substances such as chloride at high concentrations and usually cannot provide precise results of organic pollutants in water samples; plus the analysis process is faster for TOC than $BOD_5$.

Studies demonstrated a low coefficient of correlation between $BOD_5$ and TOC of 0.24 for surface water, while other studies reported a good coefficient of correlation between $BOD_5$ and TOC or between COD and TOC of 1.0 and 0.7 for river water samples, respectively (LEE; LEE; YU; RHEW, 2016).

Publications originating from studies in under-developed countries (Brazil and Korea) show that values are not much different from each other, although BOD is always a very local variable. In agricultural areas, BOD comes, for instance, from vegetative organisms and feces from other animals (birds, mammals, etc).

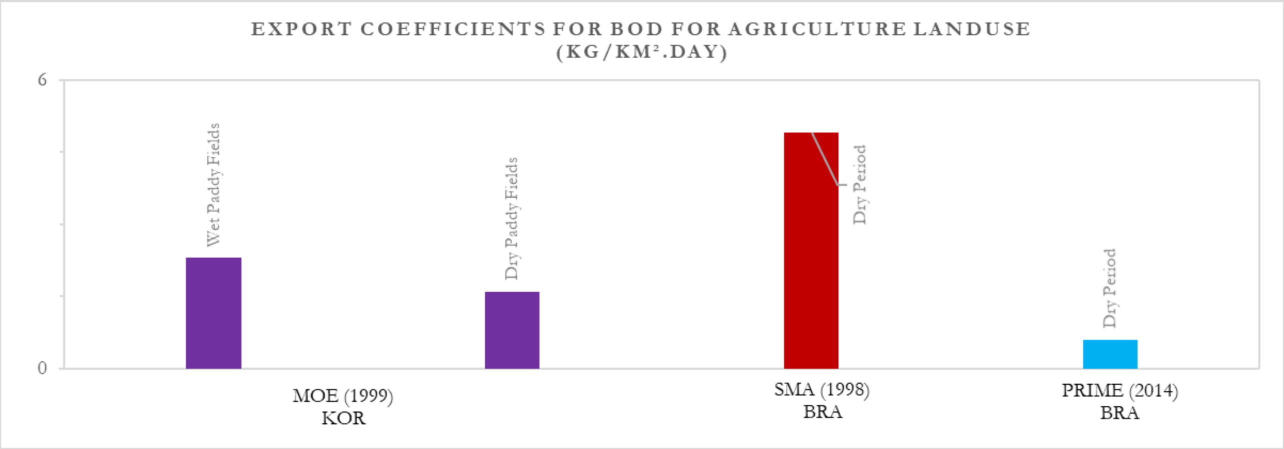



Figure 16 - Export Coefficients for BOD for agriculture land use

Source: Magalhães, et al (2021)

Pollution problems tend to be greater in urban areas. Nutrient values tend to be higher than in preserved areas and organic matter and BOD values observed in Brazil are many times higher. In commercial areas, on the work of FCTH (2017) values are 230 times higher than the ones on the work of MOE (1999). This brings out a concerning problem experienced in Brazil, and specially in this study area (Jaguaré – São Paulo): the direct discharges of untreated raw domestic sewage into water bodies.

*3.4.2 Event Mean Concentration (EMC) Method*

The EMC in storm water events method is a concept that has wide use in international literature. It states that, for a given land use and occupation, monitored concentrations along with statistical analyses applied to a set of rainy events, produce a "typical" average concentration of rainfall events that, when multiplied by the drained volumes, generates estimates of loads input during these events.

Even though concentrations often vary, by several times of magnitude, during the storm event, the EMC can be used to characterize runoff constituents (NOVOTNY, 1994; SANSALONE JOHN; BUCHBERGER STEVEN, 1997). The EMC is a flow-weighted average of constituent concentration. The EMC for an individual storm event is defined as the total pollutant load divided by total runoff volume, as described by Equation (7).

$$EMC = \sum Q_i \times C_i \Big/ \sum Q_i \tag{7}$$

In which $Q_i$ is the time variable flow and $C_i$ is the time variable concentration.

In order to obtain the nonpoint pollution load carried by urban drainage during each event, the load is multiplied (after discounting the value of the base load of the water body) by the considered time interval, as shown in Equation (8).

$$\text{MASS} = \text{Load x Time} \tag{8}$$

In which Load is the mass flow rate (mg/s); and Time is the time interval between collections (s).

The most adequate way to obtain the EMC values is through an automatic sampler. Automatic sampling uses instrumentation to monitor site conditions and perform sample collection without the constant presence of a technician. With this equipment, one can set up the system before a rain event occurs and when that happens, the equipment activates, and collects the sample according to the programming (by time, by volume, *etc*.). The information can be quickly forwarded for analysis via one of numerous telemetry options or a technician can return to the site and retrieve the samples and data. Figure 17 illustrates a portable automatic sampler, the most used device to monitor nonpoint pollution.

Table 4 and Table 5 show the Event Mean Concentrations obtained in two watersheds in Brazil, respectively *Sistema Produtor Alto Tietê* (SPAT) and Jaguaré River Basin. It is important to state that, for EMC, concentrations vary in magnitudes from each local study site and also, from each individual rain event. Still, a whole campaign including several rain events to achieve this number seems highly acceptable to establish this average number.

Table 6 shows some papers containing EMC values on international literature. It is possible to observe that, when comparing the same constituents, values are closer to the ones observed in Brazil, except for Total Suspended Soils (TSS) values, in which Brazil presents much higher numbers than the ones seen in international literature.

While looking at EMC values for Urban uses in SPAT and comparing to values obtained in Jaguaré, one can see that numbers present at the same order (between 50 and 180 mg/L), as Jaguaré watershed is essentially urban occupation. And even though international papers usually study Chemical Oxygen Demand (COD), values are related, once they are in the same order.

Figure 17 – Portable Automatic Sampler
Source: (NOGUEIRA, 2020)

Table 4 - Event Mean Concentrations (SPAT) - mg / L

| Land Use and Occupation | Total Phosphorus | Total Nitrogen | BOD | SS |
|---|---|---|---|---|
| Woods | 0.06 | 0.735 | 9.7 | 25 |
| Reforestation | 0.035 | 0.524 | 3.4 | 70 |
| Agriculture | 3.355 | 8.253 | 23 | 2645 |
| Farms | 0.483 | 2.449 | 27.5 | 55 |
| Urban | 1.208 | 2.719 | 78.7 | 625 |
| Field | 0.024 | 0.523 | 6 | 71 |

Source: (SSRH, 2016)

Table 5 - Event Mean Concentrations (Jaguaré) - mg / L

| Urban Areas (Neighborhood) | Total Phosphorus | Total Nitrogen | BOD | SS |
|---|---|---|---|---|
| Parque Tizo | 2.52 | 1.42 | 52 | 1583 |
| Nascentes | 1.10 | 0.96 | 84 | 22026 |
| Jacarezinho | 1.40 | 1.70 | 112 | 1077 |
| Água Podre | 0.70 | 2.20 | 187 | 589 |
| Kenkiti | 0.66 | 3.74 | 88 | 278 |
| Sapé | 2.99 | 1.41 | 175 | 1861 |

Source: (FCTH, 2017)

Table 6 - Event Mean Concentrations for international papers - mg / L

| Papers | Total Phosphorus | Total Nitrogen | COD | TSS |
|---|---|---|---|---|
| Isfahan Runoff - Iran (2004) | 0.274 | 6.75 | 649 | 149 |
| Droste and Hartt – Canada (1975) | 0.522 | 2.98 | 150 | 300 |
| NURP – USEPA - USA (1983) | 0.42-0.88 | 1.90-4.18 | 82-178 | 180-548 |
| CDM - Smullen et al. - USA (1999) | 0.315 | 2.39 | 52.8 | 78.4 |

Source: (TAEBI; DROSTE, 2004)

### *3.4.3 Mathematical and Numerical Modeling*

Modeling nonpoint pollution is, indeed, the transformation of the rainfall into a flow associated with the quantification of the mechanisms of deposition and accumulation of pollutants in the hydrographical basin and their entrainment and transport to the streams. They are complex models, both from the point of view of their equation (including more sophisticated hydrological aspects such as the kinematic wave theory), as from the point of view of the data (extension of the drainage network and its roughness, in addition to requiring field sampling of rainy events at a level of detail that is sometimes lower than the time), including the quality and quantitative aspects (EIGER; ARANHA; GOMES; PEREZ *et al.*, 1999).

Briefly, the mathematical modeling of nonpoint pollution is based on the observation that, during a rainy event, the temporal rate of lost mass of a given constituent is directly proportional to the mass available to be transported and to the surface drainage flow by of the drainage area of the river basin. This model is based on conclusions obtained in experiments carried out by Sartor & Boyd (1972) and constitutes the mathematical basis adopted for a series of diffuse loads studies (Huber, 1986).

Mathematically, this model is written as the Equation (9), in which: M is the mass of the constituent available on the surface of the river basin; t is the time; k is the constant of proportionality that can be understood as a wash off coefficient; $Q_{es}$ is the surface runoff flow, that is, that flow due to rainfall and A is the watershed drainage area.

$$\frac{dM}{dt} = -k \times M \times \frac{Q_{es}}{A} \tag{9}$$

The equation above can be integrated as shown in Equation (10). Knowing that $A$ is constant and assuming that $k$ is also constant during a rainy event, then the above equation produces:

$$M(t) = M_0 \times \exp\left(-\frac{k}{A} \times \int_0^t Q_{es} \times dt\right) = M_0 \times \left[-\frac{k}{A} \times V_{es}(t)\right] \tag{10}$$

Therefore, the total mass transported by surface flow from the beginning of the rainy event (Mes) to the time t is given by Equation (11).

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

The pollutant mass accumulated on the surface of the basin during the dry season and transported to the body of water during surface runoff, can be considered as the polluting mass of the urban rain drainage contribution. In the prediction of the diffuse load, the pollutant mass of the events that occurred in the monitored period is added and divided by the time interval of this period, resulting, therefore, in the nonpoint pollution carried by the storm event in the study area.

Six models (STORM, HSPF, BASINS, SWMM and HEC-HMS) are highlighted briefly at this point and will be described in detail hereafter. Other models have been adapted from SWMM (e.g., FHWA, RUNQUAL) and STORM (e.g., SEMSTORM) and given modified names, but the principles are similar.

The first significant use of continuous simulation in urban hydrology was found with the *Storage, Treatment, Overflow, Runoff Model* (**STORM**), developed by the Center for Hydrological Engineering of the Corps of Engineers (USACE HEC) (ROESNER, 1974). Accumulation and washing formulations are used to simulate six pre-specified pollutants. It also provides application guidelines (Abbott, 1977) and includes dry-weather flow input for combined sewer simulation.

STORM utilizes simple runoff coefficient, SCS and unit hydrograph methods for generation of hourly runoff depths from hourly rainfall inputs. No flow routing is performed, but runoff may be routed through a constant-rate treatment device, with excess flow diverted to a storage device. The build-up and wash off formulations are used for simulation of six pre-specified pollutants. However, the model can be manipulated to provide loads for arbitrary conservative pollutants (NAJARIAN; GRIFFIN; GUNAWARDANA, 1986).

The Hydrological Simulation Program Fortran (**HSPF**) is a summary of the hydrological routines that originated with the Stanford Watershed Model in 1966 and incorporated many diffuse source modeling works from the EPA laboratory (JOHANSEN; IMHOFF; KITTLE; DONIGIAN, 1984). It is the only comprehensive model of watershed hydrology and water quality that allows the integrated simulation of land and soil contaminant runoff processes with In-stream hydraulic and sediment-chemical interactions. This model has been widely used for modeling non-urban and nonpoint sources. Flow, sediment, temperature, algae, nutrients, BOD and OD are modeled.

Currently, HSPF has been used inside the **BASINS** (Figure 18) environment. *Better Assessment Science Integrating Point and Nonpoint Sources* (BASINS) is a multipurpose environmental analysis system designed to help regional, state, and local agencies in the USA to perform watershed and water quality-based studies. It was developed by the U.S. Environmental Protection Agency (EPA) to assist in watershed management, development of Total Maximum Daily Loads (TMDLs), coastal zone management, nonpoint source programs, water quality modeling, and National Pollutant Discharge Elimination System (NPDES) permitting (EPA, 2019).

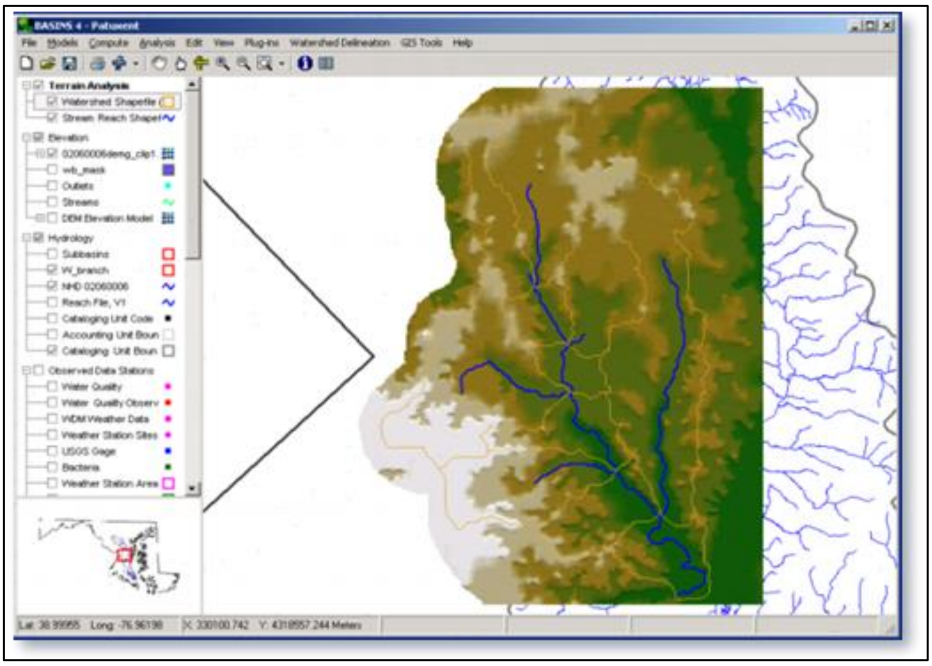


Figure 18 - Basins Model Layout
Source: (EPA, 2019)

The original version of the *Storm Water Management Model* (SWMM - Figure 19) was developed by EPA Metcalf & Eddy (1971). Version 4 (HUBER; DICKINSON, 1992) of the model performs both continuous and single-event simulation throughout the whole model, can simulate backwater, surcharging, pressure flow and looped connections (by solving the complete dynamic wave equations) and has a variety of options for quality simulation, including traditional build-up and wash off formulations as well as rating curves and regression techniques.

**SWMM latest** version (5.2), that **replaced version 5.1** (ROSSMAN, 2015) is a very complete, complex and segmented software. It performs continuous and single event simulation; it can simulate backwaters, pressure flow and loop connections (solving the complete dynamic equations of the waves) and has a variety of options for quality simulation, including accumulation and washing. For quality, it simulates sediment, temperature, algae, nutrients, BOD and OD.

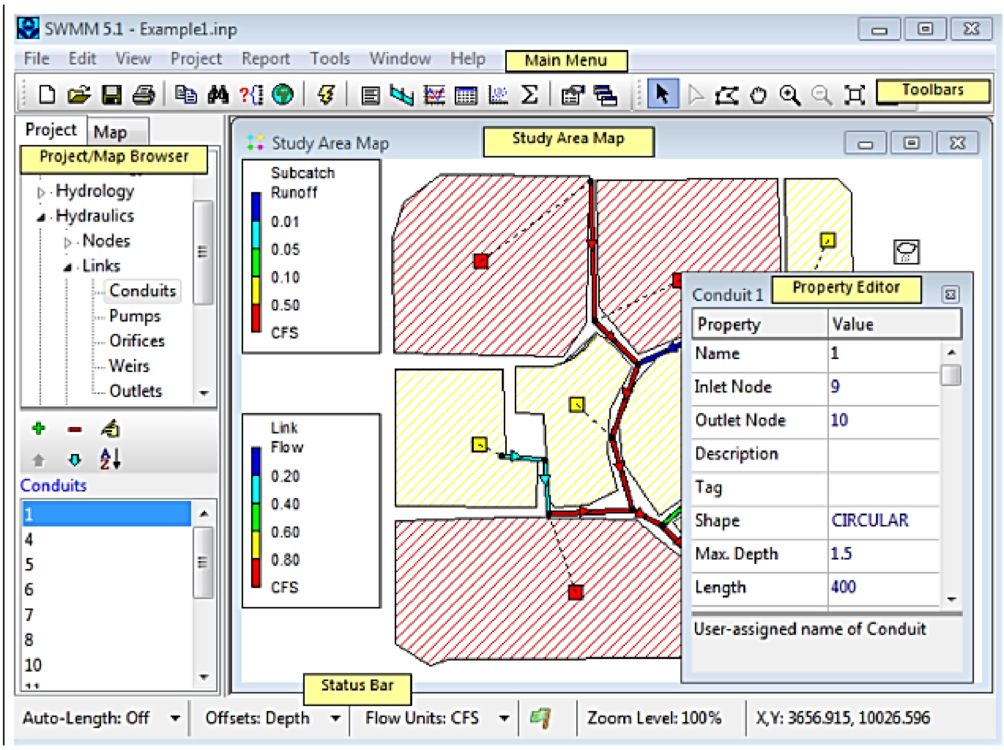



Figure 19 - SWMM Model Layout

Source: (ROSSMAN, 2015)

The Hydrologic Modeling System (**HEC-HMS**) (Figure 20) is designed to simulate the complete hydrologic processes of dendritic watershed systems. The software includes many traditional hydrologic analysis procedures such as event infiltration, unit hydrographs, and hydrologic routing. Advanced capabilities are also available for gridded runoff simulation using the linear quasi-distributed runoff transform (ModClark). Supplemental analysis tools are provided for model optimization, forecasting streamflow, depth-area reduction, assessing model uncertainty, erosion and sediment transport, and water quality.

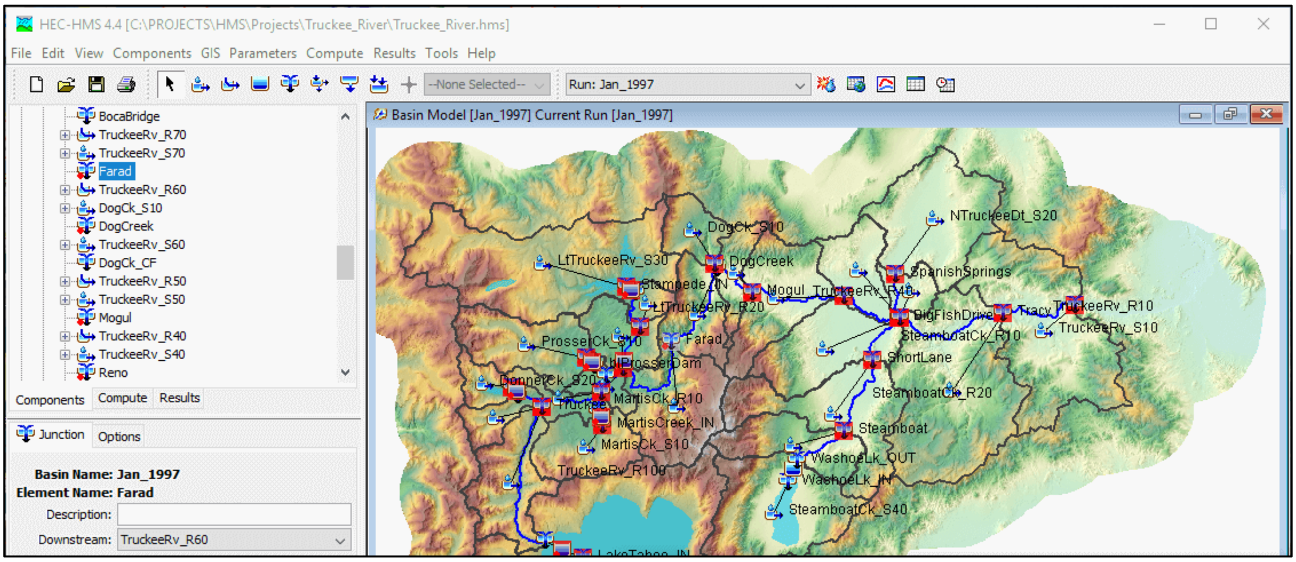



Figure 20 - HEC HMS Model Layout

Source: (USACE, 2022)

However, the aforementioned software requires knowledge and, sometimes, training from the modeler for its correct use. The performance of more complex models is not necessarily better since most of the involved activities come from the input data interfaces and parameters. The complexity, processing time, memory usage and computer processing can make project hours unfeasible.

Ferreira, Muhlenhoff and Fernandes (2018) reviewed 10 (ten) nonpoint pollution models and they pointed out a concern with the compatibility and applicability of these models, accounting their impact when evaluating mitigation measures, convincing and involving the population as an integral part of the water resources management solution.

### *3.5 COUPLING MODELS*

To represent a steady flow, a hydraulic model is usually sufficient, while a dynamic unsteady flow requires a hydrological model (with stormwater events). The ability to model the hydrological process is an important feature of hydraulic-hydrological models. While purely hydrological models aim to acquire the flood hydrograph at an outlet of a basin, hydraulic-hydrological models strive to comprehend the hydraulic and hydrological processes that occur within the basin, allowing quantification of important factors for analysis and decision-making (DOS SANTOS, 2009).

From Laniak *et al* (2013) paper, the concept of Integrated Environmental Modeling (IEM) was defined: a subject inspired by the need to solve increasingly complex real-world problems involving the environment and its relationship to human systems and activities.

Many watershed simulation models are based on hydrological models coupled with pollutant accumulation and washing models. These models comply with rainfall-runoff models, mass balance and are combined with functions that describe specific behaviors, i.e.: soil loss equations, export coefficients, and transformation of nutrients and pesticides (FERREIRA; MUHLENHOFF; FERNANDES, 2018).

### *3.6 SANITATION SYSTEMS AND URBAN RIVERS*

Separate sewer systems have been increasingly used in metropolitan areas in emerging countries in recent decades, resulting in fast urban development. Meanwhile, in many countries, urbanization has resulted in substantial urban water pollution, emphasizing the significance of stormwater management (MA; HAO; ZHAO; FANG *et al.*, 2018).

The absolute separator system was developed in the United States of America in 1879, and it is a better system in regions with high rainfall in the summer and dry climate in the winter, because it avoids the need for large pipe diameters to drain the flow in the summer, which would otherwise be idle in the winter and for that reason its adopted mainly in Brazil (VOLSCHAN; TSUTIYA; MARTINS; YAZAKI, 2009).

According to the most recent research carried out in Brazil by the IBGE (2020), in 2017, in 57.6% of Brazilian municipalities there was sanitary sewage service in operation. So, frequently, sewage is launched directly to rivers or drainage system and, sometimes, when conducting a nonpoint pollution analysis, this information must be taken into consideration for separating base from wash off loads.

Table 7 shows sewage contribution (loads) by person and day. When comparing these values with the export coefficients in the Guarapiranga study (Table 1), it is possible to relate it directly to the class “Population with direct sewage discharge into water streams” which is around 48 g/inh.day exactly between the range observed below.

Table 7 - Sanitary sewage per-capita loads (g/inh.day)

| **Total Phosphorus** | | **Total Nitrogen** | | **BOD** | | **Suspended Solids** | |
|---|---|---|---|---|---|---|---|
| Range | Typical | Range | Typical | Range | Typical | Range | Typical |
| 0,7-2,5 | 1 | 6-10 | 8 | 40-60 | 50 | 35-70 | 60 |

Source: Arceivala (1981), Pessoa & Jordão (1985), Qasim (1985), Metcalf & Eddy (1991), Cavalcanti et al (2001), Apud Von Sperling (2005).

### *3.7 BEST MANAGEMENT PRACTICES*

Stormwater and nonpoint pollution **Best Management Practices** (BMPs) are engineered facilities designed to reduce and/or treat stormwater runoff, which mitigate the effects of increased stormwater runoff peak rate, volume, velocity and the wash pollutant load due to urbanization. A BMP, or treatment device that includes two or more BMPs, should be designed to meet one or more of the following requirements (ARC, 2016):

i. *Reduce total runoff from the drainage area using the Runoff Reduction Volume;*
ii. *Treat the Water Quality Volume (the runoff generated by the first 30mm of rainfall);*
iii. *Control the Channel Protection Volume (detention of 1-year, 24-hr rainfall event);*
iv. *Control for Overbank Flood Protection (detention of 25-year, 24-hr storm peak discharge rate to the predevelopment rate); and*
v. *Provide for Extreme Flood Protection by either: (1) controlling the peak discharge increase through detention; or (2) safely passing the flow through the structural control and allowing it to discharge into a receiving water.*

Some principles consistent with integrated stormwater management and the treatment train approach are presented by the Minnesota Stormwater Manual (2020):

i. Evaluating where the water comes from and where it will go when it leaves.
ii. Preventing the potential for a pollutant to be washed-off is the first step in a treatment train approach to runoff management.
iii. Unless there is a good reason not to (such as a source of toxic material in the watershed) there must be an aim to soak in as much water as possible.
iv. A vegetative cover is preferable than bare soil, and native vegetation is always better than decorative grass.
v. The less active management a BMP requires to properly operate, the better.
vi. Thoughtful design and sound construction can reduce the level of maintenance required for effective operation and performance of BMPs.
vii. Proper maintenance will prolong the life and sustain an optimum level of pollution removal of a BMP.
viii. Each site requires its own unique characterization to best address its stormwater management needs and coordination with all affected parties is essential to success.
ix. Management designs should consider all impacts, including secondary environmental factors, health and human safety, maintenance, and financial burden.

There is a wide variety of BMPs already developed all over the world and the most used in Brazil are described in detail, in the following sections.

*3.7.1 Bioretention Area*

The bioretention area (Figure 21) is a shallow stormwater basin or landscaped area that utilizes engineered soils or native, well-draining soil and vegetation to capture and treat runoff. It requires low land, it is adaptable to many situations, and often a small BMP is used to treat runoff close to the source. Some design criteria for bioretention areas are:

i. Maximum contributing drainage area of 2 hectares (20.000m$^2$);
ii. Treatment area consists of ponding area, organic layer, planting, and vegetation;
iii. Requires landscaping planning;
iv. Standing water has a maximum drain time of 24 hours;
v. Pretreatment recommended to prevent clogging of underdrains or native soil; and

vi. Ponding depth should be a maximum of 30,5 cm, preferably 23 cm.

Bioretention areas slightly differ from rain gardens as they are an engineered structure that has a larger drainage area and may include an underdrain (Figure 22). Some expected disadvantages are: they require landscaping planning; they are not recommended for areas with steep slopes; medium to high capital cost; cost maintenance; and soils may clog over time  As for water quality interest, bioretention areas can remove 85% of Total Suspended Solids; 80%-60% of Nutrients (TN and TP); 95% of Metals (Cadmium, Copper, Lead, and Zinc) and 90% of Pathogens (Fecal Coliform) (ARC, 2016).

Figure 21 - Bioretention Area
Source: (ARC, 2016).

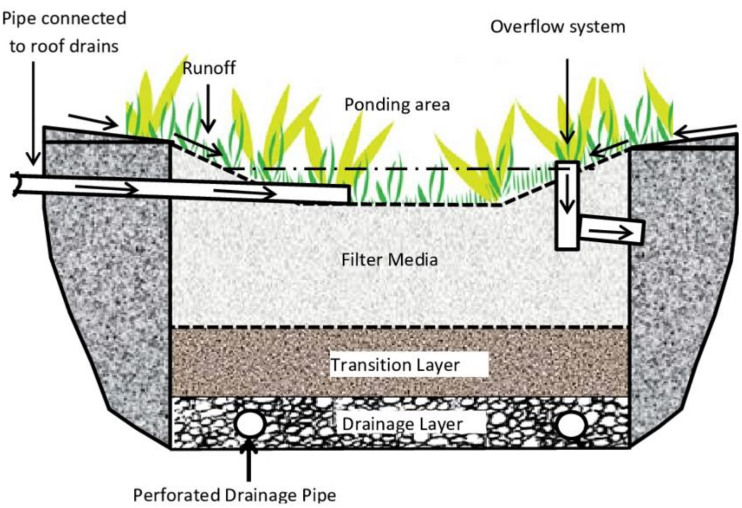



Figure 22 - Schematic of a Section View of a Bioretention Area
Source: (RAHMAN; IMTEAZ; ARULRAJAH, 2016)

### *3.7.2 Bioslope*

Bioslopes (Figure 23) are water quality best management practices that use a permeable engineered soil media to capture and treat stormwater runoff from adjacent longitudinal paved areas (road, parking lot, etc.). Bioslopes are typically installed along embankments or other slopes and designed to treat sheet flow stormwater runoff.

Adaptable to many linear situations, and often a small BMP used to treat runoff close to the source. As advantages, it requires minimal land and reduces runoff volume and velocity. And with the disadvantages of limiting the use to sheet flow only; it is not suitable for embankment slopes steeper than 3:1; and it does not meet quantity control stormwater requirements. As for pollutant removal, 85% of Total Suspended Solids; 75% of metals (Cadmium, Copper, Lead and Zinc); 60%-25% of nutrients (Total Phosphorus and Total Nitrogen); and 60% of pathogens (Fecal Coliform) can be removed. The design criteria for bioslopes are:

i. Longitudinal slopes must be less than 5%
ii. Minimum 2-feet (60cm) width
iii. Side slopes 3:1 or flatter; 4:1 recommended
iv. Length is usually the length of adjacent paved area being treated
v. Sized to capture the peak flow rate of discharge
vi. Pretreatment provided through a filter strip

Figure 23 – Bioslope
Source: (ARC, 2016)

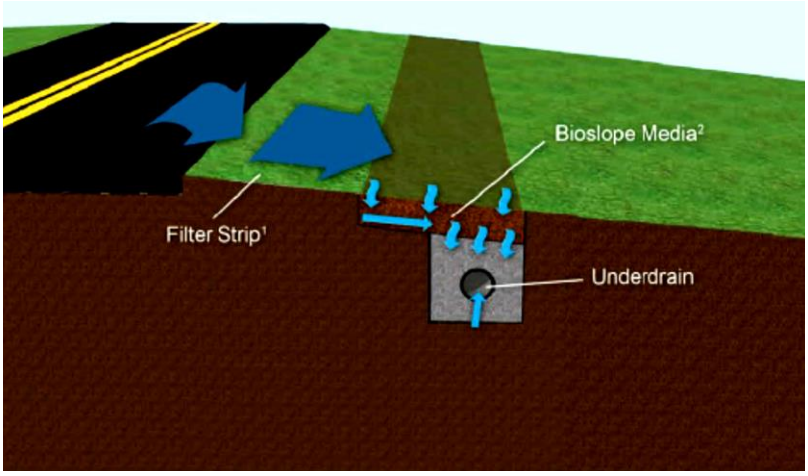



Figure 24 - Bioslope schematic section view
Source:(ARC, 2016).

### *3.7.3 Vegetative Buffer/Filter Strips*

Vegetated buffers (Figure 25) are widely used in agricultural production for reducing agricultural nonpoint-source pollution and have been well-studied in the scientific literature. They are designed to use vegetation to remove sediment, nutrients, and pesticides from surface water runoff through filtration, deposition, adsorption, and infiltration (ZHANG; LIU; ZHANG; DAHLGREN *et al.*, 2010).

Many studies suggest that vegetated buffers are effective in removing pollutants from runoff. For example, Patty; Réal and Joël Gril (1997) found that buffers with widths of 6m, 12m, and 18 m could reduce 87 to 100% of suspended sediment, 47 to 100% of nitrate, 22 to 89% of soluble P and 44 to 100% of the herbicide from agricultural runoff . The pollutant mitigation efficacy of vegetated buffers depends on three factors (NORRIS, 1993).

i. the physical properties of the buffer, such as width, slope, soil type, and vegetation cover;
ii. the properties of the pollutant in question, such as the sediment particle size, the form of N or P, or the biophysical properties; and
iii. the placement of the buffer, such as its proximity to pollutant sources.


Figure 25 - Different types of vegetative strips

Source: https://www.nrcs.usda.gov/wps/portal/nrcs/oh/home/.

In Brazil, the role of vegetation buffers has been discussed since the year 2000 for agricultural and urban purposes in terms of reducing nonpoint pollution loads, as mentioned by Abe *et al* (2016) and Souza *et al* (Souza 2013) and they confirmed their importance in the provided ecosystem, especially in improving the water quality of the water bodies.

Actions aimed at the maintenance and recovery of these compartments, both in urban and rural areas should be encouraged, since they avoid the eutrophication process of water bodies, contribute to the stability of hydrological and biogeochemical cycles and provide conditions for multiple sustainable uses of the basin (ABE; RODRIGUES FILHO; CAMPANELLI; SIDAGIS-GALLI *et al.*, 2016).

For design criteria, “buffer width” is defined as the parallel dimension to runoff flow and its efficiency is directly connected to the width. That is expected because infiltration is taking place first and pollutants are lost to infiltration for each successive unit of buffer width. Then, the larger and heavier forms of pollutants will be trapped in the upper buffer while the smaller particles will be more difficult to contain (ZHANG; LIU; ZHANG; DAHLGREN *et al.*, 2010).

It is very important to correctly size the length of the filter strip. So, Table 8 presents a guidance for sizing vegetated filter strips concerning its flow and type of surrounding area.

Table 8 - Vegetated Filter Strips Sizing Guidance

| **Parameter** | **Impervious Areas** | | **Pervious Areas (lawns, etc.)** | |
|---|---|---|---|---|
| Maximum inflow approach length (feet) | 35 | 75 | 75 | 100 |
| Filter strip minimum length (feet) | 15 | 25 | 12 | 18 |

Source: (CLAYTOR; SCHUELER, 1996)

### *3.7.5 Permeable Paver, Pervious Concrete and Porous Asphalt*

Permeable pavement (Figure 26) consists of a pavement surface composed of structural units with void areas that are filled with pervious materials such as gravel, sand, or grass turf. They are installed over a gravel base course that provides structural support and stores the stormwater runoff that infiltrates through the system into underlying permeable soils.

The permeable paver system is an excellent stormwater treatment practice due to the variety of pollutant removal mechanisms, because each of the components of the permeable paver system is designed to perform a specific function. The grass filter strip pre-treatment component reduces incoming runoff velocity and filters particulates from the runoff. The planting soil or rock in the permeable paver system acts as a filtration system, and clay in the soil provides adsorption sites for hydrocarbons, heavy metals, nutrients and other pollutants. It can remove up to 80% of Total Suspended Solids; 50% of nutrients (BOD, Nitrogen and Phosphorus) and 60% of metals (ARC, 2016).

Figure 26 - Permeable paver

Photo by Melinda Myers.

Pervious concrete is a mixture of coarse aggregate, Portland cement and water that allows for rapid infiltration of water and overlays a stone aggregate reservoir. This reservoir provides temporary storage as runoff infiltrates into underlying permeable soils and/or out through an underdrain system.

Pervious concrete systems have a high removal rate for both soluble and particulate pollutants, which become trapped, absorbed or broken down in the underlying soil layers. Due to the potential for clogging, pervious concrete surfaces should not be used for the removal of sediment or other coarse particulate pollutants.

Pollutant removal can be improved through routine vacuuming, sweeping, and high pressure washing of pervious concrete systems, maintaining a drainage time of at least 24 hours, pretreating the runoff, having organic material in the subsoil, and using clean washed aggregate. Permeable pavement can remove up to 80% of Total Suspended Solids; 50% - 65% of nutrients (BOD, Nitrogen and Phosphorus) and 60% of metals (ARC, 2016).


Figure 27 - Porous concrete
Source: (PSBMPM, 2006).

Porous asphalt (Figure 28) allows the infiltration of water through the pavement and into underlying soils. It can be used to reduce the effective impervious area on a site, therefore reducing the design volumes and peak discharges that must be controlled. Porous asphalt can also eliminate problems with standing water, provide for groundwater recharge, control erosion of streambeds and riverbanks, facilitate pollutant removal, reduce thermal pollution of receiving waters, and provide for a more aesthetically pleasing site.


Figure 28 - Porous asphalt
Source: (INSTITUTE, 2010).

As it provides for the infiltration of stormwater runoff, it has a high removal rate for both soluble and fine particulate pollutants, which can be trapped, absorbed, or broken down in the underlying soil layers. Due to the potential for clogging, porous asphalt should not be used for the removal of sediment or other coarse particulate pollutants. Maintenance efforts and frequency is directly related to the amount of accumulated or trapped sediment.

A work developed by Alizadehtazi *et al* (2016) analyzed several kinds of surfaces (including bioretention facilities). From this study it is possible to see that, infiltration rates vary considerably both within the same type of surface and among different surfaces and that porous concrete has the highest infiltration rates among all studied surfaces (Figure 29).

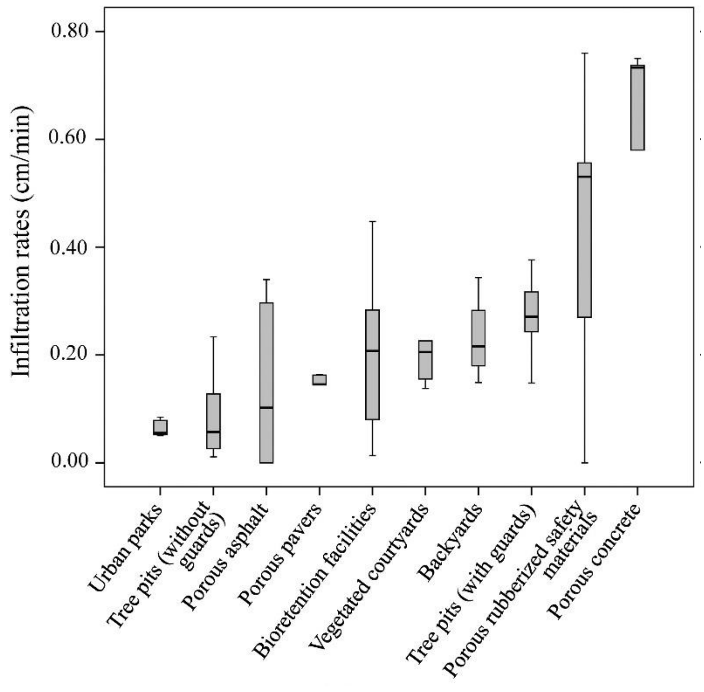



Figure 29 - Comparison of Observed Infiltration Rates of Different Permeable Urban Surfaces
Source: (ALIZADEHTAZI; DIGIOVANNI; FOTI; MORIN *et al.*, 2016; INSTITUTE, 2010).

### *3.8 RAINFALL DISTRIBUTION*

As seen, rainfall is one of the key aspects to hydrology models and therefore can directly affect results when aiming for load distribution. In this context, comprehending the precipitation in a watershed is very complex, as there are many variables involved in the studied area, such as space and time. Precipitation hardly follows an identical physical pattern. Spatial variation changes quickly, as the rain center changes all the time and the temporal variation is extremely random – rains can last from a few minutes to several hours or days and with a wide range of intensity (MARCIANO; BARBOSA; SILVA, 2018).

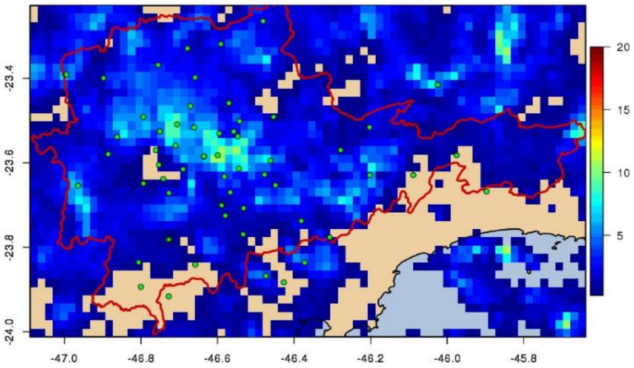
The most used tools in precipitation monitoring are rain gauge networks and remote sensing. Surface networks (rain gauges) specifically represent the intensity of precipitation with a high degree of reliability, but with problems of spatial representation in addition to the high cost of installation, maintenance and logistics problems (ROCHA FILHO; CONDE; ANDRIOLI, 2015)

The use of satellites to investigate climate (as well as land uses and other information) is rising in the academic field and agricultural scenario, as remote sensing is a useful tool, especially in regions with inaccurate or poorly controlled data (Wagner et al., 2012 *apud* (ALVES; SANTOS FILHO; CALDEIRA; CARNEIRO *et al.*, 2021). Still, the weather radar does not directly measure precipitation. Calibration techniques have been developed to enable its use in meteorology and hydrology, because, due to its spatial and temporal scope, it has become an important instrument for monitoring (MOREIRA, 2005).

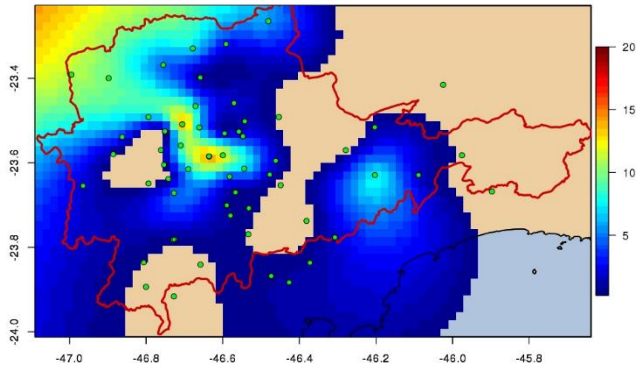
So, rain gauges assess the intensity and duration of rain efficiently, but have no spatial representativeness, even in a dense measurement network. The spatial representativeness error is more significant for intense convective rain, generally associated with cells in the order of 10 km in diameter. The radar, on the other hand, allows a good spatial and temporal sampling of the precipitation rate estimate, but with greater uncertainty than that of a network of rain gauges, due to the sources of error (CALVETTI; BENETI; PEREIRA FILHO, 2003).

In the **conditional merging** method, radar measurements are used as a spatial boundary condition for an interpolated field from surface measurements. A complete description of the methodology can be found in Ehret (2003). It is assumed that the radar is able to accurately capture the spatial field of precipitation, but not its intensity (ROCHA FILHO; CONDE; ANDRIOLI, 2013).

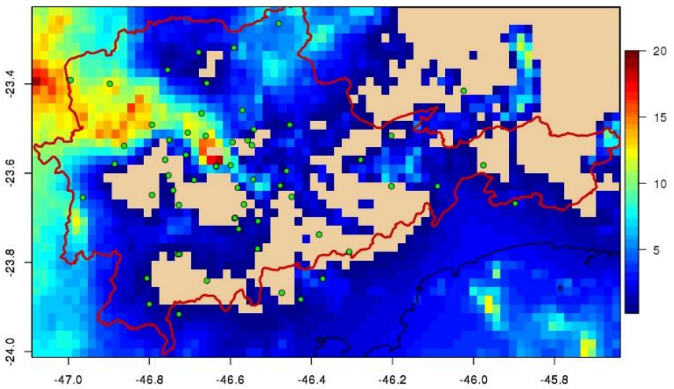
This work from Rocha Filho, Conde and Andrioli (2013) showed that conditional merging can improve radar precipitation estimates over a given area. However, the lack of rain gauges outside the domains can cause estimation problems in the boundary regions.



(a)



(b)



(c)

Figure 30 - Precipitation fields accumulated in 10 minutes: (a) Estimated by weather radar; (b) Kriging of telemetry stations (dots); (c) Estimated from the conditional merging method.

Source: (ROCHA FILHO; CONDE; ANDRIOLI, 2013)

# CHAPTER 4

## MONITORING

*"Water is the driving force in all nature"*

Leonardo da Vinci

### *4.1 IMPORTANCE OF MONITORING*

No pollution management program can be successfully arranged without some information on the state and quality of the aquatic environment. A minimum of data is needed on water flows and water quality. Despite this, the level of monitoring in Brazil is inadequate. Where data is inadequate, the management problem becomes one of managing risk and uncertainty. Risk management also requires some monitoring as well as research to determine the risk associated with different pollutants.

Nonpoint pollution evaluation, forecast, and management require water quality monitoring combined with good land treatment. Typically, baseline conditions are monitored for at least two years, followed by BMP installation and monitoring for another three to six years, for a total project duration of five to ten years. Data collected before and after BMP deployment is statistically evaluated to see if water quality changes can be linked to BMP implementation (LOMBARDO; GRABOW; SPOONER; LINE *et al.*, 2000).

Also, monitoring and data generation must usually be undertaken by governance because of the interdependency of waters flowing between States and Provinces. The difficulty is that programs of data collection and analyses lack political appeal and therefore are usually inadequate to the task at hand. This situation is present, not only in Brazil, but all over the world.

More information about each watershed will be shared on CHAPTER 6, however, the next sections will describe monitoring programs developed to assess pollution in each location.

### *4.2 MONITORING IN IPANEMA WATERSHED*

Created on May 20, 1992 by Federal Decree N. 530, the Ipanema National Forest is a Federal Conservation Unit, managed by the Chico Mendes Institute for Biodiversity Conservation (ICMBio), from the Ministry of the Environment. It is located 120 km from the city of São Paulo and covering part of the municipalities of Iperó, Araçoiaba da Serra and Capela do Alto, its creation was inserted in the context of the United Nations Conference on Environment and Development, Eco-92.

The Historical Site of the Ipanema National Forest (Flona de Ipanema) gathers constructions from different periods in the history of the Brazilian steel industry. The constructions date from 1811 (when the Hedberg furnaces were built) to 1913 (period when the engineer Elias Marcondes worked) due to the iron deposits found on Araçoiaba hill about 429 years. Flona de Ipanema is one of the largest Atlantic Forest ecosystems existing in Brazil today.

The Ipanema River Basin (Figure 31) belongs to the Water Resources Management Unit (UGRHI) No. 10, according to State Law 7,663 of 12/30/91. The basin is located in the southeastern center of the State of São Paulo, being constituted by the Sorocaba river basin and other tributaries of the Tietê river (SGIRH, 2020).

Ipanema watershed has become a suitable area for monitoring due to its unique characteristics, as well as the safety of performing jobs and transporting samples for researchers. This was one of the locations considered for the analysis of diffuse pollution since it is a mixed-use basin in a rapidly developing region.

From 1997 to 2015, in order to implement a project on the Ipanema River, a monitoring program was introduced along it. Figure 32 shows that, from the points installed in the Ipanema River in this project, the points upstream (MAR 8) and downstream (MAR 1) of the Hedberg Reservoir are of great importance for the correlation scenarios and for verifying how the diffuse pollution has changed over the years due to changes in land use and occupation. Attention for points 5, 6, 7 and 9 that are on Sorocaba River.

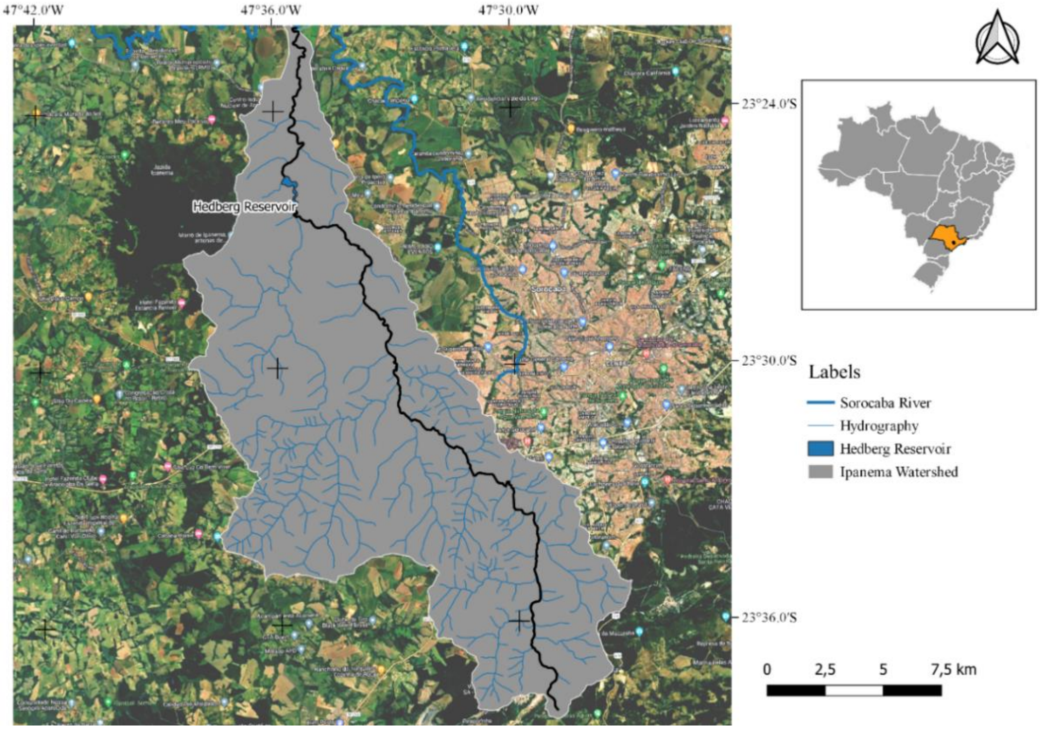



Figure 31 – Ipanema River Basin

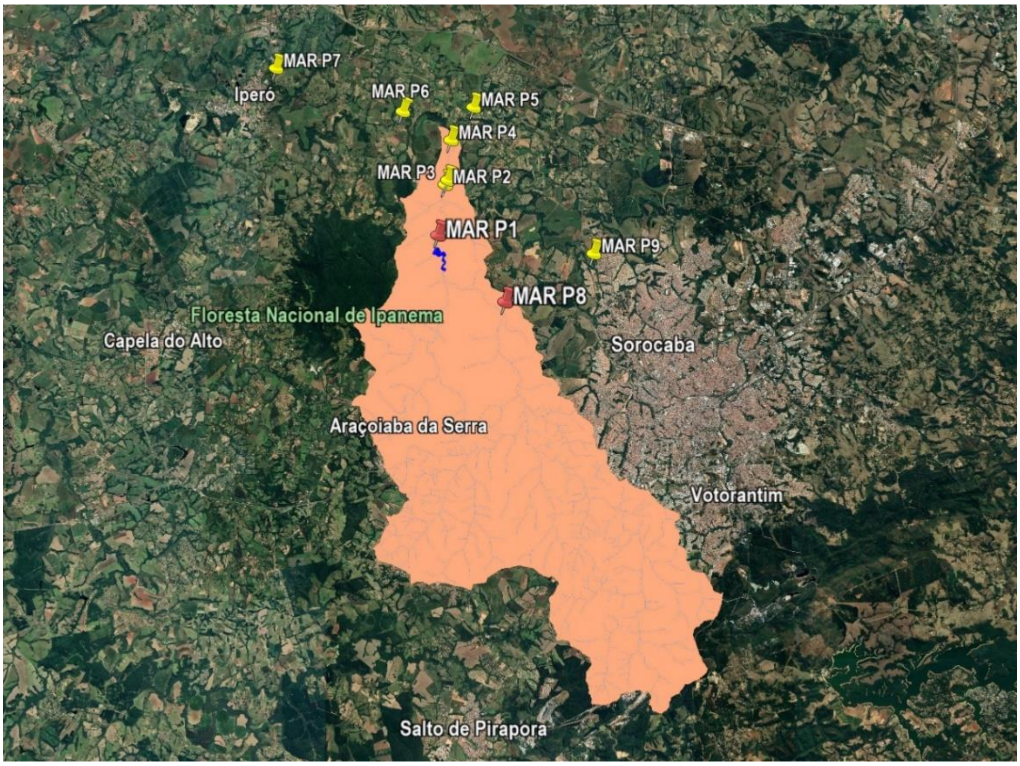



Figure 32 - Monitoring points in previous study on Ipanema Watershed

Source: Author (2022) and (FCTH, 2016)

From 2016 to 2020, two monitoring points (Entrance and Middle) were created inside the Hedberg Reservoir for Hydrodynamics and water quality assessment of lakes by thermal behavior and modeling (AMORIM, 2020). And, exclusively for this project, some points were added into this assessment: Point 1 and Spillway, as shown in Figure 33.

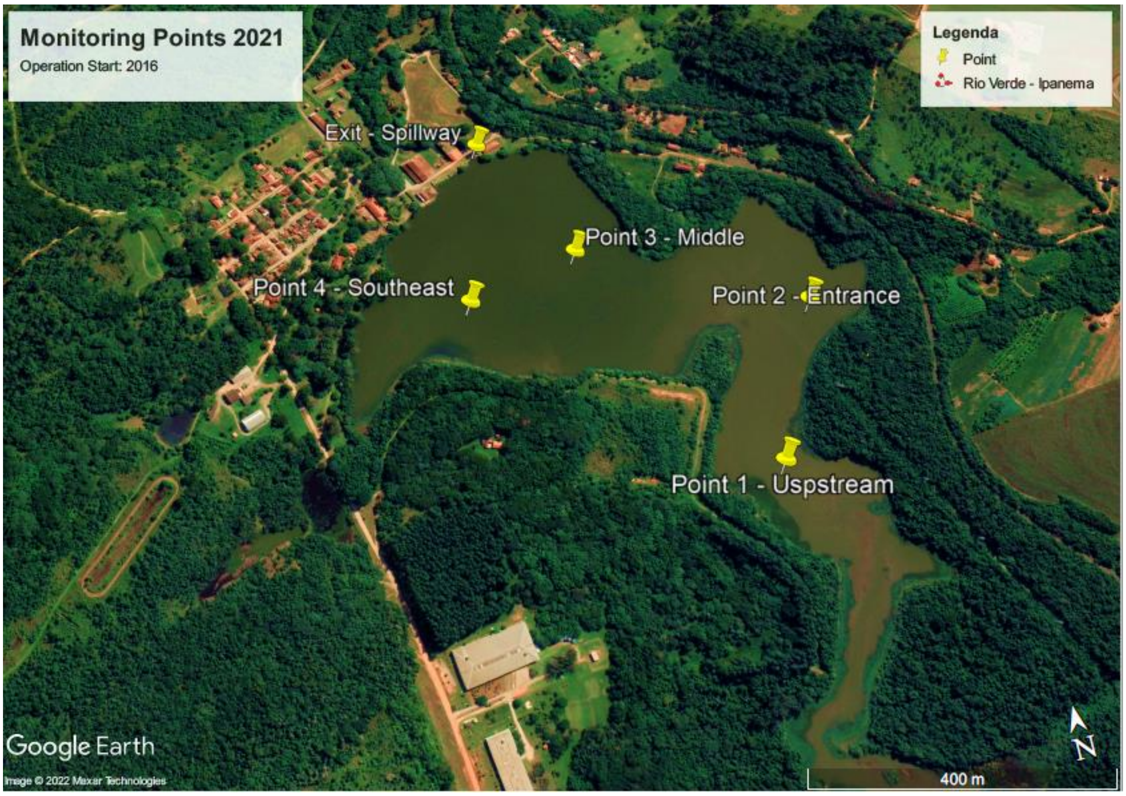



Figure 33 - Monitoring points used on the-current project.
Source: Author (2022) adapted from Google Earth® (2022)

According to Amorim (2020) the Hedberg reservoir has a surface area of 0.26 km², a mean depth of 4.5 m and a polymictic behavior, with several stratifications and mixing events throughout the year. Water quality evaluation showed problems with an excess of nutrients. The monitoring inside the Hedberg Reservoir is described with detail in Amorim (2020) work.

#### *4.2.1 Data from Wastewater Treatment Plants*

According to *Atlas Esgotos* Report, in Ipanema Watershed there were 5 (five) Wastewater Treatment Plants (WWTP): Green Valley and Novo Mundo partially receiving sewage from

Votorantim; Ipaneminha and Quintais do Imperador partially receiving sewages from Sorocaba and Vacariú receiving sewage from Araçoiaba da Serra, as depicts Figure 34 (ANA, 2017).

Recently, plant administrators from Votorantim city (WWTP Novo Mundo and Green Valley) informed that those two Plants were no longer in operation since 2020 (May and December, respectively) and those were sending sewage for treatment in another Plant: "VotoCel" that releases treated sewage into Rio Sorocaba. So, that evidence shows that water quality results from long campaigns in the 90's and before, would not be adequate to calculate base loads and predict current nonpoint pollution anymore.

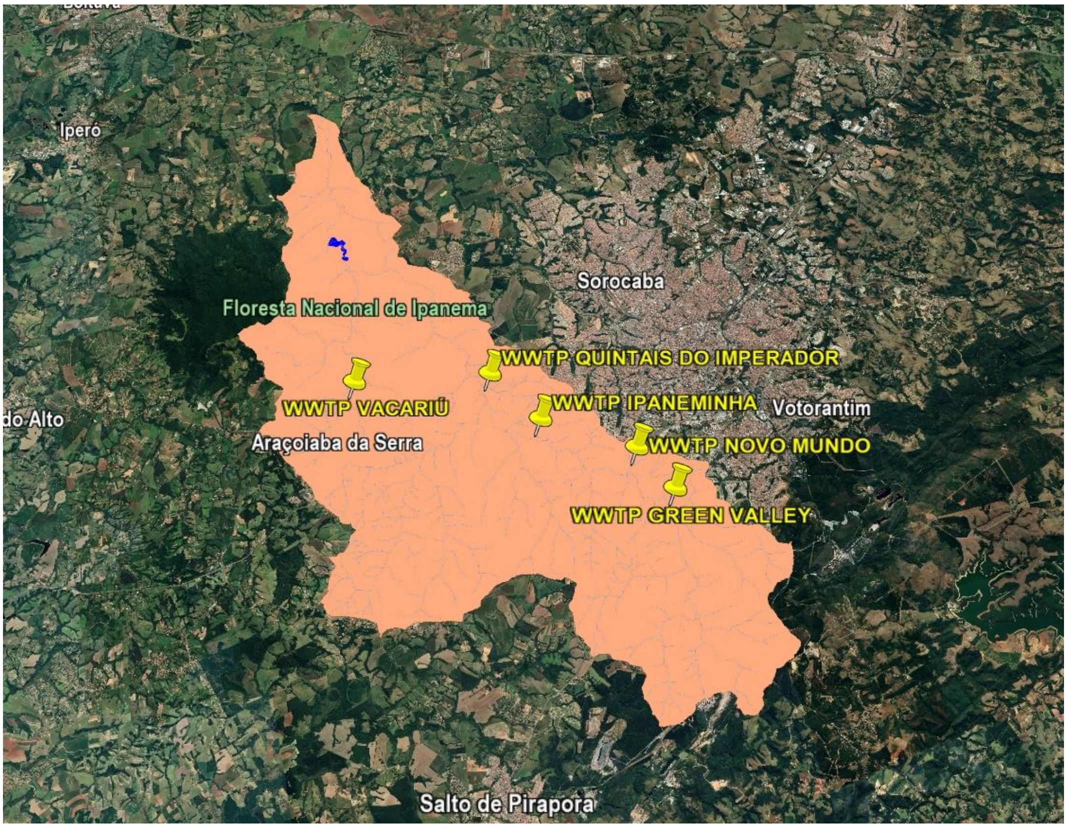



Figure 34 - WWTP contributing to Ipanema River in 2017
Source: (ANA, 2017)

Also, according to plant administrators from WWTP Ipaneminha and Quintais do Imperador (SAAE Sorocaba), their operation began in July 2010 and July 2009 respectively. According to

WWTP Vacariú administrators, its operation began in December 2009, but its effects would not be seen in Point 8 campaign results and Point 1 finished its monitoring in 2008.

For better understanding the variability of concentrations observed in our monitoring programs from 2017 forward, WWTP Ipaneminha, Quintais do Imperador and Vacariú (current WWTP releasing treated sewage into Ipanema or its tributary, as it is the case of Vacariú) informed a series of average analysis on their released sewage.

Figure 35, Figure 36 and Figure 37 show concentrations for BOD, TN and TP respectively for WWTP Ipaneminha, which releases treated sewage in average 2,19 L/s. Firsthand, it is possible to notice that highest BOD concentrations released were in the driest months (May, June, July, etc.) and peaks reach 300 mg/L which disagrees with expected efficiency informed in *Atlas Esgoto* Report (85%). TN concentrations are many times higher than concentrations expected by CONAMA 430 (limit for TNam 20 mg/L) and TP releases are higher in 2021 which alerts for possible eutrophication and algae blooming events.

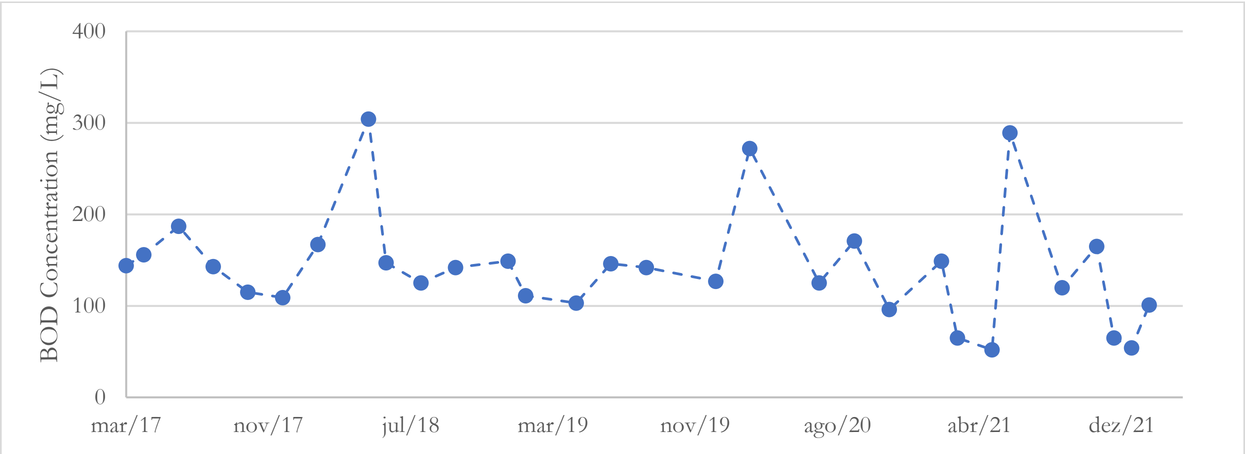



Figure 35 - BOD released by WWTP Ipaneminha

Source: Private report from SAEE Sorocaba

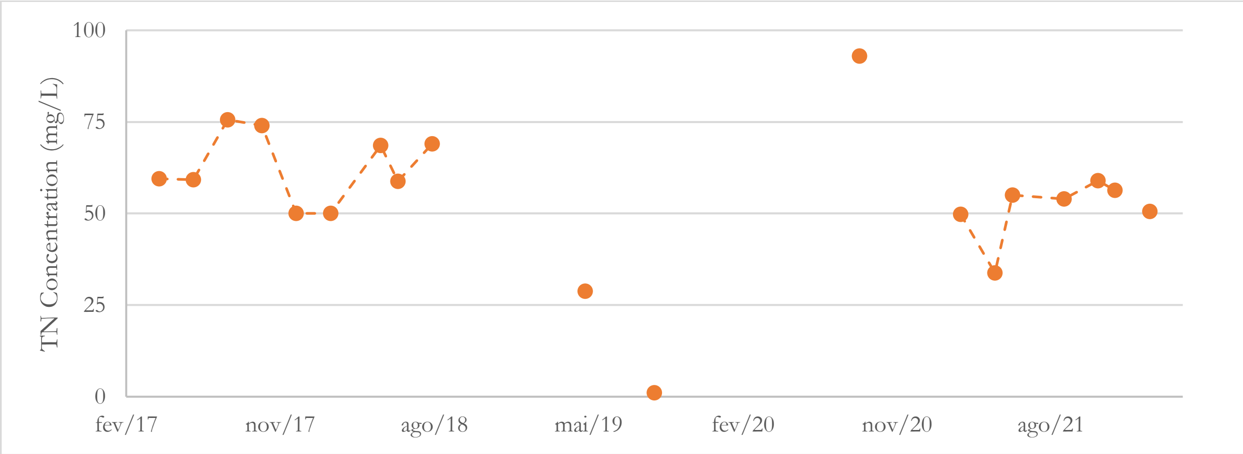



Figure 36 – Total Nitrogen released by WWTP Ipaneminha

Source: Private report from SAEE Sorocaba

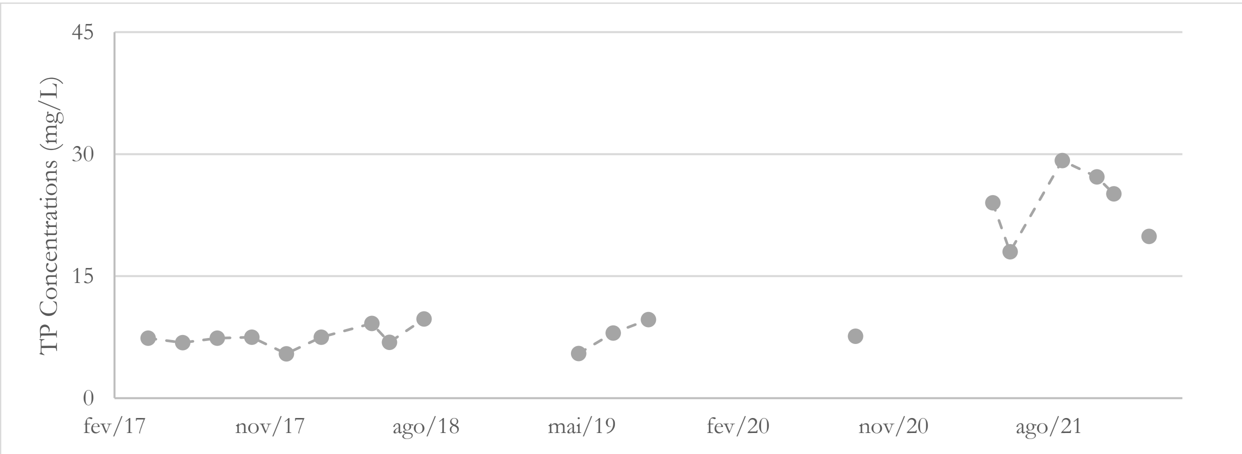



Figure 37 – Total Phosphorus released by WWTP Ipaneminha

Source: Private report from SAEE Sorocaba

As for WWTP Quintais do Imperador, Figure 38, Figure 39 and Figure 40 show concentrations of BOD, TN and TP respectively, which releases treated sewage in an average flow of 9,9 L/s. Keeping the same concentration scale, it is possible to notice that BOD concentrations are many times lower than Ipaneminha and the average BOD for all this period is 27,5 mg/L. TN concentrations are, on average, lower than CONAMA 430 limit, but are still higher than expected and, finally, TP releases are higher in 2021 when compared to the entire data set.

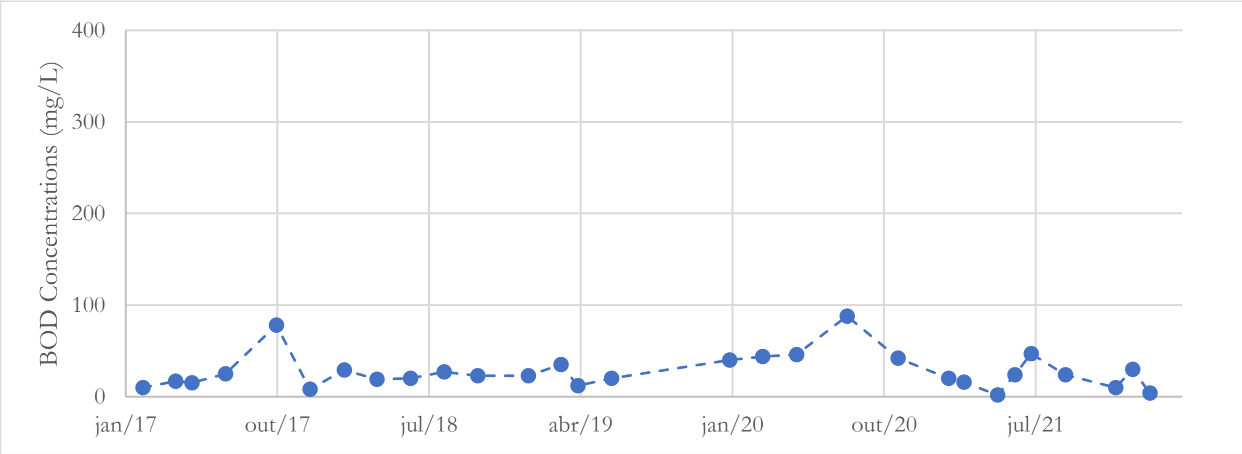



Figure 38 – BOD released by WWTP Quintais do Imperador

Source: Private report from SAEE Sorocaba

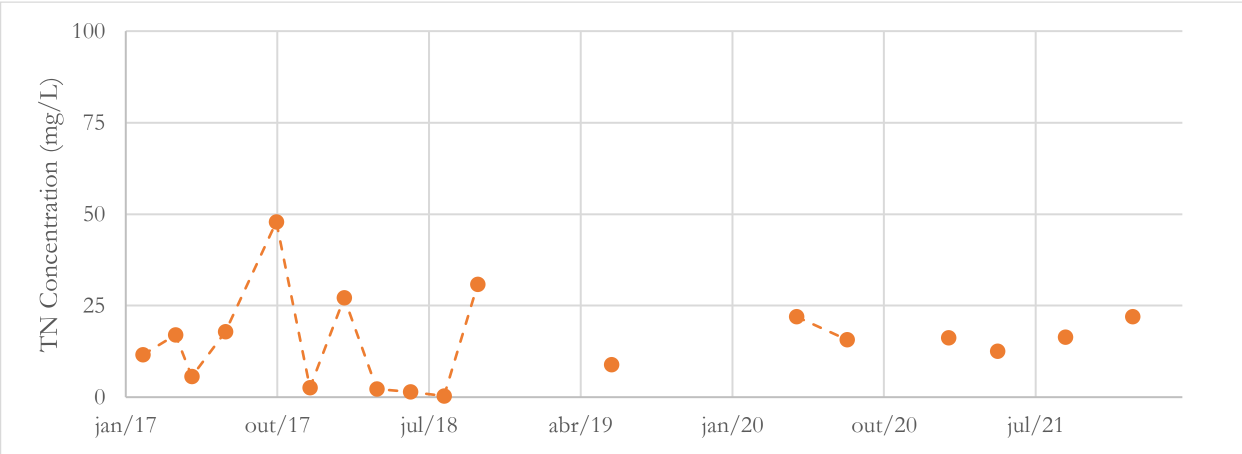



Figure 39 – Total Nitrogen released by WWTP Quintais do Imperador

Source: Private report from SAEE Sorocaba

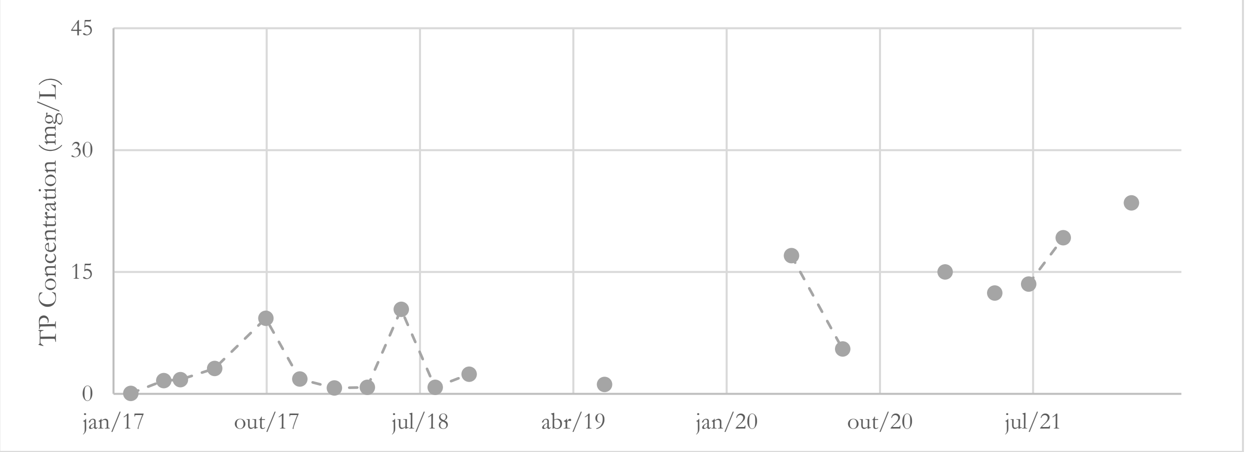



Figure 40 – Total Phosphorus released by WWTP Quintais do Imperador

Source: Private report from SAEE Sorocaba

Information about WWTP Vacariú was given, although TN and TP were not informed by the administrators. So, Figure 41 shows BOD concentrations entering and being released with an average flow of 22 L/s. Atlas Esgoto report states that the treatment is provided by anaerobic and facultative pond and its efficiency is about 75%. It is possible to notice that BOD influx concentrations rise along this period and its average is 60 mg/L. Plant administrators informed that BOD behavior were explained to new connections being made into sewage infrastructure main collectors that were previously sent directly to water bodies.

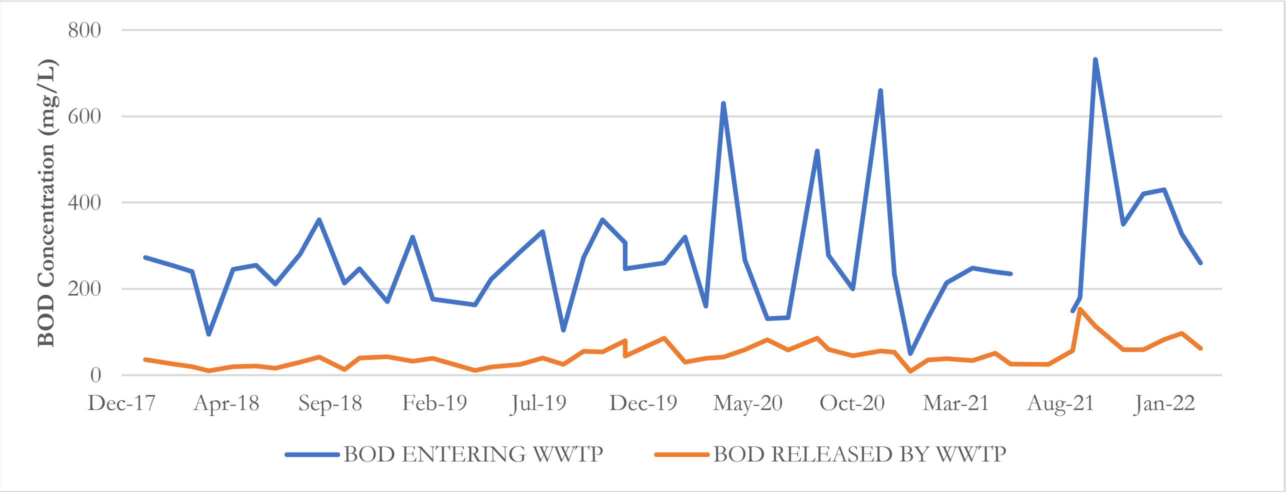



Figure 41 - BOD entering and released by WWTP Vacariú

Source: Private report from Águas de Araçoiaba

*4.2.2 Data from 90's*

As said previously, one of the most striking features of nonpoint pollution is its variability through time and space. Thus, to better understand the impacts of land use and occupation changes and development of sanitation infrastructure in the watershed, data collected from previous works will be presented and discussed on this topic.

From Figure 42 and Figure 43 for points 8 and 1 respectively, which represent BOD concentrations through a large time scale monitoring campaign, it is possible to see that BOD statistically has its average lower than 1,8 mg/L and 1,5 mg/L respectively which agrees with the concentration limits imposed by CONAMA 357 (CONAMA, 2005) for its class (II). The peaks above the class limit (2 mg/L) can be seen during rain events (or periods), such as January, late September and November. This behavior is well observed upstream and downstream Hedberg Reservoir, even though downstream from the reservoir, peaks are reduced mainly because of hydrodynamics and fate/transport process occurring on this water body.

Additionally, it is possible to see an upward tendency in the concentrations over time, both as a result of and even after the start of the WWTP activities, also due to the area's urbanization.

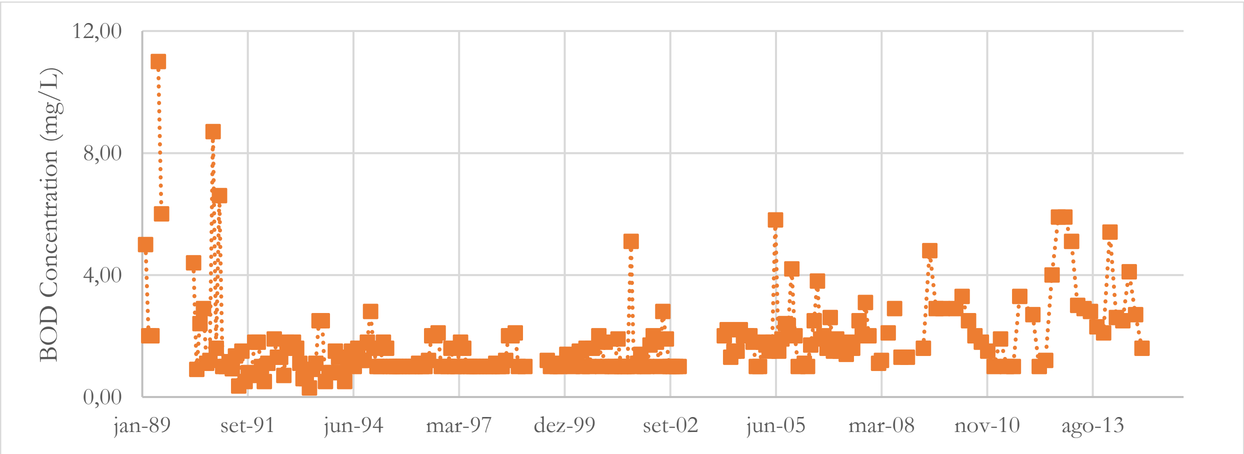



Figure 42 - BOD Monitoring Results from 1989 to 2015 for Point 8 (Upstream Hedberg Reservoir)

Source: (FCTH, 2016)

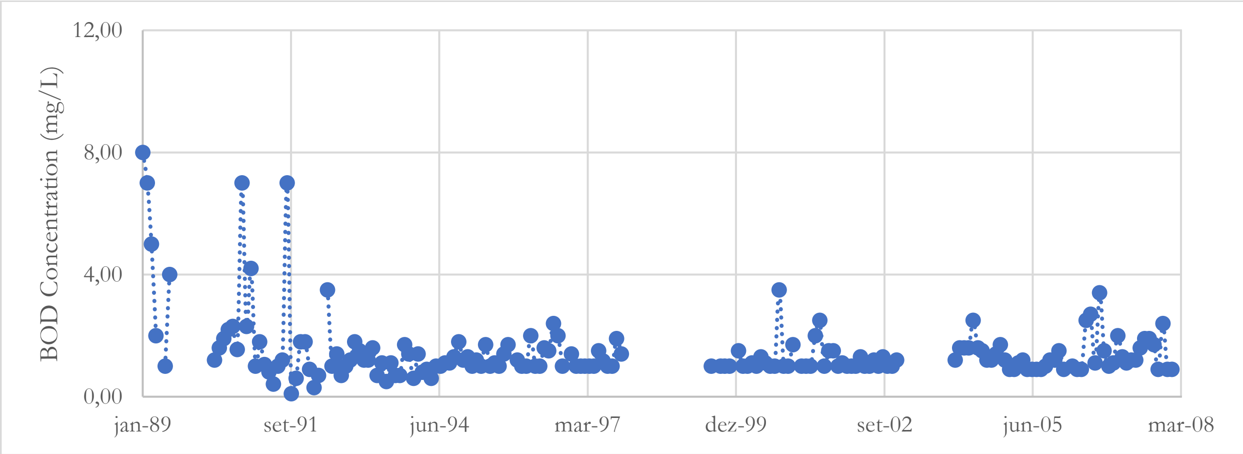



Figure 43 - BOD Monitoring Results from 1989 to 2008 for Point 1 (Downstream Hedberg Reservoir)
Source: (FCTH, 2016)

The same behavior can be seen in Figure 44 and Figure 45 for points 8 and 1 respectively, which represent Total Nitrogen (TN) concentrations through a large time scale monitoring campaign. It is possible to see that TN statistically has its average lower than 0,9 mg/L and 0,5 mg/L respectively and despite CONAMA 430 not limiting TN concentrations for its class (II), when observing the nitrogen fractions results (ammoniacal, nitrite and nitrate), all of them do not overpass their respective limits. The peaks above the class limit (2 mg/L) can be seen during rain events (or periods), such as January, late September and November.

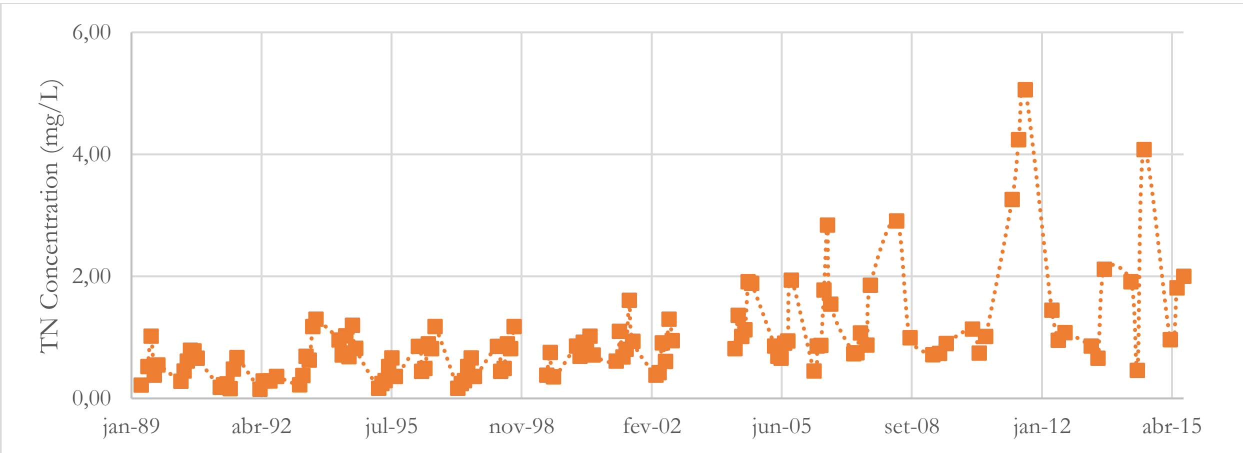



Figure 44 - TN Monitoring Results from 1989 to 2015 for Point 8 (Upstream Hedberg Reservoir)
Source: (FCTH, 2016)

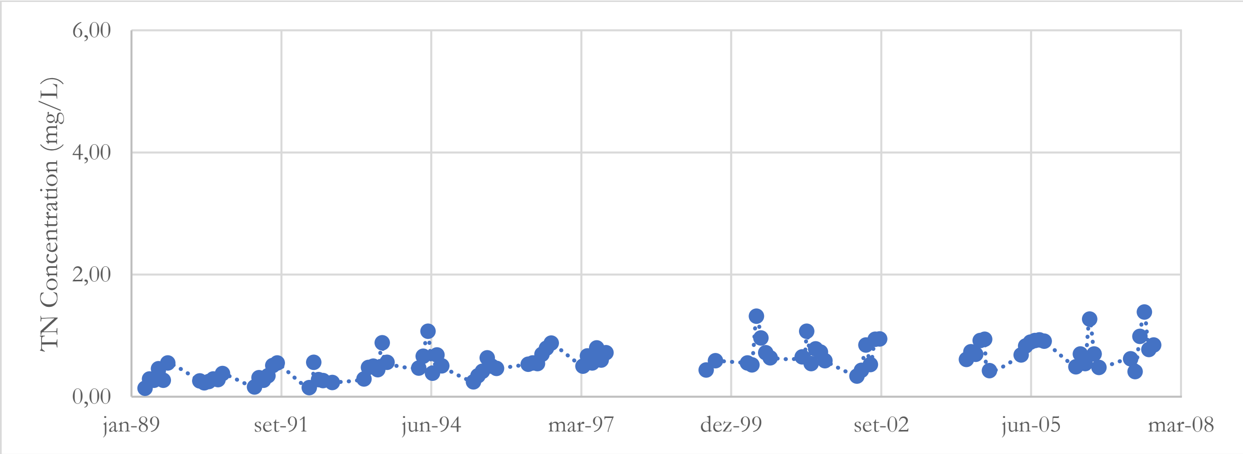



Figure 45 – TN Monitoring Results from 1989 to 2008 for Point 1 (Downstream Hedberg Reservoir)

Source: (FCTH, 2016)

As for Total Phosphorus (TP), as one can see in Figure 46 and Figure 47 for points 8 and 1 respectively, it is possible to see that TP statistically has its average lower than 0,014 mg/L and 0,008 mg/L respectively and it agrees with CONAMA 430 class limit of 0,1 mg/L (II) for lotic environments. Also, the peaks can be seen during the first rain events (or periods), such as January, late September and November, indicating nutrient washing off from croplands into water bodies.

The same upward tendency in the concentrations over time for TN and TP is observed as seen previously for BOD. Resulting from the increase of the WWTP activities, also due to the area's urbanization.

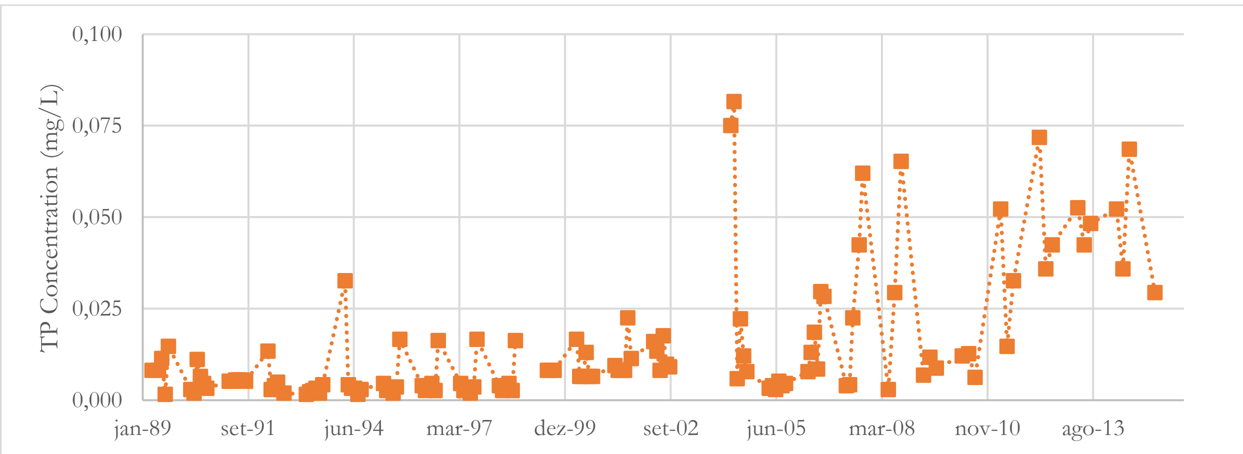



Figure 46 - TP Monitoring Results from 1989 to 2015 for Point 8 (Upstream Hedberg Reservoir)

Source: (FCTH, 2016)

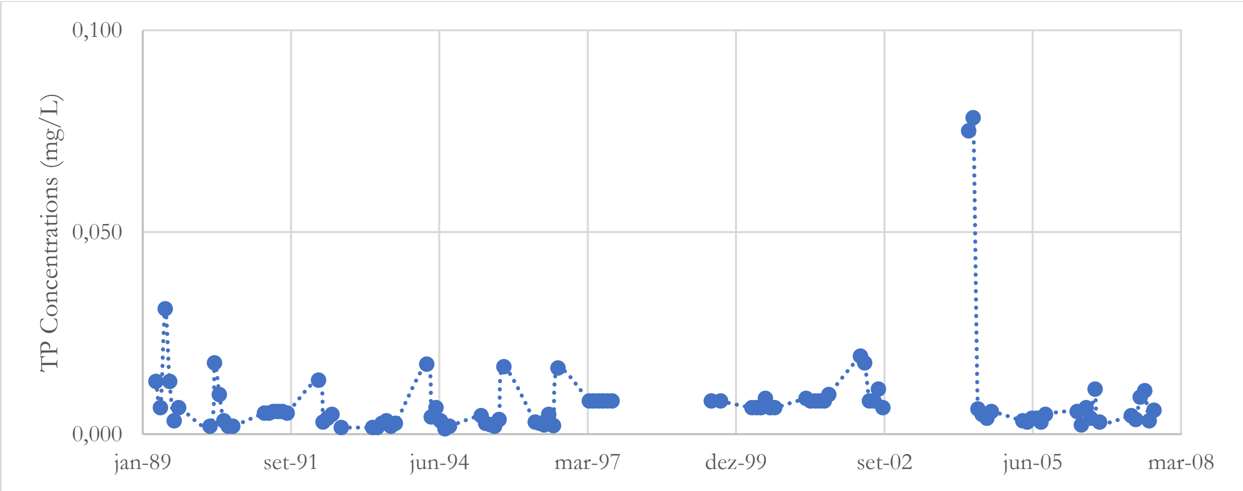



Figure 47 - TP Monitoring Results from 1989 to 2008 for Point 1 (Downstream Hedberg Reservoir)
Source: (FCTH, 2016)

*4.2.3 Data from 2010's Monitoring*

As said before, from 2017 to 2020, two monitoring points (Entrance and Middle) were created inside the Hedberg Reservoir to study the hydrodynamics and quality of the lake. Because processes inside the lake usually alter quality (such as sedimentation, oxidation, photosynthesis from algae, etc.), two additional points (Upstream and Spillway) were created exclusively for this project to study inlets and outlets from the Reservoir.

To provide other information, a meteorological station was installed also (Figure 48) measuring in a 10-minutes time step: depth levels (which gives flow through the dam); rainfall (mm); incident radiation (W/m²); relative humidity (%); pressure (mbar); wind velocity (m/s) and its direction.

Figure 49 shows points inside Hedberg Reservoir where temperature was monitored in different depths with sensors and Figure 50 illustrates the water sampling and verifications performed at each point – Middle and Entrance. Although temperature, chlorophyll-a, and other analyses measured inside the reservoir would not be exactly suitable for this project, they were considered for correlations and calibrations because this lake, in particular, has low detention period rates and low depth, so it could be considered that some transformations were insignificant through its course.

Figure 50, for instance, illustrates the researchers collecting water quality samples using portable “NAVA” bottles (left image - a) and measuring Secchi depth (right image – b).

Figure 48 - Meteorological Station in Hedberg Reservoir

(a) (b)

Figure 49 - Point “Middle” (a) and the temperature sensors (b)


(a)

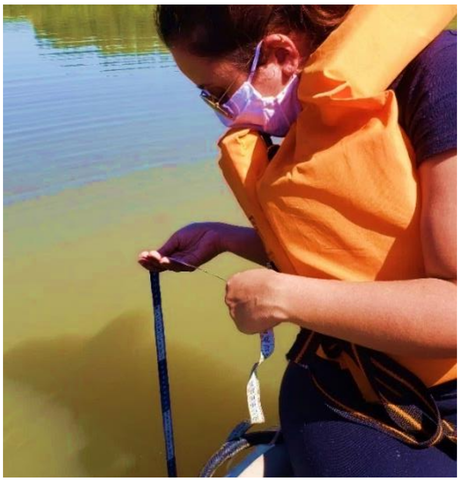

(b)

Figure 50 – Water sampling (a) and Secchi-Depth measurements (b)

When collecting water samples at the upstream point, as this spot is already on the river, depth was short, so samples were collected by submerging bottles. As for the Spillway point, bottles were inclined to the spillway angle and collected water that poured from the dam, as shown in Figure 51 images b and d. Also, it was necessary to constantly verify the dam conditions, because vegetation would occasionally obstruct it (Figure 51 - a and b) and the flow information would be compromised.

The results obtained for BOD are detailed on Figure 52. From this, it is possible to observe that BOD concentrations had a great variability in the first campaign (2017/2018). In 2021, BOD concentrations were always found to be lower than the quantification limit (2 mg/L). That can be supported by the termination of two WWTP and from the new connections to the main sewage collectors in Araçoiaba da Serra, preventing untreated sewage from going directly into water bodies.

Similar behavior can be seen in Figure 53, where TN concentrations are lower in 2021 when compared to 2017 and 2018. Although, when 2021 monitoring is on focus (Figure 54), it is not possible to notice any clear relation with rainfall and TN concentrations sampled. That might be explained by high concentrations of TN being released by WWTP. As base load is high, wash off cannot be seen during rain episodes.

(a) (b)

(c) (d)

Figure 51 –Spillway partially obstructed by vegetation (a); water sampling downstream the spillway (b); water sampling at clean and functional spillway (c); samples in ideal situation (d)

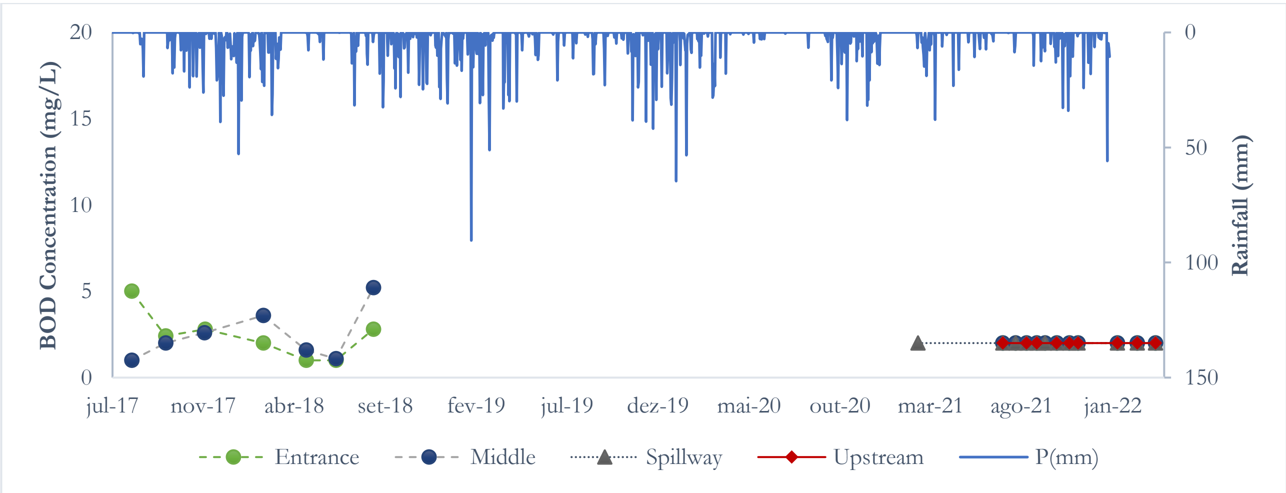



Figure 52 - BOD Concentrations (mg/L) from August 2017 to April 2022

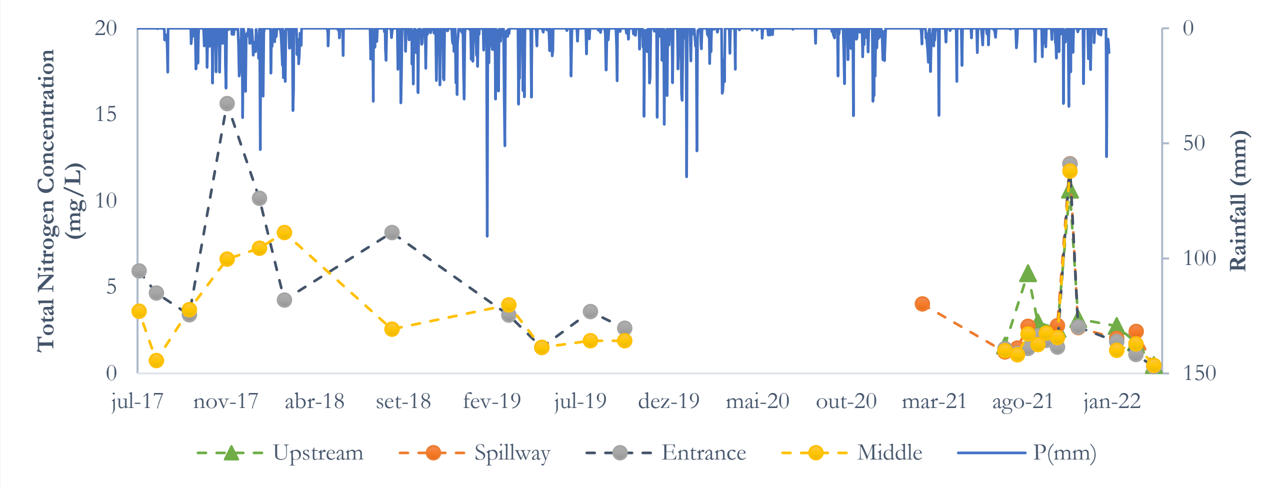



Figure 53 - TN Concentrations (mg/L) from August 2017 to April 2022

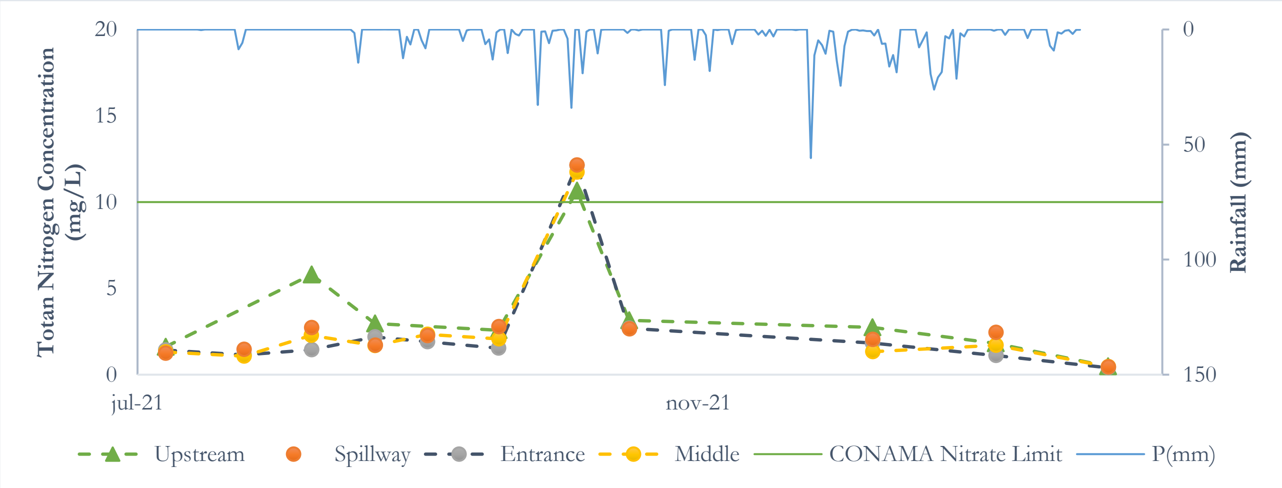



Figure 54 - Closer look at TN Concentrations (mg/L) in 2021

That does not go the same way for Total Phosphorus. Whereas TP concentrations are lower in 2021 when compared to 2017 and 2018 (Figure 55) too, when 2021 monitoring is on focus (Figure 56it is possible to notice a strong relation with rainfall and TP concentrations sampled. This suggests what was expected, as Brazil is the world's fourth largest consumer of phosphorus as an agricultural fertilizer (FATO, 2021). Concentrations are many times higher than regulation limits by CONAMA 430, which is 0,05 mg/L for intermediate water bodies (between lentic and lotic environments).

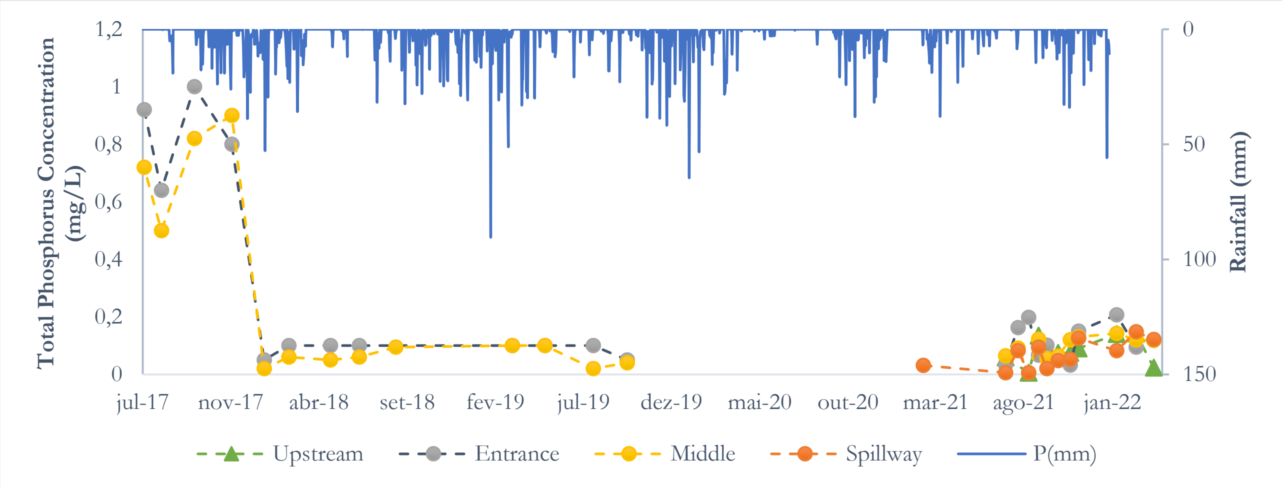



Figure 55 - TP Concentrations (mg/L) from August 2017 to April 2022

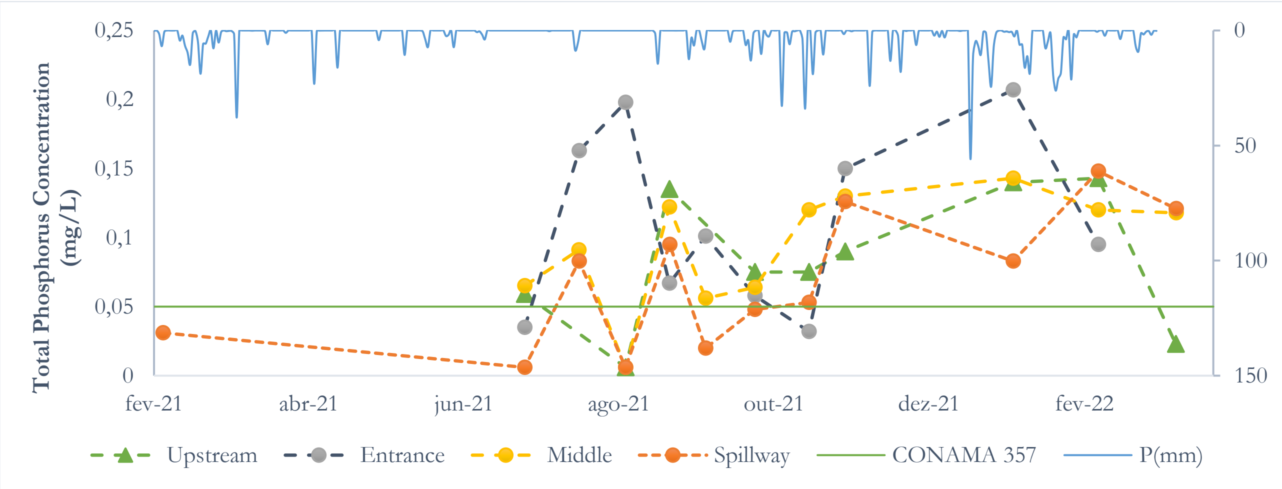



Figure 56 – Closer look at TP Concentrations (mg/L) in 2021

## *4.3 MONITORING IN JAGUARÉ WATERSHED*

The Jaguaré watershed (Figure 57) is 32 km² and is inside the city of São Paulo. It is part of the Pinheiros River basin, which in turn is a tributary of the Tietê River. The Jaguaré watershed has already been the subject of some recovery protection projects, which took place in the form of stretches of Linear Parks proposed by São Paulo Municipality, segments of the basin already served by the *Córrego Limpo* Program and most recently, infrastructure adequation and sewage treatment by *Novo Rio Pinheiros* Project.

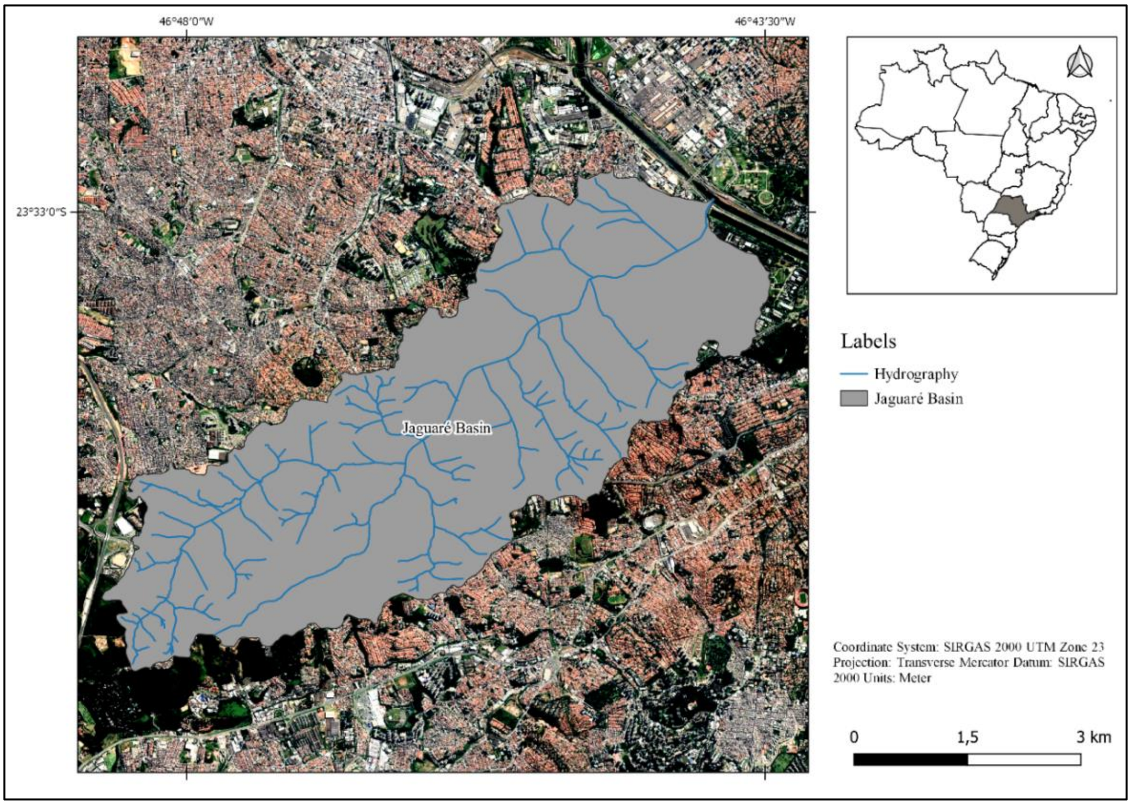



Figure 57 - Jaguaré Watershed

Jaguaré is a hydrological basin with different patterns of urban occupation: both slums, middle class areas equipped with infrastructure, industrial areas and high-end housing areas. The basin also has typical segments of urban expansion zones, the so-called outskirts of the metropolis, where occupation inexorably precedes the arrival of infrastructure, ignoring environmental, sanitary and urban legislation.

Decree No. 8468, from September 8, 1976, established as duties of the *Companhia Ambiental do Estado de São Paulo* – CETESB: planning and execution of continuous monitoring campaigns, as well as laboratory tests and analysis of results for the evaluation of the quality of inland waters. Since then, the monitoring in the different watersheds of the state of São Paulo has been carried out and presented annually by the company, in the format of the Inland Water Quality Reports.

These reports, available on the CETESB website, consolidate the data obtained during bimonthly sampling in different water bodies. The data are made available by sampling points and expose about 60 water quality variables (physical, chemical, hydrobiological, microbiological and ecotoxicological), considered the most representative. They are also accessible through the *infoáguas* portal, managed by CETESB itself (CETESB, 2022).

The area of interest for the developed project is the Jaguaré River Basin, located within the Pinheiros River Basin, which in turn is located within the Alto Tietê Watershed (UGRHI 06). The measurements of these points are bimonthly and started in 2014. The monitoring point for the existing basic network in the Jaguaré River Basin is UARE04550 (Jaguaré).

The monitoring carried out by SABESP from 2018 to 2019 took place considering a need to deepen the knowledge of the water quality characteristics in the Pinheiros Watershed, for a better assessment of the impact of the works planned for the expansion and optimization of the Sanitary Sewage System (SSS). Two points were considered for the monitoring campaign (P6 and P7), one located at the same place as the one monitored by CETESB and the other at Av. Escola Politécnica x Marg. Pinheiros, right before its own mouth at Pinheiros.

Finally, in order to better supply the database on load releases into the Pinheiros River, SABESP contracted a quali-quantitative monitoring at several points in the Pinheiros Watershed in 2019. This project was carried out by FCTH, for the development of hydrological monitoring of the metropolitan water production system of SABESP.

The measurement period was from October to December 2019, ensuring that the collections were carried out in dry periods (at least 3 days without rain), this premise guarantees that the measured loads refer to the generated effluent load, excluding the load from surface washing. All the points monitored are shown in Figure 58. The campaigns in Jorge Ward Point measured the following constituents:

- Flow rate;
- BOD;
- COD;
- Suspended Solids;
- Kjeldahl Nitrogen;
- Ammoniacal Nitrogen;
- Nitrite and Nitrate;

• Total Phosphorus.

*Observation: Suspended Solids were only measured in 24 hours – monitoring campaign***.**

The campaigns in Mouth Point measured only BOD, as organic matter has been one of the major problems for Pinheiros and Tietê mainly.

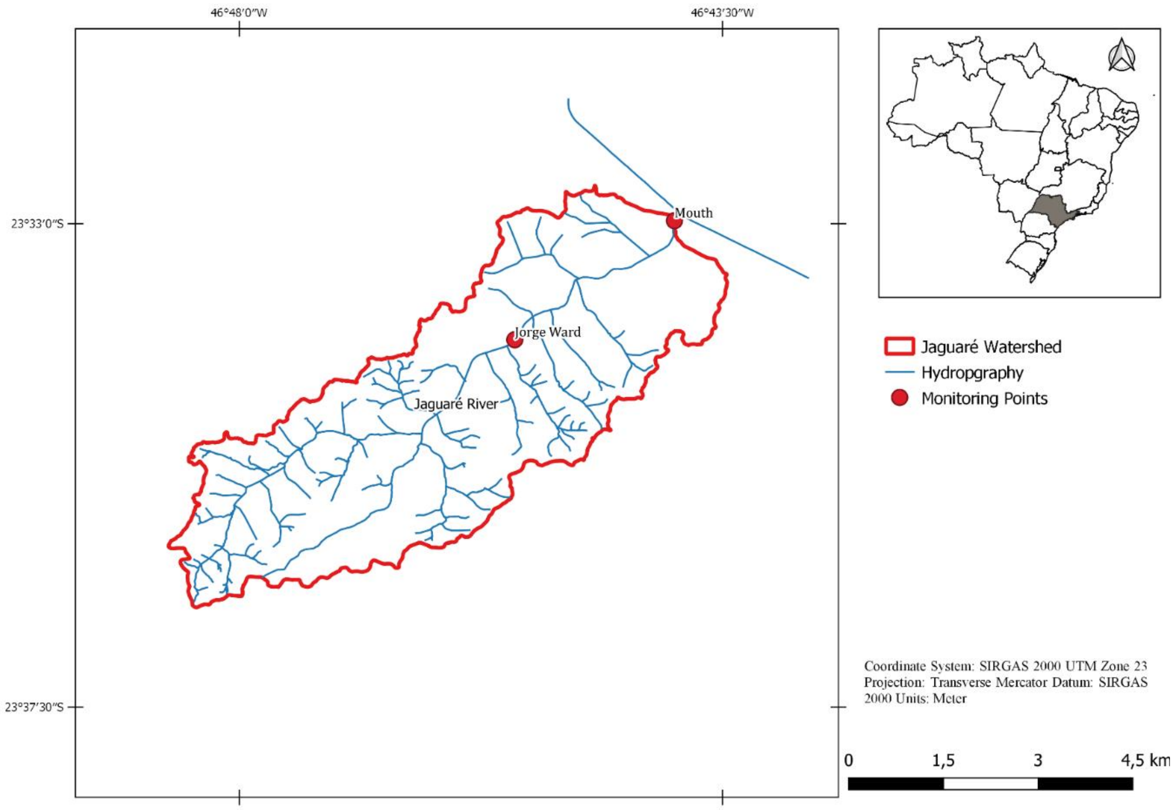
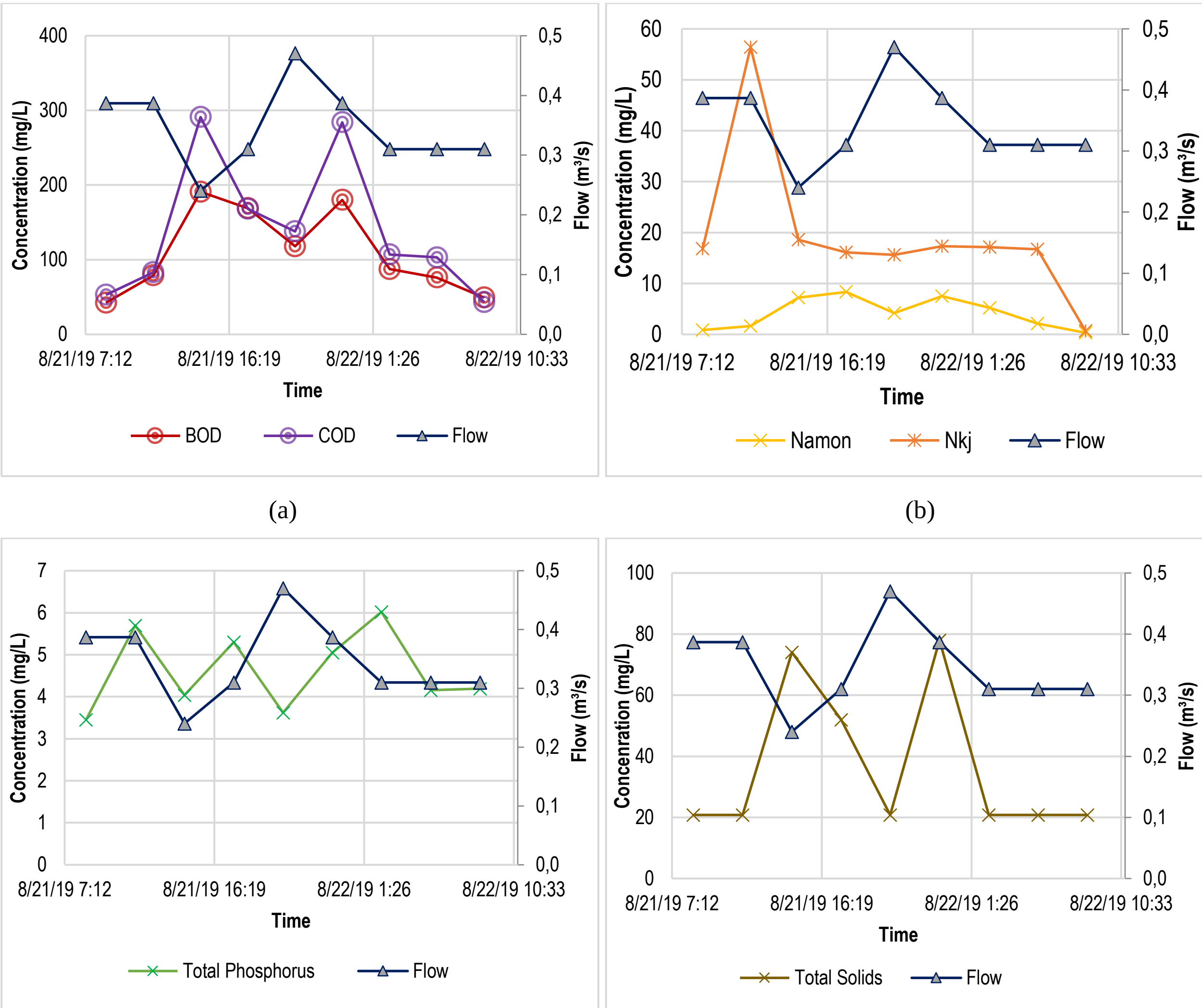



Figure 58 - Monitoring points in Jaguaré River

Sample collections were divided into two different groups: 24h monitoring and complete monitoring. The first consisted of campaigns lasting 24 hours in which the variables mentioned above were measured. The complete monitoring had not ended by the time this project was finished.

The 24-hour monitoring allowed the evaluation of the fluctuation within the period of the day of the variables investigated. In this case, all of them change according to the flow, therefore, peak flow times (between 18:00 and 20:00) promote peaks in the other variables. The difference in time of occurrence between the peak flow and the peak of the concentration of the variable under analysis depends on the topography and soil cover in the basin, since the surface runoff occurs in different ways according to each one of them, generating a greater or lesser lag between the records of flow peaks and the peaks of the other variables.

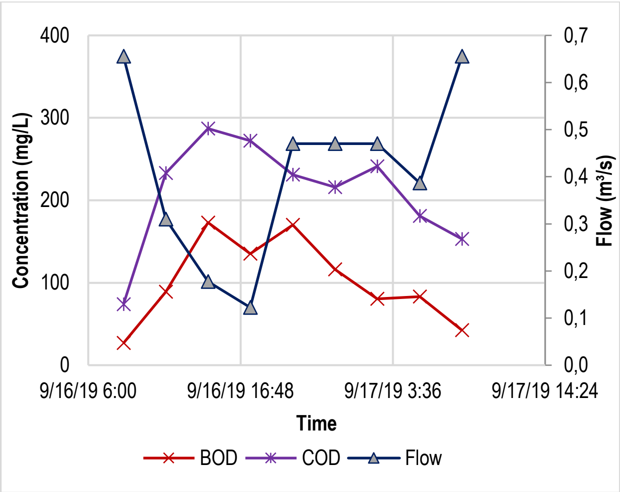



(c) (d)

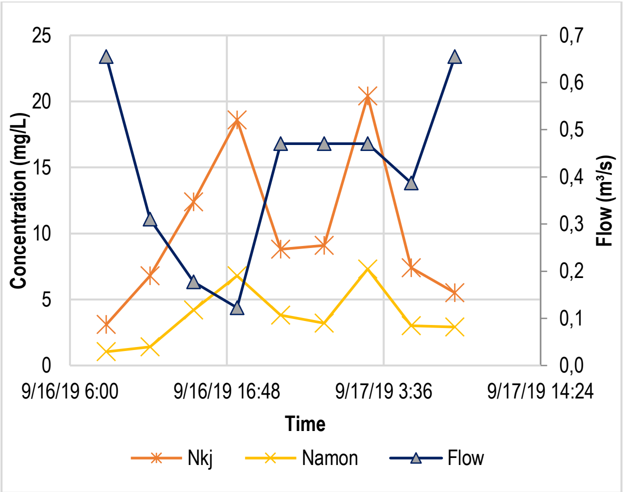
Figure 59 - Jaguaré 24 h monitoring on August, 21th (first campaign).

In Figure 59-a, for the first campaign, COD concentrations are very close to those of BOD at different times, indicating that the organic portion is predominant in the collected sample. This behavior was not repeated in the second campaign (Figure 60). The concentrations of COD and BOD in the Jaguaré basin are also high. The concentrations of Kjeldahl and Ammoniacal Nitrogen are also high and those of Nitrite and Nitrate are low (hidden from this report), indicating that the conversions between the nitrogen fractions did not occur completely, because the flow consists majorly by untreated sewage.

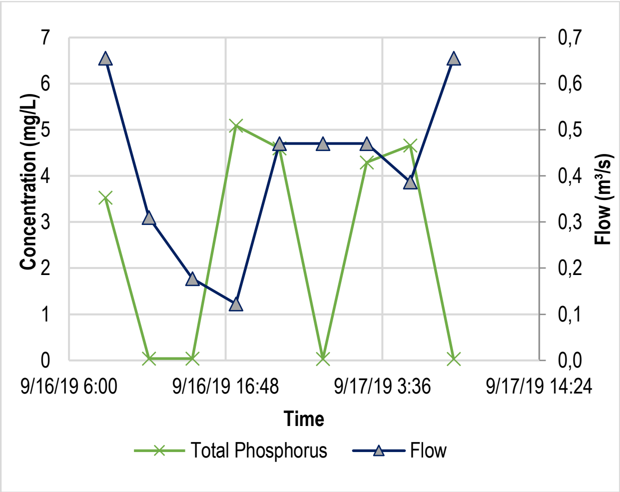
In Figure 59-c/d, one can observe high concentrations of Phosphorus in the Jaguaré stream. The concentrations found in the two campaigns are similar, despite great variability in the second campaign, demonstrating some reliability in the results. High concentrations of Total Suspended Solids are observed in the two campaigns. Surprisingly, BOD peaks were at 14:30 and 23:30 for the first campaign and 14:30 and 20:30 for the second campaign. Flow peaks were around 11:30 and 20:30 for the first campaign and (probably) around 07:30 and 20:30 for the second campaign.



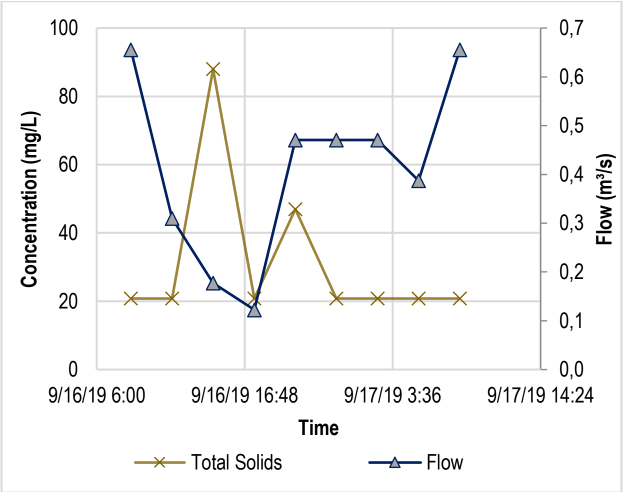

(a)




(b)




(c)




(d)

Figure 60 - Jaguaré 24 h monitoring on September, 19th (second campaign).

This massive database, along the 5-years period, was consolidated into a statistical analysis and for calibration a box plot was developed, with the data described in Table 9 and Table 10. Boxplots are a standardized way of displaying the distribution of data based on a five number summary (minimum, first quartile [Q1], median, third quartile [Q3] and maximum).

Table 9 - Consolidated Results from monitoring campaign for Jorge Ward Point

| | AVERAGE | Q1 | MEDIAN | Q3 | MAX | MIN |
|---|---|---|---|---|---|---|
| **DBO** | 85,61 | 51,50 | 77,95 | 113,75 | 191,00 | 21,00 |
| **NT** | 20,21 | 11,74 | 18,77 | 27,31 | 56,56 | 0,91 |
| **PT** | 3,10 | 2,10 | 3,03 | 4,19 | 6,02 | 0,03 |

Table 10 - Consolidated Results from monitoring campaign for Mouth Point.

| | AVERAGE | Q1 | MEDIAN | Q3 | MAX | MIN |
|---|---|---|---|---|---|---|
| **DBO** | 59 | 35,8 | 45,8 | 79,8 | 159 | 10,2 |

# CHAPTER 5

## MODEL AND SOFTWARE DEVELOPMENT

*"Nothing is softer or more flexible than water, yet nothing can resist it"*

Lao Tzu

Mathematical modeling is defined as the translation of the conceptual model into mathematical schemes, numerical values of the parameters (coefficients) of the equations and input and output data. Model complexity can vary according to the amount of information required, however it is necessary to evaluate cost-benefit, since very complex models can take a long time to be executed, and their results do not present significant differences from simplified versions (ROSMAN 2020; VON SPERLING, 2007).

The translation of mathematical models can be performed by different calculation methods, most of which can be solved by using a numerical model. The numerical models allow the solution of more comprehensive problems when compared to the other modalities (CHAPRA, 2008).

With the use of modeling, decision making can be subsidized. Technicians can carry out diagnostic analysis encompassing the costs of monitoring and measuring by integrating distant stations, extending knowledge to unmeasured locations, and understanding dynamic processes. For this reason, simulation is a determining tool in environmental licensing processes and in the definition of response, monitoring and mitigation strategies (ROSMAN 2020).

### *5.1 CABC MODEL*

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), is a system of models intended for hydrological simulation of catchment basins using Soil Conservation Service (SCS), and Unit Hydrograph methods or the SMAP method for flow generation (LOPES; BRAGA JR; CONEJO, 1982).

It uses a flux network that allows the discretization of the area in different sub catchments according to topography, land use, and occupation, being very adequate to use in nonpoint pollution analysis. So, it includes in its routines all the tasks pertinent to these types of calculation (FCTH, 2002).

Developed in a Windows® environment (Figure 61) and with simple programing language (*Visual Basics*), it incorporates all the facilities of tracing and drawing, simplifying the work of the designer and eliminating often strenuous tasks such as the delimitation of hydrographic basins, obtaining the area of these basins, the dimensions of significant points and the slope of the natural channels (FCTH, 2002).

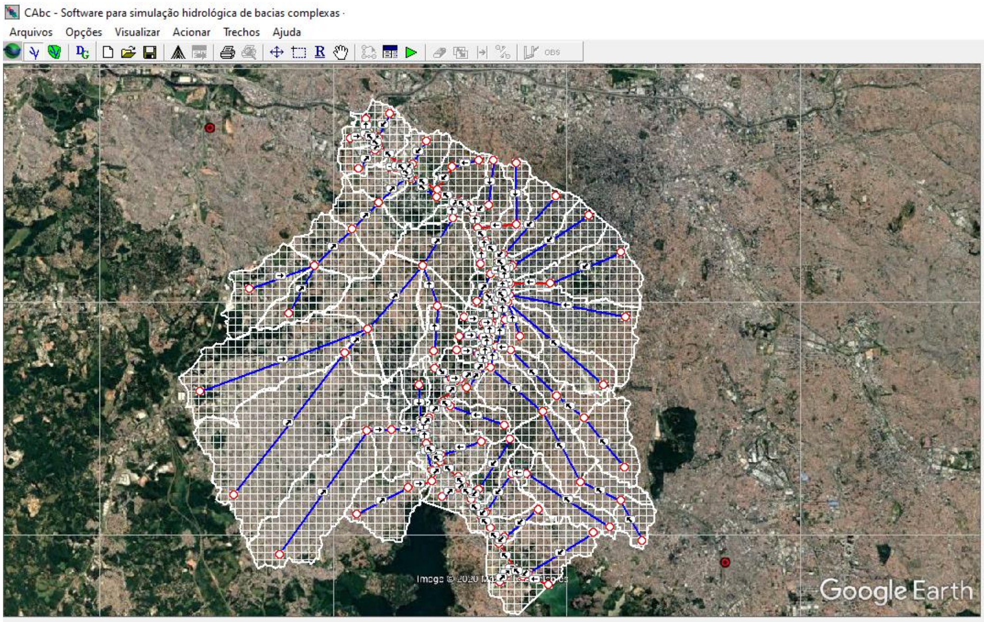



Figure 61 - CAbc Software Layout

The CAbc model applies to urban and rural drainage problems, especially those that can be classified as 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 be taken into account through segmentation into sub-basins and makes it a differential for this model (FCTH, 2002). For these reasons, CAbc was chosen to be adapted for nonpoint pollution analysis. Its fundaments, along with the embedded calculations and computations are briefly described in the following sections.

## 5.1 MODEL DEVELOPMENT

Among the methods available in CAbc for flow forecasting, SMAP model was chosen, a mathematical model of hydrological simulation of the rain-flow transformation type. Conceptually, it consists of a system of three reservoirs (Figure 62), which represent the series of stores to which the water is subjected during the hydrological cycle.

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 (e.g., a whole year) and not only for a given precipitation event. The hydrological model will generate the calibration parameters for a series of calculated flows.

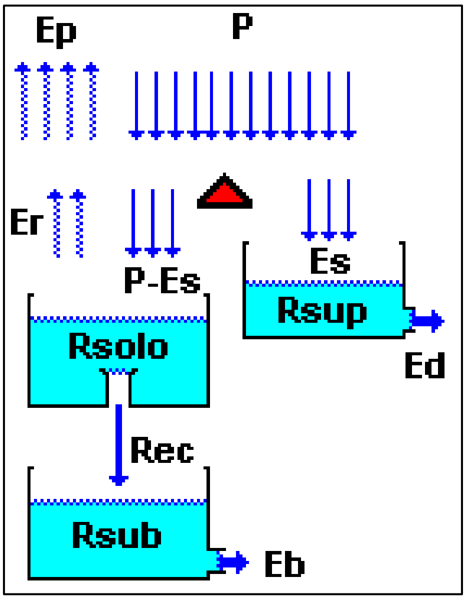



Figure 62 - Illustration of the Daily Flow Forecast Model
Source: (LOPES, 1999; LOPES; BRAGA JR; CONEJO, 1982)

In the daily basis conception, (Figure 62), input data are the total daily rainfall, potential evapotranspiration and the drainage area values. In order to calibrate the parameters involved in the modeling, a historical flow series is necessary, including drought periods and flood events. In this way, the adjustment of the parameters must be done to minimize the discrepancy between the flow values calculated with the values observed in flow stations (LOPES; BRAGA; CONEJO, 1982).

The calibration of the SMAP model can be done manually, through trial-and-error processes, or automatically, through mathematical optimization methods. Manually, it requires more experience from the modeler and constitutes a more laborious and subjective process. On the other hand, it has the advantage of total monitoring by the hydrologist to determine each parameter. The automatic calibration, in turn, facilitates the work and reduces the subjectivity of the manual process.

Regarding the mathematical aspect, the state variables of the reservoirs represented in Figure 13 are updated daily in the model as shown by Equations (12), (13) and (14).

$$\boldsymbol{R_{(i+1)} = Rsolo_{(i)} + P - Es - Er - Rec} \tag{12}$$

$$\boldsymbol{Rs_{(i+1)} = Rsup_{(i)} + Es - Ed} \tag{13}$$

$$\boldsymbol{Rb_{(i+1)} = Rsub_{(i)} + Rec - Eb} \tag{14}$$

In which: Rsolo is the soil reservoir (aerated zone); Rsup is the reservoir on the surface of the basin; Rsub is the underground reservoir (saturated zone); P is precipitation; Es is runoff; Ed is direct flow; Er is real evapotranspiration; Rec is the underground recharge; Eb is the basic outflow

The model is initialized using Equations (15), (16) and (17).

$$\boldsymbol{Rsolo_{(1)} = Tu_{in} \times Str} \tag{15}$$

$$\boldsymbol{Rsup_{(1)} = 0} \tag{16}$$

$$\boldsymbol{Rsub_{(1)} = \frac{Eb_{in}}{(1 - kk) \times (Ad \times 86,4)}} \tag{17}$$

In which, Tuin is the initial moisture content (ad.); Ebin is the initial basic flow ($m^3$ / s) and Ad is the drainage area ($km^2$).

And it consists of **5** transfer functions and its complements (Equations (18 to (27). First, If **(P > Ai)**, then:

$$S = Str - Rsolo \tag{18}$$

$$\mathbf{Es} = \frac{(\mathbf{P} - \mathbf{Ai})^{\mathbf{2}}}{(\mathbf{P} - \mathbf{Ai} + \mathbf{S})} \tag{19}$$

$$\text{Else} \rightarrow Es = 0 \tag{20}$$

Afterward, If **((P-Es)>Ep)** then:

$$Er = Ep \tag{21}$$

$$\text{Else} \rightarrow \mathbf{Er} = (\mathbf{P} - \mathbf{Es}) + (\mathbf{Ep} - (\mathbf{P} - \mathbf{Es})) \times \mathbf{Tu} \tag{22}$$

$$Tu = \frac{Rsolo}{Str} \tag{23}$$

If **(Rsolo** > **(Capc*Str)** then:

$$\mathbf{Rec} = \mathbf{Crec} \times \mathbf{Tu} \times (\mathbf{Rsolo} - (\mathbf{Capc} \times \mathbf{Str})) \tag{24}$$

$$\text{Else } Rec = 0 \tag{25}$$

$$\mathbf{Ed} = \mathbf{Rsup} \times (\mathbf{1} - \mathbf{K2}) \tag{26}$$

$$\mathbf{Eb} = \mathbf{Rsub} \times (\mathbf{1} - \mathbf{Kk}) \tag{27}$$

There are **six** calibration parameters for the SMAP model (LOPES; BRAGA; CONEJO, 1982):

1. Str - soil saturation capacity (mm)
2. K2t - runoff constant recession (days)
3. Crec - groundwater recharge parameter (%)
4. Ai - initial abstraction (mm)

5. Capc - field capacity (%)
6. Kkt - basic outflow constant of recession (days)

The model adjusts the units of the parameters with Equations (28) and (29):

$$\mathbf{KK} = \mathbf{0,5}^{(\mathbf{1}/\boldsymbol{kkt})} \quad (28)$$

$$\mathbf{K2} = \mathbf{0,5}^{(\mathbf{1}/\boldsymbol{K2t})} \quad (29)$$

In which: Kkt and K2t are expressed in days in which the flow falls by half; Crec and Capc are multiplied by 100. The eventual overflow of the soil reservoir is transformed into runoff. Finally, the flow calculation is given by Equation (30).

$$\mathbf{Q} = \frac{(\mathbf{Es} + \mathbf{Eb}) \times \mathbf{Ad}}{\mathbf{86,4}} \quad (30)$$

The CAbc **Quality Module** can and must be understood in 3 components. The first component consists in the hydrology and rainfall-flow transformation. As explained in the beginning of this section, while using SMAP method and radar rainfall, the hydrologic model generates 3 separated flows for each “B” sub-basin:

i. $Q_T$ – Total Flow
ii. Qs – Superficial Flow
iii. Qb – Base Flow

The network flow then transfers this to each “i” node and through each “R” they are transferred to another sub-basin and added to another flow generated in its sub sequenced basin. Also, at each node, an imported flow can be included to represent an additional flow that is not related to rainfall. As 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, as described by Figure 61.

.

Non-served population represent the part of releases that are not treated, so the releases are as suggested by Table 7 thus incorporated through its *per-capita* flow – q - (L/inh.day) and mass -m - (g/inh.day) of each pollutant (BOD, TN and TP). That said, the product of the multiplication of each by the population provides water ($q_1$) and mass ($M_1$) flow respectively. That flow is added into the existing flow (natural provided by rainfall) and the mass is divided by total flow giving, finally, concentrations, as described by Equations (31), (32) and (33).

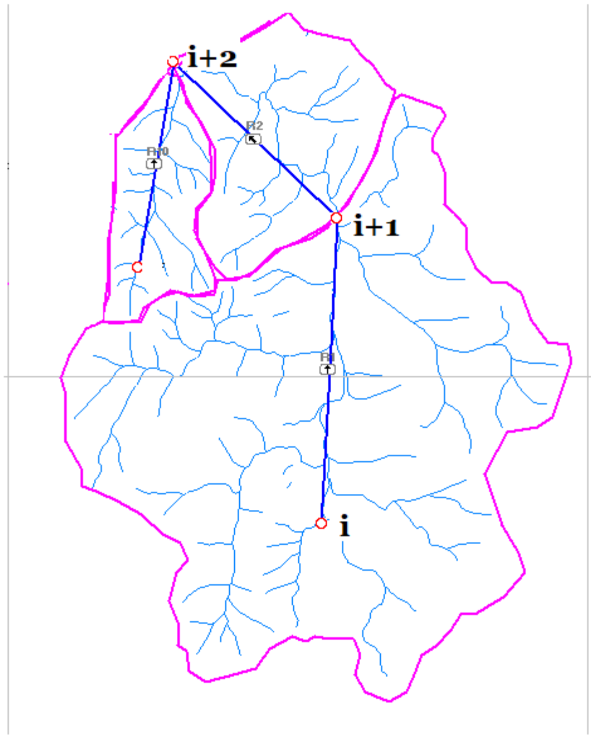



Figure 63 - CAbc schematic view

The next release, point releases, are much easier to understand. One must provide flow - $q_2$ - ($m^3$/s) and concentration - $C_2$ - (mg/L). The point release flow is also added into the existing flow and the concentration is turned into a mass release by multiplying it by its own flow. The final base release is given by diffuse (with no recognizable source) given by dry weather unit loads (kg/ha.y). These unit loads can be calculated or calibrated using literature values (as item 3.4.1 Export Coefficients or Unit Loads Method). Later, those coefficients are multiplied by its area and – after unit conversion – gives a mass flow ($M_3$) for each time step of the model (minutes, day, year, etc), as described in Equation (34).

Finally, each concentration and/or mass calculated ($M_1$, $M_2$ and $M_3$) are summed and divided by Total Flow (in this case, base flow produced in each sub-basin), as described in Equations (35) and (36).

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, remembering that when comparing to laboratory results, the 5-day type is more suitable.

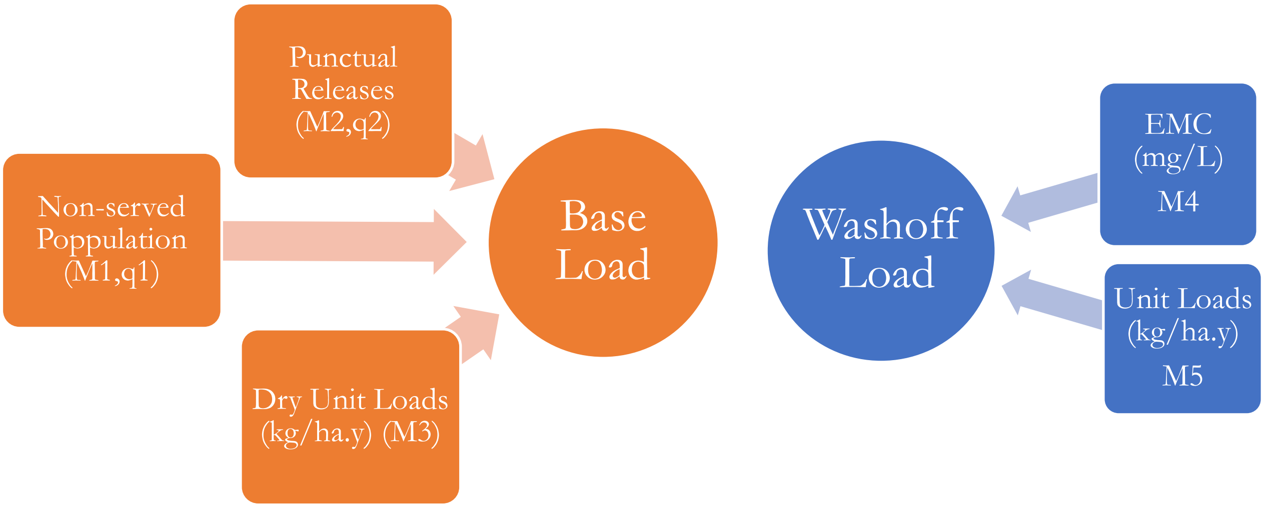



Figure 64- Load Model in CAbc Qual

$$q_1 = \frac{C \times q \times P}{86400} \tag{31}$$

$$M_1 = \frac{m \times P}{86400} \tag{32}$$

$$C_1 = \frac{M_1}{q_1} \tag{33}$$

$$M_3 = \frac{EC_S \times A}{365 \times 86400} \tag{34}$$

$$Q_{b_{i+1}} = Q_{b_i} + q_1 + q_2 + q_{imp} \tag{35}$$

$$C_{b_{i+1}} = \frac{C_{b_i} \times Q_{b_i} + C_1 \times Q_1 + C_2 \times q_2 + M_3}{Q_{b_{i+1}}} \tag{36}$$

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); $q_1$ is non-served population release ($m^3/s$); m is the sanitary sewage *per-capita* contribution (g/inh.day); $M_1$ 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); $M_3$ is the mass given by diffuse contributions (g/s); $C_2$ is the point release concentration (mg/L); $q_2$ is point release flow ($m^3$/s); $q_{imp}$ is the imported flow ($m^3$/s); $Qb_{i+1}$ is total base flow ($m^3$/s); $Cb_{i+1}$ is total base concentration (g/$m^3$ or mg/L).

The second part of the model, as said before, is when there is rainfall and, mathematically, the accumulation and wash off process are also detailed in section *3.4.3 Mathematical and Numerical Modeling*. The inputs required are: EMC (mg/L) and Wet Season Unit Loads (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 When there is rain the model calculates all surface volume ($V_{es}$) for each time step ($\Delta$t) based on a hydrological model to generate runoff as shown in Equation (37). Then based on EMC and/or Wet Season Unit Loads it generates wash off loads, as described by Equations (38) and (39), respectively. Then, finally as Equation (40) shows, final surface mass (M0) is obtained for modeling through Equation (11), which is being replicated in Equation (41) for better understanding.

$$q_w = \frac{V_{es}}{\Delta t} \tag{37}$$

$$M_4 = EMC \times V_{es} \tag{38}$$

$$M_5 = \frac{EC_w \times A}{86400 \times 365} \tag{39}$$

$$M_0 = M_4 + M_5 \tag{40}$$

$$M_{es}(t) = M_0 \times \left\{1 - exp\left[-\frac{k}{A} \times V_{es}(t)\right]\right\} \tag{41}$$

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. Figure 65 illustrates how the results are shown. 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 on a quickly descending line and, during dry periods, pollutants build up (accumulate) on the surface, resulting on an ascending line. For concentration, the opposite occurs. In the example, when it rains, the pollutants accumulated on the surface are transported to the streams and concentration rises. During the dry period, concentrations increase because base flow reduces, making the volume for the dilution much lower than normally observed.

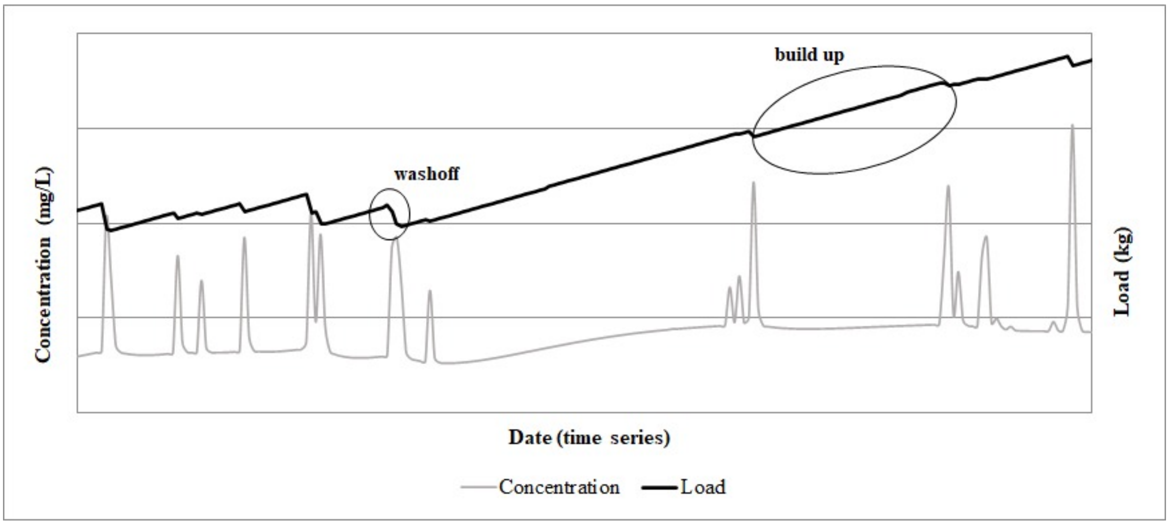



Figure 65 - Model results illustration

### *5.2 SOFTWARE DEVELOPMENT AND FEATURES*

For the hydrological model, CAbc-Qual allows the user to select between SCS, Triangular or SMAP, as illustrated in Figure 66. For the purposes of water quality (NPS pollution) evaluation, SMAP model is the most suitable, because it allows the flow separation into base and runoff flows in order to obtain endemic and nonpoint pollution (base and wash off loads respectively).

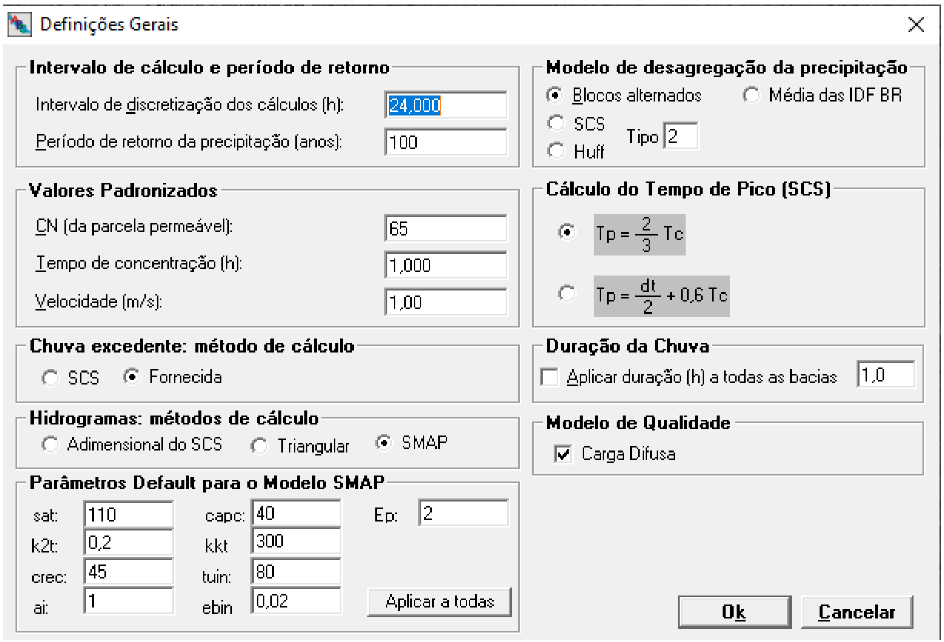



Figure 66 - General Definition window on CAbc

There are 3 main drawings (.dxf, .dwg) that must feed the CAbc model for building the net flux on it: (i) the topography (contour lines); (ii) the hydrology; and (iii) the basin contour and all the sub basins limits, if they exist. Figure 67 illustrates a project with those drawings.

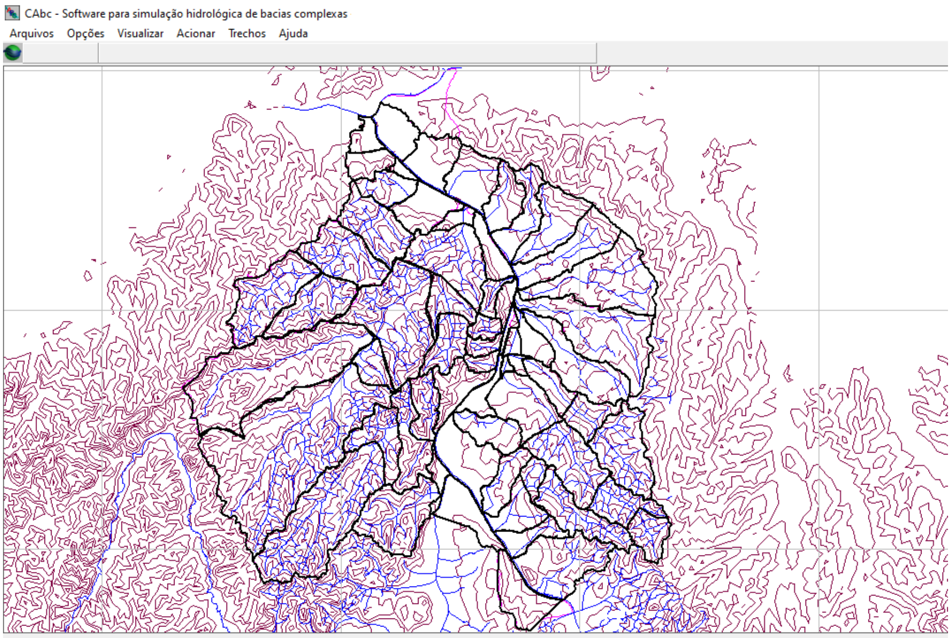



Figure 67 - CAbc input data (topography, hydrology and basins contours)

For precipitation, CAbc requires precipitation data from a radar (.asc archives) (Figure 68-1) or one can also generate a synthetic rain (Figure 68-2). Then the user has to load the information into the database (Figure 68-3) and then apply it into the basins (Figure 68-4). It is possible to give rain information in any range (hourly, daily, etc.) and in any grid distance.

Figure 69 illustrates how spatially distributed rain is shown in CAbc-Qual. In that image, each pixel grid is the total precipitation intensity observed by the radar and rain gauge network (if using the merging method) accumulated in the provided series. The grid is usually 1km x 1km, but it can vary depending on the radar type and setup.

Figure 67 also shows the distribution for the year 2021 in Pinheiros watershed, highlighting Jaguaré watershed and using the conditional merging method while Figure 70 shows the distribution in Ipanema watershed for the same year. The few data provided by rain gauges in the surroundings prevented the merging method to be executed, so in this case the obtained rainfall was an estimation made by the radar. Comparing both, one can see that as Jaguaré is a small watershed, rainfall distribution is not as remarkable as in Ipanema.

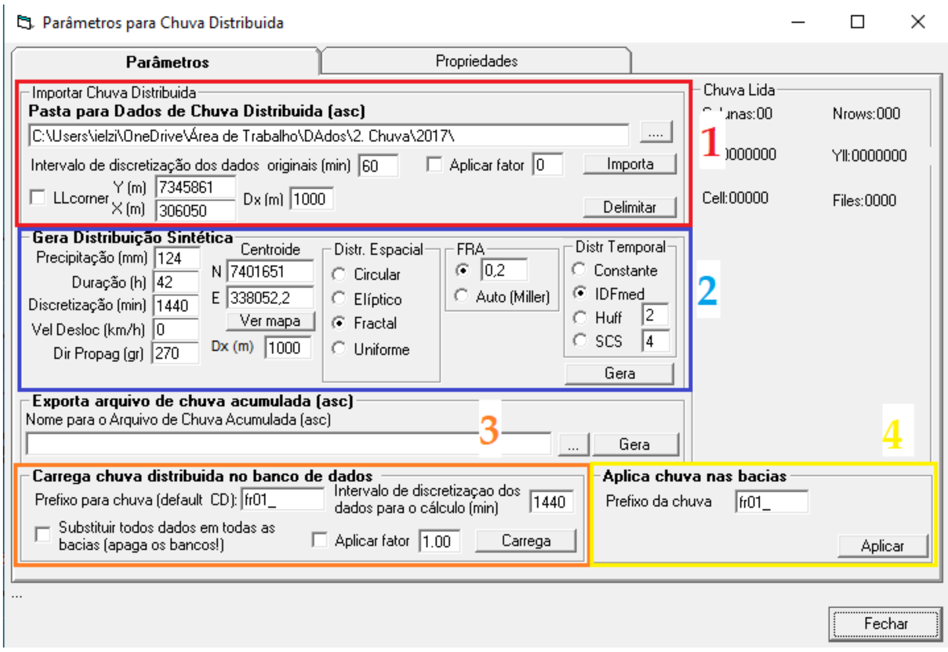



Figure 68 – Spatially Distributed Rain (1) Import Data (2) Generates a Synthetic Rain Distributed (3) Loads rain into database (4) Apllies into basins

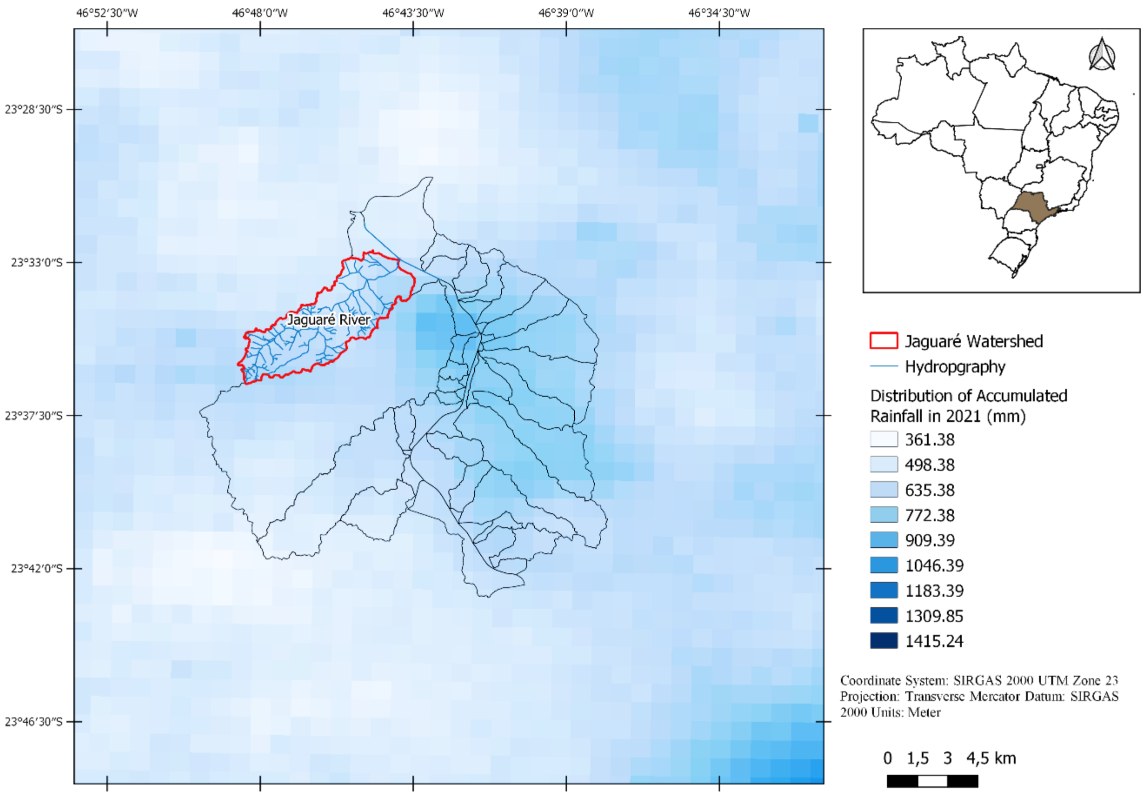



Figure 69 – Example spatially distributed rain (accumulated in 1 year – 2021)

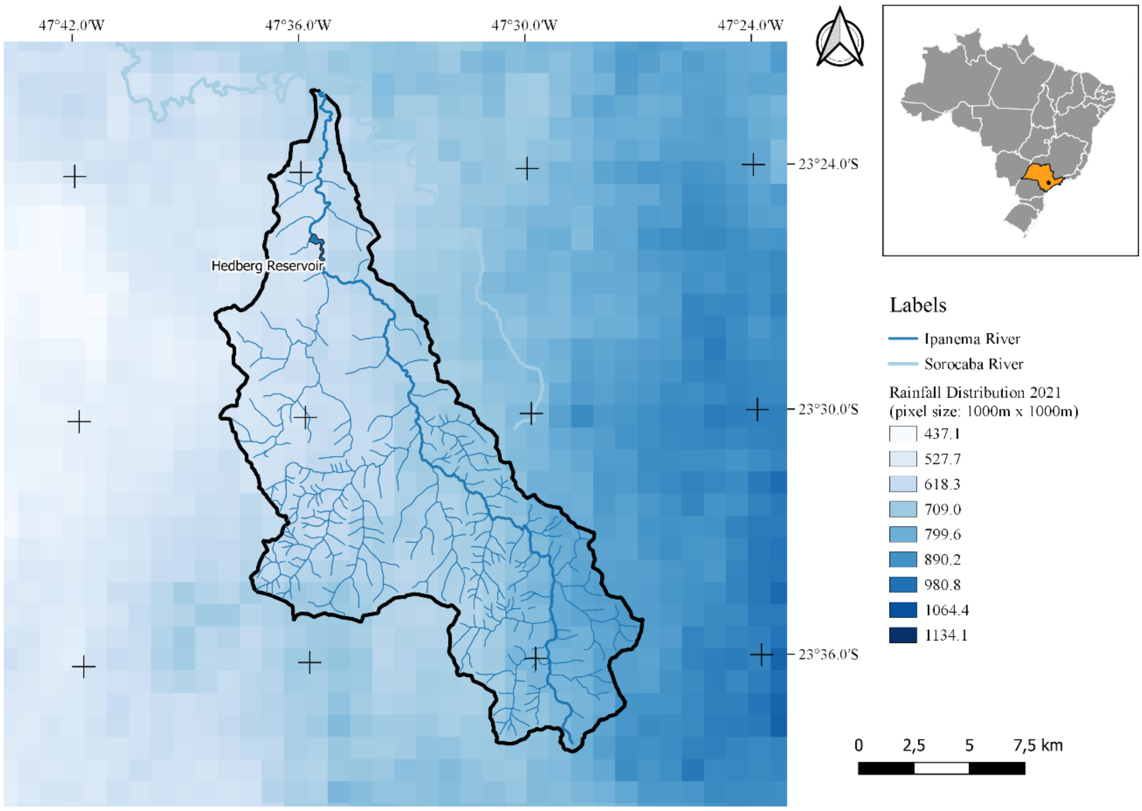
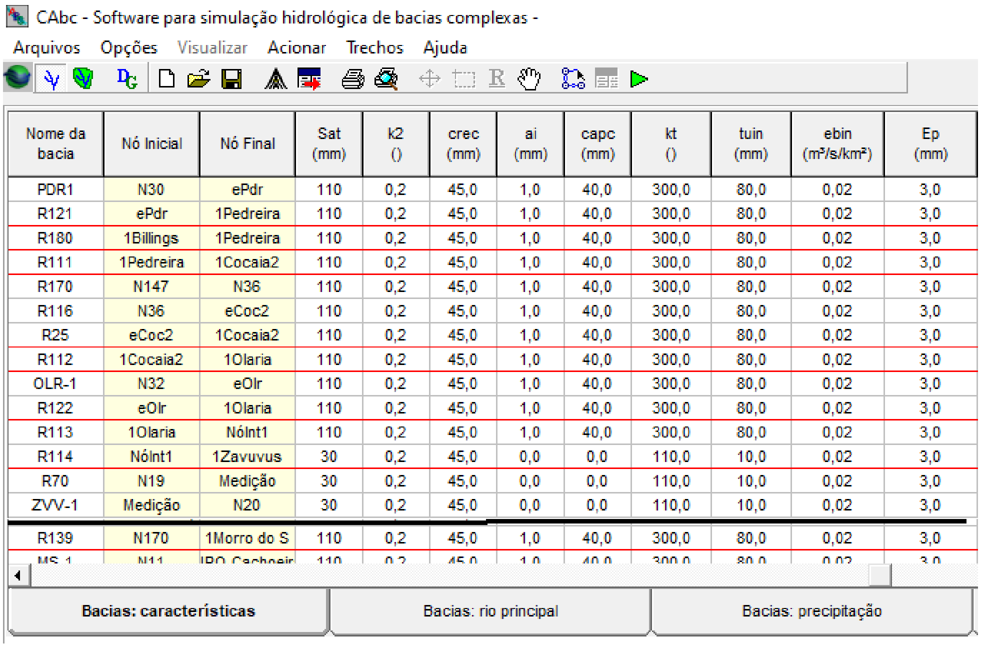



Figure 70 – Example spatially distributed rain in Ipanema (accumulated in 1 year – 2021)

For nonpoint pollution assessment, as already mentioned, SMAP model can be applied. The parameters (Figure 71) that are used should be obtained for all sub-basins in the project. If the user has no information on observed flow, default parameters can be used as shown in Figure 66 - General Definitions. Additionally, if the watercourses have a specific point release (not related to rainfall and with no quality information), Figure 72 shows the form where imported flow data are inserted.

In this model, as already said, to establish the diffuse contributions in the receiving bodies, EC (or UL) along with EMC and mathematical modeling were used to obtain a whole series of concentrations over a year. Base loads are the compilation from 3 contributions (Non-served Population, EC and point releases) and wash off loads are represented by wet season EC and/or EMC. These loads will produce, when divided by the total flow, concentrations for each constituent.

These coefficient inputs are made as Figure 73 illustrates. It is necessary to fill non-served population for each sub-basin; per-capita contribution rates for each constituent (BOD, TN and TP) coefficients based on the sanitation infrastructure; its EMC coefficients (BOD, TN, TP and TSS); the initial mass available on the surface (in %); and the K coefficient.




| Nome da bacia | Nó Inicial | Nó Final | Sat (mm) | k2 () | crec (mm) | ai (mm) | capc (mm) | kt () | tuin (mm) | ebin (m³/s/km²) | Ep (mm) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| PDR1 | N30 | ePdr | 110 | 0,2 | 45,0 | 1,0 | 40,0 | 300,0 | 80,0 | 0,02 | 3,0 |
| R121 | ePdr | 1Pedreira | 110 | 0,2 | 45,0 | 1,0 | 40,0 | 300,0 | 80,0 | 0,02 | 3,0 |
| R180 | 1Billings | 1Pedreira | 110 | 0,2 | 45,0 | 1,0 | 40,0 | 300,0 | 80,0 | 0,02 | 3,0 |
| R111 | 1Pedreira | 1Cocaia2 | 110 | 0,2 | 45,0 | 1,0 | 40,0 | 300,0 | 80,0 | 0,02 | 3,0 |
| R170 | N147 | N36 | 110 | 0,2 | 45,0 | 1,0 | 40,0 | 300,0 | 80,0 | 0,02 | 3,0 |
| R116 | N36 | eCoc2 | 110 | 0,2 | 45,0 | 1,0 | 40,0 | 300,0 | 80,0 | 0,02 | 3,0 |
| R25 | eCoc2 | 1Cocaia2 | 110 | 0,2 | 45,0 | 1,0 | 40,0 | 300,0 | 80,0 | 0,02 | 3,0 |
| R112 | 1Cocaia2 | 1Olaria | 110 | 0,2 | 45,0 | 1,0 | 40,0 | 300,0 | 80,0 | 0,02 | 3,0 |
| OLR-1 | N32 | eOlr | 110 | 0,2 | 45,0 | 1,0 | 40,0 | 300,0 | 80,0 | 0,02 | 3,0 |
| R122 | eOlr | 1Olaria | 110 | 0,2 | 45,0 | 1,0 | 40,0 | 300,0 | 80,0 | 0,02 | 3,0 |
| R113 | 1Olaria | NóInt1 | 110 | 0,2 | 45,0 | 1,0 | 40,0 | 300,0 | 80,0 | 0,02 | 3,0 |
| R114 | NóInt1 | 1Zavuvus | 30 | 0,2 | 45,0 | 0,0 | 0,0 | 110,0 | 10,0 | 0,02 | 3,0 |
| R70 | N19 | Medição | 30 | 0,2 | 45,0 | 0,0 | 0,0 | 110,0 | 10,0 | 0,02 | 3,0 |
| ZVV-1 | Medição | N20 | 30 | 0,2 | 45,0 | 0,0 | 0,0 | 110,0 | 10,0 | 0,02 | 3,0 |
| R139 | N170 | 1Morro do S | 110 | 0,2 | 45,0 | 1,0 | 40,0 | 300,0 | 80,0 | 0,02 | 3,0 |

Figure 71 – SMAP Model Parameters

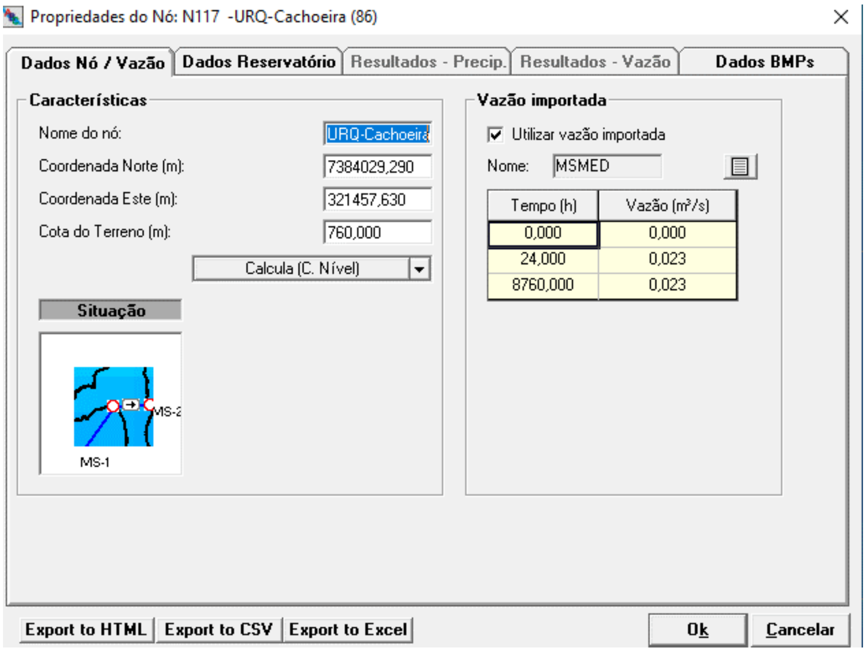



Figure 72 – Imported Flow on Cabc

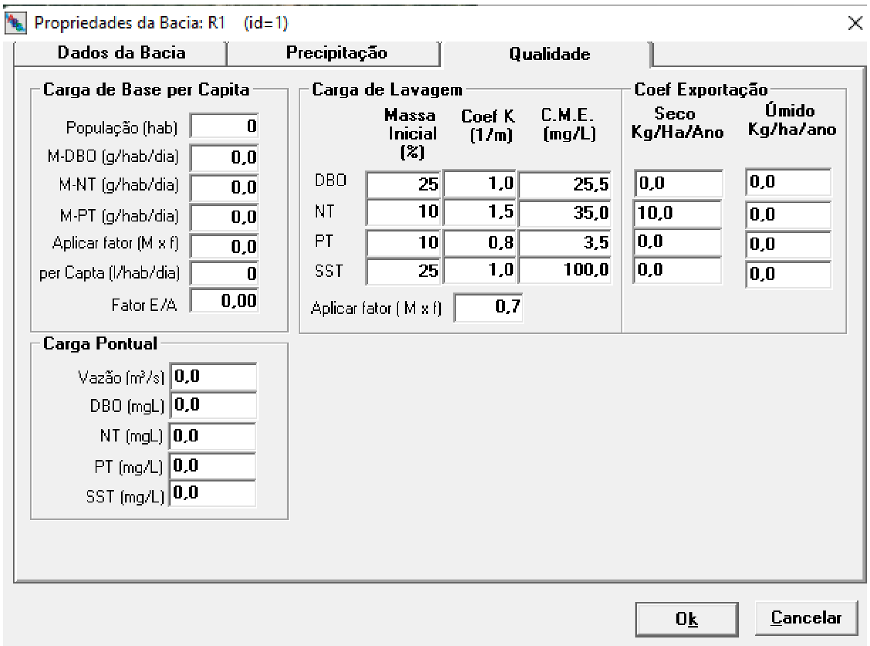



Figure 73 – Water Quality Basin Properties – Base (endemic) Load and Wash Off Load.

As means to implement BMPs, an ***“in situ* treatment facility”** was developed, which can be interpreted as a Non-Conventional Solution (NCS) or Alternative Treatment Methods (ATM), and is illustrated on Figure 74, that treats all surface flow and returns to the water course based on the treatment capacity, efficiency, and goals for each constituent and its calculation is based on simple mixing equation.

It is important to state that this BMP is not equal to conventional WWTP, but to offer an economic and efficient alternative to reduce a portion of the polluting load (endemic and washed). This way, these facilities can be considered as a type of Best Management Practices (BMPs). However, the *in situ* facilities propose to treat more than just diffuse (nonpoint) pollution, but all the load that flows superficially in urban streams. Figure 75 details how they are modelled inside Cabc-Qual.

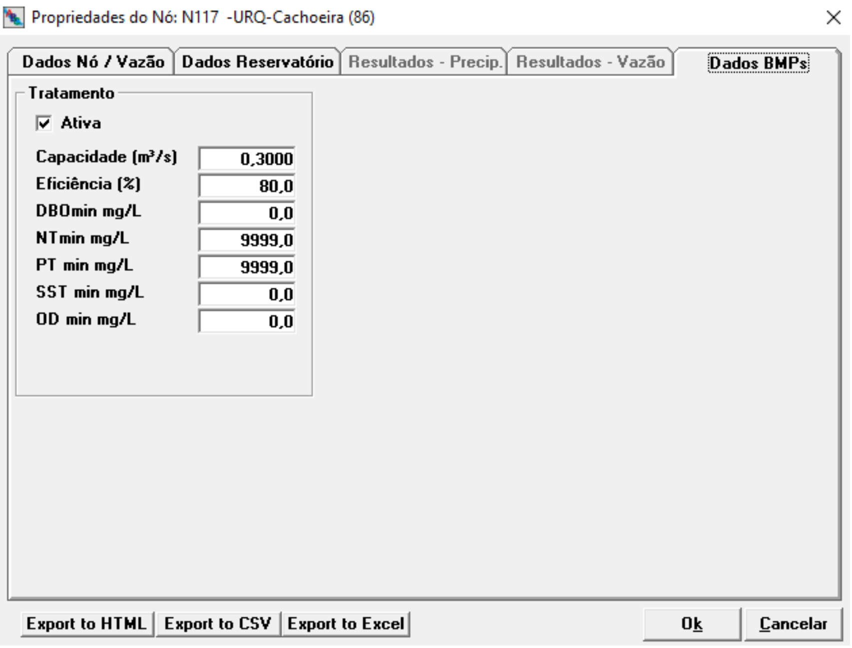



Figure 74- BMP in Cabc-Qual

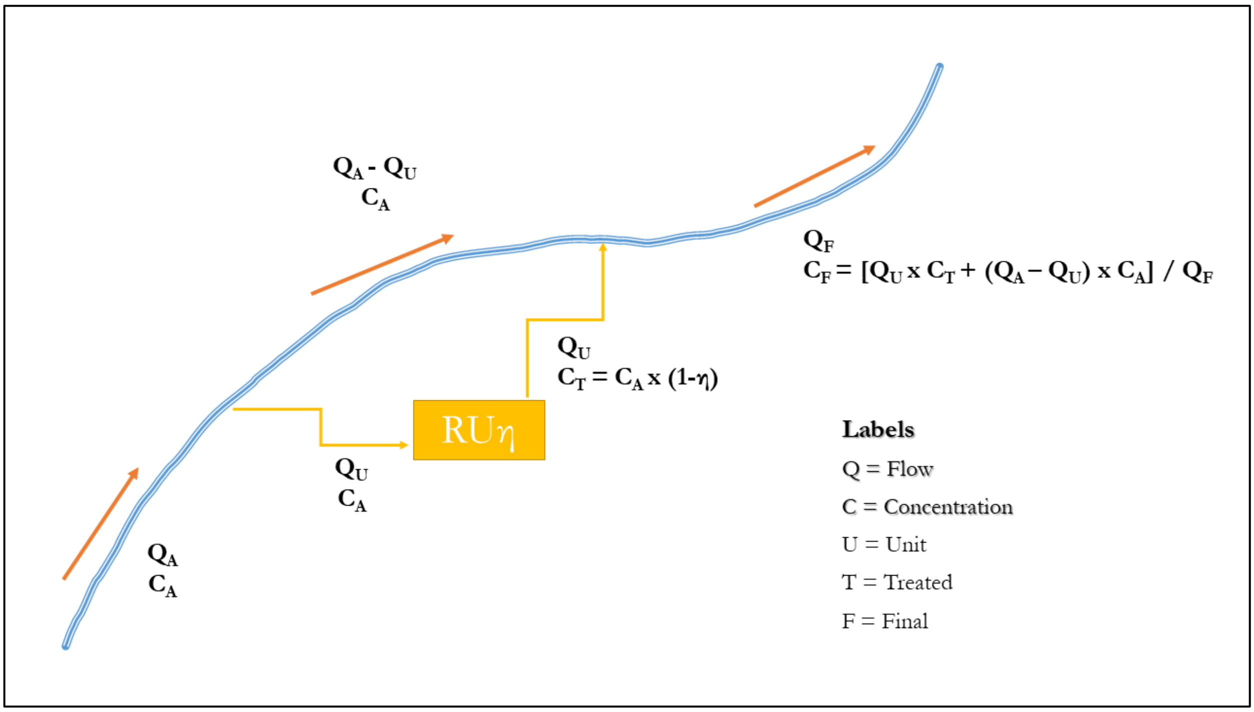



Figure 75 – In situ treatment operation schematic model

# CHAPTER 6

## MODEL TEST: CASE STUDIES

*"Water is the vehicle of nature"*

Leonardo da Vinci

In this chapter, two case studies are presented. One is a predominantly urban basin and the other is a mixed watershed. They were used during the model development and aided in this process. Its set-up, calibration and validation will be presented in the following sections.

### *6.1 IPANEMA WATERSHED (MIXED BASIN)*

As presented in the section 4.2 MONITORING IN IPANEMA WATERSHED, both the Ipanema watershed as the reservoir historical relevance reflects the current concern with the growing urbanization of the surroundings. Even though the reservoir is in a legal conservation area, the headland and the surroundings of the basin have been suffering from constant waterproofing and anthropic pollution (Figure 76). The changes observed prove that monitored data obtained from 1995 to 2015 are not suitable for current analysis. That way, significant changes in concentrations should be expected in results.

The total contribution area at the section of Hedberg Dam is 216 km² and its land use and occupation, as it is possible to observe in Figure 77, currently, consists of Agriculture or Pasture (68%), forest (22%) and urban infrastructure (10%). For the purposes of simplification, the different types of land use and occupation were organized to fit only those three previously mentioned groups.

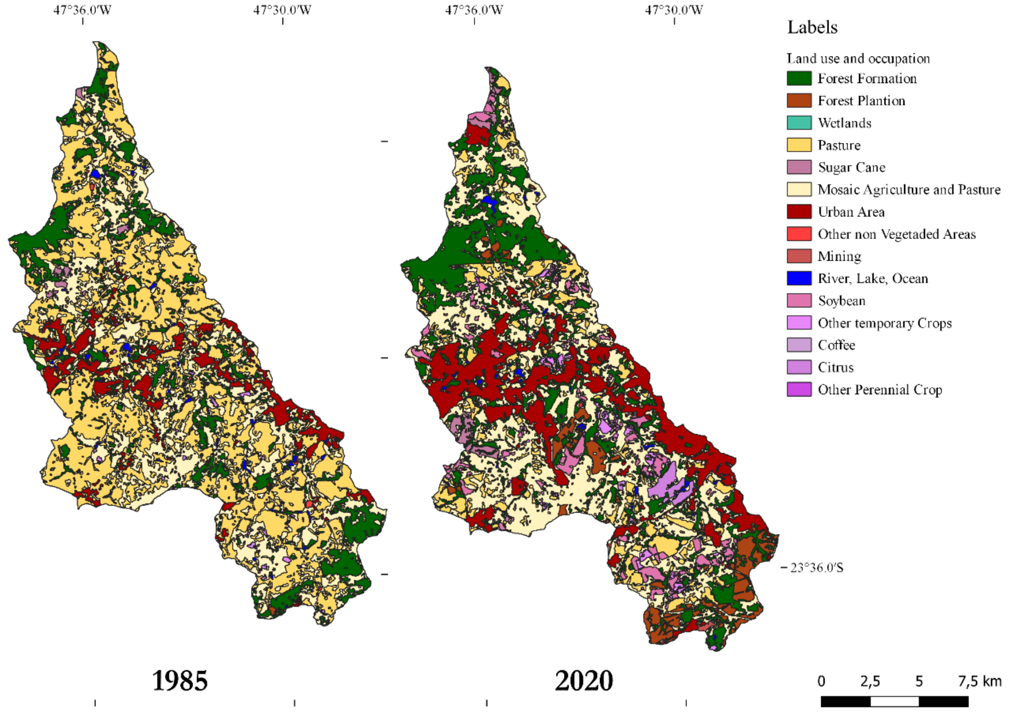



Figure 76 – Urbanization of the surroundings

Source: Author (2022) Adapted from MapBiomas (2020)

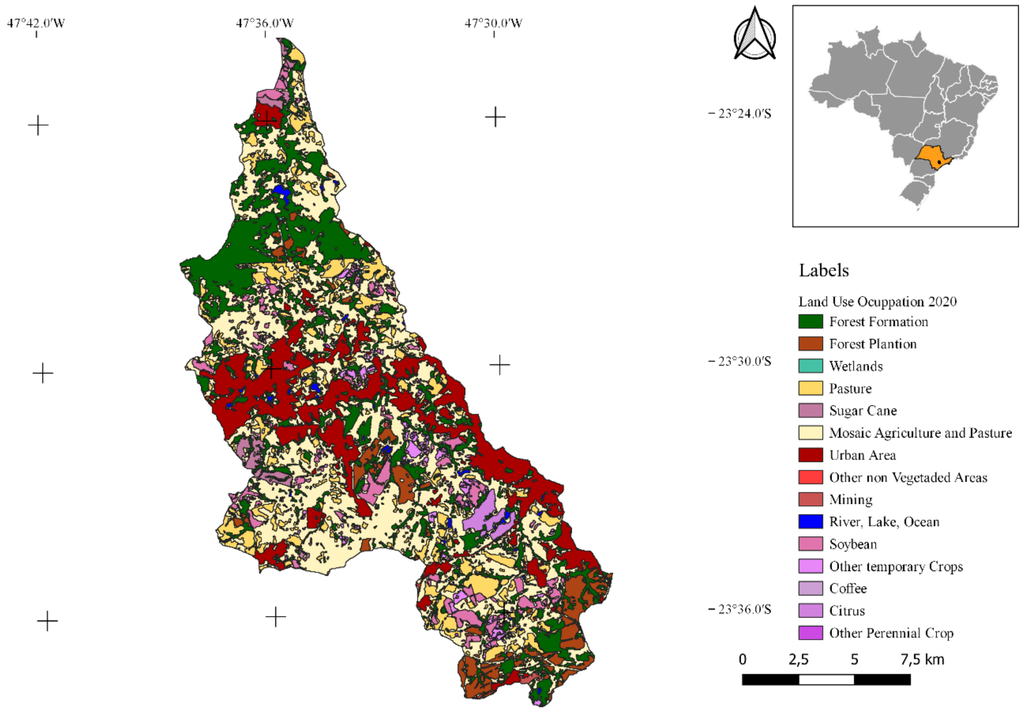



Figure 77 – Ipanema Basin Land Use and Occupation

Source: Author (2022) Adapted from MapBiomas (2020)

### *6.1.1 Methods*

First, data from Ipanema was imported (contour lines, hydrography, and borders) and 13 sub-basins were drawn to better represent the watershed. The criteria used to build the spatial discretization in sub catchments are land use homogeneity, natural drainage network and the location of the WWTP and/or industrial disposals (Figure 78). Despite the known land uses and occupations in the watershed and spatial load sources distribution, the calibration and validation steps of the model were only possible at the point shown in the red circle, where the monitoring was carried out.

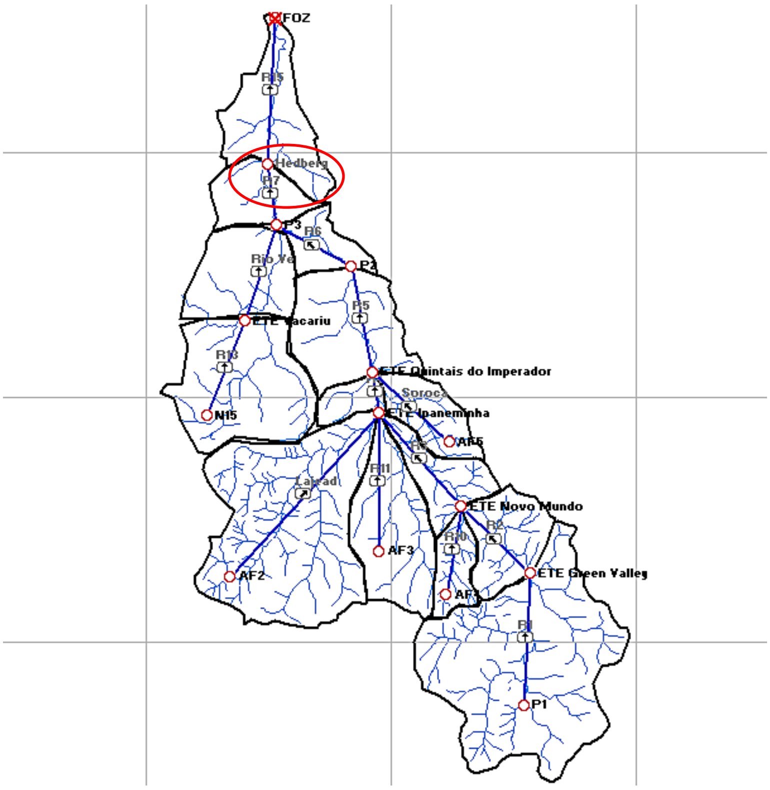



Figure 78 – Ipanema watershed in Cabc-QUAL

### *6.1.2 Model Calibration and Validation*

For calibration, data from 2016 and 2017 were used. Figure 79 shows the rain in CAbc applied to Ipanema watershed and Figure 79 shows flow station location inside the watershed. It is fundamental to emphasize that rain data was accumulated daily, but there was no field surface network to merge data, so rainfalls (this case) are radar estimates only. Finally, flow measurements were made in 10-minute time steps, that later were treated in daily average for calibration and validation.

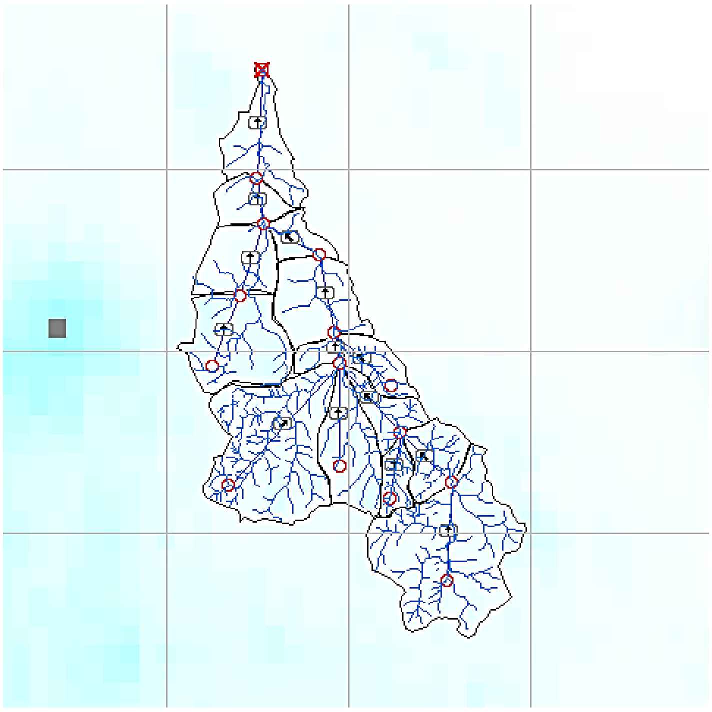


Figure 79 – Ipanema watershed and applied radar observed precipitation illustration (daily accumulated, 2016)

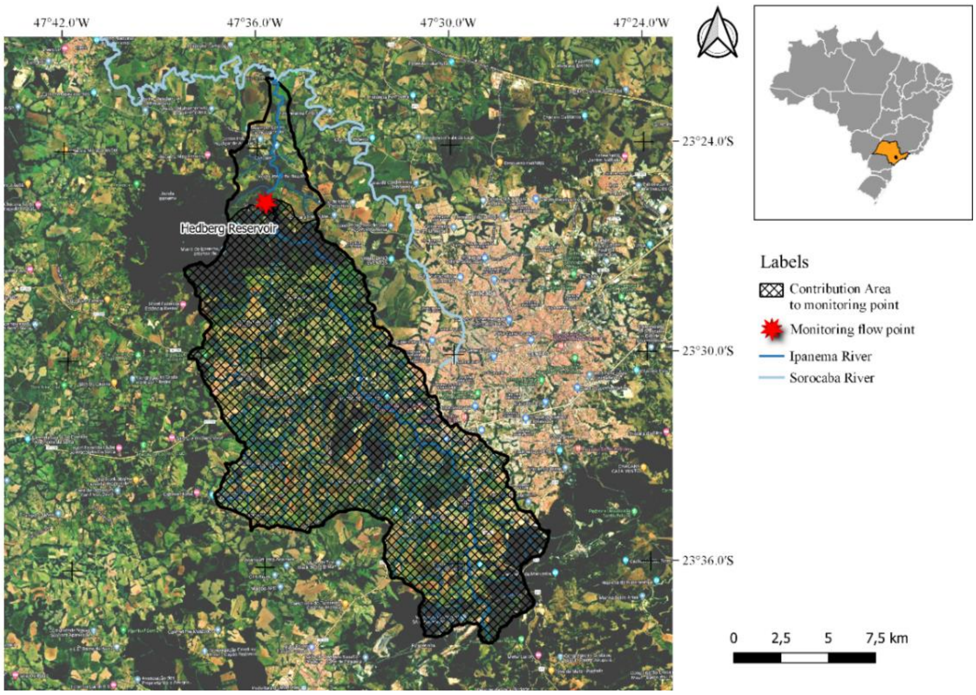



Figure 80 – Flow Monitoring point inside Ipanema Watershed (10-minute time step)

Also, each pixel observed in the radar data is 1000m x 1000m in size and, as explained before, each grid is the total precipitation observed by the radar and rain gauge network (merged data) in a specific day in the time series input.

The calibration in SMAP model produced the simulated flow shown in Figure 81. It is possible to observe that calibration presented a very good result in terms of flow when compared to 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. Table 11 shows the calibrated parameters for this study on SMAP Model.

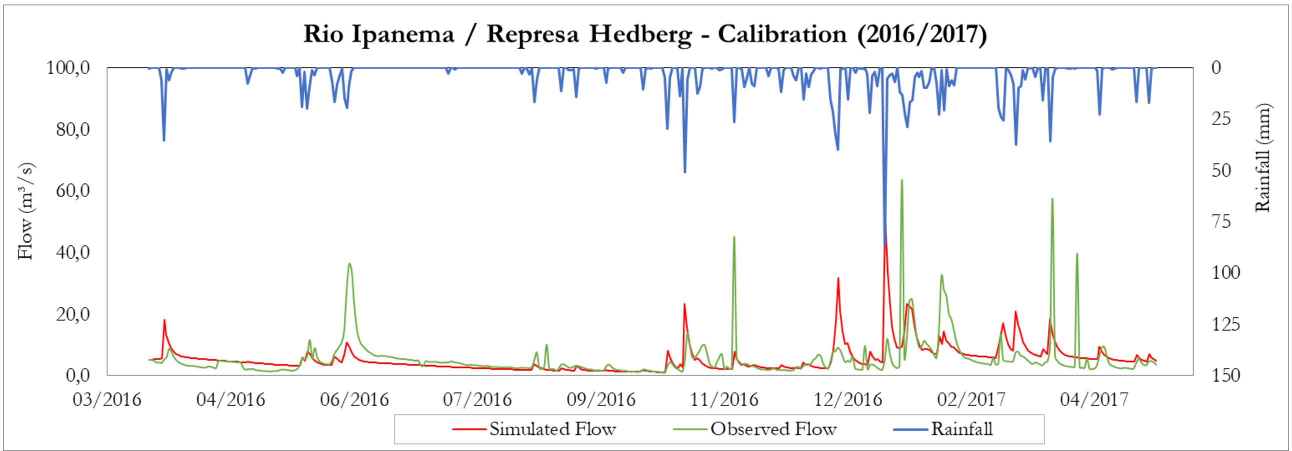



Figure 81 - Calibration of the Ipanema River/Hedberg Reservoir in 2016/2017.

Table 11 - Calibrated Parameters in SMAP model

| ***Parameters*** | |
|---|---|
| sat | 90 |
| k2t | 1,5 |
| crec | 20 |
| ai | 2 |
| capc | 18 |
| Kkt | 50 |

For validation, data from 2017 and 2018 were analyzed using the same calibrated parameters. First, this result showed poor adequate results, showing that adjusts needed to be done. So, parameters were altered one more time to fit observed results. That said, Figure 82 and Table 12 shows these results.

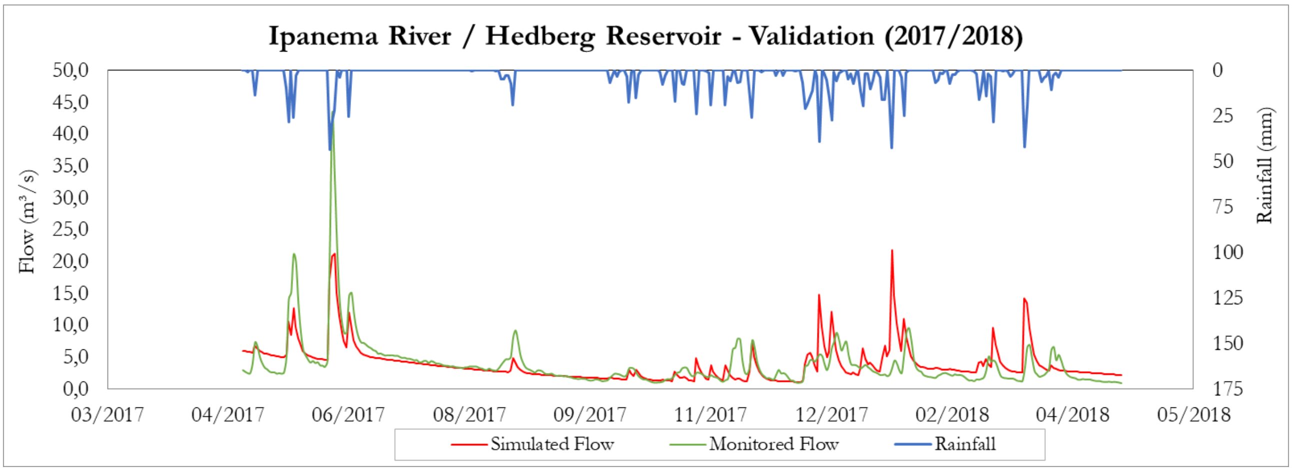



Figure 82 - Validation of the Ipanema River/Hedberg Reservoir in 2017/2018

Table 12 - Validated Parameters in SMAP model

| ***Parameters*** | |
|---|---|
| sat | 150 |
| k2t | 1,5 |
| crec | 11 |
| ai | 2 |
| capc | 40 |
| Kkt | 60 |

Despite the parameters obtained in calibration not being suitable for the validation, this new round and new parameters (new calibration) were used for other years (2021) and can be used for further time series. Sometimes, some (or all of the) calibration parameters must be adjusted for hydrological models, especially when soil humidity and base flows fail in its representation; also when **land use and occupation modifies**.

When analyzing the model performance, many index and coefficients were studied to understand if the calibration was satisfactory. Many papers have studied relations between hydrological models and its error performance and commonly some are constantly being used: Nash and Sutcliffe Efficiency (NSE); Root Mean Square Error (RMSE); and Standardized RMSE (RSR) (REUSSER; BLUME; SCHAEFLI; ZEHE, 2009; RITTER; MUÑOZ-CARPENA, 2013; WASEEM; MANI; ANDIEGO; USMAN, 2017). Each index performance varies according to Table 13.

Table 13 – Performance rating of selected efficiency criteria

| Performance Rating | RSR | NSE | RMSE |
|---|---|---|---|
| Very good | 0 < RSR < 0,5 | 0,75 < NSE < 1 | RMSE = 0 |
| Good | 0,5 < RSR < 0,6 | 0,65 < NSE < 0,75 | - |
| Satisfactory | 0,6 < RSR < 0,7 | 0,5 < NSE < 0,65 | - |
| Unsatisfactory | RSR > 0,7 | NSE < 0,5 | - |

Source: Adapted from (N. MORIASI; G. ARNOLD; W. VAN LIEW; L. BINGNER *et al.*, 2007)

NSE and RMSE are used worldwide, but they usually penalize outliers, which would compromise base/average results. RSR, otherwise, normalizes the RMSE with the standard deviation of the observed values. These indexes for the model validation are presented in Table 14. From that it is possible to see that, despite RMSE value being far from the very performance rate, it can be considered satisfactory for RSR and NSE, when compared to the values on Table 13.

Table 14 – Index errors obtained in the hydrological model

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

That said, relying on Average Errors was intentional for the purpose of long-term Average Flows in this study, acknowledging that adjusting peak values was not intended. On the other hand, the model was calibrated to reduce the differences between total volume inflow and outflow to a minimum. Table 15 shows the Average Errors obtained in the hydrological model. From that, it is possible to observe that the average error for the entire series is approximately zero. As for the standard deviation, the error is close to 26%, which can seem high, but as stated before, simulated peaks are not always adhered to observed peaks for the reasons mentioned before.

Table 15 - Average Errors Obtained in the Model

| | Simulated Flow (m³/s) | Observed Flow (m³/s) | Average Error (%) |
|---|---|---|---|
| **Average** | 3,935 | 3,930 | 0,13% |
| **Standard Deviation** | 2,966 | 3,995 | -26% |

*6.1.3 2021 Results*

Using parameters defined on Table 12, simulated and monitored flow were compared to each other, to verify if the model was able to correctly predict concentrations. As Figure 83 shows, the model was able to correctly predict flow discharges from Hedberg Reservoir. The period from mid-September to mid-October is highlighted, a period where a large amount of vegetation was identified at the spillway outlet, as said before, jeopardizing correct measurements.

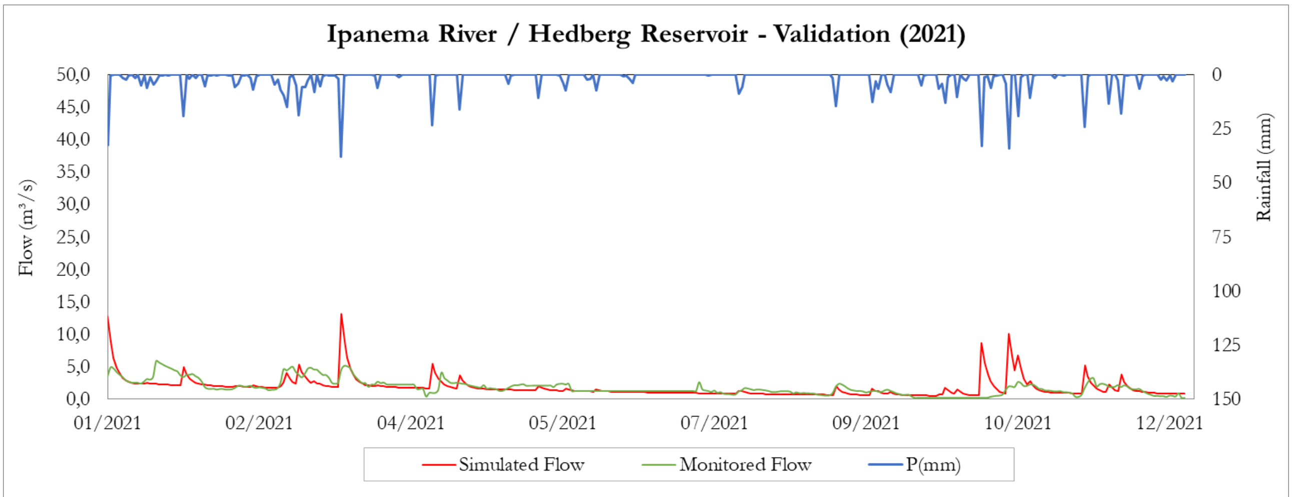


Figure 83 - Validation for 2021 data

Also, it is important to emphasize that, from a 6-years series, the rainfall observed in 2021 presented the lowest annual accumulated rainfall, almost 45% lower than the year with the highest accumulated rainfall (Figure 84 - year 2017). That agrees with the low flow observed in the spillway outlet, which in 2021 had an average of 1,85 m³/s, almost 2 m³/s lower than the validation period (2017-2018).

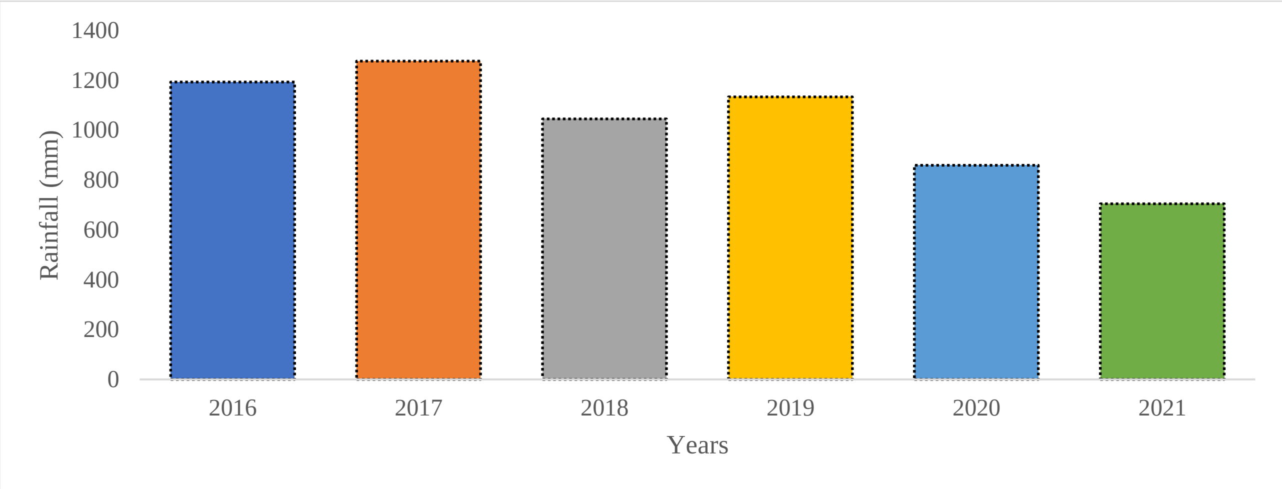



Figure 84 - Average rainfall in the watershed (Ipanema) from 2016 to 2021

Figure 85, Figure 84, Figure 85 and Figure 87 show, respectively, a curve behavior for BOD, Total Phosphorus (TP), Total Nitrogen (TN) and Total Suspended Solids (TSS) 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 expected/monitored. There are two assumptions here that can be made: ($1^{st}$) the actual average phosphorus concentrations are lower than the ones used for statistics; ($2^{nd}$) 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.

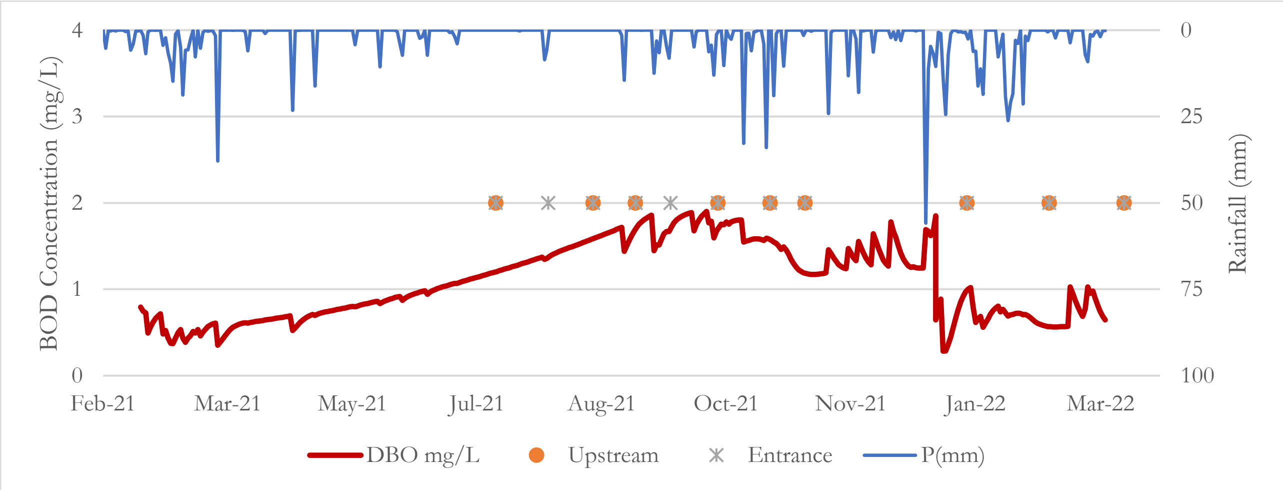



Figure 85 - BOD Concentrations [mg/L] for Hedberg Reservoir – simulated (red line) and observed (dots)

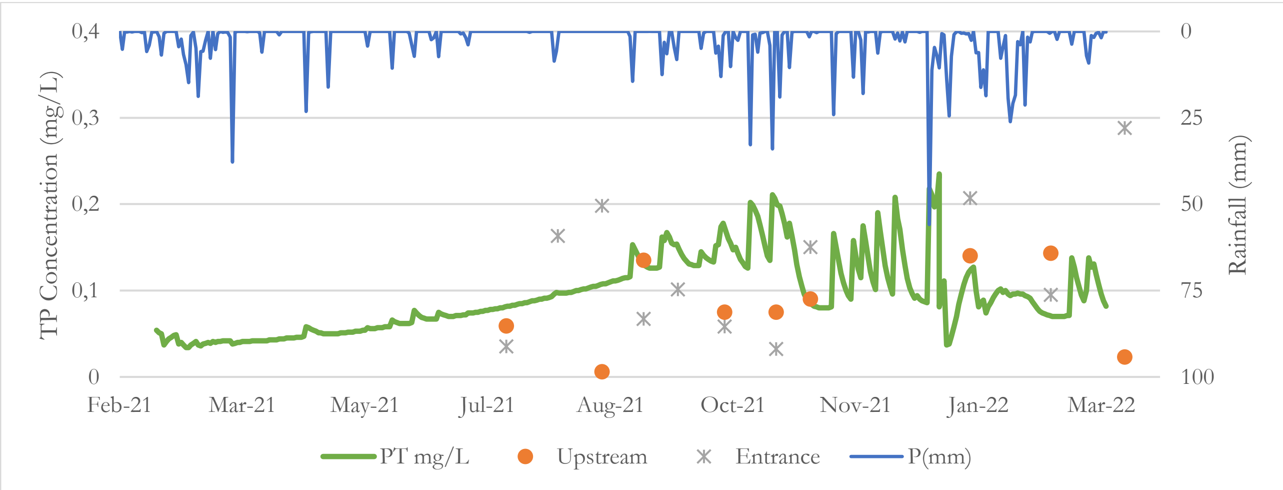



Figure 86 - TP Concentrations [mg/L] for Hedberg Reservoir – simulated (green line) and observed (dots)

On the other hand, Total Nitrogen simulation reproduced adequate concentrations for almost the entire time series (even considering the high concentrations released by WWTP). However, EMC releases were higher than the values expected in the literature.

Finally, Total Suspended solids were simulated considering only unit loads (dry and wet season). Because of the great variability of these concentrations in monitored data, regardless of rain events it was not possible to affirm that concentrations of TSS are directly related as nonpoint pollution and erodibility of the watershed, which is expected. More data should be gathered to make clearer inferences.

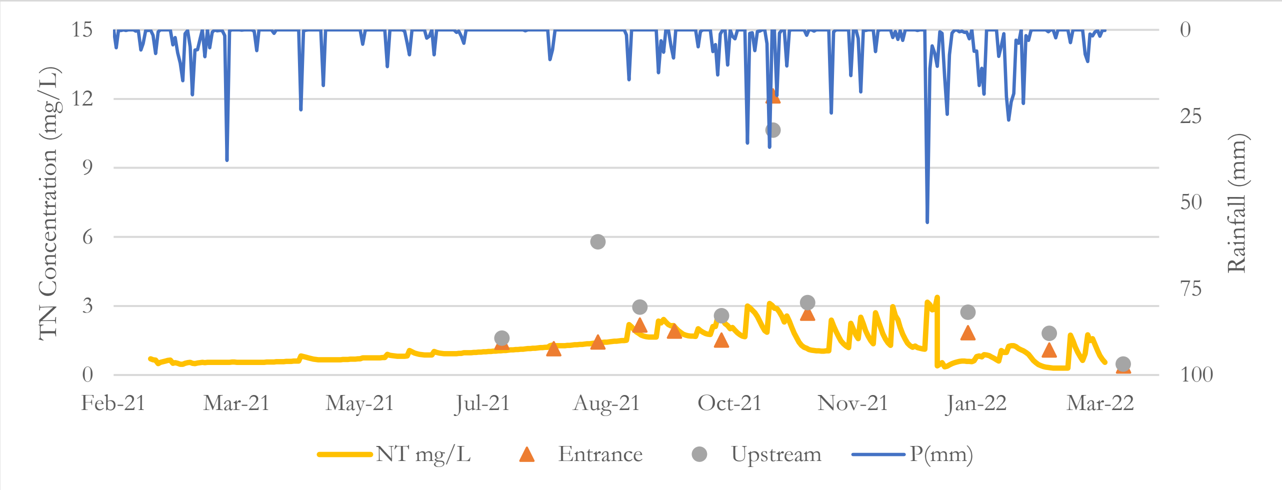



Figure 87 - TN Concentrations [mg/L] for Hedberg Reservoir – simulated (yellow line) and observed (dots)

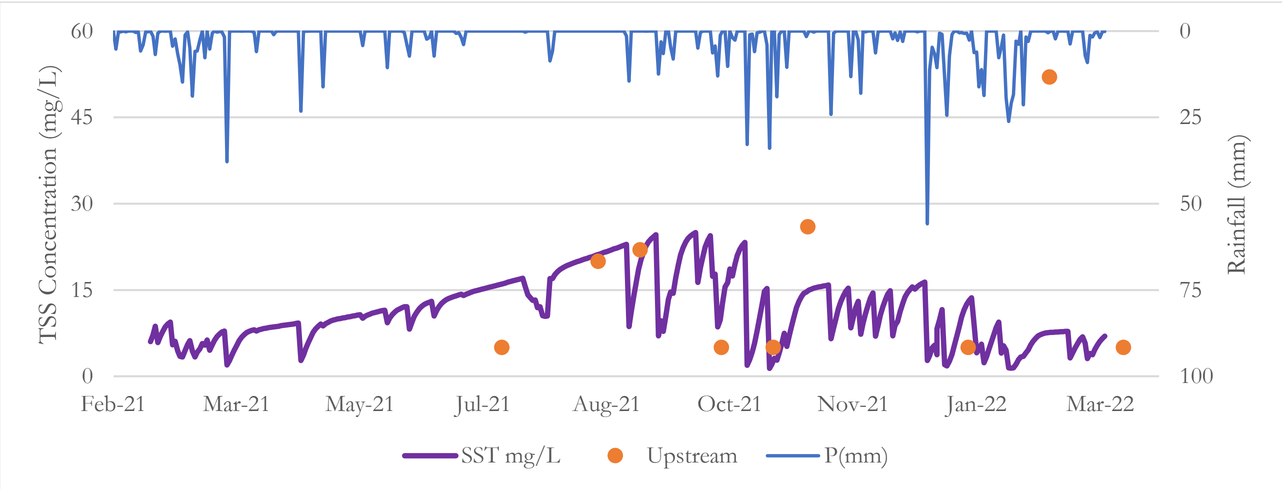



Figure 88 - TSS Concentrations [mg/L] for Hedberg Reservoir - simulated (purple line) and observed (orange dots)

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.

One can wonder if self-purification was considered for the model, since fate/transport processes are observed in surface waters. An analysis was conducted to verify this possibility. To simplify, the QUAL-UFMG was used, a mathematical model that allows the river-modeling through Excel spreadsheet. It is based on the QUAL-2E model, developed by USEPA. The model allows a quick and simple simulation, even for users without knowledge of QUAL-2E and/or more complex models (TEODORO; IDE; RIBEIRO; BROCH *et al.*, 2013).

So, a simple BOD/DO model was performed. First, as seen in Figure 89, flow was compared between the two models. It can be seen in both, that flow is almost the same. Later, BOD information input was inserted into Qual-UFMG and produced concentrations as seen in Figure 90. As seen, only where the tributary reaches the main course BOD for Qual-CAbc is higher, suggesting that for that tributary some fate and transport mechanisms might be present, especially because that tributary has little flow and high concentrations of BOD being loaded into Ipanema. Either way, concentrations differ at a 9% rate difference between them.

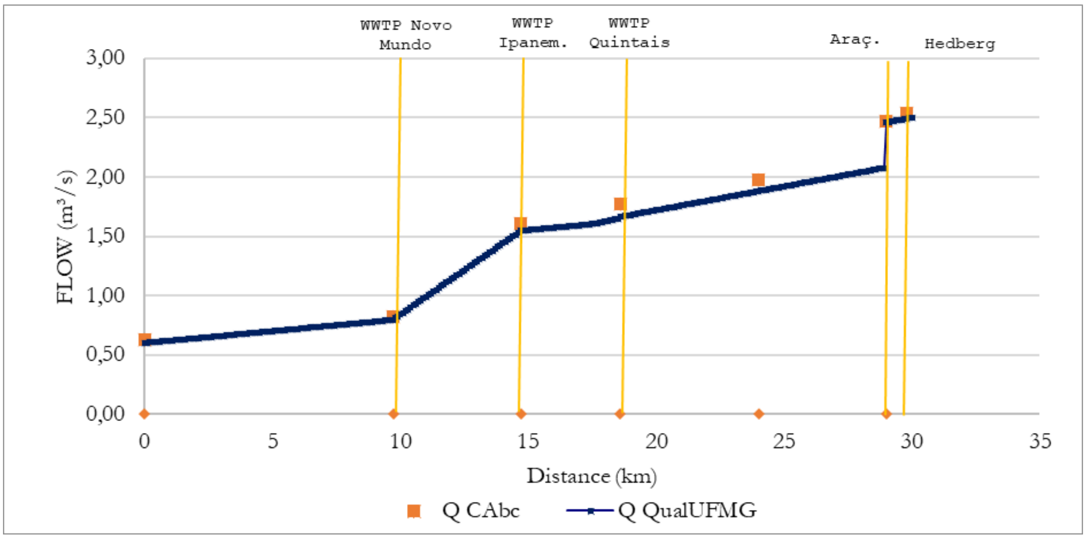



Figure 89 - Flow comparison between Qual-UFMG and Qual-CAbc

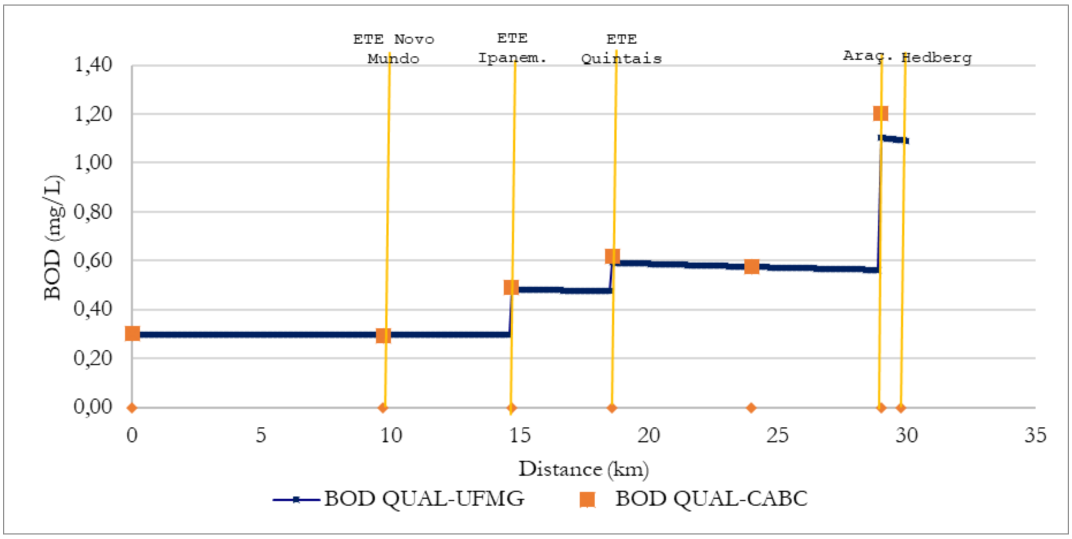



Figure 90 - BOD simulated in Qual-UFMG and Qual-CAbc

All of this suggests that, since Ipanema is clean and its surroundings are being constantly protected over the years, decay rates are low and do not alter water quality significantly. After rounds of calibration, Table 16 shows results for Unit Loads (UL) in Ipanema Watershed, considering total period (no differentiation from wet and dry season), exclusive for base loads (dry weather) and exclusive for rainfall events (wet weather).

As seen, and better detailed on Figure 91, base loads are still accountable for the largest pollution by BOD and TSS in Ipanema Watershed. BOD base loads are easily explained by the WWTP in operation. As for TN and TP, both nonpoint pollution and base loads share almost equal pollution, which is also easily explained by the fact that agriculture areas are filled with pesticides that are rich in nutrients and sewage from WWTP.

Table 16 - Unit Loads Coefficients for Ipanema Watershed (kg/km².day)

| | **BOD** | **TN** | **TP** | **TSS** |
|---|---|---|---|---|
| **Total** | 1,15 | 1,46 | 0,11 | 2,17 |
| **Dry Weather** | 0,70 | 0,76 | 0,06 | 0 |
| **Wet Weather** | 0,45 | 0,71 | 0,05 | 2,17 |

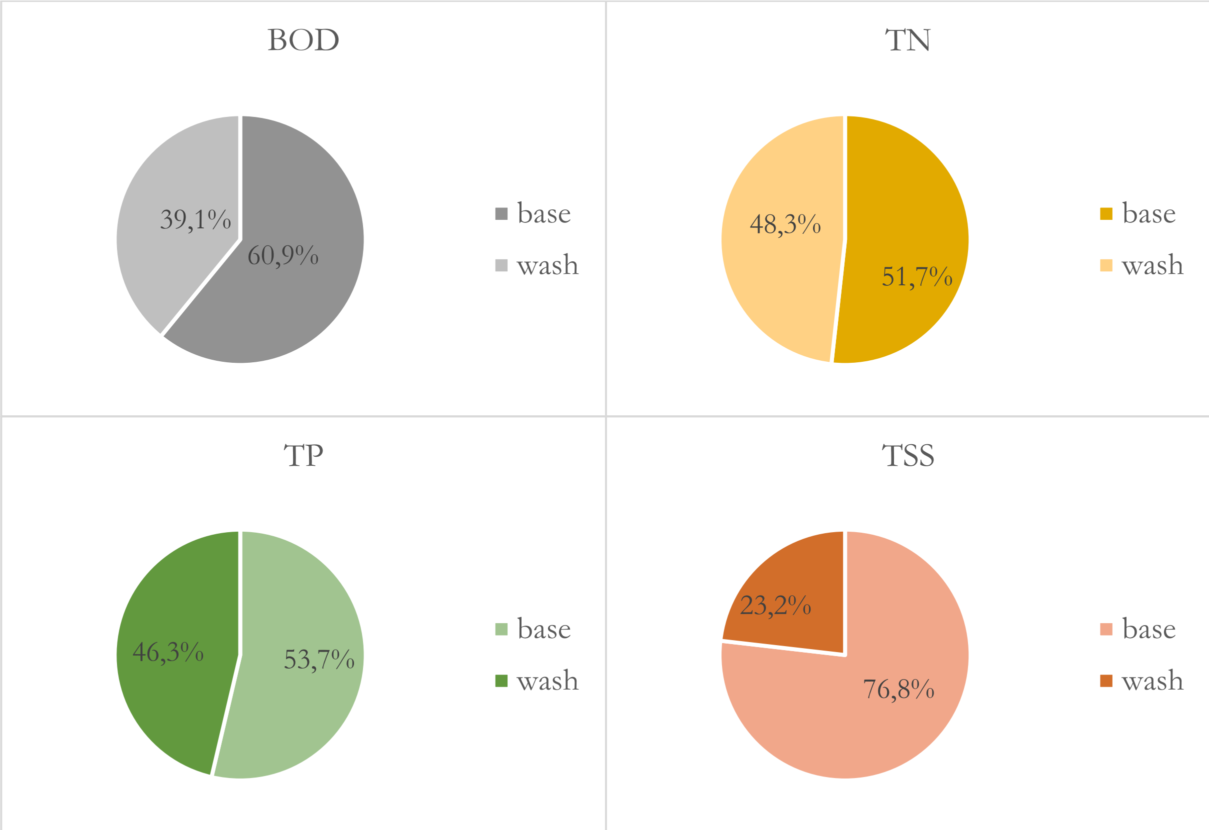



Figure 91 - Comparisons between wash and endemics (base) loads for each constituent for each constituent

Now for EMC values, Table 17 shows results obtained in the model. 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, nitrogen fertilizers are probably being highly used as well.

Table 17 -Event Mean Concentrations for Ipanema Basin (mg/L)

| | EMC (mg/L) |
|---|---|
| DBO | 17,85 |
| TN | 24,5 |
| TP | 2,45 |

The wash off parameters that represent the response of the rainfall events, K and M0 obtained are described in Table 18. Even though studies that inform these parameters results and range are not described in literature, from those it is possible to see and infer that, for Ipanema, wash off process differ from each constituent, in other words, nonpoint pollution in this watershed comes from many possible sources and intensity for each constituent.

Table 18 - Wash off parameters calibrated

| Parameter | BOD | TN | TP |
|---|---|---|---|
| **K** | 1,0 | 1,5 | 1,0 |
| **M0 (%)** | 5 | 10 | 50 |

### *6.1.4 Rainfall Spatial Distribution Observations*

As said previously, rainfall distribution can be a great source of the nonpoint pollution assessment complexity. Additionally, as mentioned, the radar rainfall for Ipanema was obtained without a conditional merging method. That way, an analysis from another telemetry network was performed to assess the implications on each dataset for hydrological modeling. So, 5 rain gauges that contained data from the calibration range period (2016-2017) were selected and an average rainfall was obtained through Thiessen's polygon (Figure 92).

Rainfall data from the radar was compared to average rainfall from Thiessen's method in Figure 93. From that, it is possible to see that accumulated rainfall obtained through the Thiessen's is higher than that from the radar. Also, some peaks obtained through the radar were not observed in Thiessen's and *vice-versa*. Finally, simulated flow obtained from the hydrological model between the two methods are compared in Figure 94 and matched with observed data.

From Figure 94 it is possible to see that both data have a good satisfactory response in average terms. However, both simulations fail to attach some peaks - one time overestimating, another time underestimating the flow. Nevertheless, standard deviations obtained in the Thiessen's method are 20% higher than from the simulation with the radar rainfall data. Either way, as Ipanema is a watershed with a significant area, it is highly recommended that the conditional merging method is performed for increasing the reliability and performance of the model.

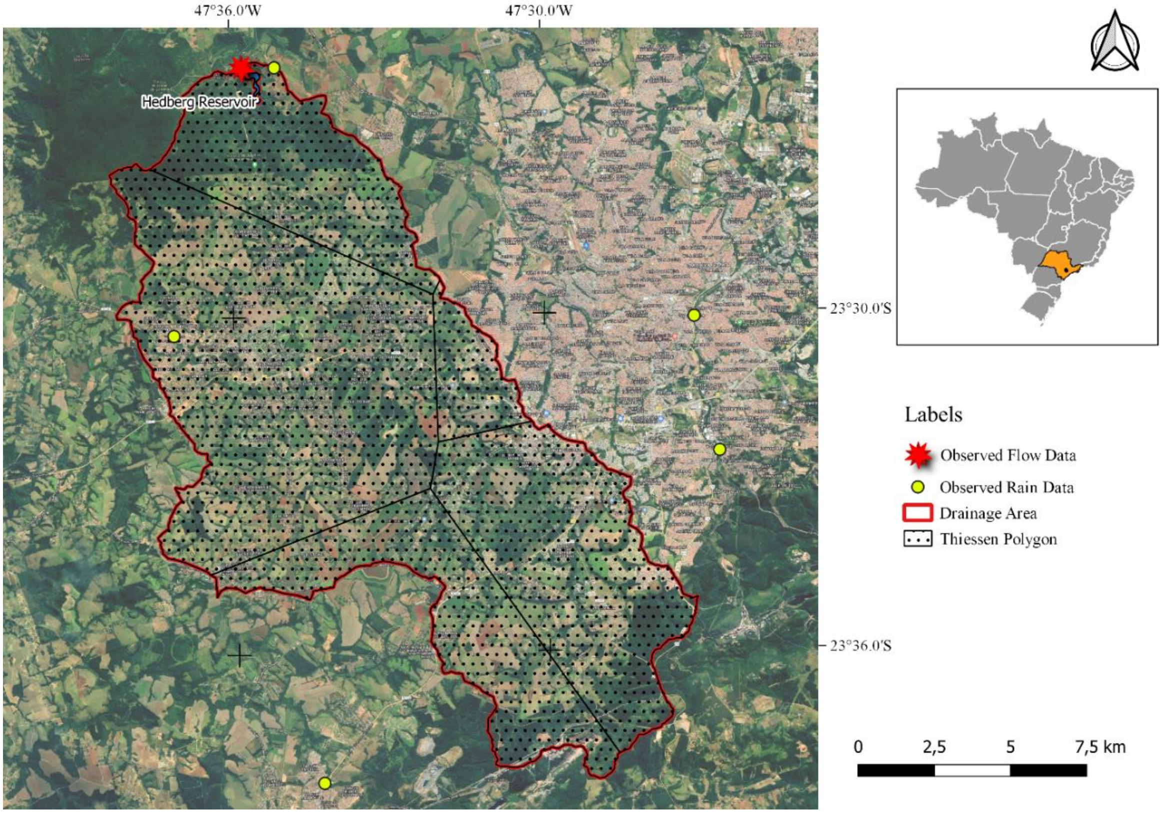



Figure 92 – Thiessen Polygon in Ipanema Watershed

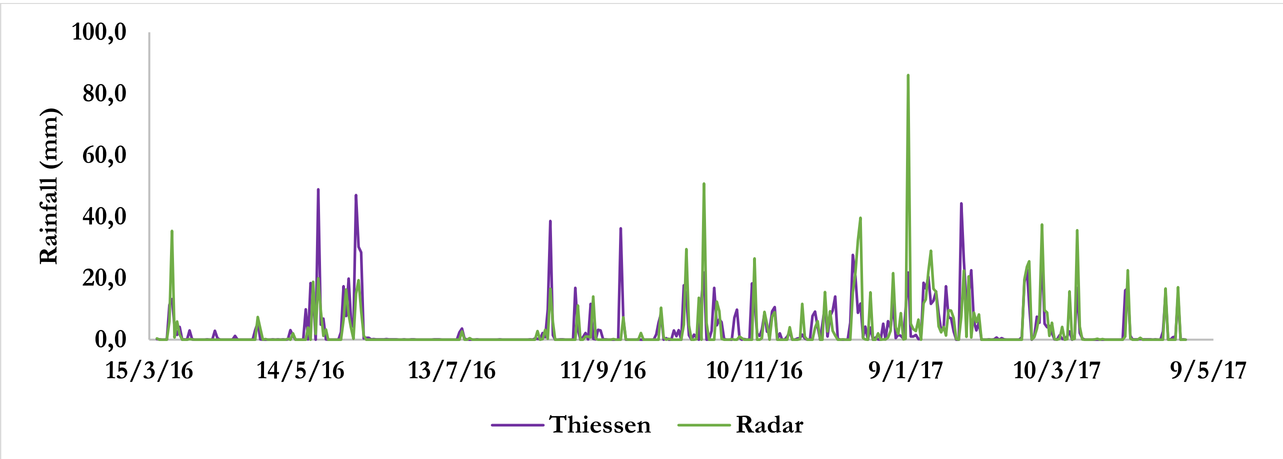



Figure 93 – Comparisons between rainfall from radar (green line) and from Thiessen's method (purple line)

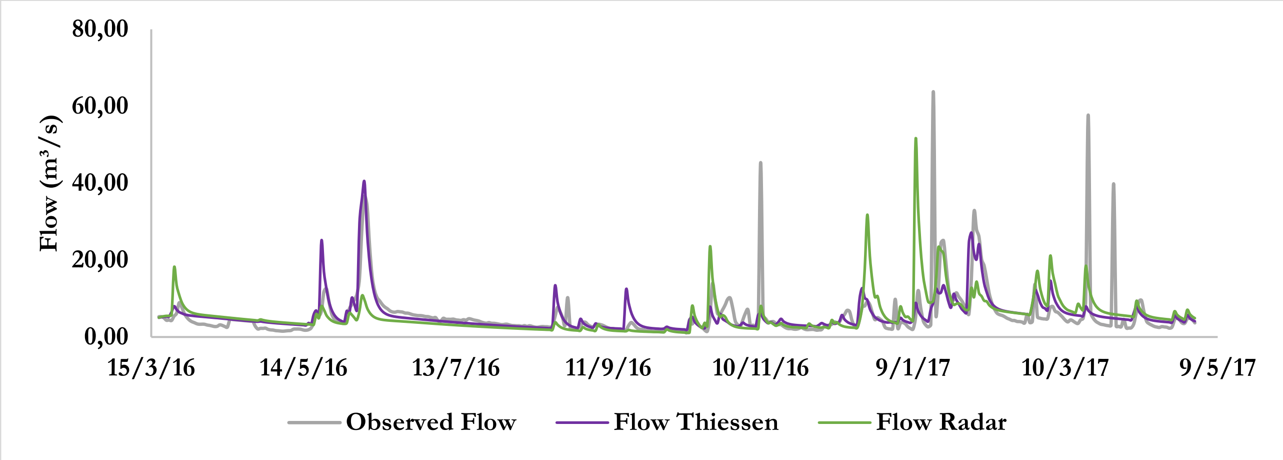



Figure 94 – Comparisons between simulated flow obtained through rainfall from radar (green line) and rainfall from Thiessen's method (purple line)

## *6.2 JAGUARÉ WATERSHED (URBAN BASIN)*

As presented in the section 4.3 MONITORING IN JAGUARÉ WATERSHED, this watershed is an especially and interesting location, as besides being an important tributary to the Pinheiros River, it has different patterns of urban occupation (Figure 94): slums; middle class areas with relatively good infrastructure; industrial areas and high-standard housing areas. The basin also has segments typical of urban expansion zones, the so-called *peripheries*, where occupation inexorably precedes the arrival of infrastructure, ignoring environmental, sanitary and urban legislation (FCTH, 2017).

For the year 2018, Jaguaré River Watershed presented approximately 93% of urban area and the other 7% was split between forest and agriculture. For that reason, this place was modeled as exclusively urban, as the majority of the pollution produced is well established as coming from untreated sewage with poor or nonexistent infrastructure.

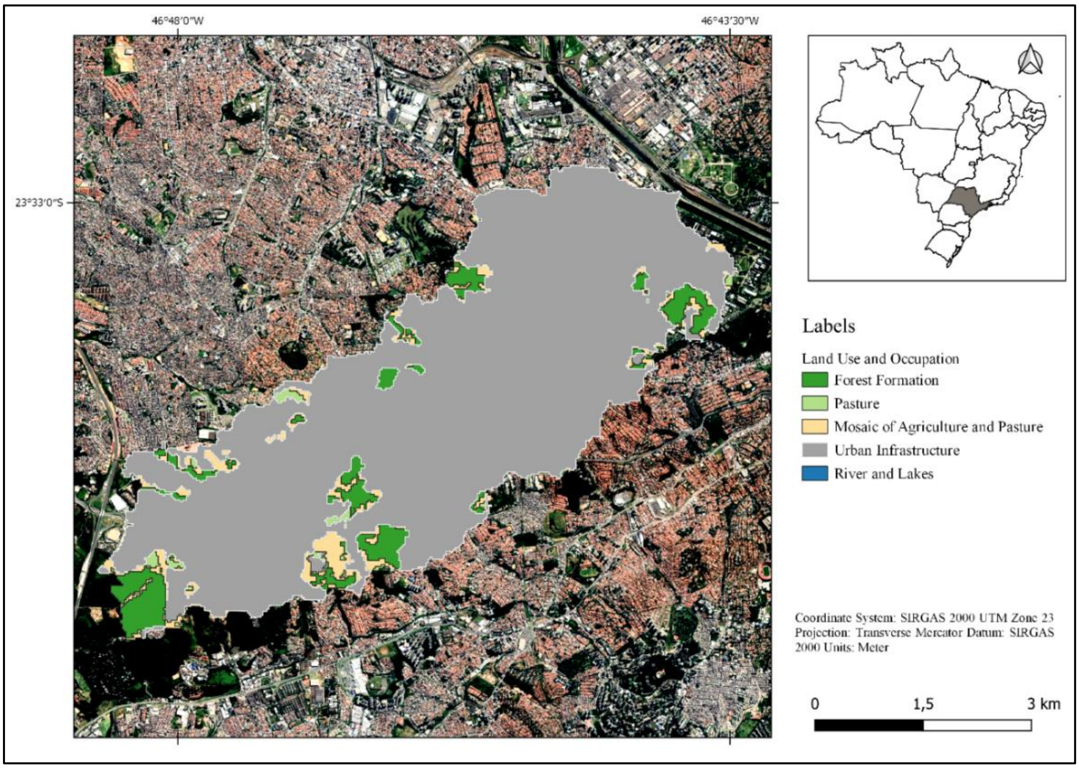



Figure 95 - Jaguaré Watershed Land Use and Occupation

Source: Author (2022) Adapted from MapBiomas (2020)

### *6.2.1 Methods*

In the same way as Ipanema, Jaguaré River Basin (Figure 96), data was imported (contour lines, hydrography, and borders) and 6 sub-basins were drawn to better represent the watershed, locating monitoring and interest points and main tributaries. This time, on the other hand, land use was not a concern, because, as mentioned above, Jaguaré was modeled exclusively as an urban watershed. Rain data was provided by radar, with conditional merging, as shown in Figure 97 with a grid space of 1000m x 1000m.

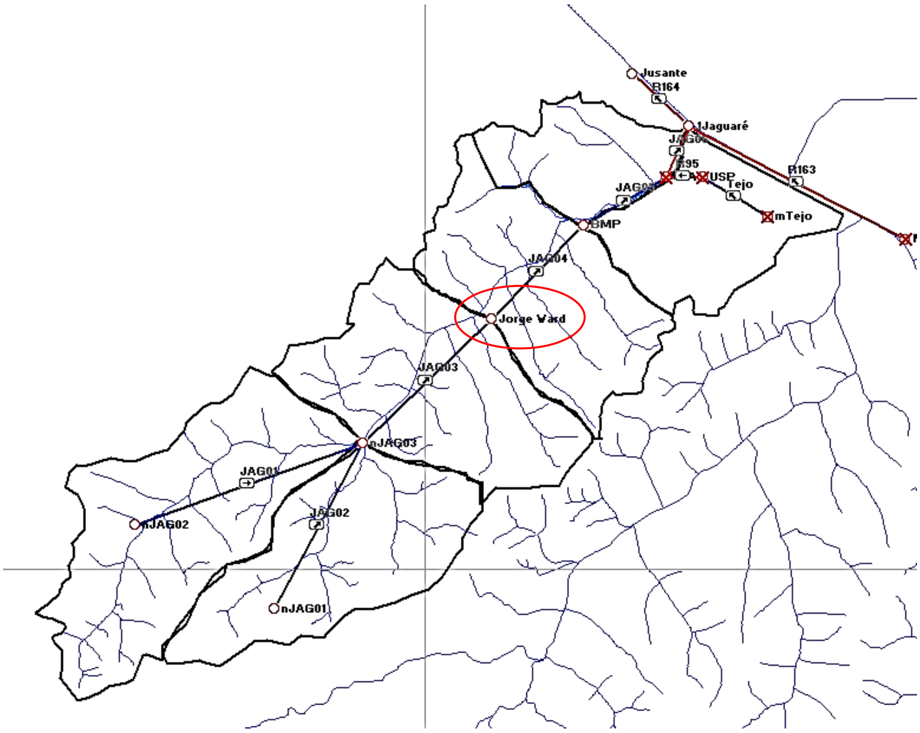



Figure 96 - Jaguaré watershed in CAbc-Qual Model with some of the sub-basins

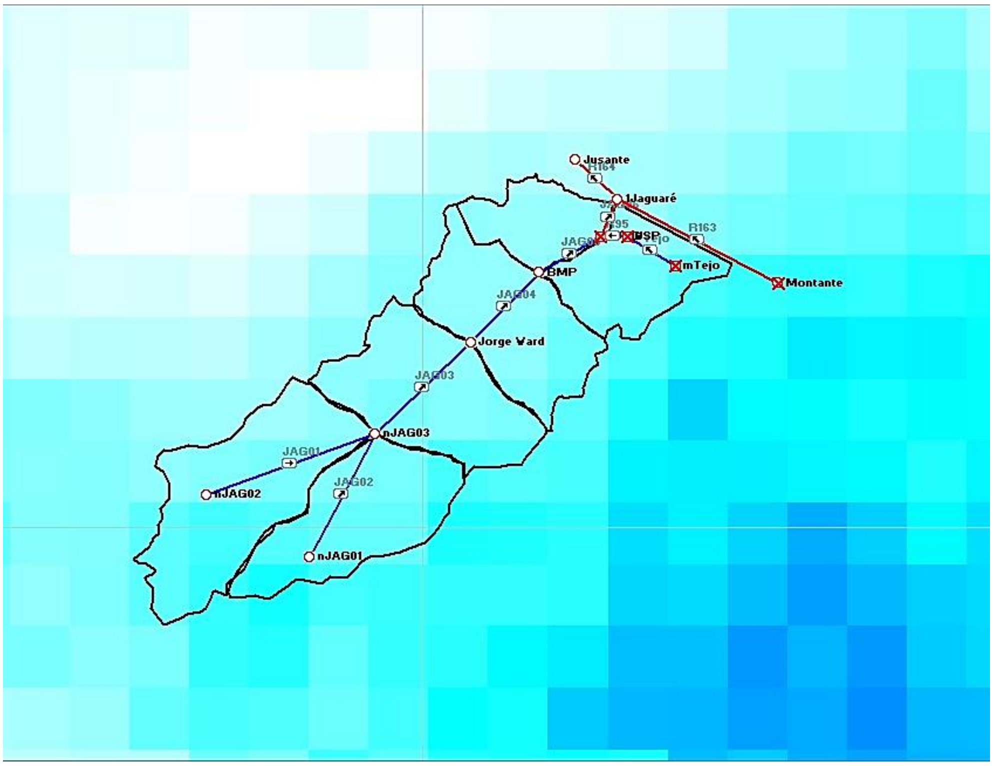



Figure 97 - Jaguaré River Basin in CAbc-Qual Model with some of the sub-basins rainfall series (2017)

As said before, only the point known as “Jorge Ward” (red circle in Figure 96) had long series of monitored flow and it was used for calibration and validation (Figure 58). Populations included in the model as non-served population and sewage flows from those that produce untreated sewage, and consequently, base pollution, are described at Table 19. That information was provided by SABESP for each sanitation sub-basin and then compiled into each hydrological basin. In 2018, this watershed had 268.732 inhabitants, which means almost 58% of the inhabitants are not served by sanitation systems.

Table 19 – Current non-served population in Jaguaré Watershed by point of interest (2018)

| Point of Interest | Population (inh) | Imported Flow (m³/s) |
|---|---|---|
| Jorge Ward | 97686 | 0,200 |
| RU Jaguaré | 24866 | 0,051 |
| Mouth | 32257 | 0,066 |

Source: Adapted from SABESP (2018)

### *6.2.2 Model Calibration and Validation*

The calibration in the SMAP model produced the simulated flow shown in Figure 98 for its respective catchment (“Jorge Ward” Point) whose area is 18km² (accounting for about 56% of the total watershed area). It is possible to observe that calibration gave satisfactory results when compared to observed flow. Some peaks of the observed data were not possible to be replicated, for the same reasons already explained for Ipanema Watershed. This time, on the other hand, variations between observed and simulated peaks are not as high as before, so standard deviation is lower than it was in the other study case. Table 20 shows the calibrated parameters for this case study on SMAP Model.

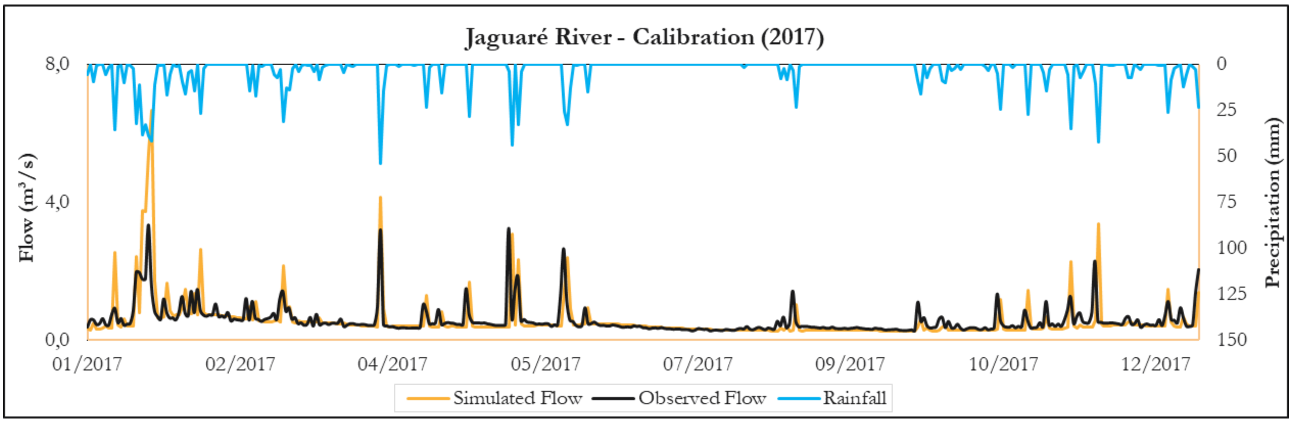



Figure 98 - Calibration of the Jaguaré River in 2017.

Table 20 - Calibrated Parameters for Jaguaré River Basin

| **Parameters** | |
|---|---|
| sat | 130 |
| k2t | 0,2 |
| crec | 5,1 |
| ai | 1,1 |
| Capc | 0 |
| kkt | 8 |

It is important to reinforce that the parameters obtained in the SMAP model are not as commonly expected for a hydrological model. Jaguaré, as well as all the Pinheiros watershed, is highly impervious, which prevents most of the groundwater to be recovered. Furthermore, untreated sewage at some points was basically a great part of the surface flow. Even in other watersheds studied in Pinheiros, SMAP parameters vary in many orders from each specific place (FCTH, 2021).

For validation, data from 2018 were analyzed using the same calibrated parameters as Table 20 and Figure 99 shows these results. It is possible to see that the parameters are adequate for this time period too. Again, three performance indexes for the hydrological model were used: NSE, RMSE and RSR and are exposed in Table 21. This time it is possible to see that RMSE presents an error index close to the ideal (zero), while NSE and RSR present an unsatisfactory error index. Nevertheless, as explained in section 6.1.2 Model Calibration and Validation, the goal was to minimize total inflow and outflow volumes and to achieve an average flow close to the observed data. That way, Table 22 shows the Average Errors obtained in the hydrological model.

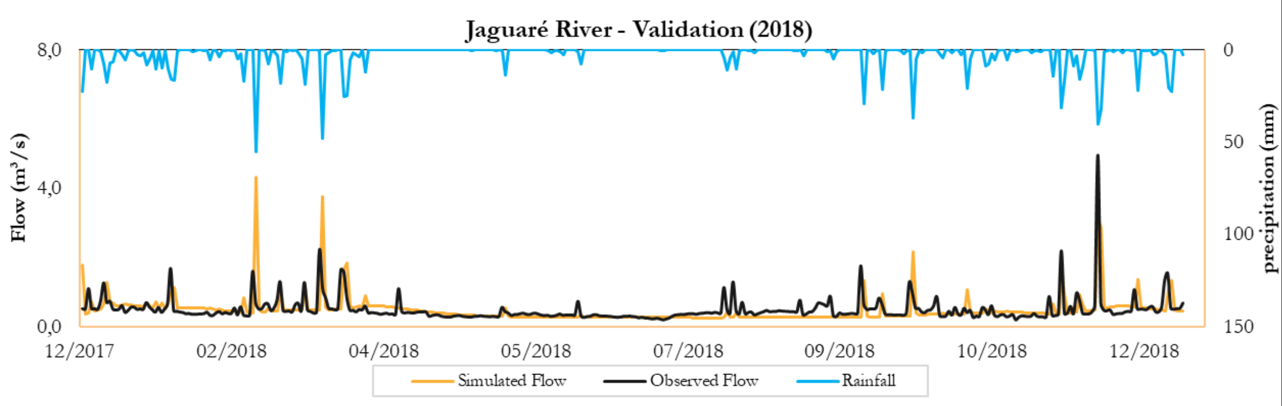



Figure 99 - Validation of the Jaguaré River in 2018

Table 21 – Errors obtained in the Model

| | **Error** |
|---|---|
| **RMSE** | 0,40 |
| **NSE** | -0,21 |
| **RSR** | 1,10 |

Table 22 - Average Errors Obtained in the Model

| | **Simulated Flow (m³/s)** | **Observed Flow (m³/s)** | **Average Error (%)** |
|---|---|---|---|
| Average | 0,49 | 0,49 | 0% |
| Standard Deviation | 0,411 | 0,361 | 14% |

*6.2.2 Water Quality Results*

After filling SMAP parameters in, CAbc-QUAL can be executed, but not before the unit loads EMC, $M_0$ and K are set for each constituent and population to obtain the concentrations. Figure 100, Figure 101 and Figure 102 show concentrations monitored and simulated at CAbc-Qual at

"Jorge Ward Point" for BOD, TN and TP respectively. And Figure 103 show BOD concentrations for "Mouth Point".

Simulated results are compared with the box plot series of observed data, obtained by a statistical analysis from 5 years of monitoring from CETESB and SABESP (see section 4.3 MONITORING IN JAGUARÉ WATERSHED). The campaigns executed during 2018 are highlighted by *x* symbols. Results show that CAbc-Qual Model is working correctly, so simulated average concentrations do stay inside the observed concentrations and the monitored points in 2018, as well.

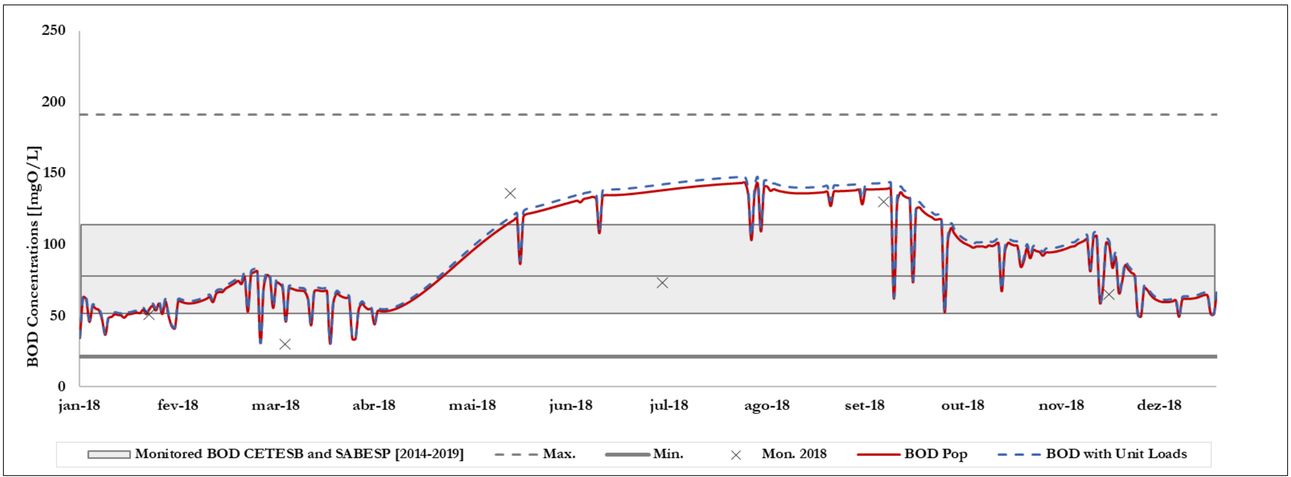



Figure 100- BOD Concentrations [mg/L] for Jaguaré River Basin simulated and monitored at Jorge Ward

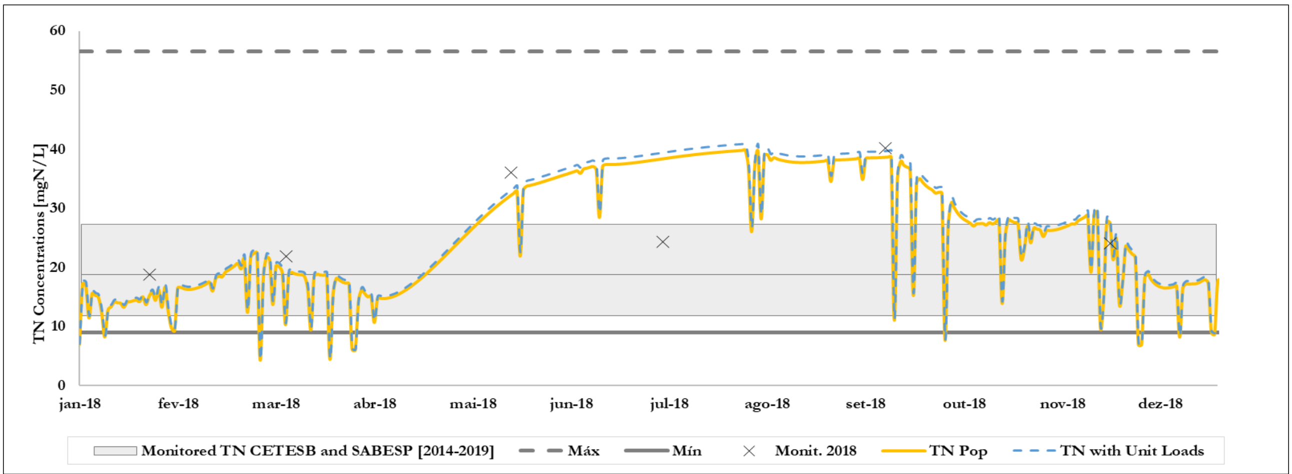



Figure 101 - TN Concentrations [mg/L] for Jaguaré River Basin - simulated and monitored at Jorge Ward

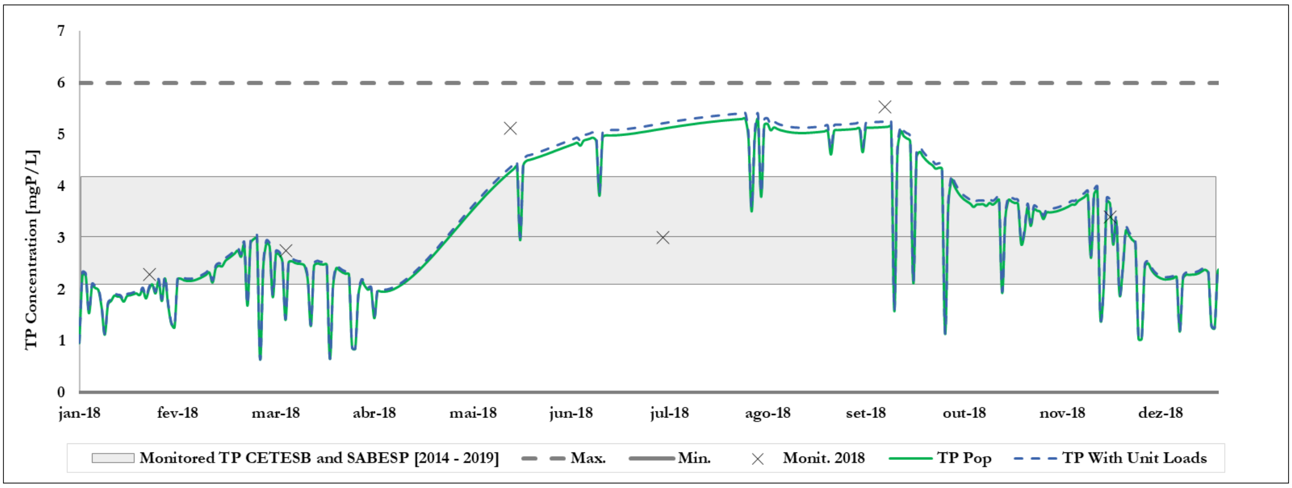



Figure 102 - TP Concentrations [mg/l] for Jaguaré River Basin - simulated and monitored at Jorge Ward

From the figures, it is possible to see that the behavior of the concentrations (see solid lines) changes from what was observed in Ipanema Watershed. In Jaguaré, as expected, base concentrations are many times higher than wash off loads. Note that, each time rain occurs, the concentration reduces, in other words, the fringe points down, instead of up, as seen in Ipanema, for instance.

Besides that, simulations were performed including UL in Dry Weather (dashed blue lines). From those, one can see that UL increases concentrations (as expected) and accounts for many other contributions that might have not been considered by non-served population. One could ask: "what are other releases that would be classified under base contributions?". Supposably, illegal or not regulated releases from commerce or industries (such as car washes, schools, etc.) or even contamination in groundwater flow. However, sanitary sewage contributions are already recognized to be high and including UL would affect sensibility. That way, only non-served population were considered as base concentrations.

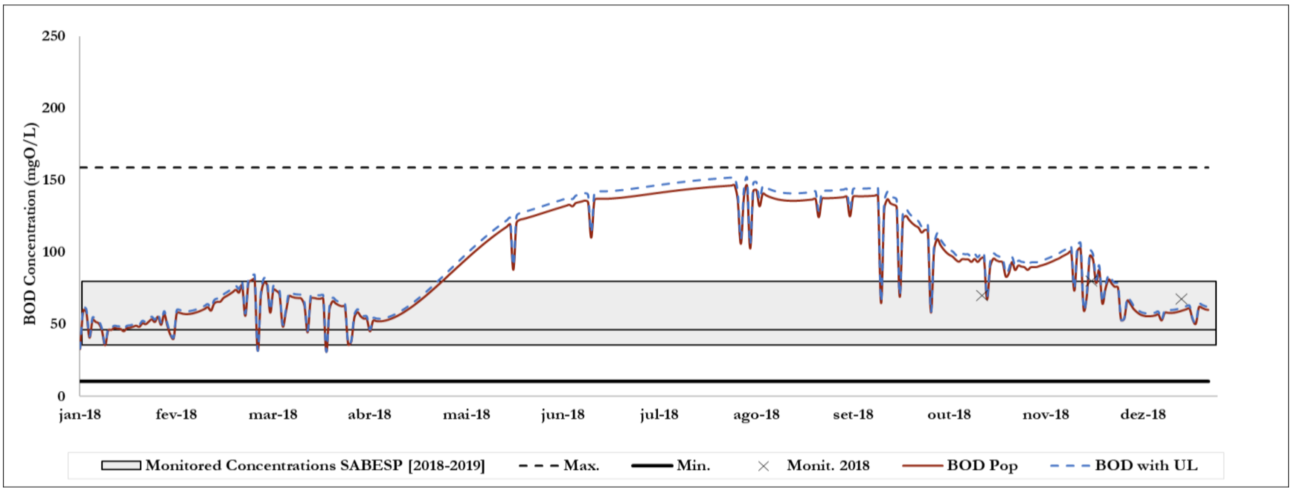



Figure 103 - BOD Concentrations [mg/l] for Jaguaré River Basin - simulated and monitored at Mouth

EMC concentrations were chosen as the best form to represent nonpoint pollutions (as it is easier and modeler experience with the method has proven its functionality). So, Table 23 and Table 24 show Unit Loads for Jaguaré in kg/km².day and in g/inh.day, respectively. That can be understood by observing that under-developed areas contribute more to pollution and therefore, management solutions should be taken from that point up, i.e., sewage infrastructure and BMP inserts should focus on the upstream part of Jaguaré watershed, while the downstream surface is about 20% cleaner.

Table 25 shows EMC results. As clearly one can interpret by the tables and by Figure 104, base loads are many times higher than wash off loads and the upstream watershed has more surface pollution than the downstream (after Jorge Ward point). Base loads vary from 88 % to 93 % of total load.

Table 23 – Unit Loads for Jaguaré Watershed (kg/km².day)

| | **BOD** | **TN** | **TP** |
|---|---|---|---|
| Total | 147,5 | 38,5 | 5,2 |
| Base Load | 129,7 | 35,2 | 4,71 |
| Wash Off Load | 17,73 | 3,15 | 0,45 |

Table 24 - Unit Loads for Jaguaré Watershed (g/inh.day)

| | BOD | TN | TP |
|---|---|---|---|
| Total | 29,53 | 7,68 | 1,03 |
| Base Load | 25,98 | 7,05 | 0,94 |
| Wash Off Load | 3,55 | 0,63 | 0,09 |

That can be understood by observing that under-developed areas contribute more to pollution and therefore, management solutions should be taken from that point up, i.e., sewage infrastructure and BMP inserts should focus on the upstream part of Jaguaré watershed, while the downstream surface is about 20% cleaner.

Table 25 - EMC for Jaguaré Watershed (mg/L)

| Point of Interest | BOD | TN | TP |
|---|---|---|---|
| Jorge Ward | 78 | 7,0 | 1,2 |
| Mouth | 62,5 | 5,6 | 0,96 |

The wash off parameters that represent the response of the rainfall events, K and M0 obtained are described in Table 26. From the parameters, as compared in the previous study, it is possible to see that wash off processes are the same from each constituent, in other words, the wash rates (intensity) and pollutants mass available in the beginning are equal for each constituent. From that it can be inferred that nonpoint pollution in this watershed comes from the same source, for instance: solid waste, lack of sweeping, animal feces, etc. (all urban impacts).

Table 26 - Wash off parameters calibrated

| Parameter | BOD | TN | TP |
|---|---|---|---|
| **K** | 3,0 | 3,0 | 3,0 |
| **M0 (%)** | 50 | 50 | 50 |

Finally, from the simulations, it is also possible to observe the seasonal behavior of the pollutants. When comparing simulated lines from the boxplots, it is noteworthy how they detach from the gray area (quartiles and medians). In the context of the management actions, analysis and regulations when framing water bodies, these results show there is another level when taking this into consideration. Instead of regulating releases, can we set limits for concentrations throughout a year? So, how long do the pollutants stay below / above a reference limit concentration and for how long is it acceptable for them to be?

Figure 105 shows, for the Jaguaré case, that the current situation is critical. When analyzing BOD concentrations over a year for 3 different reference limits - 30 mg/L; 45 mg/L and 60 mg/L- it is possible to see that concentrations are higher than this 100%, 86,3% and 69% of the time respectively. Can management actions change those parameters? And for how long?

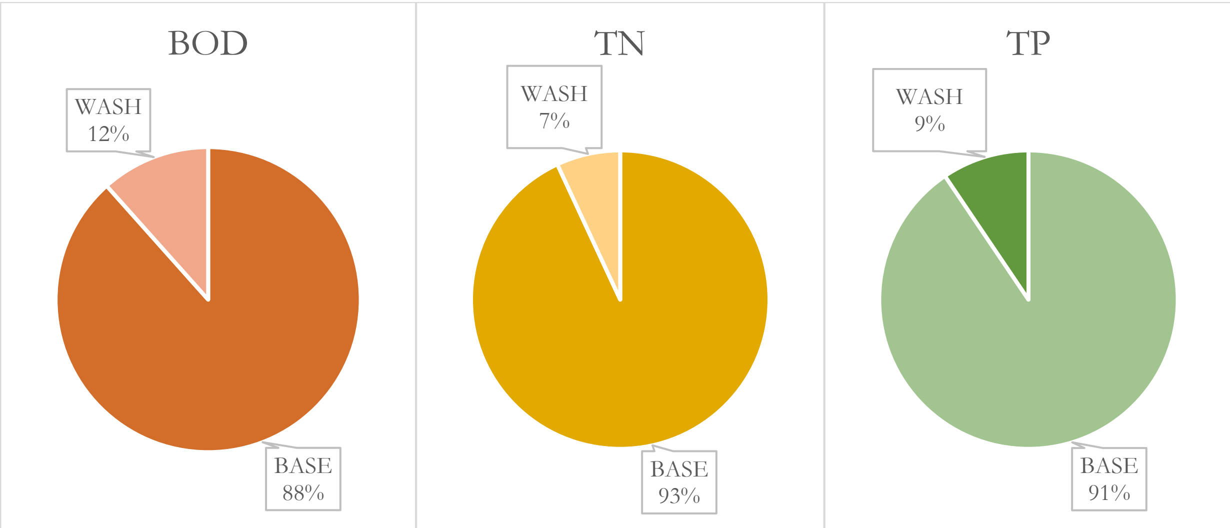



Figure 104 – Base and Wash off Loads in Jaguaré Watershed

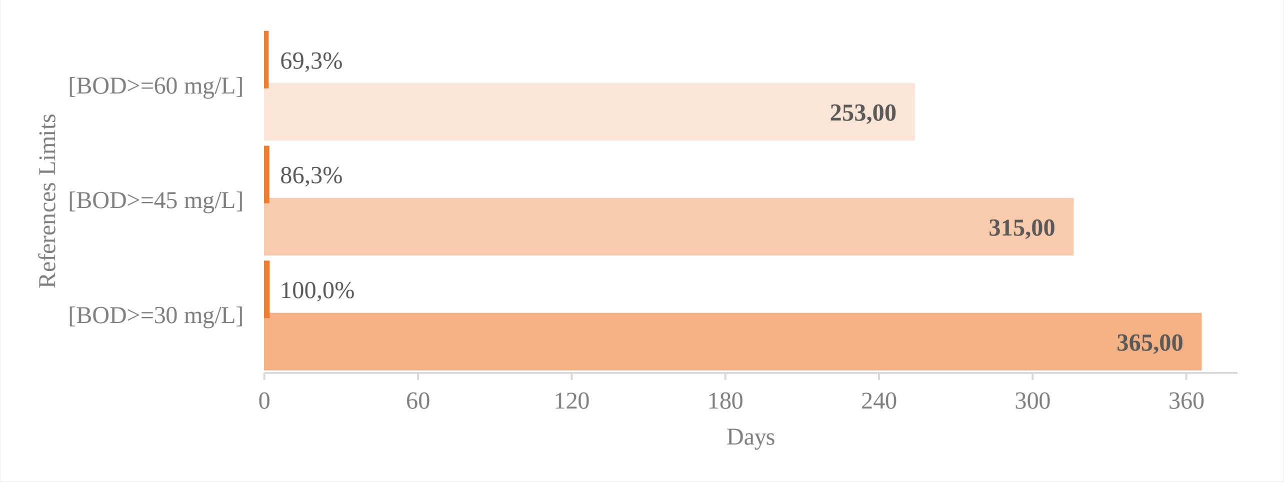



Figure 105 – BOD permanence in Jaguaré – Current Situation (2018)

Similarly to the previous case study, one can wonder if Jaguaré river has any level of self-purification. From Dissolved Oxygen (DO) levels monitored in the campaigns (Figure 106 and Figure 107), one can see that despite having some outlier peaks, the average DO concentrations are about 1,3 $mgO_2/L$. According to Radwan (2003), prolonged exposure to low dissolved oxygen levels (<5–6 mg/L) may not directly kill an organism, but will increase its susceptibility to other environmental stresses. While exposure to <30% saturation, where DO concentration is lower than 2 mgO/L, for one to four days may kill most of the biota in a system.

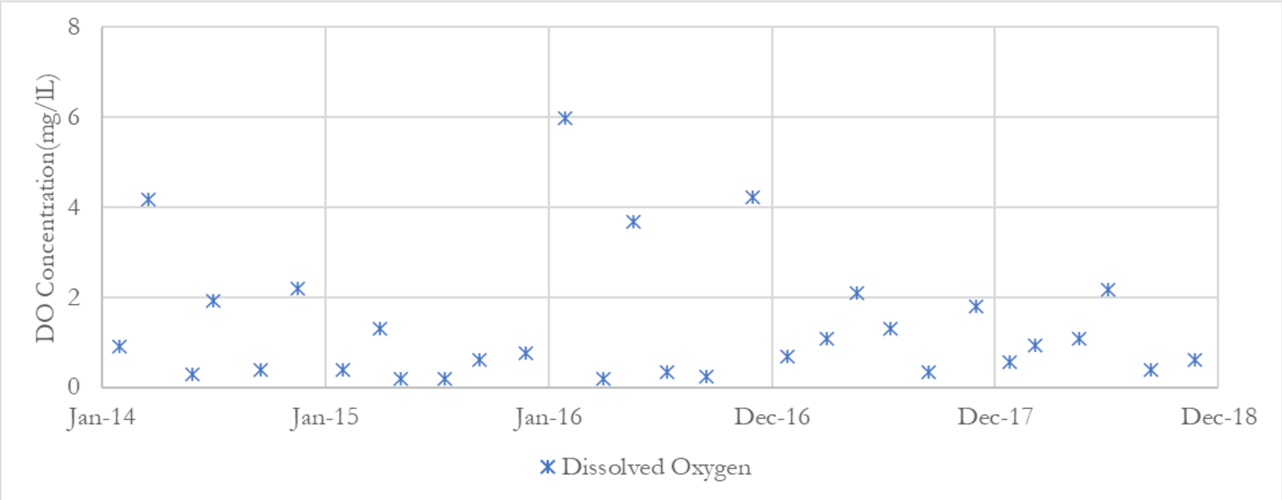



Figure 106 – Monitored Dissolved Oxygen (DO) concentrations in Jaguaré "Jorge Ward"(mg/L)

Source: (FCTH, 2021)

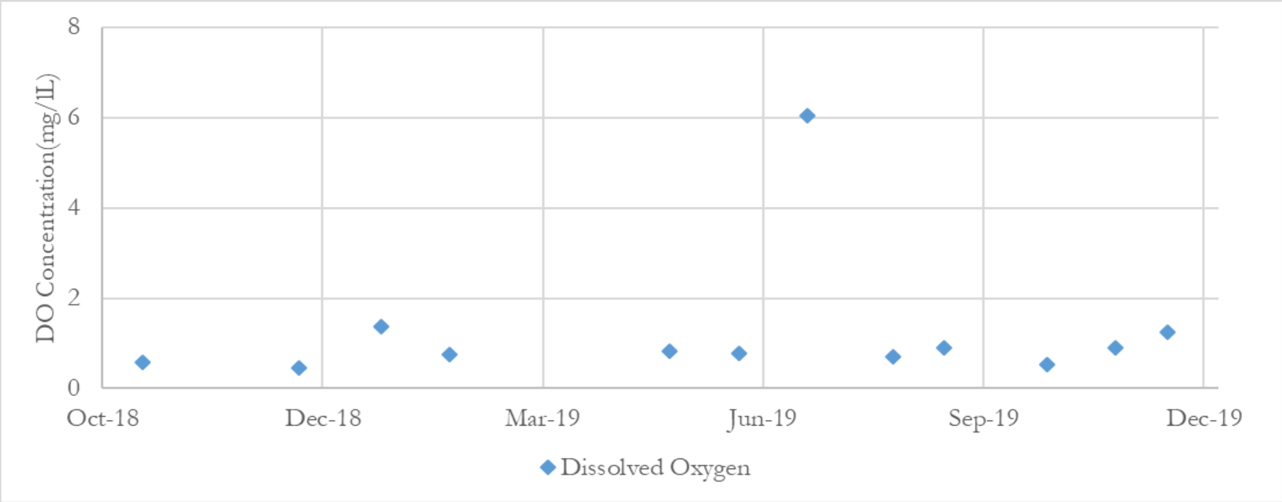



Figure 107 - Monitored Dissolved Oxygen (DO) concentrations in Jaguaré "Mouth"(mg/L)

Source: (FCTH, 2021)

That said, it is possible to infer that unlikely self-purification can happen, as the aerobic bacteria cannot perform such transformations under these conditions, even though organic matter was determined to be labile in the current situation in the Pinheiros River (FCTH, 2021).

*6.2.3 2022 Prognosis*

SABESP, in order to improve water quality in this area for the aforementioned "Novo Pinheiros Project" **proposed** new structuring works and local treatment units called Recovery Units (or RUs) by the end of 2022. The goal is to obtain BOD concentrations under 30 mg/L along Pinheiros valley to make the return of aquatic life possible and recover the waterfront for people's use. Table 27 a new non-served population into the system, indicating that the exceeding previous population now is collected and transferred into WWTP Barueri or ABC. Recovery Unit (RU) Jaguaré would be settled as in Figure 108.

It is fundamental to state that this location, as seen before, is not ideal, because this position is far too close to the mouth, where concentrations are many times higher. On the other hand, as this is a particularly problematic area where, many times, infrastructure works are not feasible at this time, this location was chosen to improve the quality of the water that will be released into Pinheiros (BAPTISTELLI, 2020).

As seen by Table 19 and Table 27, the population reduction is about 70%, what would diminish BOD loads from 4,571.5 kg/day to 1,339.5 kg/day, approximately. The Recovery Unit Jaguaré shall have the characteristics described by Table 28.

Table 27 - Non-served population in Jaguaré Watershed **proposed** by point of interest in 2022

| Point of Interest | Population (inh) | Imported Flow (m³/s) |
|---|---|---|
| Jorge Ward | 10446 | 0,023 |
| RU Jaguaré | 2659 | 0,006 |
| Mouth | 32257 | 0,016 |

Source: SABESP (2020)

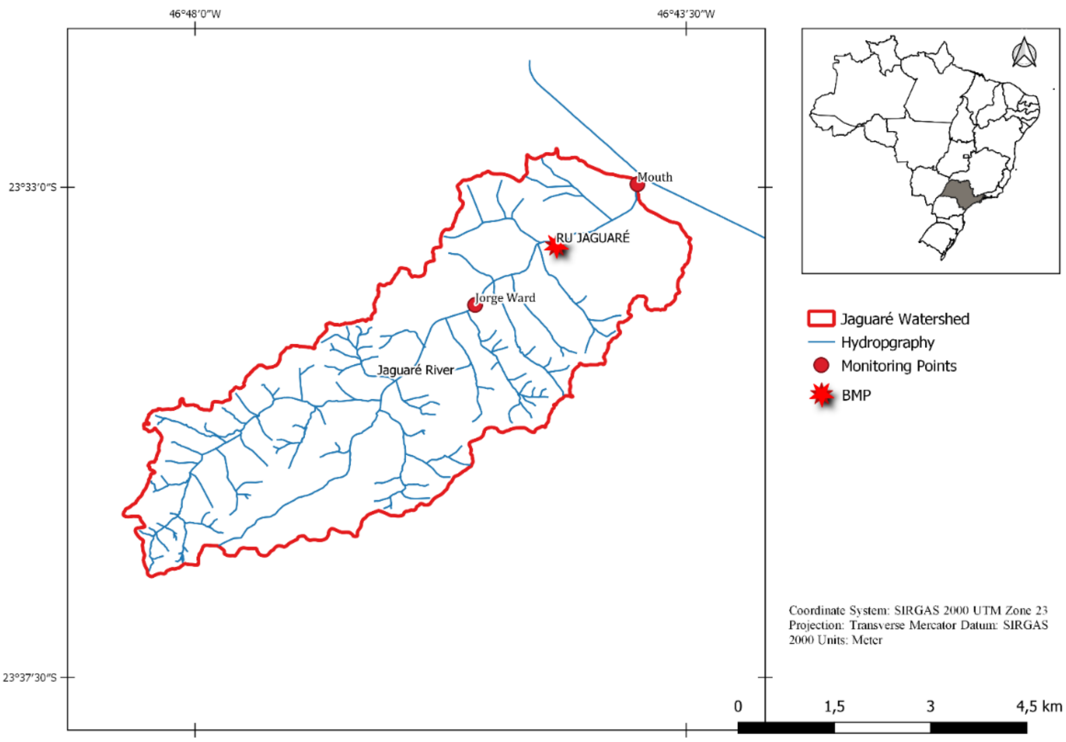



Figure 108 – Jaguaré BMP Location in 2022

Table 28 - Jaguaré Recuperation Unit

| RU | Capacity (L/s) | Non-Served Population into the RU (inh) | Efficiency (%) |
|---|---|---|---|
| Jaguaré | 300 | 12452 | 50% |

Source: SABESP (2020)

Also, it is important to state that Recovery Units were intended, *a priori*, for BOD treatment (organic matter), while infrastructure works aim to reduce all the concentrations of constituents, mainly because they include non-served population releasing sewage into the water body.

However, to make such estimates and simulations, a rainfall-flow prognosis should take place. So, the study of future scenarios begins with a sufficient representation of the existing condition and the assurance that the mathematical model is aligned to the research environment and, thus, capable of being utilized for this purpose; the calibration and validation processes were completed for this purpose.

The modal year represents rainfall and surface flows that occurred in the watershed and were considered significant in the time frame analysis, i.e., the hydrology pattern to be set for that year. As a result, the chosen modal year will not be able to represent unusual events in the basin, such as large rainstorms or droughts, but it will be able to represent recurring or average events.

The flow permanence curve and the average yearly precipitation were used to determine the modal year in this investigation. These indicators allow the detection of exceptional hydrological events while also considering soil cover, moisture, and infiltration conditions. Because there were no major structural, demographic, or hydrological changes in the research site during this time, the decision made was to use data from the previous five years for these analyses. The evaluated period was from 2015 to 2019, the results are shown in Table 29 and Figure 109.

Table 29 - Annual Total Precipitation in Jaguaré River basin in the period between 2015 and 2019

| | |
|---|---|
| 2015 Total Precipitation (mm) | 1456,1 |
| 2016 Total Precipitation (mm) | 1257,9 |
| 2017 Total Precipitation (mm) | 1419,5 |
| 2018 Total Precipitation (mm) | 932,9 |
| 2019 Total Precipitation (mm) | 1730,1 |
| **Average Annual Precipitation 2015 - 2019 (mm)** | **1359,3** |

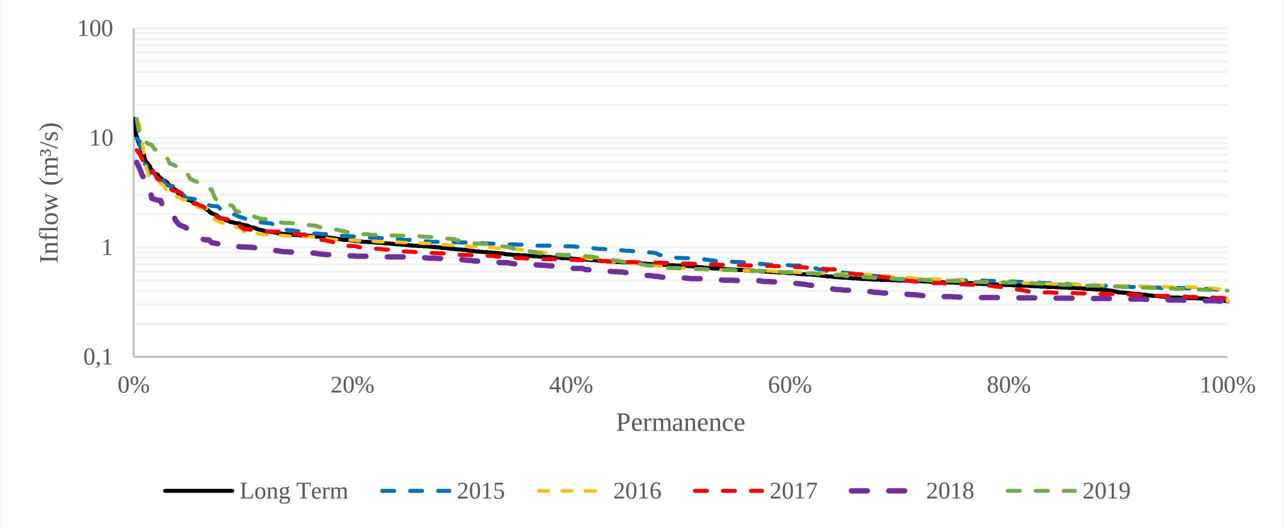



Figure 109 – Jaguaré permanence flow curves from 2015 to 2019

The years 2015, 2016 and 2017 are the ones that are closest to the long-term averages for both indicators studied, hence these are the years that can be used to reflect the most frequent hydrological circumstances in the river basin. So, 2017 was chosen as the modal year in this study because it fits the criteria and represents the most current urbanization and infrastructural circumstances.

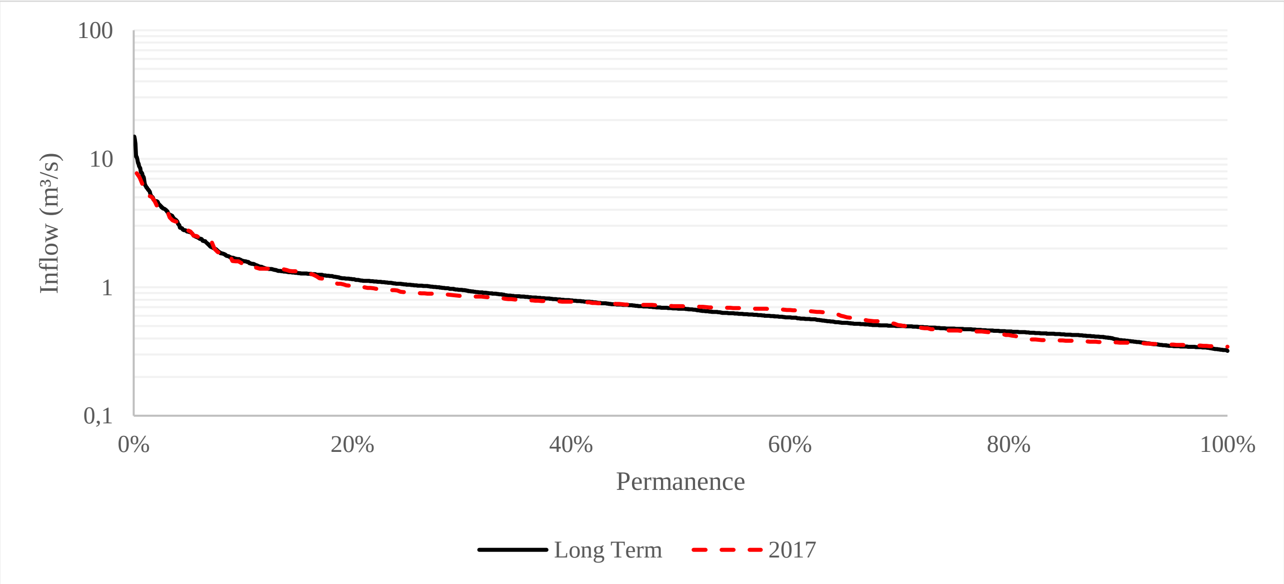



Figure 110 – Jaguaré permanence flow for the year 2017 (modal year) compared to the long-term permanence curve

With the modal year set, 3 important scenarios were chosen to investigate water quality after the modifications around the area: Scenario 1 is the one where there are only modifications in the infrastructure and no RU (C1), whereas the population is as described in Table 19. Scenario 2 is the one where there are modifications in the infrastructure plus the operation in the RU. And finally, Scenario 3 is the one where there is no infrastructure work done, but only RU operation. Table 30 outlines the 3 scenarios as mentioned.

Figure 111, Figure 112 and Figure 113 present the results from Scenario 1 for BOD, TN and TP respectively. From those, it is possible to immediately observe that concentrations altered many times, which contributes to a 40% decrease in the concentrations in some cases (especially during droughts). Plus, it is possible to see during wet seasons that for rain events, instead of reducing concentrations, one can see an input of concentrations (fringes going up), as sawn in Ipanema Watershed.

Table 30 – Scenarios proposed by "Novo Rio Pinheiros" Project

| Scenario | Modifications |
|---|---|
| C1 | Infrastructure works with non-served population equals to the Table 27 |
| C2 | Infrastructure works with non-served population equals to the Table 27 plus active R.U. |
| C3 | Original non-served population (Table 19) with only active R.U. |

Source: SABESP (2020)

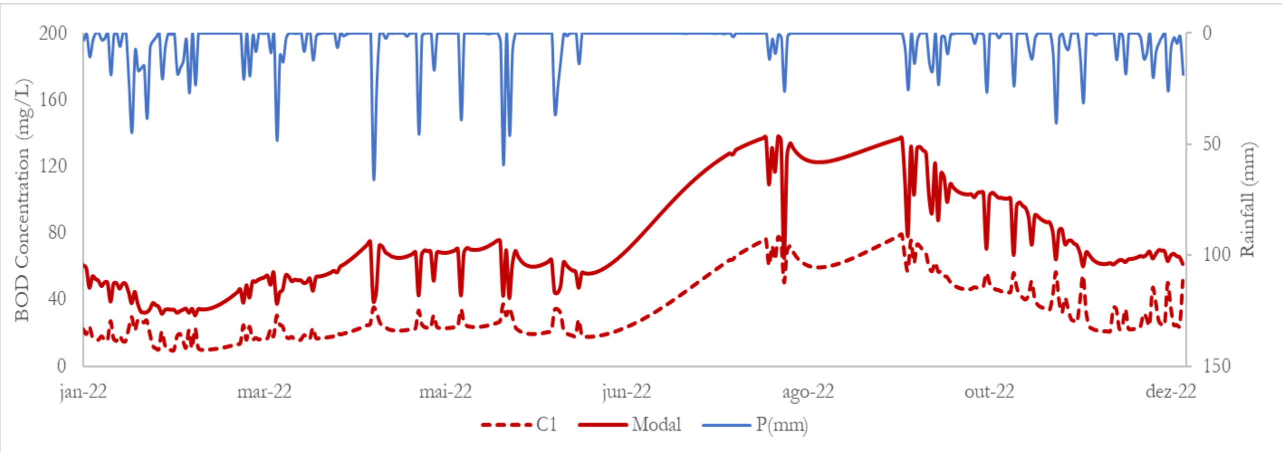



Figure 111 – BOD concentrations – Comparing Modal and C1 Scenario (mg/L)

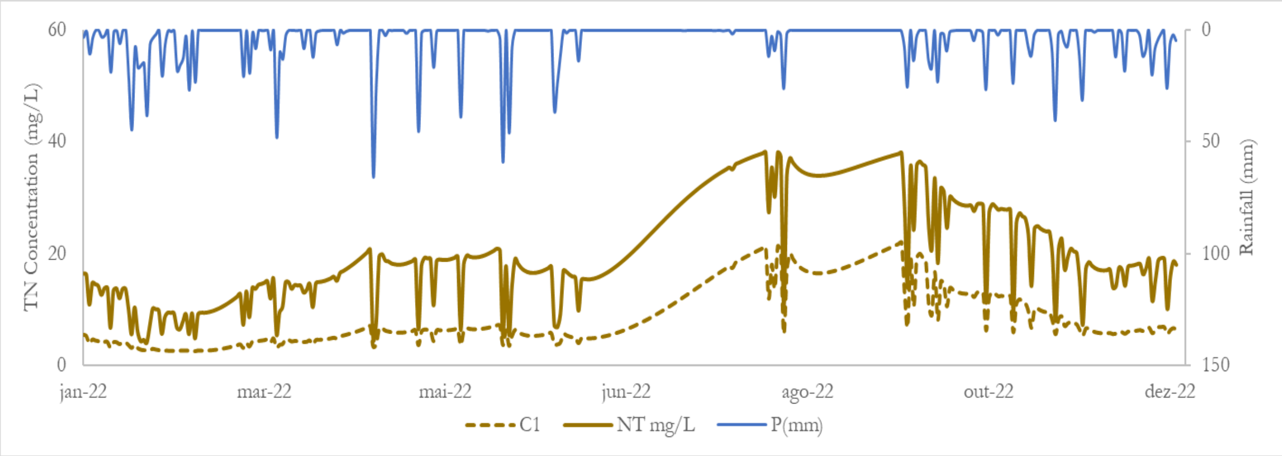



Figure 112 – NT concentrations – Comparing Modal and C1 Scenario (mg/L)

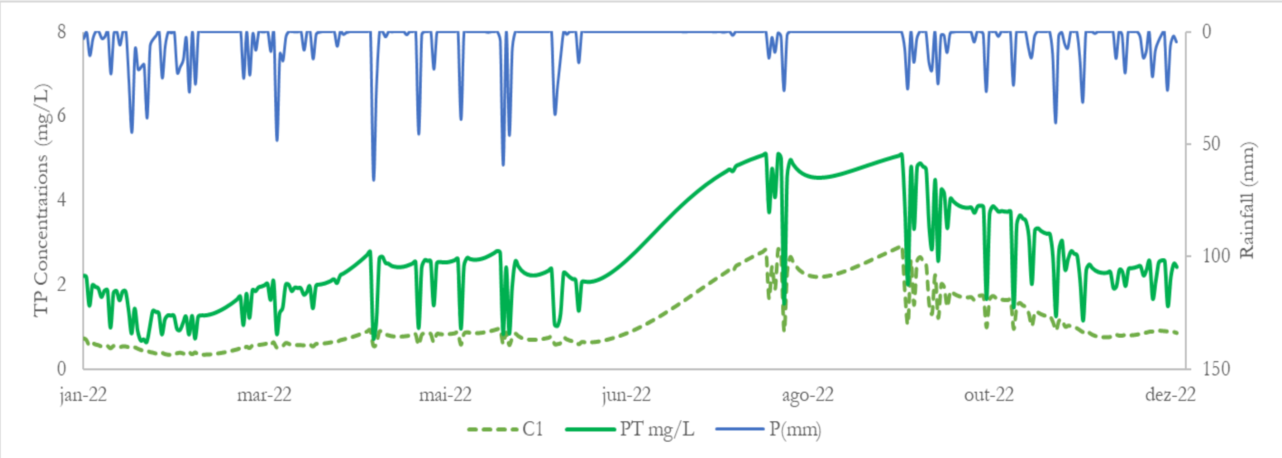



Figure 113 – TP concentrations – Comparing Modal and C1 Scenario (mg/L)

Figure 114, Figure 115 and Figure 116 illustrate results from Scenario 2 for BOD, TN and TP respectively. From those it is also possible to see the same behaviors seen in Scenario 1, plus a more considerable reduction from concentrations during dry period.

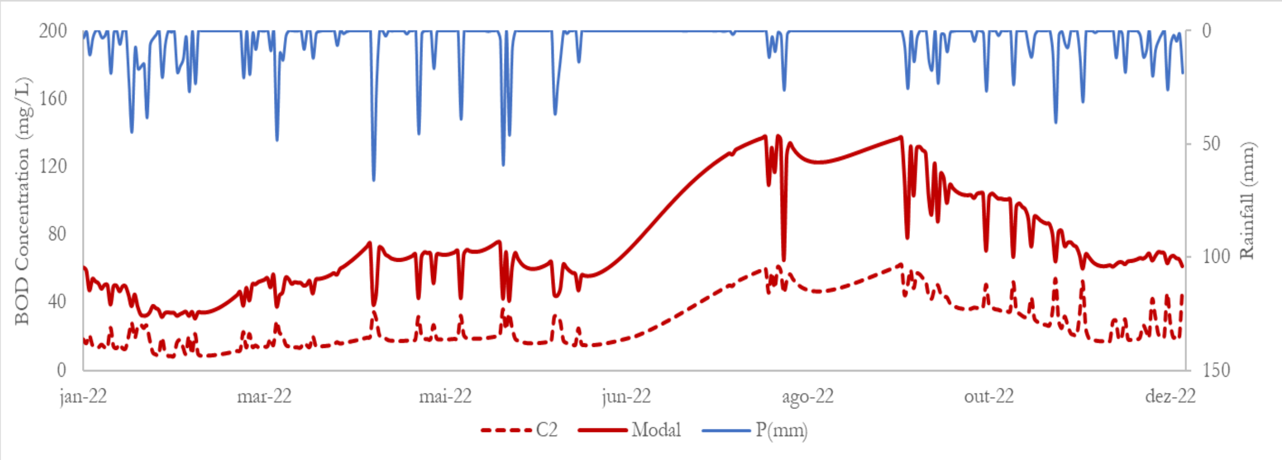



Figure 114 – BOD concentrations – Comparing Modal and C2 Scenario (mg/L)

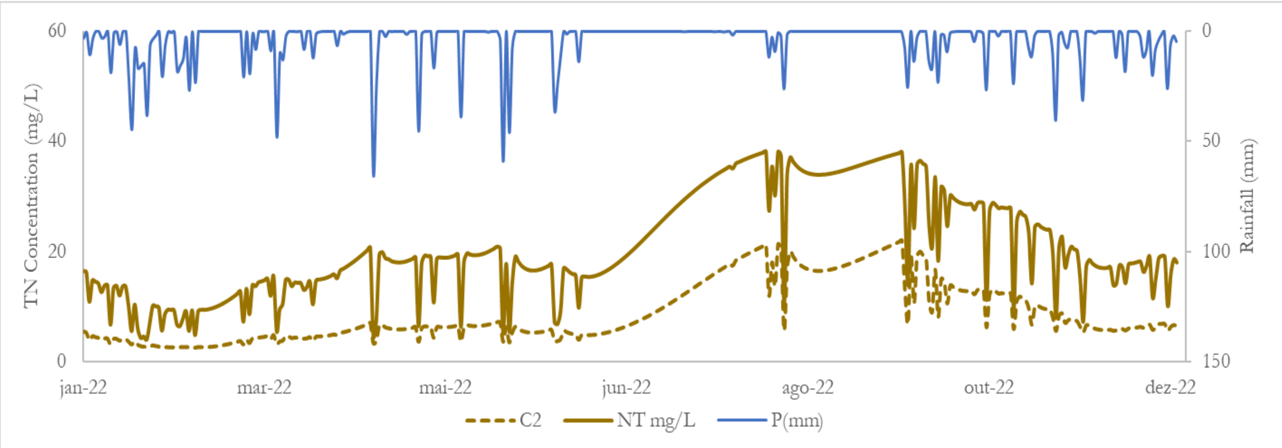



Figure 115 – TN concentrations – Comparing Modal and C2 Scenario (mg/L)

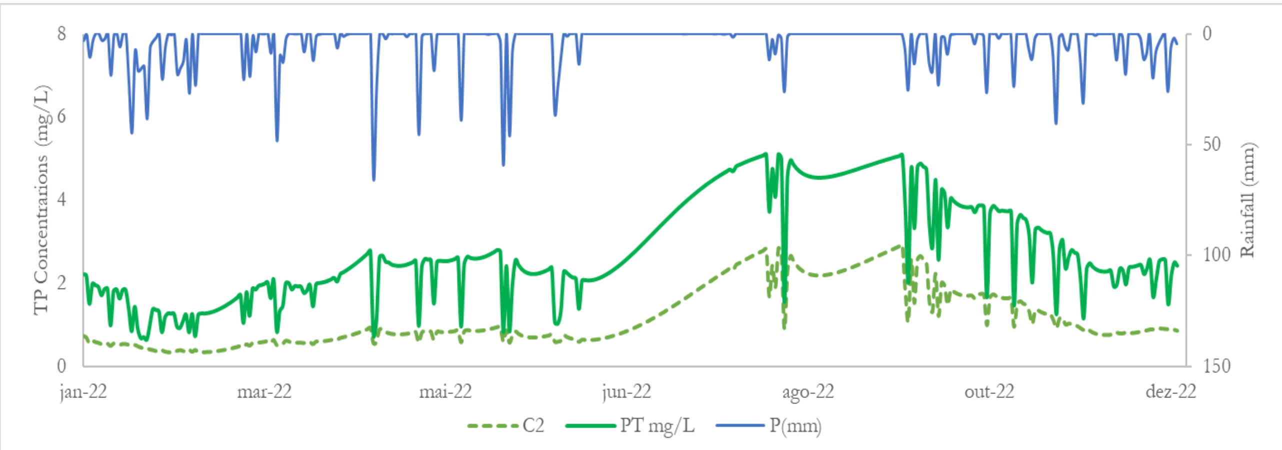



Figure 116 – TP concentrations – Comparing Modal and C2 Scenario (mg/L)

Finally, for Scenario 3, Figure 117 shows results for BOD Concentrations, as in this scenario the difference between modal year and prognosis is due only to the RU operation and as mentioned, it only alters BOD. There is a high reduction in concentrations, but it is possible to infer that the capacity and efficiency do not match performance expectations if considered alone, especially during wet-seasons.

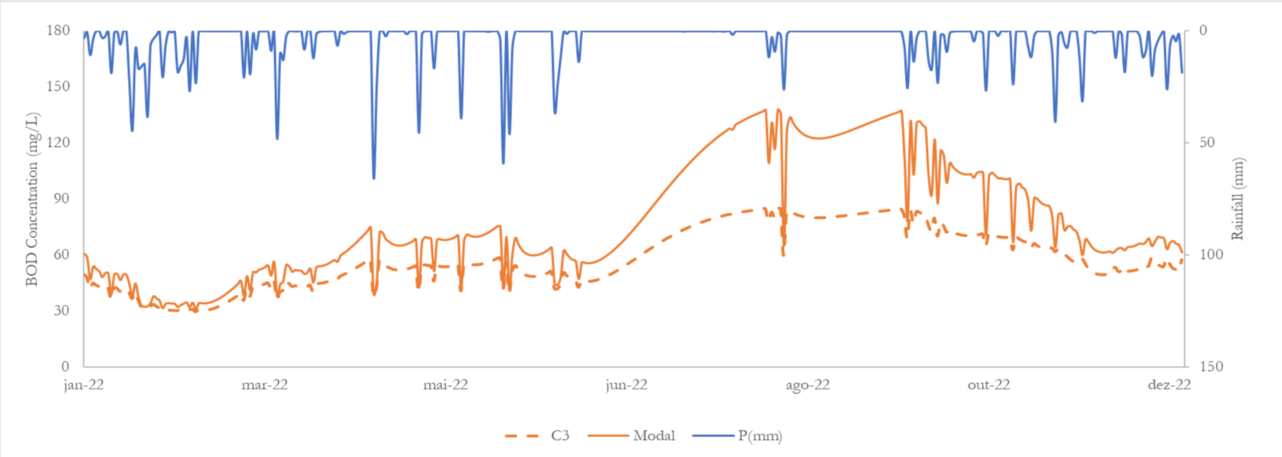



Figure 117 – BOD concentrations – Comparing Modal and C3 Scenario (mg/L)

When comparing all the scenarios, as in Figure 118, it is possible to conclude that, unquestionably, the scenario with all the interventions is the best way to modify the conditions observed in Jaguaré River and therefore, on its receiver, Pinheiros River. When analyzing the load modification for scenario 2, with all the interventions, it is possible to see that BOD changes from almost 90% base load to an equally 50-50 base and wash off load, as illustrated in Figure 119. That cannot be seen for TN and TP because the RU only treats organic matter (parametrized BOD), decreases in these concentrations are only due to infrastructure works.

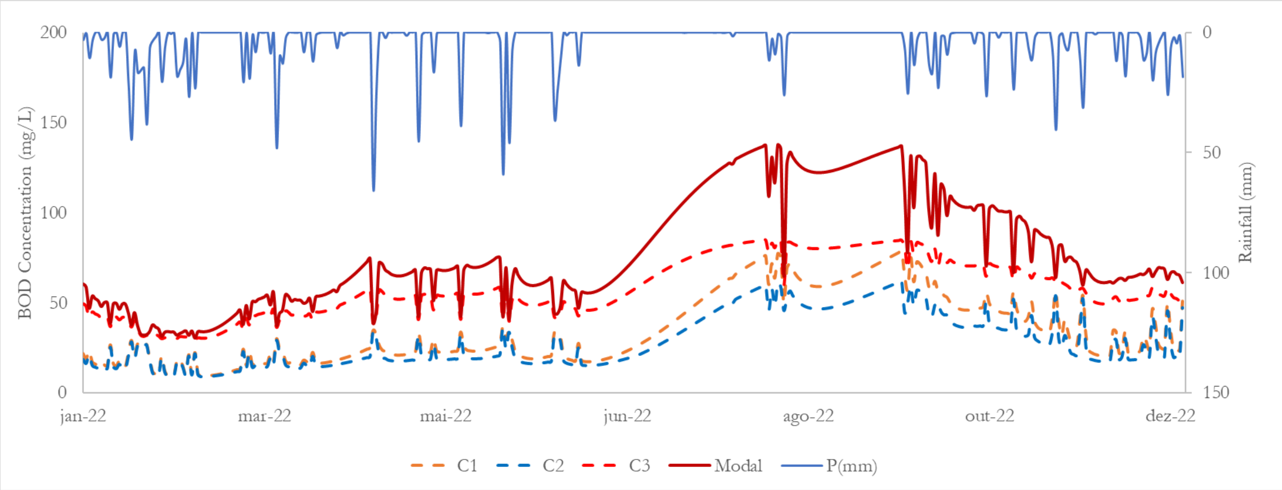



Figure 118 – BOD concentrations – Comparing Modal, C1, C2 and C3 Scenarios (mg/L)

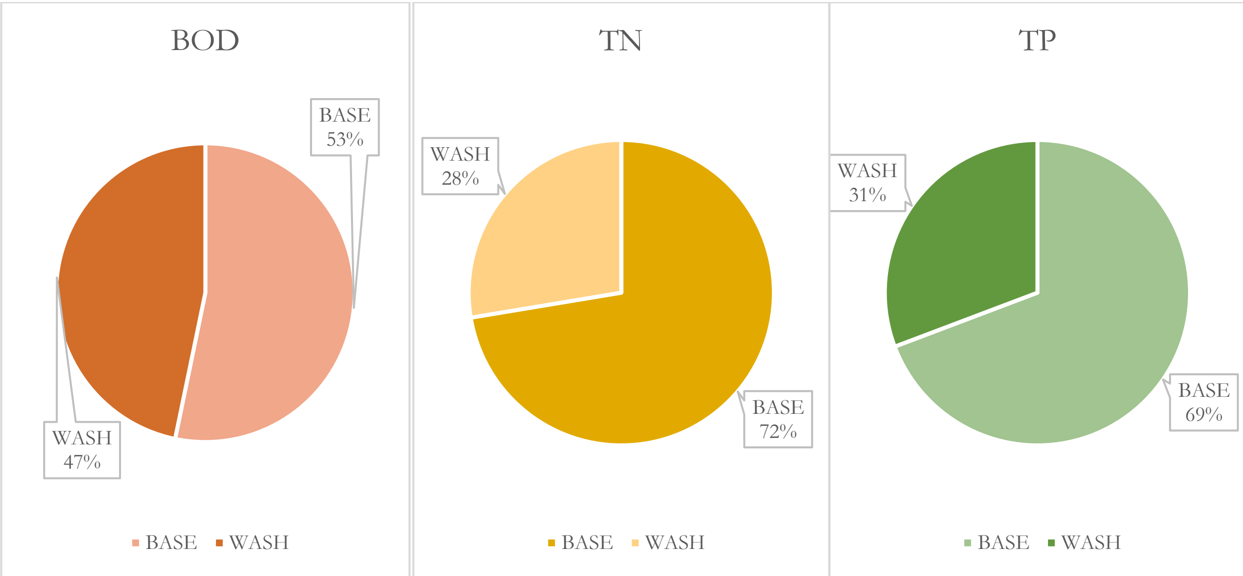



Figure 119 - Base and wash off load distribution in Jaguaré Mouth for Scenario 2 (all the interventions)

Finally, from the results, it is clear that the seasonal behavior is maintained in all simulations from all scenarios, so, concentrations rise in dry weather and lower during wet season. However, in Scenarios 1 and 2, when rain occurs, concentrations rise, proving that base flow for the prognosis is much closer to the ideal. For Scenario 3, where only BMP was applied, the behavior remained similar to the modal (current) situation. In some way, all of this was expected: when applying infrastructure work, concentration decreases and when also applying BMP, concentrations are even lower.

Additionally, it is now possible to see, during a whole hydrological year, how many times concentrations are above/under the reference (or regulation) limits. Figure 120 shows the permanence curves for BOD in all scenarios and it is quite clear that, as long as expectations are established, management actions can be executed more realistically, without taking actions only during dry periods and considering how nonpoint pollution affects the watershed during rain events, which now rise in concentrations in this location.

For instance, it is possible to see that base and scenario 3 concentrations tend to never achieve the 30 mg/L reference limit. On the other hand, Scenario 1 tends to reach this limit about 60% of the time and Scenario 2, 55% of the time. It is highly recommended that actions are adjusted to better fit expectations in terms of depollution projects.

Figure 121 presents results accounting for how many days Jaguaré Watershed exceeds different references limits throughout a year in different scenarios. From that, it is possible to observe that, for Scenario 1 and 2 results are very similar, indicating that if management actions in Scenario 2 were much higher than Scenario 1, how would managers justify the few differences between them in terms of results?

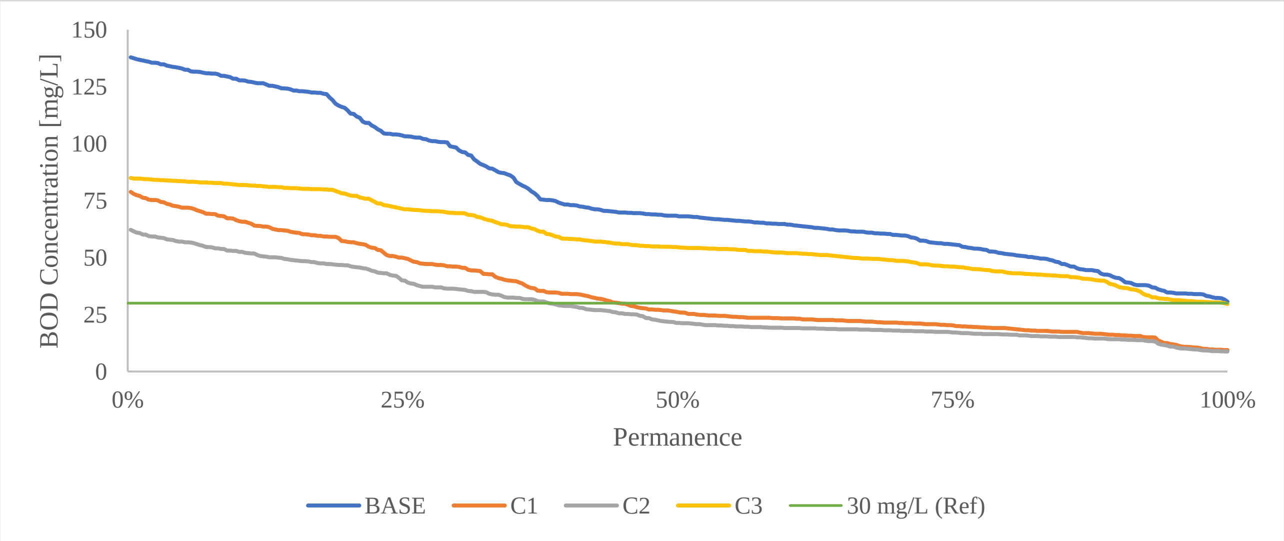



Figure 120 – BOD Permanence in all scenarios in Jaguaré Watershed

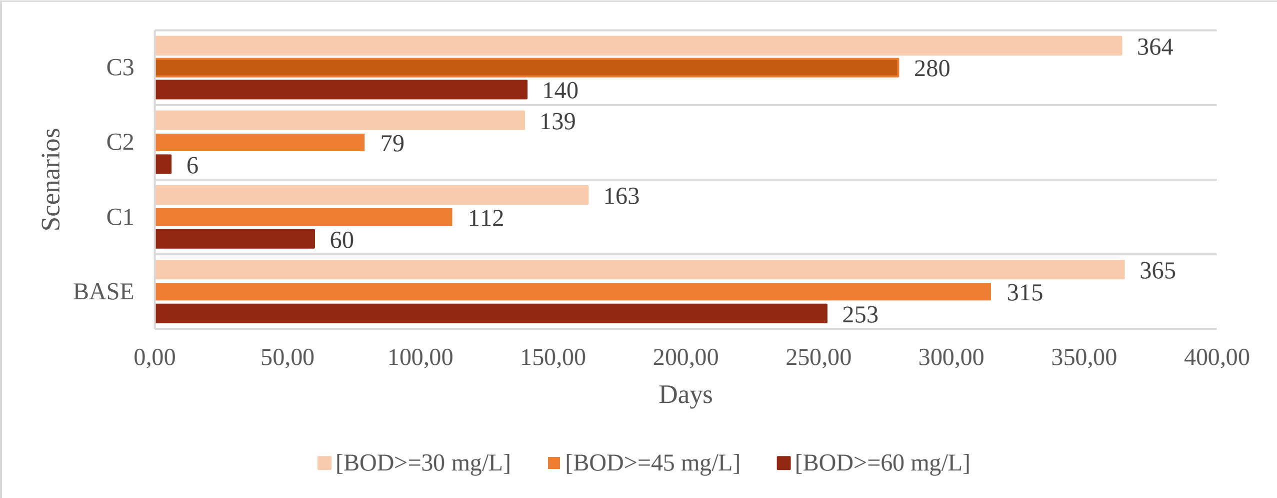



Figure 121 – Accounting for how many days Jaguaré watershed BOD concentration exceeds 30, 45 and 60 mg/L

As seen, scenarios 1 and 2 proposed by SABESP for the “Novo Rio Pinheiros” project do improve the current water quality scenarios which promise to give even lower concentrations in Pinheiros River itself. However, since the establishment of the “*Novo Marco Legal do Saneamento*” (Law 14026 of July 15th, 2020), the Federal Government's goal is to achieve universal sanitation services by 2033, ensuring that 99% of the Brazilian population has access to drinking water and 90% to sewage treatment and collection.

So, with those numbers in mind, one might wonder “how much load would have to be removed for Jaguaré to show concentrations much closer to the ones in CONAMA 430 regulation?” or “how would the behavior of Jaguaré be if all the population had its sewage contributions sent to treatment?". Thinking of those possibilities, 3 additional scenarios (C4, C5 and C6) were created, and they are detailed as shown in Table 31.

Figure 122, Figure 123 and Figure 124, show results from the simulations performed for BOD, TN and TP respectively, for Scenario 4. From those, it is possible to see that base concentrations would tend to 0 (zero) when there is no rainfall and the behavior that once was of increased concentrations during dry seasons does not exist anymore for all pollutants. Also, concentrations surpass the reference limit of 30 mg/L exclusively during some rain events (modal year).

Table 31 – Aditional Scenarios / Simulations

| Scenario | Modifications |
|---|---|
| C4 | 0(zero) non-served population with no RU |
| C5 | 0(zero) non-served population plus RU active |
| C6 | Reduction of 50% from C2 population and RU Efficiency set to 80% |

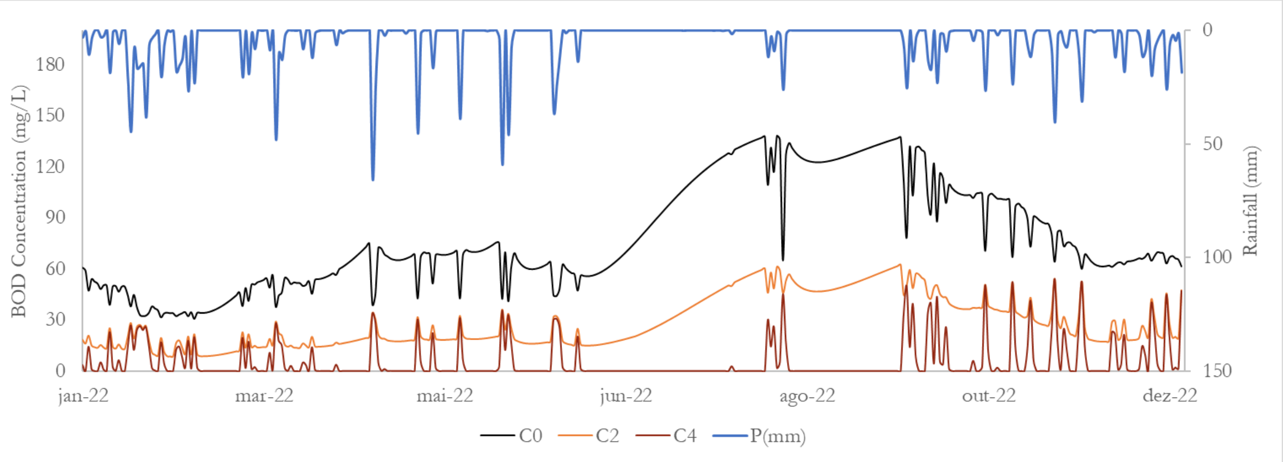



Figure 122 – Comparing BOD concentrations for base (C0) and prognosis Scenarios 2 and 4 (mg/L)

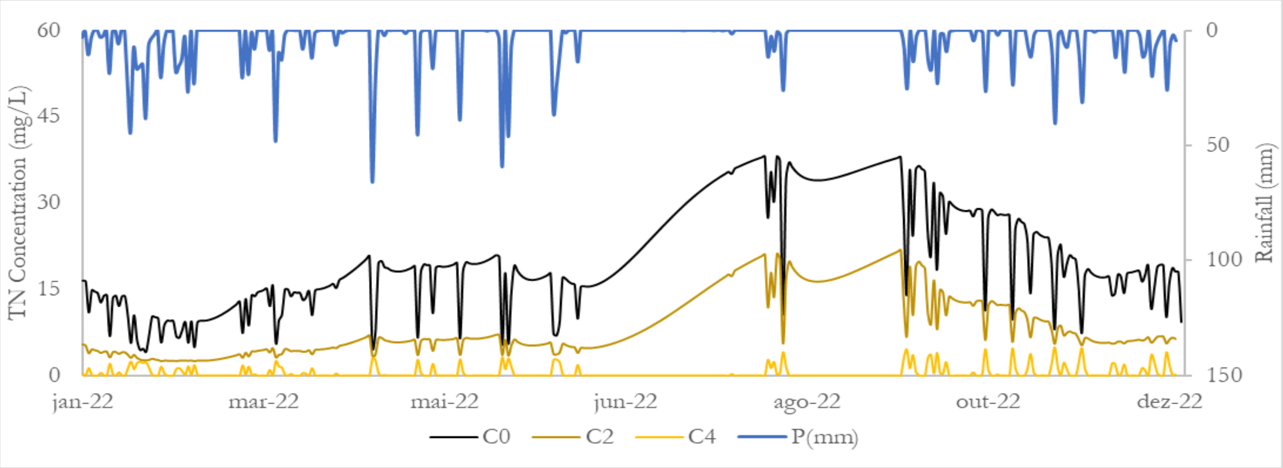



Figure 123 – Comparing TN concentrations for base (C0) and prognosis Scenarios 2 and 4 (mg/L)

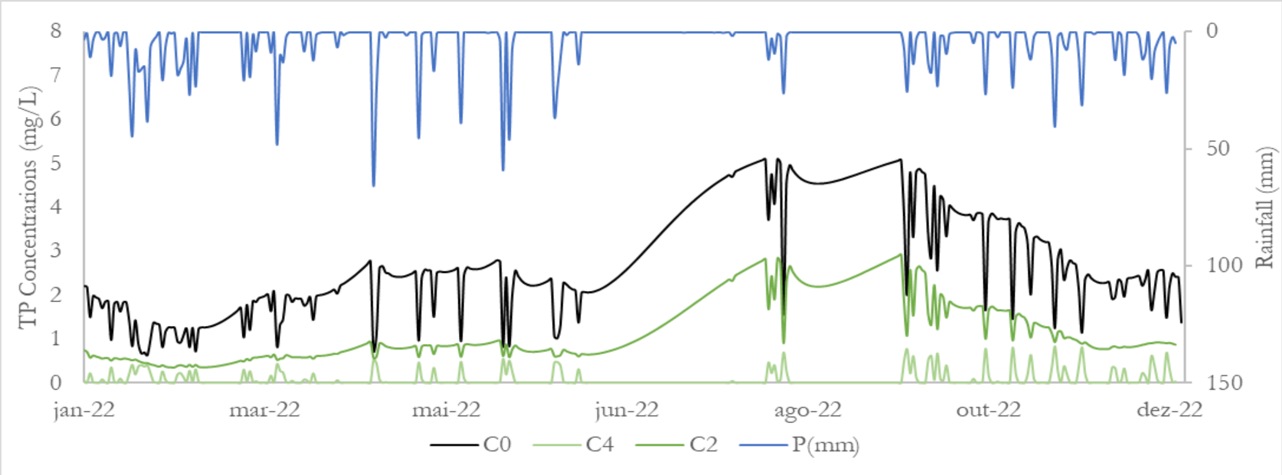



Figure 124 – Comparing TP concentrations for base (C0) and prognosis Scenarios 2 and 4 (mg/L)

For Scenario 5, which also accounts for zero non-served populations, but with active Recovery Units, it is possible to see that there is almost no difference between Scenario 4 and 5, which suggests that RUs are only truly effective for high base pollution. This conclusively shows that if there ever would exist a scenario like this, RUs (with the characteristics they were developed to operate) would be useless. Figure 125, Figure 126 and Figure 127 show these results for BOD, TN and TP respectively.

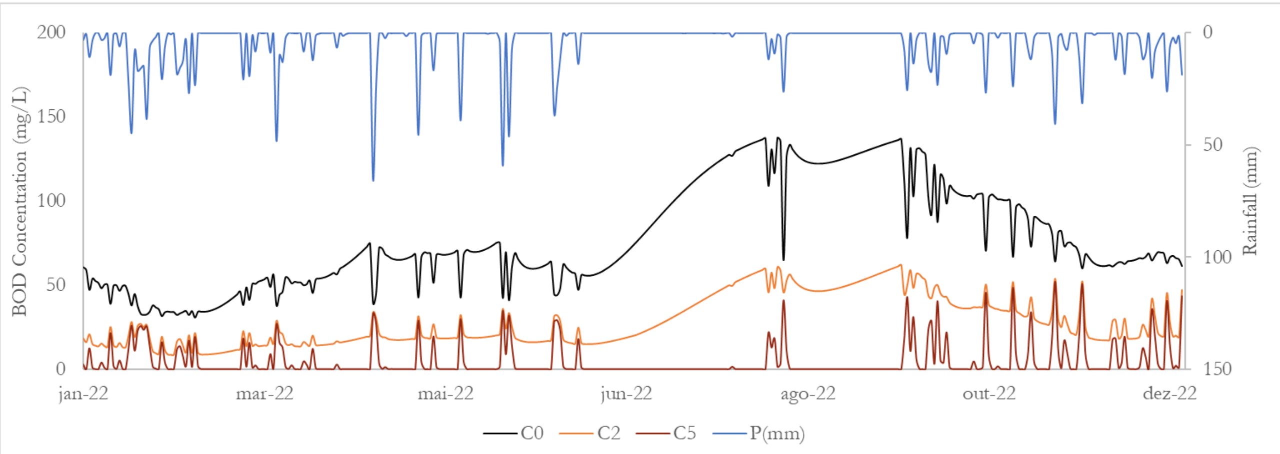



Figure 125 – Comparing BOD concentrations for base (C0) and prognosis Scenarios 2 and 5 (mg/L)

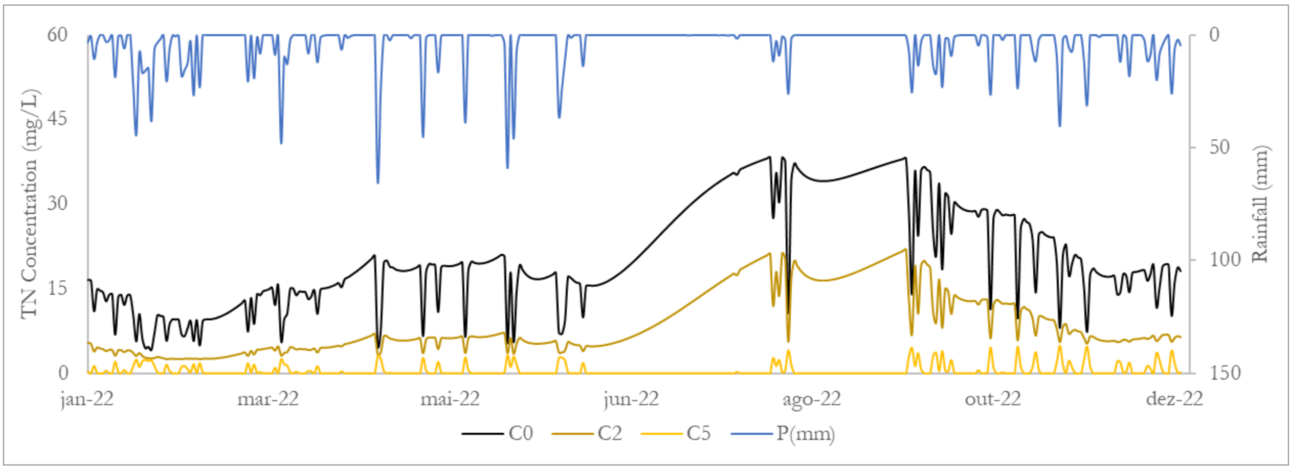



Figure 126 – Comparing TN concentrations for base (C0) and prognosis Scenarios 2 and 5 (mg/L)

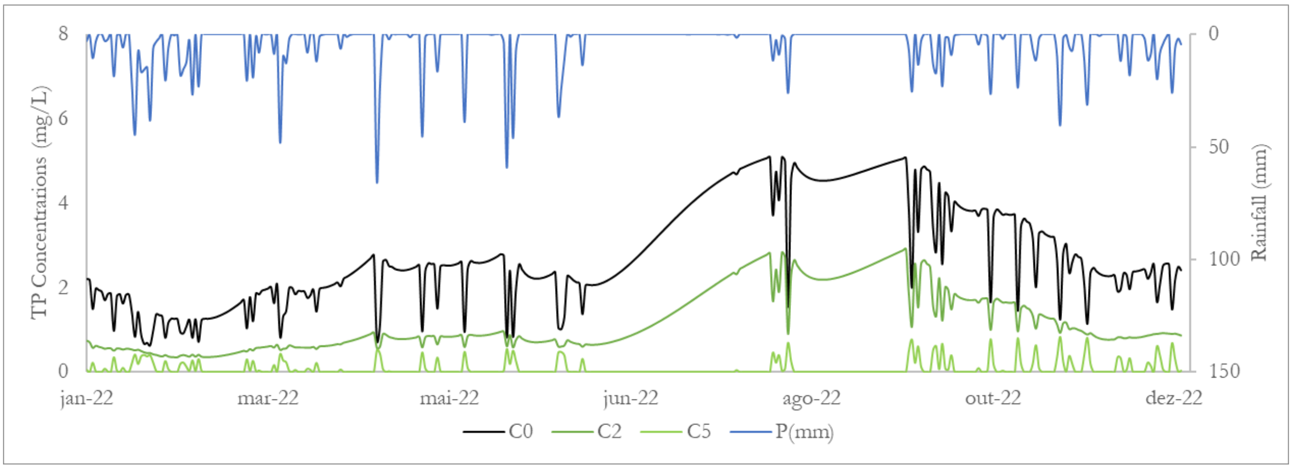



Figure 127 – Comparing TP concentrations for base (C0) and prognosis Scenarios 2 and 5 (mg/L)

Now, Scenario 6 was developed and applied to answer the following question: “would there be a way to achieve better levels of permanence below the 30 mg/L level without setting impractical goals, as well as having 100% of the watershed population attended by the sanitation system?”. In this Scenario, non-served population would be 8,4% of the total watershed population and RU efficiency would be 80% (instead of original 50%).

So Figure 128, Figure 129 and Figure 130 show the results for BOD, TN and TP respectively. From that, it is possible to see that concentrations are reduced by 50% and when looking at the 30 mg/L reference limits, from June to October BOD concentrations hardly achieve that limit. This Scenario keeps RUs still active when infrastructure works are increased, allowing it to treat contaminated base flow.

Finally, Figure 131 shows BOD permanence of each scenario and from that it is possible to conclude that when taking the 30 mg/L reference limit, all three scenarios are satisfactory because they only exceed this limit about 5% of the time. If considering the Class 3 CONAMA 357 regulation limit (BOD < 10 mg/L), Scenarios 4 and 5 exceed limits only 15% of the time, while Scenario 6 exceeds the concentration half of the time, becoming unsatisfactory.

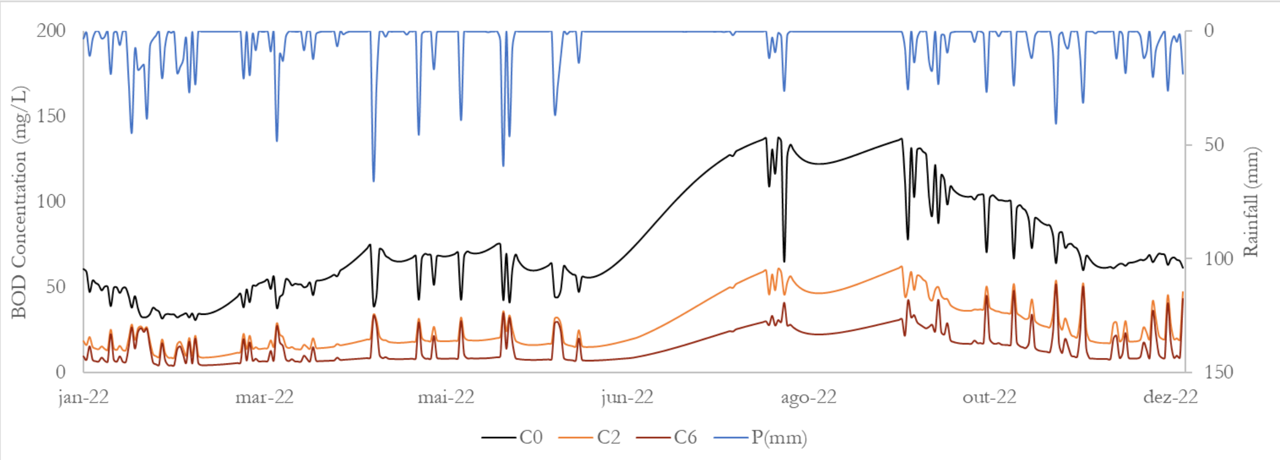



Figure 128 – Comparing BOD concentrations for base (C0) and prognosis Scenarios 2 and 6 (mg/L)

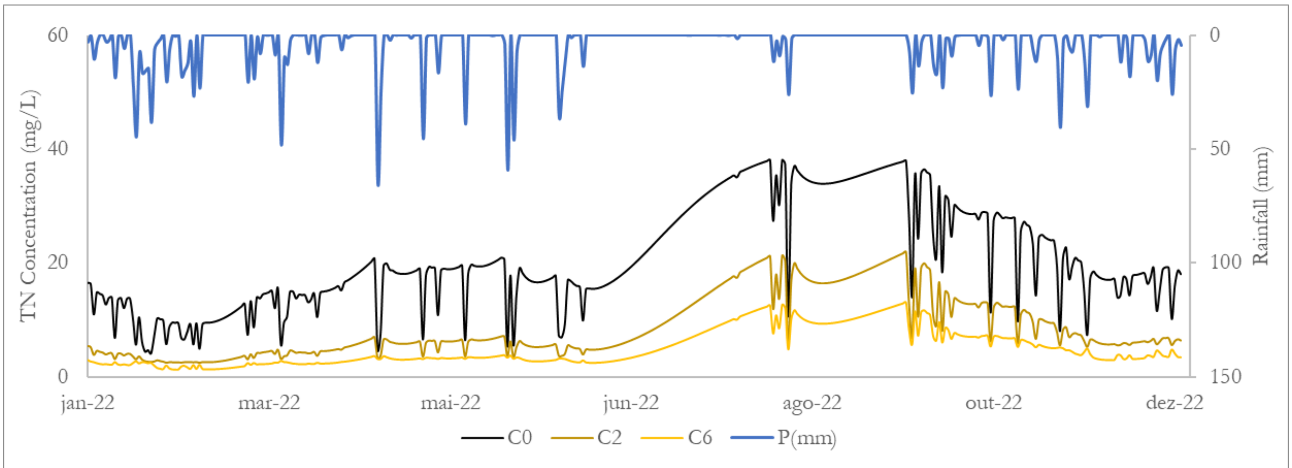



Figure 129 – Comparing TN concentrations for base (C0) and prognosis Scenarios 2 and 6 (mg/L)

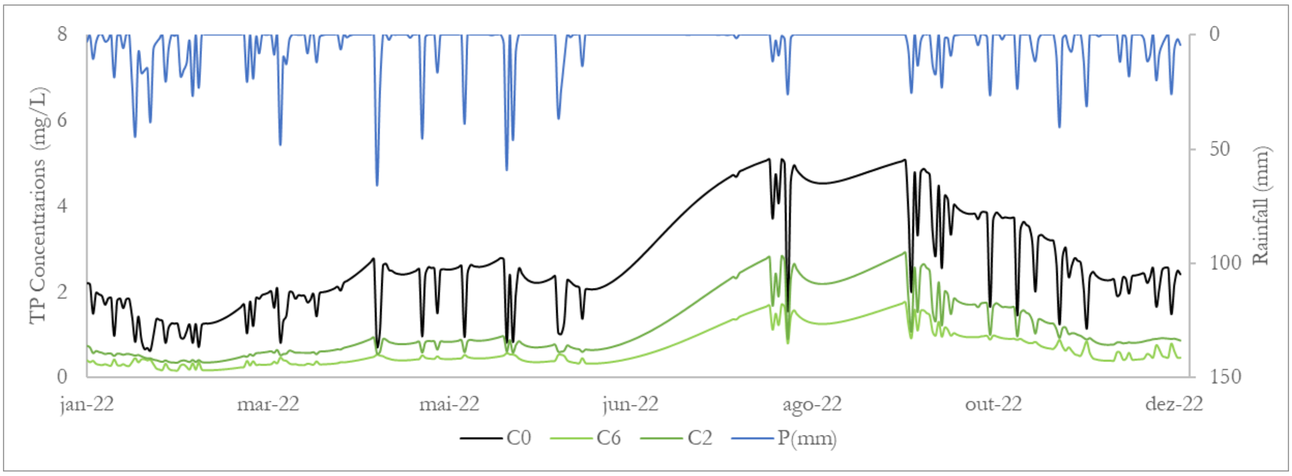



Figure 130 – Comparing TP concentrations for base (C0) and prognosis Scenarios 2 and 6 (mg/L)

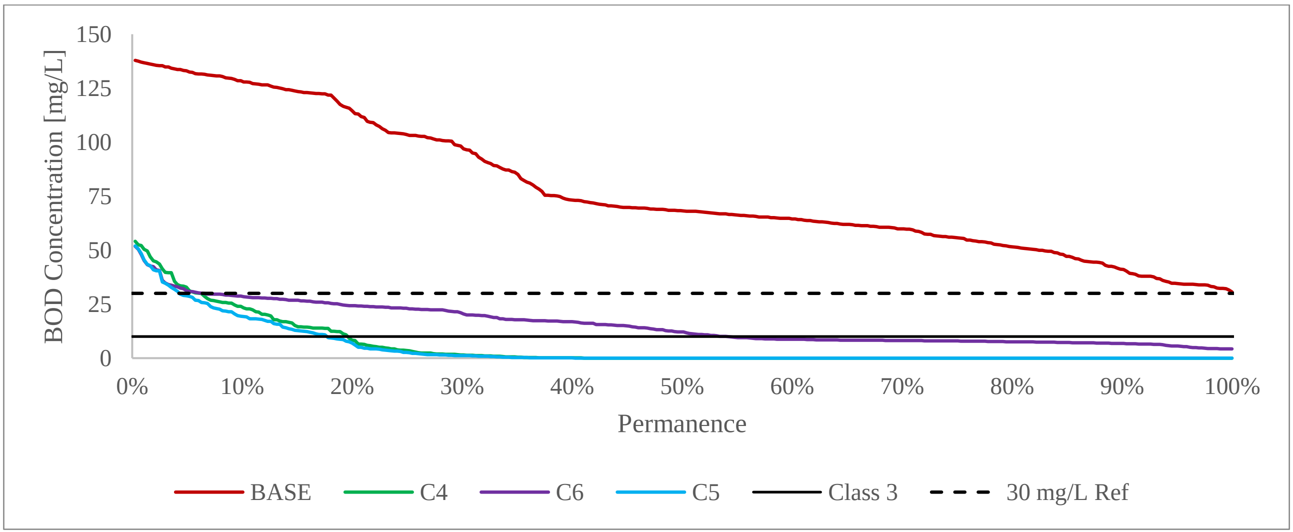



Figure 131 – BOD concentrations – Comparing Base, C4, C5 and C6 Scenarios (mg/L)

Further prognosis scenarios could still be studied for reducing nonpoint pollution exclusively in the future, while applying BMP as mentioned in section 3.7 BEST MANAGEMENT PRACTICES. This fact can be possible using CAbc-QUAL and verifying critical points that contain the highest levels of wash off loads.

# CHAPTER 7

## DISCUSSIONS AND CONCLUSIONS

*"If there is magic on this planet, it is contained in water"*

Loren Eiseley

As seen, nonpoint pollution is taking its place of importance (as it should) in recent years in many investigations and articles around the world. Nevertheless, this analysis still lacks attention and actions in Brazil. When investigating and developing this model, some questions were taking place and now can be further discussed.

i. Is it possible and relevant to model pollutants loads seasonally?

With the aid of the study cases, it was possible to visualize and understand the pollutants behavior along the year. For instance, in Ipanema, which has low levels of base concentrations, concentrations rose during rain events (fringes up), as expected as accumulated pollutants were washed from the watershed surface constantly. Jaguaré presented the opposite behavior: because of its high levels of base pollution when rain events took place, concentrations reduced (fringes down) for the dilution characteristics.

It was possible to represent behavior during the dry season too, showing the pollutants accumulation along large periods without rainfall, in the case of Jaguaré we could see concentrations increasing many times due to large amounts of sewage. During wet seasons, for both studies, concentrations reduced because of the increased base flow. Either way, the model approach proved to be efficient, fast, easy to handle and provided reliable results for a dynamic hydrological and quantitative modeling, representing each case with each particularity.

As for its relevance, fully understanding the seasonal behavior has huge impacts on watershed management as it is possible to predict for how long pollutants reach **desired or undesired limits** and to take actions towards set goals and manage control infrastructure and bmp's. So, yes it has been proved that it is possible and relevant to model pollution dynamics in a watershed for a long time series and observe seasonal behaviors.

ii. Is it feasible to consider different land uses and sanitation systems (infrastructures) to compute pollutant loads in a complex watershed?

One of the effects of urbanization is the constant changes in land use. Even in places with settled rates of urban areas, the disorganized growth already made impacts when considering sanitation systems planning. Higher, inferior, or intermediate standard occupations already took place where infrastructure did not. These facts make this issue complex and account for many variables.

Both study cases presented highly differentiated sanitation systems, infrastructures, and land uses. While Ipanema is in a highly protected area, with forest, farming, and urban area and only 3 release points, Jaguaré is placed in a highly urbanized area (close to 98% urban area), with a sanitation infrastructure under implementation. The land use and occupation could be fairly represented by each particular EMC or UL coefficient and was adequate to each specific characteristic.

The sanitation system and infrastructure contrast were accurately represented by the non-served population inputs and point releases when existing. Water quality responses to inputs (parameters and data) vary for each case and they respected monitored data. Therefore, the model was able to represent each case with satisfactory results.

iii. How striking is the rain spatial and time distribution when it comes to nonpoint pollution?

As seen, nonpoint pollution presents great variability in terms of **time** and **space**. Each hydrological year is different, whereas rain distribution varies along the year itself, extreme events cannot be predicted sometimes. and rain distribution changes throughout many years (e.g., some years are rainier than others). Rainfall spatial distribution can affect hydrological models performance and therefore, water quality results. These effects are more obvious in a large catchment area.

However, as seen in the Ipanema study case, the use of radar rainfall showed not as significant as expected when the merging method cannot be applied because results from the rain gauges network did not differ much from the radar as shown when modeling the hydrology. As for rainfall time parameter, results variations were evident when comparing results from a permanent model (QUAL UFMG) to CAbc-QUAL in the self-depuration analysis. So, rainfall distribution affects water quality with each second it occurs, and using average flows over time shall result in underestimations in water quality because of wash off events.

iv. Is it possible to calibrate the seasonal behavior of water quality in complex watersheds considering singular and sparse data and simple parameters?

As seen, monitoring is a vital part of the nonpoint pollution assessment. One of the main problems is related to the high costs to perform continuous and long campaigns as well as automatic sampling during rain events. When it came to analyzing data from Ipanema, it was a concern that the sparse and singular campaigns (11 campaigns in 7 months) would not provide good calibration, which proved not to be true. Even though we recommend more campaigns and rain events samples to corroborate EMC values, simulated results came really close to expectations.

Likewise, it was often seen that ULs were given and used as a whole input number in load management, as seasonality is not discussed, which means it was commonplace to see papers giving total load potentials for a whole year. In terms of EMC, those parameters were only used for monitoring events and assessments, frequently being undertaken for modeling possibilities. Those are simple and easy to calibrate parameters, plus they have already been studied for years, which provides good literature to compare results, as done with both presented study cases.

v. Is it possible to evaluate structural and non-structural actions to reduce water pollution or improve water bodies quality status?

As seen through the study cases, the model makes it possible to evaluate the spatial distribution of the pollutants, which means that it allows the identification of the critical areas where actions should take place in order to reduce water pollution. For instance, in Jaguaré it was possible to see that the upstream catchment area was far more polluted than downstream. But executing infrastructure works and the lack of space to locate the *in-situ* treatment facility upstream made this possibility unfeasible. Nevertheless, the model allows the users to study a handful of possibilities.

vi. Is it possible to evaluate the real effect of mitigation devices, like the so-called Best Management Practices (BMP), as a tool to increase water quality conditions in different watersheds?

When studying Jaguaré case study, a prognosis for an *in-situ* treatment facility installation was analyzed in CAbc-QUAL. Results show that it can correctly estimate new concentrations based on efficiency (%) and flow capacity ($m^3/s$) and account for primary estimations and predictions for the BMP choice of location. The model still needs to be able to treat only direct surface runoff. That new criteria could be applied for studying different BMP, such as bioretention areas, wetlands, permeable pavement, etc. This new feature could give an even larger application to CAbc-QUAL and be used as a primary and pre-project tool to help identify, better place and model BMP effectiveness. This way, nonpoint pollution prevention devices shall be better designed, engineered and more easily applied.

## *7.1 IPANEMA MAIN CONCLUSIONS*

Even though in the Ipanema study case monitoring data was sparse and hard to obtain, results showed good reliability and response to input data compared to what was seen during campaigns (and even with what was seen in years before that). For this case, its many changes throughout the years (and currently ongoing), made it clear that automatic sampler data from rain events are needed for better EMC verification and to corroborate the behavior from nonpoint pollution concentrations presented.

Firstly, the hydrological model was calibrated to reduce the differences between total volume inflow and outflow to a minimum, and to produce an average error of approximately zero for the entire series.

Secondly, for water quality assessment, BOD concentrations were always lower than the quantification limits (2 mg/L), which indicate that BOD is not the best parameter to quantify organic matter in this watershed because it cannot exhibit its variations in detail. For TP, monitored concentrations were higher than the reference limits for intermediate environments. Besides that, TP had to be reduced for calibration, which can indicate that phosphorus near the reservoir would be imprisoned by algae and then driven outside of the reservoir by the flux.

TN simulation reproduced adequate concentrations, even though EMC releases were some times higher than expected from those from the literature. As for TSS, it was not possible to affirm that concentrations of TSS are directly related to nonpoint pollution and erodibility of the watershed, which is expected. More data should be gathered to make clearer inferences.

Finally, a simple BOD/DO model was performed using Qual-UFMG. It was seen that only where the main tributary reached the main course, BOD for Qual-CAbc was higher, suggesting that for that tributary, some fate and transport mechanisms might be present, especially because that tributary has little flow and high concentrations of BOD being released. All of this suggests that transport/fate rates are low and do not alter water quality.

### *7.2 JAGUARÉ MAIN CONCLUSIONS*

In contrast, good monitoring data distribution for Jaguaré watershed from many years of observations made a data statistical analysis possible. Despite its “anthropized” hydrology, results fitted very monitored data. One more time, it was possible to observe that some peaks of the observed data were not possible to be replicated, because of differences between rain and flow time step. On the other hand, average error also tends to zero when comparing yearly inflow and outflow.

As for the load model, it was possible to see that the behavior of the concentration changes from what was observed in Ipanema Watershed. In Jaguaré, as expected, base concentrations are many times higher than wash off loads for the current situation. Base loads are many times higher than wash off loads and the upstream watershed has more surface pollution than the downstream (after Jorge Ward point).

Furthermore, it was possible to infer that unlikely self-purification could happen in Jaguaré, as the DO concentrations were so low that aerobic bacteria cannot perform such transformations under these conditions, also the low raters of velocity and therefore the low rates of re-aeration, the amount of *in natura* sewage makes harder for the process of self-purification, even in anaerobic state, to happen.

Finally, a prognosis study for the future was performed and a modal year was determined to make such estimates and simulations. The extreme reduction in domestic sewage flows for the prognosis was such that it transformed the behavior of pollutants throughout the hydrological year. The diffuse pollution is expected to be of the highest importance once the domestic sewage is taken care of.

The prognosis for the current ongoing project “Novo Rio Pinheiros” is highly effective and can be used to study all sub-basins in Pinheiros, which are the areas that need more attention in order to obtain better results. Jaguaré (as well as the other sub-basins in Pinheiros) would benefit a lot from automatic sampling.

## *7.3 FINAL HIGHLIGHTS AND RECOMMENDATIONS*

The Unit Loads and EMC obtained, despite being exclusive for each case study, have consistent values, as shown in literature and in accordance with their respective land use and occupation. In any case, all of them bring up the extremely important and frequently overlooked matter: monitoring, especially during rain events. All major watersheds need frequent monitoring in many relevant points (i.e., the have to be spatially distributed) to help identify critical places and as proved by CAbc-Qual, periods of elevated concentrations.

Also, the presented results draw attention to a whole lot of possibilities. Firstly, it was discussed that point sources which are easily trackable, and their releases are already considered in existing regulations (e.g., CONAMA 357). Nevertheless, it was possible to see in the Ipanema study case, that even though releases were inside what was allowed for each industry and for each constituent, the combination between the sewage release and farming (as it consists of great areas of agriculture) inputted high concentrations of phosphorus and nitrogen. So, can regulations be more adequate when dealing with all types of pollution?

Would it be possible, through this work, to establish TMDL for managing watersheds in Brazil and developing a new way to regulate the watershed pollution, involving all branches of society, the users and governance? For example, implementing fertilizers input limits to farming in order to prevent eutrophication in reservoirs, implementing inspections in large commercial and industrial areas (like construction sites, auto repairs, car washes, etc.), and increasing sweeping and cleaning frequency in urban areas.

To sum up, we have developed a different approach on how to consider and estimate pollutant loads for nonpoint pollution assessments, which proved to provide reliable and accurate results, both with a large set of monitored data as well as with sparse and few campaigns. Besides, using two strikingly different watersheds, the obtained results also proved that seasonal and dynamical approach into nonpoint pollution modeling works, and it is an advance in the field of watershed management.

Further prognosis scenarios could still be studied for exclusively reducing nonpoint pollution in the future, while applying BMP or Nature Based Solutions (NBS). This can be possible using CAbc-QUAL and verifying critical points that contain the highest levels of wash off loads.

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