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SIMULATION OF SURFACE WATER POLLUTION IN A WATERSHED SUBJECT TO PROGRESSIVE URBANIZATION

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Abstract: The large alterations in land use and occupation associated with progressive urbanization tend to increase the direct and indirect impacts on the water quality of streams and rivers. Relying on various land occupation scenarios in a watershed subject to progressive urbanization, considering a horizon of 30 years, this study estimated the pollutant loads of all its sub-basins, simulated the dispersion of pollutants along its main watercourse and estimated the pollutant loads at the basin's outlet. The method used to estimate the pollutant loads was adapted from that proposed by Schueler (1987), with inclusion of the Soil Conservation Service method (SCS, 1973) to estimate the surface runoff or excess rainfall. The dispersion of pollutants in the principal stream was simulated by numerically solving the advection-diffusion equation, after discretization by finite differences, employing a computational code implemented in the Visual Basic language. The ranking of the pollutants in decreasing order of gross annual loads for the 30-year scenario showed the highest production of suspended sediments (510 to 4882 tons/year), followed by BOD with 42 to 172 tons/year and nutrients (13 to 62 tons/year for total nitrogen and 6 to 29 tons/year for nitrite and nitrate). Zinc accounted for the smallest discharge, with 1.7 to 7.9 tons/year. In turn, in the ranking by the correlation coefficient between the loads of each pollutant and the advance of urban occupation, represented indirectly by the number curve (NC) parameter, BOD was most sensitive to urban expansion, since it had the strongest correlation with the number curve (about 41%). TSS and zinc were less influenced by the occupation processes of the watershed, although they were closely correlated with rainfall. In general, the method used in this study can help planners make decisions about urbanization guidelines and zoning rules. The results indicate the importance of establishing policies for moderate occupation of watersheds and reduction of the diffuse pollution caused by urbanization.

Keywords: Pollutant load; diffuse pollution; progressive urbanization; land use and occupation

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INTRODUCTION

The advance of urban occupation of rural areas or areas with native vegetation changes the natural conditions, through cutting, grading, filling and creation of microdrainage systems (gutters, storm drain inlets and galleries) that modify the runoff flow directions. Besides this, the runoff in urban areas tends to carry a wide range of pollutants, generally in higher concentrations than found in rural areas. The final destination of these substances is the watercourses flowing through valleys and other low-lying areas.

Urban areas generate large amounts of hydrocarbons, heavy metals (zinc, copper and lead, among others), organic matter, nutrients (nitrites, nitrates and phosphorus), bacteria, lubricating oils and greases, plastic, paper and inorganic sediments. The harm caused to soil and water by these pollutants and wastes is aggravated by the presence of areas with exposed ground and lack of urban infrastructure such as paved roads, sewer systems and drainage systems, along with the existence of construction work in progress (Poleto & Castilho, 2008).

Besides the aspects that aggravate the pollution generated in urban areas, Von Sperling (2007) stressed that even in preserved watersheds, the water quality is affected by sedimentation from runoff. This results from the action of rainfall on the soil particles, which are carried to water bodies. Besides this, the dissolution of substances by water in contact with the soil causes alterations in the water quality of rivers and streams. Anthropic interference generally increases the potential of runoff to carry pollutants. Therefore, the forms of land use and occupation affect the quality of surface and ground water.

Measures to control diffuse pollution are more laborious than in the case of point source pollution. By their nature, they require land use planning, in particular considering the impacts of urbanization. With respect to the timing of the impacts on water bodies, diffuse urban pollution can generate acute or cumulative disturbances. The acute effects occur in short periods, normally resulting from one or a few pollutant release events. The cumulative impacts are caused by the gradual buildup of pollutants and become critical when the total load of a particular pollutant surpasses the threshold considered safe, as established in legal or regulatory rules. Among these cases, the accumulation of nutrients and heavy metals is of particular concern. At present, the cumulative effects are estimated by from the monthly or annual loads of the various pollutants generated in the watershed.

To apply the estimation method proposed here, we chose a partially urbanized watershed, that of Lageado Stream. The generation of diffuse pollution in this basin is of particular interest regarding managing the water supply to the city of Uberaba (Minas Gerais state), since the basin has latent urbanization tendencies (Costa, 2015). Furthermore, Lageado Stream is one of the main tributaries of the Uberaba River, whose mouth is located upstream from the city's current water catchment site.

Considering various future progressive urbanization scenarios, we estimated the pollutant loads generated in all the sub-basins forming the Lageado Basin. This allowed simulating the dispersion of pollutants along the stream's course and finally computing the pollutant loads and concentrations at the basin's outlet. The parameters analyzed were: TSS; BOD; total Kjeldahl nitrogen (N_{total}), nitrite and nitrate (NO_2^- and NO_3^-), total phosphorus (P_{total}); and the heavy metal zinc (Zn).

STUDY AREA

The city of Uberaba (MG), located in the Triângulo Mineiro mesoregion, is currently tending to expand toward the northeast, more specifically in the basin of Lageado Stream, a tributary of the left margin of the Uberaba River. Its location in relation to the urban grid is depicted in **Fig. 1**. This map reveals that urban fragments are already established in the southwestern part of the basin, and incipient occupied areas also are located in its south and center. Besides this, the basin's outlet is located upstream from a storage dam built on the Uberaba River that forms a reservoir for the municipal water supply. This reveals that intensified urbanization in the basin can pose a threat to the raw water quality at the current catchment site along the Uberaba River.

Satellite images indicate that Lageado Basin is currently occupied by native vegetation, pastures, planted fields, rural dwelling sites and residential areas. For this study, the basin was divided into 48 sub-basins, 24 of them with single inflow points in Lageado Stream and the other with diffuse inflows. This division was based on the natural drainage system and the planialtimetric map of the basin.

METHODS

Occupation scenarios

The current situation of urban occupation served as the starting point for simulating the pollution loads generated in the basin. Starting from this baseline situation, we incorporated future scenarios of probable urbanization, using primary data, such as subdivision projects already registered with the Uberaba Municipal Environmental Secretariat (PMU, 2004) and earth movements visualized by recent satellite images, as well as secondary data obtained from the technical staff of

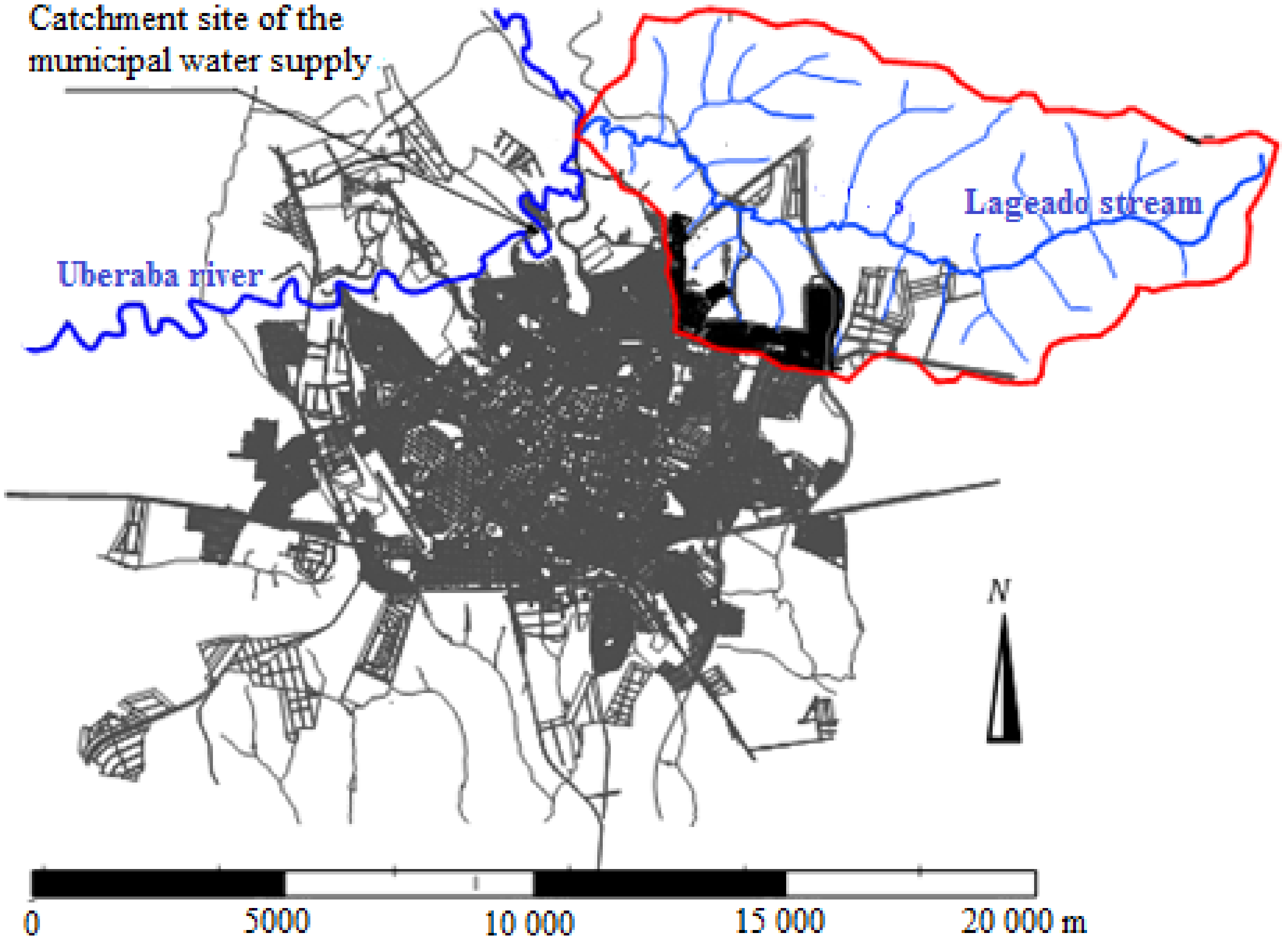
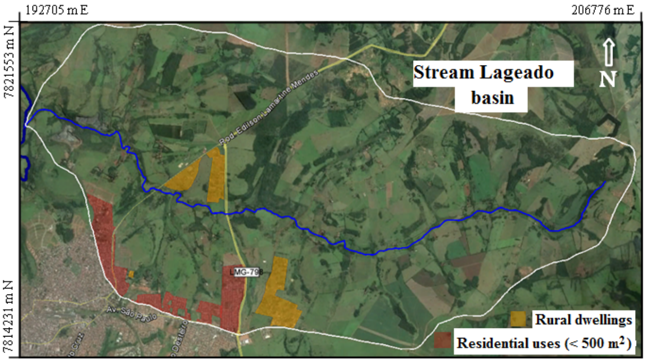


Fig. 1 Lageado Basin and its location in relation to the Uberaba urban network, showing the areas of incipient occupation and the catchment site of the municipal water supply.

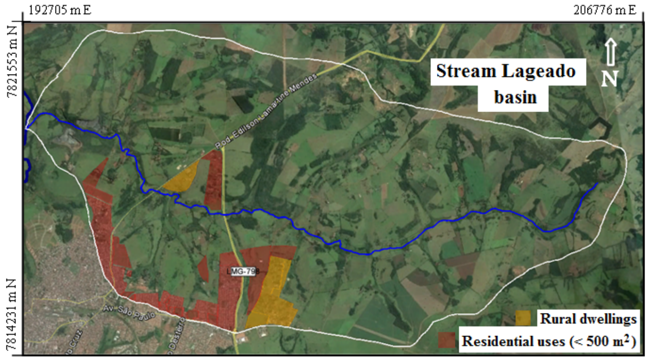
the municipal water and sewer department. Besides this, the future scenarios were based on the hypotheses that the urban growth will mainly occur along the north-south axis, with greatest residential density in lots covering up to 500 m^2 and rural dwellings, and preferential expansion on the left bank of Lageado Stream. Another important assumption was that existing paved roads will act as preferential vectors for growth of the city.

The establishment of the urbanization scenarios was progressive, using intervals of 10 years, conciliated as those that will possibly produce more perceptible changes in the land use. These scenarios, illustrated by **Fig. 2**, were generated for a horizon of 30 years, allowing quantifying the temporal evolution of the pollutant discharges in each of the 48 sub-basins composing the drainage area of Lageado Stream.

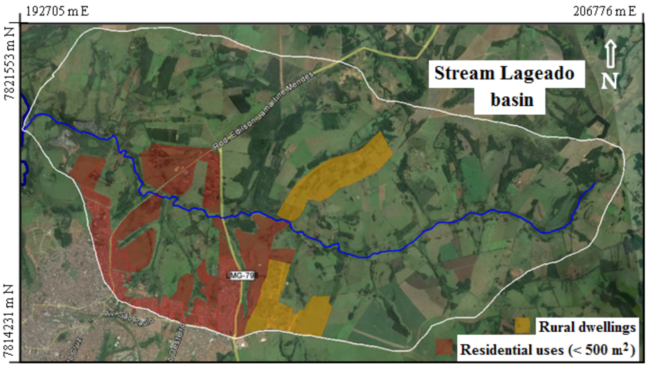
We also analyzed an extreme urbanization scenario, defined as total occupation of the basin for residential uses (lots up to 500 m^2), only with conservation of the legally required permanent preservation areas (APPs in the Portuguese initials). Since Lageado Stream and its tributaries are at most 10 m wide, the APPs along them must have width from the shoreline of 30 m on each side of the watercourses, as specified in the Brazilian Forest Code (Brasil, 2012). This maximum urbanization scenario is the most unlikely (total occupation of the basin, especially on the stream's right margin, will probably take many years), and is not associated with a specific time horizon, since this correlation could cause large uncertainties. Nevertheless, the objective of introducing it is to demonstrate how critical urbanization can lead to substantial increases in pollutant loads.



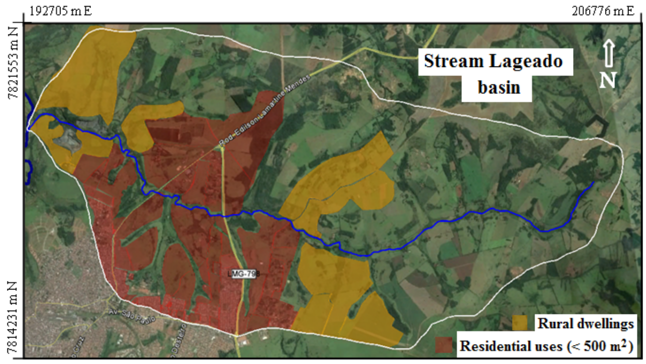
(a) Current occupation scenario



(b) Occupation scenario for a 10-year horizon



(c) Occupation scenario for a 20-year horizon



(d) Occupation scenario for a 30-year horizon

Fig. 2 Urban occupation scenarios for the Lageado Basin.

Estimates of the pollutant loads and concentrations in the sub-basins

To estimate the pollutant discharges generated in each of the 48 sub-basins, we used the method proposed by Schueler (1987). This method was used by Meneses Filho & Tucci (2003) to predict the pollution loads generated under various occupation conditions of a micro-basin in the metropolitan region of Porto Alegre, Brazil. An advantage of this method is that it relies on parameters that can be obtained easily in practice, such as rainfall series and morphometric parameters of the basin of interest, besides allowing quantification of areas referring to different land uses. The use of this set of attributes makes the method of Schueler useful to predict the different steps of urban occupation processes, helping managers make decisions and formulate guidelines for urban growth.

In general lines, the method is based on two steps. The first consists of estimating the runoff, based on precipitation and occupation of the basin for different uses. The second involves quantifying the pollutant loads at the outlet of each sub-basin. These loads are the discharges of determined substances, measured by mass (kilograms or tons) per unit of time (seconds, hours, months or years). In its original form, Schueler's method is based on **Eqs (1)** and **(2)**.

$$Q = P.Pj.Cs.A \qquad (1)$$

$$L = Q.C \qquad (2)$$

In these equations, Q is the runoff volume generated in a specified time interval, P is the rainfall depth in that interval, Pj is the fraction of rainfall events able to produce runoff, the factor A is the watershed area and Cs is the runoff coefficient, a dimensionless parameter that expresses the ratio between effective rainfall and rain depth. The variable L denotes the runoff load of the pollutant generated in the time interval analyzed. Finally, the term C is the average pollutant concentration in the runoff.

The climate variable that feeds the model is precipitation, expressed in rainfall depth. The variations of this independent variable can be obtained from historical series, which can present anywhere from hourly to yearly variations. In this study, we used the monthly precipitation series from two rain gauge stations, code numbers 1947026 and 83577 (INMET, 2014), translated to the centroid of the Lageado Basin. **Figure 1** depicts the location of these gauges. These historical records tally the rainfall depth in each month over a horizon of 457 months (38 years).

Like any weather element, rainfall is a random phenomenon whose forecast for future scenarios over the medium and long terms can only be estimated by probabilistic methods. Here we used Monte Carlo simulation, in which a large number of results is generated from randomly generated inputs of a variable. This enables predicting a range of probable values for the dependent variable targeted for quantification. In this study, the dependent variable is the series of pollutant loads (L) estimated for each of the probable urbanization scenarios. The monthly rainfall series figures act as one of the inputs subject to many random variations. More specifically, the monthly values of P of the series were multiplied by random coefficients, so that the rainfall depths could be reduced to the minimum value or increased to the maximum value of the series. This procedure established a highly random character for the synthetic rainfall series, over the medium and long terms.

In **Eq. (1)**, the volume Q of the runoff generated per time interval is calculated according to the precepts of the rational method, which uses the runoff coefficient (Cs) as the weighting factor to transform rainfall depth into runoff flow. This method provides maximum volumetric discharge values and can only be applied to small watersheds, with drainage area not greater than 3 km^2. Besides this, **Eq. (1)** also requires as an input the fraction of rainfall events that generate runoff. In this context, the factor Pj cannot always be predicted. The literature has indicated magnitudes of Pj between 0.5 and 1, with a typical value of 0.9 for the United States in general and for average yearly rainfall volumes (Meneses Filho & Tucci, 2003; Tomaz, 2006). For brief isolated downpours, the value of 1 is normally adopted. On the other hand, note that the product of P, Pj and Cs in **Eq. (1)** represents the excess rainfall or runoff (Pe). This term can also be calculated by other methods, including applicable to larger areas than those for which the rational method is considered valid. In light of this, here we used the method proposed by the Soil Conservation Service (SCS, 1973).

The SCS method estimates the runoff in function of the rainfall depth (P) and an empirical coefficient called the curve number (CN), which introduces the potential for combination of different soil types and land uses to generate runoff. The CN is a dimensionless factor that theoretically can vary from 0 to 100, where large values are associated with greater runoff values, generated by the occurrence of soils with low infiltration and/or impermeable areas in the watershed. Since each of the 48 sub-basins has distinct combinations of soil type and land use, here we work with a CN value resulting from the combination of the soil maps and land use/occupation maps. The different combinations provide sub-areas that act as weights for formation of the resulting CN (CN_{RES}), which can be calculated by **Eq. (3)**.

$$CN_{RES} = \frac{CN_1 \cdot A_1 + CN_2 \cdot A_2 + ... + CN_n \cdot A_n}{A_1 + A_2 + ... + A_n} = \sum_{i=1}^{n} \frac{CN_i \cdot A_i}{A} \quad (3)$$

Equation (3) expresses the weighted average, where A is the total area of the sub-basin, CN_i and A_i are, respectively, the curve number and the sub-area corresponding to a combination between soil type and land use, and n is the number of different sub-areas in a given sub-basin. Next, **Eqs (4)** and **(5)** govern the runoff.

$$S = 25.4 \cdot \left(\frac{1000}{CN_{RES}} - 10 \right) \quad (4)$$

$$P_e = \frac{(P - 0.2 \cdot S)^2}{(P + 0.8 \cdot S)} \quad for\ P \geq 0.2 \cdot S$$
$$P_e = 0 \quad for\ P < 0.2 \cdot S \quad (5)$$

In **Eq. (4)**, S is the soil water retention potential, a variable that reflects the tendency of rainwater to be contained in depressions, attenuating runoff by forming pools that can gradually infiltrate the soil or evaporate. **Equation (5)** indicates that runoff (Pe) is only generated when the rainfall depth (P) exceeds the retention potential by 20%. In this sense, it is possible through this method to determine which rainfall events in a series really generate runoff. In both equations, S, P and Pe are measured in millimeters (mm).

With the introduction of the SCS method in the Schueler method, the volumetric discharge of runoff from a sub-basin with area A is calculated by **Eq. (6)**.

$$Q = P.P_j.C_s.A \equiv P_e.A \quad (6)$$

Finally, with the introduction of Q in **Eq. (2)**, the loads (L) of pollutants can be quantified for synthetic rainfall series, imposed as input data of the problem. All that is necessary is to stipulate values for the concentration (C) of each pollutant carried by the runoff. **Table 1** reports typical values for the seven pollutants most commonly found in runoff.

From the data contained in **Table 1**, it can be concluded that the values of C are not exactly known. Instead, they vary around a median, according to specific coefficients of variation (CV). Because of this uncertainty, we also applied Monte Carlo simulation techniques for the pollutant concentrations, to generate mass quantities for scenarios where the possible values of C fluctuate randomly between minimum and maximum values, according to the coefficients of variation of each parameter.

Table 1. Typical concentration values of pollutants in runoff. Source: Urbonas and Stahre (1993)

Parameter	Residential use		Commercial use		Industrial use		Non-urbanized	
(mg/L)	Median	CV	Median	CV	Median	CV	Median	CV
BOD	10	0.41	7.8	0.52	9.3	0.31	0	0
TSS	101	0.96	67	1.1	69	0.85	70	2.9
Zn	0.135	0.84	0.154	0.78	0.226	1.1	0.195	0.66
N_{Total}	1.9	0.73	1.29	0.5	1.18	0.43	0.965	1
NO_2^- and NO_3^-	0.736	0.83	0.558	0.67	0.572	0.48	0.543	0.91
P_{total}	0.383	0.69	0.263	0.75	0.201	0.67	0.121	1.7

From the pollutant discharge values, quantified for synthetic monthly precipitation series, it is also possible to estimate the concentrations of pollutants entering Lageado Stream from its 48 point and diffuse tributaries. This allows computing the concentrations of pollutants injected in Lageado Stream (C_{INJ}) according to **Eq. (7)**.

$$C_{INJ} = L / Q_{INJ} \quad (7)$$

In **Eq. (7)**, L is the pollutant load, calculated by **Eq. (2)**, while Q_{INJ} represents the flow contributed to Lageado Stream. We took as a base the synthetic flow series generated by a regionalization procedure. As in the case of the rainfall levels, these flows were altered by the same random factors varying between 0.20 and 1.50, generating a wide range of synthetic hydrographs representing the inflow to Lageado Stream.

In short, techniques to generate synthetic series, obtained by random multipliers, duly controlled between maximum and minimum values, were imposed for precipitation (P) and inflows to Lageado Stream (Q_{INJ}). Besides this, the technique was also applied for the concentration of pollutants in the runoff (C of **Table 1**). In this way, 1000 combinations were simulated between distinct synthetic series, for each of the 48 sub-basins of the Lageado Basin. This extensive number of results allowed extracting probable discharges and average pollution graphs.

Dispersion of pollutants along Lageado Stream

It was necessary first to ascertain the topography of the hydrological system, indicating the 48 affluents (point and diffuse), the nodes (representing the confluences between the affluents and Lageado Stream) and the stretches (the stream was divided into 21 segments).

The affluent flows and pollutant concentrations in the 48 sub-basins were used as input data to simulate the dispersion of pollutants along Lageado Stream. Monte Carlo simulation was used to estimate the flow series and pollutant concentrations at the outlets of the 48 sub-basins for the next 30 years (2015 to 2045, with urbanization scenarios of 10, 20 and 30 years), generating 1000 random series. The input data for the flows were the regionalized synthetic series for the past 38 years (1977 to 2014). For each of the 48 tributary sub-basins of Lageado Stream, based on the set of 1000 random flow series from 2015 to 2045, an average hydrograph was extracted, representing the inflows to the main channel of the stream. For pollutant concentration, the input for the simulations consisted of only one concentration series for each pollutant in each period. In this single series, each monthly pollutant concentration corresponded to the average of the 1000 values of the random series.

In general, starting from the mass balance of pollutants at the nodes, we simulated the dispersion of each pollutant along Lageado Stream by applying the advection-diffusion equation, which considers transient, diffusion, advection and source terms. We implemented a solution algorithm based on the finite differences method in the Visual Basic language, assuming some simplifications for numerical solution of the equation, namely:

- one-dimensional flow and stationary conditions for the affluent water quality, on a monthly time scale;
- permanent and uniform flow (use of Manning's formula to associate flow with the hydraulic characteristics);
- fixed discretization of 50 m along Lageado Stream;
- fixed coefficient of longitudinal dispersion (diffusion term) for all 21 stretches, equal to 10 m^2/d (this order of magnitude was based on the study of Salla *et al.*, 2014b);
- equal coefficients representing the source term, such as degradation, sedimentation, reaeration, nitrification and adsorption, in all the stretches, with the values taken from Salla *et al.* (2014a; 2014b), because they performed studies in watercourses with similar morphological and pollution level characteristics regarding point and diffuse sources.

For the BOD parameter, the processes of degradation, reaeration and sedimentation were considered, while for the parameter P_{total}, degradation and sedimentation were used. For the parameters TSS and Zn, the sedimentation and adsorption processes were adopted. Finally, nitrification was considered for the nitrogen series.

Estimate of the pollutant loads at the outlet of the Lageado Basin

The application of the method proposed by Schueler (1987) in Lageado Basin as a whole led to direct estimates of the pollutant discharges at river's mouth. In the context of this study, those discharges are indicators of the extent to which urbanization in the Lageado Basin can increase the pollutant loads upstream from the present water catchment site for the city of Uberaba, whose storage dam is located 4 km downstream from the basin's outlet.

RESULTS AND DISCUSSION

Estimate of the pollutant loads and concentrations in the sub-basins

The urbanization process tends to intensify the production of a huge range of pollutants. Nevertheless, the main constituents can be grouped into sediments, organic matter, nutrients and heavy metals. The distributions of these are associated with average concentrations flowing into the water body for all the constituents. In this study, the values were extracted for intervals of 10 years (situation now and 10, 20 and 30 years in the future). As an example, **Fig. 3** depicts the results of the spatial distributions for a 10-year urbanization scenario, for probable mean loads (in tons/month) and concentrations (mg/L) generated in each sub-basin contributing to Lageado Stream. The left-hand column represents the loads and the right one the concentrations injected at the outlet of each sub-basin.

According to **Fig. 3a**, the occurrence of BOD in nearby water bodies with exclusively non-urban land use, such as pastures and native vegetation, is negligible. Urban occupation tends to increase the resulting loads and concentrations. The maximum BOD load for the 10-year scenario in the urban area was 1.3 to 1.5 tons/month and the maximum concentration was de 7.2 to 8.0 mg/L.

Sediments are an important category of pollutants generated in urban zones. Although they also can originate from natural terrain, depending on aspects like slope, plant cover, soil compaction and surface erosion, production of sediments can be increased by urban development, mainly during construction projects, caused by land grading, plant clearance and the presence of aggregates like gravel and sand. When urbanization is already established, generation of sediments tends to be lower than from undeveloped areas and construction sites. Nevertheless, the sources of sediments are not eliminated, and the phenomenon of adsorption can lead to agglutination of particles with other pollutants, such as pesticides, microorganisms and heavy metals. This characteristic makes the mineral solids generated in urban areas potentially hazardous to watercourses. As shown in **Fig. 3b**, TSS was responsible for the highest discharges and also the highest concentrations (maximum loads of 25 to 28 tons/month and maximum concentrations of 90 to 96 mg/L). This translates into direct negative impacts on the water quality of Lageado Stream, along with another equally serious problem, namely more intense silting of the Uberaba River, principally upstream from the dam for catchment of water to supply the city of Uberaba.

Nitrogen is a natural constituent of proteins and other biological compounds. Therefore, its presence in domestic and industrial wastes and animal excrement considerably increases its levels in water bodies that receive urban runoff. The main problem caused by the buildup of nitrogen in surface water is the growth of algae. At high concentrations, it can lead to eutrophication in stretches of rivers and streams with high residence time due to slow current. Besides this, the biochemical process of transforming ammoniacal nitrogen into nitrite and then into nitrate consumes oxygen in water bodies. The fertirrigation of farmed areas is also another important diffuse source of nitrates. According to **Fig. 3c**, the maximum load of N_{total} for the 10-year scenario in the urban area was 0.39 to 0.43 tons/month and the maximum concentration was 1.6 to 1.7 mg/L. In turn, the maximum load of NO_2^- and NO_3^- for the 10-year scenario in the urban area was 0.17 to 0.19 tons/month and the maximum concentration was 0.65 to 0.70 mg/L (see **Fig. 3d**).

The phosphorus present in surface waters can have natural origin, such as leaching from rocks and decomposition of organic matter. The anthropic contributions from urban areas can come from domestic and industrial wastes, animal excrement and fertilizers. Urban areas are also subject to clandestine discharge of domestic sewage, carrying soaps and detergents, another important source of phosphorus. High levels of phosphorus in lentic environments cause proliferation of algae and eutrophication. According to **Fig. 3e**, the maximum load of P_{total} for the 10-year scenario in the urban area was 0.070 to 0.077 tons/month and the maximum concentration was 0.31 to 0.34 mg/L.

Leaching from construction materials, roofing and painted structures, vehicle exhaust and atmospheric deposition are the main sources of heavy metals from urban regions. In the particular case of roofs, exposure to the weather causes leaching of heavy metals.

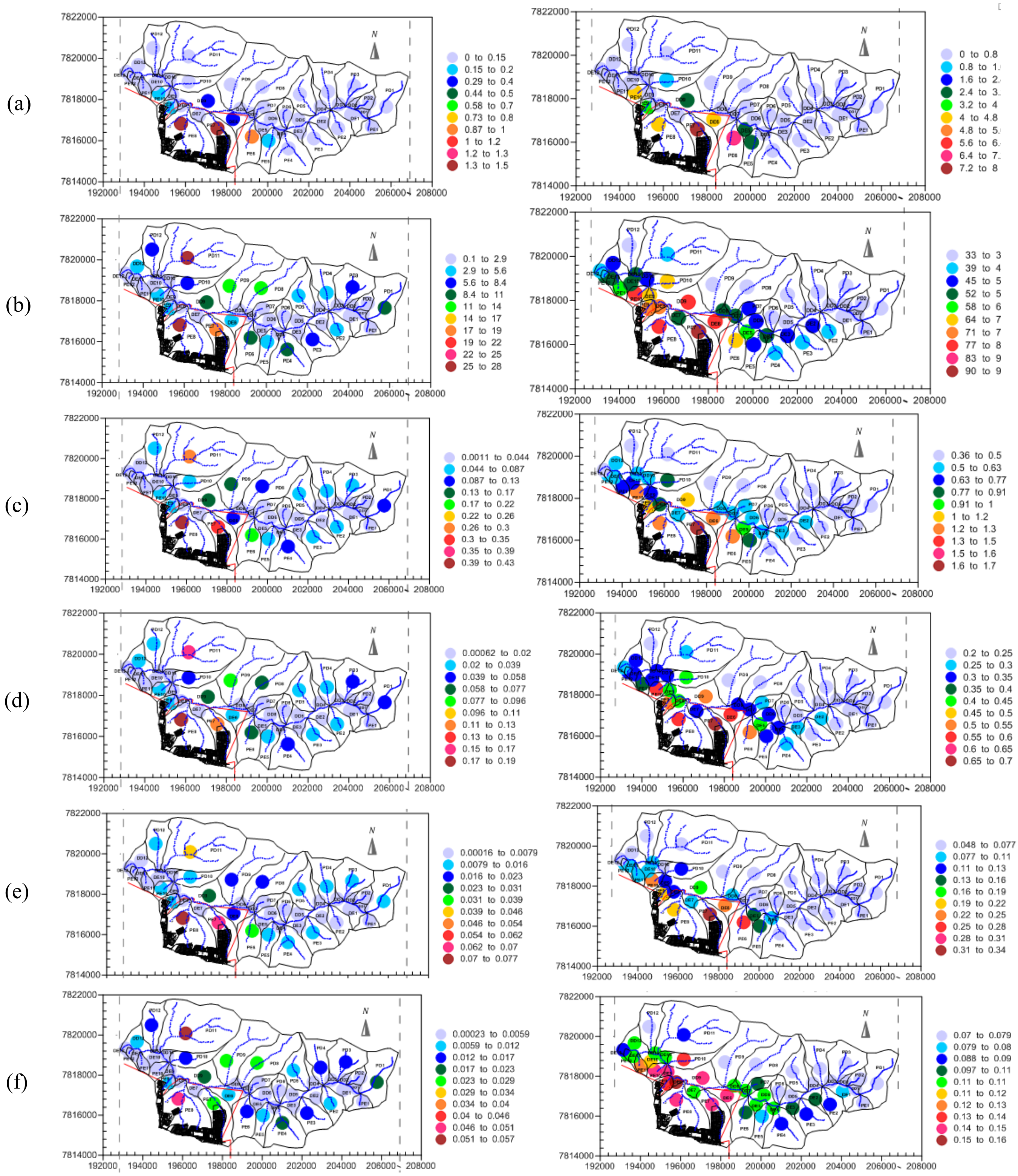
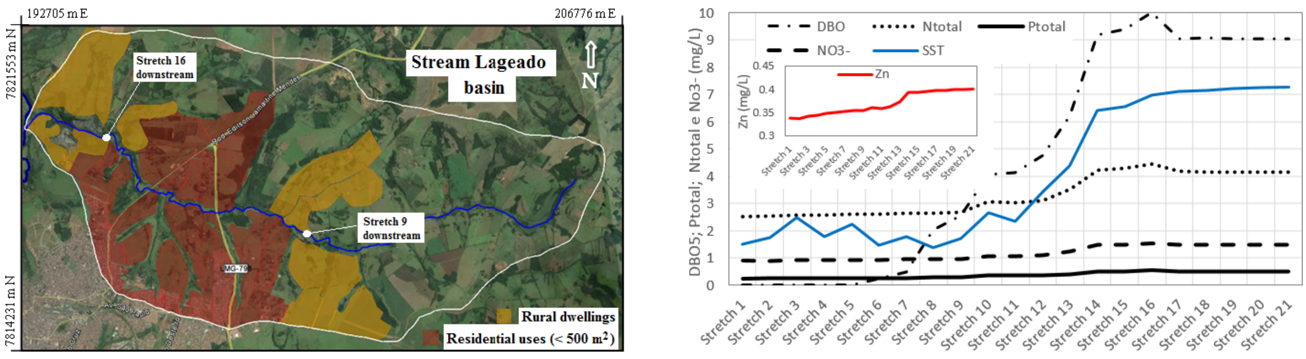


Fig. 3 Spatial distributions, for a 10-year urbanization scenario, of the probable mean loads and concentrations generated in each sub-basin contributing to Lageado Stream for the parameters: (a) BOD, (b) TSS, (c) N_{total}, (d) NO_2^- and NO_3^-, (e) P_{total} and (f) zinc.

In general, enameled clay roof tiles tend to produce higher concentrations of lead, while metal roofing sheets tend to generate more zinc (due to galvanization). Zinc is a constituent found naturally in the soil, and is widely used in manufactured products. In general, goods made of or plated with zinc are highly durable. For this, besides roofing, zinc can be found in vehicle brightwork, electrical and electronic devices, hardware items, building coatings and tires. In the last case, the particles from tire wear contain considerable amounts of



(a) (b)

Fig. 4 (a) Identification of stretches 9 and 16 of Lageado Stream; (b) Longitudinal distribution of the concentrations of pollutants in Lageado Stream for the 30-year urbanization scenario.

zinc, and lower quantities of copper and lead. In general, these particles only stay suspended in the air for short periods, so they build up on paved surfaces and are carried away by rainwater, directly affecting the watercourses that receive this runoff. As can be seen in **Fig. 3f**, the maximum load of Zn for the 10-year scenario in the urban area was 0.051 to 0.057 tons/month and the maximum concentration was 0.15 to 0.16 mg/L.

Simulated dispersion of pollutants

Irrespective of the scenario analyzed (10, 20 or 30 years of urbanization), the longitudinal distribution of the concentrations of the pollutants along Lageado Stream clearly revealed the influence of urban settlement on the water quality. Using the scenario of 30 years of urbanization as an example (**Fig. 4a**), the influence of urbanization became more intense as of stretch 9 (**Fig. 4b**). Starting with this segment, there was a clear trend for higher concentration of all the pollutants in function of urbanization with residential lots up to 500 m^2, reaching the maximum level near stretch 16. As of stretch 16, in the scenarios with rural residences (where less runoff is generated and natural self-purification is relatively more influential), the concentrations of most pollutants gradually declined. The exceptions to this pattern were total suspended solids and zinc. For these two parameters, the point-source and diffuse inputs prevailed over the physical process of sedimentation of inorganic material and adsorption of zinc.

For the 30-year urbanization scenario, in all the stretches the levels of suspended solids and total phosphorus were higher than the limits established by Resolution 357/2005 from the National Environmental Council (CONAMA) and Joint Normative Deliberation 01/2008 from the State Environmental Policy Council/State Water Resources Council (COPAM/CERH-MG) for class 2, which is less restrictive than class 1. In this analysis, we considered classes 1 and 2, since a large portion of Lageado Basin consists of permanent preservation areas and also due to the importance of the stream for the municipal water supply of Uberaba.

The TSS parameter reached a maximum of 250 mg/L (well above the upper limit of 100 mg/L defined by the resolutions), while the total phosphorus reached a maximum value of 0.53 mg/L (also well above the maximum threshold of 0.1 mg/L defined in the resolutions). Finally, the BOD level was also above the maximum regulatory levels starting with stretch 12, reaching 10 mg/L in stretch 16. As depicted by **Fig. 4a**, this region is the most urbanized in the 30-year scenario.

Estimate of the loads and concentrations of pollutants at the outlet of Lageado Basin

This section presents the simulated series with temporal evolution of the loads and concentrations for a horizon of 38 years, subject to changes in land use because of urban occupation. The series presented here correspond to the average of 1000 possible scenarios, involving different random combinations for rainfall, runoff flows and concentrations of substances in rainwater.

- BOD and TSS

Figure 5 summarizes the most probable temporal variations of the loads and concentrations of BOD and TSS in the outflow of Lageado Stream. These series are superimposed on the graph of evolution of urbanization in the watershed. According to these predictions, over a horizon of 38 years the urbanization index will reach 38.23%. This value refers to the sum of residential occupation (with lots covering up to 500 m^2) and rural dwellings (assumed to be mainly residential, with lot areas of 2000 m^2 or greater). The first pattern that stands out is the synchrony between the increase of urbanization and increase in the order of magnitude of the loads and concentrations of BOD entering the stream. This synchrony is not clear for TSS, although the influence of the urbanization process is not negligible on generation of TSS, presenting a direct relationship with heavy downpour events.

Among the statistics that can be extracted from these series are the maximum estimated values and average values for each 10-year interval. At the end of the simulated horizon, the average BOD levels will rise by 579% (6.8 times in relation to the baseline period) and the average input concentrations at the confluence with the Uberaba River will increase by 453% (5.5 times in relation to the starting period). With respect to TSS, from the initial scenario to that longer than 30 years, the average loads should increase by 64% (1.64 times) and the average concentrations should rise by 34% (1.34 times). It is interesting to note that this increase of 34% is very near that for urban use after 30 years, of 28.95% (from 9.29% to 38.23%).

The simulated load series allowed plotting cumulative probability curves, indicating the chances of matching or surpassing a determined discharge threshold. In general, these curves were shifted to the right with greater urban occupation, indicating rising possibilities of a determined discharge being exceeded with expanded land use. In this analysis we also added the fifth scenario, where urbanization covers the entire watershed except for the permanent preservation areas along the banks of the streams.

An initial visual inspection reveals the BOD (**Fig. 5a**) is most sensitive to the expansion of urbanization, since the curves are spaced further apart. The scenario of maximum urbanization tends to cause a large displacement of the curve to the right, reflecting a considerable increase in the generation of organic matter in the extreme occupation circumstance.

The probability curves computed for TSS discharges (**Fig. 5b**) indicate less relevant alterations until the 20-year scenario. As of then, the greater density of residential zones and rural dwellings along the lower and middle courses of Lageado Stream, with highlight on urban expansion on its right bank, produces larger shifts of the curves. In comparison with the probable scenarios up to 30 years, the hypothetical scenario of extreme occupation shows a markedly greater displacement of the curve, in particular indicating that occupation of areas near the headwaters will greatly increase the discharge of suspended solids at the basin's outlet (see **Fig. 5b**).

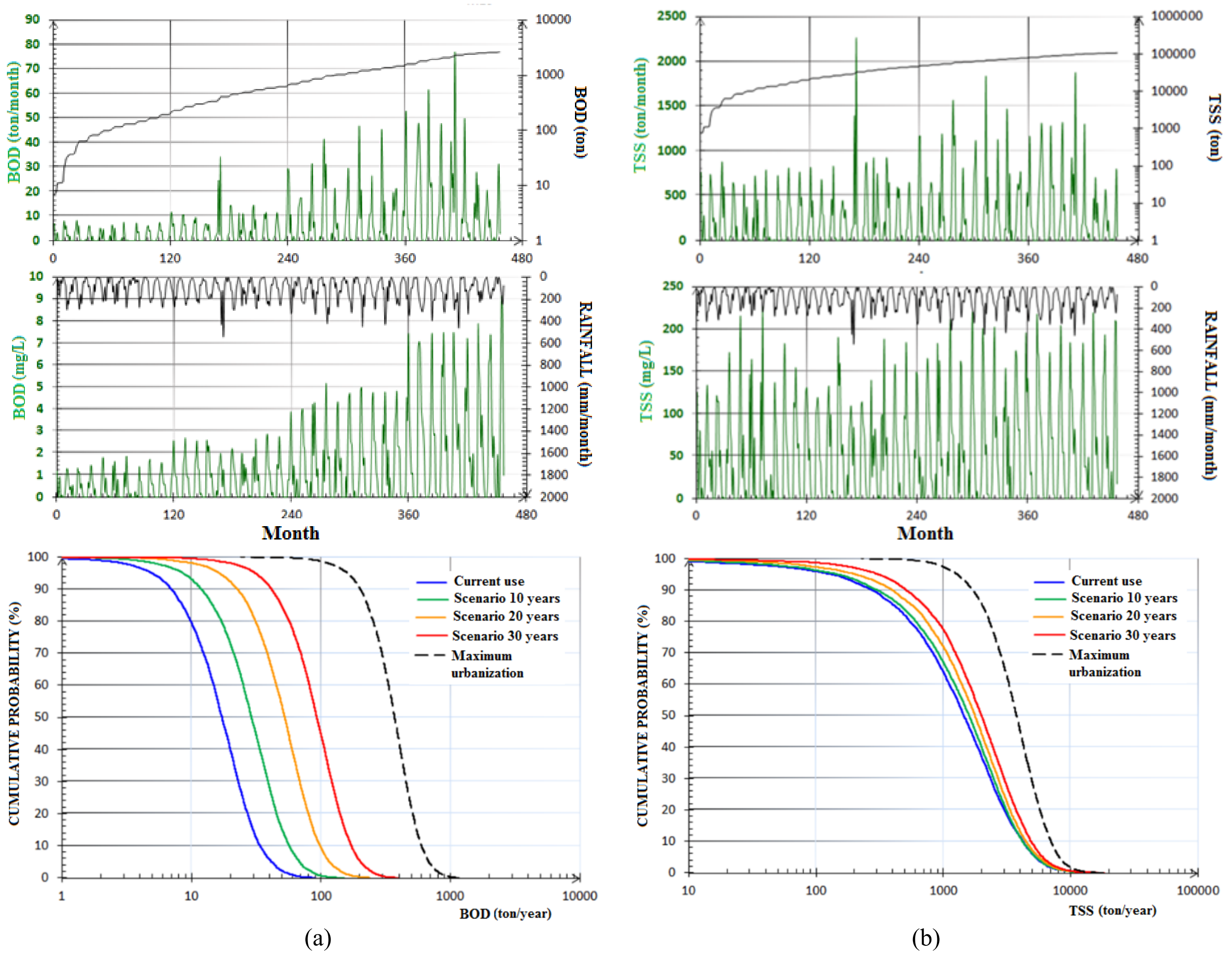


Fig. 5 Probable series of loads and concentrations at the outlet of Lageado Basin, considering a 38-year horizon for: (a) BOD; and (b) TSS.

Although it is not possible to determine with precision the loads that will actually be generated in each scenario, because rainfall is subject to random changes, the probability curves enable establishing the upper and lower limits of occurrence. With this it is possible to identify the most probable ranges of the pollutant loads in the different urbanization scenarios. For BOD, analysis of the values of the ninth and first deciles shows that in the current situation the likelihood is 80% of the discharges being between 7.0 and 33.8 tons/year. For the future urbanization scenarios, this same percentage likelihood is associated with loads between 11.94 and 56.86 tons/year (for 10 years), 22.66 and 98.12 tons/year (for 20 years), and 41.56 and 172.23 tons/year (for 30 years). In the final scenario of total urbanization, the 80% probability range is between 201.78 and 597.82 tons/year.

With respect to TSS, the same analysis reveals that in the 10-year scenario, there is an 80% chance that the discharges will be from 227 to 4250 tons/year, while for the other intervals this likelihood is associated with loads between 303 and 4200 tons/year (for 20 years), 397 and 4472 tons/year (for 30 years) and 510 and 4882 tons/year (for 38 years). Finally, in the maximum urbanization scenario, the 80% region of the graph pertains to the range from 1706 to 7041 tons/year. These differences with the 30-year scenario call attention to the importance of preserving areas near the headwaters, drained by the first third of the course of Lageado Stream.

Total nitrogen, nitrite and nitrate

Excessive discharges of nutrients at the outlet of Lageado Basin can result in conditions propitious for proliferation of algae in lentic zones of the Uberaba River. The first of these zones, just downstream from the confluence of the two watercourses, is the catchment reservoir for water supply to the city of Uberaba. The proliferation of algae reduces the penetration of sunlight in the water, and for places with low turbulence like reservoirs, the dissolved oxygen input rates decline drastically. The probable loads and concentrations of total nitrogen, nitrite and nitrate are presented in **Fig. 6**.

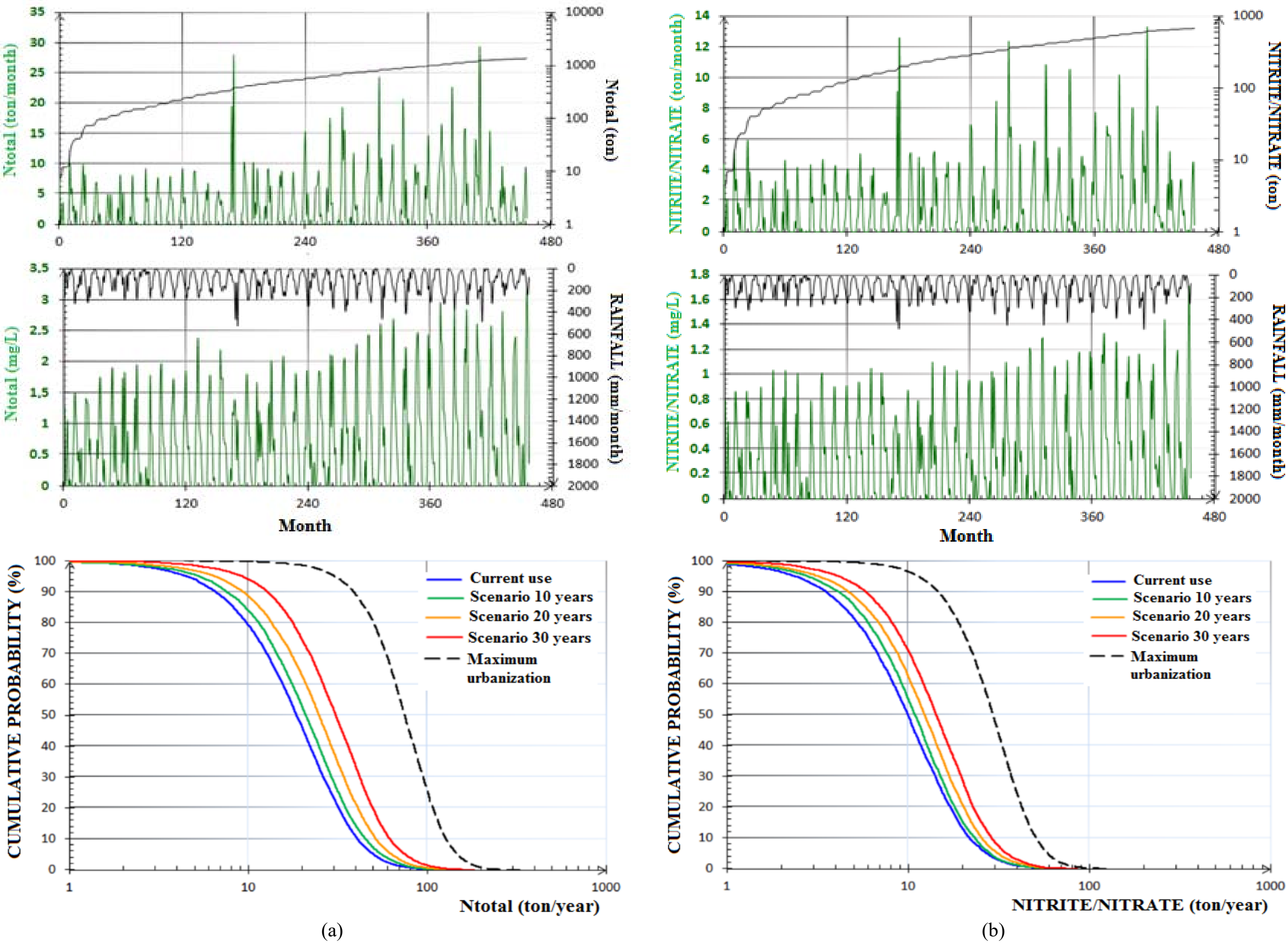


Fig. 6 Series of probable loads and concentrations in Lageado Basin, considering a 38-year horizon for: (a) N_{total} and (b) nitrite and nitrate.

The correlations between the mass discharges and level of urbanization were similar for the total nitrogen and nitrate (as shown by joint analysis of the graph of occupation percentage in **Fig. 5** and the graph of loads in **Fig. 6**). A strong relationship exists between the pollutant loads generated with rainfall. Analysis of the average loads and concentrations within each decade reveals that urban expansion causes increases in the loads and concentrations of all the parameters (see **Figs 6a** and **6b**).

The simulations indicate that from the initial occupation scenario to the scenario after 30 years, the total nitrogen should increase by 105% (2.05 times) and the average concentrations by 72% (1.72 times). For nitrite and nitrate, the increase in loads should be 83% (1.83 times) and the concentrations should rise by 53% (1.53 times) in relation to the present condition.

With respect to the probability curves, for total nitrogen the analysis of the loads between the ninth and first deciles indicates that during the first 10 years of urbanization, an 80% probability exists that the discharges will be between 6.56 and 40.77 tons/year. For the other intervals, the 80% probabilities for loads are between 7.55 and 45.14 tons/year (for 20 years), 9.34 and 51.51 tons/year (for 30 years) and 12.77 and 61.57 tons/year (for 38 years). In the maximum urbanization scenario, the values corresponding to the 80% likelihood of occurrence are between 38.70 and 127.39 tons/year. The same analysis for nitrite and nitrate indicates an 80% probability of loads between 3.51 and 21.74 tons/year (in the first 10 years); 4.13 and 23.38 tons/year (in 20 years); 4.68 and 25.42 tons/year (for 30 years); 5.84 and 28.76 tons/year (after 30 years), while in the extreme scenario the values are between 14.59 and 50.87 tons/year. Note that the probable discharge ranges do not vary greatly with the urban land use scenarios, except for the maximum occupation scenario.

Total phosphorus (P_{total}) and zinc (Zn)

Like nitrogen, excessive discharges of phosphorus at the outflow from Lageado Basin can result in conditions propitious for the reproduction of algae in lentic zones of the Uberaba River. The series of probable loads and concentrations of total phosphorus are presented in **Fig. 7a**.

The correlations between the mass discharges and level of urbanization for total phosphorus are similar to those for total nitrogen and for nitrite and nitrate (compare **Fig. 6** with **Fig. 7a**).

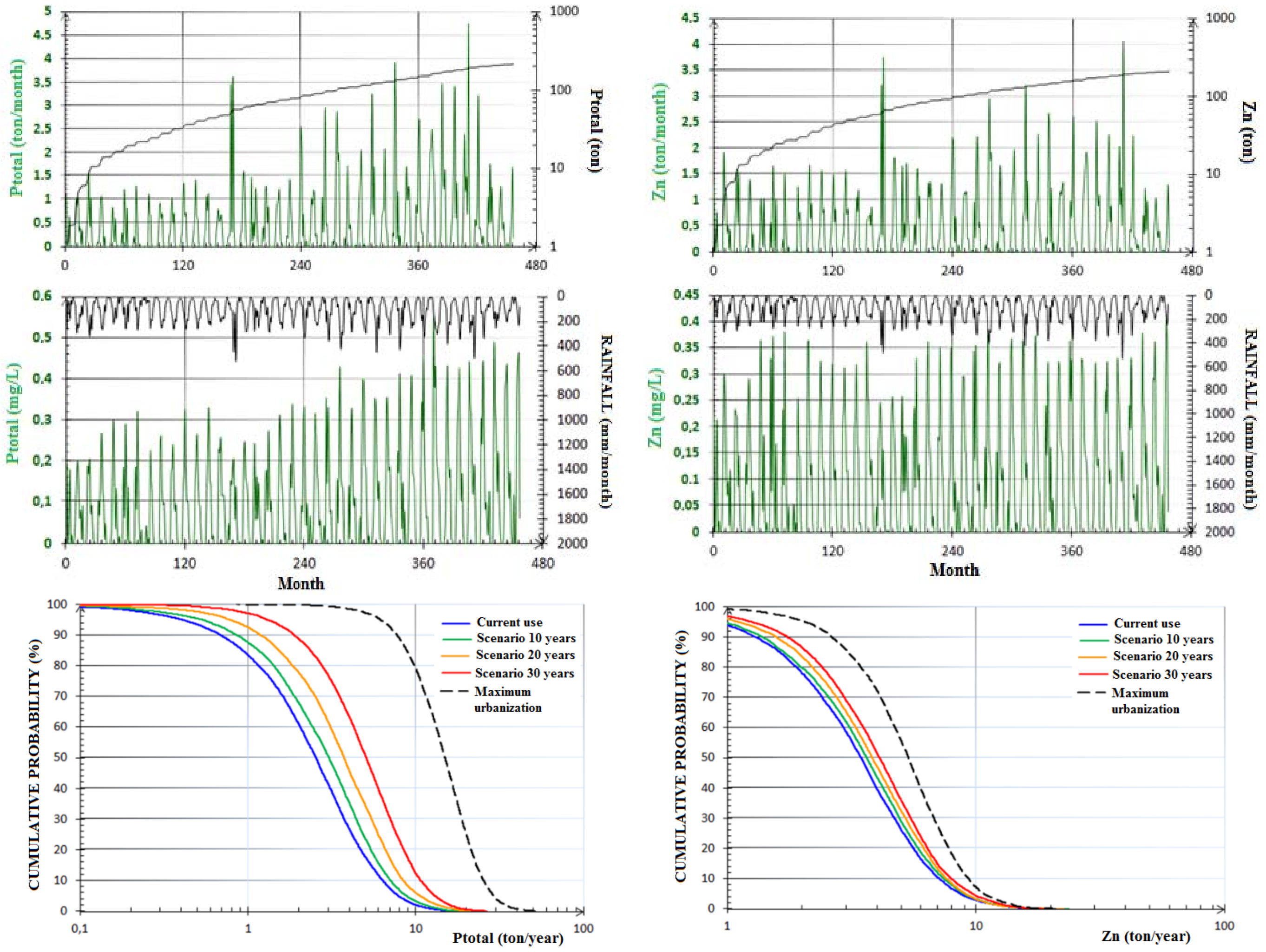
The simulations indicate that from the initial occupation scenario to that after 30 years, the average loads of phosphorus are more sensitive, since in that time interval the average loads will rise by 143% (2.43 times) and the concentrations will increase by 103% (2.03) times. With respect to the loads between the ninth and first deciles, there is an 80% chance that the total phosphorus parameter will be between 0.68 and 6.34 tons/year (from present use until 10 years in the future); 0.85 to 7.06 tons/year (in 20 years); 1.18 and 8.43 tons/year (in 30 years); and 1.88 and 10.67 tons/year (after 30 years). For the same probability, in the extreme scenario the loads would be between 7.72 and 25.35 tons/year.

Regarding zinc, the urban contributions to the levels of heavy metals in the surface waters come mainly from construction projects (paints, coatings and roofing materials), vehicles (brightwork, paints, lubricants and tires), asphalt and dry and wet atmospheric deposits. The synthetic series of probable zinc discharges are shown in **Fig. 7b**.

In a general analysis of **Fig. 7b**, the concentrations of zinc at the mouth of Lageado Stream do not indicate sensitivity to urban occupation, since the variations are within a single spectrum over the 38 years considered. Nevertheless, comparison of the results for average loads and concentrations within each decade reveals a gradual increase in both measures for zinc.

The low sensitivity of zinc to the effects of urbanization was confirmed by the statistical treatment of the data, since between the initial and final scenarios, the increase in load was 49% (1.49 times), while the concentrations increased by 23% (1.23 times). Despite this, in absolute quantitative terms, zinc accounts for the highest injection rates of heavy metals at the Lageado Stream-Uberaba River confluence when compared to lead and copper. The concentrations of zinc are almost two times the order of magnitude of the concentrations of copper and about eight times higher than those of lead.

As in the case of the other pollutant categories, the cumulative probability curves of the zinc parameter allow identifying probable ranges for the discharges at the outlet of Lageado Basin. According to **Fig. 7b**, although the discharges are higher, the limits of the ranges of occurrence are not significantly different. Hence, there is an 80% probability that the loads will be between 1.29 and 7.10 tons/year (in the 10-year scenario); 1.38 and 7.39 tons/year (in 20 years); 1.57 and 7.6 tons/year (in 30 years); 1.74 and 7.93 tons/year (in 38 years); and finally between 2.63 and 9.33 tons/year (in the maximum urbanization scenario).



(a) (b)

Fig. 7 Probable series of loads and concentrations in the Lageado Basin, considering a horizon of 38 years, where: (a) P_{total} and (b) Zinc.

Comparison of pollutants with the legal limits

The parameters TSS and total phosphorus will be above the present limits set by CONAMA Resolution 357/2005 and COPAM/CERH-MG Normative Deliberation 01/2008 throughout the period analyzed. Besides this, the results show a trend for progressive increase in the concentrations over time (more strongly for total phosphorus).

With respect to the BOD parameter, in the 10-year urbanization scenario the concentration will be lower than the permissible limit established by the same two resolutions (see **Fig. 5a**), for classes 1 and 2. However, for the 20-year urbanization scenario, the concentration will be higher than the limit set by the two resolutions, considering stream class 1 (BOD5 $\leq$ 3.0 mg/L), but below the limit for class 2 (BOD5 $\leq$ 5.0 mg/L). In turn, in the 30-year urbanization scenario, this parameter will be above the limits for both classes 1 and 2.

Finally, for the organic nitrogen and nitrite parameters, the concentrations will be lower than the limits established by the resolutions throughout the period evaluated (see **Fig. 6**).

Ranking of the pollutants

We established a ranking of the seven pollutants in Lageado Basin, classifying them from two standpoints: decreasing order of gross annual discharges and the strength of their correlation with urbanization. In the first case the pollutants are ranked from greater to lesser impact on the Uberaba River, while in the second they are classified from higher to lower sensitivity to urban occupation. **Table 2** presents the ranking of the most probable pollutant discharges, including the alterations resulting from the various scenarios for occupation of the watershed.

Table 2. Ranking of the main annual discharges at the outlet of Lageado Stream

Order	Pollutant	Category	Discharges (tons/year) with 80% probability of occurrence scenarios				
			Present	10 years	20 years	30 years	Max. Occupation
1	TSS	Sediment	227 to 4250	303 to 4200	397 to 4472	510 to 4882	1706 to 7041
2	BOD	Org. matter	7 to 34	12 to 57	23 to 98	42 to 172	202 to 598
3	N_{total}	Nutrient	7 to 41	8 to 45	9 to 52	13 to 62	39 to 127
4	NO_2^- e NO_3^-	Nutrient	4 to 22	4 to 23	5 to 25	6 to 29	15 to 51
5	P_{total}	Nutrient	0.68 to 6.34	0.85 to 7.06	1.18 to 8.43	1.88 - 10.67	7.72 to 25.35
6	Zn	Heavy Metal	1.29 to 7.10	1.38 to 7.39	1.57 to 7.60	1.74 to 7.93	2.63 to 9.33

Table 3. Ranking of the pollutants by their correlation with the curve number (CN)

Order	Pollutant	Correlation coefficients	
		Runoff	CN
1	BOD	0.82	0.41
2	P_{total}	0.98	0.24
3	N_{total}	0.94	0.20
4	NO_2^- and NO_3^-	0.95	0.17
5	TSS	0.95	0.14
6	Zn	0.96	0.12

Based on the probable discharge values, the leading pollutant from Lageado Basin is sediments, followed by the parameter associated with the presence of organic matter (BOD), and then nutrients. Zinc accounts for the lowest discharge by mass.

The generation of pollutants in a watershed susceptible to urbanization basically depends on rainfall levels, and more specifically, the tendency for rain to produce runoff. If precipitation events do not result in runoff, the pollutants do not reach the watershed's outlet. In this context, all the simulated cases for Lageado Basin resulted in correlation coefficients greater than 80% between the monthly discharge of pollutants (in tons/month) and effective rainfall (in mm). Although not as intensively as precipitation, land uses also influence pollution loads. In this respect, the loads of all the pollutants increased with urbanization. In the context of Lageado Basin, we ranked the pollutants according to the correlation coefficient between the loads of each pollutant and the expansion of urban occupation, represented indirectly by the curve number (CN). The results are summarized in **Table 3**.

Note that for Lageado Basin, BOD is the most sensitive parameter to expansion of the urban area, since it presented the highest correlation with the curve number (about 41%). The parameters TSS and Zn are lease influenced by the occupation process of the watershed, even though they are strongly correlated with precipitation.

CONCLUSIONS

The simulations of various occupation scenarios of the 48 contributing sub-basins revealed a general trend for gradual increase of discharges and concentrations of all seven pollutants considered. We can conclude, first of all, that non-negligible correlations exist between generation of pollutants and advancing urbanization. BOD presented the highest sensitivity to urbanization, followed by P_{total}, N_{total}, NO_2^- and NO_3^-, and Zn. Also, TSS had a direct association with instantaneous heavy rainfall events.

With respect for satisfaction of the limits established by CONAMA Resolution 357/2005 and COPAM/CERH-MG Normative Deliberation 01/2008 for class 2 watercourses, the nitrogen series will remain under the limit in all the scenarios, TSS and P_{total} will be above the limits for all the scenarios, and BOD will only be above the threshold after 20 years.

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