Water quality impacts of Green and Blue Infrastructure Implementation in the Vargem das Flores Reservoir Catchment, Brazil

Impacts sur la qualité de l'eau de la mise en œuvre des infrastructures vertes et bleues dans le bassin versant du réservoir de Vargem das Flores, Brésil

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RÉSUMÉ

Ce travail vise à analyser le potentiel des principes des Infrastructures Vertes et Bleues pour gérer les charges polluantes diffuses dans le bassin d'un réservoir qui fournit de l'eau à environ 600 000 habitants dans une métropole brésilienne. Un modèle calibré de qualité de l'eau développé dans le Storm Water Management Model a été utilisé pour simuler des scénarios futurs alternatifs d'utilisation des terres. Tout d'abord, un scénario a été simulé en considérant le développement urbain selon la législation actuelle d'utilisation des terres. Ensuite, un scénario alternatif en appliquant les principes des Infrastructures Vertes et Bleues aux nouvelles zones développées. Les résultats ont indiqué une contribution significative de la pollution diffuse dans la dégradation de la qualité de l'eau du réservoir, spécialement dans la charge de solides transportés par les bassins les plus urbanisés. L'application des cellules de biorétention pour traiter des nouvelles zones imperméables a atténué la pollution diffuse dans la simulation, en maintenant des charges polluantes similaires aux niveaux actuels.

MOTS-CLÉS

modélisation de la qualité de l'eau; scénarios futurs; SWMM; développement à faible impact

ABSTRACT

This work aims to analyze the potential of Green and Blue Infrastructure principles to manage non-point pollutant loads in the catchment of a reservoir that supplies water for around 600.000 inhabitants in a Brazilian metropolis. A calibrated water quality model developed in the Storm Water Management Model was used to simulate alternative future land use scenarios. First, a scenario considering the urban development according to the current land use legislation was simulated. Then, an alternative scenario applied Green and Blue Infrastructure principles in the new developed areas. Results indicated a significant contribution of diffuse pollution in the reservoir's water quality degradation, especially in solids load transported by the most urbanized catchments. The application of bioretention cells to treat new impervious areas mitigated the diffuse pollution in the simulation, maintaining pollutant loads similar to present levels.

KEYWORDS

water quality modelling; future scenarios; SWMM; low impact development.

1 INTRODUCTION

Non-point sources (NPS) of pollution are among the main threats to water quality worldwide and, especially in urban areas, its regulation is challenging due to their high spatial and temporal variability. NPS control is more complex and requires the engagement of a much larger number of land users than point sources pollution (OECD Environment Directorate, 2017). Nevertheless, NPS control and regulation are much less costly economically and environmentally when compared to the treatment costs of their possible impacts such as eutrophication and silting of water bodies (Chang & Yu, 2020;

Silva et al., 2019). The adoption of source control measures and adequate drainage in construction processes can minimize the impacts of urbanization on surface water quality. Development guided by the principles of Water Sensitive Urban Design and with implementation of Green and Blue Infrastructure (GBI) can be far less impacting on the water courses of a catchment (Qiu et al., 2018; Reisinger et al., 2018). Low Impact Development (LID) devices as bioretention cells, permeable pavements, infiltration trenches, among others, are being widely supported by researchers, governments, and non-governmental organizations as possible solutions to manage stormwater quantity and quality. Liu et al. (2017) reviewed 161 monitoring and modelling studies that evaluated the effectiveness of GBI in reducing runoff and pollutants in urban areas. Wide ranges of percentual decrease of parameters concentrations were found in these studies, including cases where the GBI devices removed runoff pollutants with efficiencies up to 99%-100%, but also situations where the vegetation substrate worked as pollution source.

Although uncertainties in water quality simulation are greater for both LIDs and reservoirs, SWMM can be used as a tool to simulate the impact of land use changes and the deployment of GBI on a reservoir's water quality. This is precisely the proposal of this work: to evaluate the impacts on water quality and on the silting up process of a reservoir due to changes in land use and land cover and the implementation of GBI in its contribution catchment. Using an adjusted water quality model, future impacts related to expected LULC changes were simulated, and SWMM functionality was tested to simulate improvements in water quality by LID devices implementation.

2 METHODS

The methods applied to this study can be synthesized by the diagram in Figure 1.

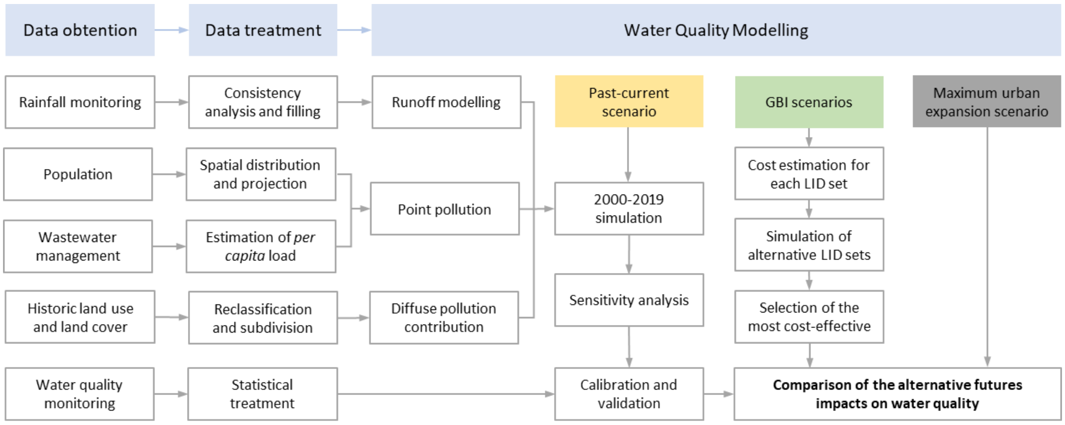

Figure 1 - Diagram of methods

The Storm Water Management Model version 5.2 (Rossman & Simon, 2022) was used to the water quality simulation. The model was adjusted based on rainfall and water quality monitoring data from 2001 to 2019. The hydrological model calibrated and validated by Rosa, Silva, Araújo, et al. (2022) was used as the starting platform, in which the simulated water levels achieved a good fitting to the monitored water levels of the reservoir, with Nash-Sutcliffe coefficient ranging from 0,80 to 0,87, and determination coefficient from 0,88 to 0,79. Both the point and non-point source of pollution were considered to adjust the simulated to the monitored annual pollutant loads and concentrations, so the volume of untreated sewage discharged annually in each subcatchment and Land Use and Land Cover (LULC) changes from 2001 to 2019 were estimated and inserted in the model. The water quality module was adjusted to represent the diffuse pollution and dilution effects for Chemical Oxygen Demand (COD), Total Phosphorus (TP), Ammoniacal Nitrogen, and Total Suspended Solids (TSS). Three LULC scenarios (see Figure 2) were compared: the current LULC, with 15,2% of imperviousness; a future scenario with the maximum urban development following the guidelines of the current municipal master plans (PDM), with 47,5% of impervious area; and a prospective scenario with the protection of forest fragments and the implementation of Green and Blue Infrastructure principles on new developed areas, with a total impervious area of 30,2% (Rosa, Silva, Chong, et al., 2022). In GBI scenario, 10,1% of catchment area have lower terrain slope (< 20%) and could be treated with infiltration devices. SWMM 5.2 enable the assessment of pollutant removal only for the LID practices that contain underdrain. Thus, the pollutant removal rate can be defined by the user for bioretention cells, permeable pavements, infiltration trenches, and rain barrels. The latter, as well as the other techniques, were not considered in this study because of this limitation. For both future scenarios (PDM and GBI), no change on the sewage load was considered, adopting the hypothesis that the new occupations would be provided with sewage collection and treatment network. In this sense, the comparison of future scenarios is focused only on the effects of LULC changes on the diffuse pollution load.

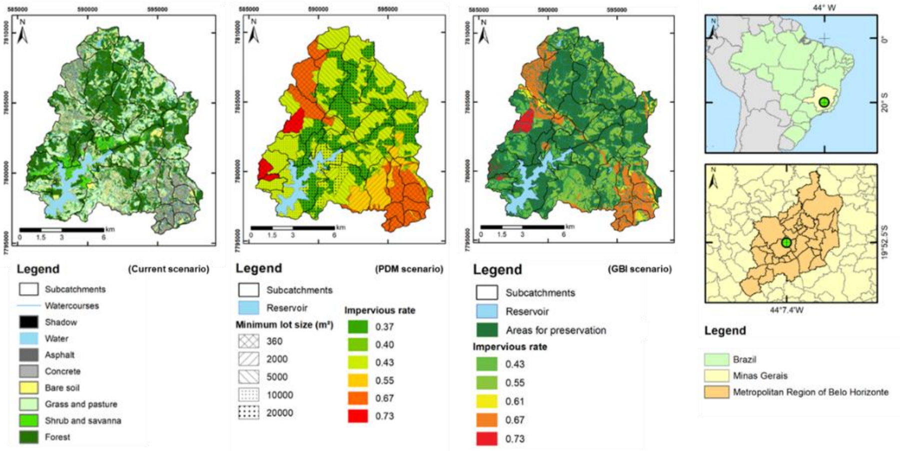

Figure 2 - LULC scenarios studied by Rosa, Silva, Chong, et al. (2022) and considered in this study

The suitable area for LID implementation in each subcatchment was divided into impervious areas inside blocks (in private areas) and impervious areas outside the blocks (sidewalks and public roads). Bioretention cells (BC) and infiltration trenches (IT) were considered to treat the first areas, and for the latter, permeable pavements (PP) were also considered as treatment alternatives. These devices were distributed in 32 combinations, considering the percentage of private impervious areas treated by 0%, 50%, or 100% by BC and IT, and 0%, 33%, 50%, and 100% of public impervious areas treated by BC, IT or PP. Costs estimated by Rosa, Silva, Chong, et al. (2022) were considered in the cost-effectiveness evaluation, and used in the comparison with conventional water treatment costs (Coutinho, 2007).

3 RESULTS

Since the analysis of the monitored water quality data, it was clear that TSS was the only studied pollutant with higher concentrations during the rainy season for all catchments, evidencing that non-point and surface washoff are the main source of TSS. In this sense, the simulated LID devices were able to treat about 40% of the total TSS load when treating the new suitable impervious areas or public (5,39 km²) or private (7,25 km²), and about 50% of the total TSS load when combined treatment of both areas. In general, all LID combination scenarios showed similar effectiveness in removing all nutrients, with a maximum difference of 3.64 percentage points in TSS removal between the most efficient (BC&IT+PP) and the least efficient (BC+IT) combination. On the other hand, the total capital and maintenance cost varied greatly between scenarios, so the highest cost (IT+PP) was 5,65 times higher than the lowest cost (BC+BC). Thus, bioretention cells were selected as the most cost-effective LID to represent the GBI scenario, considering that the implementation and maintenance of BC to treat the new 12,64 km² impervious areas would cost 76,7 million Brazilian reais and remove 52,1% of total TSS load, 19,5% of TP load and 17,1% of COD load flowing into the reservoir. Table 1 presents the total annual washoff loads of TSS, COD, TP, and Ammonia-N.

Table 1 - Washoff pollutant annual total loads (ton/year) in the three studied LULC scenarios

Scenarios	Pollutant total annual loads (ton/year)			
	TSS	COD	TP	Ammonia-N
Calibrated	17.801	1.144,7	10,90	8,10
PDM	37.369	1.377,6	21,33	6,39
GBI	16.950	725,1	12,34	3,77

The annual cost per kg of treated pollutant would be R$ 7,33 per kg of TSS removed, R$ 127,16 per kg of COD removed, and R$ 18.726,97 per kg of TP removed. Those unit costs for non-point source treatment can be compared to the costs of a water treatment plant located in the neighboring catchment of Pampulha Reservoir (15 km of distance to Vargem das Flores reservoir). Considering treatment costs and efficiencies presented by Coutinho (2007), the implementation, and first year operation and maintenance costs updated to 2022 values would be R$ 24,26 per kg of TSS removed, R$ 66,96 per kg of COD removed, and R$ 2.656,25 per kg of TP removed.

GBI scenario could reduce the TSS concentrations to values similar to the current levels. This indicates that the implementation of bioretention cells on 33% of the new developed areas that were technically suitable for that would mitigate the additional TSS diffuse pollution associated with this urban development. In PDM scenario, the total annual TSS load inflow to the reservoir would increase from 17,8 to 37,4 MT/yr, or 2,1 times the load in the current scenario. This increase in TSS load can accelerate the process of silting and loss of useful volume of Vargem das Flores reservoir, so that the total siltation of the reservoir could be brought from year 2066 to 2042. Nevertheless, the results indicate that the GBI scenario could protect the reservoir from this process, with the maintenance of total TSS annual load in the same current magnitude, even allowing the urban development of additional area of 38,9 km².

4 CONCLUDING REMARKS

This abstract summarizes a broad study that evaluated the water quality changes in a catchment that contributes to a reservoir that supplies water for 600.000 people in the third biggest Brazilian metropolis, Belo Horizonte. The past urban development contributed to the degradation of water quality in the catchment, especially until the 2010s, when a sewage collection and treatment system was built. In addition to sewage contribution, the results of this work highlight the prominence of non-point source pollution on the load of TSS that is annually transported to the reservoir. As previously mentioned, the reservoir undergoes an accelerated process of silting up, and the catchment is still under pressure for further development, with recent legislation changes that eased restrictions for urban sprawl. The community and public managers mobilized for the protection of the reservoir and a new public discussion on the revision of land use legislation was launched in 2021. This study intends to contribute to this discussion, reinforcing the benefits of adopting GBI principles to guide urban development in the catchment, protecting the water quality and preventing flood downstream the reservoir, as identified in previous works (Rosa, Silva, Araújo, et al., 2022; Rosa, Silva, Chong, et al., 2022). The alternative development scenario proposed here, with implementation of GBI principles, protecting the main forest fragments, reforesting rural riparian areas, and treating new suitable impervious areas with bioretention cells, proved to be effective in mitigating diffuse pollution associated with the new development.

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