University of Technology Sydney
Institute for Sustainable Futures

Universidade Federal de Minas Gerais
Escola de Engenharia
Pós-Graduação em Saneamento, Meio
Ambiente e Recursos Hídricos

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Assessing the Benefits of Green and Blue Infrastructure in Peri-Urban Areas

Thesis submitted in fulfilment of the requirements for
the degree of

Doctor of Philosophy in Sustainable Futures
at University of Technology Sydney

and

Doctor in Sanitation, Environment and Water Resources
at Universidade Federal de Minas Gerais

under the supervision of Prof. Dr. Nilo de Oliveira Nascimento (UFMG)
and Prof. PhD Damien Giurco (UTS)

and co-supervision of Prof. Dra. Talita Fernanda das Graças Silva (UFMG),
Prof. Joanne Chong (UTS) and PhD Rachel Watson (UTS)

Sydney
2023

Belo Horizonte
2023

CERTIFICATE OF ORIGINAL AUTHORSHIP

I, Deyvid Wavel Barreto Rosa, declare that this thesis is submitted in fulfilment of the requirements for the award of Doctor of Philosophy in the Institute for Sustainable Futures at the University of Technology Sydney.

This thesis is wholly my own work unless otherwise referenced or acknowledged. In addition, I certify that all information sources and literature used are indicated in the thesis.

I certify that the work in this thesis has not previously been submitted for a degree, nor has it been submitted as part of the requirements for a degree at any other academic institution except as fully acknowledged within the text.

This thesis is the result of a Collaborative Doctoral Research Degree program between the Universidade Federal de Minas Gerais (Brazil) and the University of Technology Sydney (Australia).

This research is supported by the Australian Government Research Training Program and the Brazilian Government Program for Institutional Internationalisation (CAPES-PrInt).

Production Note:
Signature removed prior to publication.

Deyvid Wavel Barreto Rosa

Date: *1st April 2023*

Place: *Sydney, Australia*

Deyvid Wavel Barreto Rosa

Assessing the Benefits of Green and Blue Infrastructure in Peri-Urban Areas

PhD thesis submitted to the Post-Graduate Program in Sanitation, Environment and Water Resources, Universidade Federal de Minas Gerais, as a partial requisite for obtaining a Doctorate in Sanitation, Environment and Water Resources.

Concentration area: Hydraulics and Water Resources

Research line: Hydrology and urban drainage

Supervisors: Prof. Dr. Nilo de Oliveira Nascimento (UFMG) and Prof. PhD Damien Giurco (UTS)

Co-supervisors: Prof. Dra. Talita Fernanda das Graças Silva (UFMG), Prof. Joanne Chong (UTS) and PhD Rachel Watson (UTS)

Sydney
2023

Belo Horizonte
2023

R788a

Rosa, Deyvid Wavel Barreto.
Assessing the benefits of green and blue infrastructure in peri-urban areas [recurso eletrônico] / Deyvid Wavel Barreto Rosa. - 2023.
1 recurso online (323 f. : il., color.) : pdf.

Orientadores: Nilo de Oliveira Nascimento, Damien Giurco.
Coorientadoras: Talita Fernanda das Graças Silva, Joanne Chong, Rachel Watson.

Tese (doutorado) - Universidade Federal de Minas Gerais, Escola de Engenharia.

Bibliografia: f. 294-323.
Exigências do sistema: Adobe Acrobat Reader.

1. Engenharia sanitária - Teses. 2. Recursos hídricos -Desenvolvimento - Teses. 3. Serviços ambientais - Teses. 4. Infraestrutura urbana - Teses. 5. Hidrologia urbana - Teses. 6. Vargem das Flores, Reservatório de - Teses. I. Nascimento, Nilo de Oliveira. II. Giurco, Damien. III. Silva, Talita Fernanda das Graças. IV. Chong, Joanne. V. Watson, Rachel. VI. Universidade Federal de Minas Gerais. Escola de Engenharia. VII. Título.

CDU: 628(043)

Ficha catalográfica elaborada pela Bibliotecária Roseli Alves de Oliveira CRB/6 2121
Biblioteca Prof. Mário Werneck, Escola de Engenharia da UFMG

Dedico este trabalho ao menino Deyvid,
que nunca imaginou que chegaria tão longe;

Acknowledgements/Agradecimentos

Esta tese é fruto de uma jornada de 5 anos iniciada por (praticamente) outra pessoa. Em dezembro de 2017, quando recebi a notícia de que havia sido aprovado no processo seletivo do doutorado, era um jovem rapaz cheio de cabelos escuros que ainda morava com a mãe, terminando o primeiro semestre como professor universitário e já ansioso para as mudanças que se encenavam. Meu projeto de pesquisa era ambicioso e, logo no primeiro ano, vários cabelos brancos apareceram, me casei, assumi um cargo de gerência numa autarquia estadual, o Brasil foi atropelado pelas eleições mais catastróficas de sua história – e mal imaginávamos a dimensão do que ainda estava por vir.

Naquele mesmo dezembro de 2017, professor Nilo estava do outro lado do mundo quando me avisou que um acordo de cotutela havia sido estabelecido entre a UFMG e a UTS, o que abria uma janela de oportunidade interessante para o futuro. Respondi agradecido pela novidade com um misto de excitação e ceticismo, pensando que o doutorado na UFMG já era muito mais do que eu me imaginava capaz.

Ainda com o projeto de pesquisa ambicioso em mente, aproveitei a oportunidade para cursar disciplinas em outros departamentos na UFMG. Vivi ricas experiências ao me aventurar desde a estatística (obrigado, professora Sílvia!) até a pesquisa qualitativa (obrigado, professora Sonaly!) e ao mercado de carbono (obrigado, professora Taciana) no DESA, da ecologia da paisagem no IGC (obrigado, professora Sonia!) ao planejamento regional no Cedeplar (obrigado, professor Roberto e professora Clarice!).

Adotei a bacia do reservatório de Vargem das Flores como estudo de caso, tendo observado a polêmica e recente mudança da legislação urbanística em Contagem, que ameaçava esse importante manancial de água. A última crise hídrica (2014-2015) já havia produzido imagens inéditas do reservatório em seu nível d’água mínimo, alcançando o volume morto sobre o qual ouvíamos diariamente até que as chuvas voltassem no fim de 2015. Outros problemas do reservatório eram velhos conhecidos da população de baixa renda de Betim, que conheciam “Várzea das Flores” sobretudo como um (perigoso) local para recreação e lazer nos fins de semana. Nas páginas dos jornais e na boca do povo, a “barragem” era conhecida pelo risco de se contrair “xistose” ao nadar em uma de suas praias, de se afogar ao se prender em alguma das árvores mortas submersas, ou de não poder nadar por causa de uma provável cerimônia de batismo de grupos evangélicos ou uma operação policial de busca pelo corpo de algum cidadão que teria sido “desovado” nas águas do reservatório.

Poder contribuir com a discussão pública sobre uma região tão próxima e com uma ameaça tão contemporânea trouxe motivação e entusiasmo, pelo interesse que sempre tive em fazer pesquisa que tenha claro impacto social. Por essa oportunidade, e também por todas as outras, agradeço imensamente ao meu orientador e professor Nilo. Agradeço ao Nilo por toda a gentileza e generosidade, por toda a disponibilidade, mesmo nos momentos mais difíceis, e por sempre transmitir uma tranquilidade quase nirvânica. Agradeço, também, por abrir tantas portas para que eu pudesse contribuir em projetos interessantíssimos e socialmente relevantes, muito além de minhas melhores projeções.

Aproveito para agradecer a minha coorientadora e professora Talita, por me ensinar tanto com sua gentileza, seu rigor ético e científico. Por ser sempre compreensiva e generosa, inclusive no período em que fui professor substituto no EHR.

A primeira etapa de coleta de dados para início da construção dos modelos foi uma oportunidade de encontrar profissionais disponíveis para contribuir com a pesquisa. Agradeço à Nádia Santos, do Igam, à Aliane Baeta, da Fundação João Pinheiro, à Nádia Daian, do setor de geoprocessamento da Prefeitura de Contagem, ao Lincoln Baker, da Prefeitura de Betim, à Karoline Tenório e ao Rogério Sepúlveda, da Copasa, pelo fornecimento de dados indispensáveis para elaboração dos estudos e pelas oportunidades de apresentar os resultados e contribuir com as discussões sobre a gestão da bacia de Vargem das Flores.

Logo no início da pesquisa, na concepção dos cenários futuros de desenvolvimento urbano, contei com a excelente contribuição e diálogo pelos quais agradeço à Luciane Mitraud e ao professor Rogério Palhares, pelo compartilhamento de seu precioso conhecimento sobre a bacia de Vargem das Flores.

Já em agosto de 2019, quando foi aberto o edital do programa de internacionalização (Print) da Capes para bolsas de doutorado sanduíche no exterior, a ida à Austrália começou a parecer uma possibilidade real. Agradeço a todas as pessoas que de alguma forma contribuíram para que eu tivesse sucesso em minha aplicação. Muito obrigado, Professora Talita (UFMG), Marília Carvalho e Sônia Ferreira (Igam), Professor Márcio Mendes (PUC-Minas), e Anna Maciel (Veredas) pelas parcerias de trabalho e pelas cartas de recomendação essenciais no processo seletivo da bolsa de doutorado sanduíche.

Logo em seguida, conquistada a bolsa, surgiu a possibilidade de que a experiência na UTS se tornasse um doutorado em cotutela, e iniciei a aplicação na UTS. Entre a preparação do projeto de atividades no exterior e o conjunto de documentos para atender aos requisitos do edital, iniciei o contato com meu orientador na UTS, Professor Damien Giurco, a quem agradeço imensamente por toda a generosidade.

Many thanks to Damien, a true gentleman, for all the kindness and hospitality, for all encouragement and availability, and for the sensitivity of speaking in English calmly and with perfect diction with me when I still had difficulty understanding most native speakers.

I also thank my co-supervisors at UTS, Joanne and Rachel, for their patience, careful reading, encouraging words, and persistence in my supervision even after leaving ISF.

Em março de 2020, quando todos fomos surpreendidos pela pandemia de Covid-19, as fronteiras da Austrália se fecharam, e todos fomos isolados em casa sem perspectivas de reabertura. Nesse momento, agradeço a todos os profissionais da saúde que perseveraram em seus trabalhos exaustivos e que, com isso, salvaram a vida de muita gente. Agradeço aos profissionais da saúde mental aos quais tive acesso, por proverem as ferramentas necessárias para sobreviver a esse período de muita ansiedade. Agradeço à Marina e Amanda, por serem profissionais generosas e competentes, me ouvindo pacientemente e fazendo as melhores perguntas, verdadeiras luzes nos momentos mais escuros. Aos doutores Wilson, Bruno e Caetano, pelas prescrições que foram combustível e suporte durante anos intensos e exigentes. À Teresa Cristina, pelas valiosas lições de yoga, únicas horas das semanas em que me desligava temporariamente do trabalho.

Escrever a tese em inglês foi extremamente desafiador. Agradeço novamente aos meus orientadores e coorientadoras por toda a paciência em ler e por todo o retorno positivo que recebi, que foi combustível indispensável para que eu persistisse nessa aventura. Agradeço, também, aos professores Roberto Monte-Mór e Guilherme Marques, pela leitura atenciosa do texto, pela disponibilidade em participar do exame de qualificação e por todas as sugestões e comentários. *I would also like to thank the examiners of the final panel, professors Dominique Hes, Neil Armitage, Heloisa Costa and Geraldo Costa, for all the valuable comments and suggestions that were essential for the thesis to reach this more complete and cohesive version.*

Entre 2020 e 2021, com as fronteiras australianas ainda fechadas, precisamos adiar a viagem por cinco vezes. Em cada uma das vezes, contei com a disponibilidade e paciência de várias pessoas para atualizar todos os documentos: da UFMG, obrigado Prof. Nilo, ao Júlio da secretaria do PPG-SMARH, à coordenadora do PPG Profa. Sonaly, à Marina Bueno e Prof. Fábio Alves da Pró-Reitoria de Pós-Graduação da UFMG. *From UTS, Prof. Damien, Rupert,* *Suzanne Cronan, Wendy Wang, Brandon Nguyen from ISF, Jing Zhao from GRS, thank you for welcoming me and for your patience in repeatedly providing me with the necessary documents so that I could reschedule coming to Australia.*

Em dezembro de 2021, graças às vacinas, finalmente o cenário melhorou o suficiente para que as fronteiras fossem reabertas. Logo pegamos o voo para o outro lado do mundo, felizes e descrentes de que aquilo estava finalmente acontecendo.

Thanks to Rupert, for welcoming me to UTS, for being a great buddy, always supporting and sharing encouragement (and beer) along the way. I also thank all ISFers that welcomed us: Stuart, Maria, Chris, Jason, Tim, Suz, Brandon, Saori, Melita, Dana, Juliet, Pierre, Josie, Rusty, Monique, Sarah, Maartje, Kerryn, Jordan, and Stephen for all the support and prompt help throughout the period we spent at ISF. Special thanks to ISF PhD mates Anja, Ahn, Jessica, Tamara, and Somayeh for their support and encouragement.

Agradeço aos amigos Bernardo e Deborah, pelas valiosas dicas sobre a vida na Austrália, pelo afeto caloroso e o sotaque reconfortante, por nos apresentarem a pessoas incríveis, Mateus, Marina, Gabriela, Murilo, Giovanni, Jake, Luiz, Lucas e Letícia, por todo o carinho e incentivo, e pela compreensão das ausências.

Agradeço também à Profa. Priscilla e ao Pedro Drumond, pelo incentivo e pelas dicas sobre a vida na Austrália. À Profa. Priscilla, também pelo suporte durante o período em que se tornou a coordenadora do PPG-SMARH.

Da UFMG, também agradeço à Vanessa e ao André, por tudo o que aprendi durante a parceria de trabalho. Aos engenheiros e engenheiras Bruno, Amanda, Túlio, Diogo, Rafael, Diovani, Kauê, Fernanda, Camilla e Isadora pelo apoio e parceria durante as orientações de iniciação científica ou trabalhos de conclusão de curso, e pelas preciosas contribuições a esta tese.

Agradeço a minha família e amigos, mãe, pai, Ló, Zazá, Memel, Davi, Gabi, Sarah, Enrique, Karen, Lívia, Brendow, Lucas, pelo afeto, pelo incentivo, e pela compreensão das ausências. Por serem âncoras nos períodos de mar agitado e tempestuoso.

O maior agradecimento do mundo vai para Helen, por ser minha melhor amiga, maior incentivadora, combustível de toda a minha coragem e ousadia, corresponsável por todas as minhas conquistas.

À Capes, UFMG e UTS, pelo suporte financeiro e institucional.

“Der reißende Strom wird gewalttätig genannt.
Aber das Flußbett, das ihn einengt,
nennt keiner gewalttätig.”

“The river that everything drags is known as violent,
but nobody calls violent
the margins that arrest him.”

“Do rio que tudo arrasta se diz que é violento,
mas ninguém chama de violentas
as margens que o comprimem.”

Bertolt Brecht

RESUMO

A adoção da infraestrutura verde e azul (IVA) no planejamento urbano pode reduzir e mitigar diversos impactos hidrológicos, ambientais e sociais da urbanização. Esta tese visa explorar e aplicar métodos para quantificar os benefícios da implantação da IVA, com a finalidade de contribuir com o debate público e a decisão em prol de um desenvolvimento urbano que seja sustentável e sensível à água. Um conjunto de ferramentas foi desenvolvido e aplicado para estimar os benefícios da implantação da IVA em uma bacia hidrográfica periurbana, a do reservatório de Vargem das Flores, parte do sistema de abastecimento de água da Região Metropolitana de Belo Horizonte. Considerando a recente discussão e mudança na legislação de uso e cobertura do solo (UCS) da região, diferentes cenários foram preparados utilizando-se uma base de dados georreferenciada obtida junto a instituições municipais e estaduais. Um modelo de mudança de UCS foi empregado para projetar a expansão urbana na bacia até 2040, e um cenário alternativo com a ampla implantação de IVA com relação custo-efetividade otimizada foi proposto. O Storm Water Management Model (SWMM) foi então empregado para avaliar os potenciais impactos hidrológicos e na qualidade da água dos cenários de UCS, e a área inundada à jusante do reservatório foi mapeada com a aplicação conjunta do SWMM e do Hydrologic Engineering Center - River Analysis System (Hec-RAS). Os resultados confirmaram os impactos da expansão urbana nos processos hidrológicos, com o aumento do escoamento superficial, aumento da extensão e frequência das inundações à jusante do reservatório, e na degradação da qualidade da água dos afluentes do reservatório, contribuindo para seu assoreamento e eutrofização. Os resultados também demonstraram a capacidade da IVA em mitigar os impactos do aumento da área impermeável, mantendo os processos hidrológicos e a poluição difusa em condições similares às atuais. Por fim, uma revisão bibliográfica sistemática de 742 artigos científicos mapeou quais são os métodos aplicados para quantificar os benefícios ambientais e sociais das IVA em diferentes contextos geográficos, indicando caminhos possíveis para novas frentes de pesquisa e oportunidades de colaboração.

Palavras-chave: infraestrutura verde e azul; mudanças no uso e cobertura do solo; expansão urbana; modelagem hidrológica; serviços ecossistêmicos.

ABSTRACT

Adopting Green and Blue Infrastructure (GBI) in urban planning can reduce and mitigate some hydrological, environmental, and social impacts of urbanisation. This thesis aims to explore and apply methods to quantify the benefits of GBI implementation to contribute to the public debate and decision-making for an urban development that is sustainable and water sensitive. A toolset was developed and applied to estimate the benefits of GBI implementation in a peri-urban catchment of Vargem das Flores reservoir, which is part of the drinking water supply system of the Metropolitan Region of Belo Horizonte. Considering the recent change in local land use and land cover (LULC) legislation, different LULC scenarios were prepared based on a georeferenced database obtained from municipal and state institutions. A LULC change model was employed to project the urban development in Vargem das Flores catchment up to 2040, and an alternative land use scenario was proposed, adopting the broad implementation of GBI techniques with an optimised cost-effectiveness relation. SWMM was then employed to assess potential hydrological and water quality impacts of the LULC scenarios, and the flooded area downstream of the reservoir was mapped with the joint application of SWMM and Hec-RAS. Results demonstrated GBI's capacity to mitigate the impacts of impervious area increase, maintaining the hydrological processes and non-point pollution in similar conditions to the current ones, protecting the reservoir against the acceleration of its silting and eutrophication. Finally, a systematic literature review of 742 scientific articles published in journals of many research subjects mapped the methods applied to quantify GBI's social and environmental benefits in different geographical contexts, indicating possible fronts for future research and collaboration opportunities. The review calls for interdisciplinary studies and more exchanges among research areas to improve the adoption of GBI to address the increasing demand for multiple ecosystem services in the developing world. Methods and benefits usually employed in studies about urban green areas are suggested to be applied in the urban water management designed GBI.

Keywords: green and blue infrastructure; land use and land cover changes; urban expansion; hydrologic modelling; ecosystem services.

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ACRONYMS AND ABBREVIATIONS

a.m.s.l. - above mean sea level

ADES - Área de Desenvolvimento Econômico Sustentável [Sustainable Economic Development Areas]

AIA - Áreas de Especial Interesse Ambiental [Areas of Special Environmental Interest]

Ammonia-N - Ammonia Nitrogen

ANA - Agência Nacional de Águas [Brazilian Water Agency]

APA - Área de Proteção Ambiental [Environmental Protection Area]

APE - Área de Proteção Especial [Special Protection Area]

APM - Área de Proteção de Mananciais [Water Sources Protection Area]

Aprovargem - Associação de Proteção e Defesa das Águas de Vargem das Flores [Association for the Protection and Defence of the Water of Vargem das Flores]

APUA - Associação dos Protetores, Usuários e Amigos da Represa Várzea das Flores [Association of Protectors, Users and Friends of Várzea das Flores reservoir]

B£ST - Benefits Estimation Tools

BC - Bioretention cell

BHMR - Belo Horizonte Metropolitan Region

BMPs - Best Management Practices

BOD - Biochemical Oxygen Demand

CBA - cost-benefit analysis

Cemaden - Centro Nacional de Monitoramento e Alerta de Desastres Naturais [Brazilian Centre of Monitoring and Natural Disaster Warning]

CERH - Conselho Estadual de Recursos Hídricos [State Water Resources Council]

CFD - computational fluid dynamics

CNPq - Conselho Nacional de Desenvolvimento Científico e Tecnológico [Brazilian National Council for Scientific and Technological Development]

CO - Carbon monoxide

CO_2 - carbon dioxide

COD - Chemical Oxygen Demand

COP - Conferences of Parties

COPAM - Conselho Estadual de Política Ambiental [State Environmental Policy Council]

Copasa - Companhia de Saneamento de Minas Gerais [Minas Gerais State Sanitation Company]

Cwb - humid subtropical Köppen climate zone

Dinamica EGO - Dinamica Environment for Geoprocessing Objects

DSM - Digital Surface Model

FAPEMIG - Fundação de Amparo à Pesquisa de Minas Gerais [Minas Gerais State Agency for Research and Development]

GBI - Green and Blue Infrastructure

GCOR - Green Corridors

GHG - Greenhouse Gases

GI - Green Infrastructure

GIS - Geographical Information System

GISP - Green Infrastructure Spatial Planning

GR - Green Roof

HDI - Human Development Index

Hec-RAS - Hydrologic Engineering Center - River Analysis System

IBGE - Instituto Brasileiro de Geografia e Estatística [Brazilian Institute of Geography and Statistics]

Inmet - Instituto Nacional de Metrologia [National Meteorological Institute]

IT - Infiltration Trench

IUCN - International Union for Conservation of Nature

IUWM - Integrated Urban Water Management

IVA - infraestrutura verde e azul [green and blue infrastructure]

LCA - Life Cycle Assessment

LID - Low Impact Development

LULC - Land Use and Land Cover

MOMA-SE - Modelling strategic metropolitan water sources as an input for water and land management in the face of climate change

MUSIC - Model for Urban Stormwater Improvement Conceptualization

NBS - Nature-Based Solutions

NDVI - Normalized Difference Vegetation Index

NOx - Nitrogen oxides

NPSP - non-point source pollution

NRCS - National Resources Conservation Service

NSC - Nash and Sutcliffe coefficient

NSGA - nondominated sorting genetic algorithm

O_3 - Ozone

PDDI - Plano Diretor de Desenvolvimento Integrado [Master Plan of Integrated Development]

PDM - Plano Diretor Municipal [Municipal Master Plan]

Plambel - Superintendência de Desenvolvimento da Região Metropolitana de Belo Horizonte [Superintendence of Planning of the BHMR]

PM - Particulate Matter

PP - Permeable Pavement

PRISMA - Preferred Reporting Items for Systematic reviews and Meta-Analyses, Preferred Reporting Items for Systematic reviews and Meta-Analyses

PSH - Plano de Segurança Hídrica [Water Security Plan]

RB - Rain Barrel

RD - Rooftop Disconnection

RG - Rain Garden

RP - Return Periods

SCM - Stormwater Control Measures

SNIS - Sistema Nacional de Informações sobre Saneamento [National Sanitation Information System]

SOC - Source Control

SPC - Sponge city

SUDS - Sustainable Urban Drainage Systems

SWAT - Soil & Water Assessment Tool

SWMM - Storm Water Management Model

TP - Total Phosphorus

TSS - Total Suspended Solids

UCAN - Urban Canopy

UCS - uso e cobertura do solo [land use and cover]

UFMG - Universidade Federal de Minas Gerais

UGAS - urban green areas

UGS - urban green spaces

UHI - urban heat island

UK - United Kingdom

UN - United Nations

UN SDG - United Nations Sustainable Development Goal

US-EPA - United States Environmental Protection Agency

UTS - University of Technology Sydney

UWJ - Urban Water Journal

VS - Vegetative Swale

WRF - Weather Research & Forecasting Model

WSUD - Water Sensitive Urban Design

WTA - Willingness to Accept

WTP - Willingness to Pay

ZAC - Zona de Atividades Complementares [Complementary Activities Zone]

ZAD - Zona Adensável [Increased Density Zone]

ZEIT - Zona de Especial Interesse Turístico [Zone of Special Tourist Interest]

ZEU - Zona de Expansão Urbana [Urban Expansion Zone]

ZEUIA - Zona de Expansão Urbana de Interesse Ambiental [Urban Expansion Zone of Environmental Interest]

ZOR - Zonas de Ocupação Restrita [Restricted Occupation Zones]

ZP - Zona de proteção [Protection Zone]

ZUI - Zona de Usos Incômodos [Annoying Use Zones]

ZUIA - Zona Urbana de Interesse Ambiental [Urban Zone of Environmental Interest]

1 INTRODUCTION

“Rapid urbanisation is placing mounting pressure on the ecosphere but carries promises of renewal - an opportunity to reimagine the built environment and, by extension, our very civilisation.”

International Union for Conservation of Nature (2022)

Green and Blue Infrastructure (GBI) is a term used in the context of stormwater management to refer to alternative and sustainable approaches to urban drainage, among other expressions such as Green Infrastructure (GI), Water Sensitive Urban Design (WSUD), Low Impact Development (LID), Compensatory Techniques, Source Control, Sustainable Urban Drainage Systems (SUDS), Best Management Practices (BMPs). These concepts were developed in different contexts, and although there are some differences in their specificity and focus, most of them can be applied in the urban context (Fletcher et al., 2014). One of the terms with a notable recent increase in popularity is Nature-Based Solutions (NBS), since they were considered as leading measures for climate change adaptation in the United Nations (UN) Conferences of Parties (COP) 25 and 26 (United Nations Environment Programme, 2021). UN adopted the definition of NBS according to the International Union for Conservation of Nature (2016) as “actions to protect, sustainably manage, and restore natural or modified ecosystems, that address societal challenges effectively and adaptively, simultaneously providing human wellbeing and biodiversity benefits".

Following the IUCN and UN international conferences, however, many organisations criticised the indiscriminate embrace of NBS in the discourse as the main strategy for climate adaptation, especially focusing on NBS's potential for carbon sequestration and storage, and often taking the focus away from the control of Greenhouse Gases (GHG) emissions by the consumption of fossil fuels. Even so, many studies emphasise the importance of the many benefits of NBS for social and ecological adaptation to climate change, especially in urban areas (Seddon, 2022).

In this study, the term Green and Blue Infrastructure is the most frequently used. GBI is understood as a multifunctional network of parks, gardens, and urban afforestation that, connected, form green corridors, with decentralised rainwater drainage techniques, such as green roofs, permeable pavements, bioretention cells, and infiltration trenches, among others (Nascimento et al., 2016). GBI performs hydrological functions by capturing, retaining, infiltrating, and promoting evaporation and evapotranspiration, reducing runoff and improving water quality. The ability of these techniques to promote multiple environmental, economic, and social benefits and services has made GBI strategies increasingly popular in recent years (Elmqvist et al., 2015). In addition to reducing the runoff volume, GBI can treat diffuse pollution, improve water quality, and bring other positive impacts that have monetary and social value. Other benefits are the reduction of energy consumption, the improvement of air quality, the reduction of emissions, carbon sequestration, real estate valuation, the creation of leisure and recreation opportunities, and benefits related to community health (Center for Neighborhood Technology, 2010). Implementing GBI can also increase the resilience of communities and enhance flexibility, given the need to adapt the urban infrastructure to climate change impacts (Voskamp & Van de Ven, 2015). Figure 1.1 presents a summary of environmental, economic, and social benefits that can be associated with the main GBI practices.

Figure 1.1 – Benefits of Green and Blue Infrastructure

Benefit	Reduces Stormwater Runoff											Improves Community Livability						
	Reduces Water Treatment Needs	Improves Water Quality	Reduces Grey Infrastructure Needs	Reduces Flooding	Increases Available Water Supply	Increases Groundwater Recharge	Reduces Salt Use	Reduces Energy Use	Improves Air Quality	Reduces Atmospheric CO_2	Reduces Urban Heat Island	Improves Aesthetics	Increases Recreational Opportunity	Reduces Noise Pollution	Improves Community Cohesion	Urban Agriculture	Improves Habitat	Cultivates Public Education Opportunities
Practice										CO_2								
Green Roofs	Yes	Yes	Yes	Yes	No	No	No	Yes	Yes	Yes	Yes	Yes	Maybe	Yes	Maybe	Maybe	Yes	Yes
Tree Planting	Yes	Yes	Yes	Yes	No	Maybe	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Maybe	Yes	Yes
Bioretention & Infiltration	Yes	Yes	Yes	Yes	Maybe	Maybe	No	No	Yes	Yes	Yes	Yes	Yes	Maybe	Maybe	No	Yes	Yes
Permeable Pavement	Yes	Yes	Yes	Yes	No	Maybe	Yes	Maybe	Yes	Yes	Yes	No	No	Yes	No	No	No	Yes
Water Harvesting	Yes	Yes	Yes	Yes	Yes	Maybe	No	Maybe	Maybe	Maybe	No	No	No	No	No	No	No	Yes

● Yes ◒ Maybe ○ No

Source: Center for Neighborhood Technology (2010).

The intense urbanisation observed all over the planet in the last two centuries has caused numerous environmental impacts, including loss of biodiversity, degradation of water quality, increase in temperature and urban heat island (UHI) development, affecting most medium and large cities. The Green and Blue Infrastructure emerges in the context of incorporating nature in urban planning and development, with great potential to mitigate most of these impacts, especially on watercourses and hydrological cycle.

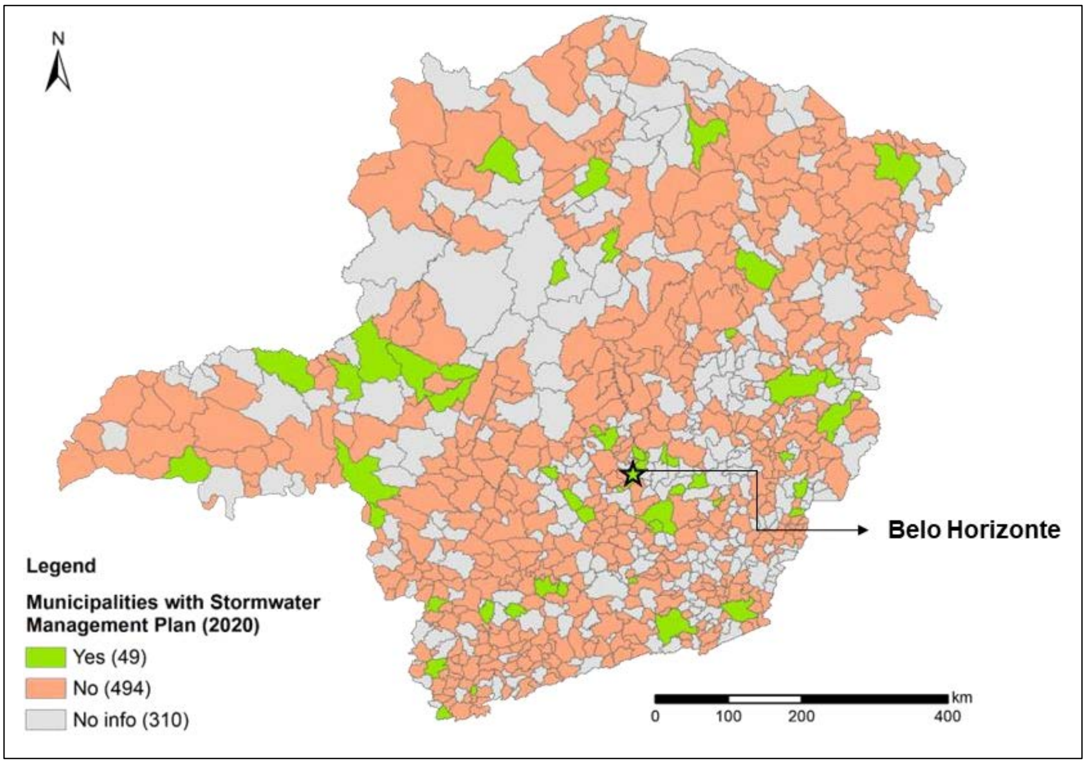
Despite the increasing interest in the topic, most studies about GBI are still performed in developed countries or China (Li et al., 2017). The Brazilian context is illustrative of this reality. Extensive research in the main Brazilian publications and event proceedings has not found studies that directly compared the cost of implementation, operation, and maintenance of GBI techniques with the many benefits that their implementation can bring. Several studies evaluate the hydrological benefits of urban drainage compensatory techniques, while some include the economic aspects (Cançado, 2009; Caputo, 2012; Drumond et al., 2013; Miguez et al., 2012; Rosa et al., 2020). Many of these studies evaluate the benefits of these techniques by modelling discrete hydrological events and do not capture their contribution to the hydrological cycle through continuous simulations or monitoring. There is little literature on the costs of compensatory techniques in Brazil; the publications of Moura (2004) and Baptista et al. (2005) stand out on this subject. In the studies of Moura (2004) and Evangelista (2011), the costs were one of the indicators among several others used for multi-criteria evaluation and assistance in selecting the best drainage techniques. These studies considered other benefits of compensatory techniques besides hydrological ones, but almost always qualitatively.

Frequently, these studies evaluate just one benefit of these practices, but it is crucial to consider a greater number of aspects for effective support for decision-making on GBI implementation. Within this context, one of the interests of the present study is to promote the Brazilian reality, a tropical emerging economy, in the milieu of GBI multiple benefit studies and to improve the decision-making process on GBI. O'Donnell et al. (2017), in their studies to recognise barriers to GBI implementation in Newcastle – United Kingdom (UK), identified that the support of quantitative and monetised evidence of multiple benefits is essential to advance GBI implementation. Benefits quantification and economic valuation can be strategic to encourage stakeholders to adopt this approach in landscape planning (Vandermeulen et al., 2011).

1.1 Scientific and social contribution

The central argument of this thesis is that elucidating multiple hydrological and socioenvironmental GBI benefits can contribute to the construction of societal awareness and support real-world decision-making. The relevance of this work is also justified by the slow adoption of GBI in Brazilian urban development plans, especially in small and medium cities that frequently lack adequate conventional infrastructure for flood control, as well as normative and institutional instruments to manage urban water sustainably. Despite the Federal regulation for compulsory development of municipal sanitation plans that should include urban drainage diagnostic and planning (Brasil, 2007), just 49 municipalities (5.7%) of Minas Gerais State have a Stormwater Management Plan (SNIS, 2022). Also, there is almost a total absence of normative instruments that promote GBI implementation in the cities of Minas Gerais State (Faria et al., 2022).

Figure 1.2 – Stormwater Management Plan in the municipalities of Minas Gerais State



Source: elaborated with data from the National Sanitation Information System (SNIS, 2022).

The regulation of GBI implementation in the state capital, Belo Horizonte, was established just in 2019, in the last version of the municipal Master Plan (Belo Horizonte, 2019), and is virtually absent in the second (Contagem) and third (Betim) biggest cities of its metropolitan region. In this way, the construction of sustainable and resilient cities (UN Sustainable Development Goal 11) discussed globally remains a reality far from most Brazilian cities. The case study of this thesis presents the vulnerability of a water source for 600,000 inhabitants of the third Brazilian metropolis in the face of pressures for further urban development "insensitive" to water.

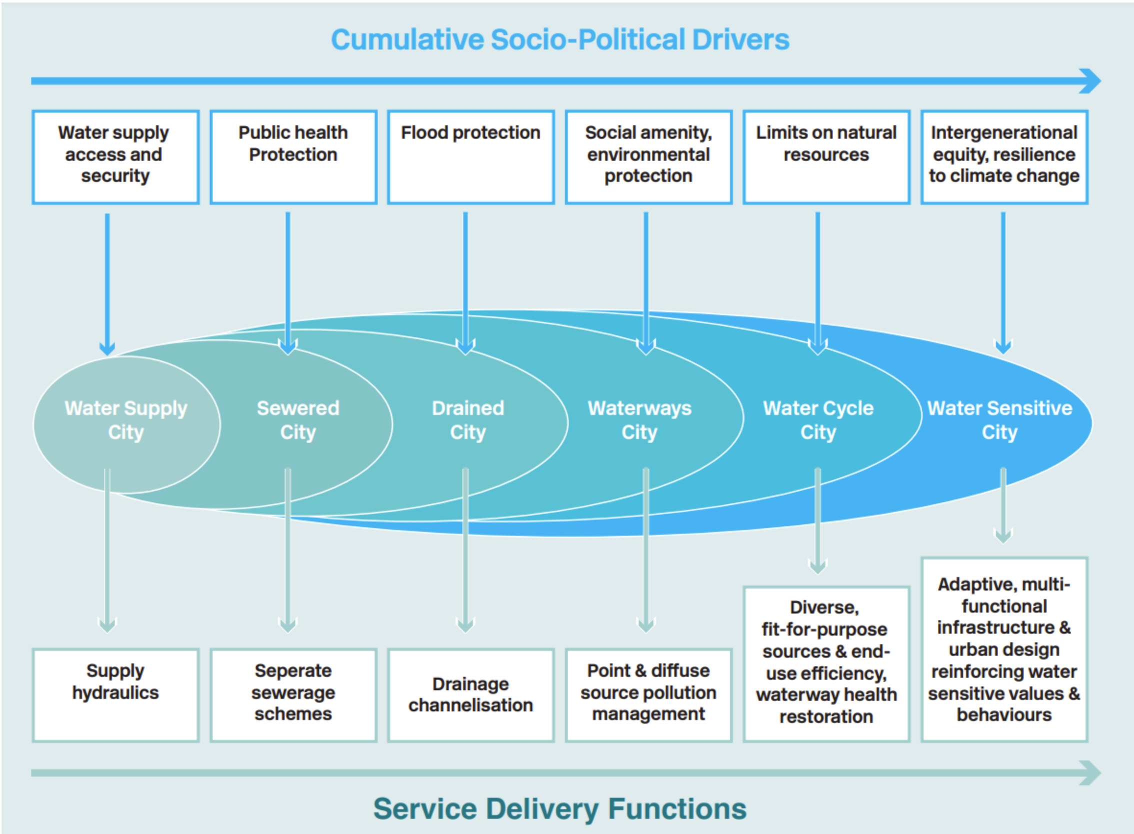
Thus, the conceptual innovation of this work lies on the quantification of hydrological and water quality benefits of GBI as a concept expanded beyond the sustainable stormwater management techniques, bringing it closer to the idea of green-and-blue network, exploring the potential of riparian areas to reduce the landscape fragmentation and the vulnerability of the forest remnants. Its methodological innovation resides in combining various computational models (land use changes, hydrological, hydraulic, and water quality) based on open-source software and public databases, increasing the method's potential reproducibility in other contexts.

The proposed study is part of the MOMA-SE research project entitled "Modelling strategic metropolitan water sources as an input for water and land management in the face of climate change" and developed in partnership with the Universidade Federal de Minas Gerais, Universidade de Brasília, Universidade de São Paulo, Brazil, and the École de Ponts ParisTech, in France. This project proposes, as a primary hypothesis, that "it is possible to increase the resilience of strategic water sources to anthropic pressures and climatic changes, through measures of land use regulation, adoption of soil and water conservation techniques based on concepts of green and blue infrastructure" (MOMA-SE, 2019). In Minas Gerais, three reservoirs with different uses and catchments with different levels of urbanisation are under study: the reservoirs of Serra Azul, Vargem das Flores, and Pampulha, all located in the Belo Horizonte Metropolitan Region (BHMR).

In this research, the Vargem das Flores reservoir catchment was chosen as a case study, selected among the catchments studied on the MOMA-SE research project because the area has undergone recent changes in land use legislation, which may allow the urban development of an extensive area previously considered rural. This change may affect the local hydrological cycle and the reservoir uses in various ways, so studying this change's impacts and evaluating techniques that can mitigate them become scientifically and socially relevant.

In this context, this research intends to contribute to advancing the shift to a Water Sensitive City (Figure 1.3). For that, the research journey of this thesis passes through the study of primary sanitation issues such as water supply and sewage management, through flood control, management of diffuse pollution, and then the multifunctionality of the green infrastructure.

Figure 1.3 – Urban water management transitions framework proposed by Brown et al. (2009)



The transition states proposed by Brown et al. (2009) will be used as a framework to assess the current development stage of Vargem das Flores catchment, as well as to benchmark alternative futures towards a water-sensitive city or the return to less developed stages of the urban water management in the area.

1.2 Objectives

The general objective of this research is to evaluate methodologies for quantifying and mapping benefits related to the implementation of Green and Blue Infrastructure in peri-urban areas. This analysis may support public discussion and decision-making with comparative scenarios and quantitative indicators evidencing the arguments on the adoption of these practices on the metropolis scale.

The hypothesis to be tested is:

"The implementation of Green and Blue Infrastructure can mitigate impacts of urban expansion, be economically viable and scientifically supported, considering the ecosystem and environmental services they provide, especially for the protection of water resources, the reduction of damage caused by floods and the social and environmental benefits they promote."

A synthetic research question could be:

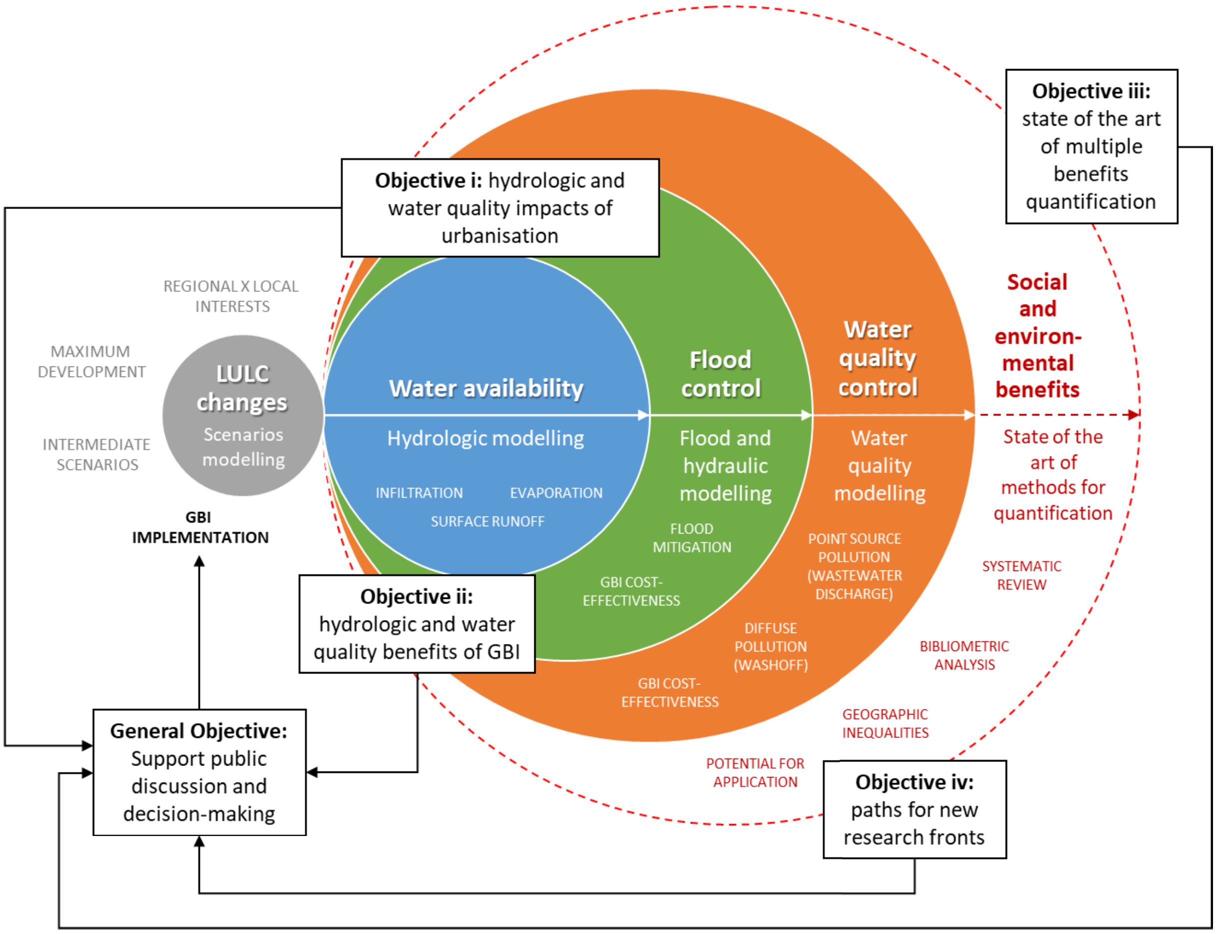
- Could the quantified benefits of deploying Green and Blue Infrastructure be effectively expressed to support social awareness and decision-making in metropolitan areas?

The specific objectives are to:

i. Evaluate the hydrological and water quality impacts of land use and land cover changes associated with urban development in a peri-urban catchment in the Belo Horizonte Metropolitan Region (BHMR);
ii. Evaluate the hydrological and water quality benefits of GBI implementation in a suburban catchment in the BHMR;
iii. Study the state-of-the-art methods to quantify ecosystem services and other benefits of GBI implementation, such as improvement of surface water quality, heat island mitigation, carbon sequestration, improvement of air quality, creation of opportunities for leisure, social interaction, urban agriculture and landscape improvement;
iv. Indicate possible paths for new research fronts and collaboration opportunities for assessing the multiple GBI benefits in different geographical realities.

The diagram of Figure 1.4 illustrates how the research objectives are connected to the study scope. The starting point is the observation of how regional and local interests can influence land use changes in the Vargem das Flores catchment in different future scenarios. In sequence, using multiple tools and models, the research develops the assessment of the impacts of LULC changes in water availability, flood control, and water quality control and opens perspectives for further evaluations of GBI benefits.

Figure 1.4 – Summary diagram of the developed research and objectives



1.3 *Thesis overview*

This document is a thesis by compilation, comprised of traditional chapters that refer to all the work carried out (Chapters 1, 2, 3, 9 and 10) and journal articles already published (Chapters 4 and 5) or in the process of publication (Chapters 6, 7, and 8). Considering the relative independence and length of the text, references are presented at the end of each chapter. The introduction of concepts and the description of the studied area may repeatedly appear in the articles because they need a minimum independent contextualisation. Therefore, the reader's patience is appreciated. At the beginning of the chapters containing the journal articles (4 - 8), the contributions and agreement of the co-authors are presented.

Chapter 1 is this introduction, which presents the context, the general and specific objectives, the hypothesis that guides this research, and an overview of the manuscript. In sequence, Chapter 2 presents a broad literature review, including a panorama about the valuation of multiple benefits of Green and Blue Infrastructure. This review was deepened and systematised in one of the following chapters (Chapter 8). Chapter 3 includes a detailed characterisation of the case study area, the Vargem das Flores reservoir catchment. These opening chapters contextualise the work developed over the five years of research, the results of which are presented in the following chapters (4-9) and discussed in the final chapter (10).

Chapters 4 and 5 focus on quantifying the impacts of urban development (4) and the benefits of GBI implementation (5) in the main water cycle processes – the infiltration, groundwater flow, and surface runoff, including the evaluation of the increase of flooding downstream of the reservoir. Chapter 4 contains the first paper, published in the Urban Water Journal (UWJ), entitled “Hydrological Impacts of Urban Expansion in a Brazilian Metropolis – Case study of the Vargem das Flores reservoir catchment” (Rosa, Silva, Araújo, et al., 2022). Chapter 5 presents the second paper, “Cost-effectiveness of Green and Blue Infrastructure Implementation in a Brazilian Metropolis – Case study of the Vargem das Flores reservoir catchment”, also published in the UWJ (Rosa, Silva, Chong, et al., 2022).

In sequence, the evaluation focuses on the impacts of land use and land cover (LULC) and the benefits of GBI on the quality of surface runoff water. Chapters 6 and 7 present the third and fourth papers entitled “Water quality impacts of Land Use and Land Cover changes in a Brazilian Metropolis: Analysis of past changes and modelling water quality” and “Water quality impacts of Land Use and Land Cover changes in a Brazilian Metropolis – Study of Green Infrastructure Implementation in the Vargem das Flores reservoir catchment”.

Then, to expand the quantification of GBI benefits beyond those related to water, a systematic review of the state of the art was conducted and presented in the fifth paper (Chapter 8) entitled: “The Multifunctional Value of Urban Green and Blue Infrastructure: a comprehensive and systematic review”.

Finally, the work done is synthesised in Chapter 9, with some perspectives for further research and the expected results. Chapter 10 presents the concluding remarks and recommendations for future works.

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2 BACKGROUND AND CONTEXT

"Nossa cultura é sob a ameaça de uma palavra abissal.
Uma ideia que preda o modo como vivemos, o nosso tempo concreto, sem mentira.
Uma mentira sobre o tempo que nos impede de viver quando somos
e nos adia para quando jamais haveremos de ser.
Chama-se futuro."

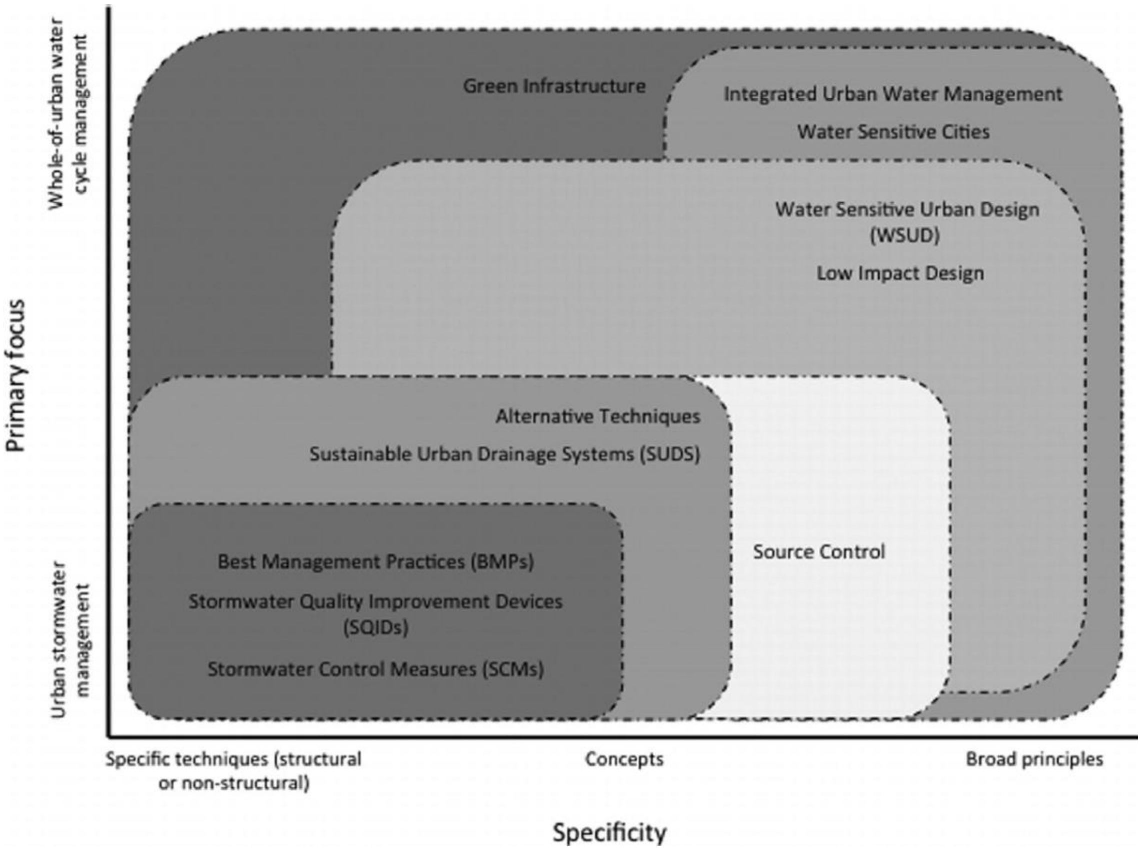
"Our culture is under the threat of an abyssal word.
An idea that preys upon the way we live, our concrete time, without lies.
A lie about time that prevents us from living when we are
and postpones us to when we will never be.
It is called the future."

O pajé do povo Abaeté em 'As doenças do Brasil',
[The shaman of Abaeté people in 'The diseases of Brazil']
a novel by Valter Hugo Mãe (2021)

As previously mentioned, there are many overlaps among various concepts associated with the term 'Green and Blue Infrastructure' such as 'Green Infrastructure', 'Water Sensitive Urban Design' (WSUD), 'Low Impact Development' (LID), 'Alternative Techniques', 'Source Control', 'Sustainable Urban Drainage Systems' (SUDS), 'Best Management Practices' (BMPs). Fletcher et al. (2014) proposed a classification and possible representation of those different scopes (see Figure 2.1).

The term Green and Blue Infrastructure was selected to describe the subject of this study, as it is considered a broader concept that goes beyond the field of urban drainage and may indicate an urban planning approach. In this sense, the term comes close to the concept of Green and Blue Network, initially proposed in France as *"Trame Verte et Bleue"* (Bergès et al., 2010), and already applied as a structuring element in the Master Plan of Integrated Development (Plano Diretor de Desenvolvimento Integrado – PDDI) of the Belo Horizonte Metropolitan Region (Nascimento, Eleutério, Costa, Vinçon-Leite, Mourão, Faria, et al., 2019).

Figure 2.1– Classification of urban drainage terminology

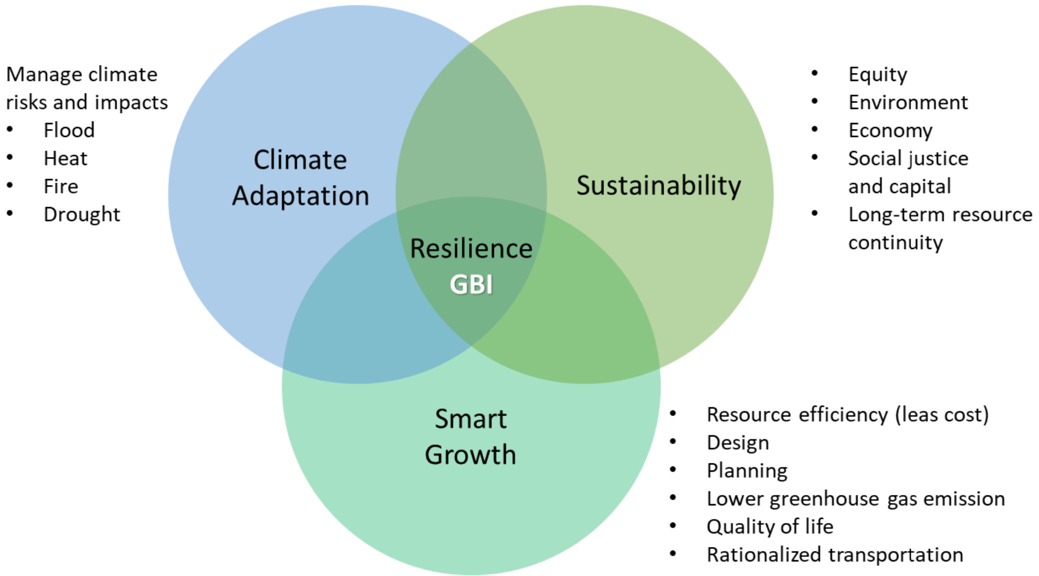


Source: Fletcher et al. (2014).

GBI is also a strategy for intelligent urban planning while enhancing liveability, providing open spaces, and promoting alternative transportation methods that emit less greenhouse gases. While reducing climate change, GBI also prepares the city to deal with it, increasing the responsiveness of the built environment to extreme weather events. Therefore, GBI, as the intersection of these three concepts, can promote a community's resilience, which becomes more prepared to withstand, cope, manage, and recover in the face of hazards and disasters (Foster et al., 2011). Figure 2.2 illustrates this conceptual framework.

Some institutional mechanisms can be used to incentivize GBI implementation: land use zoning, building codes, landscape ordinances, and environmental statutes (Foster et al., 2011). Political support is crucial for wide GBI deployment, whether by governments and decision-makers in a top-down-driven or through broad civic support and community engagement in a bottom-up-driven effort (Wouters et al., 2016).

Figure 2.2 – GBI to achieve resilience, the intersection of sustainability, smart growth, and adaptation



Source: adapted from Foster et al. (2011).

Although GBI is increasingly applied in cities worldwide as stormwater management solutions, economic unfeasibility is still among the main arguments for limiting large-scale applications (Vincent et al., 2017). Because of this, including the economic values of hydrological, social and environmental benefits can increase the benefit-cost ratio and justify more investments in GBI and less in grey infrastructure. Vincent et al. (2017) obtained this result by adding to the reduction in flood damage, the sum of reduced energy consumption due to urban cooling, the market value of stored carbon, and reduced health costs due to air quality improvement. They optimised the total value of benefits, modelling the implementation of green roofs and rain barrels in a catchment in Montevideo, Uruguay.

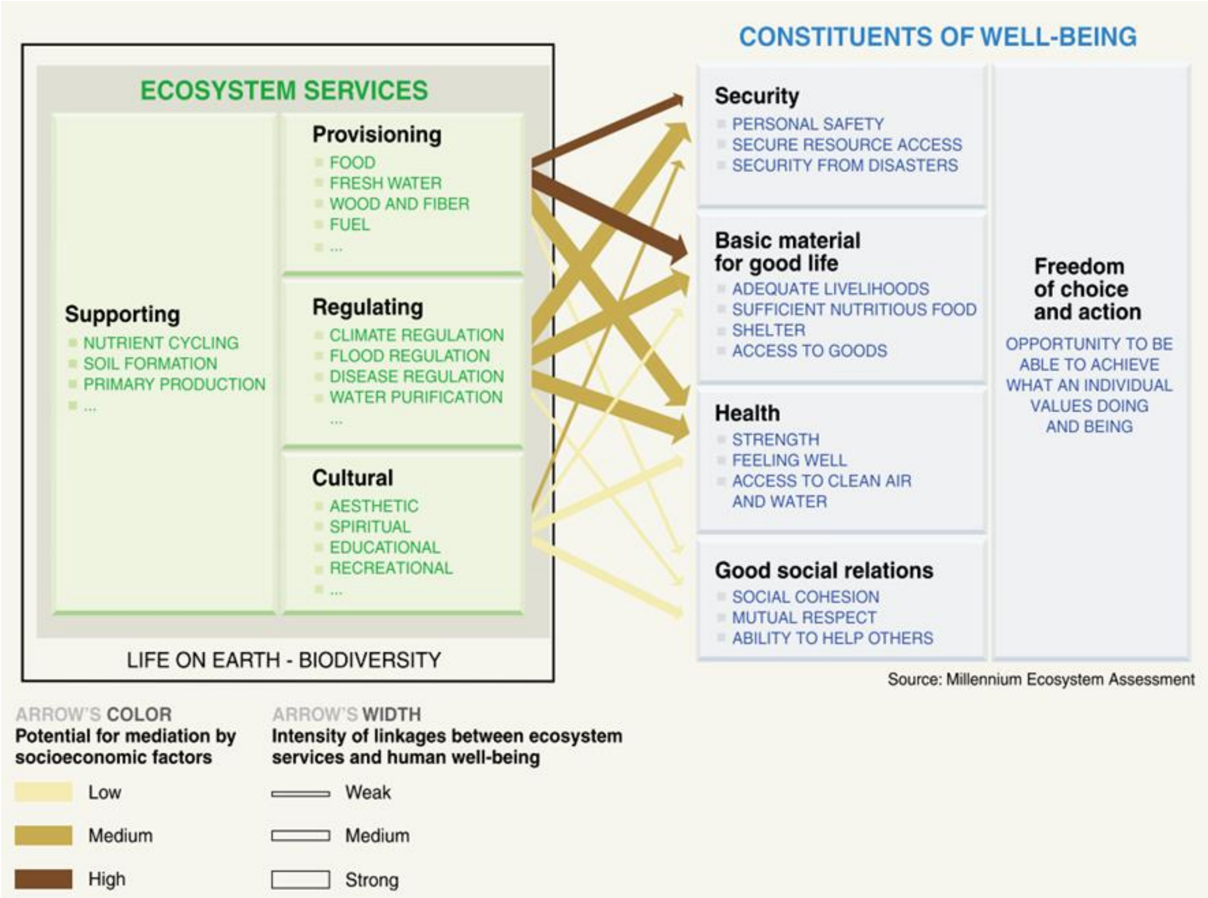
Traditional stormwater management was usually focused on structural engineering measures to deal with the runoff increased by urbanisation. Consequently, the economic analysis generally consisted of estimating construction and maintenance costs, and decisions were made based on these elements. When solutions beyond pipes, channels and ponds are considered alternatives, more comprehensive economic analysis becomes indispensable, including benefits other than hydrological. Among the environmental benefits, the United States Environmental Protection Agency (US-EPA) identifies pollution abatement, protection of downstream water resources, groundwater recharge, water quality improvements and consequently reduced treatment costs, and habitat improvements (United States Environmental Protection Agency, 2007). The same institution details the benefits related to land value and quality of life: reduced downstream flooding and property damage, real estate valuation and property tax revenue, aesthetic value, and public participation in public spaces. In the cited report, the US-EPA summarised 17 case studies of different scales in North America, comparing the costs of conventional and GBI approaches. In 15 projects, the percentual difference between conventional development and LID costs was positive, varying from 15% to 80% (cost savings relative to the conventional development cost); the few exceptions were cases with higher costs for broad implementation of green roofs and permeable pavements (United States Environmental Protection Agency, 2007). Another critical benefit identified was the increased water security, with the use of harvested stormwater as a water resource and the consequent avoidance of stormwater treatment costs.

Among the published studies that evaluate the benefits of Green and Blue Infrastructure, some monetise the environmental services of urban green areas (UGAS) (Jim & Chen, 2009; McPherson et al., 1999; Nowak, 2010). Other studies evaluate only one GBI technique in the hydrological aspect (Caputo, 2012; McCutcheon & Wride, 2013) or a particular benefit (the hydrological) of several GBI techniques (Rosa et al., 2020; Žuvela-Aloise et al., 2016). However, there is a greater potential to increase the chances of GBI adoption if the multiple benefits of multiple interventions acting together are considered, as in the referred studies from North America (United States Environmental Protection Agency, 2007). These arguments underline the interest of this thesis in adding to the study of the hydrological benefits of the GBI, the assessment of co-benefits to water quality and socio-environment.

2.1 Ecosystem services conceptualisation

Although the modern history of ecosystem services dates back to the 1970s (Gómez-Baggethun et al., 2010), the Millennium Ecosystem Assessment (2005) was responsible for mainstreaming the concept. This report presented the correlation between ecosystem services and many aspects of human wellbeing, as illustrated by Figure 2.3.

Figure 2.3 – Linkages between Ecosystem Services and Human Wellbeing



Source: Millennium Ecosystem Assessment (2005).

Since then, ecosystem services have been more commonly classified into (Millennium Ecosystem Assessment, 2005):

- Provisioning services: material outputs from ecosystems such as food, raw materials, freshwater, and medicinal resources.
- Regulating services: ecosystems regulate local climate and air quality, sequestrate and store carbon, moderate extreme events, treat wastewater, prevent erosion and maintain soil fertility, pollinate crops, and biologically control diseases.
- Supporting services: ecosystems provide living spaces for plant and animal species and maintain genetic diversity.
- Cultural services: ecosystems provide non-material benefits to people such as recreation opportunities, mental and physical health, tourism, aesthetic

appreciation and inspiration for culture, art and design, spiritual experience, and sense of place.

2.2 Methods for economic valuation of ecosystem services

The total economic value of an ecosystem can be distinguished between direct or indirect use values, associated with the current or future use of an environmental resource, and non-use values, related to the continued existence of the resource (Barbier, 1998). Direct use values result from direct human use of a service. This use can be consumptive, involving the extraction of a component of the ecosystem and reducing its quantity (e.g., harvesting fish and wild resources), or non-consumptive, without extraction and usually affecting its quality (e.g., use of water for transportation and recreation). Indirect use values are derived from regulatory functions (e.g., flood protection, water purification) while supporting and protecting activities with directly measurable values (e.g., land use, drinking supplies). Non-use values can be related to existence value and the satisfaction of individuals by the knowledge that the ecosystem continues to exist, but also to bequest values (concerning intergenerational equity), altruist values (intra-generational equity), and cultural or heritage values (National Research Council, 2005; The Economics of Ecosystems and Biodiversity, 2010).

Methods for economic valuation of ecosystem services can be classified into (De Groot et al., 2002):

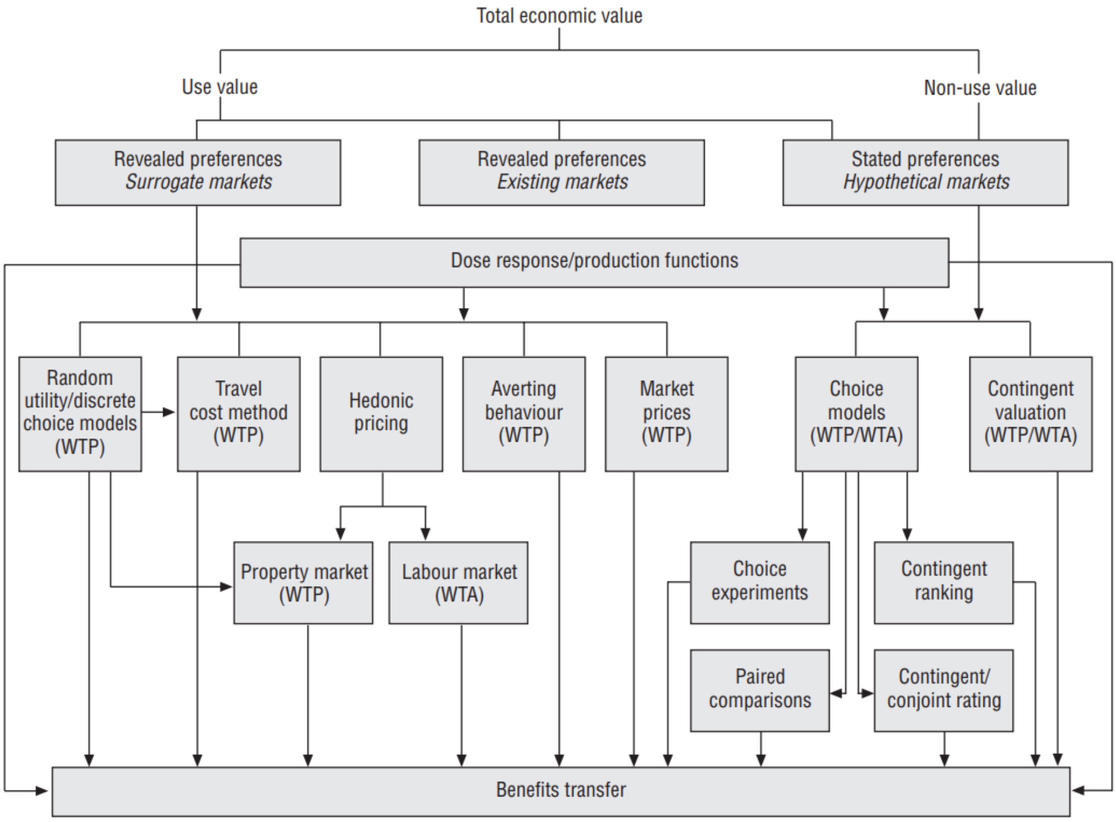
- Direct market valuation – applied when goods or functions have exchange value in explicit markets.
- Indirect market valuation – when there is no explicit market, values can be assessed by the following techniques that reveal the Willingness to Pay (WTP) or Willingness to Accept (WTA) compensation for the availability or loss of the service:
  - Avoided Cost, when society avoids costs that would occur in the absence of the service;
  - Replacement Cost, when anthropogenic systems can replace services;
  - Factor Income, when a service indirectly enhances incomes in a market;

- Travel Cost, when it is required travelling to access the service;
- Hedonic Pricing, when a service demand is reflected in goods' prices.

- Contingent valuation and choice modelling – reveal the WTP or WTA for a service in a hypothetical scenario by a survey.
- Group valuation – when values are defined by open public debate.

The total economic value approach, related to the valuation methods, is shown in Figure 2.4.

Figure 2.4 – Techniques to evaluate Total economic value components



Source: Pearce et al. (2006).

Revealed preference techniques are based on the observation of individual choices in existing or surrogate markets. Hedonic pricing and travel cost are the more commonly used methods. Market imperfections and policy failures can distort the estimated monetary values obtained through revealed preference methods. Stated preference methods simulate a hypothetical market provision ecosystem service based on surveys that elicit respondents' WTP or WTA. Non-use values can only be estimated by stated preference techniques, but contingent valuation and choice modelling can also be used to estimate use values, especially when there is no surrogate market (De Groot et al., 2002; The Economics of Ecosystems and Biodiversity, 2010).

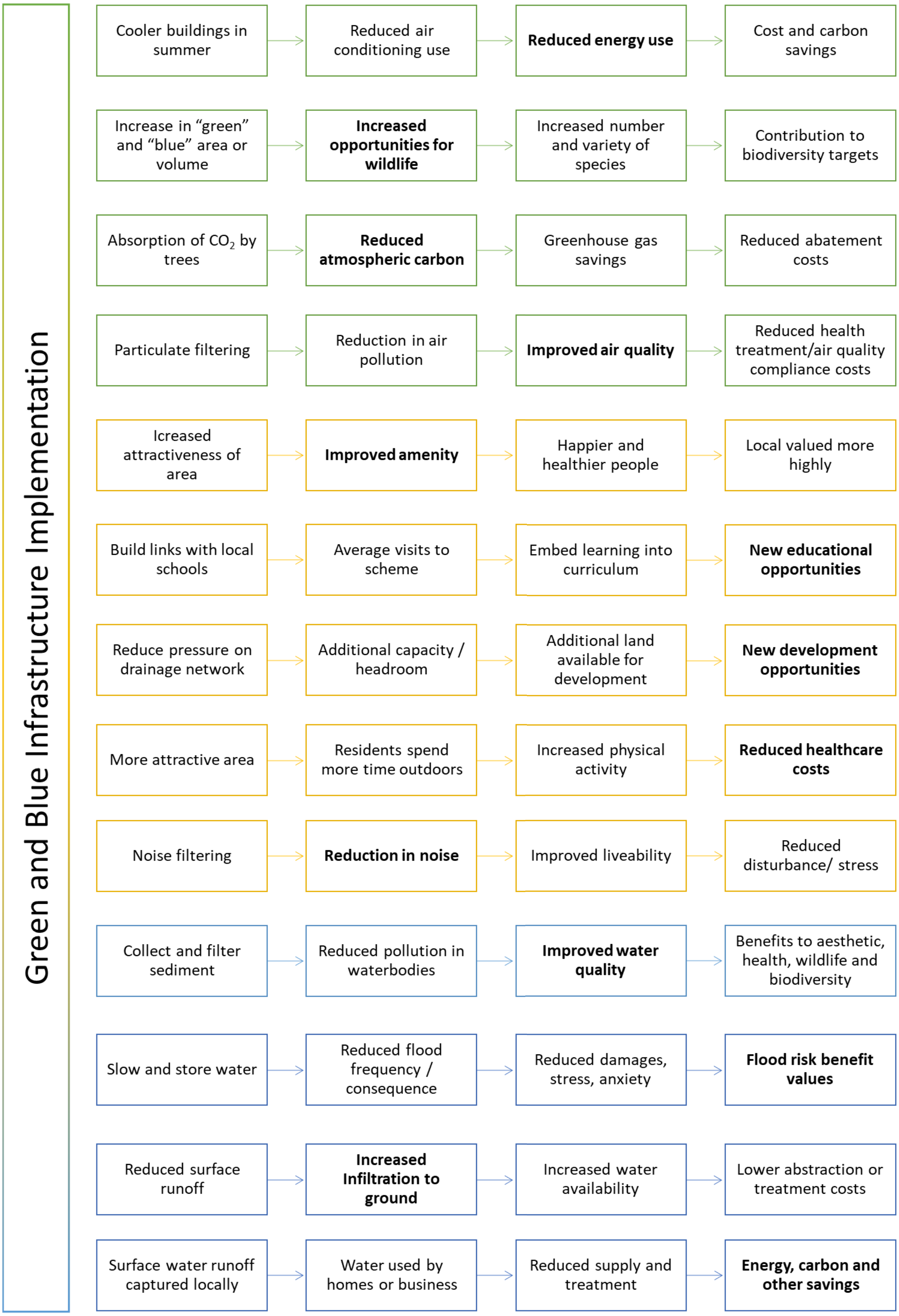
Despite being a valuable tool to synthesize and cluster many ecosystem services into the same language, monetisation can be further criticised (item 2.4). Money is a common medium through which human desires and emotions are expressed and measured, but it fails to capture social and ethical concerns (Harvey, 1996). There are also many critiques of “ecosystem services” as an anthropocentric concept that excludes the intrinsic value of nature. However, the concept has been used as a platform for integrating different worldviews, fostering transdisciplinary research approaches in the last decades (Schröter et al., 2014).

2.3 Valuation of Green and Blue Infrastructure benefits

Horton et al. (2019) described the methods used in the platform Benefits Estimation Tools (B£ST) to assess the benefits of GBI in the United Kingdom. They described the pathways illustrated in Figure 2.5 for GBI implementation's hydrologic, social and environmental benefits. B£ST uses UK government standardised information to monetise the benefits and scientific publications to assess GBI performances.

In the absence of many areas with a broad deployment of GBI, especially on the catchment scale, researchers usually apply computational models to carry out their studies (Li et al., 2017). Jayasooriya and Ng (2014) reviewed 20 models that evaluated the impacts of GBI on water quantity and quality and models capable of conducting economic analysis. SWMM appeared to be a complete tool in modelling stormwater quantity, quality, and the performance of LID techniques, supporting simulations of complex, large-scale projects. Model for Urban Stormwater Improvement Conceptualisation (MUSIC) appeared to be a reliable tool for planning GBI, although regional barriers for its application should be considered. The authors identified the valuation of environmental and economic services of GBI as a forefront research area and recommended introducing modules to increment the capabilities of the current models.

Figure 2.5 – GBI impacts pathways according to B£ST methodology



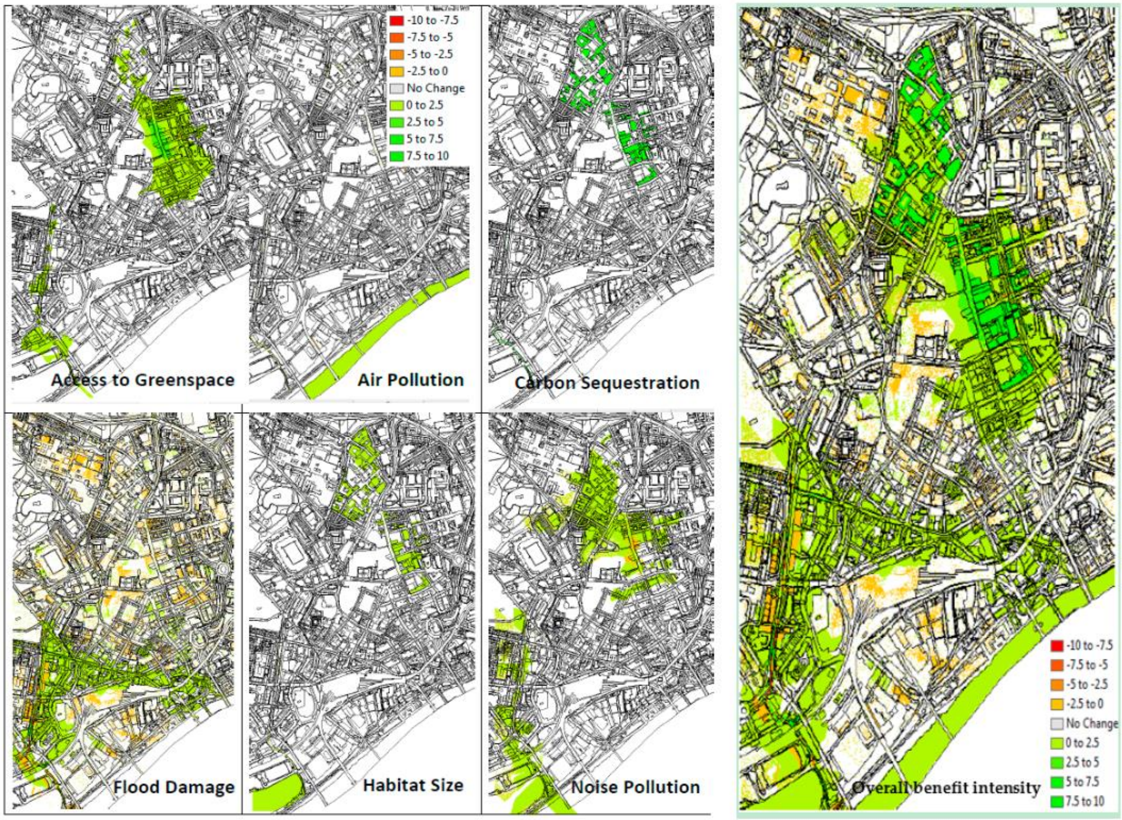
Source: adapted from Horton et al. (2019).

When evaluating the benefits of existing green areas as part of a GBI network, it is crucial to consider the socioeconomic benefits to make the restrictions for urban development reasonable in these areas. Vandermeulen et al. (2011) evaluated the economic benefits of the “green cycle belt” in Bruges (Belgium) through a cost-benefit analysis. They estimated the net present value of the project investment costs and the regional excess burden needed to execute the investment and compared it to the socioeconomic benefits provided by the GBI. Recreational benefits were estimated by travel cost method, avoiding costs by changing the commute from car to bike, the health effects from cycling were estimated with health care cost savings, the lowering of CO_2 and air pollutant emissions was monetised by the direct avoided social costs, the same method used to monetise the improvement on traffic safety. The payback period was estimated at 14 years, below the used time horizon of 20 years. Considering the indirect benefits of the green infrastructure project, the benefit-cost relation was positive, emphasising that pulling all benefits and costs into a common basis is certainly valuable for determining the attractiveness of such a project.

The inclusion of GBI as a strategy in urban spatial planning is reinforced by economic valuation, as Wilker and Rusche (2013) demonstrated. They applied contingent valuation to measure the willingness to pay of residents of the Neckar region in Germany for future GBI projects. They stated the importance of monetary valuation of green infrastructure benefits to compare different possibilities of land use, especially in urban areas. However, the transfer of findings from studies assessing residents' willingness to pay for GBI benefits, contingent upon their perception tied to socioeconomic status, presents a complex challenge. Geographical and spatial inequalities, extending from local to global scales must be accounted for, given the socioeconomic disparities in the demand and supply of GBI ecosystem services.

The spatialisation of GBI benefits is also useful for representing and analysing patterns of supply and demand and priority areas. Morgan and Fenner (2019) spatially evaluated the benefits, using concepts of benefit intensity and profile proposed by Fenner (2017). The benefits profile is the graphical representation of the relative performance of benefits according to the influenced area; the benefit intensity is the spatial representation of the normalisation of ecosystem services as a ratio to the maximum value attainable (see Figure 2.6).

Figure 2.6 – Benefit intensity spatial representation



Source: Morgan and Fenner (2019).

The economic valuation may compose a cost-benefit analysis and can serve as a basis to explore the possible trade-offs among the different GBI benefits, as the sequential studies presented below (Alves et al., 2019; Alves et al., 2018; Alves et al., 2020).

Alves et al. (2019) evaluated the co-benefits of GBI, benefits besides flood risk reduction, inserting them in an economic viability comparison of green, blue, and grey infrastructure implementation. They studied a catchment of 509 hectares on Sint Maarten Island, with high flood vulnerability. First, they estimated the flood damage reduction by subtracting the expected annual damage in the scenario with GBI measures from the one without measures. For this, they applied SWMM to obtain the water depth in points of the drainage system and identify the number of affected buildings for events of different return periods under the different GBI or grey measures scenarios. The co-benefits assessment included the estimation of heat stress reduction, air quality improvement and water savings. Their economic values were estimated based on local energy and water prices or indications from the literature. In order to compose a cost-benefit analysis (CBA), they computed investment and maintenance costs for each infrastructure. All values were converted to present values for the lifespan period of the techniques.

Using the multi-criteria method proposed by Alves et al. (2018), they evaluated the deployment of green roofs, pervious pavements, rainwater barrels, detention basins, and pipes. For the green roofs, they estimated the energy savings due to building temperature reduction, reduction of carbon dioxide emission and improvement of air quality, applying the method proposed by the Center for Neighborhood Technology (2010), and the increase of roof longevity due to the membrane protection by the soil layer. They monetised the co-benefits of rainwater barrels by estimating the direct avoided costs with water production and energy (water is obtained from seawater desalination in the studied local) and the consequent decrease of CO_2 emissions, and the WTP for avoiding impacts of droughts according to the Cooperative Research Center for Water Sensitive Cities (2016). The energy savings due to permeable pavement installation were estimated considering the houses in an area distant about 50 meters from the pavement and an average value of 40 euros per house.

They concluded that, when considering only the benefit of flooding reduction, the application of grey infrastructure (pipes) appeared as the best option, but when co-benefits were considered, rainwater harvesting offered a higher benefit-cost relation. In general, grey infrastructure appeared more feasible because of its low prices and high efficiency in avoiding flood-related damages. However, when secondary benefits are accounted for, combinations of green, blue, and grey infrastructure become economically viable. Even so, the total value of co-benefits was lower than the primary benefit, probably because authors considered only straightforwardly quantifiable co-benefits. In this sense, they recommended that future works evaluate the maximisation of flood mitigation and co-benefits along with cost minimisation and consider methods to select the best combinations of measures to improve efficiency (Alves et al., 2019).

The same research group (Alves et al., 2020) analysed the trade-offs among different benefits of GBI in stormwater infrastructure planning. They applied the methods described by Alves et al. (2019) to estimate the total benefits and a nondominated sorting genetic algorithm (NSGA-II) as an optimisation framework. They observed a substantial difference when considering the co-benefits and found the combination of green, blue, and grey infrastructure as the best strategy, reducing flood risk and providing co-benefits. However, the authors concluded that there are inevitable trade-offs among different benefits, emphasising the need to establish which benefits should be prioritised in the decision-making process.

Although green infrastructure is often applied due to its multifunctionality, studies and decision-making processes usually focus on only one or a few benefits and do not consider trade-offs and synergies, as Meerow and Newell (2017) argue. In response, they evaluated ecosystem services provided by green infrastructure in a spatial planning model called "Green Infrastructure Spatial Planning (GISP)" to prioritize areas to be treated in Detroit, United States of America. They prioritised the areas according to stormwater criteria (runoff coefficient of Rational Method and wastewater discharge), social vulnerability (socio-economic and demographic variables such as wealth, age, density, housing, and race), access to green space (walk distance to a park), air quality (annual average emissions of particulate matter, obtained in a high-resolution spatial air pollution model based on traffic), urban heat island (mean daytime land surface temperatures), and landscape connectivity (Patch Cohesion Index landscape metric, calculated in the software Fragstats). They also consulted local stakeholders to prioritize these benefits, and after they combined the six criteria. Some benefits were negatively correlated (stormwater and landscape connectivity criteria, e.g.), while others acted synergically (stormwater, urban island effect and air quality, e.g.), confirming that the trade-offs must be understood and negotiated in the political arena to develop the best solution.

Not only do trade-offs need to be considered in the GBI planning process, but also synergies that can increase benefits and their interrelationships. For example, hydrological benefits enhance ecological benefits by maintaining consistent water flows and a proper soil environment, while ecological benefits drive hydrological benefits by increasing water infiltration and filtration (Zhang & Chui, 2019). The same authors, reviewing 100 studies of hydrological and bioecological benefits of GBI, identified a gap in studies about bioecological benefits at the catchment scale.

2.4 Critical evaluation of monetisation

Monetary valuation of ecosystem components and functions is sometimes criticised as a neoliberal tool that fails to capture social and ethical concerns (Saarikoski et al., 2016). Harvey (1996) raised the question:

> "At this point, the critic of money valuations, who is nevertheless deeply concerned about environmental degradation, is faced with a dilemma: eschew the language of daily economic practice and political power and speak in the wilderness, or articulate deeply-held nonmonetizable values in a language (i. e., that of money) believed to be inappropriate or fundamentally alien. The deeper dilemma is that though money may lack moral meaning itself, it becomes the vehicle through which human desires and passions get mediated and measured."

Although criticism is often based on situations that have led to the commodification or privatisation of natural resources, it is essential not to lose a valuable idea in the attempt to get rid of what is not wanted. To go beyond the question of rejecting or not money in the valuation of nature, Kallis et al. (2013) proposed a guiding framework for deciding when to engage with the monetary valuation of an ecosystem service. The authors argued that monetisation is valid when it: improves environmental conditions, reduces inequalities and redistributes power, does not suppress other languages of valuation, and does not serve processes of enclosure of the commons. If one of these criteria is disrespected, monetary valuation is not recommended at the risk of contributing to enclosure, privatisation, or dispossession.

Therefore, monetisation can contribute to the decision-making process only when facilitating a transparent public debate, including the allocation of benefits and costs across the stakeholders and clarifying the economic importance of ecosystem services (Saarikoski et al., 2016). As discussed further, the adoption of monetisation as a method was critically reevaluated throughout this research, especially after considering the potential impacts of neoliberal-oriented political decisions in the case study area.

2.5 Gaps in the literature review

Evaluating the multiple benefits of GBI is particularly challenging in developing countries reality, considering that policies of broad implementation of GBI are only at the beginning of the discussion, though the scientific interest in this area is increasing (Valente de Macedo et al., 2021). As indicated in the previous paragraphs, most studies developed in Brazil focused on the hydrological benefits of compensatory techniques and or their economic aspects (Cançado, 2009; Caputo, 2012; Drumond et al., 2013; Miguez et al., 2012; Rosa et al., 2020). In parallel, studies from other research areas are mostly focused on the benefits of green infrastructure not primarily planned for stormwater management, such as urban green spaces. For example, there is an increasing interest in assessing the health benefits related to proximity to green areas (Cirino et al., 2022; Moreira et al., 2022; Pimentel da Silva et al., 2022).

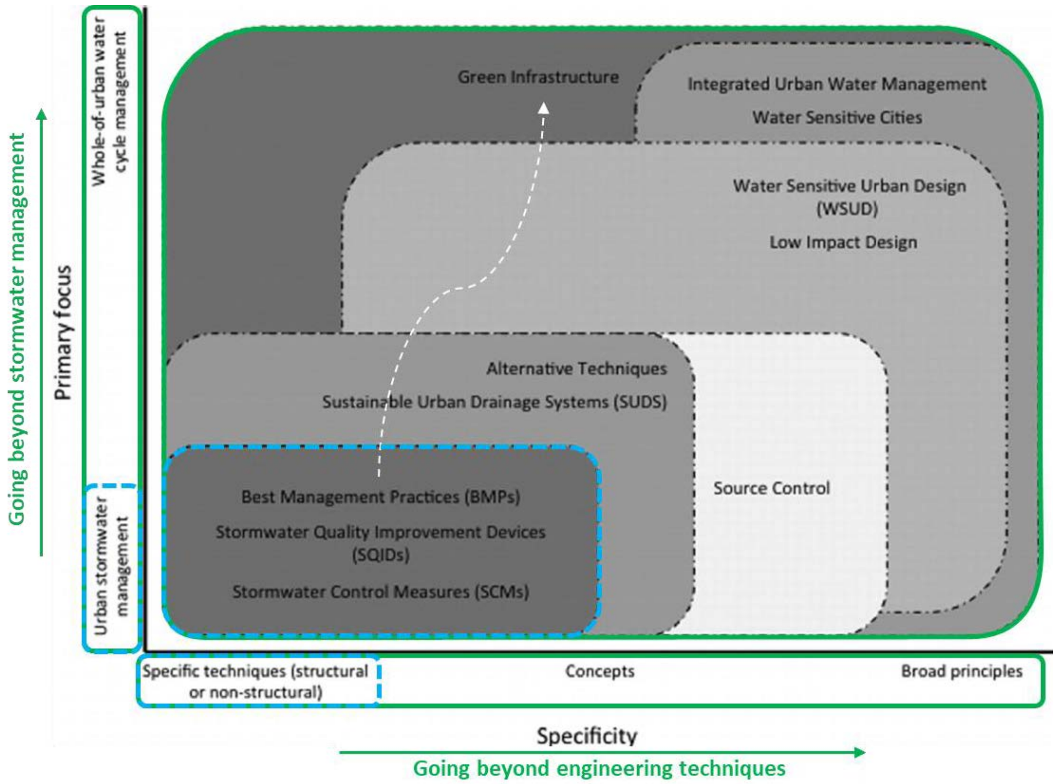
Due to the difficulty in finding feasible methods that use available (and low-cost or free source) data for a complete benefit analysis, the decision-making process on urban drainage investment generally disregards or relegates to low priority the evaluation of other GBI benefits. This critical issue is related to the scarcity of resources and capability, as in many countries, stormwater management is the responsibility of municipal and local governments. With the limited capacity to quantify the benefits of GBI, among other factors, municipalities usually opt for implementing only conventional drainage projects for specific and limited purposes. However, any comparative analysis between conventional urban drainage techniques and GBI will be incomplete if the multiple benefits that the latter can promote are not considered.

Considering that most referred studies on the multiple benefits of the simultaneous implementation of various GBI were developed in the Global North context (Center for Neighborhood Technology, 2010; Elmqvist et al., 2015; Foster et al., 2011; Gómez-Baggethun & Barton, 2013), this research is especially interested in finding methods for quantifying GBI benefits that have greater potential to be applied in developing countries contexts. For that, preference will be given to methods that use freely available data and can integrate the benefit of multiple interventions. Further attention to the state-of-the-art on the multifunctionality of multiple GBI techniques will be presented in Chapter 8.

2.6 Summary

This chapter laid the conceptual and scientific groundwork for the research into the GBI benefits in urban areas. The term Green and Blue Infrastructure was selected to describe the subject of this study, as it is considered a broader concept that goes beyond the field of urban drainage and may indicate an urban planning approach (Figure 2.7).

Figure 2.7 – Expanding the conceptual scope: adapted from Fletcher et al. (2014)



Although various methods exist for the economic valuation of GBI benefits, there are criticisms and concerns about monetising ecosystem services. This critical perspective was essential to guide the quantification effort of this thesis to nonmarket indicators, especially considering the social and economic contentious issues in the case study area. The main gaps identified in the existing literature are the context of developing countries that need further exploration and research efforts. In summary, this chapter serves as a foundation for this research by providing the necessary background knowledge, concepts, methods, and considerations related to the study of GBI and its benefits.

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3 CASE STUDY – VARGEM DAS FLORES RESERVOIR

"O território é cheio de ciência,
o limite de uma terra está em nossa consciência."

"The territory is full of science,
the limit of a land is in our consciousness."

Célia Xakriabá,
Brazilian Indigenous activist and educator from the Xakriabá people
in the state of Minas Gerais (Corrêa, 2018)

This chapter details the study area common to Chapters 4 to 7, the catchment of the Vargem das Flores reservoir, located in the Metropolitan Region of Belo Horizonte, Brazil. The description of the history of management and changes in land use in the catchment will guide the creation of alternative scenarios and highlight the reason for the interest in choosing the area as a case study.

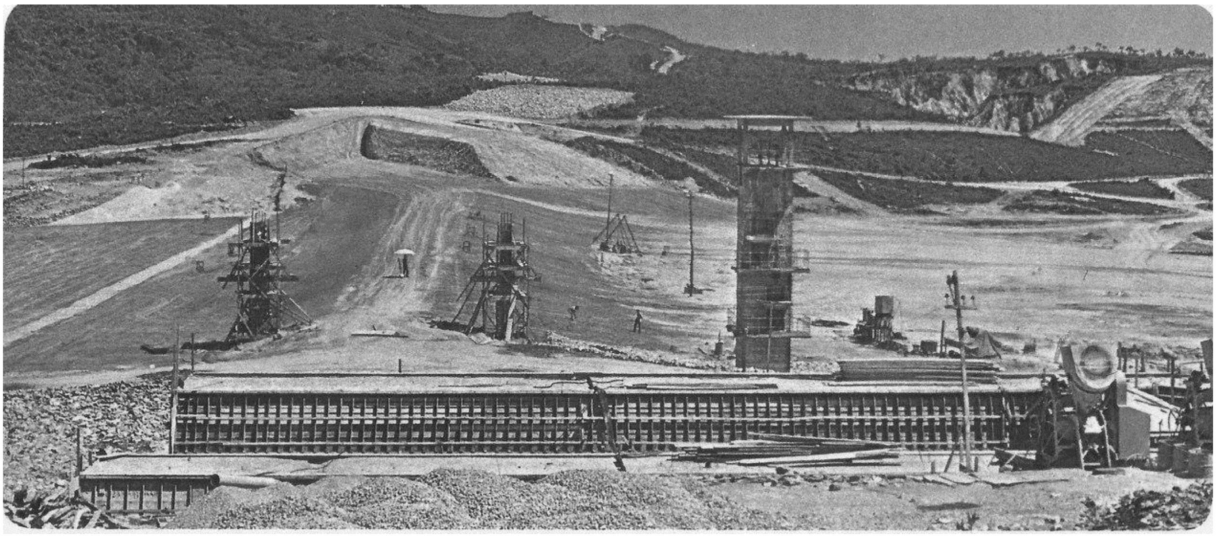
3.1 Historical background

From the 1940s, the construction of the industrial district of Contagem intensified the urban development of the western surroundings of Belo Horizonte. With the installation of industries and the remarkable population growth, the demand for water in the region increased, and a new source was sought to supply drinking water for the metropolitan region. Thus, in 1968, the municipality of Contagem was authorised to use public water from the Betim stream, which should be dammed, for domestic and industrial supply (Minas Gerais, 1968). Betim stream was diverted (see Figure 3.1), Vargem das Flores dam was built between 1968 and 1972 (see Figure 3.2), and the reservoir was filled (see Figure 3.3) and put into operation in 1973 (Práxis, 1997). The dam was built in Betim municipality, downstream, but only 38.6% of the reservoir area (elevation 845 m) and 13.8% of the catchment area are in this municipality; the rest belongs to the municipality of Contagem.

Figure 3.1 – Diversion channel of the Betim stream and the area that would be flooded by the reservoir (photo taken in 1968-1972)

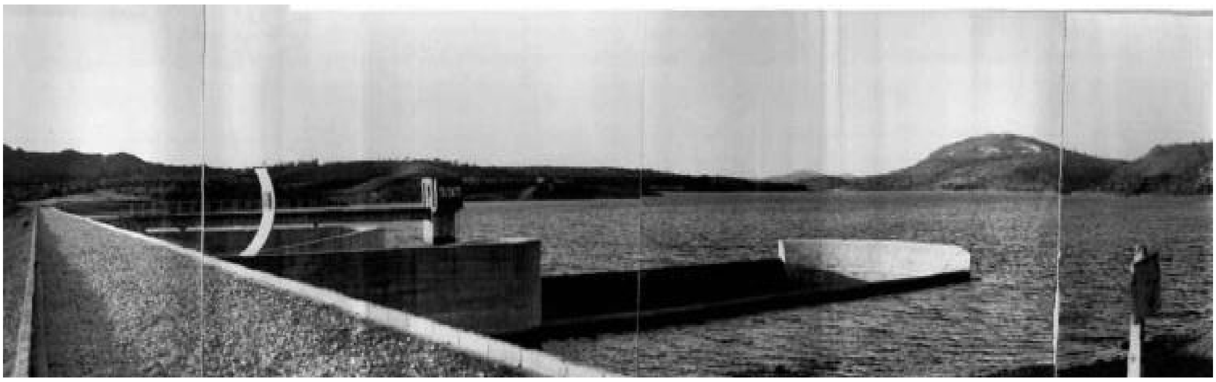
Source: Associação de Proteção e Defesa das Águas de Vargem das Flores [Association for the Protection and Defence of Vargem das Flores Waters] (Aprovargem, 2017).

Figure 3.2 – Water inlet and dam being built (photo taken in 1968-1972)



Source: Aprovargem (2017).

Figure 3.3 – Weir of Vargem das Flores Reservoir (1976)



Source: Superintendência de Desenvolvimento da Região Metropolitana de Belo Horizonte [Superintendence of Planning of the BHMR] (Plambel, 1976).

In 1974, the municipal government celebrated an agreement with the water and sewage company of Minas Gerais (Comag), currently named Copasa - Companhia de Saneamento de Minas Gerais [Minas Gerais State Sanitation Company], in order to establish conditions for sanitation in the municipality, including the concession of all facilities related to the water service for Vargem das Flores system (Contagem, 1974).

In the 1960 decade, in response to the demand for new housing areas, a region in the north of the catchment was subdivided and called Nova Contagem, but effective occupation began in the 1980s (Práxis, 1997). For a while, this portion of the catchment did not have adequate sanitation conditions, water was supplied by tanker trucks (see Figure 3.4), and the untreated sewage was thrown into Água Suja stream (literal translation “dirty water”). Despite the recent coverage by the water supply and sewage collection network (Figure 3.5) and the construction of a Sewage Treatment Plant in 2005-2007, the stream still receives an irregular discharge of sewage and solid waste (see Figure 3.6).

Figure 3.4 – Water supply through tanker trucks in the region of Nova Contagem (1990 decade)

Source: Aprovargem (2017).

Figure 3.5 – Construction of sewage network in the region of Nova Contagem (2010)

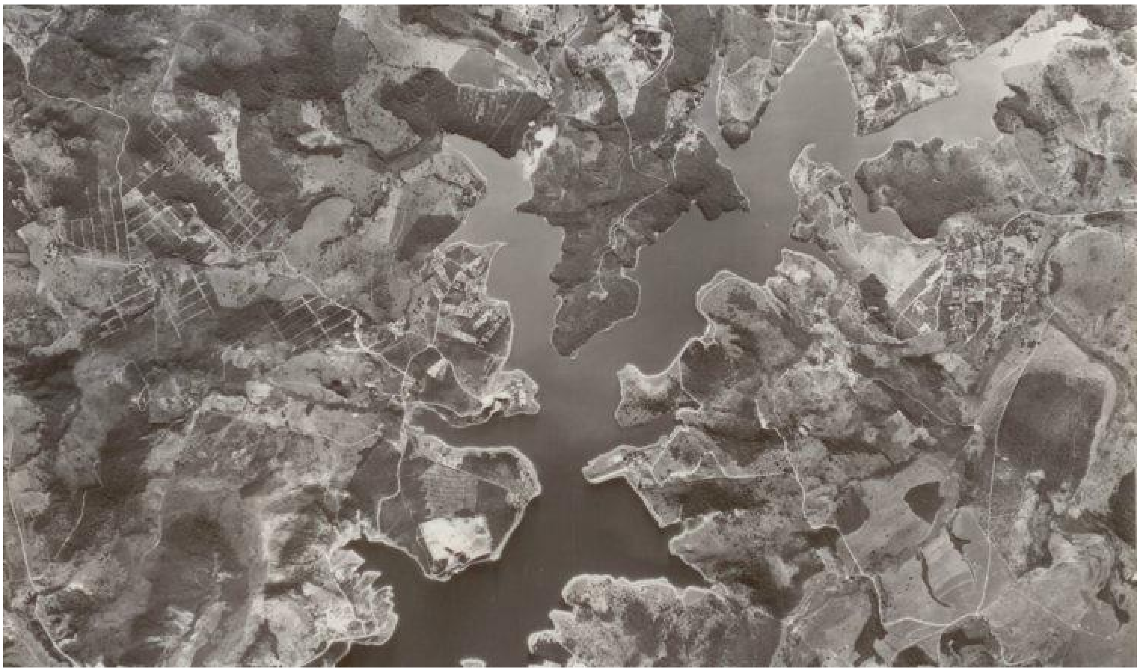
Source: Contagem (2010b).

Figure 3.6 – Degraded watercourses with sewage and solid waste in the region of Nova Contagem (2016)

Source: Master Plan of Integrated Development of the Belo Horizonte Metropolitan Region (PDDI-BHMR, 2016).

In the immediate surroundings of the reservoir, occupation remained predominantly rural (see Figure 3.7), but recently, the urban development contiguous to the city of Contagem has been approaching the reservoir (see Figure 3.8).

Figure 3.7 – Aerial photo of Vargem das Flores reservoir and surroundings (1981)



Source: Contagem (1981).

Figure 3.8 – Aerial photo of Vargem das Flores reservoir and surroundings (2019)

Source: Google Earth (2019).

The reservoir's banks are predominantly occupied by weekend houses in high-end settlements (see Figure 3.9), but there are also low-income settlements (Tupã district, e.g.). Some areas have free access to the reservoir, which has been used for leisure and recreation activities (see Figure 3.10), fishing, and religious activities by residents of the municipalities of Betim, Contagem and surroundings (Práxis, 1997).

Figure 3.9 – High-end houses by the Vargem das Flores reservoir (2016).

Source: PDDI-BHMR (2016).

Figure 3.10 – Recreation and leisure in the Vargem das Flores reservoir (2016).

Source: PDDI-BHMR (2016).

Between 2014 and 2015, as most of the Southeast region of Brazil, BHMR suffered a severe water shortage, and the water levels of the reservoirs that make up the Paraopeba System have greatly decreased (see Figure 3.11). The reservoirs recovered their volume with the resumption of rainfall and the construction of a new intake in the Paraopeba river (see Figure 3.12).

Figure 3.11 – Water intake in Vargem das Flores reservoir in the period of severe drought, 20% full reservoir (end of 2015)

Source: Campos (2020).

Figure 3.12 – Water intake in Vargem das Flores reservoir, 80% of recovered volume (2018)

Source: Campos (2020).

In 2020, in contrast, intense rainfall in the catchment raised the reservoir's water level to the maximum spillway overflow height (see Figure 3.13). Because of this, Copasa was required to present a security plan, relocating affected families in the event of downstream flooding and adopting measures to control the water level in the reservoir (Alves, 2020).

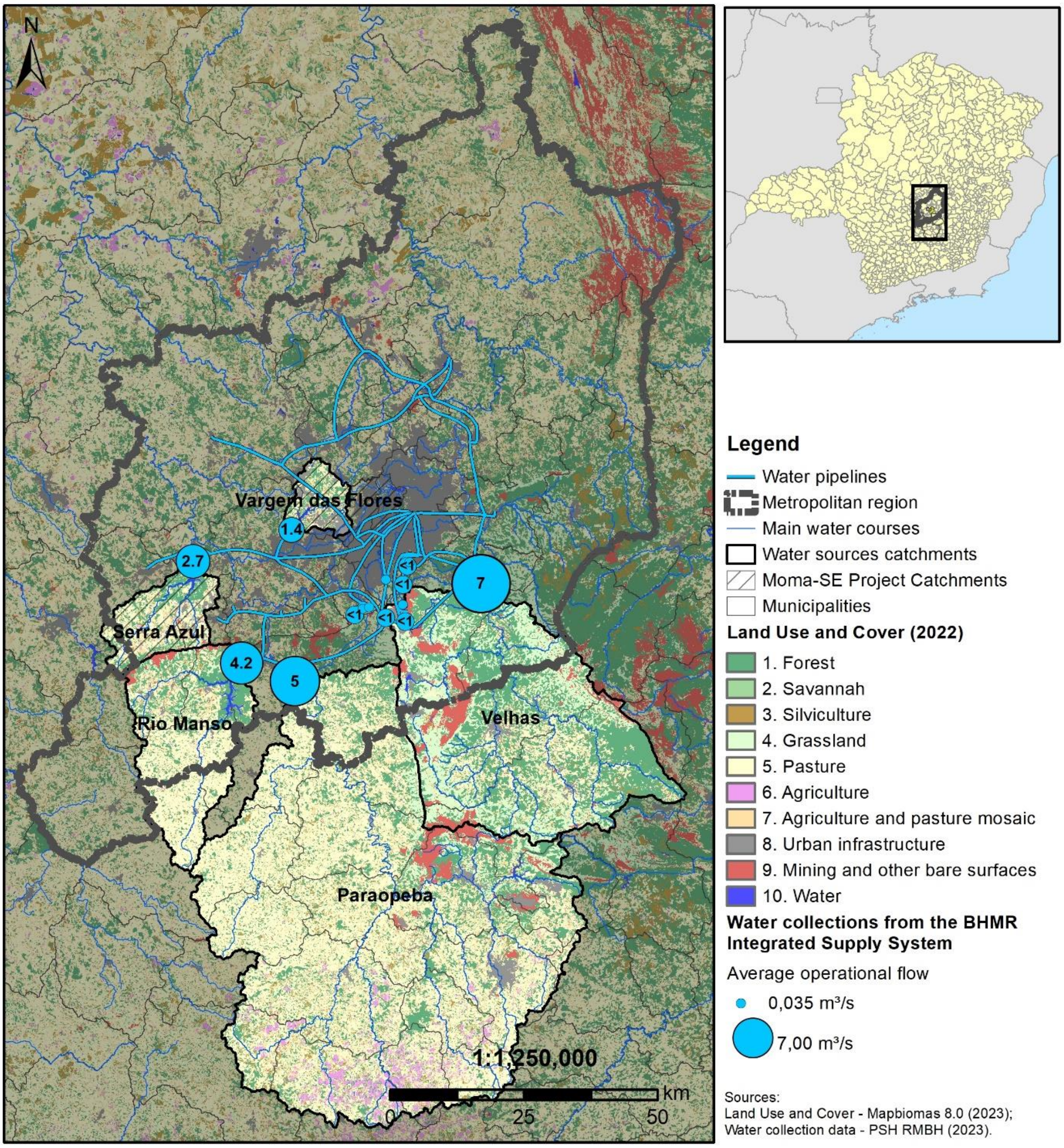
Figure 3.13 – Overflow in the spillway of Vargem das Flores reservoir, with pump installed in the right corner of the weir (31/01/2020)

Source: Alves (2020).

Despite having multiple uses, the primary function of the reservoir is still to provide water for human supply. Copasa, the company responsible for managing the BHMR's water supply system (see Figure 3.14), is authorised to capture 1.39 m³/s from Vargem das Flores reservoir, supplying a population of about 600,000 people (Pena, 2018).

The BHMR's integrated system supplies water for 5 million inhabitants in 22 municipalities, including 2.6 million in the capital (ANA, 2021). Among the five main water sources to supply the BHMR, the two biggest are direct abstractions from water courses, the Velhas River (average operational flow of 7.0 m³/s) and the Paraopeba River (5.0 m³/ s). Both catchments do not have a reservoir to regulate flow and storage and are, therefore, quite vulnerable to variations in the rainfall regime and impacts from the various risk activities in their basins. In 2020, the Paraopeba River intake has been interrupted since the rupture of the tailing dam from the Córrego Feijão mine in Brumadinho (Melo et al., 2020). The other three sources are the reservoirs of Rio Manso (4.2 m³/s), Serra Azul (2.7 m³/s) and Vargem das Flores (1.4 m³/s) (PSH BHMR, 2023). Among the five main water sources, Vargem das Flores is the only one with no tailing dam upstream of the water supply (Melo et al., 2020). The three biggest sources, Velhas, Paraopeba, and Rio Manso, have 16 tailing dams with stability not guaranteed (13, 2, 1, respectively). Even so, Vargem das Flores catchment is the closest to the metropolis urban area, and the main threat to this source is the urban development.

Figure 3.14 – Water Sources of the BHMR Integrated Public Water Supply System



Source: elaborated with data from MapBiomas (2018); PSH BHMR (2023).

In response to urban development in the catchment area, the Special Protection Area (Área de Proteção Especial – APE) Vargem das Flores was created on 08/09/1980 by the State Decree 20793, covering the entire catchment of the reservoir (Minas Gerais, 1980). Due to the lack of effectiveness in protecting water sources in the catchment, another conservation unit was created on 26/06/2006 by State Law 16197, the Environmental Protection Area (Área de Proteção Ambiental – APA) Vargem das Flores, covering the same area (Minas Gerais, 2006). These legal instruments defined that the forests and other natural vegetation should be permanently protected and that subdivision projects should be submitted to the prior consent of the Superintendence of Planning of the BHMR (Superintendência de Desenvolvimento da Região Metropolitana de Belo Horizonte – Plambel). Even so, the instruments of land use regulation that more explicitly restricted urban development in the catchment were the Municipal Master Plans and the Laws of Land Use and Occupation of Contagem (1995, 2006, 2010a), which defined specific zones and urban controls restricting development.

The amendment to State Constitution n. 65 of 2004 created a new institutional model for metropolitan management and defined the need for a Master Plan of Integrated Development (PDDI) for the BHMR (Minas Gerais, 2021). During the preparation of the PDDI-BHMR, a participatory process conducted by the Universidade Federal de Minas Gerais, Vargem das Flores catchment was considered a macrozone of metropolitan interest justified by its environmental and drinking water supply relevance. In this sense, the PDDI broadly reproduced Contagem’s land use regulation in force at that time, though adopting more restrictive urban parameters (e.g., minimum lot area, maximum impervious surface per lot) (Nascimento, Eleutério, Costa, Leite, et al., 2019). The PDDI proposal for Vargem das Flores catchment was developed in a joint agreement with Contagem City Hall, but this regulation did not come into force since the PDDI still needed to be approved by the Minas Gerais state parliament to be fully applied.

Nevertheless, after the 2016 municipal election, a new political group with a neoliberal orientation took over the Contagem City Hall, implementing a policy promoting urban sprawl (Carvalho, 2021). The administration of Contagem municipality conducted a process fraught with irregularities and little public participation, resulting in a new municipal master plan, approved in 2018, easing restrictions for the catchment occupation (Contagem, 2018). In a last attempt to protect the catchment area from intense urban development, a political mobilisation was made (see Figure 3.15), and restrictions were established in the Land Use and Occupation Law voted by the City Council (Contagem, 2020). The Mayor vetoed many law articles, a political impasse was established, and the City Council overthrew some of these vetoes.

This contentious change in land use legislation in Contagem produced intense political debate and protests arranged by civil society organisations (see Figure 3.16 and Figure 3.17). Some of these organisations were created specifically to defend Vargem das Flores, such as the Association for the Protection and Defence of the Water of Vargem das Flores (Aprovargem), the movement SOS Vargem das Flores, and the Association of Protectors, Users and Friends (APUA) of the Várzea das Flores Reservoir.

Figure 3.15 – Posters in defence of Vargem das Flores at a public hearing on land use legislation in the Municipal Parliament of Contagem

Source: Câmara Municipal de Contagem (2020).

Figure 3.16 – Protest organised by Aprovargem against changes in land use legislation in Contagem.

Source: Aprovargem (2020).

Figure 3.17 – Demonstration for the protection of Vargem das Flores held on the reservoir's banks, with the presence of the SOS Vargem das Flores movement.

Source: Sindieletro (2019).

APUA Várzea das Flores participates in the Betim Municipal Environmental Council and the Vargem das Flores Environmental Protection Area State Council, in addition to carrying out environmental education actions in the region (see Figure 3.18).

Figure 3.18 – APUA Várzea das Flores lecture on rainwater storage.

Source: APUA (2016).

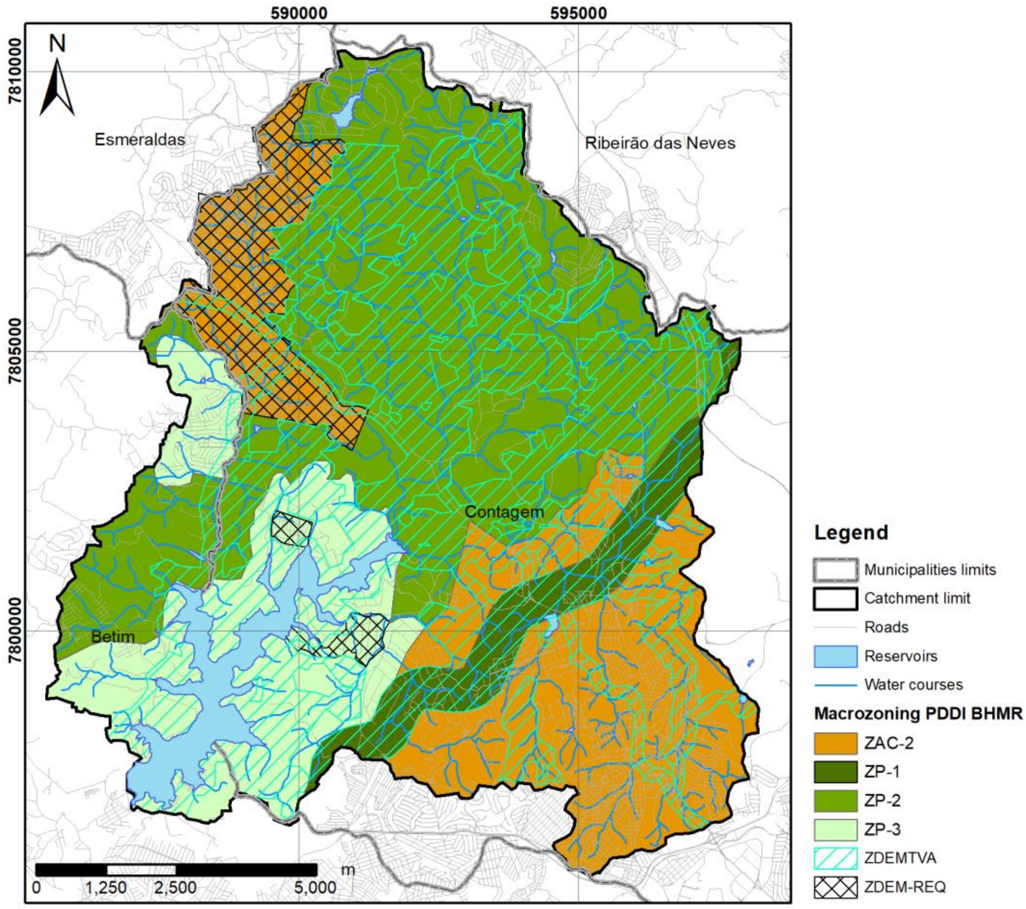
3.2 Land use legislation

In Brazil, the urban land subdivision must follow the criteria defined by Federal Law n. 6766 of 19/12/1979. According to that law, it is not allowed to subdivide land with a slope of 30% or more in areas prone to flooding and areas of ecological preservation, and at least 35% of the glebe area must be destined for public equipment. According to Silva (2010), approximately 20% of the area is usually destined for roads, 15% for green areas, and 5% for institutional areas.

3.2.1 Master Plan of Integrated Development of BHMR – Macro-zoning phase

Figure 3.19 presents the macro-zoning map according to the PDDI-BHMR, and Table 3.1 presents the urban controls by each zone in the catchment. The zones are split into Protection Zones (ZP) and Complementary Activities Zones (ZAC).

Figure 3.19 – Macro-zoning map proposed by PDDI to Vargem das Flores catchment



Source: adapted from PDDI-BHMR (2017).

Table 3.1 – Urban controls by macro-zoning proposed by PDDI to the catchment

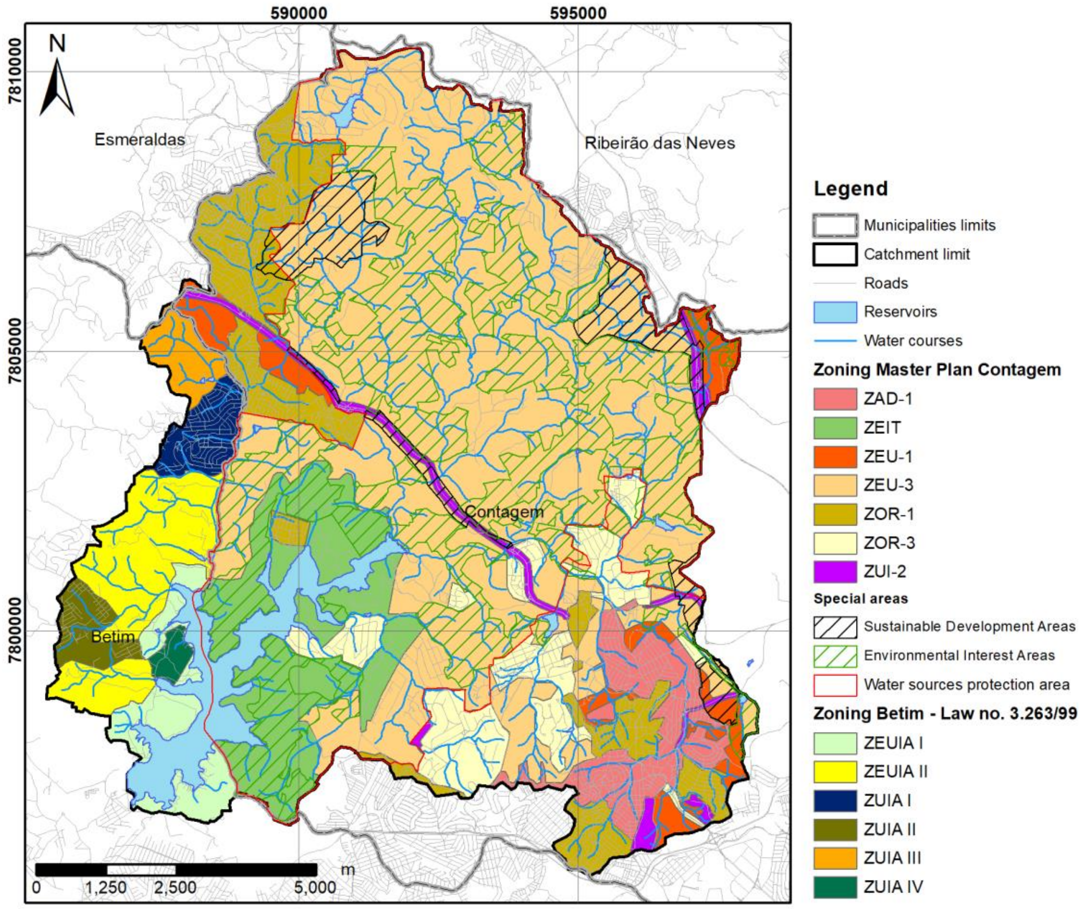
Zone	Minimum Lot Size m²	Land Quota per Residential Unit m²	Maximum Utilisation Coefficient	Minimum pervious rate %
ZP-1	-	-	0.05	95
ZP-2	20,000	5,000	0.1	85
ZP-3	10,000	2,000	0.5	80
ZAC-2	360	60	1.5	30

Source: adapted from PDDI-BHMR (2017).

3.2.2 Municipal Master Plans

Figure 3.20 presents the zoning map according to the Master Plan of Contagem (2018) and Municipal Law of Betim no. 3263/1999 (Betim, 1999). Urban controls in force in Betim's Urban Zones of Environmental Interest (ZUIA) and Urban Expansion Zone of Environmental Interest (ZEUIA) are presented in Table 3.2.

Figure 3.20 – Proposed zoning by municipal land use legislation in the catchment



Source: adapted from Betim (1999) and Contagem (2018).

Table 3.2 – Urban controls in Betim portion of Vargem das Flores catchment

Zone	Minimum Lot Size m²	Land Quota per Residential Unit m²	Maximum Utilisation Coefficient m²	Minimum pervious rate %
ZUIA I	360	180	1.0	20
ZUIA II	360	360	0.5	20
ZUIA III	5,000	5,000	0.2	70
ZUIA IV	10,000	10,000	0.3	70
ZEUIA I	10,000	10,000	0.3	70
ZEUIA II	10,000	10,000	0.3	70

Source: adapted from Betim (1999) and Contagem (2018).

Zones in the 2018 Municipal Master Plano of Contagem are Annoying Use Zones (ZUI), Increased Density Zone (ZAD), Restricted Occupation Zones (ZOR), Urban Expansion Zone (ZEU), and Zone of Special Tourist Interest (ZEIT). These zones are overlaid by areas of interest, which may have different urban controls defined in specific legislation. Urban controls in force in the Contagem portion of the catchment according to Municipal Law n. 295/2020 (Contagem, 2020) are presented in Table 3.3.

The Sustainable Economic Development Areas (ADES) are planned to implement economic activities as "industrial districts" with restrictions for implementing activities with great environmental impact. The Areas of Special Environmental Interest (AIA) are areas with remanent vegetation cover or other relevant environmental attributes that aim at water preservation, fauna habitat, soil stability, landscape protection and balanced maintenance of green areas in the municipality. Criteria for occupation or protection of ADES must be defined in specific laws, and no specific urban parameters have been established in the current legislation (Contagem, 2018, 2020).

The Water Sources Protection Area (APM) has the objective of maintaining and conserving the hydrographic network for the protection of water resources and perennation of Vargem das Flores reservoir, and has some specific urban controls defined in the current legislation (Contagem, 2018, 2020): lots may not present more than one-third of their area with a slope equal to or greater than 30%; all areas less than 30 m from the margins of the *maximorum* level of the reservoir (elevation 840 m) and the surrounding areas with an altitude of less than 845 m are *non-aedificandi*; and all fluvial channels and flood-prone areas are *non-aedificandi*.

Table 3.3 – Urban controls in the Contagem portion of Vargem das Flores catchment

Zone	APM	AIA	Minimum Lot Size m²	Minimum pervious rate %	Land Quota per Residential Unit m²	Maximum Use Coefficient m²
ZUI-2			360	30	-	Residential: 1.0 - Other: 2.0
	X		360	70		
		X	2,000	70		
	X	X	5,000	70		
ZAD-1			360	30	-	2.0
	X		360	70		
		X	2,000	70		
	X	X	5,000	70		
ZOR-1			360	30	120	Tupã: 0.5 - Other: 1.0
	X		360	70		
		X	2,000	70		
	X	X	5,000	70		
ZEU-1			360	30	-	1.0
	X		360	70		
		X	2,000	70		
	X	X	5,000	70		
ZOR-3*			2,000	50	2,000	Residential: 0.5 - Other: 0.4
	X		2,000	70		
		X	2,000	75		
	X	X	5,000	75		
ZEU-3*			2,000	50	2,000	Residential: 0.5 - Other: 0.4
	X		5,000**	70		
		X	2,000	75		
	X	X	20,000	80		
ZEIT	X		20,000	70	20,000	Residential: 0.5 - Other: 0.4
	X	X		80		

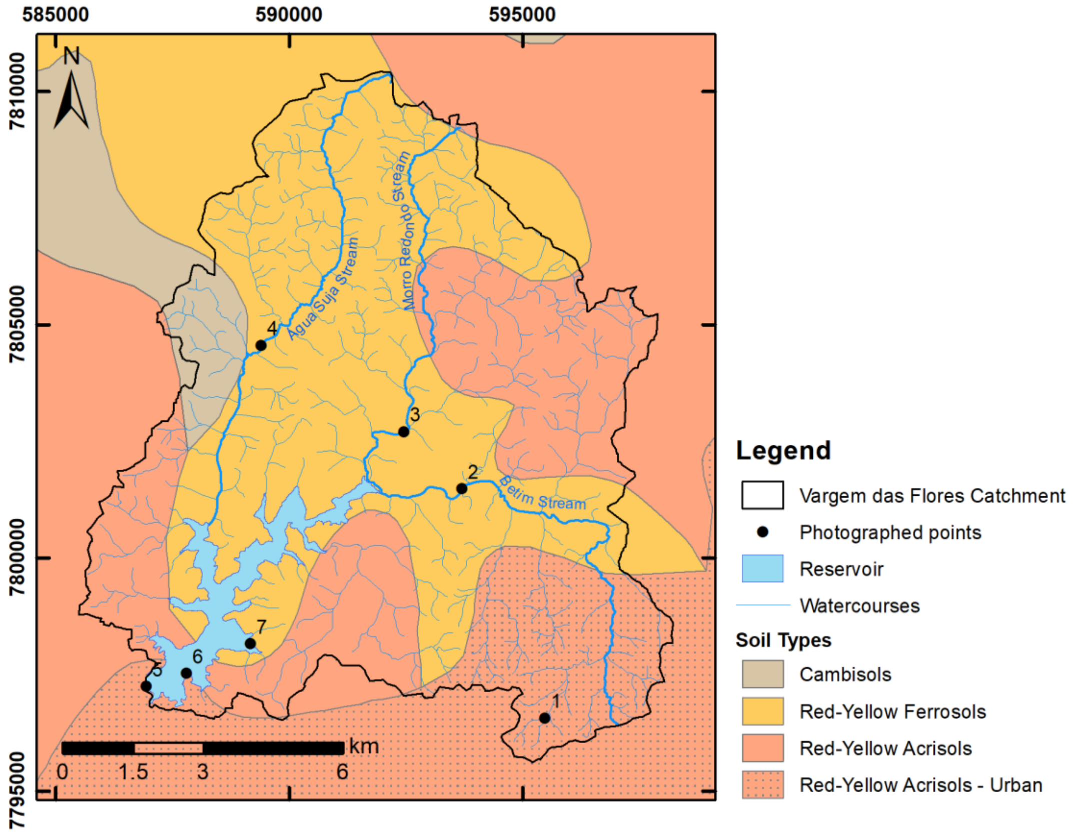
* In areas with a water network, the minimum lot size is 1,000 m²; in areas with sewer treatment outside APM, the minimum lot size is 360 m², and the quota is 90 m². ** In areas with a water network minimum, lot size 3,000 m².

Source: adapted from Contagem (2020).

3.3 Geology, pedology and climate

Vargem das Flores catchment is entirely contained within the Belo Horizonte Complex geological unit, characterised by a granite-gneissic-migmatite basis dating from the Mesoarchean period (Romano et al., 2014). According to Costa (2002), the lithologies that make up the Belo Horizonte Complex change and give rise to deep sandy-clay soils with thicknesses over 50 m. Figure 3.21 illustrates the soil types in the catchment, according to the State Secretariat of Environment and Sustainable Development (SEMAD, 2010).

Figure 3.21 – Soil map of the region of Vargem das Flores catchment

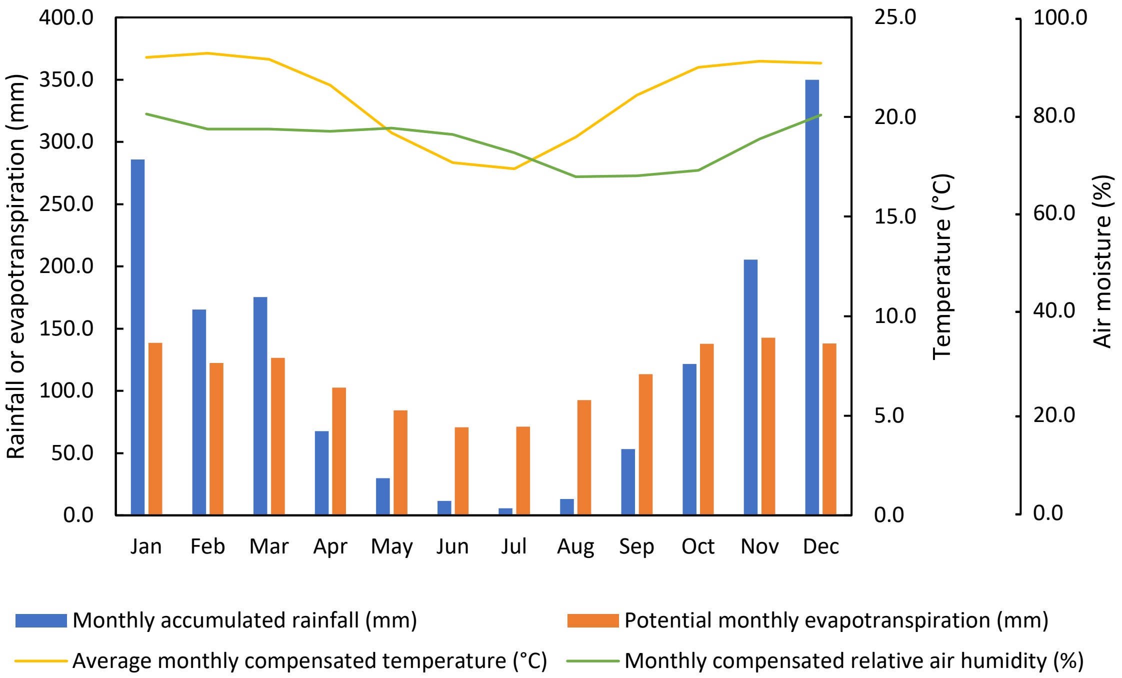


Source: adapted from Secretaria Estadual de Meio Ambiente e Desenvolvimento Sustentável - SEMAD (2010).

The types of soils found in the catchment are: the red yellow ferrosol, horizon A moderate and clay texture, average saturated hydraulic conductivity of 5.1×10^{-7} m/s; and the red yellow acrisol, A moderate and clayey/sandy texture, average saturated hydraulic conductivity of 1.1×10^{-6} m/s; and the cambisol with clay texture, A moderate (Costa, 2002; SEMAD, 2010).

Alvares et al. (2013) state that Vargem das Flores catchment is in the humid subtropical Köppen climate zone with dry winter and temperate summer (Cwb). The climatic patterns registered between 1981 and 2010 in the nearest National Meteorological Institute (Instituto Nacional de Meteorologia – INMET) station indicate that the annual average rainfall is 1,488 mm, and the annual potential evapotranspiration is 1.341 mm (INMET, 2019). The monthly patterns are illustrated in Figure 3.22.

Figure 3.22 – Climatic characteristics of the region of Vargem das Flores catchment (Station Ibirité 1981-2010)



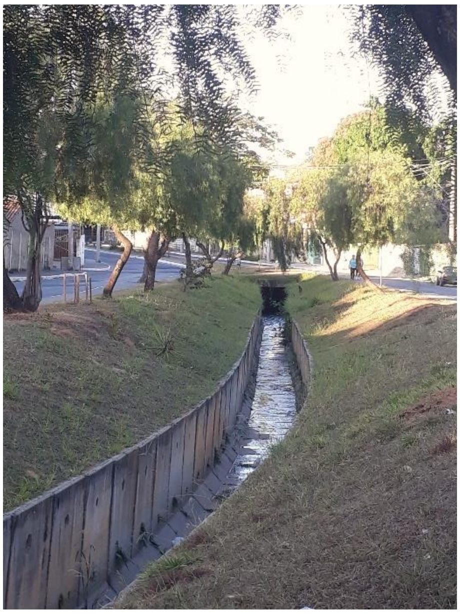
Source: adapted from INMET (2019).

3.4 *Water resources*

The main watercourses contributing to Vargem das Flores reservoir are Betim, Morro Redondo and Água Suja streams. Betim stream source is in the central region of Contagem, and the watercourse is channelised right at the headwaters (see Figure 3.23 a) but returns to the natural channel when leaving the urban area (see Figure 3.23 b). From the upstream, the appearance of the water indicates the likely discharge of untreated wastewater into the watercourse.

Moro Redondo stream has the most preserved subcatchment among the Vargem das Flores tributaries, which can be noted in the water aspect in Figure 3.24 (a). On the other hand, the Água Suja stream still receives pollutant load, as shown in Figure 3.24 (b).

Figure 3.23 – Photos of Betim stream (a) near the spring, in the central region of Contagem (point 1 in Figure 3.21) and (b) downstream, in the rural area (point 2 in Figure 3.21)



(a)

(b)

Source: author's collection.

Figure 3.24 – Photos of (a) Morro Redondo stream (point 3 in Figure 3.21) and (b) Água Suja stream (point 4 in Figure 3.21)

(a)

(b)

Source: author's collection.

Figure 3.25 and Figure 3.26 show some parts of the reservoir banks and the return channel downstream of the reservoir.

Figure 3.25 – Photos of (a) the return channel downstream of the reservoir (point 5 in Figure 3.21) and (b) an aerial view of the reservoir (point 6 in Figure 3.21)

(a) (b)

Source: author's collection.

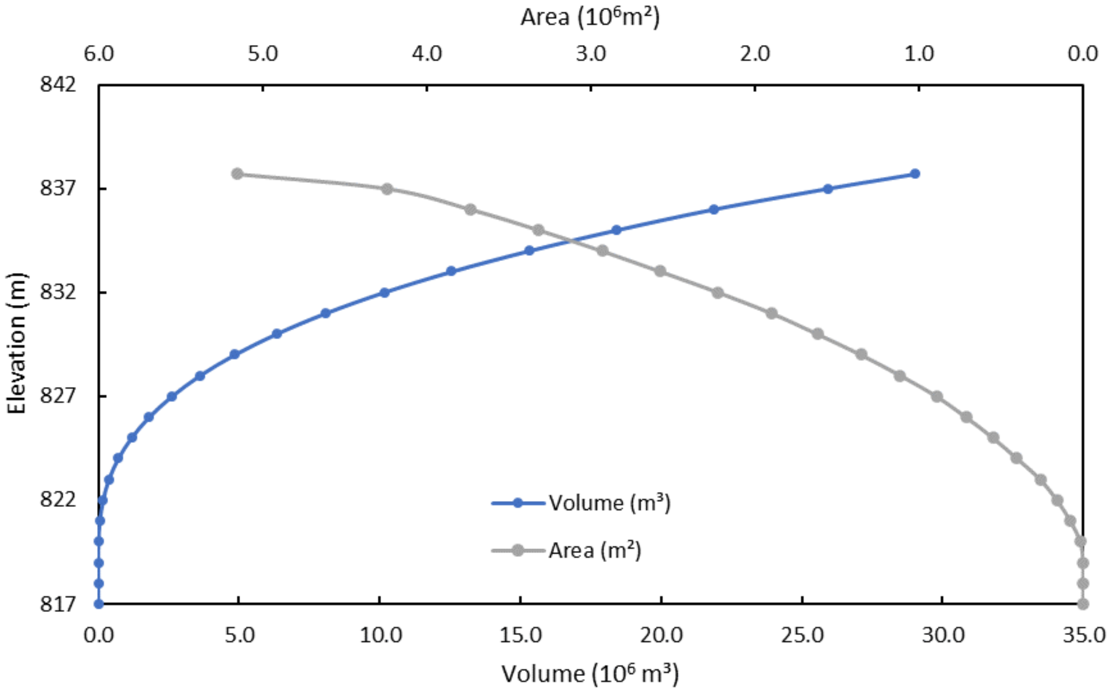
Figure 3.26 – Photos of Vargem das Flores banks (a) view of a club (point 6 in Figure 3.21) and (b) view of a restaurant (point 7 in Figure 3.21)

(a) (b)

Source: author's collection.

Vargem das Flores reservoir extends over an area of 515.18 hectares at elevation 837.7 m, with a storage volume of 29,007,704 m³ and a perimeter of 38.2 km (Santos, 2012). The maximum water depth from which the emergency overflow starts is 21.78 m, and the bottom of the deepest water intake is at an elevation of 828.1 m. The curves that represent the relation between elevation, area and volume are shown in Figure 3.27.

Figure 3.27 – Elevation-Area-Volume curves of Vargem das Flores reservoir – 2009 bathymetry



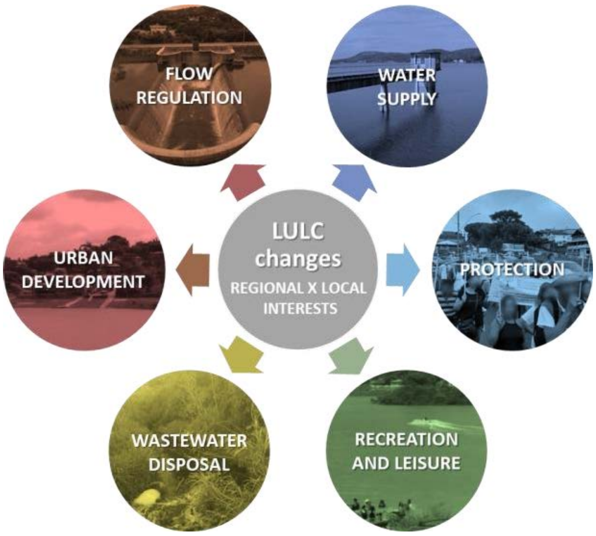
Source: adapted from Santos (2012).

According to Viana (2009), the reservoir has no bottom discharge or residual flow valve. Copasa (2019) stated that the volume captured for the Water Treatment Plant varies between 0.7 m³/s and 1.2 m³/s, and the ecological flow is maintained by constant pumping of 0.296 m³/s.

3.5 Summary

Considering the background presented in this chapter, it is noted how the discussion about land and water multiple uses (see Figure 3.28) in Vargem das Flores catchment is up to date and how environmental studies are needed to support public debate and decision-making.

Figure 3.28 – Multiple uses and interests in conflict at Vargem das Flores catchment



The historical context of urban development and land use changes in the region highlights the challenges related to the coexistence of urban expansion and environmental protection. Since the reservoir construction, legal frameworks, including land use controls and the creation of conservation units, have tried to protect the catchment environment to guarantee the water supply function. Even so, political and economic pressures to develop new urban areas in the catchment showed that no regulatory framework is immutable and legal protection can be revoked. In addition, Vargem das Flores's case study illustrates the contrast between normative protections on paper and the realities of "Business as Usual" development. In Brazil, the existence of land use plans and protective laws does not guarantee their effective implementation. This dichotomy reveals the critical tension between environmental preservation and urban development, where community involvement and activism play a significant role. Every change in land use impacts water, nutrients, and sediment cycles, interfering with the possible uses of the water body. Understanding this complex interplay is essential for this research and is explored in the next chapters.

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4 ARTICLE 1: Hydrological Impacts of Urban Expansion in a Brazilian Metropolis – Case Study of the Vargem das Flores Reservoir Catchment

"Aqui, tudo parece que é ainda construção e já é ruína."

"Here, everything seems to be under construction and already in ruins."

Caetano Veloso, in 'Fora da ordem' [Out of order] (Veloso, 2003)

This chapter presents the first effort at quantifying the regulating ecosystem services provided by the existing green and blue infrastructure in the catchment of the Vargem das Flores reservoir. As existing green and blue infrastructure, the remaining forest fragments and the reservoir itself are included, which regulate the flows in the Betim stream, providing water for supply and controlling floods downstream of the dam. The method applied to quantify these GBI benefits consists of modelling the hydrological impacts of future land use and land cover scenarios that consider removing part of the vegetation cover and advancing urbanisation in the catchment.

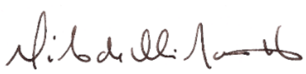
All data used and referenced in this article are open source or were obtained free of charge from public institutions through direct contact, as in the case of data obtained with Copasa, Fundação João Pinheiro, Contagem's and Betim's City Halls, or from databases available on their websites, as in the case of the Brazilian Centre of Monitoring and Natural Disaster Warning (Cemaden) and the Brazilian Annual Land Use and Land Cover Mapping Project (MapBiomas). Most of the mentioned databases are available for much larger areas and can be applied in similar studies to be developed in other catchments and scales. The models applied in this article are also all open source: the environmental modelling platform Dinamica EGO developed by the Centre for Remote Sensing at the Institute of Geosciences of the Federal University of Minas Gerais (CSR-UFMG); the Storm Water Management Model (SWMM) developed by the US Environmental Protection Agency; and the U.S. Army Corps of Engineers Hydrologic Engineering Center - River Analysis System (Hec-RAS).

The Version of Record of the paper “*Hydrological impacts of urban expansion in a Brazilian metropolis – Case study of the Vargem das Flores reservoir catchment*” was published on 27/05/2022 in the *Urban Water Journal* and is available at http://www.tandfonline.com/10.1080/1573062X.2022.2075769. The manuscript presented in this chapter refers to the revised version after peer review and accepted for publication form, that is, the “post-print” (Rosa, Silva, Araújo, et al., 2022). Item 4.8.1 Appendix was included to present additional details of the LULC change and the hydrological models that could not fit in the published article due to size limitations.

4.1 Contributions to co-authored publications

The undersigned authors agree that the nature and extent of the contributions to the work “*Hydrological impacts of urban expansion in a Brazilian metropolis – Case study of the Vargem das Flores reservoir catchment”* were as follows (Table 4.1).

Table 4.1 - Contributions of co-authors - Paper 1

Co-author	**Nature of contribution**	**Extent of contribution (%)**	**Signature**	**Date**
Deyvid Wavel Barreto Rosa	Study design, data acquisition and interpretation, modelling, drafted manuscript	85		05/12/2022
Talita Fernanda das Graças Silva	Study design, reviewed manuscript	5		06/12/2022
Rogério Palhares Zschaber de Araújo	Study design, reviewed manuscript	5		09/12/2022
Nilo de Oliveira Nascimento	Study design, reviewed manuscript	5		12/12/2022

4.2 Abstract

This paper aims to evaluate the hydrologic impacts of urban expansion in a peri-urban catchment that drains to a reservoir of the drinking water supply system of the Belo Horizonte Metropolitan Region in Brazil. Despite the metropolitan interest and efforts to protect the catchment, a recent change in zoning ordinances allowed urban expansion in the area. To evaluate the potential hydrological impacts of this land use regulation change, scenarios of urban expansion were conceived and simulated in the model Dinamica EGO. The Storm Water Management Model (SWMM) was then employed to assess the potential hydrological impacts of the land use change projections. Observed precipitation and water level data of the reservoir were used to calibrate and validate the hydrological model. Results confirm impacts on several catchment hydrological processes following the progressive urban expansion in the area, particularly on volumes of infiltration, groundwater flow and runoff, increasing peak flows and flooding downstream the reservoir.

Keywords: land use changes; water supply reservoir; hydrologic modelling; SWMM; Dinamica EGO.

4.3 Introduction

Urban expansion is the result of a complex set of social and economic factors, such as land value, population growth, rising incomes, and decreasing commuting costs, etc. (Brueckner, 2000). Furthermore, the flexibilisation of control ordinances of urban growth can accelerate this process and, in some cases, a planning strategy may play an even more important role than population growth in land use and land cover (LULC) change (Ahmadisharaf et al., 2020). Therefore, decision-making support techniques can be useful in discussions aiming at defining criteria for changes in urban land use. This is especially true in the context of a metropolis, where conflicts between regional and local interests, as well as long-term planning processes and short-term issues, frequently emerge (Tonucci Filho & Freitas, 2020).

Urbanisation profoundly changes the land cover, with vegetation removal and the increase of impervious surfaces, altering inputs to the hydrological cycle. Infiltration decreases, lowering the natural groundwater recharge, the water table level and consequently, the groundwater flow (Bhaskar et al., 2016; Wakode et al., 2018). Urbanisation can decrease the baseflow in streams and increase surface runoff, flow velocity and pollutant build-up and washoff, leading to greater variations in flow throughout the year, rising frequency and intensity of floods and pollutant load into water bodies (Aboelnour et al., 2020; Brabec et al., 2002; He & Hogue, 2012; Silva et al., 2022). Deforestation associated with urban expansion also decreases evapotranspiration and rainfall interception by the vegetation cover (Zheng et al., 2020).

Hydrological modelling is a useful tool to evaluate, by altering model input parameters, the impacts of LULC changes in the water cycle (Dwarakish & Ganasri, 2015). The connection of a hydrological model with a LULC change model allows long-term scenario-based assessments and is a valuable decision-making support tool for urban planning, especially in developing countries such as Brazil, where institutional frameworks for sustainable urban development are still incipient (Choi & Deal, 2008; Oliveira et al., 2012).

Among the different modelling techniques to evaluate LULC changes, cellular automata stands out as a promising approach that presents good performance compared to other methods (Sanchez et al., 2014), and many studies have applied it to forecast urban growth (Gounaridis et al., 2018; Khatibi et al., 2018; Yang et al., 2020). Dinamica Environment for Geoprocessing Objects (EGO) is an open-source model that has been successfully applied in different landscape change studies (Soares-Filho et al., 2009).

This paper aims to evaluate the impact on hydrological processes of urban expansion under different scenarios of land use regulation in a peri-urban catchment that drains to a water supply reservoir in the Belo Horizonte Metropolitan Region (BHMR). in Brazil. To assess hydrological impacts of LULC change, this study jointly applies Dinamica EGO for the projection of LULC changes and the Storm Water Management Model – SWMM, a hydrological open-source model often used in urban catchment contexts (Niazi et al., 2017). Few studies applied these models together to assess the increase in the flood hazard, simulated using SWMM, caused by urban growth, simulated using Dinamica EGO (Huong & Pathirana, 2013; Rufino et al., 2018;

Sanchez et al., 2014). This model integration allows a more detailed analysis of the impacts of complex and time-varying land use scenarios and may contribute to the public discussion about the impacts of LULC changes in the catchment water cycle and their consequences for the catchment water production and flood risk.

SWMM was selected to simulate the hydrological impact of LULC because, although it was originally designed for modelling urban catchments, the model has flexibility for simulating areas with mixed rural-urban land use and peri-urban areas, presenting good performance in the simulation of such LULC contexts under pre and post-urbanisation conditions (Acharya, 2018; Jang et al., 2007; Jun et al., 2010; Niazi et al., 2017). Furthermore, SWMM can simulate different low-impact development (LID) structures and stormwater quality. This work will continue to evaluate alternative land use scenarios for the present case study, considering the adoption of Green and Blue Infrastructure (GBI) to mitigate the impacts of urbanisation on water quantity and quality.

4.3.1 Case study

The catchment of Vargem das Flores reservoir covers 120.25 km^2 and has 136,161 inhabitants distributed between the municipalities of Contagem (86.2% of its area) and Betim (13.8%), in BHMR, Brazil (Brazilian Institute of Geography and Statistics 0 IBGE, 2010). Belo Horizonte is the capital of Minas Gerais State, and its metropolitan area, with a population of 5.2 million inhabitants, gathers 32 municipalities in a territory of 10,000 km^2 (IBGE, 2010).

The catchment urbanisation process started in the 1970s in its southeastern portion, contiguous to the historic central district of Contagem, and in its northwestern portion, with the development of a social housing settlement named Nova Contagem. The Vargem das Flores reservoir was implemented in the same period, with the main purpose of supplying drinking water to BHMR.

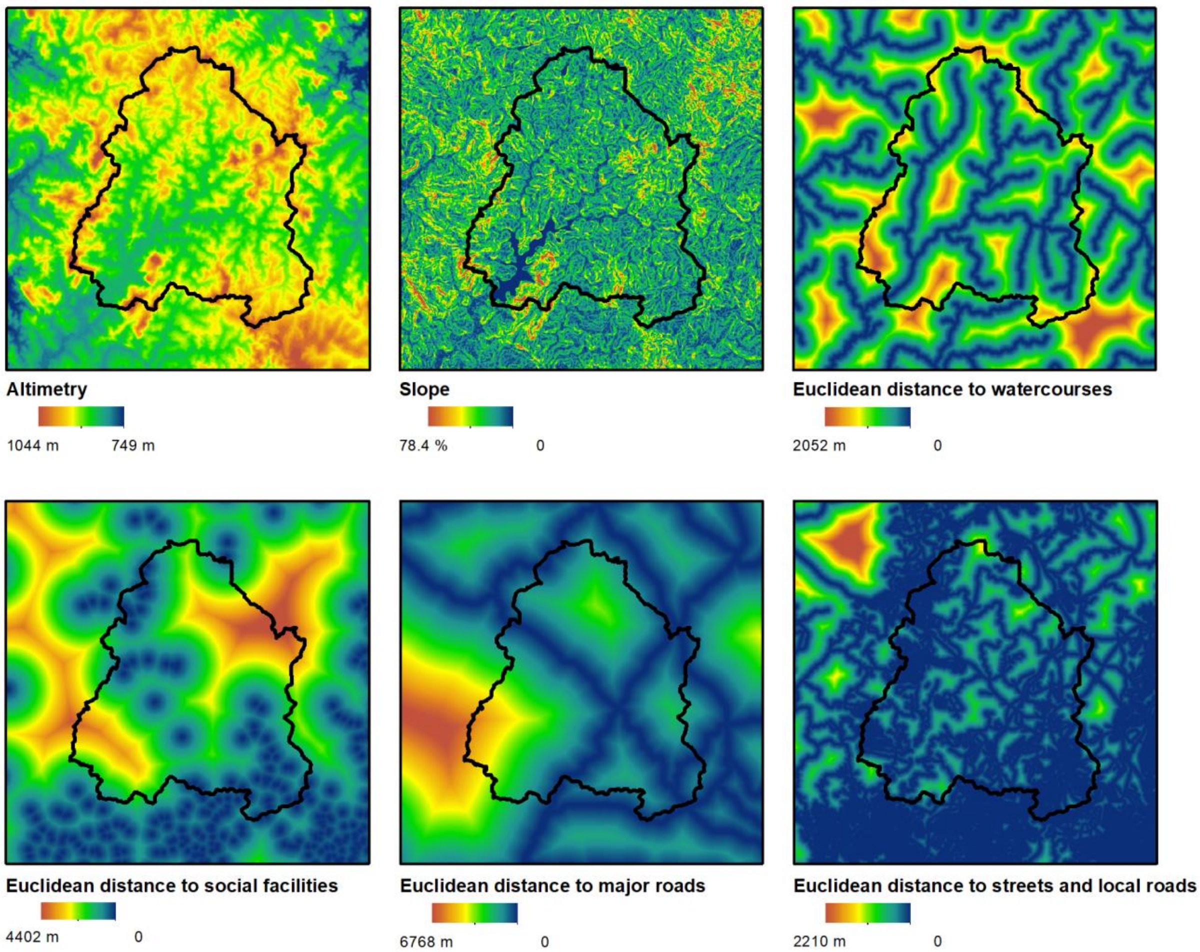
Due to the strategic importance of the reservoir in assuring part of the water supply for BHMR, the catchment was defined as an Environmental Protection Area in 2006 (Minas Gerais, 2006). This status of protected area was also present in the 2010 Contagem Master Plan. This legal framework managed to reduce urban development in the area. In 2017, the PDDI-BHMR adopted the land use regulation of Contagem municipality for the catchment, establishing, however, more restrictive urban controls (Nascimento, Eleutério, Costa, Vinçon-Leite, Mourão, & Faria, 2019). The PDDI proposal for the Vargem das Flores catchment was developed in common agreement with both Contagem and Betim local governments. Nevertheless, after the 2016 municipal election, a new political group took over Contagem municipality, bringing up a new policy significantly more prone to urban sprawl than the previous one. A new municipal master plan was then approved in 2018, easing restrictions for the catchment's urban development (Contagem, 2018).

4.4 Material and methods

LULC scenarios were constructed based on the zoning ordinances of the two municipalities where the catchment is located (Betim, 1999; Contagem, 2018). In addition to urban development criteria defined at the local level, land use scenarios also considered the criteria defined by the Brazilian Federal Act No. 6,766/1979, which regulates urban land subdivision. Municipal and federal normative were employed to develop scenarios of full urban development (Municipal Master Plans - PDM scenarios). In parallel, the metropolitan PDDI macro-zoning proposal (PDDI, 2017) provided alternative land use controls to develop environmental protective scenarios (PDDI scenarios). More details about preparing alternative LULC scenarios are presented in the Appendix (item 4.8.1).

Vargem das Flores catchment was divided into subcatchments according to its hydrography and for both scenarios, land use controls were applied to every subcatchment considering the year 2040 as the design horizon. The year 2040 was chosen based on the expectancy of population growth saturation estimated for this area (IBGE, 2020). Future urban development was estimated using the Dinamica EGO model based on trends that have been observed during the last 30 years. The distance to existing urban areas at the early phase of the studied period (1990), topographic and morphologic features such as slopes, hills, and distance to watercourses, as well as the availability of infrastructure and services (distance to roads, educational, cultural, and leisure facilities) were used as guiding variables to identify more prone areas to urban sprawl (Figure 4.1).

Figure 4.1 – Physical and anthropic spatial variables used to calibrate the LULC change model at Dinamica EGO.

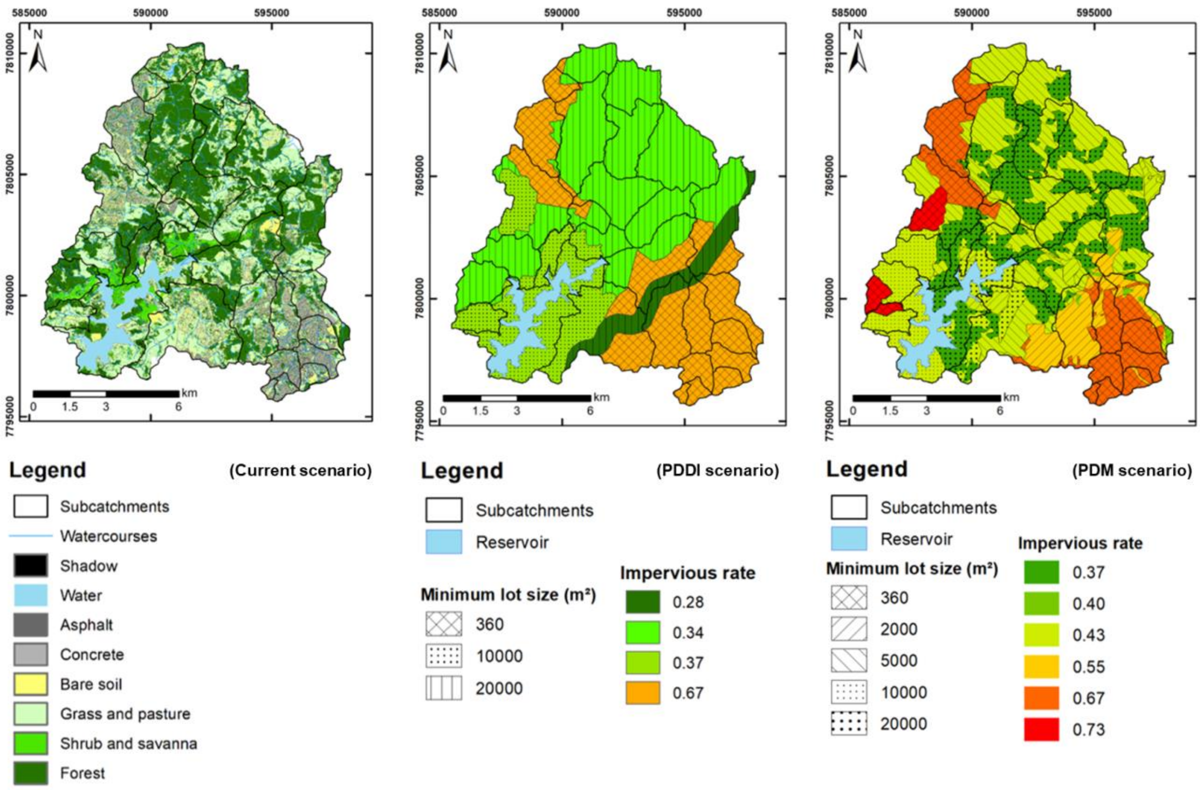


Dinamica EGO model was calibrated and validated using land use data obtained from Landsat satellite images from 1990 to 2018 classified according to MapBiomas (2018). LULC maps of 1990 and 2010 were used for model calibration, and validation was based on the comparison between the observed urban boundary (classified Landsat image from 2018) and the model projection to 2018. The model goodness of fit was assessed through the fuzzy similarity index. More details about the LULC change modelling are presented in the Appendix (item 4.8.2).

Four LULC prospective scenarios were studied as follows: PDM_{max}, with maximum urban development of the catchment according to the current municipal master plans; $PDDI_{max}$, with maximum urban development of the catchment according to the limits imposed by the metropolitan development plan; PDM_{2040}, with projected urban development of the urban area in 2040, following simulated development trends in Dinamica EGO associated to zoning controls based on the municipal master plans and; $PDDI_{2040}$, with projected urban development of the urban area in 2040, following simulated development trends in Dinamica EGO associated to zoning controls based on the metropolitan development plan.

Figure 4.2 shows the land cover in the Vargem das Flores catchment in October 2013. The preponderant classes in the catchment were arboreal vegetation (40.9%) and grass (31.7%). 13.3% of the catchment is composed of impervious areas and divided between paved roads (7.5%) and buildings (5.7%). The result of this classification is here named "Current scenario", since this is the most recent high-resolution image available for the entire catchment.

Figure 4.2 – Current land use cover map, urban development controls by Metropolitan Development Plan ($PDDI_{max}$) and by Betim and Contagem Municipal Master Plans (PDM_{max}).



Changes in catchment hydrological processes were evaluated using the hydrological model SWMM 5.1. Rainfall data at hourly time step was obtained from the rain gauge network operated by the National Centre of Monitoring and Natural Disaster Warning, in operation since the beginning of 2014. The 64-month time series with available data was divided into two periods for SWMM calibration (2017 – 2019) and validation (2014 – 2016).

Physical characteristics of Vargem das Flores catchment were obtained from Fundação João Pinheiro: aerial orthophotos with a spatial resolution of 0.4 m and a Digital Surface Model (DSM), with a spatial resolution of 1.2 m, both from 2013. A Geographical Information System (GIS), QGis 3.16.1, was employed to estimate catchment areas and average slopes through three-dimensional spatial analysis tools. Subcatchment widths were initially estimated by dividing their area by the average maximum length of runoff flow using the hydrographic and topographic basis. The percentage of impervious area of every subcatchment was estimated from the LULC classification. Orthophotos were processed using the GIS through semi-supervised classification (SPC). Manning roughness coefficients and the depth of storage depressions of pervious and impervious areas were calculated by pondering the values recommended by Rossman and Huber (Rossman & Huber, 2016b) for each surface type provided by the LULC classification. More details about the preparation of input data for the hydrological model are presented in the Appendix (item 4.8.3).

In a first approach, the National Resources Conservation Service - NRCS method was used to simulate the effective rainfall in the catchment. Although this method represented the runoff well, especially in the case of heavy rainfall events in the most urbanised subcatchments, it prevents the assessment of the effects of LULC on groundwater flow processes related to the main purpose of the reservoir under study – the guarantee of water for public supply during the dry seasons. Therefore, the method of Green-Ampt was selected to calculate rainfall infiltration because it allows groundwater flow simulation, improving the quality of continuous simulation. Green-Ampt model parameters were estimated based on literature values for sandy loam soil type (Costa, 2002; Rossman & Huber, 2016b; SEMAD, 2010), predominant in Vargem das Flores catchment, and local groundwater characteristics (Cândido et al., 2017).

To guide the model calibration process, a parameter sensitivity analysis was first performed to identify the more sensitive parameters in runoff generation. Vargem das Flores catchment is not equipped with fluviometric stations, but reservoir water levels, outflow, and water withdrawal volumes were available daily. These data were used to assess model performance during calibration and validation.

Model calibration was performed through a manual trial and error procedure to optimise the Nash and Sutcliffe coefficient (NSC). The values of the more sensitive parameters were changed around their initial estimated values, within ranges recommended in the literature. The best sets of parameter values were then retained for subsequent rounds of calibration. This procedure was repeated until no significant improvements in the NSC value could be achieved. Modelling uncertainties in reservoir water level simulation were estimated by selecting the parameter sets that resulted in NSC values equal to or greater than 0.75, which is usually considered a “very good” adjustment (Moriasi et al., 2007). More details about the calibration of the hydrological model are presented in the Appendix (item 4.8.4).

4.5 Results

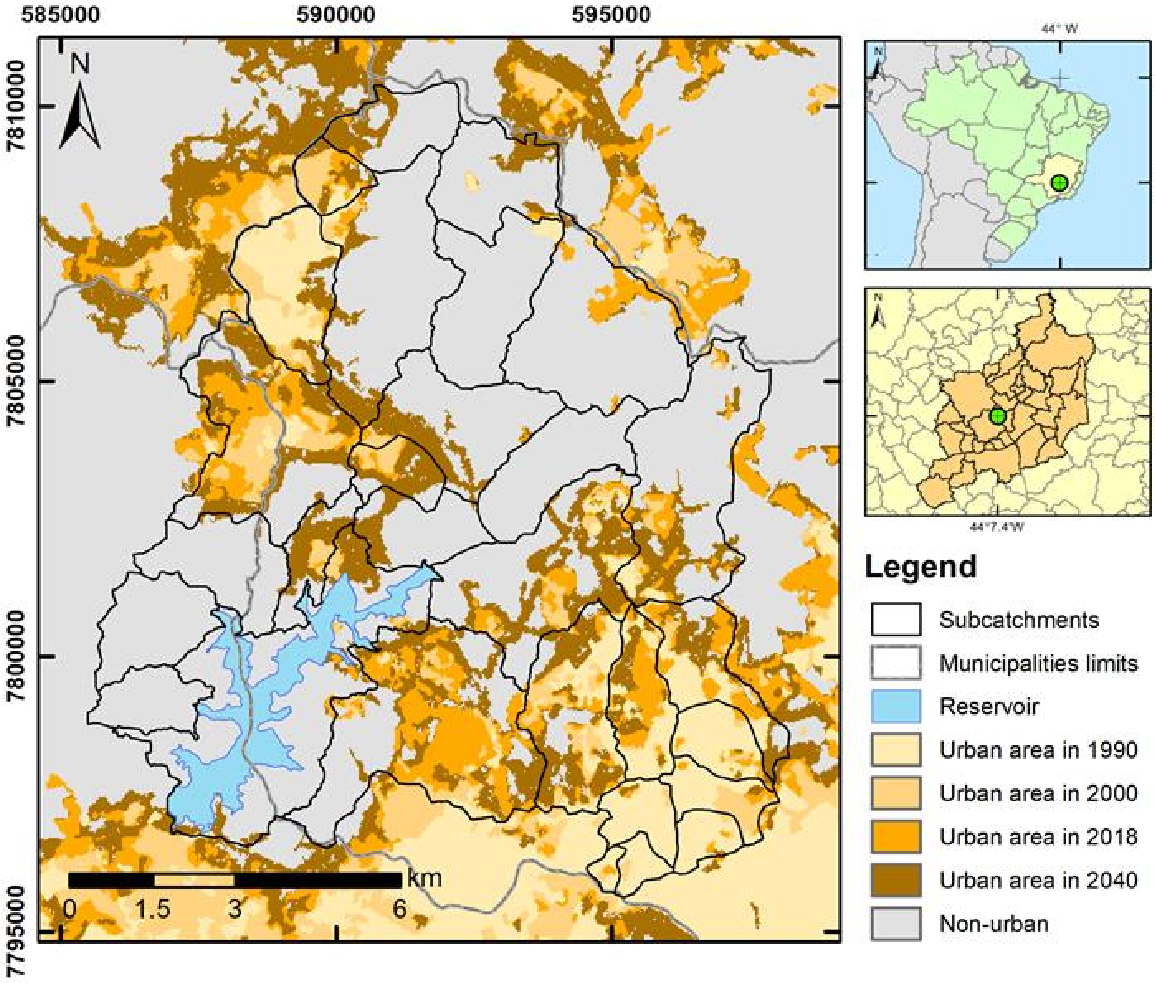
4.5.1 Land use and land cover scenarios

Expansion of the urban area was observed throughout the 28-year period from 1990 to 2018, with a slowed expansion rate over time. This may be caused by the reduction in the population growth rate but also due to recent economic factors related to real estate dynamics and regulatory restrictions – until 2018, most of the catchment area was legally classified as rural, which in Brazil prevents formal urbanisation.

In the calibration process of the Dinamica EGO model, the most influential variables were distances to existing urban areas, to social facilities and to streets and roads. All these variables were correlated with each other, but not to a level that would require the exclusion of any of them from a statistical point of view, even though there is no consensus on the threshold for exclusion (Soares-Filho et al., 2009). The validation of the urban land use forecast produced good results, with fuzzy similarity rates between simulated and observed urban areas in 2018 of at least 65.1% when comparing cell to cell, and up to 93.7% when comparing a window of 11x11 cells.

Based on these model performance results, the urban area expansion for 2040 was projected (Figure 4.3).

Figure 4.3 – Observed urban sprawl from 1990 to 2018, and projection for 2040.



A 66.3% increase in the catchment urban area is expected from 2018 to 2040, leading to a total urban development covering 41.4% in 2040. This new urban development should follow the planning guidelines established by the current municipal legislation. Based on the urban controls (minimum lot size and maximum impervious rate) and subtracting the areas planned for urban subdivision, the areas to be occupied by roads and buildings in every subcatchment were calculated, and the areas to be kept permeable in the lots. Therefore, the total impervious area in the PDM_{max} scenario would reach 47.44% for the maximum urban development legally allowed and 24.77% for the 2040 projection (PDM_{2040} scenario). For the PDDI scenarios, the impervious area would reach 43.63% at $PDDI_{max}$ and 23.07% at $PDDI_{2040}$.

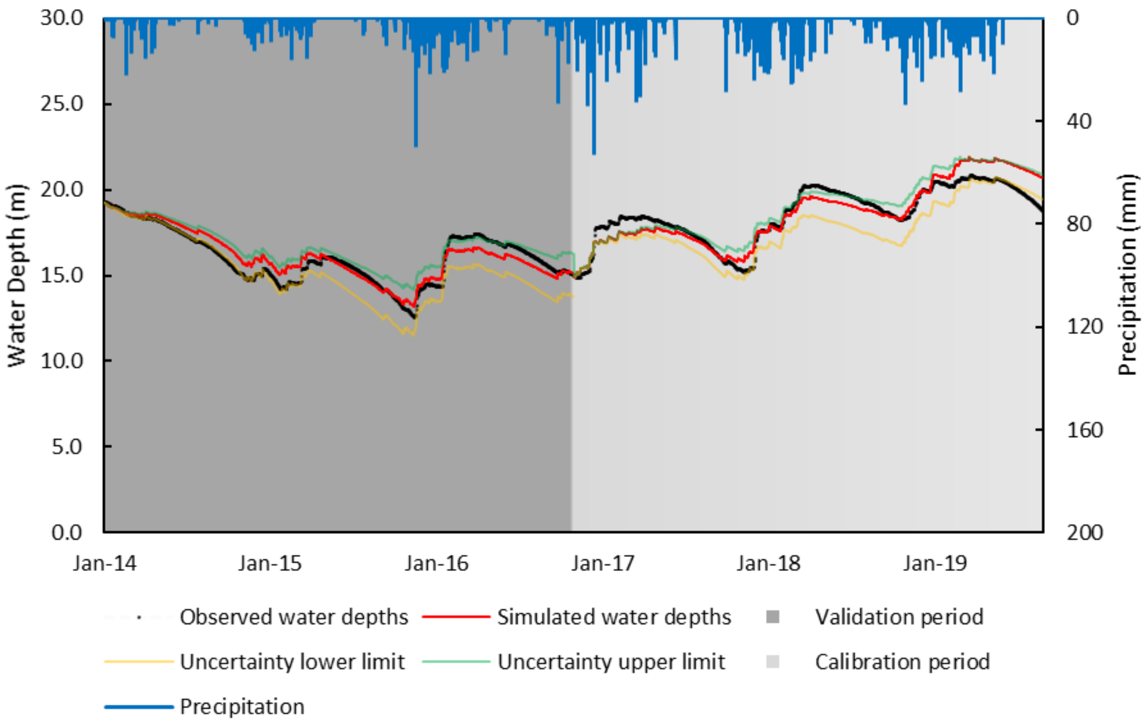
4.5.2 SWMM sensitivity analysis, calibration, and validation

The most sensitive parameters of the model, that is, those that produced the greatest variations in the inflow volume to the reservoir for a given variation in the parameters, were: percentage of impervious area; soil's saturated hydraulic conductivity; soil porosity; upper soil zone evaporation fraction; initial moisture content of the unsaturated upper zone. These parameters were changed during the calibration process in order to get the best fit for the observed reservoir water level. The most sensitive parameters are related to rainfall infiltration and to the upper unsaturated soil zone, indicating the greatest influence of this process on the catchment's water balance and the preponderance of surface runoff over the contribution of groundwater runoff to the reservoir.

Less influential parameters for the reservoir water level, such as the surface roughness coefficient and the depth of depression storage, remained with the same initial estimations based on values indicated in the literature and considering the land cover classes in each subcatchment. Average parameter values were calculated by weighting areas according to land cover classes. The roughness coefficient ranged between 0.011 and 0.013 for impervious areas and 0.110 to 0.220 for pervious areas. The depression storage depth in impervious areas ranged between 1.4 and 2.0 mm and 6.0 to 8.6 mm in pervious areas.

The adjustment of the hydrological model achieved good results: the Nash-Sutcliffe coefficient reached 0.80 in calibration and 0.87 in validation. The range of uncertainty encompassed the observed data 81% of the time (Figure 4.4). Other adjustment metrics also confirm the good fit: the determination coefficient was 0.88 for calibration and 0.79 for validation, and the Root Mean Square Error was 0.72 m in calibration and 0.76 m in validation.

Figure 4.4 – Vargem das Flores reservoir observed and simulated water depths for calibration (dark grey) and validation (light grey) periods. Uncertainty lower and upper limits are also represented.



4.5.3 Hydrological simulation of the LULC scenarios

After the calibration of the hydrological model, LULC prospective scenarios were simulated, with the percent of impervious areas changed in each scenario, maintaining unchanged the other input parameters. A synthesis of hydrological simulation results of different LULC scenarios is presented in Table 4.2. These results refer to the simulation of rainfall recorded during a hydrological year (October 2016 to September 2017) with annual precipitation close to the historical average. The initial reservoir and soil moisture states for all scenarios were equalised to the values observed in the current scenario. More details about the hydrological modelling of the alternative LULC scenarios are presented in the Appendix (item 4.8.5).

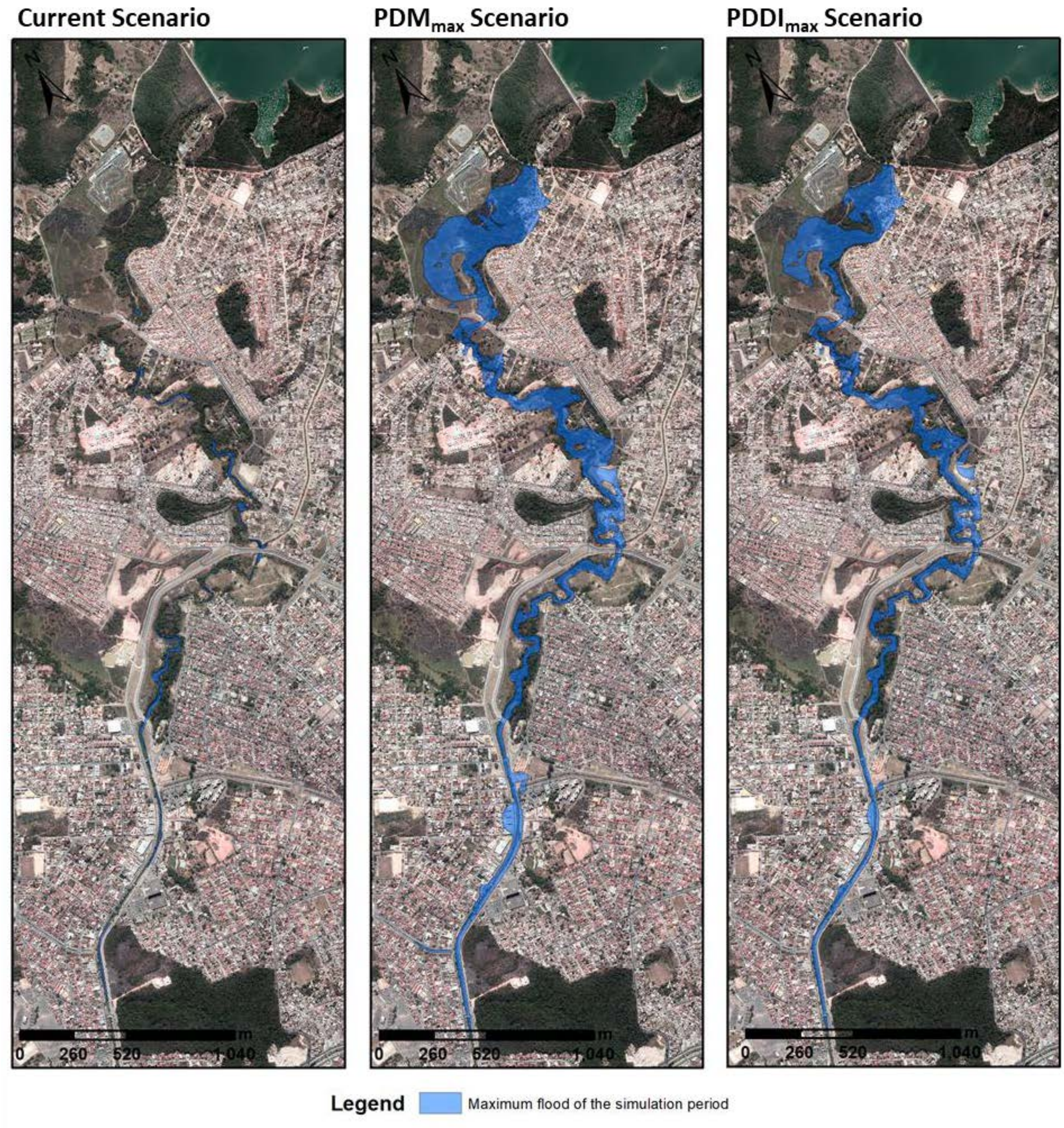
Table 4.2 – Synthesis of hydrologic simulation results of the different LULC scenarios during one hydrological year.

Parameter	Scenarios				
	Current	$PDDI_{2040}$	PDM_{2040}	$PDDI_{max}$	PDM_{max}
Maximum inflow to reservoir ($m^3.s^{-1}$)	188.04	285.73	297.82	487.24	509.25
Total inflow volume to reservoir (hm^3)	30.448	39.325	41.046	61.646	65.392
Maximum water level of the reservoir (m)	17.80	19.77	20.10	22.08	22.12
Maximum outflow of the reservoir ($m^3.s^{-1}$)	0.30	0.30	0.30	27.39	34.72
Average annual infiltration in catchment (mm)	838.8	753.7	740.7	576.0	536.9
Average annual evaporation in catchment (mm)	594.9	520.0	508.0	358.5	318.9
Average lateral outflow from groundwater (mm)	139.5	130.0	127.2	114.5	113.0
Average water table (m)	865.56	865.43	865.30	865.14	865.08
Average runoff coefficient	0.136	0.206	0.236	0.386	0.486

Remarkable differences are observed in the runoff generation between scenarios. As expected, the increase of impervious surface increased the runoff and produced more inflow volume to the reservoir during the rainy season and lower volumes during the dry season. That is why the PDM_{max} scenario produced the greatest inflow, followed by the $PDDI_{max}$, the PDM_{2040} and the $PDDI_{2040}$ scenarios. These differences in inflow volumes naturally lead to differences in storage volume and water level in the reservoir.

During the current scenario, no overflow was observed during the simulation period (2014-2019), and the outflow was restricted to the ecological flow (0.30 m^3/s). Downstream the reservoir, no flooding events were observed since the reservoir stored inflow during rain events, and neither overflow nor outflow greater than ecological flow was simulated from the reservoir. The same was observed in $PDDI_{2040}$ and PDM_{2040} scenarios. In PDM_{max} scenario, in the third month of simulation, the water level has risen to the weir level and an overflow of 11.01 $m^3 \cdot s^{-1}$ was observed. With the reservoir completely full, an overflow was observed at every intense rainfall nearly twice a month. In the $PDDI_{max}$ scenario, the same behaviour was noticed from the fourth simulation month (January). In this case, the overflow remained smaller than in the PDM_{max} scenario. These outflows indicated by the simulation of PDM_{max} and $PDDI_{max}$ scenarios resulted in flooding downstream of the reservoir (Figure 4.5). In PDM_{max} and $PDDI_{max}$ scenarios, areas of 38.13 and 33.66 hectares would be flooded, respectively.

Figure 4.5 – Maximum flooded area downstream Vargem das Flores reservoir for prospective LULC scenarios, caused by the intense sequential rainfall observed in February 2017.



The infiltration and the groundwater flow were also affected by the LULC changes. In the PDM_{max} scenario, with greater soil sealing, the total infiltration was reduced by 36%, decreasing the water table on average by 0.48 m, while the groundwater contribution to the total inflow to the reservoir was reduced by 19%. Substantial decreases in evaporation, up to 46%, were also observed, which may lead to micro-climate changes with the reduction of air moisture.

4.6 Discussion and concluding remarks

This study evaluated the LULC changes and their hydrological impacts in a catchment located in a Brazilian metropolitan region. Five scenarios considering the municipal and metropolitan land use ordinances were constructed: a current scenario, two scenarios representing the final urban development stage and two intermediate scenarios estimated using a cellular automata model considering spatial variables relevant to the urban growth in the study area.

The calibration of the models produced good adjustments between the observed and simulated data. In Dinamica EGO, the similarity rates between simulated and observed urban areas were at least 65.1% for a window size of 30 m comparison and up to 93.7% for a window of 330 m. Comparable similarity rates were obtained in previous studies (Gounaridis et al., 2018; Khatibi et al., 2018; Sanchez et al., 2014; Yang et al., 2020). In SWMM, the adjustment between the simulated and observed water level of the reservoir was good (NSC = 0.80 in calibration and NSC = 0.87 in validation). Similar results were also obtained in previous studies that used flow or level measurements for model performance assessment (He & Hogue, 2012; Rosa et al., 2020; Siqueira et al., 2019).

It is important to consider the implications of these results for the reality of a developing country metropolis. Land use control easing processes have recently become more frequent in Brazilian municipalities, so the contribution of a well-founded study on the impacts of different urban development scenarios would be valuable to support planning decision-making processes better. This is especially important in a context where the conflicts between the local and regional, private, and collective interests are clearly at stake, and local decisions were taken to the detriment of metropolitan regional interests.

Another aspect related to the reality of a developing country is the limited availability of monitoring data at detailed spatial and temporal scales. The model performance was satisfactory despite the limitations of the available data. Hourly precipitation data was used as input to the hydrological model, while calibration was based on comparing observed and simulated reservoir water levels in daily frequency. This was possible because the effects of rainfall accumulated throughout the day were correctly represented by the model since the reservoir water balance was calculated considering all the main inputs and outputs. Besides, because of the reservoir routing process, the rate of change of volume and water level in the reservoir is slower than the rate of change of the inflows.

As shown, the resulting urban development according to the criteria established by the current municipal land use ordinance would considerably change the water cycle in the catchment. With the soil sealing of more than half of the catchment area, infiltration and evaporation are expected to decrease considerably, while surface runoff would substantially increase. The groundwater flow would also decrease, whilst the reservoir water table would be lowered. All these hydrologic impacts of urban development align with those described in the literature (Aboelnour et al., 2020; Bhaskar et al., 2016; Wakode et al., 2018).

In addition to the impacts on water quantity, urbanisation also affects the quality of surface water, intensifying erosion processes, particularly in the urban expansion phase, leading to the siltation of streams and reservoirs (Poleto & Fernandes, 2018), and increasing wet weather diffuse pollution associated to a wide range of pollutant sources. Lack of sanitation infrastructure and appropriate solid waste management, which are common in developing countries, are additional sources of surface water pollution in the urban environment (Cerqueira et al., 2020). For lentic water bodies, the main consequences of these varied pollutants are loss of storage capacity and an increase in eutrophication processes, particularly when lakes and reservoirs receive large charges of organic matter and nutrients (Silva et al., 2019; Tromboni & Dodds, 2017).

The resulting changes in the hydrological cycle may lead to water quality degradation and an increase in sediment transportation, accelerating the degradation process of Vargem das Flores reservoir – reducing its useful life and increasing the water treatment costs. The runoff increase and the reduced storage capacity of the reservoir will also raise the probability of floods downstream of the reservoir, where there is an important urban area.

The mentioned changes in the water cycle were evaluated using the SWMM, which, in the next step of this research, will be applied to simulate the water quality and Low Impact Development (LID) devices in the catchment aiming at evaluating alternative scenarios of urbanisation with LID implementation, protection of riparian areas and forest remnants. Beyond the hydrologic impacts on water quantity, impacts on water quality, and other environmental and social impacts, including the provision of ecosystem services related to these scenarios, are also included in the scope of future studies. In 2021, the public discussion process on the revision of the land use legislation for the municipality of Contagem was launched. Due to current local political agreements and important citizens' mobilisation on the subject, planning guidelines and actions to protect the Vargem das Flores catchment are expected to be incorporated in the new Master Plan and Zoning Ordinances. The authors have been invited to present the results of this research to local planning officials and have agreed to contribute to this discussion by presenting alternative scenarios for a water-sensitive urban development. The sanitation company responsible for operating the reservoir has also expressed interest in using the models and outputs of this work to guide environmental recovery actions in the catchment, including the implementation of LID techniques in areas suitable for that. Economic evaluations related to this alternative urban development are part of the next stages of this research project. This shall consider the opportunity and recovery costs, as well as the possibility of setting up a payment system for environmental services to encourage the protection of forest remnants, the restoration of the natural hydrological cycle and the recovery of degraded areas.

4.7 Acknowledgements

The authors would like to thank the research funding agencies, Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq), Fundação de Amparo à Pesquisa de Minas Gerais (FAPEMIG) and Coordenação de Aperfeiçoamento de Pessoal de Nível Superior – Brasil (CAPES) for their financial support, the Brazilian Centre of Monitoring and Natural Disaster Warning (Cemaden), Minas Gerais Sanitation

Company Copasa, Fundação João Pinheiro, Contagem's and Betim's City Halls, for the provision of essential data for the development of this research. The project is linked to the project MoMa, financed by Capes (Ministry of Education) and ANA (Brazilian Water Agency), Grant number: 88887.15881/2015-01 and ANA 2776/2015. Nilo de Oliveira Nascimento is financed by CNPq-Pq Grant number 312458/2017-7.

4.8 Appendices

4.8.1 Land use and land cover scenarios

The construction of the LULC scenarios was based on the current scenario land cover (Table 4.3). Areas covered with asphalt and construction were maintained as existing urban areas. The proportion of classes bare soil, grassland, savannah and forest was replicated to define the land cover of pervious areas inside lots in new urban areas.

Table 4.3 – Area per land cover class for each subcatchment

Subcatchment	Area per land class (hectares)								
	Shadow	**Water**	**Asphalt**	**Construction**	**Bare soil**	**Grassland**	**Savannah**	**Forest**	**Total**
Aboboras	4.58	5.75	38.38	17.04	39.10	267.08	4.75	421.49	798.18
AguaSuja1	0.93	14.49	5.32	8.20	28.00	75.40	1.49	129.05	262.89
AguaSuja2	5.88	0	17.48	8.49	24.04	145.27	4.71	547.51	753.38
AguaSuja3	18.55	2.16	81.35	35.07	64.37	301.60	5.21	302.94	811.24
AguaSuja4	8.92	1.76	10.11	0.47	1.71	127.05	46.13	156.32	352.48
Batatal	4.73	0	6.69	0.67	14.76	95.94	3.81	64.09	190.69
BelaVista	20.03	0.58	80.48	61.02	118.01	474.75	29.24	281.13	1065.23
Betim1-0	0.54	0	9.12	10.23	4.49	6.56	0.09	1.50	32.54
Betim1-1	1.52	0	20.70	22.94	5.57	9.44	0.56	7.00	67.73
Betim1-2	3.14	0	24.18	24.52	16.72	16.76	1.56	13.94	100.81
Betim1-3	3.72	0	49.64	46.04	11.55	19.18	4.62	15.39	150.15
Betim1-4	2.98	0	51.80	46.47	14.53	26.09	3.16	12.43	157.46
Betim2-0	3.16	0	44.53	49.14	24.54	37.01	1.75	17.78	177.91
Betim2-1	8.94	1.90	37.77	51.28	22.31	95.42	3.45	107.84	328.91
Betim3	16.24	3.22	30.87	17.76	68.22	226.55	20.92	379.29	763.09
CampoAle	5.94	1.91	10.94	8.38	42.42	305.71	5.16	342.77	723.23
DarcyRib	4.41	0	14.87	9.83	6.49	70.65	1.39	45.53	153.17
Direta	25.10	483.84	57.67	15.59	55.91	308.20	131.44	272.45	1350.20
Lagoa	11.39	7.08	56.33	56.98	38.86	162.10	13.31	163.89	509.93
Laje	13.38	2.12	1.51	0.70	3.41	52.13	60.47	174.50	308.21
MorroRed1	0.43	0	3.47	0.33	19.98	153.75	2.77	182.29	363.02
MorroRed2	5.31	0.84	8.31	1.62	17.26	142.76	3.14	299.36	478.59
MorroRed3	10.82	0	11.91	5.76	13.50	134.45	2.99	304.72	484.14
MorroRed4	8.75	0	5.77	0.52	4.50	61.41	84.71	93.44	259.10
Olaria	6.93	0	10.09	3.85	4.42	18.58	25.94	103.74	173.55
Praia	6.45	0	48.36	53.36	32.81	67.14	2.61	62.85	273.58
Retiro	3.66	0	59.08	97.07	35.49	102.82	0.56	120.56	419.25
VargemdoSa	6.08	0	7.53	2.97	8.22	164.95	11.80	171.06	372.60
VilaEspe	0.92	0	15.78	18.99	16.23	41.83	1.03	35.49	130.28

In sequence, the zoning ordinances of the two municipalities where Vargem das Flores catchment is located allowed mapping the urban controls, such as minimum pervious surface per lot, floor area ratio and maximal lot size (Betim, 1999; Contagem, 2018) (Table 4.4). In parallel, the PDDI macro-zoning proposal (PDDI-BHMR, 2017) provided land use controls to develop an alternative scenario. The area corresponding to each land zone was calculated for each subcatchment (Table 4.5).

Table 4.4 – Land Zones ordinances according to municipal land use legislation (Contagem* and Betim**)

Zoning ordinances	Land Zones							
	ZEIT*	ZEU-1*	ZEUIA I*	ZOR-3*	ZUI-2**	ZUIA I**	ZUIA II**	ZUIA III**
Minimum Pervious Rate	70%	40%	70%	50%	30%	20%	20%	70%
Minimum Lot Area (m²)	10000	360	10000	2000	360	360	360	5000
Maximum Built Area (m²)	3000	216	3000	1000	252	288	180	1000

Table 4.5 – Area per land zone for each subcatchment

Subcatchment	Area per land use class (hectares)								
	ZEIT	ZEU-1	ZEUIA I	ZOR-3	ZUI-2	ZUIA I	ZUIA II	ZUIA III	Total Area
Aboboras	0.00	81.48	0.00	681.71	35.20	0.00	0.00	0.00	798.39
AguaSuja1	0.00	0.00	0.00	256.24	6.65	0.00	0.00	0.00	262.89
AguaSuja2	0.00	12.43	0.00	676.78	64.95	0.00	0.00	0.00	754.16
AguaSuja3	0.84	103.68	48.65	184.74	153.11	174.28	0.00	145.76	811.06
AguaSuja4	30.60	0.00	247.57	74.31	0.00	0.00	0.00	0.00	352.48
Batatal	0.00	0.00	147.69	0.00	0.00	0.00	43.00	0.00	190.70
BelaVista	326.05	0.00	0.00	712.41	38.27	0.00	0.00	0.00	1076.74
Betim1-0	0.00	0.00	0.00	0.00	32.54	0.00	0.00	0.00	32.54
Betim1-1	0.00	0.00	0.00	0.00	67.73	0.00	0.00	0.00	67.73
Betim1-2	0.00	48.33	0.00	10.66	41.86	0.00	0.00	0.00	100.86
Betim1-3	0.00	0.00	0.00	0.99	149.15	0.00	0.00	0.00	150.15
Betim1-4	0.00	18.02	0.00	0.40	139.04	0.00	0.00	0.00	157.46
Betim2-0	0.00	32.46	0.00	1.49	143.95	0.00	0.00	0.00	177.90
Betim2-1	0.00	53.84	0.00	183.64	92.52	0.00	0.00	0.00	329.99
Betim3	4.07	0.00	0.00	725.95	33.55	0.00	0.00	0.00	763.57
CampoAle	0.00	0.00	0.00	742.48	0.00	0.00	0.00	0.00	742.48
DarcyRib	3.39	0.00	0.00	97.53	52.39	0.00	0.00	0.00	153.31
Direta	783.26	0.00	527.20	29.09	13.29	0.00	1.41	0.00	1354.25
Lagoa	0.00	0.89	0.00	442.14	67.14	0.00	0.00	0.00	510.17
Laje	0.00	0.00	208.75	0.00	0.00	0.00	97.32	0.00	306.07
MorroRed1	0.00	0.00	0.00	363.02	0.00	0.00	0.00	0.00	363.02
MorroRed2	0.00	0.00	0.00	478.59	0.00	0.00	0.00	0.00	478.59
MorroRed3	0.00	1.38	0.00	456.56	28.03	0.00	0.00	0.00	485.97
MorroRed4	95.17	0.00	0.00	153.95	9.98	0.00	0.00	0.00	259.10
Olaria	142.60	0.00	0.00	10.55	20.40	0.00	0.00	0.00	173.55
Praia	0.00	24.16	0.00	80.03	169.37	0.00	0.00	0.00	273.56
Retiro	0.00	15.21	0.00	47.72	355.89	0.00	0.00	0.00	418.82
VargemdoSa	0.00	0.00	0.00	370.27	2.97	0.00	0.00	0.00	373.24
VilaEspe	0.00	0.00	0.00	22.93	107.34	0.00	0.00	0.00	130.28

In addition to urban development criteria defined at the local level, the land use scenarios also considered the criteria defined by Federal Act No. 6,766/1979 (Brasil, 1979), which regulates urban land parcelling. According to this law, land parcelling for urban use is not allowed in steep slope areas (greater than 30%), neither in flood-prone areas, nor in environmental protection areas, established according to the Brazilian Forest Code. Moreover, 40% of the area to be developed must also be destined for public facilities. According to Silva (2010), approximately 20% is destined for roads, 15% for green areas and 5% for institutional areas. In this sense, the non-urban areas with slopes slower than 30% were distributed among roads, green areas, institutional areas, and lots subdivided into impervious and pervious areas (Table 4.6).

Table 4.6 – Areas by land use per subcatchment

Subcatchment	Public areas (hectares)			Private areas in lots (hectares)		Total Area
	Roads	Green Areas	Institutional	Impervious	Pervious	
Aboboras	159.68	119.76	39.92	248.41	230.41	798.18
AguaSuja1	52.58	39.43	13.14	79.67	78.07	262.89
AguaSuja2	150.83	113.12	37.71	234.01	217.71	753.38
AguaSuja3	162.21	121.66	40.55	276.03	210.78	811.24
AguaSuja4	70.50	52.87	17.62	72.37	139.13	352.48
Batatal	38.14	28.60	9.53	47.22	67.19	190.69
BelaVista	215.35	161.51	53.84	276.98	357.55	1065.23
Betim1-0	6.51	4.88	1.63	13.67	5.86	32.54
Betim1-1	13.55	10.16	3.39	28.45	12.19	67.73
Betim1-2	20.17	15.13	5.04	38.14	22.33	100.81
Betim1-3	30.03	22.52	7.51	62.94	27.15	150.15
Betim1-4	31.49	23.62	7.87	65.00	29.47	157.46
Betim2-0	35.58	26.69	8.90	72.60	34.15	177.91
Betim2-1	66.00	49.50	16.50	112.25	84.67	328.91
Betim3	152.71	114.54	38.18	232.12	225.53	763.09
CampoAle	148.50	111.37	37.12	203.50	222.75	723.23
DarcyRib	30.66	23.00	7.67	51.73	40.11	153.17
Direta	270.85	203.14	67.71	246.82	561.68	1350.20
Lagoa	102.03	76.53	25.51	160.92	144.94	509.93
Laje	61.21	45.91	15.30	86.43	99.35	308.21
MorroRed1	72.60	54.45	18.15	108.90	108.90	363.02
MorroRed2	95.72	71.79	23.93	143.58	143.58	478.59
MorroRed3	97.19	72.89	24.30	147.41	142.34	484.14
MorroRed4	51.82	38.86	12.95	67.51	87.95	259.10
Olaria	34.71	26.03	8.68	37.40	66.73	173.55
Praia	54.71	41.03	13.68	103.86	60.29	273.58
Retiro	83.76	62.82	20.94	169.70	82.03	419.25
VargemdoSa	74.65	55.99	18.66	111.69	111.61	372.60
VilaEspe	26.06	19.54	6.51	51.96	26.20	130.28

This data was used to calculate the input parameters to the SWMM model. The sum of public green areas and lots' pervious areas defined the total pervious area for each subcatchment. The new proportion of areas covered by asphalt and concrete was used to adjust the Mannings N and the depth of depression storage on impervious areas. For the pervious areas, the proportion of bare soil, grassland, savannah and forest was recalculated, and the Mannings N and the depth of depression storage in pervious were adjusted for each subcatchment.

4.8.2 Modelling LULC change

The Dinamica EGO model was calibrated and validated using land use data from MapBiomas (2018) from 1990 to 2018 (Table 4.7). MapBiomas Project is a multi-institutional initiative to generate annual land cover and use maps using automatic classification processes applied to Landsat satellite images, with spatial resolution of 30 m. The LULC maps of 1990, 2000, and 2010 were used for model calibration, and the model validation was based on the comparison between the observed urban boundary and the model projection for 2018.

Table 4.7 – Observed urban areas and their expansion from 1990 to 2018, based on MapBiomas (2018)

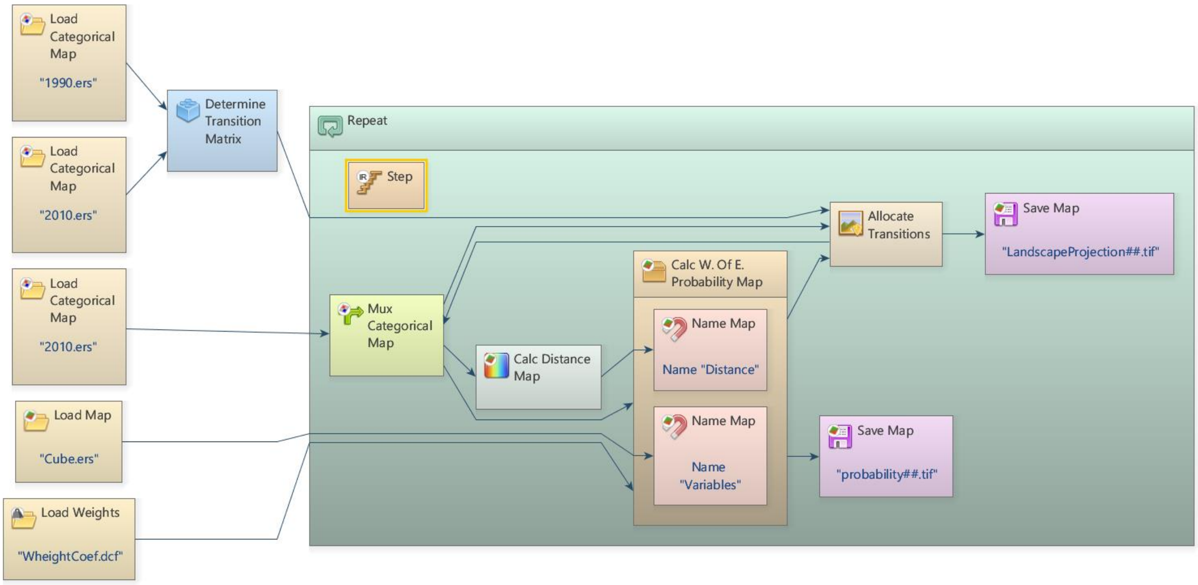
Year	Urban area (km²)	% of Catchment Area	Added area (km²)	Urban expansion annual rate
1990	13.43	11.1%		
			7.36	4.47%
2000	20.79	17.3%		
			5.42	2.34%
2010	26.21	21.7%		
			4.85	2.14%
2018	31.06	25.8%		

The process of LULC change modelling in Dinamica Ego is synthesized in Figure 4.6. The input data for the LULC change modelling are:

- Transition matrix, computing the total and the annual rate of urban expansion by comparing the initial (1990) and final (2010) landscape, considering the transition from non-urban to urban;
- Cube Map that contains all the spatial variables that can influence LULC changes (slope, elevation, distance to watercourses, distance to roads, and distance to educational, cultural, and leisure facilities);

- Weights of Evidence coefficients, where the influence of each spatial variable on the transition from non-urban to urban is computed;
- Categorical Map that is the starting year of the projection (2010 in the calibration stage, and 2018 after the validation);
- Distance Map to the existing urban areas, calculated from the initial simulation year.

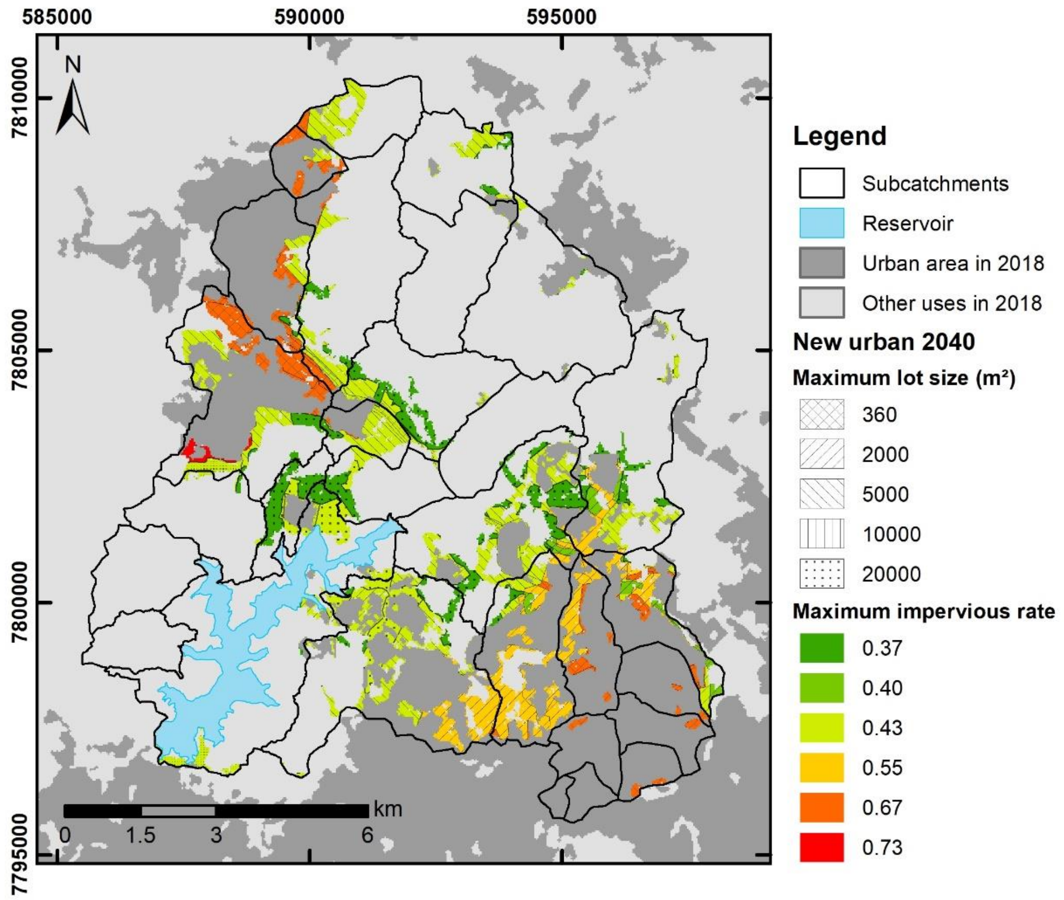
Figure 4.6 – LULC change model diagram on Dinamica EGO



From the Weights of Evidence calculated tables, the correlation between the spatial variables and the transition to urban class was evaluated in the calibration process. Dinamica EGO calculates pairwise tests such as Chi-Square, Cramer, Contingency, Entropy and Joint Information Uncertainty to identify which variables are highly correlated and which should be excluded to avoid redundancy. After this step, no strong correlation was observed between the variables, so none were excluded from the Cube Map.

After computing the projection from 2010 to 2018, the similarity was calculated to assess the projection quality. The model goodness of fit was assessed by a fuzzy similarity index, calculated not only to cell by cell overlay comparison, but also considering the cells in the neighbourhood (CSR UFMG, 2019; Soares-Filho et al., 2009). As previously mentioned, the validation of the urban land use forecast produced good results, with fuzzy similarity rates between simulated and observed urban areas in 2018 of at least 65.1% when comparing cell to cell, and up to 93.7% when comparing a window of 11x11 cells. Finally, the 2018 map was loaded as the initial Categorical Map for the simulation of urban expansion until 2040. To these new urban areas, the urban controls defined by the land use legislations were considered to prepare the intermediate LULC scenarios (Figure 4.7).

Figure 4.7 – Map indicating areas new urban areas in 2040, where the municipal urban controls (maximum lot size and impervious rate)



From this map, it was possible to compute the total impervious area in 2040 (existing impervious in 2018 + new impervious in 2040), applying the same proportions of different land uses described in item 4.8.1. The same process was repeated to prepare the PDDI 2040 scenario, considering the urban controls defined in the metropolitan plan. The final impervious rates for all five LULC scenarios are presented in Table 4.8. The impervious rate for each subcatchment is one of the input parameters in the hydrological model. The other parameters were calculated by the same process described in item 4.8.1.

Table 4.8 – Impervious area rate per each subcatchment for the different LULC scenarios

Subcatchment	Impervious area rate for each LULC scenario (%)				
	Current	PDM 2040	PDM final	PDDI 2040	PDDI final
Aboboras	8.38	16.25	42.22	13.51	40.23
AguaSuja1	6.19	16.03	43.61	11.44	35.83
AguaSuja2	4.17	10.88	43.14	8.54	37.10
AguaSuja3	17.62	44.81	56.11	35.22	45.56
AguaSuja4	3.69	4.64	41.72	3.69	34.26
Batatal	4.75	4.75	49.77	4.75	36.97
BelaVista	16.24	31.64	45.01	29.71	44.56
Betim1-0	72.59	72.59	72.59	72.59	72.59
Betim1-1	79.09	79.09	79.09	79.09	79.09
Betim1-2	59.83	65.66	65.73	62.86	62.86
Betim1-3	78.41	78.41	78.41	78.41	78.41
Betim1-4	76.34	76.34	76.34	76.34	76.34
Betim2-0	64.32	66.65	66.65	65.80	65.80
Betim2-1	33.40	50.69	56.07	57.16	59.34
Betim3	7.81	21.63	41.05	24.05	45.82
CampoAlegre	3.23	6.33	40.68	3.73	34.00
DarcyRibeiro	19.93	39.17	48.24	32.99	41.53
Direta	6.63	9.52	41.70	6.63	36.97
Lagoa	27.27	47.23	54.39	50.42	58.22
Laje	0.90	0.90	52.54	0.90	34.14
MorroRedondo1	1.26	7.03	41.35	5.25	34.00
MorroRedondo2	2.52	2.98	39.30	2.52	34.00
MorroRedondo3	4.48	12.32	39.78	9.42	34.97
MorroRedondo4	3.01	9.50	40.17	6.92	35.10
Olaria	10.04	22.98	38.65	20.19	36.81
Praia	45.69	63.26	63.49	65.15	65.54
Retiro	45.09	61.95	64.13	61.10	63.29
VargemdoSape	3.44	3.64	41.03	3.44	34.00
VilaEsperanca	32.26	60.26	62.77	59.02	61.42
TOTAL	15.22	24.77	47.44	23.07	43.63

4.8.3 Hydrological model preparation

The other SWMM input parameters remained the same in all scenarios. The average slope of each subcatchment (Figure 4.8) was computed using the Digital Terrain Model with a spatial resolution of 1.2 m. Thiessen polygons were used to relate four rain gauges coded as 311860101, 311860102, 311860103 and 311670505 to the nearest sub-catchments (see Figure 4.8). However, after a consistency analysis wherein the accumulated rainfall series were compared to the daily series of the nearest rain gage stations operated by the INMET (2019), data from stations 311860103 and 311670505 were discarded due to long gaps and possible registration errors. The remnant gaps in the selected data from the other two stations were treated with data from the nearest rain gauge to allow continuous simulation. With all parameters defined, the hydrological model in SWMM (Figure 4.9) was ready to be run.

Figure 4.8 – Map of Thiessen polygons (left) and slope map (right)

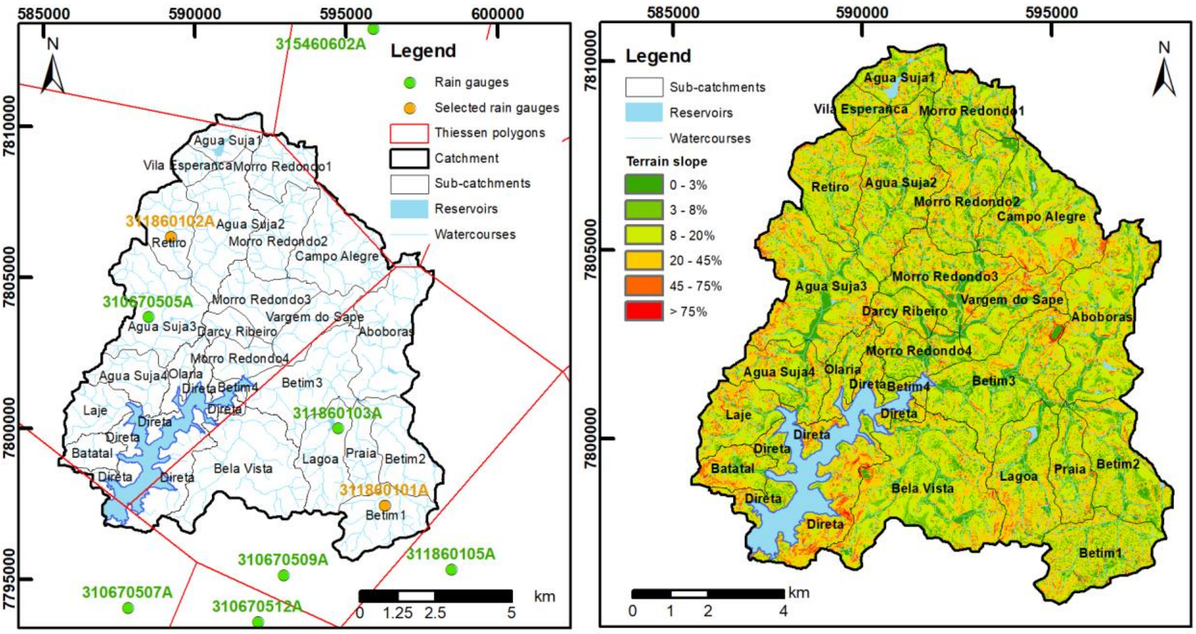
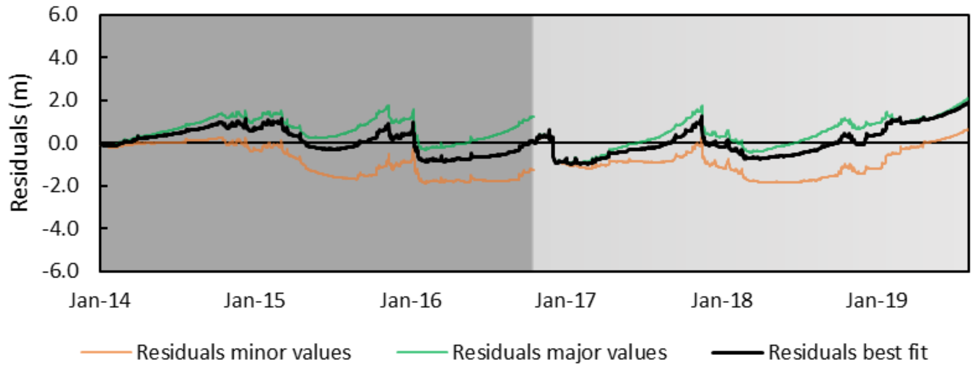


Figure 4.9 – Topologic diagram of the catchment model in SWMM

4.8.4 Hydrological model calibration

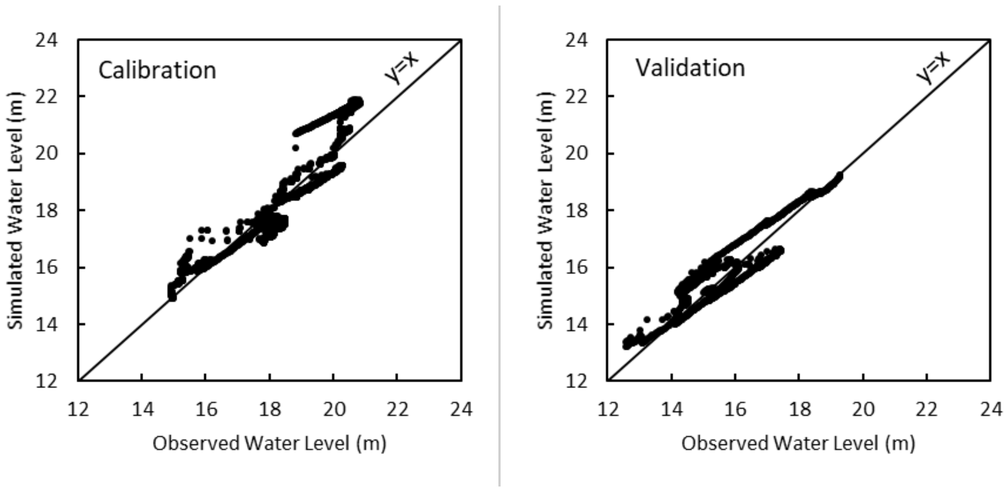
Besides analysing the Nash-Sutcliffe coefficient, the determination coefficient, and the Root Mean Square Error, the analysis of residuals can be useful to assess the model's goodness of fit. The residuals, the difference between simulated and observed water levels, remained always inferior to 2.0 m in magnitude, even considering the range of uncertainty. As shown in Figure 4.10, in certain years, there was a tendency to overestimate the water level at the beginning of the rainy season and an underestimation at the end of the rainy season and during the dry season.

Figure 4.10 – Residuals variation during calibration and validation periods, including residuals of best fit (black line), minor (yellow line) and major (green line) residual values



Despite a possible temporal variation of the residuals, a variation pattern in relation to the water level was not noted. Figure 4.11 presents dispersion plots of observed and simulated water level values for calibration and validation periods. In the ideal absence of errors or trends in the simulation, all pairs of observed water level (abscissa) and simulated water level (ordinate) would align with the bisector, where the ordinate equals the abscissa.

Figure 4.11 – Simulated and observed water levels (black dots) in calibration and validation. The black line represents equality between simulated and observed values



There is no significant dispersion around the y=x line in both calibration and validation periods, and no error trends are observed, indicating a good adjustment. Water level data during the validation period are closer to the bisector than during calibration, confirming that the model performance in validation was better than in calibration. The most distant points in the calibration period are the highest water levels, a result related to the model overestimation that occurred in the last year of simulation.

Concerning the parameters initially estimated according to the previously described methods, the impervious areas were increased by 20%, and the sub-catchment widths were multiplied by 2.5. The soil parameters that produced the best fit can be associated with a soil characterized between loamy sand and sandy loam, with a saturated hydraulic conductivity of 16.24 mm/h, suction head of 95.7 mm, porosity of 0.448, wilting point of 0.074, and a field capacity of 0.165. The fraction of total evaporation available for the upper unsaturated soil zone was 0.5, and the depth into the saturated zone over which evaporation can occur was 5.0 m. When the aquifer is completely saturated, the seepage rate to deep groundwater remains 0.002 mm/hr, as initially estimated. The coefficients A1, A2, B1, and B2, from the SWMM equation for lateral groundwater flow, were calibrated to 0.000038 (A1 and A2) and 0.5 (B1 and B2), representing the low exchange rates between groundwater and the streams.

4.8.5 Hydrological model simulation of the alternative LULC scenarios

The results are presented in Figure 4.12, focusing on peak flows (A) and baseflows (B). Remarkable differences are observed in the runoff generation between scenarios. As expected, the increase of impervious surface produced more inflow volume to the reservoir during the rainy season and lower volumes during the dry season. That is why the PDM scenario resulted in the greatest inflow (the maximum inflow and the total inflow volume were, respectively, 171% and 115% higher than in the current scenario), followed by the PDDI scenario (maximum inflow and volume 159% and 102% higher, respectively), the PDM 2040 scenario (maximum inflow and volume 58% and 35% higher, respectively), and the PDDI 2040 scenario (maximum inflow and volume 52% and 29% higher, respectively). These differences in inflow volumes naturally lead to differences in storage volume and water level in the reservoir (see Figure 4.13).

Figure 4.12 – Reservoir inflow according to different LULC scenarios from November 2016 to October 2017. Graph A represents the greatest inflows, and graph B represents the lowest

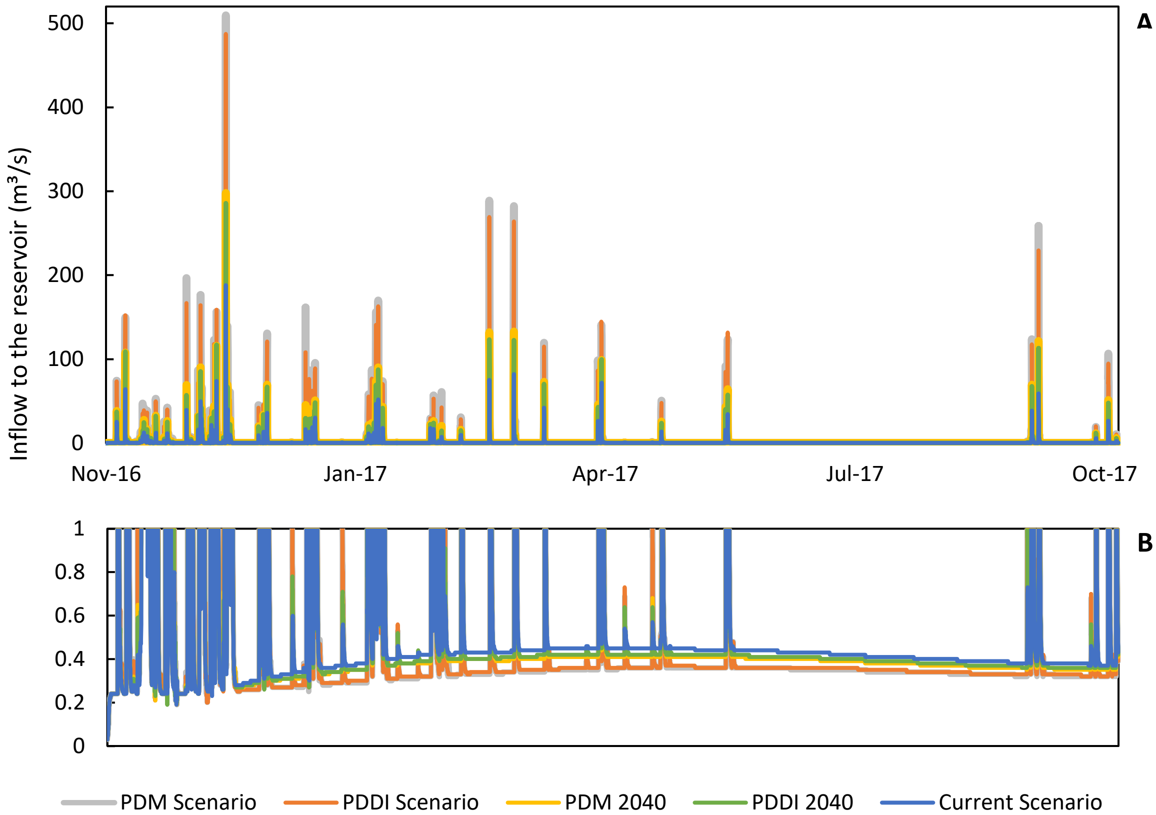
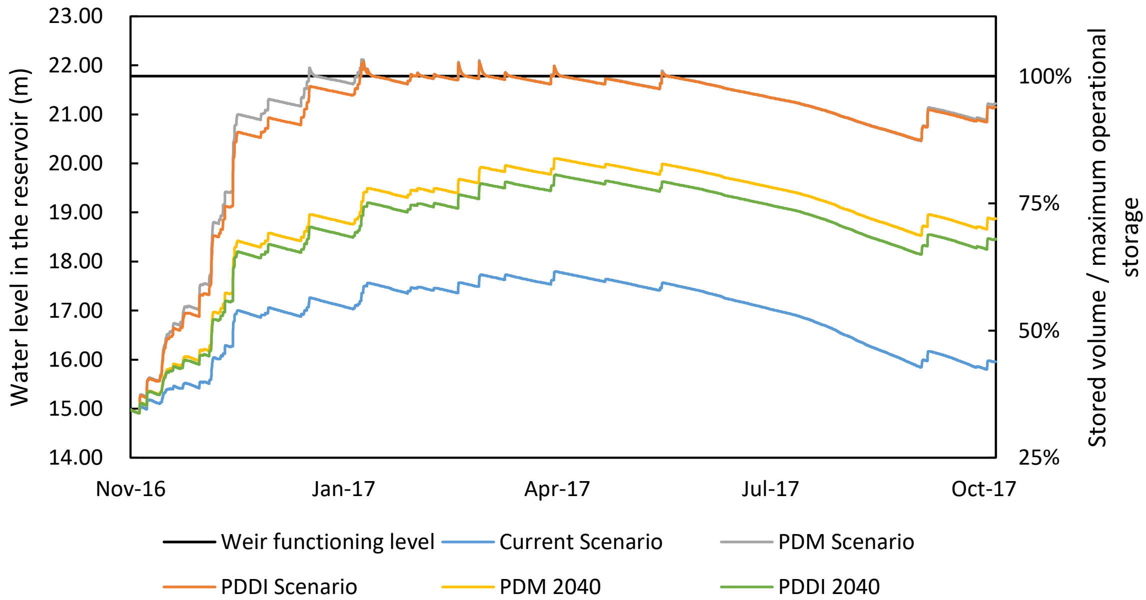
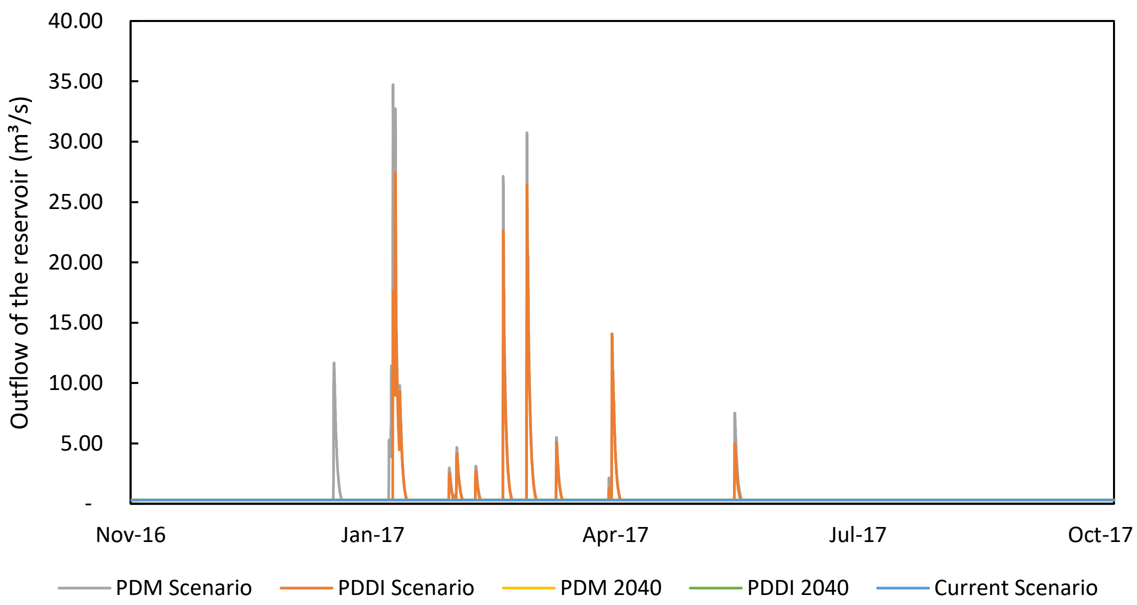


Figure 4.13 – Water levels in Vargem das Flores reservoir fort LULC scenarios



In the current scenario, the water level never exceeded 17.80 m, no overflow was observed, and the outflow was restricted to the ecological flow (0.30 m³/s). In the 2040's scenarios, the water levels were higher by more than 2 m, but still lower than the overflow weir level (21.78 m), keeping the outflow restricted to the ecological flow. In the PDM scenario, in the third month of simulation (January), the water level has risen to the weir level and an overflow of 11.01 $m^3 \cdot s^{-1}$ was observed. With the reservoir completely full, at every intense rainfall, an overflow was observed. In the PDDI scenario, the same phenomenon occurred from the fourth simulation month (February). In this case, the overflow remained smaller than in the PDM scenario (Figure 4.14).

Figure 4.14 – Outflow of the reservoir for LULC scenarios



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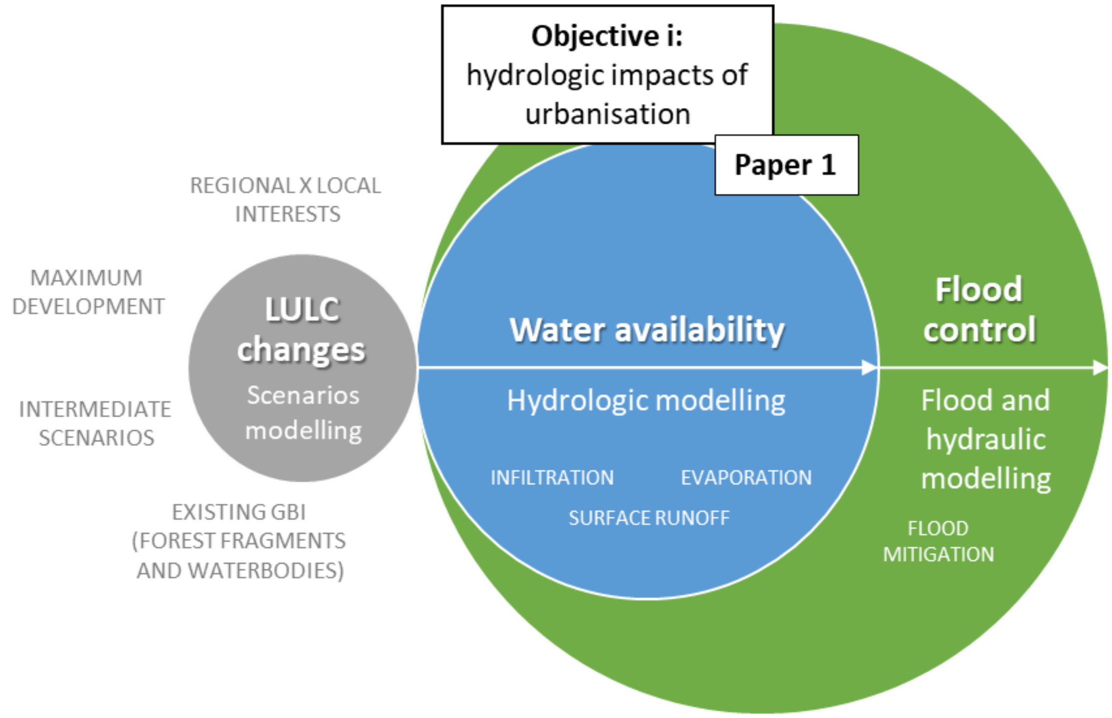
4.10 Summary

This chapter marks the initial attempt to quantify the regulating ecosystem services of the green and blue infrastructure (GBI) within the Vargem das Flores reservoir catchment, which, in this stage, consists of the remaining forest fragments and the reservoir itself. It explored how changes in land use regulations can lead to urban expansion in the area and cause many hydrological impacts, especially in controlling downstream floods (see Figure 4.15).

Figure 4.15 – Summary diagram of the developed research and objectives – Paper 1



Intermediate development scenarios for the year 2040 were developed by modelling land use and land cover changes with the Dinamica EGO model. The output data was prepared to be input to the Storm Water Management Model to evaluate the resulting hydrological impacts. The research confirmed the effects of urban expansion on various hydrological processes, such as reduced infiltration and groundwater flow, increased runoff and peak flows, and consequent downstream flooding. All data used are either open-source or obtained freely from public institutions, including databases from various organizations. These data and methods can be valuable for similar studies in different catchments and scales.

These first results emphasize the importance of effective urban planning and land use regulations to mitigate negative impacts on water resources and reduce flood risks. Furthermore, the research aligns with the broader goal of evaluating the potential benefits of implementing Green and Blue Infrastructure to mitigate urbanisation impacts and protect this critical water source and its environmental and social functions. The study's findings offer valuable information for decision-makers and urban planners, evidencing the impacts of allowing urban development in a vital water supply catchment. The next chapter will explore an alternative future scenario that allows some urban development but considers the protection of the existing GBI and the adoption of compensatory techniques to treat new impervious areas.

5 ARTICLE 2: HYDROLOGICAL RESPONSE OF IMPLEMENTING GREEN AND BLUE INFRASTRUCTURE – STUDY OF A BRAZILIAN METROPOLIS

“Temos que reflorestar o nosso imaginário e, assim, quem sabe,
a gente consiga se reaproximar de uma poética de urbanidade que devolva
a potência da vida, em vez de ficarmos repetindo os gregos e os romanos.
Vamos erguer um bosque, jardins suspensos de urbanidade,
onde possa existir um pouco mais de desejo, alegria, vida e prazer,
ao invés de lajotas tapando córregos e ribeirões.
Afinal, a vida é selvagem e também eclode nas cidades.”

“We need to reforest our imagination so that, perhaps,
we can reconnect with an urban poetics that returns
the power of life, instead of just repeating the Greeks and Romans.
Let us create a forest, suspended gardens of urbanity
where there can exist a little more desire, joy, life, and pleasure,
instead of tiles covering streams and creeks.
After all, life is wild and also blossoms in cities.”

Ailton Krenak, in ‘Futuro ancestral’ [Ancestral future] (Krenak, 2022),
Brazilian Indigenous leader, activist, writer, and environmentalist of the
Krenak people, Minas Gerais

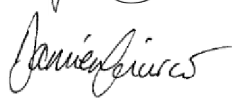
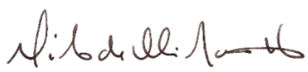
In this paper, the research moves forward to include an alternative future scenario that allows further urban development but does not compromise the regulating ecosystem services provided by the existing GBI in the catchment of the Vargem das Flores reservoir. In this alternative scenario, new elements are added to the existing green and blue infrastructure, aiming for the most cost-effective techniques to treat future impervious areas. Multiple alternatives of GBI combinations were considered, their construction and maintenance costs estimated, and their potential hydrological impacts were simulated using the SWMM model. The impacts of the alternative future urban development scenarios on the ecosystem services provided by GBI were assessed in terms of regulating the water cycle processes of infiltration, evapotranspiration, surface runoff, and flood control in the areas downstream of the reservoir.

The Version of Record of the paper *“Hydrological response of implementing green and blue infrastructure – study of a Brazilian metropolis”* was published on 26/04/2022 in the *Urban Water Journal* and is available at http://www.tandfonline.com/10.1080/1573062x.2022.2066549. The manuscript presented in this chapter refers to the revised version after peer review and accepted for publication form, that is, the “post-print” (Rosa, Silva, Chong, et al., 2022).

5.1 Contributions to co-authored publications

The undersigned authors agree that the nature and extent of the contributions to the work “*Hydrological response of implementing Green and Blue Infrastructure – study of a Brazilian metropolis”* was as follows (Table 5.1).

Table 5.1 - Contributions of co-authors - Paper 2

Co-author	**Nature of contribution**	**Extent of contribution (%)**	**Signature**	**Date**
Deyvid Wavel Barreto Rosa	Study design, data acquisition and interpretation, modelling, drafted manuscript	80		05/12/2022
Talita Fernanda das Graças Silva	Study design, reviewed manuscript	5		06/12/2022
Joanne Chong	Study design, reviewed manuscript	5		08/12/2023
Damien Giurco	Study design, reviewed manuscript	5		12/12/2022
Nilo de Oliveira Nascimento	Study design, reviewed manuscript	5		12/12/2022

5.2 Abstract

Green and Blue Infrastructure (GBI) is an urban planning approach that can reduce and mitigate the impacts of urbanisation in the water cycle. This study evaluates the hydrologic impacts of a possible deployment of GBI in a peri-urban catchment under pressure from urban development. Considering cost-effectiveness, the best combinations of GBI techniques were simulated and compared with a scenario with urban expansion. A hydrological model previously calibrated in SWMM was applied to simulate the impacts of GBI in the runoff, and a Hec-RAS model was used to assess the impact on flood. A combination of lot areas treated by rooftop disconnection and roads treated by vegetative swales achieved the lowest cost and one of the highest effectiveness in runoff reduction. Despite the growth of impervious areas by almost 100% from urban expansion, the GBI scenario would bring the hydrological conditions closer to the current ones, and the total flooded area downstream would be roughly the same as in the current scenario.

Keywords: hydrologic modelling; cost-effectiveness; flood mapping; SWMM; Hec-RAS.

5.3 Introduction

Green and Blue Infrastructure (GBI) is a new paradigm in urban landscape planning and water management that aims to build an urban environment adapted to protect or mimic the natural water cycle characteristics. GBI consists of a multifunctional network of parks and gardens, urban arborisation, stormwater infiltration devices, green roofs and facades, bioswales, porous pavements, rainwater tanks, etc. (Voskamp & Van de Ven, 2015). Its importance goes beyond the field of stormwater management since its various social and environmental benefits contribute to preventing biodiversity loss, improving human well-being and equity, and increasing resilience to climate change (Andersson et al., 2019; Ashley et al., 2013; Barbosa et al., 2019).

In principle, the term Green and Blue Infrastructure may refer to greenways, green corridors that provide connectivity among remnant green fragments, performing functions such as protecting water resources and biodiversity and promoting recreational and social cohesion (Frischenbruder & Pellegrino, 2006). That closely relates to the oldest and most widely used "green infrastructure" concept, first applied in landscape architecture and ecology (Benedict & McMahon, 2000). When considering, among its ecosystem services, the potential use of green infrastructure in stormwater management, the term has become one of the most employed in the context of urban drainage, alongside Best Management Practices and Low Impact Development (Fletcher et al., 2014).

Studies have demonstrated the effectiveness of GBI in decreasing surface runoff and, consequently, decreasing the frequency of floods and expenditures with conventional drainage systems (Li et al., 2017; Rosa et al., 2020; United States Environmental Protection Agency, 2007). GBI impacts other hydrological processes by increasing infiltration, evapotranspiration, groundwater flow, and improving runoff water quality, as evidenced by many studies (Ahiablame et al., 2012; Liu et al., 2017). In parallel with benefits related to stormwater management, and because of them, studies have been approaching the social and environmental co-benefits of GBI implementation (Alves et al., 2019; Andersson et al., 2019; Center for Neighborhood Technology, 2010). It is important to consider them since it is politically and economically not justifiable to restrict occupation in an urban area to implement a device whose sole functions are runoff reduction and diffuse pollution abatement. Multiple uses, with associated amenities, are important to justify freezing those areas for real estate development.

It is important to analyse the optimal type and location of source control devices, maximising their effectiveness and minimising their costs. An optimisation framework that considers the assessment of GBI performance in flood risk reduction and the increase of other benefits can be a helpful decision-making tool for stormwater management (Alves et al., 2020). The comparison of the hydrologic effectiveness with construction, operation and maintenance costs may be made over time, considering the impacts of climate change, urbanisation, and inflation (Wang et al., 2016). Some studies coupled the Storm Water Management Model (SWMM) and a chosen platform in order to optimize design parameters and Low Impact Development (LID) devices selection, achieving the best effectiveness, but mainly on a subcatchment scale (Eckart et al., 2018; Zhang et al., 2013; Zhu et al., 2019).

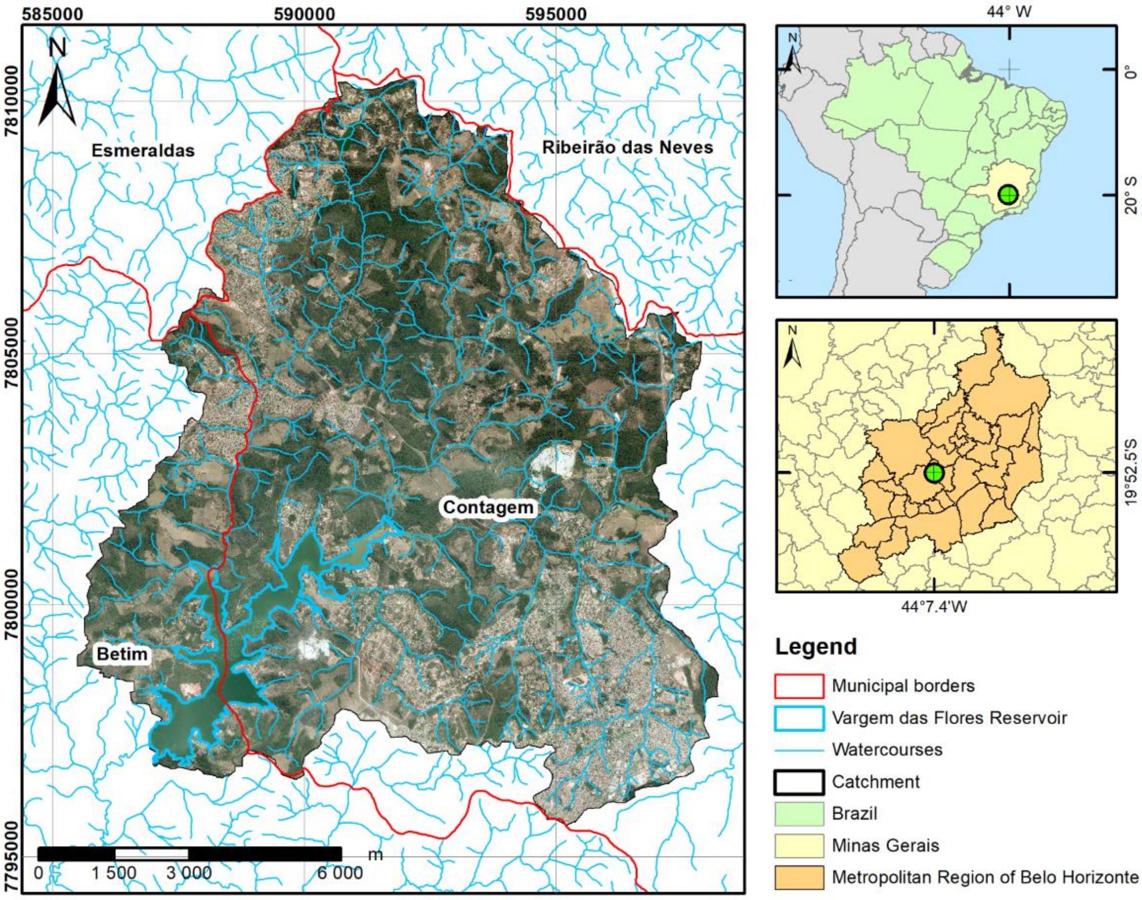
Urbanisation may cause more severe impacts in a catchment water cycle than climate change if considered by itself, and the adoption of appropriate LID devices can mitigate part of these impacts (Wang et al., 2018). In this sense, it is essential to consider the adoption of a GBI approach when making decisions on urban planning. However, the broad application of GBI would likely involve occupation restrictions and LID treatment in public and private areas that would not necessarily receive direct benefits in hydrological aspects. So, it is important to consider the other social and environmental benefits of GBI and the management of public and private interests. When the context is a metropolis, conflicts between regional and local interests, long-term plans and one-off projects may emerge (Tonucci Filho & Freitas, 2020). Nevertheless, the adoption of Green and Blue Infrastructure in planning “can even reduce opposition to new development by assuring civic groups and environmental organisations that growth will occur only within a framework of expanded open space and conservation lands” (McMahon, 2000). Finally, in intermunicipal systems, the study of the optimal location of Green and Blue Infrastructure technologies becomes even more relevant to increase the effectiveness of safeguarding water supply (Todeschini et al., 2018).

The principal aim of this work is to evaluate the potential of optimal GBI implementation in reducing impacts on the water cycle caused by the urbanisation of part of a peri-urban catchment equipped with a reservoir for drinking water purposes. This study also analyses the impact of the different proposals for the urbanisation of the catchment on flood production downstream of the reservoir. Authors also expect that these results may contribute to the public discussion about the impacts of land use and land cover (LULC) changes in the catchment, including the argument of the alternative proposal of urbanisation with GBI implementation.

5.4 Methods

The catchment of Vargem das Flores reservoir was selected as a case study area. It covers an area of 120.25 km², distributed between the municipalities of Contagem (86.2% of its area) and Betim (13.8%). Both municipalities are part of the Belo Horizonte Metropolitan Region - BHMR, the capital of Minas Gerais State, in the southeast region of Brazil, as shown in Figure 5.1.

Figure 5.1 – Vargem das Flores catchment location map

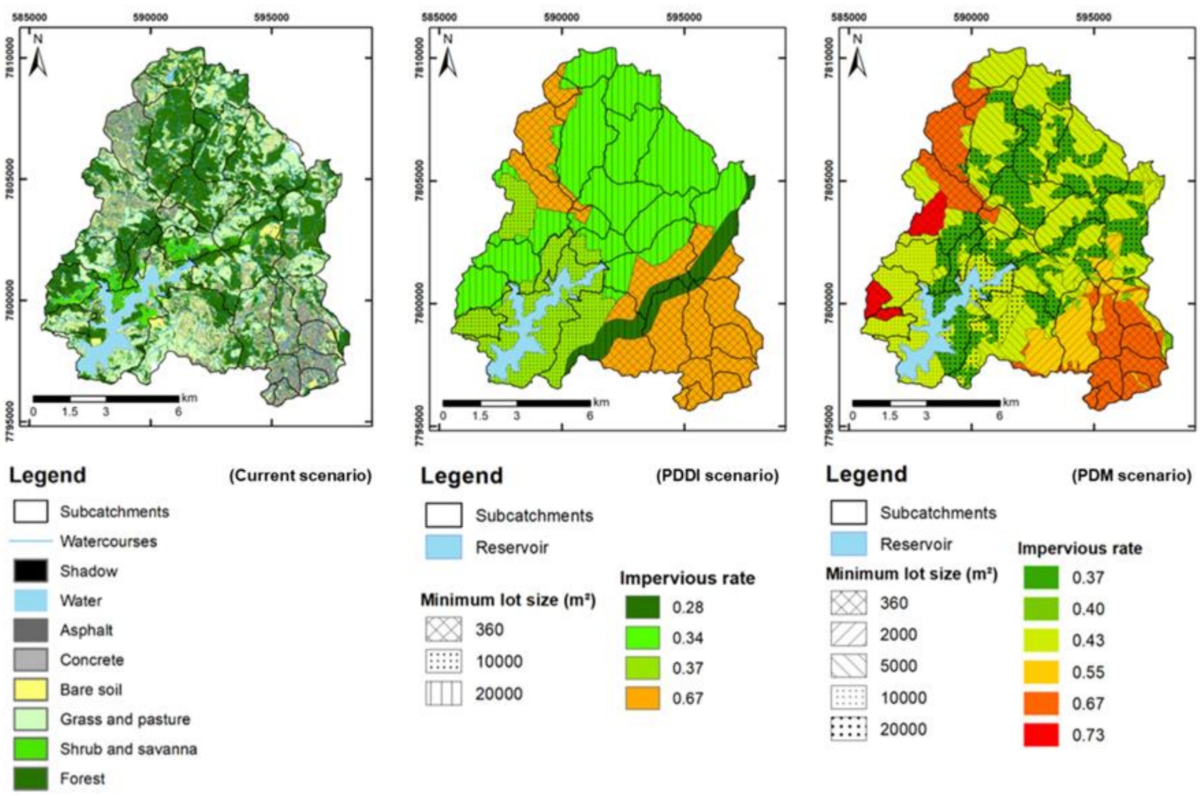


Vargem das Flores reservoir was implemented in 1972, with the main purpose of supplying drinking water to part of the BHMR, and the Minas Gerais Sanitation Company Copasa operates it. Despite the metropolitan interest in protecting the catchment due to its strategic importance for drinking water supply (Minas Gerais, 2006), the municipality of Contagem recently approved a new municipal master plan (Contagem, 2018), easing restrictions for urban development in the whole area. This urbanisation may impact the reservoir service lifetime, increase water shortage and flood risks, and degrade its water quality, increasing treatment costs.

Hydrologic modelling and spatial characterisation of the studied catchment were based on the previous work realised by Rosa, Silva, Araújo, et al. (2022). A georeferenced database was constructed with terrain slope, land use and land cover classification, and urbanistic parameters according to legislation, following two land use scenarios that reflect the local and metropolitan conflicts of interest in the catchment other than the current land use. The SWMM model, after calibration and validation, was used to simulate the catchment hydrological response according to two land use scenarios. The time series of hourly precipitation data recorded by two rainfall stations between 2014 and 2020 was used as input for the model. The observed water depth data of the reservoir was used to calibrate and validate the hydrological model, which achieved a good fit: the Nash-Sutcliffe coefficient reached 0.80 in calibration and 0.87 in validation; the determination coefficient was 0.88 for calibration and 0.79 for validation, and the Root Mean Square Error was 0.72 m in calibration and 0.76 m in validation (Rosa, Silva, Araújo, et al., 2022).

In sequence, the hydrological model was used to simulate the impacts of land use scenarios considering the municipal legislation (PDM scenario) and a less intense development proposal from the Metropolitan authority (PDDI scenario). The land use and cover scenarios simulated by Rosa, Silva, Araújo, et al. (2022) are presented in Figure 5.2.

Figure 5.2 – Land use and land cover scenarios considering urban development of Vargem das Flores catchment studied by Rosa, Silva, Araújo, et al. (2022)

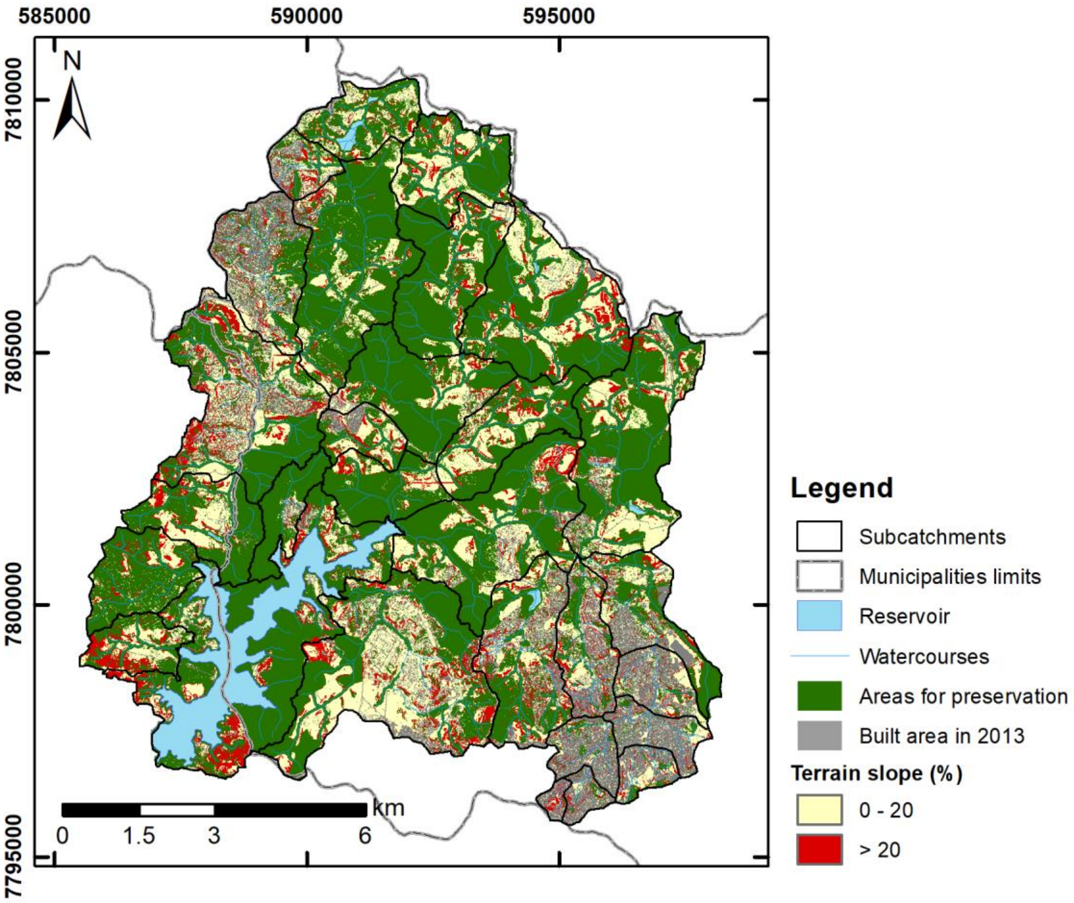


According to the land use and land cover classification of the orthophotos of 2013, the average imperiousness rate for all the catchment was 15.22%. Applying the minimum lot size area and the maximum impervious rate for each lot, the average imperiousness rate for all the catchment in the PDM scenario would be 47.44%, and in the PDDI scenario, it would be 43.63%. In the PDM and PDDI scenarios, no exclusive areas were designated for preservation, so some level of peri-urban occupation would be allowed even in the riparian and forest remnant areas (Rosa, Silva, Araújo, et al., 2022).

The results obtained by Rosa, Silva, Araújo, et al. (2022) were compared in this work with an alternative land use and land cover scenario based on the adoption of a generalized GBI approach in all the catchment areas. The construction of the GBI scenario started with the identification of the remnant forest patches and the riparian areas not urbanized, selected to be recovered and to function as ecological corridors. The remaining area suitable for urban expansion was separated into areas for conventional urban drainage systems and areas with the potential for implementation of GBI techniques. This distinction was defined according to the terrain slope, as steeper areas may be unsuitable for implementing infiltration devices, for instance. The map indicating these areas is presented in Figure 5.3. More details about the preparation of the GBI scenario are presented in the Appendix (item 5.7.1).

The threshold value of 20% was applied for the slope, although some authors recommend lower values (Schueler, 1987; Woods Ballard et al., 2015). Some recent studies have suggested that the infiltration capacity is still considerable until a slope of 15% (URS Australia, 2003) or 20% (Lucke et al., 2012). Adopting the threshold of 20% slope for suitable implementation of infiltration devices means that 73.9% of new impervious areas could be treated with infiltration devices. Due to the regional topographic characteristics, if the slope threshold is changed by 10% or 15%, respectively, 32.2% or 56.9% of the new impervious areas could be treated with infiltration devices. That is, as adopting a more restrictive threshold would greatly reduce the area that infiltration techniques could treat, the value of 20% slope was adopted considering that there are constructive alternatives for implementing these structures that can maintain their infiltration and storage capacity.

Figure 5.3 – Map indicating the areas for preservation (green), the built area in 2013 (grey), and the remaining area suitable to occupation divided into areas with terrain slope greater than 20% (red) and with slope smaller than 20% (yellow), which is suitable to LID implementation



Source: built from FJP (Fundação João Pinheiro, 2013)

The calibrated hydrological model indicated high permeability rates (16.2 mm/h) and water table depths greater than 1.0 m during the simulation period, indicating that soil permeability and groundwater depth were not restrictive for GBI devices in the catchment (Rosa, Silva, Araújo, et al., 2022). Both values meet the literature recommendations for applying GBI infiltration techniques (São Paulo, 2012; URS Australia, 2003; Woods Ballard et al., 2015).

For each subcatchment, the total suitable area for GBI implementation was calculated based on the mentioned criteria. Rooftop disconnection, green roof, rain garden, and rain barrel were selected to treat the rooftops and impervious areas inside lots, that is, the private impervious areas. Infiltration trench, bioretention cell, permeable pavement, and vegetative swale were selected to treat the roads and impervious areas outside lots, that is, the public impervious areas.

Inside each of these two groups of techniques, the percentage of the area treated by each GBI device was varied from 0%, 25%, 50%, 75%, and 100% of the suitable area to consider other potential restrictive factors such as local adaption difficulties, willingness to adopt the approach at private and or public spheres, and others. The combination of these variations resulted in 1225 alternative GBI technique sets (see Table 5.2). They were simulated with the hourly measured rainfall of one hydrological year, from October 2016 to September 2017, when a total annual rainfall (1,310 mm) was registered close to the historic rainfall average (1,380 mm). From the hydrological simulation, the peak flows and the runoff volumes were computed and compared to the conventional urbanisation scenario (Municipal Master Plans – PDM Scenario).

Table 5.2 – Combination of GBI techniques deployment to treat impervious areas inside lots and roads

Treating impervious area inside lots	Fraction of impervious area treated by each LID	Treating roads	Fraction of impervious area treated by each LID
GR	1	PP	1
RG	1	VS	1
RD	1	BC	1
RB	1	IT	1
GR + RG GR + RD GR + RB RG + RD RG + RB RD + RB	0.5 + 0.5 0.25 + 0.75 0.75 + 0.25	PP + VS PP + BC PP + IT VS + BC VS + IT BC + IT	0.5 + 0.5 0.25 + 0.75 0.75 + 0.25
GR + RG + RD GR + RG + RB GR + RD + RB RG + RD + RB	0.25 + 0.25 + 0.5 0.25 + 0.5 + 0.25 0.5 + 0.25 + 0.25	PP + VS + BC PP + VS + IT PP + BC + IT VS + BC + IT	0.25 + 0.25 + 0.5 0.25 + 0.5 + 0.25 0.5 + 0.25 + 0.25
GR + RG + RD + RB	0.25 + 0.25 + 0.25 + 0.25	PP + VS + BC + IT	0.25 + 0.25 + 0.25 + 0.25

*BC: bioretention cell, GR: green roof, IT: infiltration trench, PP: permeable pavement, RB: rain barrel, RD: rooftop disconnection, RG: rain garden, VS: vegetative swale.

These results were crossed with the sum of the implementation and maintenance costs of all the techniques applied in each case. The unit costs of every GBI technique were estimated based on the material and labour quantification for standard design, according to the controlled area, as presented in Table 5.3. The presented costs for green roofs and permeable pavements refer only to the increase in expenses in implementing and maintaining these devices compared to a concrete slab and an asphaltic pavement, respectively. The unit costs were obtained from the monthly unit price list for construction and consulting services (February 2020) from Sudecap, a Belo Horizonte municipal agency whose database is usually used as a reference for engineering projects and studies in the state of Minas Gerais (Sudecap, 2020). More details about the cost composition for each GBI type are presented in the Appendix (item 5.7.2).

Table 5.3 – GBI techniques implementation and maintenance costs and the ratio of treated area per technique area

GBI Technique	Symbol	Ratio treated area (m^2) per m^2 of technique	Implantation Cost per m^2 of treated area (BRL)	Maintenance Cost per m^2 of treated area (BRL)
Bio-Retention Cell	BC	26.0	5.54	0.53
Rain Garden	RG	12.1	3.66	0.95
Green Roof	GR	1.0	117.78	16.10
Infiltration Trench	IT	23.6	10.99	1.83
Permeable Pavement	PP	2.0	28.03	22.20
Rain Barrel	RB	35.5	7.43	0.13
Rooftop Disconnection	RD	1.0	0.84	0.05
Vegetative Swale	VS	9.9	2.82	1.63

BRL is the Brazilian currency, Real (BRL). 1.00 BRL is about $ 0.18 US (October 2021).

The drainage devices were sized for a 10-year return period rainfall of 24 hours. The duration of 24 hours was adopted because this is the critical one for the runoff contribution of all the catchments to the reservoir. The area treated by green roof and rooftop disconnection was considered equal to the roof area. Rain barrel dimensions were calculated to treat a roof area where the volume of a 10-year return period and 24 hours of duration rainfall falls. The area treated by vegetative swale was considered as the one that fills the swale with a 10-year return period and 24 hours of duration rainfall. Finally, according to Woods Ballard et al. (2015), permeable pavement can treat twice its area.

The areas treated by the bioretention cell, rain garden, and infiltration trench were calculated by the equation proposed by Woods Ballard et al. (2015):

$$A_f = \frac{V_t L}{k(h + L)t}$$

Where:

A_f = surface area of filter bed (m²)
Vt = volume of water to be treated (m³)
L = filter bed depth (m)
k = coefficient of permeability of filter media for water (m/s)
h = average height of water above filter bed (m)
t = time required for water quality treatment volume to percolate through filter bed (s) – adopted 24 hours

The dimensions and characteristics of the GBI technique layers were defined according to the best practices and to the recommendations of Woods Ballard et al. (2015) and Rossman and Huber (2016b), as shown in Table 5.4.

After the costs and effectiveness computations, it was possible to select the best GBI combination with the lowest cost and the greater runoff reduction. This optimal solution was defined as the GBI scenario, in which simulation results were compared to the other LULC scenarios described by Rosa, Silva, Araújo, et al. (2022). The observed rainfall from March 2019 to February 2020 was simulated because the reservoir was completely full in January 2020, and it was interesting to evaluate the overflow in the different scenarios. On the other hand, flood risk depends on the initial state of the reservoir and a complete risk assessment must integrate this variable. Design events with 2-, 10-, 50-, and 100-year return periods were also simulated, considering the reservoir was completely full at the beginning of the design rainfall events. Design rainfall and hyetographs were prepared according to the regional intensity-duration-frequency equation and the design hyetographs developed by Pinheiro and Naghettini (1998) for the Belo Horizonte metropolitan region.

Table 5.4 – GBI input parameters in SWMM estimated according to recommendations of Woods Ballard et al. (2015) and Rossman and Huber (2016b)

Layer	Parameter	BC	RG	GR	IT	PP	RB	RD	VS
Surface	Berm Height (mm)	200	150	100	100	0			500
	Vegetation Volume Fraction	0.1	0.2	0.1	0	0			0.1
	Surface Roughness (Manning n)	0.1	0.4	0.4	0.1	0.015		0.4	0.35
	Surface Slope (%)	3	3	3	3	3		10	5
	Storage Depth (mm)							2	
	Swale Side Slope (run/rise)								3
Soil	Thickness (mm)	500	500	150		500			
	Porosity (volume fraction)	0.45	0.45	0.45		0.45			
	Field Capacity (volume fraction)	0.17	0.17	0.17		0.17			
	Wilting Point (volume fraction)	0.074	0.07	0.07		0.07			
	Conductivity (mm/hr)	16.24	16.24	16.24		16.24			
	Conductivity Slope	40	40	40		40			
	Suction Head (mm)	95.7	95.7	95.7		95.7			
Storage	Thickness (mm)	400			1500	400			
	Void Ratio (Void/Solids)	0.6			0.6	0.6			
	Seepage Rate (mm/hr)	16.24	16.24		16.24	16.24			
	Clogging Factor	36			36	36			
	Barrel Height (mm)						900		
Drain	Flow Coefficient (mm/hr)	3.33			3.33	3.33	5		
	Flow Exponent	0.5			0.5	0.5	0.5		
	Offset (mm)	390			1490	390	0		
	Control Curve								
	Drain Delay (hrs)						12		
Drainage Mat	Thickness (mm)			50					
	Void Fraction			0.5					
	Roughness (Manning's n)			0.4					
Pavement	Thickness (mm)					150			
	Void Ratio (Void/Solids)					0.2			
	Impervious Surface Fraction					0.1			
	Permeability (mm/hr)					5000			
	Clogging Factor					540			
	Regeneration Interval (days)					1			
	Regeneration Fraction					1			
Roof Drain	Flow Capacity (mm/hr)							1000	

*BC: bioretention cell, GR: green roof, IT: infiltration trench, PP: permeable pavement, RB: rain barrel, RD: rooftop disconnection, RG: rain garden, VS: vegetative swale.

Subsequently, the hydrologic outputs were inserted in the HEC-RAS 5.1 hydraulic model to evaluate the flow downstream of the reservoir under the different scenarios considered. All hydraulic data of the downstream riverbed and floodplain topography were obtained from the municipality of Betim, which is concerned with evaluating flood impacts due to LULC changes upstream of Vargem das Flores reservoir. Only the impacts of land use changes upstream of the Vargem das Flores reservoir were considered to minimize the multitude of scenarios related to discharge contributions and flood risk in the tributaries of the Betim River downstream of the Vargem das Flores dam. Therefore, the simulations performed here only refer to high waters in the Betim River, although high waters in the Betim River can also impact flood risk in the tributaries due to backwater effects. The flood extension was assessed with Hec-GeoRas, and the flood maps were generated in a GIS environment.

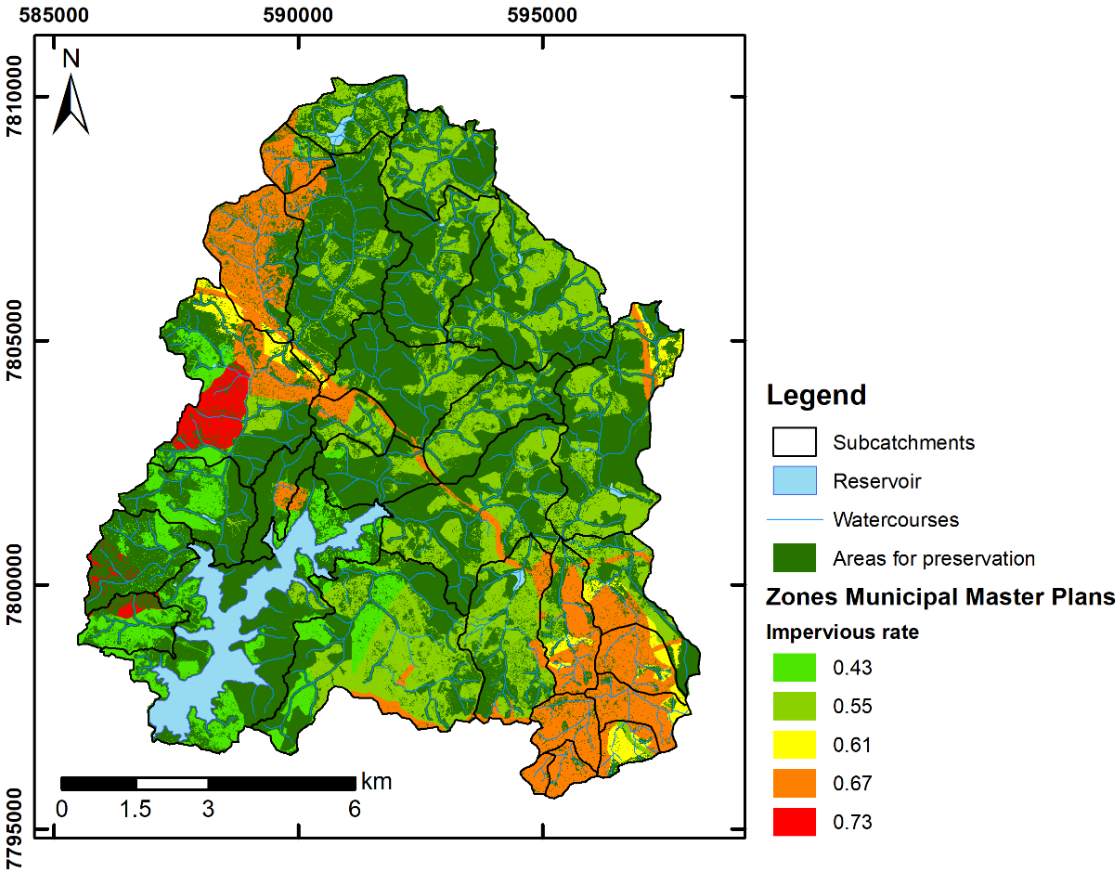
5.5 Results

Results of GBI scenario construction, including cost-effectiveness analysis, hydrologic and hydraulic simulations of the different LULC scenarios, are presented in this section.

5.5.1 Scenario construction

Considering that new occupations would not be allowed in riparian areas and existing forest fragments, the maximum impervious rate of the remaining area defined by municipal master plans from Contagem and Betim is presented in Figure 5.4.

Figure 5.4 – Map of areas for preservation and urbanistic guidelines of Municipal Master Plans for the remaining area. Source: adapted from Betim (1999) and Contagem (2018)

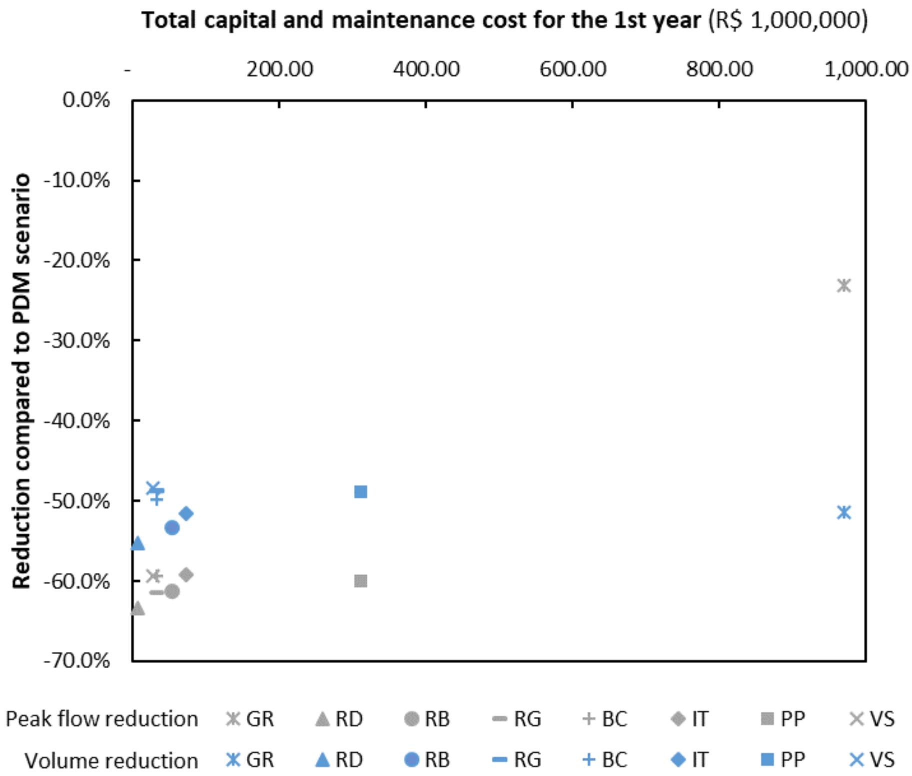


In this scenario, the reservoir extends over 4.05% of the catchment area, 35.18% would be protected, and the remaining 60.77% could be occupied. Considering this and the maximum impervious rates established by local legislation, the total impervious area in this scenario would be 30.22%. This would be an intermediate imperviousness rate between the current situation (15.22%) and the scenarios with complete application of municipal (47.44%) and metropolitan (43.63%) legislation (Rosa, Silva, Araújo, et al., 2022).

5.5.2 Cost-effectiveness of LID implementation

The impacts of each GBI technique implementation in terms of peak flow and runoff volume reduction in relation to the total cost in the first year (capital cost and first-year maintenance cost) are presented in Figure 5.5. These results refer to inflow to the reservoir simulated with hourly rainfall observed between October 2016 and September 2017, a hydrological year with rainfall close to the average historical values.

Figure 5.5 – Peak flow and runoff volume reduction compared to PDM scenario, result of each GBI techniques implementation, function of the total capital and maintenance cost for the first year – simulation of 2016-2017 rainfall (BC: bioretention cell, GR: green roof, IT: infiltration trench, PP: permeable pavement, RB: rain barrel, RD: rooftop disconnection, RG: rain garden, VS: vegetative swale)



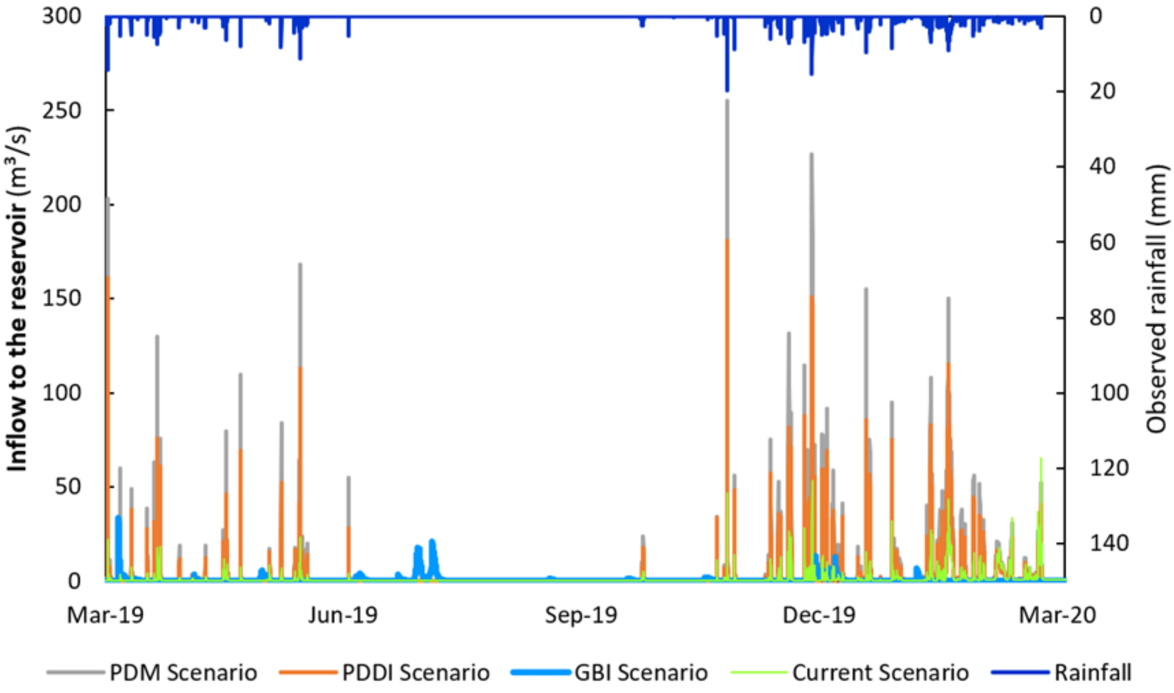
Peak flow reduction varied more than runoff volume reduction, as shown by the amplitude of ordinates results on the chart. The least efficient GBI technique is the green roof, as it has the highest cost (more than four times higher than the second most expensive technique, the permeable pavement), the lowest effectiveness in peak flow reduction, and a runoff volume reduction similar to that of the other investigated LIDs. Permeable pavement is also low efficient, as its costs are at least three times higher than the other techniques and does not present effectiveness that justifies this level of costs. The other techniques present lower costs, but rooftop disconnection is the most efficient GBI technique, as it costs just BRL 6.40 million and decreases peak flow and volume to a minimum.

After the 1225 combination of GBI devices simulation, the peak flow variations were compared to the total cost in the first year. In general, the distribution of results followed an increasing pattern, i.e., the higher the costs, the lower the effectiveness in reducing peak flow. From the 1225 combinations, the most cost-effective group of combinations considering decreased peak flow and costs is the one that combines 100% of suitable lot areas treated by rooftop disconnection and 100% of suitable roads treated by vegetative swale. It is important to highlight that only the peak flow reduction was considered a parameter of effectiveness and, maybe, considering other factors, the best combination would be different.

5.5.3 Hydrologic simulation of the LULC scenarios

GBI and other LULC scenarios were simulated, with the percent of impervious areas changed in each scenario and the other input parameters unchanged. Results of inflow to the reservoir simulated with rainfall observed between March 2019 and February 2020 are presented in Figure 5.6. The initial water depth of the reservoir was 20.58 m, the observed water depth on 1st March 2019. This means the reservoir was 83.7% full at the beginning of the simulation. This period was selected to be simulated because it was a wetter rainy period than the historical average. Under simulated current conditions, the reservoir's water level reached the weir level by the end of January 2020.

Figure 5.6 –Inflow to the reservoir in the different LULC scenarios during one year of simulation (2019 – 2020)



It is observed that the inflow to the reservoir, that is, the surface and subsurface contribution of all catchments, remained close to the current scenario in the GBI scenario. Even with the doubling of the impervious area in the catchment, implementing GBI devices would decrease the surface runoff to a level similar to the current situation. In the last month of the simulation, an increase in runoff production is observed at the end of the rainy season. This is probably due to the saturation of GBI devices and the consequent reduction in their storage and infiltration capacity. In the Current scenario, the reservoir water level has reached the weir overflow level without overpassing it. In the GBI scenario, an increase in the water level above this threshold was observed, leading to the reservoir weir overflow. Therefore, the simulations of the PDM and the PDDI scenarios resulted in several reservoir weir overflow events. On the other hand, the GBI scenarios simulations for the same rainfall time series did not result in weir overflows mimicking the Current scenario simulation on this aspect.

A summary of all hydrologic impacts of LULC scenarios simulation is listed in Table 5.5.

Table 5.5 – Synthesis of hydrologic simulation of the observed rainfall between March 2019 and February 2020 in the different LULC scenarios

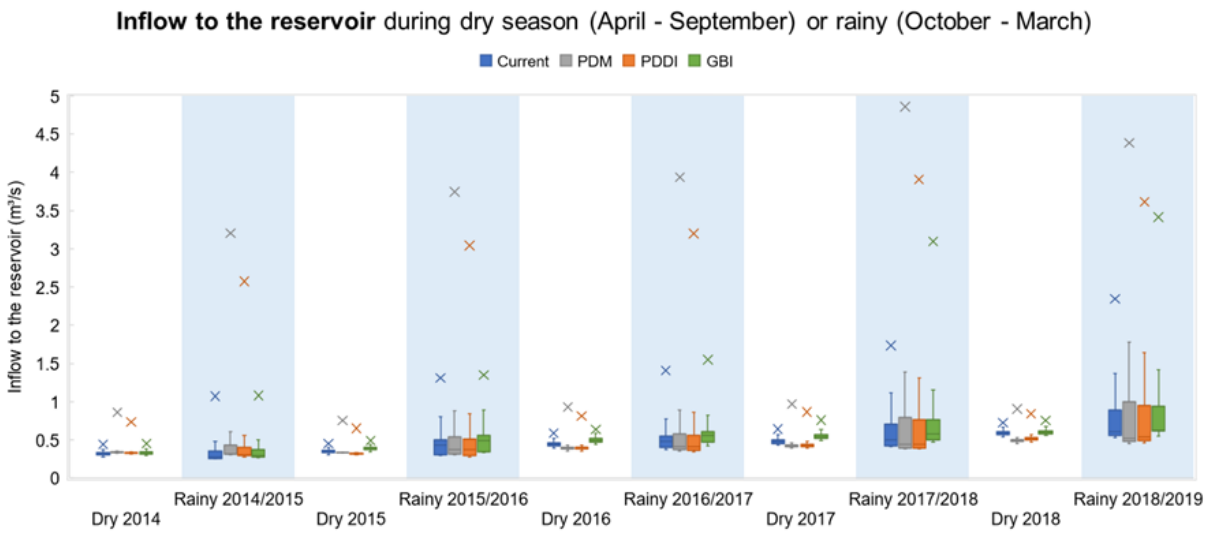
Parameter	Scenarios			
	Current	**PDDI**	**PDM**	**GBI**
Maximum reservoir inflow (m³/s)	65.10	180.51	255.10	75.25
Total inflow volume to the reservoir (hm³)	41.16	78.84	98.24	42.93
Maximum reservoir water level (m)	21.75	22.38	22.51	21.98
Maximum reservoir outflow (m³/s)	0.30	78.94	101.20	13.13
Total reservoir outflow volume (hm³)	9.75	47.01	65.69	11.09
Average annual infiltration in catchment (mm)	1148.5	834.0	672.4	1070.4
Average annual evaporation in catchment (mm)	557.7	355.6	247.4	484.6
Average lateral outflow from groundwater (mm)	143.9	133.6	132.3	146.5
Average water table level (m)	865.73	865.59	865.56	865.82

The GBI implementation would decrease the maximum and total inflow, respectively, by 71% and 56% compared to the PDM Scenario. So, the values would come close to the current scenario, less than 10% higher. However, differently from the current scenario, in the GBI scenario, at the end of the simulated 12-month period, the useful volume of the reservoir would be saturated, and the water level would exceed the overflow weir level (21.78 m). Even so, the maximum outflow would be 87% lower than in the PDM scenario.

Also, for the GBI scenario, the average annual infiltration would decrease only 7% in relation to the Current Scenario. The average lateral outflow from groundwater would increase by 2% in relation to the Current Scenario, while the water table would rise by 0.09 m. The average annual evaporation would decrease by 13% in relation to the Current Scenario.

All these changes in the hydrological cycle can decrease the catchment's water availability for water supply. Figure 5.7 presents the box plots of the inflows to the reservoir in the different scenarios during five hydrologic years (2014 to 2019), excluding the maximum flows (greater than 5.0 m³/s). This exclusion is justified only for evaluating the minimum flow rates since the impacts of the different scenarios on the maximum flow rates have already been presented above. The evaluation presented in Figure 5.7 is qualitative, so the choice of this limit is justified only for better visualisation of the results in the graph.

Figure 5.7 – Box Whisker graphs of the inflow to the reservoir during five hydrologic years (2014 to 2019), separated into dry season (April to September) and rainy season (October to March – highlighted with the blue background). The cross indicates the mean, the box represents the first and third quartiles, and the median divides the box into the interquartile range, the lines extending outside of the box show the outlier range

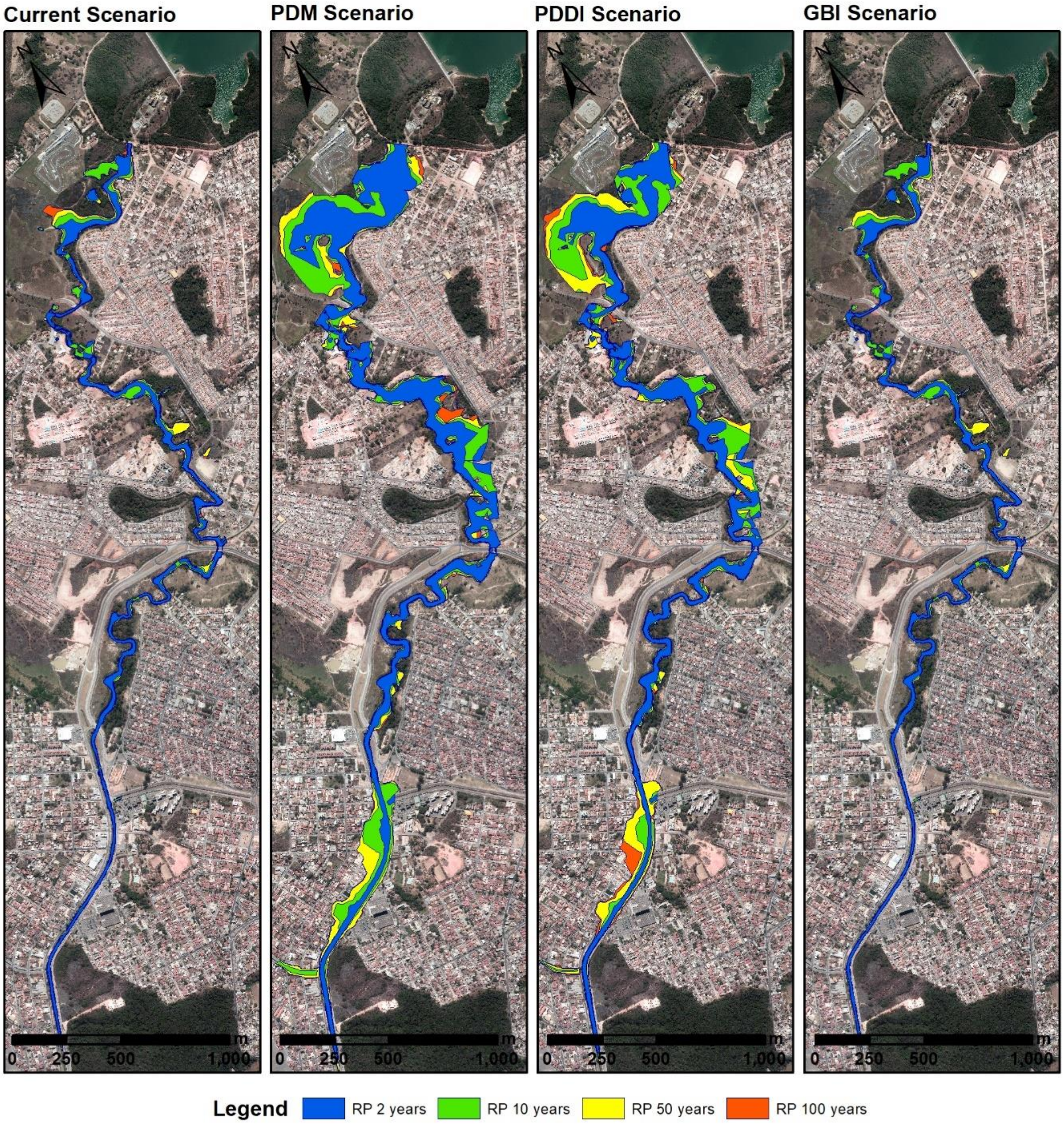


It can be seen from the diagrams that the mean flows follow the same pattern observed for the maximum flows; that is, the higher the imperviousness, the higher the mean and maximum flows. On the other hand, the boxes, i.e. the median flows and the first and third quartiles, vary inversely with the flood flows. Especially in the dry seasons, it is possible to notice that the scenarios of greater impervious rate (PDM and PDDI) decrease the median and minimum flows in relation to the current scenario. The GBI scenario, on the other hand, maintains or increases the average and minimum water levels, contributing to the maintenance of the volume stored in the reservoir during the dry season and guaranteeing greater security in the water supply during the most critical period.

5.5.4 Flood mapping of the different LULC scenarios

Maps of flooded areas downstream of the reservoir in different LULC scenarios simulating the design events with 2-, 10-, 50-, and 100-year return periods (RP) are presented in Figure 5.8. The total 24-hour duration rainfall for 2-, 10-, 50-, and 100-year return periods were, respectively, 96.3 mm, 146.7 mm, 190.9 mm, and 209.7mm.

Figure 5.8 – Flooded area downstream of the reservoir in the different LULC scenarios, simulation of rainfall project events of 2, 10, 50 and 100 years of return period (see part of the reservoir and its dam in the top-right corner of each map).



Source: aerial orthophotos from Fundação João Pinheiro (2013)

It is possible to observe the impact of future urbanisation in increasing the extent and frequency of flooding downstream of Vargem das Flores reservoir. PDM and PDDI scenarios produced similar flood maps, with impacts in the further downstream stretch, which corresponds to a key central area of the municipality, where an important regional hospital, residential and commercial areas and a main road with heavy traffic are located. It is possible to note that the GBI scenario would keep about the same flood risk as the Current scenario for the design rainfall events, even for the most intense and rare simulated event (RP 100 years). It should be noted that the Vargem das Flores reservoir was not conceived and cannot be operated for flood attenuation. Therefore, the reservoir reactions to land use changes in its contributing area depend on its initial state just before the rain event.

In order to evaluate more realistic conditions, sequential rainfall and saturation of infiltration and storage systems were simulated with the rainfall observed between March 2019 and February 2020.

For this simulation period, the Betim riverbed could drain the flows in the Current scenario, as there was no outflow beyond the ecological flow. In fact, from 2019 to 2020, no floods occurred due to the reservoir outflows. The municipality recorded some floods due to downstream tributary flow contributions. Even so, compared to PDM and PDDI scenarios, the flood in the GBI scenario would be much smaller, and the existing channels could transport the flows coming from the reservoir in the simulation period. One has to consider that the land use has considerably changed for those scenarios, and the conceived GBI for the area seems to be able to absorb the hydrological impacts of increased impervious area in the Vargem das Flores catchment.

A summary of flooded areas downstream of the reservoir in the different LULC scenarios is presented in Table 5.6.

Table 5.6 – Flooded area (in hectares) downstream of the reservoir in the different LULC scenarios for each rainfall event and return period (RP).

Rainfall event	**Flooded area for each event (ha)**			
	Current Scenario	**PDDI Scenario**	**PDM Scenario**	**GBI Scenario**
RP 2 years	9.99	24.68	31.88	9.90
RP 10 years	14.91	37.87	47.88	14.75
RP 50 years	18.11	48.85	56.73	17.96
RP 100 years	19.46	52.42	59.27	17.96
2019-2020	2.85	33.66	42.13	10.31

For the design events, the simulated flooded areas in PDDI and PDM scenarios PDDI were, respectively, 2.6 and 3.15 times greater than in the Current scenario. In the GBI scenario, the flooded area was reduced by 3% compared to the Current scenario and 69% to the PDM scenario. As weir overflows were observed for the March 2019-February 2020 simulation, the resulting flooded areas increased by 30.8 and 39.3 hectares, respectively, in PDDI and PDM Scenarios compared to the Current Scenario. For the same rainfall period, in the GBI scenario, the flooded area increased by 7.46 hectares compared to the Current scenario and decreased by 76% compared to the PDM scenario. In PDM and PDDI scenarios, the same rainfall registered between March 2019 and February 2020 would cause floods along the urban areas of the Betim municipality located downstream of the dam, including the flooding of an avenue leading to an important regional hospital. In the GBI scenario, this avenue would not be flooded, and the flooded areas would be predominantly rural or unoccupied.

5.6 Conclusions and future work

This paper presented the hydrologic impacts of urban expansion in a sensible catchment regarding water security located in a Brazilian metropolis. It concludes that urban expansion in the area can simultaneously increase the risk of flood occurrence and reduce minimum flows. Although considering the impacts on the whole water cycle in the area, the paper focuses more on flood risk and the possibility of adopting the GBI approach as a strategy to minimise those impacts. Furthermore, the paper concludes that deploying GBI would imply the protection of riparian areas and existing forest fragments and the implementation of source control devices for stormwater management in the catchment planned new developments. The areas intended for protection or treatment were identified by geoprocessing a database of classified aerial orthophotos and a Digital Terrain Model.

The capital and maintenance costs and the effectiveness in runoff peak flow reduction of eight GBI devices (bioretention cell, rain garden, green roof, infiltration trench, permeable pavement, rain barrel, rooftop disconnection, vegetative swale) were compared in order to select their optimal combination in the catchment. Results demonstrated that a combination of lot areas treated by rooftop disconnection and roads treated by vegetative swales achieved the lowest cost and one of the highest effectiveness in runoff reduction. Studies in subcatchment scale and catchment scale (Li et al., 2017) have arrived at results similar to those found here, vegetative swale has the best cost-effectiveness ratio, and green roof has the worst cost-effectiveness among the analysed GBI techniques.

This alternative scenario, the GBI scenario, would allow urban growth to double the existing urban area while restricting impacts on hydrological processes. However, by aiming to protect riparian areas and remanent forests, GBI would lead to developing a smaller area than that currently allowed by municipal legislation or even that suggested by metropolitan guidelines. Nevertheless, in the GBI scenario, the hydrologic response of the catchment would be remarkably similar to the current scenario, suggesting that adopting GBI principles to guide urbanisation can greatly mitigate the hydrological impacts of soil sealing in the catchment.

The results showed that if urbanisation takes place according to the parameters proposed by the legislation in force, the impacts downstream of the reservoir may be significant. The flooded areas would increase and reach important regions of the municipality located downstream of the dam. This brings a new aspect to the conflict between local and regional interests associated with urbanising or preserving this strategic catchment for the metropolitan region.

In addition to reducing the occurrence of flooding downstream of the reservoir, the GBI implementation can bring several other quantifiable benefits. It would certainly preserve or even improve the surface water quality, avoiding increased treatment costs. It may also reduce the volume of sediment transported to the reservoir, avoiding the reduction of its service life. Besides these water-related impacts, other environmental and social benefits related to the GBI adoption can be evaluated in future works. After its quantification and possible monetisation, the benefits can be compared to the total cost of GBI implementation and maintenance, contributing to the decision-making process.

Future works may deeply focus on the conflicts related to land use, local and regional interests in this sensible catchment and their implications for the drinking water system regarding water security in terms of water quality and quantity. In quantitative terms, a probabilistic approach taking into account the distribution of Vargem das Flores reservoir's initial states combined with rainfall variability and different land use scenarios seems to be a requirement for better water security evaluation. Another possibility is to explore multiple uses of the reservoir, including a retrofit of its outlet structures to allow their operation for flood alleviation purposes and other local demands, such as the reservoir being part of an eco-tourism program.

In more general terms, local and regional conflicts involving environmental issues and, particularly, land use policies in metropolitan regions can be explored through a more comprehensive assessment of GBI benefits provision, which includes not only hydrological and climate aspects (e.g., flood control, diffuse pollution abatement, reduction of heat island effect, etc.) and biological aspects (improving biodiversity, fauna mobility through green corridors) but also social and economic aspects (e.g., exploitation of eco-tourism, offer of green job opportunities, promotion and diffusion of the local culture, community involvement, etc. These multiple benefits offer opportunities for the conception of implementation of new regional policies based, for instance, on compensatory frameworks between the regional and the local scales to compensate for the direct and opportunity costs incurred by a more restrictive land use legislation.

5.7 *Appendix*

5.7.1 Computing areas that can be treated by LIDs

Table 5.7 presents the new areas that could be urbanised, protecting remnant forest patches and the riparian areas not urbanised, according to the municipal land use zoning. The urban controls (minimum lot size and minimum pervious rate) for each zone were presented in item 4.8.1 (Table 4.4).

Table 5.7 – Areas available for urban expansion per land class according to LULC legislation

Subcatchments	Area per land class (ha)						Total new development area (ha)
	ZEU-1	ZOR-3	ZUI-2	ZEUIA-1, ZEIT	ZUIA-I, ZUIA-II	ZUIA-III	
Aboboras	21.96	194.67	16.29	0	0	0	232.92
AguaSuja1	0	89.46	4.41	0	0	0	93.87
AguaSuja2	8.73	102.96	26.37	0	0	0	138.06
AguaSuja3	56.07	35.19	61.83	27	88.02	44.82	312.93
AguaSuja4	0	1.89	0	106.11	0	0	108
Batatal	0	0	0	79.38	0	0	79.38
BelaVista	0	329.4	13.23	128.88	0	0	471.51
Betim1-0	0	0	10.8	0	0	0	10.8
Betim1-1	0	0	13.5	0	0	0	13.5
Betim1-2	19.26	2.25	12.33	0	0	0	33.84
Betim1-3	0	0.36	29.07	0	0	0	29.43
Betim1-4	11.43	0	27.63	0	0	0	39.06
Betim2-0	19.26	0.81	38.16	0	0	0	58.23
Betim2-1	16.29	57.69	24.93	0	0	0	98.91
Betim3	0	201.6	13.5	2.52	0	0	217.62
CampoAle	0	246.69	0	0	0	0	246.69
DarcyRib	0	45.81	16.92	0.18	0	0	62.91
Direta	0	10.98	3.42	196.92	0	0	211.32
Lagoa	0.18	158.76	17.82	0	0	0	176.76
Laje	0	0	0	39.96	0	0	39.96
MorroRed1	0	131.31	0	0	0	0	131.31
MorroRed2	0	93.6	0	0	0	0	93.6
MorroRed3	0.72	78.12	10.8	0	0	0	89.64
MorroRed4	0	35.46	4.77	8.28	0	0	48.51
Olaria	0	0	6.75	9.09	0	0	15.84
Praia	14.04	25.74	54.99	0	0	0	94.77
Retiro	10.08	4.86	110.61	0	0	0	125.55
VargemdoSa	0	126.36	1.35	0	0	0	127.71
VilaEspe	0	9.99	42.93	0	0	0	52.92

Following the criteria defined by Federal Act No. 6,766/1979 (Brasil, 1979), which regulates urban land parcelling, 40% of the area to be developed must also be destined for public facilities (20% is destined for roads, 15% for green areas and 5% for institutional areas) (Silva, 2010). The remaining 60% are divided into lots, subdivided into impervious and pervious areas according to the pervious rate defined in the land use legislation. With the area covered by each zone and the respective urban controls, it was possible to calculate the SWMM input parameters per subcatchment (Table 5.8).

Table 5.8 – Computing new impervious areas that could be treated by GBI

Subcatchment	New impervious areas (ha)			% of Areas with Slope < 20%	New impervious areas that could be treated (ha)		Average lot size	Number of new lots
	Total	Public	Private		Public	Private	(m²)	
Aboboras	131.38	51.20	80.18	68.3%	34.96	54.75	1731	316
AguaSuja1	52.16	20.39	31.77	69.6%	14.20	22.11	1923	115
AguaSuja2	79.62	28.73	50.89	69.0%	19.82	35.09	1583	222
AguaSuja3	190.12	73.43	116.69	61.8%	45.41	72.16	2041	354
AguaSuja4	46.67	22.81	23.86	63.3%	14.44	15.11	9860	15
Batatal	43.53	19.58	23.94	55.7%	10.91	13.34	8655	15
BelaVista	245.45	106.05	139.41	70.3%	74.50	97.93	4141	237
Betim1-0	5.73	2.44	3.29	43.5%	1.06	1.43	360	40
Betim1-1	7.83	3.48	4.35	60.3%	2.10	2.62	360	73
Betim1-2	16.70	7.39	9.32	69.9%	5.16	6.51	469	139
Betim1-3	17.19	8.05	9.14	65.3%	5.26	5.97	380	157
Betim1-4	21.23	10.08	11.15	73.1%	7.37	8.16	360	227
Betim2-0	29.64	12.14	17.50	73.6%	8.93	12.88	383	337
Betim2-1	58.37	23.98	34.39	71.8%	17.22	24.69	1317	188
Betim3	121.01	47.15	73.86	70.0%	33.01	51.72	1991	260
CampoAle	135.68	50.64	85.04	63.3%	32.04	53.80	2000	269
DarcyRib	36.61	14.76	21.85	66.2%	9.76	14.46	1582	91
Direta	93.73	91.08	2.64	62.0%	56.51	1.64	9386	2
Lagoa	99.37	41.84	57.53	63.3%	26.46	36.39	1833	199
Laje	23.69	10.19	13.49	58.4%	5.95	7.88	8242	10
MorroRed1	72.22	26.58	45.64	68.6%	18.22	31.29	2000	156
MorroRed2	51.48	19.80	31.68	65.1%	12.90	20.63	2000	103
MorroRed3	50.64	19.40	31.24	64.7%	12.56	20.23	1789	113
MorroRed4	26.26	10.47	15.79	70.9%	7.42	11.19	3204	35
Olaria	8.43	3.74	4.69	66.5%	2.48	3.12	5892	5
Praia	57.52	23.10	34.42	66.3%	15.31	22.81	805	283
Retiro	82.93	29.86	53.07	65.7%	19.61	34.84	423	823
VargemdoSa	70.40	26.75	43.65	63.2%	16.90	27.58	1983	139
VilaEspe	34.26	12.20	22.06	66.4%	8.10	14.65	670	219

5.7.2 Cost composition for different LID devices

Table 5.9 – Capital and maintenance costs of each evaluated LID

Infiltration Trench (1 m)	**Treated area: 100 m²**			
Construction	**Quantity**	**Unit**	**Unit Cost**	**Total Cost**
Excavation	0.9	m³	R$ 4.66	R$ 4.19
Excavated material transportation	11.7	m³.km	R$ 1.31	R$ 15.33
Geomembrane	7.91	m²	R$ 5.48	R$ 43.37
Gravel	0.9	m³	R$ 88.26	R$ 79.43
Drain (150 mm)	1.7	m	R$ 8.04	R$ 13.67
				R$ 155.99
Maintenance				
Excavation surface layer	0.2	m³	R$ 41.46	R$ 8.29
Gravel	0.2	m³	R$ 88.26	R$ 17.65
				R$ 25.94

Rooftop Disconnection (m²)	**Treated area: 100 m²**			
Implementation	**Quantity**	**Unit**	**Unit Cost**	**Total Cost**
Tube	4	m	R$ 16.35	R$ 65.40
Energy-dissipation	0.2	m³	R$ 91.29	R$ 18.26
				R$ 83.66
Maintenance				
Cleaning	1	m²	R$ 4.60	R$ 4.60
				R$ 4.60

Permeable Pavement (1 m²)	**Treated area: 2 m²**			
Construction	**Quantity**	**Unit**	**Unit Cost**	**Total Cost**
Excavation	1.05	m³	R$ 4.66	R$ 4.89
Excavated material transportation	7.15	m³.km	R$ 1.31	R$ 9.37
Regularisation	1	m²	R$ 1.86	R$ 1.86
Geomembrane	2	m²	R$ 5.48	R$ 10.96
Gravel	0.4	m³	R$ 105.57	R$ 42.23
Drain (150 mm)	0.083	m	R$ 8.04	R$ 0.67
Compacted backfill	0.5	m³	R$ 3.52	R$ 1.76
Pavement in concrete block	1	m²	R$ 65.95	R$ 65.95
Sand	0.05	m³	R$ 89.66	R$ 4.48
				R$ 137.69
Maintenance				
Brushing	1	m²	R$ 41.46	R$ 41.46
Sand substitution	0.05	m³	R$ 89.66	R$ 4.48
				R$ 45.94

Conventional Pavement				
Construction	**Quantity**	**Unit**	**Unit Cost**	**Total Cost**
Excavation	0.5	m³	R$ 4.66	R$ 2.33
Excavated material transportation	6.5	m³.km	R$ 1.31	R$ 8.52
Regularisation	1	m²	R$ 1.86	R$ 1.86
Gravel	0.2	m³	R$ 113.46	R$ 22.69
Base	0.2	m³	R$ 109.79	R$ 21.96
Priming	1	m²	R$ 8.76	R$ 8.76
Painting	1	m²	R$ 1.74	R$ 1.74
Asphalt	1	m²	R$ 13.78	R$ 13.78
				R$ 81.64
Maintenance				
Painting	0.1	m²	R$ 1.74	R$ 0.17
Asphalt	0.1	m²	R$ 13.78	R$ 1.38
				R$ 1.55
Difference				
Implementation				**R$ 56.05**
Maintenance				**R$ 44.39**

Table 5.7 (cont.) – Capital and maintenance costs of each evaluated LID

Green Roof (1 m²)	**Treated area: 1 m²**			
Construction	**Quantity**	**Unit**	**Unit Cost**	**Total Cost**
Asphalt membrane	1	m²	R$ 42.00	R$ 42.00
Mechanical protection (mortar)	1	m²	R$ 39.24	R$ 39.24
Gravel	0.05	m³	R$ 88.26	R$ 4.41
Geomembrane	1	m²	R$ 5.48	R$ 5.48
Substrate	0.15	m³	R$ 85.71	R$ 12.86
Grass	1	m²	R$ 13.79	R$ 13.79
				R$ 117.78
Maintenance				
Mowing grass	4	m²	R$ 2.30	R$ 9.20
Replanting	0.5	m²	R$ 13.79	R$ 6.90
				R$ 16.10

Rain Barrel (1 m²)	**Treated area: 35 m²**			
Construction	**Quantity**	**Unit**	**Unit Cost**	**Total Cost**
Excavation	0.9	m³	R$ 4.66	R$ 4.19
Excavated material transportation	11.7	m³.km	R$ 1.31	R$ 15.33
Regularisation	1	m²	R$ 1.86	R$ 1.86
Floor slab	1	m²	R$ 43.68	R$ 43.68
Waterproofing	1	m²	R$ 14.02	R$ 14.02
Masonry	1.8	m²	R$ 48.26	R$ 86.87
Slab	1	m²	R$ 45.27	R$ 45.27
Tube	3.2	m	R$ 16.35	R$ 52.32
				R$ 263.54
Rain Barrel Maintenance				
Cleaning	1	m²	R$ 4.60	R$ 4.60
				R$ 4.60

Rain Garden (unit)	**Treated area: 50 m²**			
Construction	**Quantity**	**Unit**	**Unit Cost**	**Total Cost**
Tube	1	m	R$ 16.35	R$ 16.35
Energy-dissipation	0.2	m³	R$ 91.29	R$ 18.26
Excavation	0.62	m³	R$ 4.66	R$ 2.90
Excavated material transportation	8.08	m³.km	R$ 1.31	R$ 10.59
Substrate	0.62	m³	R$ 85.71	R$ 53.29
Grass	4.15	m²	R$ 13.79	R$ 57.16
Shrub	4.00	unit	R$ 2.00	R$ 8.00
Drain (150 mm)	2.04	m	R$ 8.04	R$ 16.37
				R$ 182.91
Maintenance				
Mowing grass	8.29	m²	R$ 2.30	R$ 19.07
Replanting	2.07	m²	R$ 13.79	R$ 28.58
				R$ 47.65

Bio-Retention Cell (unit)	**Treated area: 100 m²**			
Construction	**Quantity**	**Unit**	**Unit Cost**	**Total Cost**
Energy-dissipation	0.2	m³	R$ 91.29	R$ 18.26
Excavation	4.23	m³	R$ 4.66	R$ 19.73
Excavated material transportation	55.04	m³.km	R$ 1.31	R$ 72.10
Substrate	1.92	m³	R$ 85.71	R$ 164.95
Grass	3.85	m²	R$ 13.79	R$ 53.08
Shrub	3.85	unit	R$ 2.00	R$ 7.70
Gravel	1.54	m³	R$ 88.26	R$ 135.88
Geomembrane	7.70	m²	R$ 5.48	R$ 42.18
Drain (150 mm)	5	m	R$ 8.04	R$ 40.20
				R$ 554.09
Maintenance				
Mowing grass	11.55	m²	R$ 2.30	R$ 26.56
Replanting	1.92	m²	R$ 13.79	R$ 26.54
				R$ 53.10

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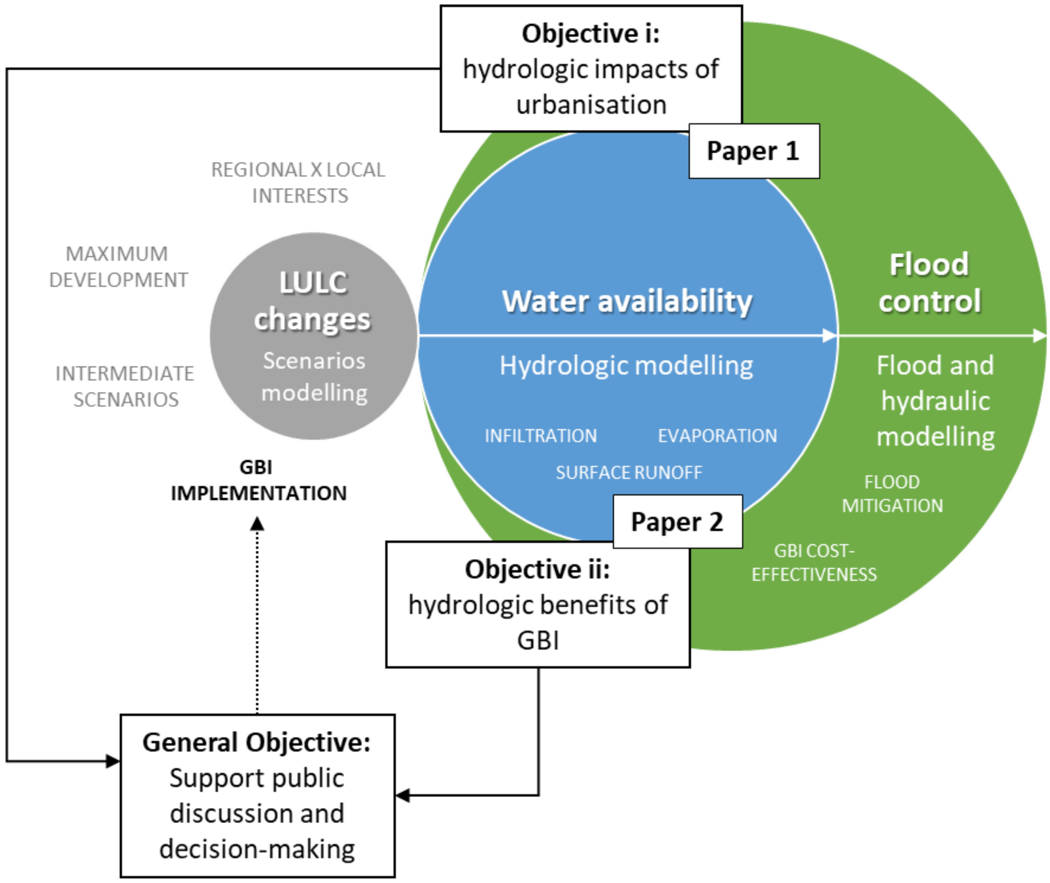
5.9 Summary

This paper expanded the contribution to the objectives outlined in the thesis by evaluating the potential hydrological benefits of implementing Green and Blue Infrastructure in future urban development (Figure 5.9). In this alternative scenario, besides protecting the existing forest fragments, non-consolidated riparian areas would be revegetated, and new urban areas could develop in grassland and pasture areas. Still, all those newly developed areas would be treated with compensatory techniques to reduce the hydrological impact of impermeabilisation.

Figure 5.9 – Summary diagram of the developed research and objectives – Paper 2



The cost-effectiveness of the alternative GBI techniques was assessed to find the optimal combination of techniques for peak flow and runoff volume reduction. In this sense, the reduced costs with conventional drainage infrastructure provided by the proposed alternative could also be considered a GBI benefit. This economic analysis provides valuable information that can support decision-making by the urban planners for GBI deployment in new urban areas in the catchment. Future work may detail the economic study of GBI implementation, considering gradual implementation over time and bringing all costs back to 'Present Worth'.

Lastly, the hydrologic simulations and flood mapping results presented in this paper contribute directly to the thesis's objective of evaluating the hydrological and water quality impacts of LULC changes associated with urban development and assessing the benefits of GBI implementation in the case study catchment. By simulating different LULC scenarios, including the GBI scenario, the study offers insights into the potential of GBI to mitigate flood risks and reduce the impacts of urban expansion on the water cycle. The paper's conclusion that GBI principles can significantly mitigate the hydrological impacts of soil sealing while maintaining water security aligns with the overarching hypothesis of the thesis, supporting the argument for adopting GBI in urban planning for multiple benefits beyond stormwater management. The following research step is to evaluate the GBI benefits to water quality protection by reducing the diffuse pollution loaded into the reservoir. This benefit is critical for the studied catchment, as the reservoir is a water source historically threatened by the input of sediments and organic matter.

6 ARTICLE 3: Water quality impacts of Land Use and Land Cover changes in a Brazilian Metropolis: Analysis of past changes and modelling water quality

"Em Minas Gerais, nossa luta é pra ressignificar o nosso estado.
Minas não é só de minério, nós lutamos pelas minas d'água
que brotam em cada cidade."

"In Minas Gerais, our fight is to redefine our state.
Minas [mines] are not just ore, we fight for the water mines [water sources]
that spring up in every city."

Adriana Souza, teacher and environmental activist,
leader of the movement 'SOS Vargem das Flores', in Contagem, Brazil

This paper presents the evolution of the efforts on quantifying the ecosystem services of GBI in the Vargem das Flores catchment, now considering the impacts of land use and cover in water quality regulation. The studied area is a representative example of the developing world reality, where the emergent demand to control the diffuse pollution coexists with the emergency to solve the persistent lack of sanitation and basic urban infrastructure. In this stage, the research outputs allowed the assessment of the threats of eutrophication and silting processes to the reservoir's functionality.

Following the efforts to circumvent the limitations of data availability and scarcity of resources, the methodology was adapted to adjust the model results to past trends in monitoring data. Multiple public databases were consulted to trace back the wastewater contributions and the past land use and land cover changes in the subcatchments. Water quality monitoring data provided by the sanitation company Copasa, the water quality module was inserted and adjusted in the previous calibrated SWMM model. In this sense, the intention of using publicly available and open-source databases and models was maintained.

The manuscript presented in this chapter refers to the "preprint" of the article submitted to the "Journal of Cleaner Production", under review until the publication of this thesis.

6.1 Contributions to co-authored publications

The undersigned authors agree that the nature and extent of the contributions to the work *“Water quality impacts of Land Use and Land Cover changes in a Brazilian Metropolis: Analysis of past changes and modelling water quality”* was as follows (Table 6.1).

Table 6.1 - Contributions of co-authors - Paper 3

Co-author	Nature of contribution	Extent of contribution (%)	Signature	Date
Deyvid Wavel Barreto Rosa	Study design, data acquisition, treatment and interpretation, modelling, drafted manuscript	75		05/12/2022
Camilla Vivian Porto Satler Hot	Data treatment, modelling, drafted manuscript	5		09/12/2022
Isadora Teixeira Gomes	Data treatment, modelling, drafted manuscript	5		07/12/2022
Diogo Ferreira Ventura	Data treatment, modelling, drafted manuscript	5		09/12/2022
Talita Fernanda das Graças Silva	Study design, reviewed manuscript	2.5		06/12/2022
Joanne Chong	Study design, reviewed manuscript	2.5		08/12/2023
Damien Giurco	Study design, reviewed manuscript	2.5		12/12/2022
Nilo de Oliveira Nascimento	Study design, reviewed manuscript	2.5		12/12/2022

6.2 Abstract

This paper aims to present the calibration process of a water quality model and its application to assess the water quality impacts of land use and land cover changes between 2001 and 2019, in the catchment of a reservoir (Vargem das Flores) that supplies water for around 600.000 inhabitants in a Brazilian metropolis (Belo Horizonte Metropolitan Region, Minas Gerais). The wastewater pollution was estimated using demographic and sanitation cover data. Water quality monitoring data were analysed and compared to observed land use and land cover changes to estimate the contribution of diffuse pollution. These data were used to calibrate a water quality model developed in the Storm Water Management Model (SWMM). Results indicated a greater impact of diffuse pollution than point-source pollution during the studied period (2001- 2019) in the reservoir's water quality degradation, especially regarding total suspended solids load yielded by the most urbanised subcatchments. Future urban development can cause even more water quality degradation, and the increase of sediment load can further shorten the lifetime of the reservoir.

Keywords: water supply reservoir; diffuse pollution; water quality modelling; SWMM.

6.3 Introduction

Non-point source pollution (NPSP) is the current main threat to water quality in the Global North through the contribution of sediments and nutrients from either agricultural or urban areas (OECD Environment Directorate, 2017). In the Global South, however, sanitation is a persistent issue, so water sources are doubly threatened by the impacts of land use changes and the growth of urban populations (Silva et al., 2022). Urban development changes the hydrological cycle and the balance of sediments in the catchment, while processes of deforestation and earthmoving expose the soil to erosion, making sediments available to be transported by stormwater to waterways. This sediment transportation deteriorates water quality and causes silting of watercourses (Carvalho, 2008). The removal of riparian vegetation makes watercourses even more vulnerable to the impacts of Land Use and Land Cover (LULC) changes in their water quality. In addition to suspended solids, rainwater also carries pollutants present in the atmosphere and on catchment surfaces to watercourses, mostly affecting their nutrients and heavy metals concentration (Miserendino et al., 2011; Silva et al., 2019).

Sediment deposition in reservoirs is a major issue because it leads to silting and consequent reduction in the reservoir's service life. Nutrient and pollutant inputs – in addition to degrading water quality, restricting some uses and increasing treatment costs – can also lead to eutrophication, further aggravating the reservoir condition (Chang & Yu, 2020; Silva et al., 2019). The United States Environmental Protection Agency (US-EPA) declares the NPSP as "one of America's most widespread, costly and challenging environmental problems" (US Environmental Protection Agency, 2019), and the consequent economic damages related to eutrophication of American freshwaters exceeds US$ 2.2 billion annually (Dodds et al., 2009).

Statistical models have been largely applied to assess the spatial and temporal relations between LULC and water quality in contexts and scales with limited observation data (Liu et al., 2015; Maillard & Pinheiro Santos, 2008; Mei et al., 2014; Mello et al., 2018; Miserendino et al., 2011; Wan et al., 2014). Those approaches usually achieve good results and provide useful tools for qualitatively examining trends and impacts of LULC changes in the water quality but are limited in the quantitative estimations of volumes, loads and the forecast capacity, especially at more detailed scales (Ding et al., 2016).

Process-based hydrologic and diffuse pollution models are useful options for this application and can support land management and planning decisions but demand a large amount of data for calibration and validation (Wan et al., 2014). SWMM, an open-source, process-based hydrological and hydraulic model largely applied for rainfall-runoff modelling and stormwater quality modelling (Niazi et al., 2017), has been recently updated by US-EPA in its version 5.2 to represent better the water quality processes (Rossman & Simon, 2022). Older SWMM versions were applied in many water quality modelling studies; see Liu et al. (2017) for a summary. It has also been used, coupled with reservoir models, in simulations of the impacts of stormwater runoff on the water quality of reservoirs, especially on nutrient loads and eutrophication (Chang & Yu, 2020; Silva et al., 2019).

This work aligns with this context, aiming to evaluate the impacts of past land use and land cover changes on the water quality of a peri-urban catchment and discuss possible impacts of future land use changes on the reservoir water quality and siltation. The contributions of this work are on the proposition of a method for calibrating a continuous water quality model using low-frequency but long-term monitoring data, associating observed variations on LULC and population growth to better represent the changes on point and non-point pollutant loads during the simulated period. The adjusted model will be used to estimate the future impacts related to expected LULC changes and test the SWMM functionality in simulating improvements in water quality associated with LID devices implementation (Chapter 7).

From the beginning of this research, authors have kept permanent contact with the sanitation company and the municipal agencies in charge of land use and water planning and management, as well as civil society organisations for exchanges on research approaches and results. The authors acknowledge the contributions received to the research approach and results assessment and hope to contribute to the land use planning process in the studied area.

6.3.1 Case study

Belo Horizonte, the capital of Minas Gerais State, is the centre of a metropolitan region home to about six million people, making it the third biggest metropolis in Brazil. Vargem das Flores reservoir is part of the metropolitan integrated drinking water system and supplies about 10% of the urban population demand, providing a flow between 0.7 m^3/s and 1.2 m^3/s. Its catchment covers 120.25 km^2 and is situated towards the edge of the main urban area, between the region's second and third most populous municipalities (87% of the catchment area in Contagem and 13% in Betim).

Vargem das Flores reservoir was implemented in 1972, with the main purpose of supplying water to part of the Belo Horizonte Metropolitan Region (BHMR), and is currently operated by the state sanitation company Copasa. The reservoir extends over 515.18 hectares at an elevation of 837.7 m a.m.s.l., with a storage volume of 29.0 million m^3 and a perimeter of 38.2 km (Santos, 2012). From 1972 to 2009, the reservoir lost 25.6% of its volume at elevation 837.0 m due to siltation. Between the last two bathymetric surveys (2000 and 2009), the reservoir lost 4 million m^3, indicating an annual volume loss of about 450,000 m^3 or 1.5% of the original volume. Assuming the same annual volume loss rate observed between 2000 and 2009, the end of the reservoir's useful life would be in 2066. Although the main purpose of the reservoir is to provide water for human supply (Figure 6.1 - A), it is also used for recreation and leisure (Figure 6.1 - B).

Figure 6.1 – Pictures taken in the catchment, illustrating the multiple uses and the dispute for the preservation of the water resources

A - Water intake in Vargem das Flores reservoir (Campos, 2020)

B - Recreation and leisure in the Vargem das Flores reservoir (PDDI-BHMR, 2016)

C - Água Suja stream polluted waters (author’s collection)

D - Degraded watercourses with sewage and solid waste in the region of Nova Contagem (PDDI BHMR, 2016)

E - Construction of sewage network in the region of Nova Contagem (Contagem, 2010b)

F - Demonstration for the protection of Vargem das Flores held on the banks of the reservoir, with the presence of the SOS Vargem das Flores movement (Sindieletro, 2019)

The reservoir represents an important landscape element in incrementing property values, with several regular and irregular subdivisions of different social strata.

Irregular subdivisions are identified by the Municipality of Contagem as the main sources of point pollution and sediment in the catchment (Contagem, 2013). One of the main tributaries of the reservoir, the Água Suja stream (translated as “Dirty Water stream”), still receives irregular discharge of sewage and solid waste (Figure 6.1 - C and D), despite the recent construction of the sewer network (Figure 6.1 - E) and wastewater treatment plant.

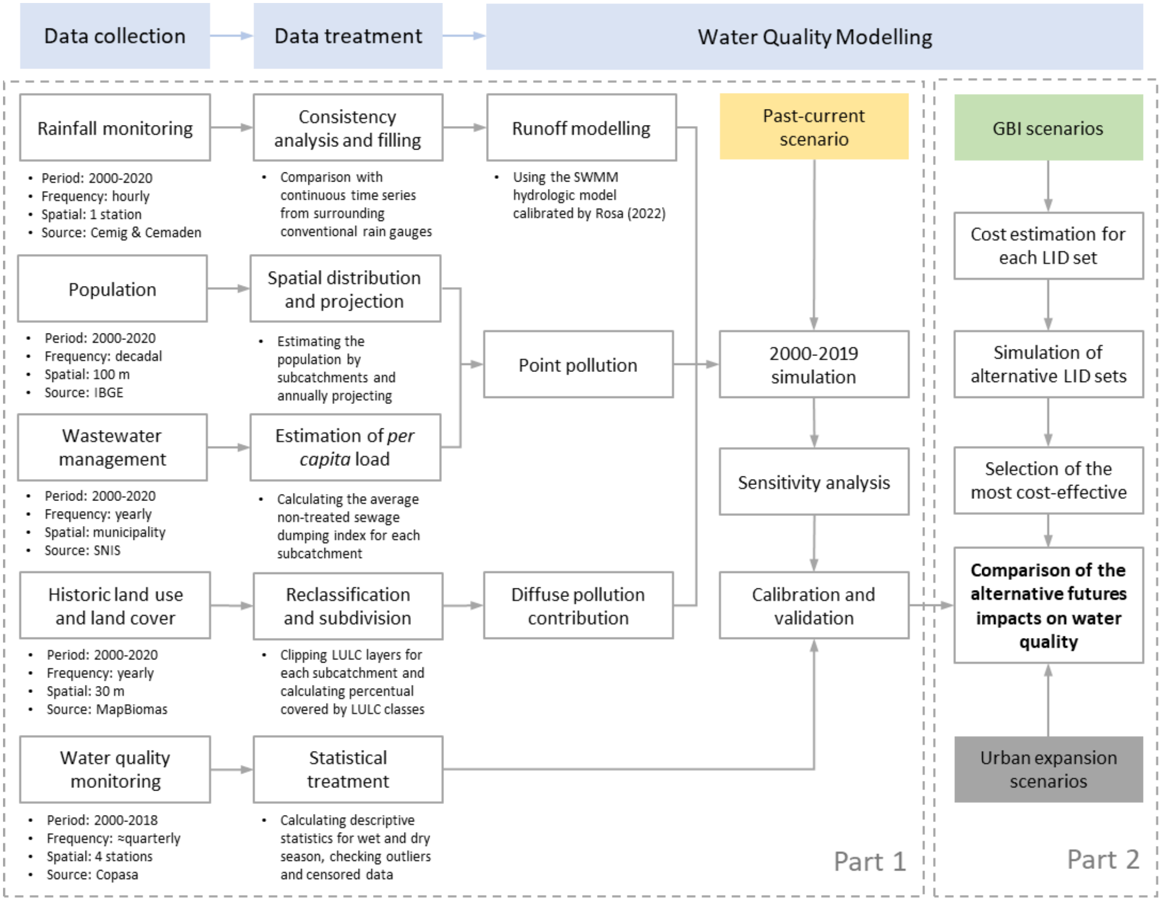
Notwithstanding the metropolitan interest in protecting the catchment, due to its strategic importance for water security, the municipality of Contagem (2018) approved a municipal master plan in 2018, easing restrictions for the catchment occupation. This recent change in land use legislation produced intense political debates and protests arranged by civil society organisations (Figure 6.1 - F), as this urbanisation can decrease the reservoir lifetime due to silting, and accelerate the water quality degradation, increasing treatment costs. Considering this background, the discussion about the future of Vargem das Flores reservoir and its catchment urban development is up to date, so environmental studies are needed to support public decision-making.

6.4 Methods

The methods applied in this study are synthesised in the diagram in Figure 6.2. This paper focuses on the description of methods and results of “Part 1”, from Data collection to calibration and validation of the water quality model.

The Storm Water Management Model version 5.2 (Rossman & Simon, 2022) was used for the water quality simulation. The water quality module was added to the hydrologic model calibrated and validated by Rosa, Silva, Araújo, et al. (2022), using hourly rainfall data from 2014 to 2019, and daily water level and outflow from the reservoir provided by Copasa. The simulation fitted very well with the monitored water levels of the reservoir, with the Nash-Sutcliffe coefficient varying from 0.80 to 0.87, and the determination coefficient from 0.88 to 0.79. Thus, one of the premises of the current study is that the model developed by Rosa, Silva, Araújo, et al. (2022) satisfactorily represents the catchment water balance.

Figure 6.2 – Diagram of methodological steps – Part 1 Water Quality



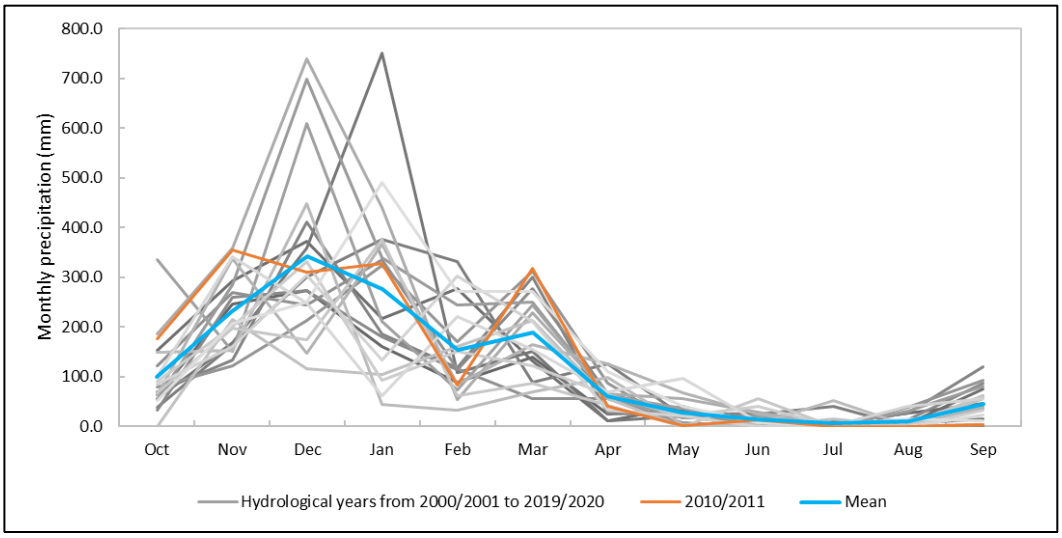
In order to perform the water quality modelling, the simulation period was extended to cover 20 hydrological years, from October 2000 to September 2020. The hourly rainfall time series obtained with the automated rain gauges operated by the Brazilian Centre of Monitoring and Natural Disaster Warning (Cemaden) was completed using data from the rain gauges listed in Table 6.2, operated by the Minas Gerais State Electricity Utility (Cemig) and the National Institute of Meteorology (Inmet). Accumulated hourly data from the rain gauges were compared to the daily accumulated series of the surrounding conventional rain gauges, and the data gaps were filled with data from the nearest rain gauges with available data.

Figure 6.3 presents the monthly precipitation for the entire time series, highlighting the mean monthly values and the 2010/2011 monthly precipitation, which was the hydrological year used to simulate the alternative scenarios. This year was chosen because it had a monthly rainfall distribution similar to the 20-year average and is the year for which population data of each subcatchment is available.

Table 6.2 – Hourly and daily rainfall data used to complete the time series from 2000 to 2020

Operation	Rain Gauge	Geographical coordinates		Data period		Frequency of available data	
		Latitude	Longitude	Start	End	Hourly	Daily
Cemig	Usina de Gás	-19.9	-44.0	2000	2008	x	
Inmet	Belo Horizonte	-19.933	-43.85	2000	2013		x
	Contagem	-19.9	-44.1	2002	2008	x	
	Florestal	-19.867	-44.417	2009	2013	x	x
	Ibirité	-20.017	-44.05	2009	2013	x	x
	Pampulha	-19.85	-43.95	2009	2013	x	x
Cemaden	Centro Contagem	-19.907	-44.08	2014	2020	x	
	Retiro Contagem	-19.837	-44.148	2014	2020	x	

Figure 6.3 – Monthly precipitation from 2000/2001 to 2019/2020, highlighting the monthly mean (blue) and the hydrological year 2010/2011 (orange) used for annual comparisons



6.4.1 Land use and land cover scenarios for diffuse pollution estimation

Land use and land cover data with 30 meters of spatial resolution was obtained from MapBiomas Project Collection 7 (Souza et al., 2020), which makes available free and accessible Landsat satellite images classified through automatic processes throughout the Brazilian territory from 1985 to 2021. The MapBiomas rasters were reclassified to seven LULC classes (Forested, Savannah, Pasture, Agriculture, Urban, Non-vegetated, and Water), for which buildup and washoff factors recommended by the literature were associated. The exponential function was selected to model buildup and washoff processes, and the initial values for equation coefficients are presented in Table 6.3. More details about the SWMM representation of the buildup and washoff processes are presented in the Appendix (item 6.8.1).

Table 6.3 – Buildup and washoff coefficients (C1 and C3) and exponents (C2 and C4)

	Parameter	TSS	COD	TP	Ammonia-N
Buildup	**C1** (kg/ha)	3.632 - Forest 39.123 - Urban 11.322 - Bare soil	6.289 - Forest 75.443 - Urban 30.603 - Bare soil	0.001 - Forest 0.168 - Urban 1.121 - Bare soil	0.062 - Forest 1.345 - Urban 1.009 - Bare soil
	C2 (1/day)	0.288	0.325	0.551	0.228
Washoff	**C3**	2.671	2.439	3.663	15.139
	C4	1.462	0.701	0.288	0.719

Sources: Chen and Adams (2007); Costa (2013); Heineman et al. (2013); Taghizadeh et al. (2021); Zakizadeh et al. (2022).

Using the LULC, rainfall and wastewater contribution data for 2001-2019, the past and current water quality conditions were assessed. The past (2001) and current (2019) scenarios were compared to future alternative scenarios, where no change in the sewage load is considered despite the expected population growth in the catchment. The adopted premise is that new occupations would be provided with an adequate sewer network and treatment facilities. In this sense, the comparison of future scenarios is focused only on the effects of LULC changes on the diffuse pollution load. For the prospective scenario, the maximum urban development would follow the guidelines of the current municipal master plans (PDM). As presented by Rosa, Silva, Araújo, et al. (2022), the average imperviousness would be 47.5% in the PDM scenario.

The dry and rainy seasons are well demarcated in the region: of the 1,453 millimetres of average annual rainfall observed between 2000 and 2020, 1289 mm fell in the six rainy months (October to March) and only 164 mm in the dry season (April to September). The effects of this concentrated distribution of rain on the water quality are well known, especially in catchments where there is urban occupation and point-source pollution contributions. In this sense, concentrations of organic pollution indicators are higher in the dry season and decrease in the rainy season due to the effect of dilution with the increase in stream flow rates. Therefore, the strategy used to adjust the model was first to calibrate the parameters that influence point pollution in the dry season (concentration of pollutants in dry weather sanitary flows - DWF and direct inflow) and, after obtaining the best possible adjustment in the dry season, adjust the model to represent the pollutant concentrations and loads in the rainy season (the C1 and C2 coefficients of buildup process, the C1 and C2 coefficients of washoff). In summary, the calibration of the dry season was focused on the representation of point-source pollution, while the calibration of the rainy season was focused on the non-point source pollution.

6.4.2 Estimating wastewater pollution

Besides the diffuse pollution, the illegal discharge of raw wastewater in the catchment watercourses increases the contribution of organic matter and nutrients to the reservoir. The pollutant load varied expressively during the studied period due to population growth and the implementation of sanitation works for the interception, transposition and treatment of sewage produced in the catchment. Population data from the national Census of 1990, 2000 and 2010 (IBGE, 2000, 2010; Práxis, 1997) were adjusted to arithmetic, geometric, decreasing growth rate and logistical growth projections to estimate its annual variation (Sperling, 2007). The geometric growth rate presented the best estimate of the catchment population in 2010. Furthermore, this method is used by the Brazilian Institute of Geography and Statistics (IBGE) to perform demographic projections in Brazil. Thus, the geometric growth model was applied to estimate the population for each subcatchment annually, considering the same population density of the 2010 census data and the mapped land use and cover classes.

The National Sanitation Information System (SNIS) provided yearly data about the per capita water consumption and the sewage collection and treatment rate for the municipalities of Betim and Contagem (SNIS, 2022). Per capita water consumption was converted into returning wastewater flow by applying a return factor of 0.8, and the sewage collection and treatment rates were applied to calculate the annual per capita untreated discharged wastewater for each subcatchment. These values were multiplied by the annual estimated population and inserted in the model as direct discharge in each subcatchment. The total volume of untreated sewage annually discharged in the Vargem das Flores catchment is presented in Table 6.4.

Table 6.4 – Estimation of wastewater discharged in Vargem das Flores catchment from 2000 to 2019

Year	Estimated population (inhabitants)	Per capita water consumption (L/inhab.day)	Non-treated wastewater discharged in watercourses %	Per capita untreated discharged wastewater (L/inhab.day)	Total flow of discharged wastewater (L/s)
2000	109,852	148.88	98.80%	117.67	149.61
2001	120,061	150.23	98.77%	118.70	164.95
2002	131,220	151.58	99.87%	121.10	183.92
2003	143,415	145.82	99.85%	116.48	193.34
2004	156,744	138.96	99.82%	110.97	201.31
2005	171,311	138.06	99.83%	110.27	218.63
2006	187,233	137.37	77.38%	85.04	184.28
2007	204,634	137.16	76.09%	83.49	197.75
2008	223,652	134.23	66.34%	71.24	184.41
2009	244,438	129.67	59.73%	61.97	175.31
2010	267,156	137.72	53.15%	58.56	181.06
2011	291,985	146.14	51.19%	59.85	202.26
2012	319,122	149.52	41.98%	50.22	185.48
2013	348,780	149.95	40.80%	48.94	197.57
2014	381,195	142.55	37.77%	43.07	190.02
2015	416,623	129.61	34.65%	35.93	173.24
2016	455,343	138.10	35.40%	39.11	206.10
2017	497,662	137.07	32.15%	35.26	203.07
2018	543,914	135.09	28.02%	30.28	190.64
2019	594,465	138.48	27.32%	30.26	208.21

In order to consider the daily and hourly variations of the wastewater flow, the typical hourly (Table 6.5) and daily (Table 6.6) variation factors suggested by Rossman and Simon (2022) were applied so that a 20-year hourly time series of wastewater flow generated on each subcatchment was obtained.

Table 6.5 – Hourly variation of wastewater flow according to Metcalf et al. (1991)

Hour	Flow variation	Hour	Flow variation	Hour	Flow variation	Hour	Flow variation
0	0.97	6	0.39	12	1.39	18	1.07
1	0.78	7	0.65	13	1.33	19	1.13
2	0.58	8	0.97	14	1.23	20	1.26
3	0.45	9	1.36	15	1.16	21	1.29
4	0.36	10	1.39	16	1.07	22	1.26
5	0.32	11	1.42	17	1.04	23	1.13

Table 6.6 – Daily variation of wastewater flow according to Rossman and Simon (2022)

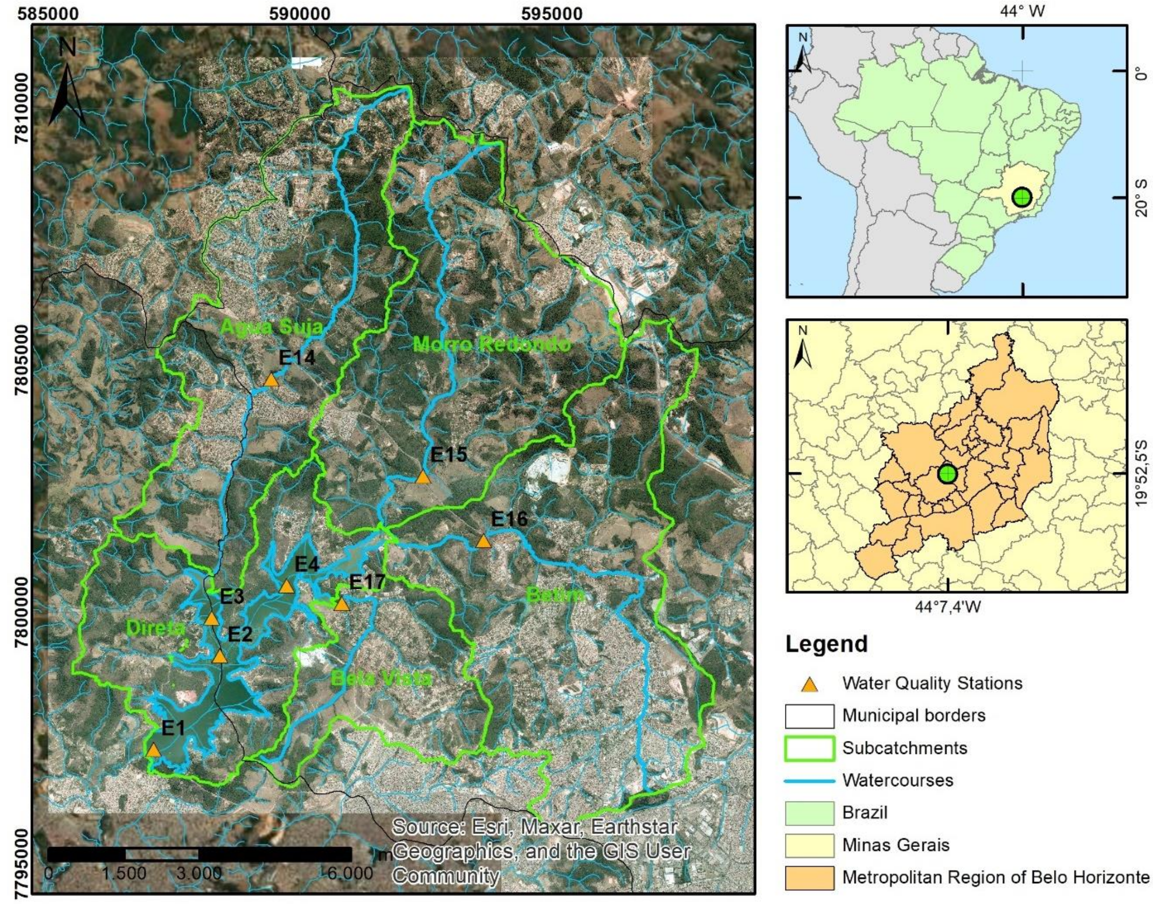
Weekday	Average variation
Monday	0.968
Tuesday	1.021
Wednesday	1.081
Thursday	1.009
Friday	0.932
Saturday	1.007
Sunday	0.981

6.4.3 Adjustment of the water quality model

The sanitation company Copasa provided water quality monitoring data that was prepared and used to assess and improve the model results. The minimum censored data were substituted by half of its detention limit value, and extreme maximum values were evaluated as outliers but maintained as valid data if physically possible to be observed in extreme weather conditions. Copasa has maintained, since 1974, a long-term monitoring program in the catchment for the main water quality parameters. Water samples are collected with approximately quarterly frequency in eight sites in the catchment area (see Figure 6.4), four inside the reservoir, and four in the main tributaries: Água Suja (E14), Morro Redondo (E15), Betim (E16), and Bela Vista (E17).

Statistical analysis was initially performed to identify trends and variations that could be related to seasonal rainfall patterns and, therefore, to the effects of diffuse pollution or wastewater dilution. The analysis concerned the parameters Chlorophyll a, Electrical Conductivity, Biochemical Oxygen Demand (BOD), Chemical Oxygen Demand (COD), Total Phosphorus (TP), Nitrate, Ammoniacal Nitrogen, Total Nitrogen, Oils and Greases, Total Suspended Solids (TSS), and Total Solids. The central tendency measures were calculated by separating the data corresponding to the dry (April to September) and the rainy season (October to March), and the hypothesis of significant difference between the medians was tested applying the Wilcoxon-Mann-Whitney *U*-test, following the recommendations of Sperling et al. (2020). If the hypothesis tests resulted in significant differences between the dry and rainy median values, the parameters were selected for simulation in the hydrological model.

Figure 6.4 – Location of monitoring sites and subcatchments



Before starting the model calibration, a sensitivity analysis was conducted for TSS by varying water quality input parameters. TSS was the pollutant most strongly impacted by surface runoff, and the sensitivity tests were performed for the TSS concentrations at Station E16, the station with the largest catchment area. The sensitivity was performed by simulating one typical hydrological year (2010/2011) and evaluating the TSS mean concentrations and variation, represented by the standard deviation. Since the water quality sampling in the studied watercourses followed an approximately quarterly frequency during the study period (2001-2019), the model calibration sought to achieve the best approximation between the central descriptive statistics and variability of simulated and monitored values. The calibration was considered satisfactory when the model results represented the same significant variability related to diffuse pollution and dilution processes.

6.5 *Results*

6.5.1 Land use and land cover scenarios

Expansion of urban areas was observed in all subcatchments from 2001 to 2019. As illustrated in the map of Figure 6.5 and the graphs of Figure 6.6, urban development was greater in Betim, Bela Vista and Água Suja subcatchments.

Figure 6.5 – LULC changes in the subcatchments of Vargem das Flores from 2001 to 2019

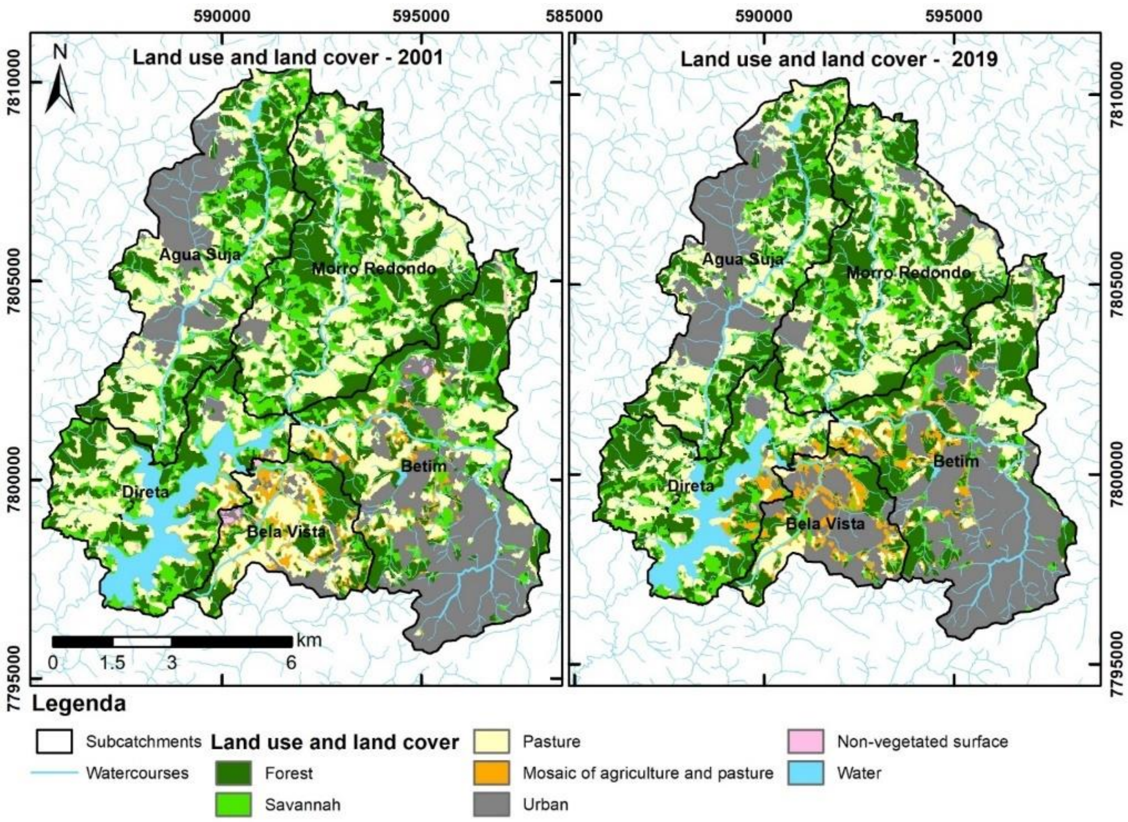
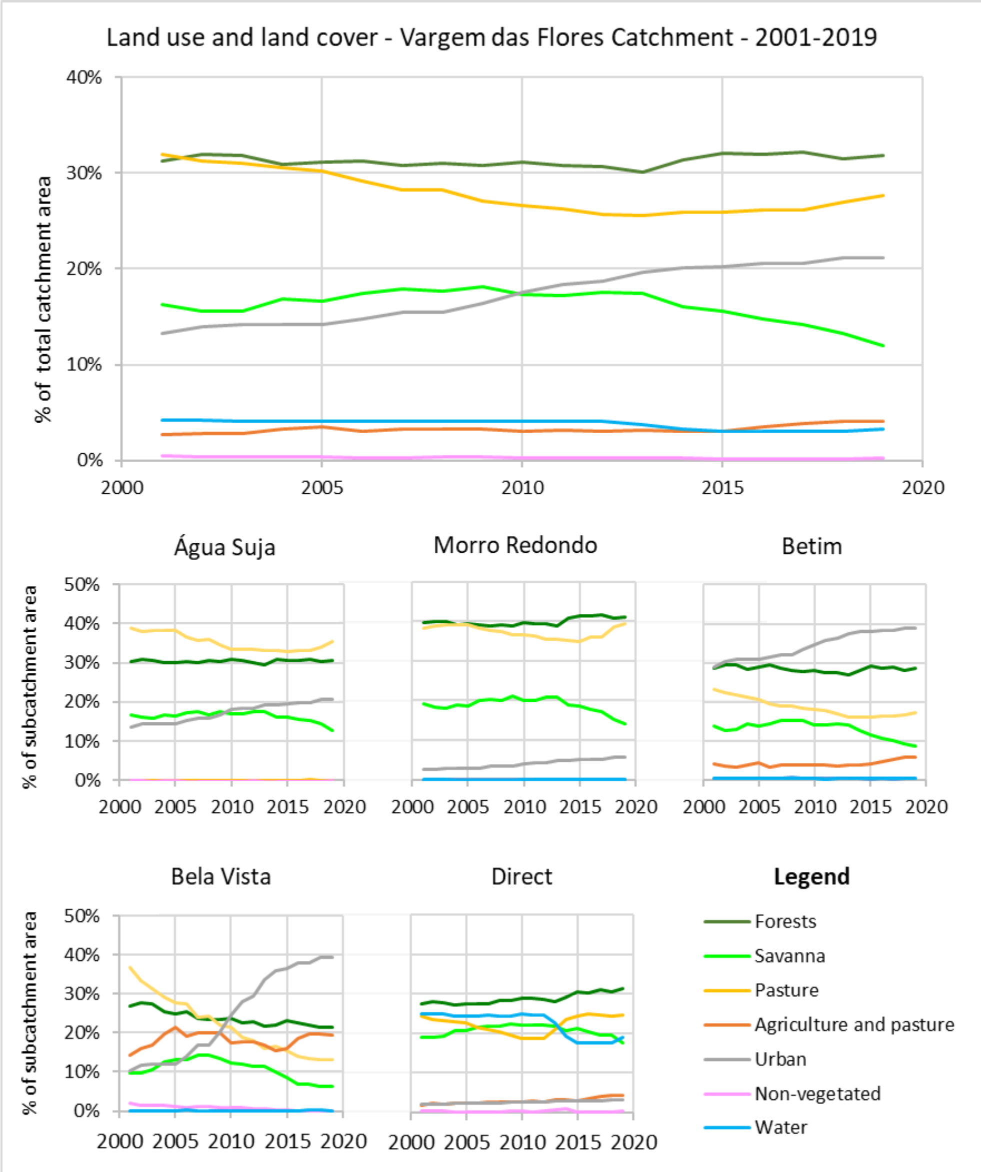


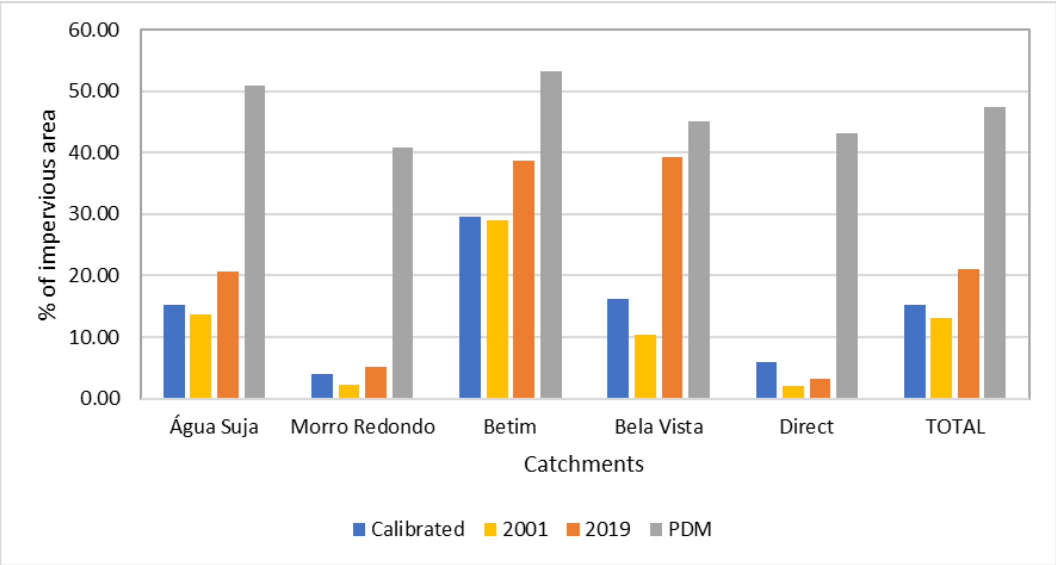
Figure 6.6 – Annual LULC changes in the catchment of Vargem das Flores reservoir and its main subcatchments from 2001 to 2019



In general, urban development occurred predominantly in formerly pasture or savannah areas. Except for the Bela Vista subcatchment, the forest fragments were not substantially affected by past LULC changes, and even a small increase in forested areas was observed in the direct contribution catchment. It is noteworthy that during the process of urban expansion, the vegetation cover is removed, and the soil is exposed so that there are signs of use transition occurring at the edges of the expanding urban sprawl in Bela Vista and Betim subcatchments, indicated by the class "Mosaic of agriculture and pasture".

Figure 6.7 compares the percentage of impervious areas in each main subcatchment and the catchment of Vargem das Flores reservoir in the different LULC scenarios, including the percentages for 2001 and 2019. For the entire catchment, the impervious area increased from 13.2% to 21.0% from 2001 to 2019, compared to 15.2% obtained in the hydrological calibrated model (with 2013 LULC classification, as presented in Chapter 4) and 47.5% in the PDM scenario.

Figure 6.7 – Percentage of impervious area in the catchment of Vargem das Flores reservoir and its main subcatchments in the different LULC scenarios



6.5.2 Water quality monitoring data

During the 18 years of water quality monitoring data obtained with Copasa (2001 to 2018), 104 samples were collected and analysed during the rainy season (October to March), and 174 during the dry season. The box-whisker graphs for Biochemical Oxygen Demand (BOD), Total Suspended Solids (TSS), Total Phosphorus (TP) and Ammonia Nitrogen (Ammonia-N) concentrations are presented in Figure 6.8, comparing the results between seasons, subcatchments and water quality standards established by the Minas Gerais State legislation (State Environmental Policy Council – COPAM and State Water Resources Council – CERH Normative Deliberation n. 01/2008). Table 6.7 presents the percentage of violations registered for each station and season, considering BOD, TP, Ammonia-N, and TSS.

Figure 6.8 – COD, TSS, TP, AN concentration Box Whisker graphs for the four main tributaries of Vargem das Flores reservoir during the dry and rainy seasons from 2001 to 2018

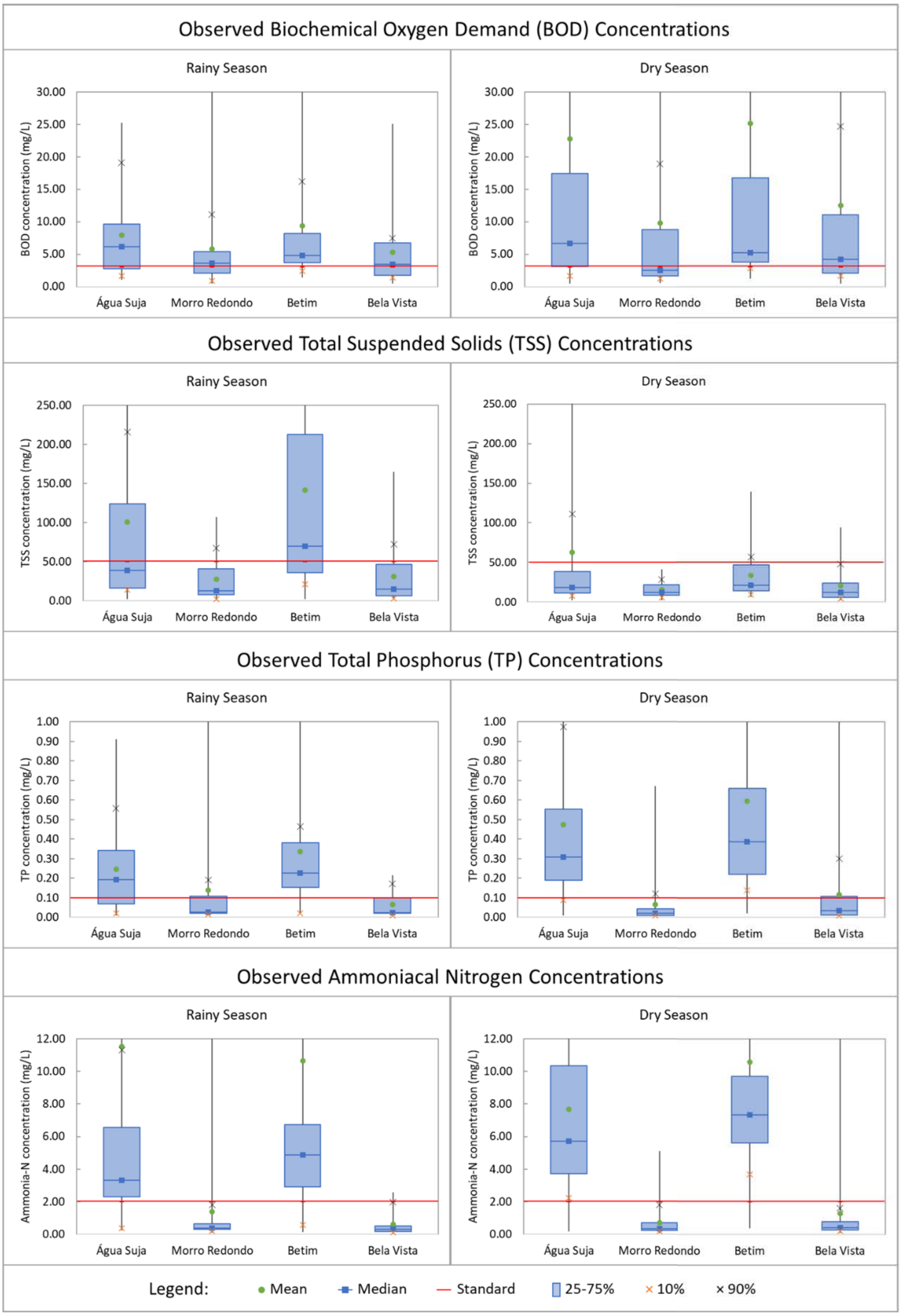


Table 6.7 – Percentage of water quality standards violations between 2001 and 2019

Station	Season	% of standards' violation			
		Biochemical Oxygen Demand (3 mg/L O)	**Total Phosphorus** (0,1 mg/L P)	**Ammoniacal Nitrogen** (2 mg/L N)	**Total Suspend Solids** (50mg/L)
E14 - Água Suja	Dry	75.0%	89.5%	97.5%	20.0%
	Rainy	68.2%	65.0%	78.3%	47.8%
E15 - Morro Redondo	Dry	42.6%	17.8%	10.6%	0.0%
	Rainy	62.1%	26.9%	6.9%	17.2%
E16 - Betim	Dry	86.0%	93.9%	98.0%	17.6%
	Rainy	82.8%	76.9%	86.2%	55.2%
E17 - Bela Vista	Dry	61.1%	26.5%	8.3%	11.1%
	Rainy	56.5%	25.0%	13.0%	26.1%

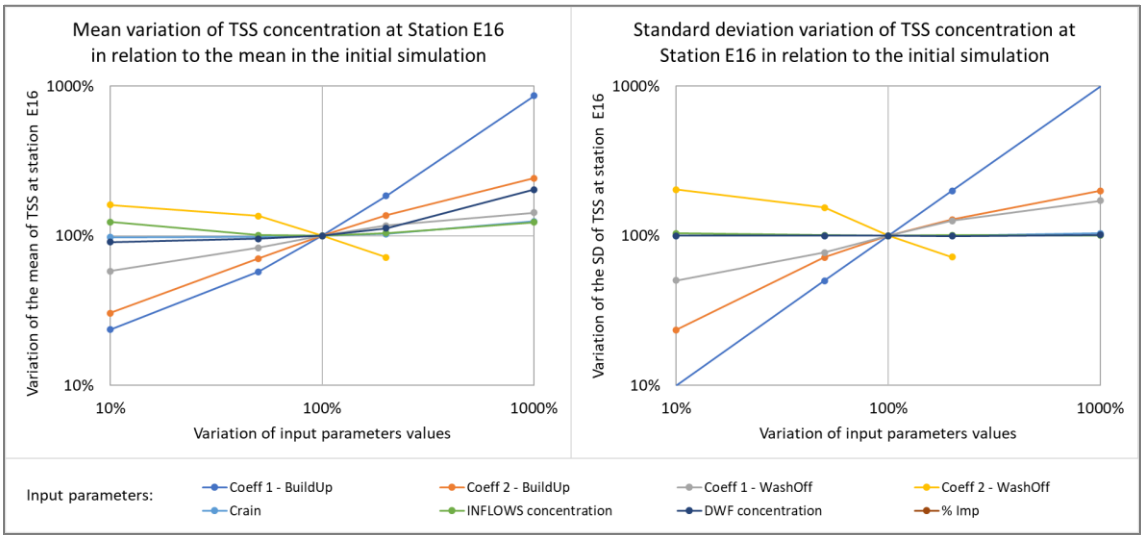
The subcatchment with the lowest urban land cover (Morro Redondo Stream – E15) mostly presented lower violation rates than the other catchments. In this catchment, water quality parameters presented higher concentrations more frequently during the rainy season, considering BOD, phosphorus and TSS. This indicates the importance of diffuse pollution carried by runoff over the natural land cover. In the other catchments, especially the most urbanised Betim (E16) and Água Suja (E14), greater pollutant concentrations were observed during the dry season, likely because lower natural flows were available to dilute the discharged sewage load. On the other hand, higher TSS concentrations were observed in these catchments during the rainy period, indicating the relevance of non-point sources for suspended solids transported to the watercourses.

Wilcoxon-Mann-Whitney *U*-test showed a statistically significant difference between rainy and dry season median concentrations of TSS in stations E14, E15 and E16, for nitrogen and phosphorus in stations E14 and E16, confirming the analyses of the Box Whisker graphs and the compared percentages of water quality standards violation. For the Bela Vista Stream station (E17), the differences were not significant, which is probably related to the greater changes observed in the LULC (Figure 6.6) over the study period. The first samples were collected when the catchment had more natural characteristics, similar to the Morro Redondo subcatchment, and the last samples were collected in a much more urbanised and altered catchment. These interpretations can be better verified considering the stream flows, allowing the comparison between pollutant loads, besides their concentrations. As there is no fluviometric monitoring in the study area, the hydrological modelling developed by Rosa, Silva, Araújo, et al. (2022) can be useful to bring some insights.

6.5.3 Water quality model calibration

Before starting the model calibration, a sensitivity analysis was conducted for TSS concentrations at Station E16 in order to identify the most influent parameters in the water quality module results. As shown in Figure 6.9, the sensitivity was evaluated in terms of the mean concentrations and their variation, represented by the standard deviation, for the hydrological year of 2010-2011. The parameters that most influenced the TSS mean values and their variability were the C1 and C2 coefficients of buildup process, the C1 and C2 coefficients of washoff, and the concentration in dry weather sanitary flows (DWF). Considering that these parameters were the most influential in the representation of diffuse pollution in the model, they were changed during the calibration process to adjust the model to monitored values. The other parameters, concentration in rainwater (Crain), concentration in infiltration and inflow (INFLOWS), and percent of impervious area (%Imp), were not changed from the initial estimated values.

Figure 6.9 – Sensitivity analysis of water quality module input parameters variation in TSS mean and standard deviation at Station E16



The Box-Whisker diagrams in Figure 6.10 and Figure 6.11 compare the observed TSS and COD concentrations (graphs in the left column) with the simulated concentrations before (graphs in the centre column) and after (graphs in the right column) calibration. It is important to bear in mind that the frequency and size of the sample dataset being compared are quite different: while the "simulated" graphs represent a 19-year time series of continuous (hourly) concentration data, the "observed" graphs represent a set of a few dozen concentrations measured at an approximately quarterly frequency over the same period. Therefore, the adjustment of concentration extreme values was expected to be limited, especially for the maximum concentrations that naturally occur after intense precipitation events. Those maximum values are not visible in almost all graphs representing simulated concentrations, as the vertical axis scale was adjusted to better visualisation of the boxes representing more frequent values. In this sense, during the trial-and-error calibration process, the adjustment of central tendency values was prioritised, especially the median, the first and third quartiles (25th and 75th percentiles). The representation of the calibration results in permanence curves presented in the Appendix (item 6.8.2) can help to visualise the model adjustment.

Figure 6.10 – Box-Whisker diagrams of TSS concentrations observed (left), simulated before (middle) and after (right) calibration, for dry (up) and rainy (down) seasons

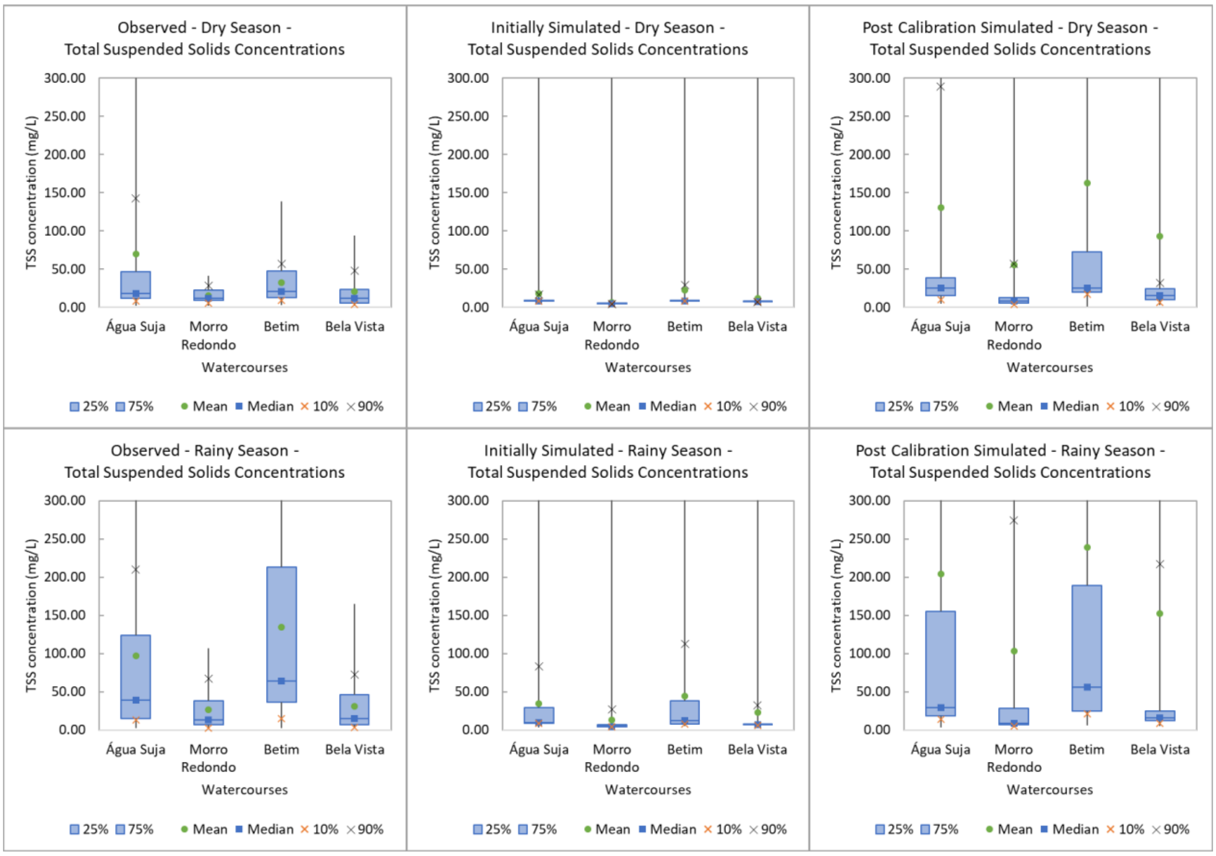
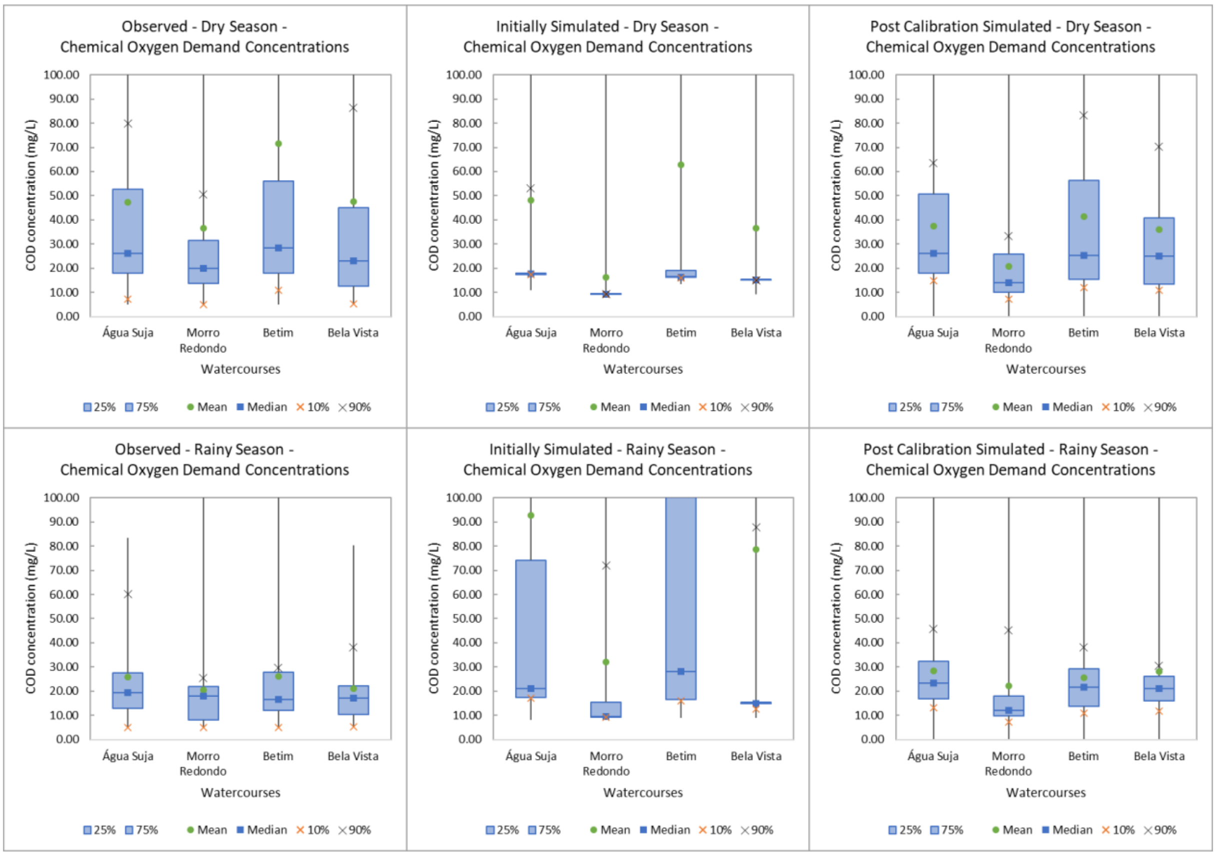


Figure 6.11 – Box-Whisker diagrams of COD concentrations observed (left), simulated before (middle) and after (right) calibration, for dry (up) and rainy (down) season



Comparing the observed concentrations with the simulation results obtained with the initial values of input parameters, it is evident that pollutant concentration variability related to the point pollution dilution by increased stream flows and diffuse pollution was not well-represented. Because the median concentrations were also underestimated in the dry season, it can be inferred that either the sewage load or the baseflow were underestimated, especially in the more urbanised subcatchments (Água Suja and Betim).

After several attempts of adjustments focused on the dry season concentrations, the following parameters were changed to allow a better representation of observed data variability and concentration: the sewage (DWF) concentrations were increased from 210 to 250 mg/L for TSS, from 430 to 475 mg/L to COD, and from 25 mg/L to 50 mg/L Ammoniacal Nitrogen. The hourly and daily variation coefficients of sewage flow presented in Table 6.5 and Table 6.6 were applied during this process after realising that more variation was still needed to represent the concentrations in the dry season.

These procedures made it possible to stretch the boxes in Figure 6.10 and Figure 6.11; that is, they increased the distance between the first and third quartiles and the median. For TSS, however, it also increased the mean, the 90th percentile and the maximum values (outside the chart scale).

In sequence, the washoff and buildup parameters were changed to fit the concentrations during the rainy season. As indicated in the observed data, the variation and central tendency values of TSS concentrations were greater during the rainy season, so the TSS maximum buildup mass was increased for urban, pasture and agriculture land uses, from 39 kg/ha, 3.6 kg/ha and 3.6 kg/ha, to 200 kg/ha, 100 kg/ha and 10 kg/ha, respectively. The coefficient 3 of the washoff load equation was increased for the urban land use, from 2.7 to 5.4 (dimensionless).

The COD adjustment followed a different aim, as the non-point source pollution was less important, and the dilution phenomena needed to be represented. So, to reduce the COD diffuse contribution, the respective maximum buildup mass for forest, pasture and urban areas was reduced from 6.3 kg/ha, 6.3 kg/ha and 75.4 kg/ha to 2.5 kg/ha, 4 kg/ha and 4 kg/ha.

The calibration process ended when no further improvement could be obtained and changes in parameter values generated a trade-off conflict between the best representation of dilution phenomena and non-point source pollution representation (graphs indicated in the right column of Figures 6.10 and 6.11). Considering that the simulation reached an acceptable representation of the order of magnitude and the balance between point and non-point source pollution, the alternative land use scenarios were simulated.

6.5.4 Simulating the impact of LULC changes on water quality

The analysis presented in this section is focused on the impacts of the past (scenarios 2001 and 2019), calibrated and projected LULC changes (PDM scenario) in the TSS, COD, TP and Ammonia-N annual washoff total loads and annual washoff loads per unit area for each subcatchment (Table 6.8). Alternatively, the Appendix (item 6.8.3) presents the simulation results of the different LULC scenarios in Box-Whisker concentration graphs.

Table 6.8 – Washoff pollutant annual total loads (ton/year) and annual load per unit area (kg/yr/ha) in the main subcatchments and the four studied LULC scenarios

Pollutant	Index	Subcatchments	Água Suja	Morro Redondo	Betim	Bela Vista	Direct	Total
		Area (ha) / Scenarios	2,730	2,853	3,358	1,077	2,025	12,042
TSS	Annual load (ton/yr)	Calibrated	4,683	2,342	1,690	7,778	1,308	17,801
		Past 2001	4,208	1,501	1,521	7,622	752	15,604
		Past 2019	4,452	2,120	1,691	7,869	915	17,047
		PDM	9,313	7,855	3,218	11,692	5,291	37,369
	Annual load per unit area (kg/yr/ha)	Calibrated	1,716	821	503	7,223	646	1,478
		Past 2001	1,542	526	453	7,079	372	1,296
		Past 2019	1,631	743	504	7,308	452	1,416
		PDM	3,412	2,753	958	10,859	2,613	3,103
COD	Annual load (ton/yr)	Calibrated	278.4	242.4	366.5	121.0	136.3	1,144.7
		Past 2001	236.0	171.7	363.9	119.7	95.9	987.3
		Past 2019	255.2	213.3	376.7	138.3	104.3	1,087.8
		PDM	325.7	326.0	403.2	130.8	191.9	1,377.6
	Annual load per unit area (kg/yr/ha)	Calibrated	102.0	85.0	109.2	112.4	67.3	95.1
		Past 2001	86.5	60.2	108.4	111.2	47.4	82.0
		Past 2019	93.5	74.7	112.2	128.5	51.5	90.3
		PDM	119.3	114.3	120.1	121.5	94.8	114.4
TP	Annual load (ton/yr)	Calibrated	2.20	1.53	4.91	1.11	1.14	10.90
		Past 2001	2.12	1.40	4.97	1.59	0.95	11.03
		Past 2019	2.24	1.44	5.19	1.93	0.96	11.77
		PDM	4.92	4.30	7.04	1.94	3.13	21.33
	Annual load per unit area (kg/yr/ha)	Calibrated	0.81	0.54	1.46	1.03	0.56	0.91
		Past 2001	0.78	0.49	1.48	1.48	0.47	0.92
		Past 2019	0.82	0.50	1.55	1.79	0.48	0.98
		PDM	1.80	1.51	2.10	1.80	1.55	1.77
Ammonia Nitrogen	Annual load (ton/yr)	Calibrated	1.73	2.32	1.99	0.63	1.44	8.10
		Past 2001	1.34	1.90	2.07	0.70	0.97	6.98
		Past 2019	1.57	2.04	2.05	0.83	0.97	7.47
		PDM	1.34	1.99	1.55	0.48	1.04	6.39
	Annual load per unit area (kg/yr/ha)	Calibrated	0.63	0.81	0.59	0.58	0.71	0.67
		Past 2001	0.49	0.67	0.61	0.65	0.48	0.58
		Past 2019	0.58	0.72	0.61	0.77	0.48	0.62
		PDM	0.49	0.70	0.46	0.44	0.51	0.53

The total annual TSS load inflow to the reservoir varied from 15,604 ton/yr in 2001 to 17,047 ton/yr in 2019, which indicates an increase of 9%. In the PDM scenario, the total annual TSS load would increase to 37,369 ton/yr, or 2.2 times the load in 2019. Part of these solids is inorganic matter, such as sediments transported by erosion, that can settle out at the bottom of the reservoir and contribute to its silting and loss of useful volume. Extrapolating the same increase rate of TSS load (+120%) to the annual silting (450,000 m³/yr) registered between 2000 and 2009 by Santos (2012), the total siltation of the reservoir useful volume could be advanced from 2066 to 2042.

Although this great increment in TSS load is an important warning sign for land management, future studies are needed in order to simulate the catchment's soil loss and the silting process in the tributaries and the reservoir, to assess better the impacts of LULC changes in the life of the reservoir.

Besides the concern with solids and sediments, Total Phosphorus is also highly impacted by LULC changes. The annual TP load into the reservoir could increase by 81%, from 11.77 ton/yr in 2019 to 21.33 ton/yr in the PDM scenario. Along with another parameter not assessed in this work (chlorophyll A), TP is an indicator of the eutrophic status of the water bodies. Preliminary analyses of the water quality monitoring data from the stations inside the reservoir indicated the predominance of mesotrophic and eutrophic conditions (Ventura, 2021). The increase in the TP load affluent to the reservoir can intensify the eutrophication process, seriously threatening the current uses of its water, with possible occurrences of a cyanobacterial boom, release of toxins and reduction of dissolved oxygen concentration.

In terms of the spatial distribution of total washoff pollutant load, the main contributor is Betim Stream for TSS (44%), COD (32%), and TP (45%), while Morro Redondo is the main contributor for Ammonia-Nitrogen (29%). As the Betim Stream subcatchment corresponds to 28% of the total catchment area, the disproportional contribution of TSS and TP can be explained by the LULC: in the Calibrated scenario, 29.5% of the catchment is impervious. The Ammoniacal Nitrogen contribution is relatively homogeneous in all Vargem das Flores main subcatchments, as shown by the similar magnitude of annual loads. This indicates that there is no great difference between the washoff Ammonia-N contribution according to different LULC in the catchment. COD follows a similar pattern.

Except for Ammonia-N, whose spatial distribution of loads indicates that rural areas are the main sources of diffuse pollution, the future urban development would homogenise the contribution per unit area in almost all subcatchments. The protection of the immediate surroundings of the reservoir, according to the PDM, would not be sufficient to protect its waters from the degradation caused by the development of upstream areas. Almost all the organic washoff loads would be transported by the streams into the reservoir, as the distances are short, and the modelling results indicated little importance of the stream auto-depuration phenomena along the watercourses to reduce the load that effectively reaches the reservoir.

6.6 Discussion and conclusion

This study evaluated the impact of land use and land cover changes in the water quality of tributaries of a reservoir that supplies water for around 600,000 people in a Brazilian metropolis. The catchment area of 120.4 km² is under intense pressure for urban development, so the impervious area has grown from 15.8 km² to 25.3 km² between 2001 and 2019, and the land use legislation allows the development of an additional 31.9 km². The impacts of LULC changes are evident and should be recognised by public managers and the population mobilised to protect this water source.

The construction of interceptor networks, transposition and sewage treatment in the existing urban areas was important to slow down the degradation of the reservoir's water quality resulting from the catchment's population growth. Those interventions slowed down the eutrophication process observed in the reservoir in the early 2000s, but the results presented in this study show that LULC changes can increase the total phosphorus input load from non-point source pollution by up to 81%, accelerating the reservoir's eutrophication process again.

The water quality parameter with the clearest influence of diffuse pollution is the TSS, whose total annual load can more than double if the development allowed by the legislation takes place without mitigating measures. This increase in solids input can accelerate the underway-silting process of the reservoir, which in 2009 had already lost a quarter of its useful volume.

The studied area is a representative example of the developing world reality, where the emergent demand to control the diffuse pollution coexists with the emergency to solve the persistent lack of sanitation and basic urban infrastructure. Furthermore, this study achieved its intended contributions by addressing a common limit to the development of similar research in the context of developing countries. The methodology for calibrating the water quality model was adapted to circumvent the limited availability of high-frequency monitoring data. In the end, the model performance in representing the diffuse pollution and diffuse processes in the catchment was satisfactory despite the limitations of the available data.

Finally, if diffuse pollution represents one of the greatest threats to water availability in developed countries, this is an even more pressing issue in developing countries. Future urban development can contribute even more to the current process of water quality degradation, and adopting measures to reduce runoff and sediment transportation is indispensable to preserve the existing water sources and improve water security in times of climate change. Future studies can assess the potential of adopting Green and Blue Infrastructure to mitigate the impacts of further urban development on the catchment's water quality.

6.7 Acknowledgements

The authors would like to thank the research funding agencies, Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq), Fundação de Amparo à Pesquisa de Minas Gerais (FAPEMIG) and Coordenação de Aperfeiçoamento de Pessoal de Nível Superior – Brasil (CAPES) for their financial support, the Brazilian Centre of Monitoring and Natural Disaster Warning (Cemaden), Minas Gerais Sanitation Company COPASA, Fundação João Pinheiro, Contagem's and Betim's City Halls, for the provision of essential data for the development of this research. The project is linked to the project MoMa, financed by Capes (Ministry of Education) and ANA (Brazilian Water Agency), Grant number: 88887.15881/2015-01 and ANA 2776/2015. Nilo de Oliveira Nascimento is financed by CNPq-Pq Grant number 312458/2017-7.

6.8 Appendix

6.8.1 SWMM representation of buildup and washoff

As presented in item 6.4.1, the exponential functions were selected to describe the pollutant buildup and washoff in SWMM (Rossman & Huber, 2016a). Equation 1 presents the pollutant buildup over time:

$$b = C_1(1 - e^{-C_2 t}) \qquad \text{(Eq. 1)}$$

Where b is the buildup [kg/ha], C_1 is the maximum buildup possible [kg/ha], C_2 is the buildup rate constant [days^{-1}], and t is the buildup time interval (days). The exponential curve approaches the maximum buildup asymptotically. The mass of buildup is calculated by the product of b, the fraction of the subcatchment covered by the land use, and the total area of the subcatchment.

Equation 2 presents the exponential function of pollutant washoff:

$$w = C_3 q^{C_4} B \qquad \text{(Eq. 2)}$$

Where w is the rate of washoff [mg/hr], C_3 is the washoff coefficient [$(mm/hr)^{C_4} hr^{-1}$], C_4 is the washoff exponent [dimensionless], q is the runoff rate over the subcatchment [mm/hr], and B is the remaining buildup [mg]. That is, the load of pollutant washoff is proportional to the surface runoff powered by a washoff exponent and the remaining pollutant buildup (Rossman & Huber, 2016a).

6.8.2 Permanence curves and the water quality model calibration

The calibration results can also be represented by permanence curves, where it is possible to not the effects of the adjustment to approximate simulated to observed TSS concentrations (Figure 6.12) and COD concentrations (Figure 6.13), where the black dots (post calibration) are closer to the red circles (observed) than the blue dots (initially simulated).

Figure 6.12 – Permanence curves of TSS concentrations observed, simulated before and after calibration in each station

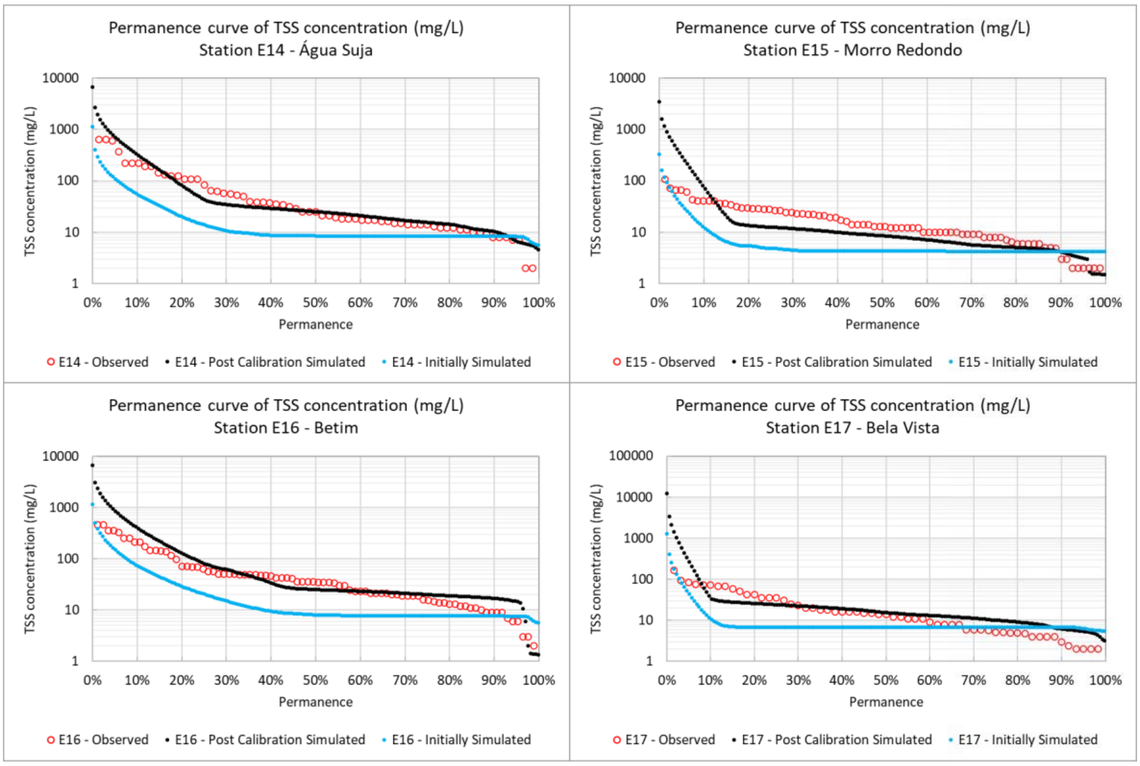
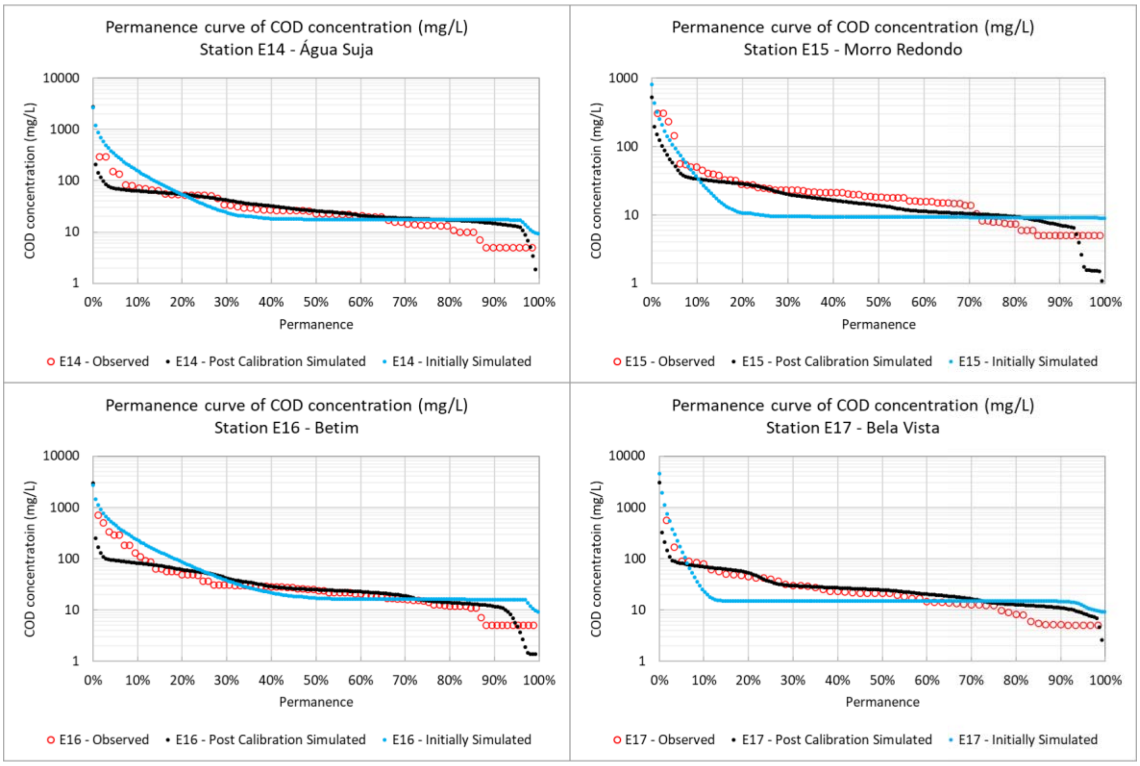


Figure 6.13 – Permanence curves of COD concentrations observed, simulated before and after calibration in each station



In the permanence curves, the results of the methodological choices made during the calibration are evident: the black dots (post calibration) are closer to the red curves (observed), mainly in the region closest to the median, between the 25th and the 75th percentiles, while the initial simulations resulted in curves almost flat in the same region.

6.8.3 Concentration Box-Whisker graphs

This analysis presents the impacts of the past and projected LULC changes in the concentrations of water pollutants related to washoff and non-point source pollution. The comparisons are focused on the rainy season concentrations of TSS, COD, TP and Ammonia-N (Figures 6.14 to 6.17).

Figure 6.14 – Box-Whisker graphs of TSS concentrations during the rainy season in the main tributaries and the total inflow to the reservoir, on different LULC scenarios

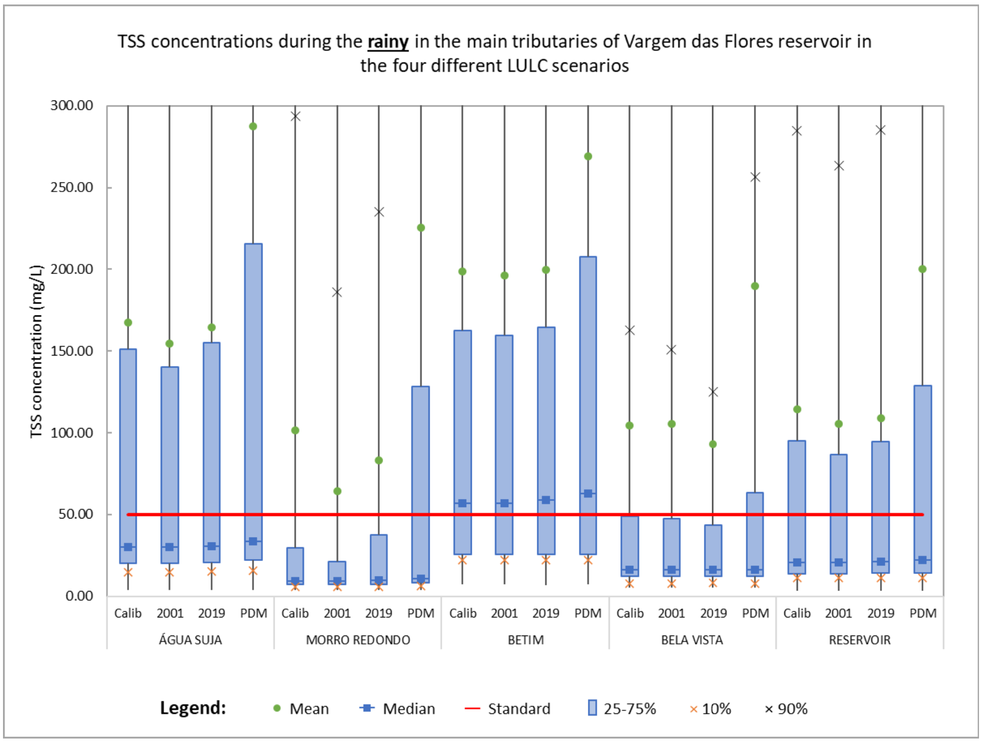


Figure 6.15 – Box-Whisker graphs of COD concentrations during the rainy season in the main tributaries and the inflow to the reservoir on different LULC scenarios

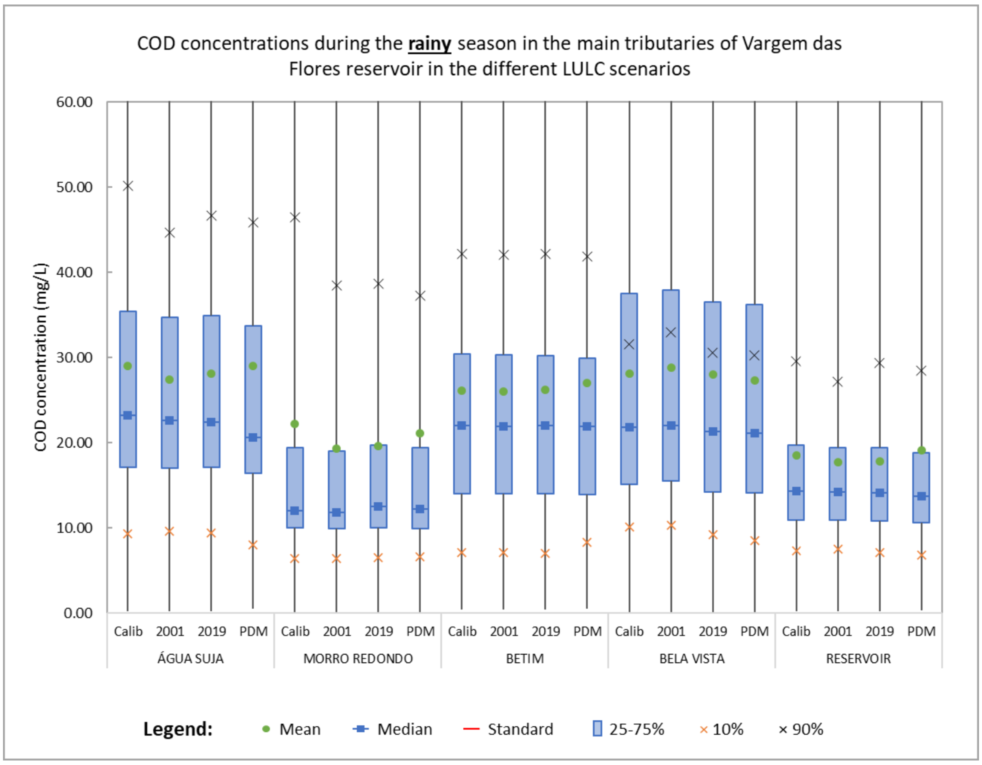


Figure 6.16 – Box-Whisker graphs of TP concentrations during the rainy season in the main tributaries and the inflow to the reservoir on different LULC scenarios

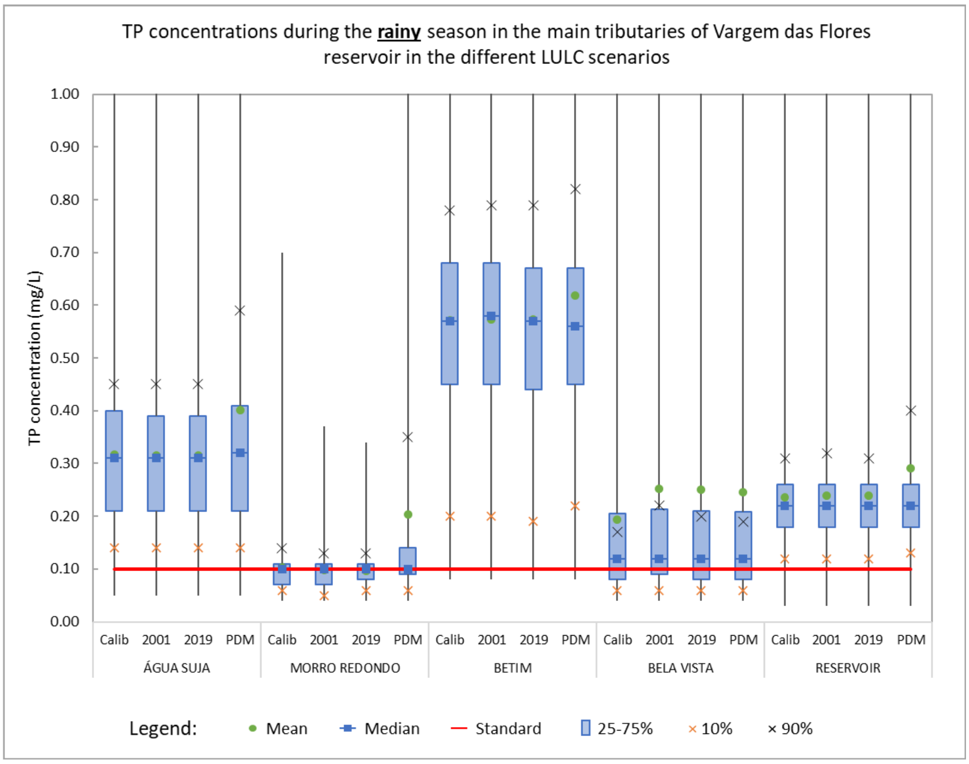


Figure 6.17 – Box-Whisker graphs of Ammoniacal-Nitrogen concentrations during the rainy season in the main tributaries and the inflow to the reservoir on different LULC scenarios

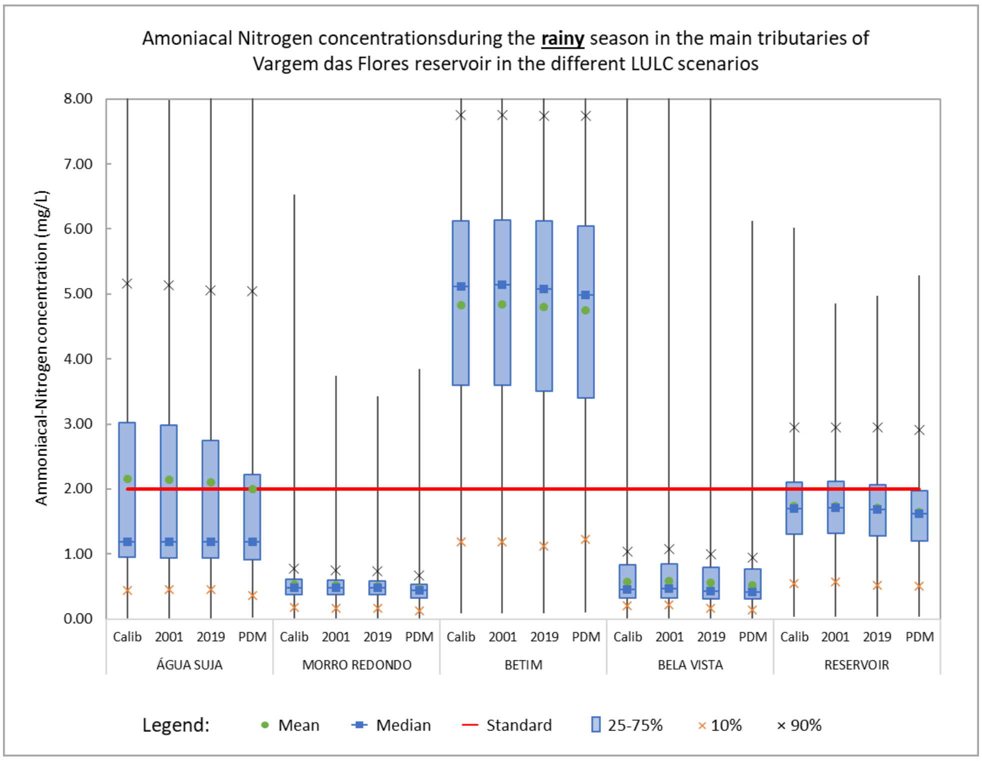


Figure 6.14 shows a clear impact of LULC changes on TSS concentrations, more visible in the mean and higher percentiles (75% and 90%). The maximum values are not visible in the scale adopted for the representation of the vertical axis due to the great difference in their magnitude, which would make the more frequent values difficult to visualize. Nevertheless, the variation of the maximum values caused a greater variation in the mean values compared to the median values. The increment in the mean concentrations varies from 32% in the already most urbanized subcatchment (Betim) to 122% in the currently most vegetated subcatchment (Morro Redondo), where the impervious area would increase from 5.1% in the 2019 scenario to 40.8% in PDM scenario. Considering all the inflow to the reservoir, the TSS mean concentration increased by 3% from 2001 to 2019 but could increase by 75% in the PDM scenario when the total imperviousness would change from 15.2% to 47.5% in all the reservoir's catchment.

Figures 6.15, 6.16, and 6.17 show that the LULC changes would have an almost negligible impact on COD, TP, and ammonia-N concentrations, which are the pollutants with lower influence of non-point pollution sources compared to TSS concentration. Despite the effect of dilution related to the increase of stream flows during the rainy season, it is possible to observe an increase in the mean and high (75% and 90%) percentile concentrations of TP in the PDM scenario. This pollutant still has an important diffuse contribution, while for COD and ammoniacal nitrogen, the variations in mean concentrations and its percentiles from 10 to 90% are almost imperceptible, and only the maximums showed visible variation.

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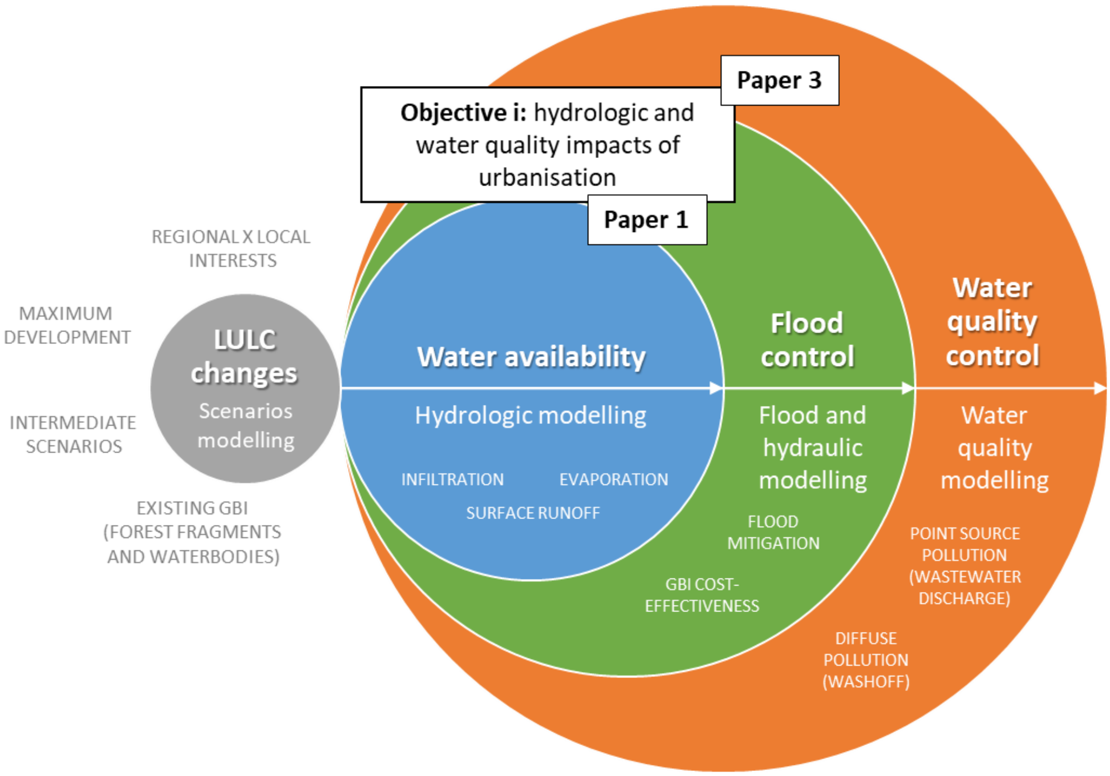
6.10 Summary

This paper presented the efforts to understand the impacts of land use changes on the water quality of the Vargem das Flores catchment. The paper described all the strategies adopted to overcome the limitations in data availability to calibrate the water quality model and simulate processes related to point and non-point source pollution. The results demonstrated that it is possible to represent, at least qualitatively, the main processes of buildup, washoff, dilution, and diffuse pollution, even without high-frequency monitoring data. With this article, the specific objective of this thesis of representing the impacts of urbanisation on the quantity and quality of water in the case study is fully achieved (Figure 6.18). Now equipped with a functional water quality model of the catchment, the following research step is to assess how the GBI can contribute to reducing the diffuse pollution loaded into the reservoir.

Figure 6.18 – Summary diagram of the developed research and objectives – Paper 3



Vargem das Flores catchment serves as a typical illustration of the challenges faced in the developing world, where the pressing need to manage diffuse pollution coexists with the urgent requirement to address the enduring issues of inadequate sanitation.

Although investments made in the last two decades have reduced the load of organic matter associated with sewage discharge into the reservoir's tributaries, the urbanisation process may resume the degradation of the reservoir's water quality with an increase in diffuse pollution. Therefore, the reservoir is again exposed to the risk of eutrophication and accelerated silting up.

Furthermore, the paper's findings call for actionable recommendations for policy and management — proactive measures to control runoff, diffuse pollution, and sediment transportation, especially in the face of urban expansion. Policymakers and stakeholders involved in land use planning and water resource management must be aware of the serious threats that this water source suffers, with the risk of reducing its useful life by 24 years. The engagement with relevant entities like governmental bodies, sanitation companies, and civil society organizations underscores the intent to bridge the gap between research findings and practical applications in the realm of policy and management, aligning with the study's objectives of contributing to effective land use planning strategies in the studied region.

7 ARTICLE 4: Water quality impacts of Land Use and Land Cover changes in a Brazilian Metropolis – Study of Green Infrastructure Implementation in the Vargem das Flores reservoir catchment

"Como povos-floresta têm apontado, esta é também uma guerra entre os que defendem 'desenvolvimento' e aqueles que defendem 'envolvimento'. Entre aqueles que querem se tornar des-envolvidos — porque deixaram de se envolver, colocando-se fora da natureza e tornando a natureza mercadoria produtora de mercadorias — e aqueles que se sabem envolvidos, porque são parte orgânica do planeta."

"As forest-peoples have pointed out, this is also a war between those who advocate 'development' [des-involvement] and those who advocate 'involvement'. Between those who want to become 'des-involved' — because they have stopped getting involved, placing themselves outside of nature and making nature a commodity producer of commodities — and those who know that they are involved, because they are an organic part of the planet."

Eliane Brum, in 'Banzeiro òkòtó: Uma viagem à Amazônia Centro do Mundo' [Banzeiro òkòtó: A trip to the Amazon Centre of the World] (Brum, 2021)

This article presents the later effort to quantify the GBI ecosystem services of regulating the sediment and nutrients cycles in the Vargem das Flores catchment. The GBI scenario was updated by optimising the cost-effectiveness relation for diffuse pollution control. In this sense, the impacts of the alternative LULC scenarios on the pollutant loads into the reservoir were assessed, supporting the preliminary analysis of the ongoing degradation processes of eutrophication and silting. These results demonstrate the GBI's potential to control diffuse pollution in new urban development areas and reduce some of the washoff pollutant loads from consolidated urban areas. Therefore, the specific objective of this research on comprehending the water quantity and quality benefits of GBI adoption in Vargem das Flores catchment is completed.

The manuscript presented in this chapter refers to the "preprint" version of the paper submitted to the "Journal of Cleaner Production".

7.1 Contributions to co-authored publications

The undersigned authors agree that the nature and extent of the contributions to the work "*Water quality impacts of Land Use and Land Cover changes in a Brazilian Metropolis – Study of Green Infrastructure Implementation in the Vargem das Flores reservoir catchment"* was as follows (Table 7.1).

Table 7.1 - Contributions of co-authors - Paper 4

Co-author	Nature of contribution	Extent of contribution (%)	Signature	Date
Deyvid Wavel Barreto Rosa	Study design, data acquisition, treatment and interpretation, modelling, drafted manuscript	75		05/12/2022
Camilla Vivian Porto Satler Hot	Data treatment, modelling, drafted manuscript	5		09/12/2022
Isadora Teixeira Gomes	Data treatment, modelling, drafted manuscript	5		07/12/2022
Diogo Ferreira Ventura	Data treatment, modelling, drafted manuscript	5		09/12/2022
Talita Fernanda das Graças Silva	Study design, reviewed manuscript	2.5		06/12/2022
Joanne Chong	Study design, reviewed manuscript	2.5		08/12/2023
Damien Giurco	Study design, reviewed manuscript	2.5		12/12/2022
Nilo de Oliveira Nascimento	Study design, reviewed manuscript	2.5		12/12/2022

7.2 Abstract

This paper aims to analyse the potential of Green and Blue Infrastructure approaches to manage non-point source pollution 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 urban development according to the current land use legislation was simulated. Then, an alternative scenario was proposed considering the adoption of the best cost-effective GBI techniques in the newly developed areas. Results indicated a significant contribution of diffuse pollution to the reservoir's water quality degradation, mainly due to the total suspended solids load transported by the most urbanised catchments. The application of bioretention cells to treat new impervious areas mitigated the diffuse pollution according to the simulations, maintaining pollutant loads similar to current levels even with more urbanisation.

Keywords: water quality modelling; diffuse pollution; future land use scenarios; SWMM; low impact development.

7.3 Introduction

Non-point sources of pollution (NPSP) are among the main threats to water quality worldwide, especially in urban areas, due to their high spatial variability and distribution. NPSP control is more complex when compared to the control of point sources of pollution and requires the engagement of a much larger number of land users (OECD Environment Directorate, 2017). Nevertheless, NPSP control and regulation are much less costly when compared to the treatment costs of their possible impacts on water bodies, such as eutrophication and silting (Chang & Yu, 2020; Silva et al., 2019). The consequent economic damages related to the eutrophication of American freshwaters, for example, exceed US$ 2.2 billion annually (Dodds et al., 2009) and are considered one of the most costly and challenging environmental problems in the United States of America (US Environmental Protection Agency, 2019).

Managing diffuse water pollution starts with identifying the main pollutant sources and assessing the impacts of planned land use changes (OECD Environment Directorate, 2017). Faced with the higher costs associated with treatment and restoration actions, the prevention of diffuse pollution is even more urgent in the context of developing countries. Protecting and reforesting riparian zones is indispensable, considering their effect on reducing nutrients and sediment runoff loading into the stream, stabilising watercourse banks, and preventing erosion processes (Maillard & Pinheiro Santos, 2008; Mello et al., 2018).

Adopting source control measures and adequate drainage in construction processes can minimise the impacts of urbanisation on surface water quality. Development guided by the principles of Water Sensitive Urban Design and with the implementation of Green and Blue Infrastructure (GBI) can reduce the impact on the water courses of a catchment (Qiu et al., 2018; Reisinger et al., 2018). Low Impact Development (LID) devices such as bioretention cells, permeable pavements, and infiltration trenches, among others, are being widely supported by researchers, governments, and non-governmental organisations as possible solutions to manage stormwater quantity and quality (Seddon, 2022; United Nations Environment Programme, 2021).

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 decreases in water quality pollutant 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 a pollution source. Due to the uncertainties related to this wide range of efficiencies of GBI in reducing pollutant loads, the authors recommended further explorations to facilitate the development of appropriate management plans. Also, few studies assessed the long-term efficiencies of GBI techniques that change over time. It is important to consider the practice efficiencies varying with time, even in modelling studies, to avoid high expectations that are impossible to achieve. Liu et al. (2017) also reviewed 174 studies about the impact of riparian forest buffers on water quality, and wide ranges of pollutant removal were found.

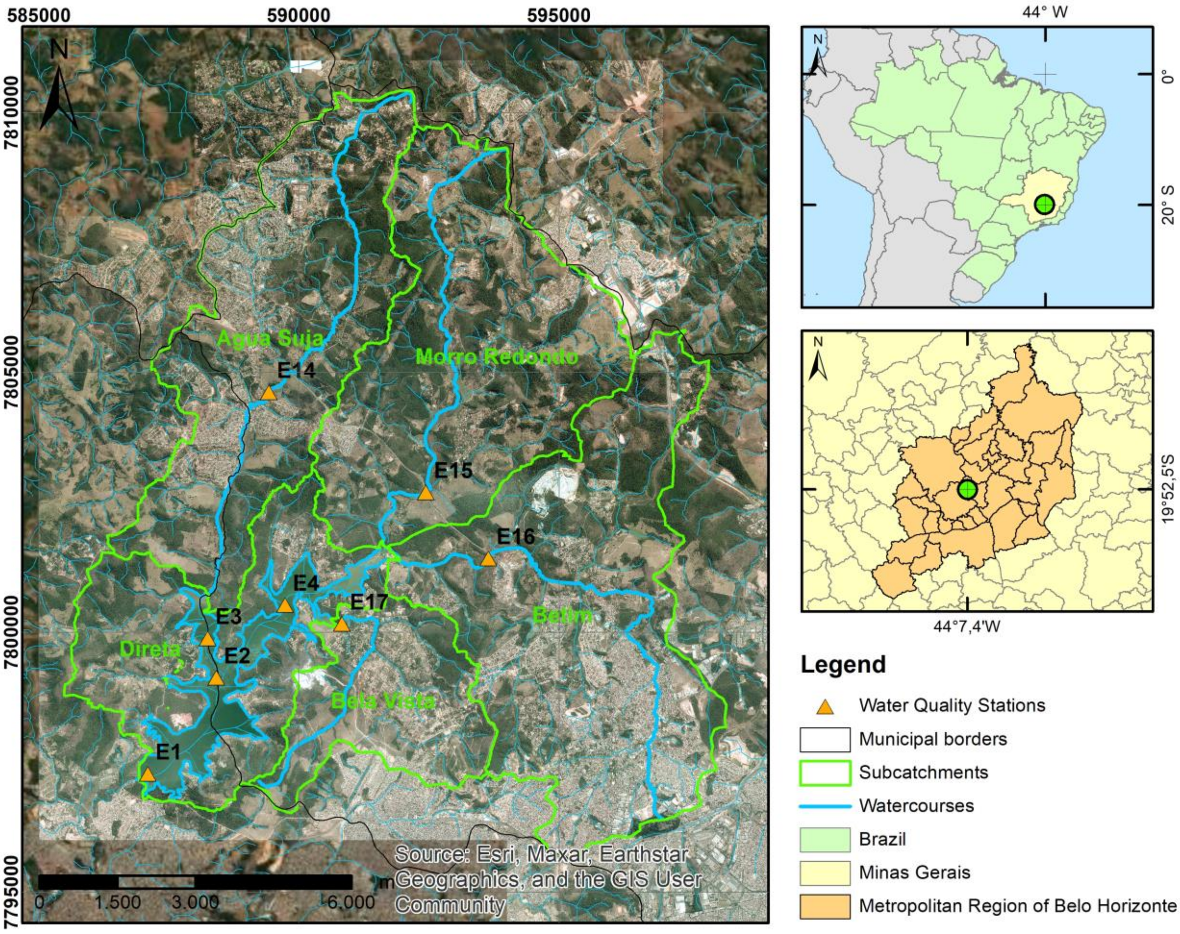
One of the models applied in many water quality studies cited by Liu et al. (2017) was the Storm Water Management Model (SWMM), recently updated by the US-EPA to represent better the water quality processes in version 5.2 (Rossman & Simon, 2022). If coupled with reservoir models, SWMM can be used to assess the impacts of stormwater runoff on the water quality of reservoirs, especially on nutrient loads and eutrophication (Chang & Yu, 2020; Silva et al., 2019).

Although uncertainties in water quality simulations increase when considering LIDs and reservoirs, SWMM can 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 the silting-up process of a reservoir due to changes in land use and land cover and the implementation of the best cost-effective GBI in its contribution catchment. Future impacts related to expected LULC changes were simulated using an adjusted water quality model, and SWMM functionality was tested to simulate improvements in water quality by LID devices implementation. The authors have already made available the tools and results from this research to the management agencies and the local society to support the ongoing discussion about land use planning in the studied area.

7.3.1 Case study

The catchment of Vargem das Flores reservoir is part of Belo Horizonte (the third biggest Brazilian metropolis) metropolitan integrated water supply system, and supplies about 10% of the urban demand, providing a flow between 0.7 m^3/s and 1.2 m^3/s to about 600,000 people (Copasa, 2019). The catchment covers 120.25 km^2 of the region’s second and third most populous municipalities (87% of the catchment area in Contagem and 13% in Betim). The sanitation company Copasa maintain a water quality monitoring plan with approximately quarterly frequency in eight sites in the catchment area (Figure 7.1), four inside the reservoir, and four in the main tributary streams: Água Suja (E14), Morro Redondo (E15), Betim (E16), and Bela Vista (E17).

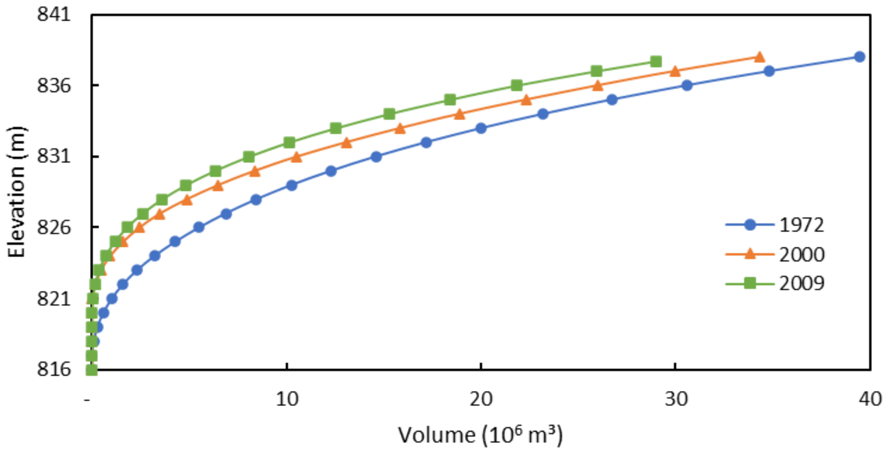
Figure 7.1 – Map of monitoring sites and subcatchments



The main purpose of the reservoir is to supply water to part of the Belo Horizonte Metropolitan Region (BHMR), but many other current uses can compromise this function. The waterbody is used for recreation and leisure, its banks are occupied by regular and irregular activities (e.g. housing, bars and others), and the main tributaries still receive an irregular discharge of sewage and solid waste despite the existence of a collection network and transposition system (Carvalho, 2021).

Since its construction in 1972, the reservoir has lost more than a quarter of its volume due to siltation (Figure 7.2). Between the last two bathymetric surveys (2000 and 2009), the reservoir lost 4 million m³, an annual volume loss of about 450,000 m³ or 1.5% of the original volume (Santos, 2012). Assuming the same annual volume loss rate observed between 2000 and 2009, the end of the reservoir's useful life would be in 2066.

Figure 7.2 – Volume *versus* elevation curves of Vargem das Flores reservoir in 1972, 2000, and 2009 (Santos, 2012)



Recent changes in land use legislation in Contagem municipality (Contagem, 2018) caused intense political debates and protests due to the risks that the urbanisation of a large part of the area previously considered as rural may represent for the reservoir. New urban development in the catchment can decrease the reservoir lifetime due to siltation and accelerate water quality degradation, increasing treatment costs. Considering this background, the discussion about the future of Vargem das Flores reservoir and the urban development of its catchment is up to date, so environmental studies are needed to support public decision-making.

7.4 Methods

The hydrological model of Vargem das Flores catchment calibrated and validated in SWMM (Rosa, Silva, Araújo, et al., 2022), and applied to simulate the hydrological impacts of GBI implementation (Rosa, Silva, Chong, et al., 2022), was updated to receive the water quality module (Chapter 6).

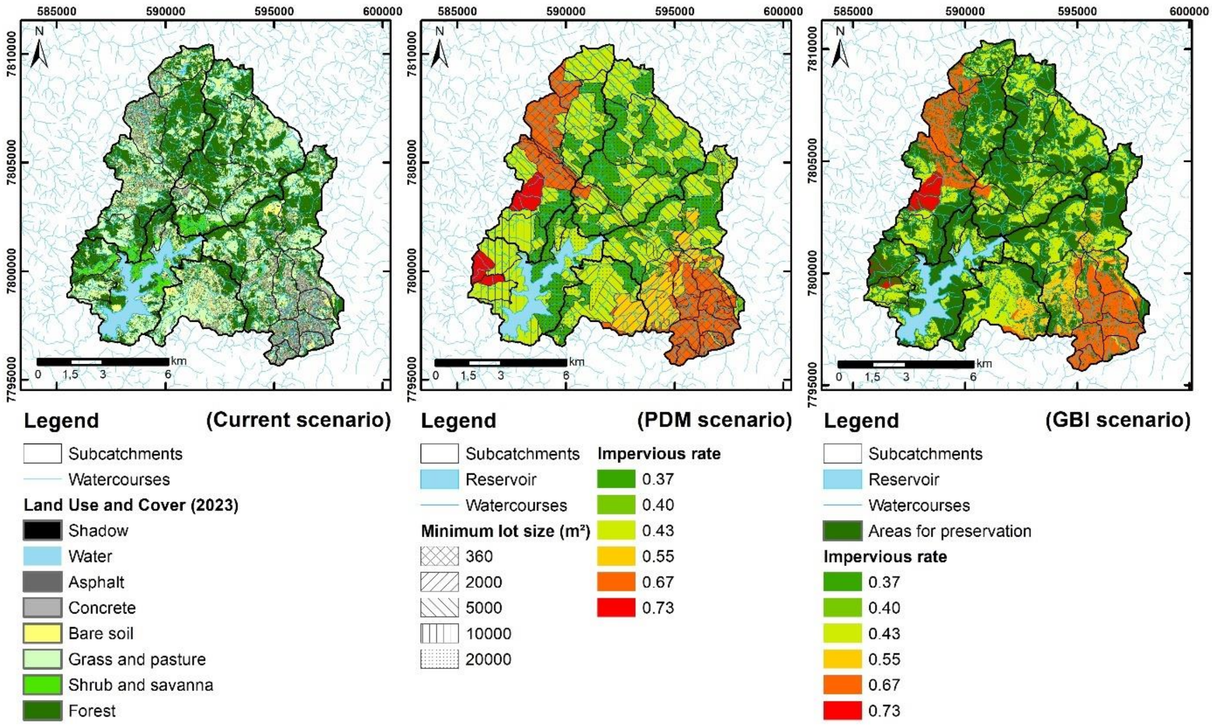
The hydrological model calibrated and validated by Rosa, Silva, Araújo, et al. (2022) was used as the starting platform, in which the simulated water levels achieved a good fitting to the monitored water levels of the reservoir, with Nash-Sutcliffe coefficient ranging from 0.80 to 0.87, and determination coefficient from 0.88 to 0.79. Rosa, Silva, Chong, et al. (2022) tested multiple alternative combinations of LID devices in SWMM (rooftop disconnection, green roof, rain garden, rain barrel, infiltration trench, bioretention cell, permeable pavement, and vegetative swale) to optimise the cost-effectiveness of the runoff peak and volume reduction. The combination of rooftop disconnection treating impervious areas in lots and vegetative swales treating roads was the most effective on runoff reduction. Despite allowing a 100% growth of the urban expansion, this GBI scenario roughly maintained the runoff volume and the flooded area downstream closer to the current scenario.

In the preparation of the water quality module, both the point and non-point sources of pollution were considered variable, so the volume of untreated sewage discharged annually in each subcatchment and Land Use and Land Cover 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 Total Suspended Solids (TSS), Chemical Oxygen Demand (COD), Total Phosphorus (TP), and Ammoniacal Nitrogen. Results of this previous stage indicated that diffuse pollution was greatly responsible for the TSS and TP loads yielded to the reservoir by the most urbanised subcatchments. In this sense, urban development with no pollution control of non-point sources could accelerate the eutrophication and silting process of the reservoir, compromising its function as a water source for 600,000 people and reducing its service life to less than half.

7.4.1 Land use and land cover scenarios

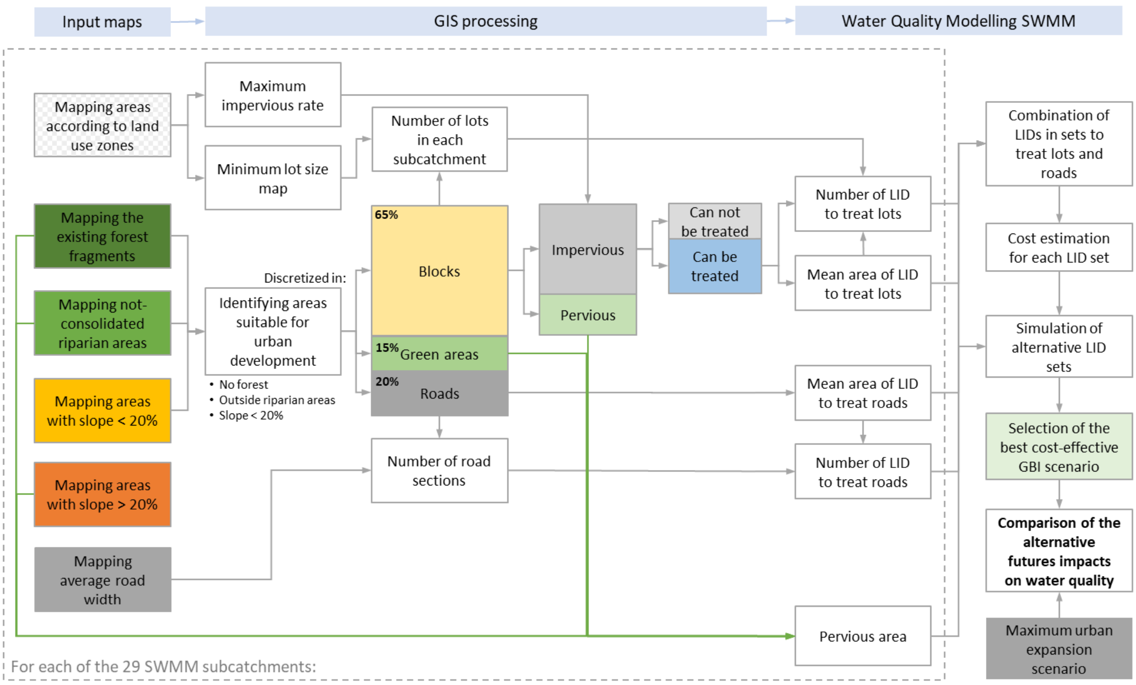
Three LULC scenarios were considered in this work, obtained and adapted from previous works developed to assess the impacts of LULC changes in the catchment water quantity (Rosa, Silva, Araújo, et al., 2022; Rosa, Silva, Chong, et al., 2022). The current scenario with catchment imperviousness of 15.2% calibrated, and the future scenario with the maximum urban development following the guidelines of the current municipal master plans (PDM), with 47.5% imperviousness. For future scenarios, no change in the sewage load was considered, adopting the hypothesis that the new occupations would be provided with sewage collection and treatment. In this sense, the comparison of future scenarios is focused only on the effects of LULC changes on the diffuse pollution load. This study considers a new prospective scenario with the implementation of Green and Blue Infrastructure in the newly developed areas (Figure 7.3).

Figure 7.3 – LULC scenarios studied by Rosa, Silva, Chong, et al. (2022) and considered in this study



The alternative future scenario with the implementation of GBI to treat diffuse pollution was proposed according to the process synthesised in Figure 7.4.

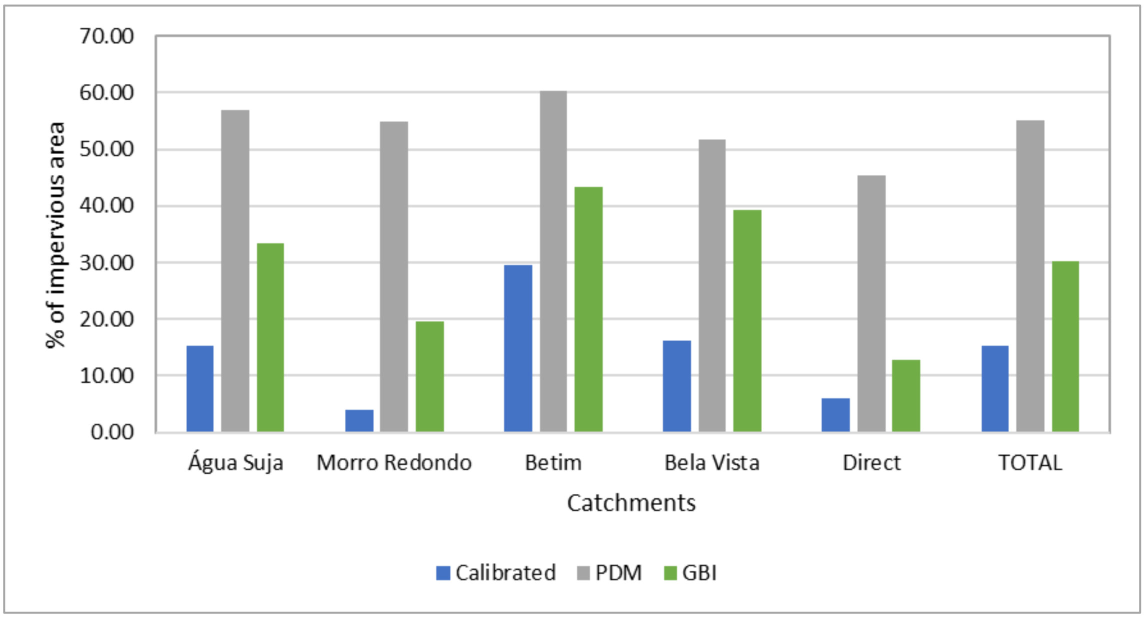
Figure 7.4 – Diagram of methods for preparing and modelling the GBI scenario



In the GBI scenario, all the existing green remnants are preserved, as well as all rural riparian areas within up to 30 meters from water courses, regulated as Environmental Preservation Areas according to the Brazilian Forest Code (Brasil, 2012). Considering the maximum impervious rates and minimum lot size established by the current master plans for the new development areas, the catchment imperviousness rate would be 30.2% (Rosa, Silva, Chong, et al., 2022).

From all the areas identified as suitable for urban development, 10.1% of the area has a low (< 20%) terrain slope and could be treated with infiltration devices. SWMM 5.2 enables pollutant removal assessment only for the LID practices that contain underdrain. Thus, the user can define the pollutant removal rate for bioretention cells, permeable pavements, infiltration trenches, and rain barrels. The latter and the other techniques (rain garden, rooftop disconnection, green roof, vegetative swale) were not considered in this study because of this limitation. Figure 7.5 compares the percentage of impervious areas in each main subcatchment and the catchment of Vargem das Flores reservoir in the different LULC scenarios. For the whole catchment, the impervious area would increase from 15.2% in the current scenario to 47.5% in the PDM scenario, and 30.2% in the GBI scenario.

Figure 7.5 – Percentage of impervious area in the catchment of Vargem das Flores reservoir and its main subcatchments in the different LULC scenarios



7.4.2 Cost-effectiveness of GBI for water quality control

Besides protecting the riparian vegetation and forest fragments, the GBI scenario included implementing LID devices to treat the new impervious areas associated with the newly developed areas. 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 possible 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 (see Table 7.2).

Table 7.2 – Alternative GBI scenarios simulated

Alternative GBI scenarios	Fraction of impervious area treated by each LID device inside blocks (private areas)		Fraction of impervious area treated by each LID device on sidewalks and public roads		
	Bio-Retention Cell	Infiltration Trench	Permeable Pavement	Bio-Retention Cell	Infiltration Trench
1	1	0	0	0	0
2	0	1	0	0	0
3	0	0	1	0	0
4	0	0	0	1	0
5	0	0	0	0	1
6	0.5	0.5	0.33	0.33	0.33
7	1	0	0.33	0.33	0.33
8	0	1	0.33	0.33	0.33
9	0.5	0.5	0.5	0.5	0
10	1	0	0.5	0	0.5
11	0	1	0	0.5	0.5
12	0.5	0.5	1	0	0
13	1	0	0	1	0
14	0	1	0	0	1
15	1	0	0.5	0.5	0
16	0	1	0.5	0.5	0
17	0.5	0.5	0.5	0	0.5
18	0	1	0.5	0	0.5
19	0.5	0.5	0	0.5	0.5
20	1	0	0	0.5	0.5
21	0.5	0.5	0.5	0	0.5
22	1	0	0.5	0	0.5
23	0	1	0.5	0	0.5
24	0.5	0.5	0	0.5	0.5
25	1	0	0	0.5	0.5
26	0	1	0	0.5	0.5
27	1	0	1	0	0
28	0	1	1	0	0
29	0.5	0.5	0	1	0
30	0	1	0	1	0
31	0.5	0.5	0	0	1
32	1	0	0	0	1

The mean pollutant removal efficiencies for each LID device used for SWMM simulations are presented in Table 7.3.

Table 7.3 – Pollutant removal efficiency adapted from Clary et al. (2020)

Parameters	LIDs pollutant removal efficiency Median efficiency [minimal: maximal] 95% confidence		
	BC	**PP**	**IT**
Total Suspended Solids (TSS)	77% [74%:83%]	71% [63%:80%]	84% [78%:88%]
Ammoniacal Nitrogen (Ammonia-N)	83% [73%:84%]	88% [80%:93%]	60% [44%:74%]
Total Phosphorus (TP)	-26% [-59%:10%]	41% [25%:46%]	45% [35%:56%]
Chemical Oxygen Demand (COD)	-17% [-94%:60%]	71% [63%:79%]	93% [85%:100%]

According to Clary et al. (2020) and Liu et al. (2017), many studies indicated that bioretention cells are ineffective in treating COD and TP, often contributing to these pollutant loads. SWMM does not allow simulating LIDs as pollution sources, so the efficiencies of bioretention cells on TP and COD treatment were considered null. The other LID input parameters related to its layers' characteristics were defined following the recommendations of Woods Ballard et al. (2015) and Rossman and Simon (2022) (see Table 7.4).

Table 7.4 – Input parameters for LIDs in SWMM

Layer	Parameter	Bioretention Cell	Infiltration Trench	Permeable Pavement
Surface	Berm Height (mm)	200	100	0
	Vegetation Volume Fraction	0.1	0	0
	Surface Roughness (Manning n)	0.1	0.1	0.015
	Surface Slope (%)	3	3	3
Soil	Thickness (mm)	500		500
	Porosity (volume fraction)	0.45		0.45
	Field Capacity (volume fraction)	0.17		0.17
	Wilting Point (volume fraction)	0.074		0.07
	Conductivity (mm/hr)	16.24		16.24
	Conductivity Slope	40		40
	Suction Head (mm)	95.7		95.7
Storage	Thickness (mm)	400	1,500	400
	Void Ratio (Void/Solids)	0.6	0.6	0.6
	Seepage Rate (mm/hr)	16.24	16.24	16.24
	Clogging Factor	36	36	36
Drain	Flow Coefficient (mm/hr)	3.33	3.33	3.33
	Flow Exponent	0.5	0.5	0.5
	Offset (mm)	390	1490	390
Pavement	Thickness (mm)			150
	Void Ratio (Void/Solids)			0.2
	Impervious Surface Fraction			0.1
	Permeability (mm/hr)			5,000
	Clogging Factor			540
	Regeneration Interval (days)			1
	Regeneration Fraction			1

Performances of the 32 LID combinations on pollutant removal were compared with the total cost of implementation, operation, and maintenance to select the best cost-effective scenario. The costs presented in Table 7.5 were estimated based on local prices by Rosa, Silva, Chong, et al. (2022).

Table 7.5 – Capital and O&M costs of LID devices

GBI Technique	Symbol	Ratio treated area (m²) per m² of technique	Implementation Cost per m² of treated area (BRL)	Maintenance Cost per m² of treated area (BRL)
Bio-Retention Cell	BC	26.0	5.54	0.53
Infiltration Trench	IT	23.6	10.99	1.83
Permeable Pavement	PP	2.0	28.03	22.20

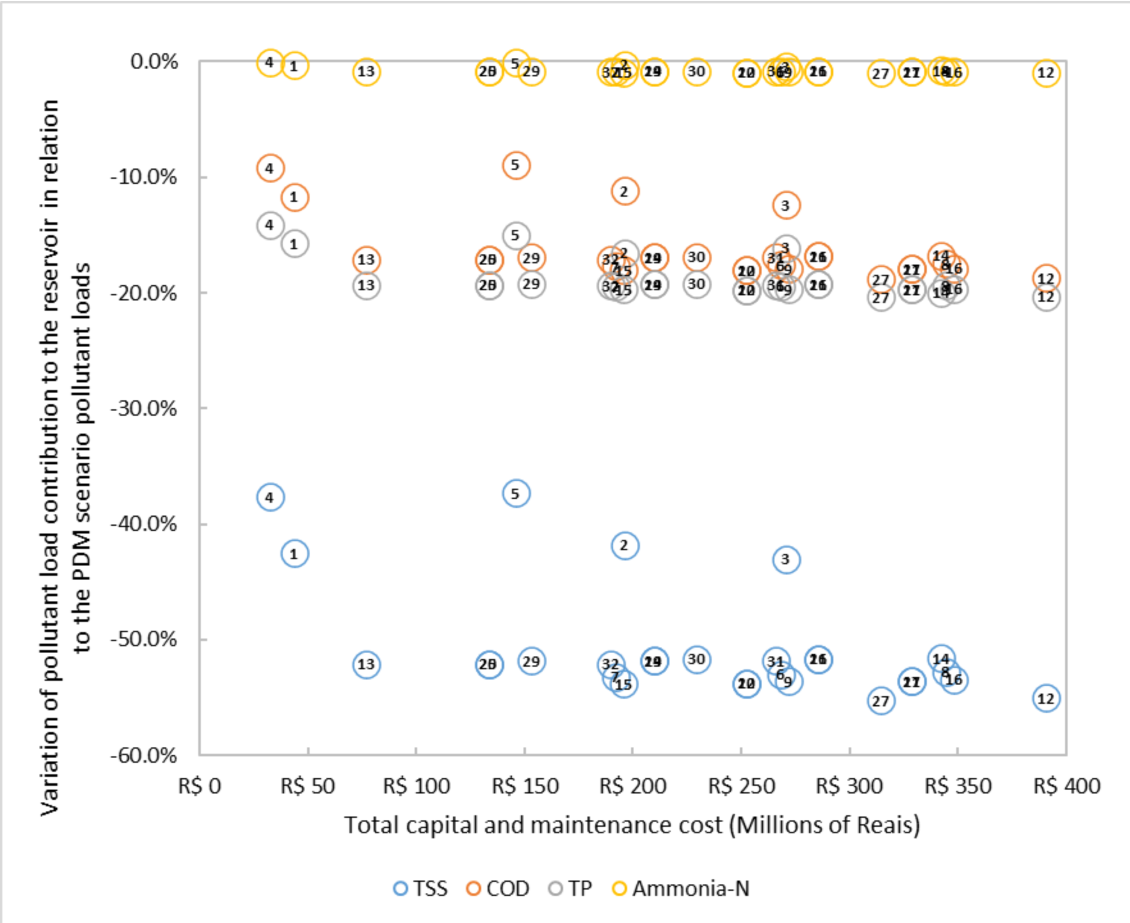
BRL is the Brazilian currency, Real. 1.00 BRL is about 0.19 USD (October 2022).

7.5 Results

7.5.1 Selecting the best cost-effective GBI scenario

Figure 7.6 shows the effectiveness of the 32 LID alternative scenarios on total pollutant (TSS, COD, TP, Ammonia-N) removal compared to the PDM scenario, simulating a typical rainfall year (2010-2011 registered rainfall). The horizontal axis represents the first year's total capital cost and maintenance (in Millions of Brazilian Reais, currency of 1 BRL = 0.19 USD in October 2022).

Figure 7.6 – Pollutant remotion efficiency and costs of the alternative 32 combinations of GBI scenarios



Firstly, the LID effectiveness on pollutant removal is remarkably different according to the importance of the diffuse contribution for the total load of each pollutant. Since analysing the monitored water quality data, it was clear that TSS was the most affected, with higher concentrations during the rainy season for all catchments, evidencing that non-point and surface washoff are the main sources of TSS. In this sense, as expected, 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) separately, and about 50% of the total TSS load when combined treatment of both areas.

For the other pollutants (organic matter and nutrients), the dilution effect was more important in the rainy season, so the concentrations decreased during the rainy season compared to the dry season in the more urbanised subcatchments. The stormwater infrastructure conveys some of these pollutants' loads due to cross connection with the sewer system, having characteristics of point pollution. In the simulation, LIDs removed about 15% of the TP total load and 10% of COD total load when performing alone, or about 20% of TP and 17% of COD total load when performing together treating public and private newly developed areas. The ammoniacal Nitrogen removal was approximately zero for all LIDs studied, since its load from NPSP is negligible, and even the effect of dilution is small.

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 (LID27 – BC+PP) and the least efficient (LID14 – IT+IT) combination. On the other hand, the total capital and maintenance costs varied greatly between scenarios, so the highest cost (LID28 – IT+PP) was 6.1 times higher than the lowest cost (LID13 – BC+BC).

Considering the low variation of effectiveness and high variation of costs, LID13 was selected as the most cost-effective LID scenario, considering that the implementation and maintenance of bioretention cells to treat the new 12.64 km² impervious areas would have the lowest cost (76.7 million Brazilian reais) and still remove 52.1% of total TSS, 19.5% of TP and 17.1% of COD loads flowing into the reservoir. The annual treated cost per kg of 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 those of a water treatment plant located in the neighbouring catchment of Pampulha Reservoir (15 km distance from Vargem das Flores reservoir). This plant can treat a stream flow of 0.75 m^3/s; the added dry period discharges from the Sarandi and Ressaca streams into the reservoir. Considering treatment costs and efficiencies presented by Coutinho (2007), the implementation and first-year operation and maintenance costs updated to 2022 values (Fundação Getúlio Vargas, 2022) 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.

7.5.2 Simulating the impact of LULC changes on water quality

The analysis presented in this section focuses on the impacts of the past and projected LULC changes in the concentrations and loads of water pollutants related to non-point sources through deposition and washoff. The comparisons are centred on the total and weighted per unit area annual washoff loads of TSS, COD, TP and Ammonia-N (Table 7.6).

In all tributaries, the proposed GBI scenario could reduce the TSS concentrations to values similar to the current levels. This indicates that implementing bioretention cells on 10.1% of the catchment, or 67% of the newly developed areas that were technically suitable for treatment, would mitigate all the additional TSS diffuse pollution associated with this urban development.

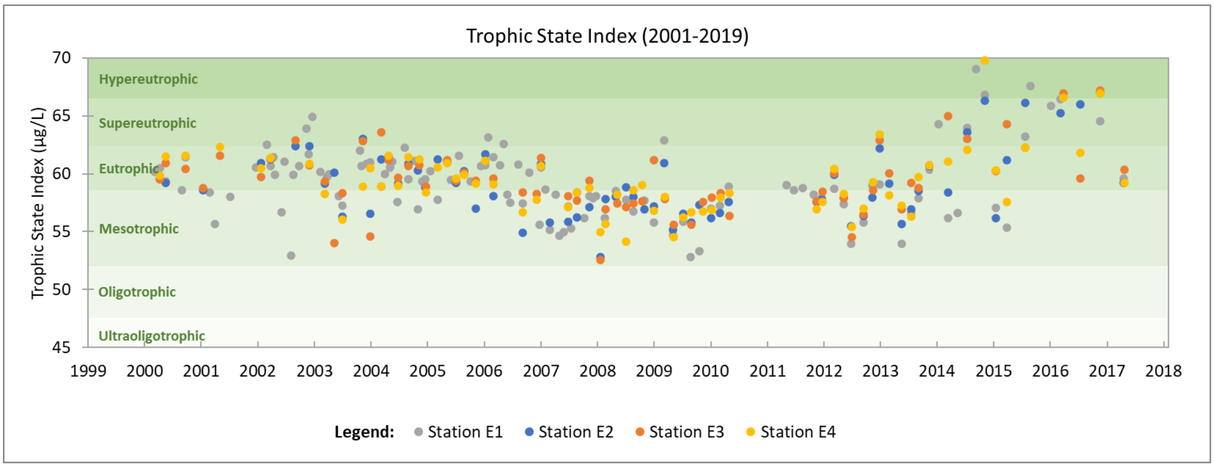
Table 7.6 – Washoff pollutant annual total loads (ton/year) and annual load per unit area (kg/yr/ha) in the main subcatchments and in the three studied LULC scenarios

Pollutant	Index	Subcatchments	Água Suja	Morro Redondo	Betim	Bela Vista	Direct	Total
		Area (ha) / Scenarios	2,730	2,853	3,358	1,077	2,025	12,042
TSS	Annual load (ton/yr)	Calibrated	4,683	2,342	1,690	7,778	1,308	17,801
		PDM	9,313	7,855	3,218	11,692	5,291	37,369
		GBI	4,198	2,318	1,554	7,470	1,410	16,950
	Annual load per unit area (kg/yr/ha)	Calibrated	1,716	821	503	7,223	646	1,478
		PDM	3,412	2,753	958	10,859	2,613	3,103
		GBI	1,538	813	463	6,938	696	1,408
COD	Annual load (ton/yr)	Calibrated	278.4	242.4	366.5	121.0	136.3	1,144.7
		PDM	325.7	326.0	403.2	130.8	191.9	1,377.6
		GBI	169.2	129.4	262.0	68.3	96.1	725.1
	Annual load per unit area (kg/yr/ha)	Calibrated	102.0	85.0	109.2	112.4	67.3	95.1
		PDM	119.3	114.3	120.1	121.5	94.8	114.4
		GBI	62.0	45.4	78.0	63.5	47.5	60.2
TP	Annual load (ton/yr)	Calibrated	2.20	1.53	4.91	1.11	1.14	10.90
		PDM	4.92	4.30	7.04	1.94	3.13	21.33
		GBI	2.75	2.11	4.98	1.13	1.37	12.34
	Annual load per unit area (kg/yr/ha)	Calibrated	0.81	0.54	1.46	1.03	0.56	0.91
		PDM	1.80	1.51	2.10	1.80	1.55	1.77
		GBI	1.01	0.74	1.48	1.05	0.68	1.02
Ammonia Nitrogen	Annual load (ton/yr)	Calibrated	1.73	2.32	1.99	0.63	1.44	8.10
		PDM	1.34	1.99	1.55	0.48	1.04	6.39
		GBI	0.79	0.95	0.92	0.27	0.84	3.77
	Annual load per unit area (kg/yr/ha)	Calibrated	0.63	0.81	0.59	0.58	0.71	0.67
		PDM	0.49	0.70	0.46	0.44	0.51	0.53
		GBI	0.29	0.33	0.27	0.26	0.41	0.31

For the PDM scenario, the total annual TSS load would increase from 17,801 to 37,369 tons/year, or 2.1 times the load in the calibrated scenario. This increase in TSS load can accelerate the silting process and loss of useful volume of Vargem das Flores reservoir, so that the total siltation of the reservoir could be brought from 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 (16,950 tons/year), even allowing the urban development of an additional area of 38.9 km².

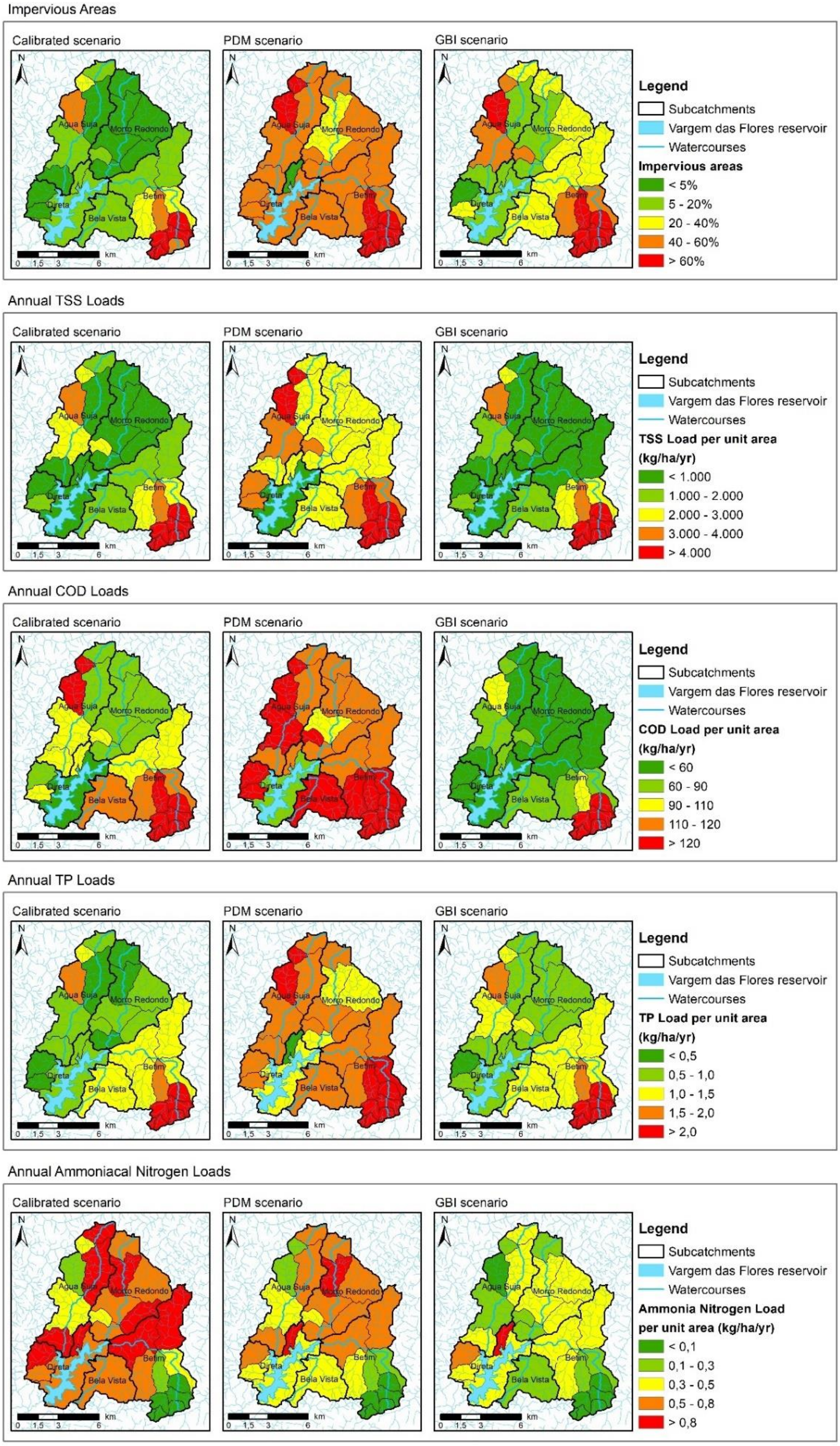
The GBI scenario would partially mitigate the TP additional load related to the new development, keeping the annual load to 12.34 tons/year. If the urban development follows the PDM scenario, the TP annual load could increase from 10.90 to 21.33 tons/year. Along with the parameter chlorophyll A, TP indicates the trophic status of waterbodies (Carlson, 1977). Preliminary analysis of the water quality data from the monitoring stations inside the reservoir indicated the predominance of mesotrophic and eutrophic conditions, with a trend to eutrophic and supereutrophic since 2016. Figure 7.7 presents the time evolution of the Trophic State Index according to the equations and classification proposed by Lamparelli (2004). The increase in the TP load affluent to the reservoir can intensify the eutrophication process, seriously threatening the current uses of its water, with possible occurrences of a cyanobacterial boom, release of toxins and consumption of dissolved oxygen.

Figure 7.7 – Temporal variation of Trophic State Index (Lamparelli, 2004) during the monitoring period (2001-2019) in four stations located inside the reservoir (indicated in Figure 7.1)



The spatial distribution of pollutant load contributions considering the 29 simulated subcatchments is presented in Figure 7.8. In all tributaries, the proposed GBI scenario could reduce the TSS concentrations to values similar to the current levels. This indicates that implementing bioretention cells on 33% of the newly developed areas that were technically suitable for that would mitigate the additional TSS diffuse pollution associated with this urban development.

Figure 7.8 – Maps of annual washoff load per unit area (kg/yr/ha) for each subcatchment



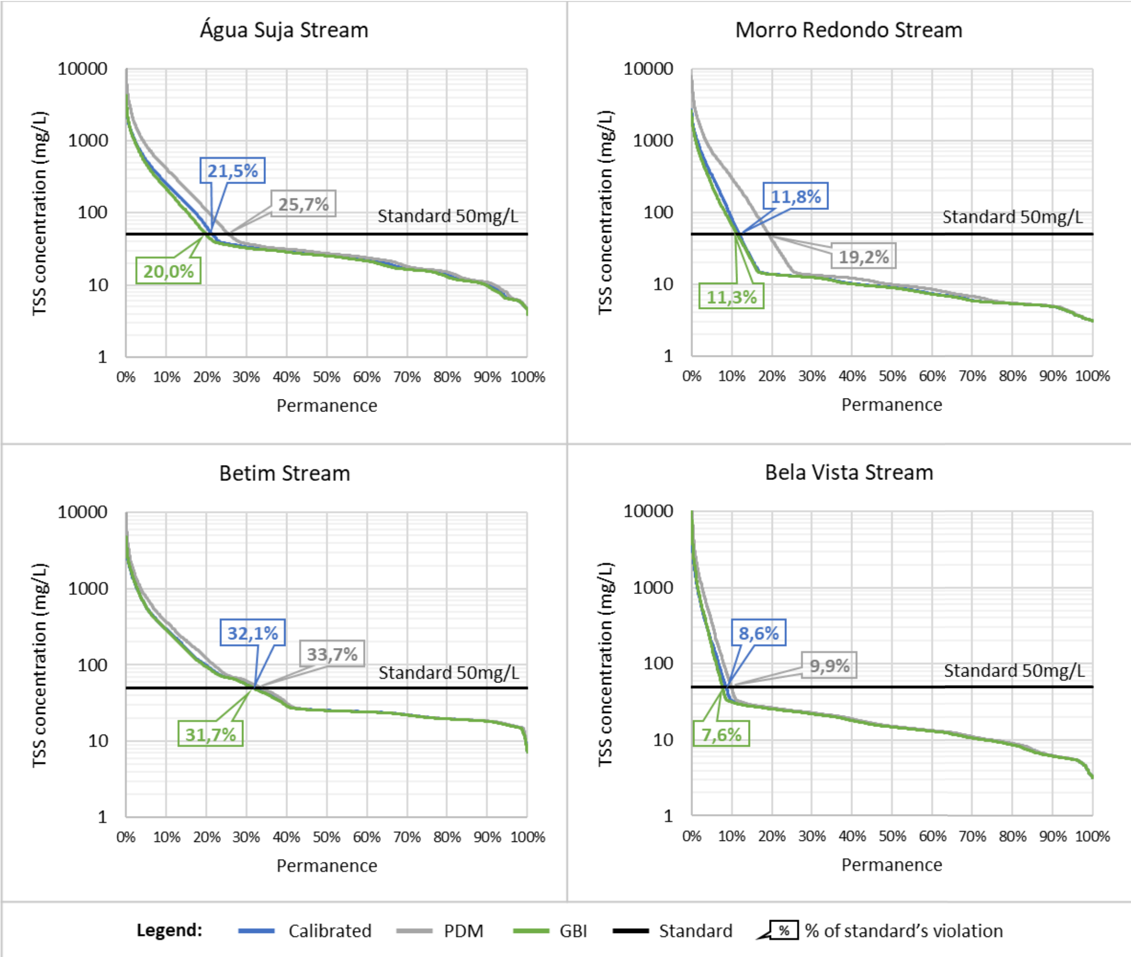
The maps presented in Figure 7.8 clearly identify the south-eastern and north-western subcatchments as the current major contributors to washoff pollution (TSS, COD and TP). These regions are the central area of Contagem municipality and the region of Nova Contagem, two urban settlements that are also the main historical contributors to wastewater pollution. Those results indicate that, although public investments in sewage interception, treatment and transposition have mainly addressed the point source pollution, the diffuse pollution produced in those areas still requires intervention.

Except for Ammonia-N, whose spatial distribution of loads indicates that rural areas are the main sources of diffuse pollution, the future development would homogenise the contribution in almost all subcatchments. The protection of the immediate surroundings of the reservoir provided for by the PDM would not be sufficient to protect its waters from the degradation caused by the development of upstream areas. Almost all the TSS, TP and COD washoff loads would be transported by the streams into the reservoir, since the distances are short, and the modelling results indicated little importance of the degradation and decay phenomena along the watercourses to reduce the load that effectively reaches the reservoir.

Although the GBI scenario allowed new developments in all subcatchments, as observed in the changed colours in the last map of the first line of Figure 7.8, the results indicate that the bioretention cells could treat not only the additional washoff pollutant load produced in new development areas but even mitigate part of the diffuse pollution already produced in some subcatchments. COD and TP washoff loads could be respectively reduced by 41% and 51% in the Bela Vista subcatchment, and the TSS washoff load could be reduced by 20% in the most downstream Betim subcatchment, even with the increase of urban development in those areas.

Finally, the most evident benefit of the GBI implementation related to water quality is the mitigation of TSS diffuse pollution. The permanence curves of TSS concentrations of the main tributaries of Vargem das Flores reservoir in the current scenario (Calibrated), PDM and GBI scenarios are shown in Figure 7.9.

Figure 7.9 – Permanence curves of TSS concentrations and standard violation in the main reservoir's tributaries for the different LULC scenarios



In the current LULC scenario, the TSS standard of 50 mg/L is violated in Betim stream 32.1% of the time, 21.5% in Água Suja stream, 11.8% in Morro Redondo stream and 8.6% in Bela Vista stream. In the PDM scenario, the period with TSS concentrations higher than the standard would increase in all tributaries, especially in Morro Redondo, where the violation would occur 19.2% of the time. In the GBI scenario, on the other hand, the violation permanence would be slightly lower than the current ones, confirming the effectiveness of diffuse pollution mitigation.

7.6 Discussion and Conclusion

This paper is the continuation of a research that evaluated 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 water quality degradation in the catchment, especially until the 2010s when a sewage collection and treatment system was built in the north-western portion of the catchment.

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, from 1972 to 2009, the reservoir underwent an accelerated process of silting up, having lost 25% of its usable volume until 2009 (Santos, 2012). Nevertheless, the catchment is still under pressure for further development, so the land use legislation was changed in 2018 to ease the restrictions for urban sprawl. The community and public managers mobilised to protect the reservoir, and a new public discussion on revising the 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 of the reservoir, as identified in previous works (Rosa, Silva, Araújo, et al., 2022; Rosa, Silva, Chong, et al., 2022).

Located on the margins of the main metropolitan urban patch and representing more than 53% of the area of Contagem municipality, the second most populated in the metropolitan region, the area will remain under pressure for further development. This development should follow a different pattern to protect the reservoir as a feasible water source, especially if the project of a major road connecting the busiest federal roads that cross the metropolitan region is implemented in the middle of Vargem das Flores catchment. All this reinforces this study's socio-environmental contribution by analysing alternatives to mitigate part of the impact of new developments in the region.

The alternative development scenario proposed here, with the implementation of Green and Blue Infrastructure 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. The GBI effectively reduced part of the existing washoff loads, even without considering the implementation of any GBI in consolidated urban areas. So, the study of GBI adoption in the retrofitting of consolidated urban areas is highly recommended since these areas are the primary sources of TSS, TP and COD in the catchment.

Finally, the water quality model developed and adjusted to the monitoring data can be a valuable tool to support land use managers in their decisions and interventions. Managing diffuse pollution represents one of the greatest challenges for land and water managers, especially as it threatens a lentic water source that is essential to water security. Further work should focus on prioritising recovery interventions according to their effectiveness in treating the main subcatchments and areas source of diffuse pollution. Future studies will use the 20-year-long hourly rainfall time series and climate change downscaled rainfall time series to evaluate long-term impacts on water availability and provide information for new investments to guarantee water security and flood control downstream of the reservoir. Another front of research that is opening up is the hydrodynamic and ecological modelling of the reservoir, which will allow the analysis of the ongoing degradation processes of eutrophication and silting.

7.7 Acknowledgements

The authors would like to thank the research funding agencies, Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq), Fundação de Amparo à Pesquisa de Minas Gerais (FAPEMIG) and Coordenação de Aperfeiçoamento de Pessoal de Nível Superior – Brasil (CAPES) for their financial support, the Brazilian Centre of Monitoring and Natural Disaster Warning (Cemaden), Minas Gerais Sanitation Company COPASA, Fundação João Pinheiro, Contagem's and Betim's City Halls, for the provision of essential data for the development of this research. The project is linked to the project MoMa, financed by Capes (Ministry of Education) and ANA (Brazilian Water Agency), Grant number: 88887.15881/2015-01 and ANA 2776/2015. Nilo de Oliveira Nascimento is financed by CNPq-Pq Grant number 312458/2017-7.

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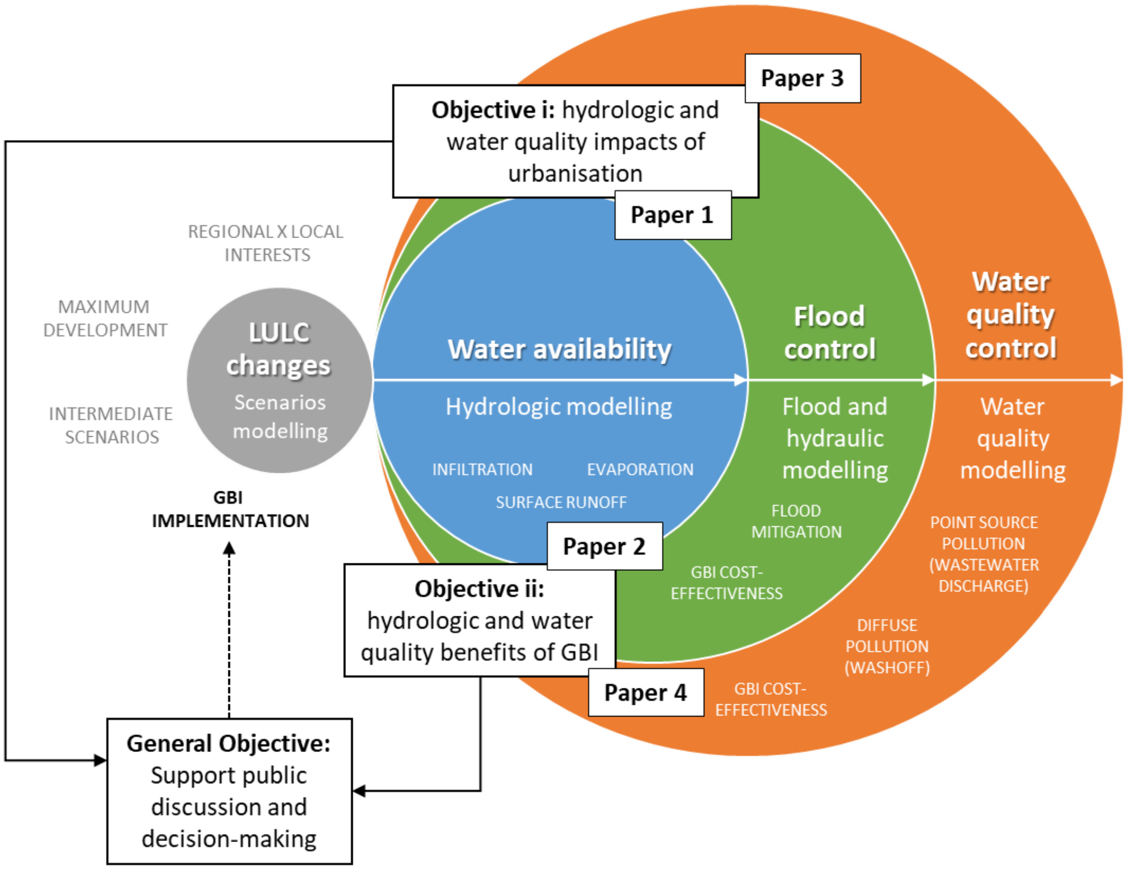
7.9 Summary

This article presented the concluding contribution to quantify GBI's ecosystem services in regulating sediment and nutrient cycles within the Vargem das Flores catchment. The GBI implementation was prepared by optimizing cost-effectiveness in controlling diffuse pollution. By comparing the alternative land use and cover (LULC) scenarios' impact on pollutant loads entering the reservoir, it was possible to assess the GBI's capacity to mitigate diffuse pollution in newly developed urban areas and some of the washoff pollutant loads from consolidated urban areas. Thus, the second specific objective of this thesis of understanding the water quantity and quality benefits of GBI adoption in the Vargem das Flores catchment has been fulfilled (Figure 7.10).

Figure 7.10 – Summary diagram of the developed research and objectives – Paper 4



After evidencing the potential impacts of urban development on the water quality of Vargem das Flores catchment, GBI adoption is underlined as an important strategy to protect the function of the reservoir as water source for 600,000 people. In this sense, the results of this research recommend that further urban development in the catchment must guarantee the protection of remnant forest fragments, reforestation of riparian areas, and treatment of new impervious surfaces with compensatory techniques. Furthermore, the inclusion of GBI in already developed urban areas should be considered to address existing sources of diffuse pollution in the catchment.

The research concludes by highlighting the potential of the water quality model developed as an aiding tool to land use managers in assessing alternative futures and decision-making on interventions in the catchment. Future research should include prioritizing recovery interventions, assessing long-term impacts on water availability due to climate change, and investigating reservoir hydrodynamic and ecological processes to assess the ongoing eutrophication and silting processes.

8 ARTICLE 5: The multifunctional value of urban Green and Blue Infrastructure: a comprehensive and systematic review

"We can no longer let the people in power decide what is politically possible.
We can no longer let the people in power decide what hope is.
Hope is not passive."

Greta Thunberg, at Youth4Climate PreCOP26 (Carrington, 2021)

This chapter presents the last effort – inside the scope of the PhD Thesis – to comprehend the state-of-the-art research methods for evaluating the multiple functions and benefits of Green and Blue Infrastructure in urban and peri-urban areas. This literature review expands the focus beyond the hydrological and water quality benefits studied in the previous chapters, providing a more holistic understanding of how GBI's socioenvironmental ecosystem services can be quantified. Firstly, the review included selecting, screening and codifying studies according to the most frequent quantified benefits, types of GBI, terms, methods, and geographic distribution. In sequence, the review summarises the main findings on quantified GBI environmental benefits, focusing on studies that applied methods with greater potential for application in developing countries.

This review aims to be more rigorous and systematic than the one presented in Chapter 2, following the guidelines proposed in PRISMA 2020 – "Preferred Reporting Items for Systematic Reviews and Meta-Analyses", as presented by Page et al. (2021). Overall, this systematic review intends to frame the previous chapters' results in a broader context and provide valuable insights for future research on the multifunctional benefits of GBI. Focusing on methodological approaches that are more feasible and demand less investment, this article aims to contribute to the ongoing development of knowledge of GBI's multiple potential benefits in the Global South.

The manuscript presented in this chapter refers to the "preprint" version of the paper submitted to the journal "Science of the Total Environment".

8.1 Contributions to co-authored publications

The undersigned authors agree that the nature and extent of their contributions to the paper *"The multifunctional value of urban Green and Blue Infrastructure: a comprehensive and systematic review"* were as follows (Table 8.1).

Table 8.1 - Contributions of co-authors - Paper 5

Co-author	Nature of contribution	Extent of contribution (%)	Signature	Date
Deyvid Wavel Barreto Rosa	Study design, data acquisition and interpretation, drafted manuscript	75		28/03/2023
Talita Fernanda das Graças Silva	Study design, reviewed manuscript	5		11/04/2023
Joanne Chong	Study design, reviewed manuscript	5		08/12/2023
Rachel Watson	Study design, reviewed manuscript	5		08/12/2023
Damien Giurco	Study design, reviewed manuscript	5		12/12/2022
Nilo de Oliveira Nascimento	Study design, reviewed manuscript	5		31/03/2023

8.2 Abstract

Green and Blue Infrastructure techniques, such as green roofs, permeable pavements, and bioretention systems, have been studied for decades and considered worldwide as promising alternatives for more sustainable and effective urban drainage systems. Even so, there is still some reluctance to their wider adoption by public and private decision-makers, especially in the Global South, due to their supposed higher costs and complexity than traditional stormwater control measures. This study looks for evidence of GBI's potential in providing ecosystem services, supporting public discussion and land managers' decisions on adopting GBI. The systematic review of 742 studies that quantitatively evaluated ecosystem services or any social, economic, or environmental benefit of urban GBI looked for the evolution of interests, terms, methods, and geographic distribution of research topics and benefits. Most studies come from researchers affiliated to institutions from the Global North; the types of infrastructure most frequently studied are urban green areas and green roofs; the most frequent benefits are related to climate, socio-cultural services and water quality; methods most common are GIS and monitoring, applied at the scale of cities and neighbourhoods. The main gaps identified are related to the estimation of multiple benefits provided by GBI, studies comparing Global North and South realities, and studies evaluating the benefits of green areas integrated with GBI and urban waters. Finally, some quantified findings on environmental benefits are presented, and feasible methods are recommended for future studies developed in the Global South.

Keywords: Ecosystem services, quantitative benefits, nature-based solutions, Global South and Global North.

8.3 Introduction

The term 'Green and Blue Infrastructure' (GBI) is one of several terms used to refer to alternative and sustainable approaches in the context of stormwater management and urban drainage, among other expressions such as 'Green Infrastructure' (GI), 'Water Sensitive Urban Design' (WSUD), 'Low Impact Development' (LID), 'Alternative Techniques', 'Source Control', 'Sustainable Urban Drainage Systems' (SUDS), and 'Best Management Practices' (BMPs). These concepts were developed in different locals and contexts, and although there are some differences in their specificity and focus, most of them can be applied in the urban context (Fletcher et al., 2014). One of the terms with a recent remarkable increase in popularity is 'Nature-Based Solutions' (NBS) since their consideration as leading measures for climate change adaptation in the UN Conferences of Parties 25 and 26 (United Nations Environment Programme, 2021). Following the conferences, however, many organisations criticised the indiscriminate embrace of NBS in the discourse as the core strategy for climate adaptation, mainly focusing on NBS's potential for carbon sequestration and storage, often taking the focus away from the control of GHG emissions by fossil fuels consumption. Even so, many studies emphasise the importance of the multiple benefits of NBS for social and ecological adaptation to climate change (Seddon, 2022).

In expanding cities, especially in the Global South, there is still a deficit of basic infrastructure for urban water management, flood control, sanitation, and treatment of diffuse pollution. While conventional engineering solutions are still adopted or even required in specific contexts, the climate emergency doubly challenges developing cities to become resilient and adaptable while juggling priorities. In this context, adopting conventional (grey) infrastructure tends to be less sustainable and less adaptable to changing climate conditions, with higher carbon footprints and often more costly to maintain and repair. On the other hand, GBI can help to reduce the impacts of extreme weather events, reducing the impacts of flooding and stormwater runoff by increasing infiltration and storage of water (Rosa et al., 2020; Rosa, Silva, Chong, et al., 2022). However, GBI goes beyond the field of urban water management while providing many other ecosystem services, such as increasing urban biodiversity and connecting fragmented ecosystems, purifying air and water, mitigating the urban heat island effect by providing shade and evaporative cooling, and reducing the need for energy-intensive cooling systems (Brink et al., 2016; Gomes et al., 2021; Pratiwi et al., 2022; Wang et al., 2020; Wong et al., 2018).

Evidencing the multifunctionality of GBI is a key strategy to increase the chances of its wide adoption despite the persistence of investments in grey infrastructure for urban stormwater management (O'Donnell et al., 2017; Tsegaye et al., 2019). In this sense, stakeholders and decision-makers should be better informed by evidence-based research about ecosystem services potentially provided by GBI, incentivising their integration with the environmental and urban development policies (Prudencio & Null, 2018). Institutional mechanisms such as land use zoning, building codes, landscape ordinances, and environmental statutes can incentivise GBI implementation at the city scale (Foster et al., 2011). Political support is also crucial for wide GBI deployment, either by governments and decision-makers in a top-down-driven or through broad civic support and community engagement in a bottom-up-driven effort (Wouters et al., 2016).

From the water-related research studies about urban GBI, many reviews have used quantitative approaches to assess the effectiveness of those practices as control measures of runoff volume and quality (Ahiablame et al., 2012; Liu et al., 2017; Zhang & Chui, 2019). Other studies, however, suggested that there are still gaps in the research about metrics to evaluate the quantity, location, and timing of multiple ecosystem services provided by GBI (Prudencio & Null, 2018). Venkataramanan et al. (2019), for example, suggested that there is still little rigorous evidence on the health and social benefits of GBI, especially for the infrastructure designed for stormwater and flood management. The same authors also highlighted the need for interdisciplinary evaluation of GBI benefits, including quantitative and qualitative methods for evaluating social-related benefits.

8.3.1 A review of the state of the art

A first search in the Scopus and Web of Science databases about quantifying multiple benefits of urban green infrastructure identified 131 review studies until June 2022. After a full-text screening, 57 studies were excluded because they focused on just one type of benefit (20 concentrated on water-related benefits, for example), and 38 focused on the multiple benefits but just one type of GBI (green roofs or urban green spaces, for example). In the Appendix (item 8.7.1), Table 8.9 and Table 8.10 summarise the 38 review studies that quantified multiple benefits of green roofs and urban green spaces (UGS). Of the 36 studies focused on multiple techniques, 15 focused on two or three are presented in Appendix Table 8.11.

Table 8.2 presents the synthesis of the final 21 review studies searched in the Scopus and Web of Science databases about the quantification of multiple benefits of many urban GBI types. The studies included in this summary table meet all the following criteria: peer-reviewed studies published in English and full-text available using institutional access to the main publishers; studies that reviewed a set of other studies that quantitatively evaluated ecosystem services or any social, economic, or environmental benefit of urban GBI; studies that assessed more than one benefit or ecosystem service; studies that evaluated benefits of at least two techniques or types of GBI. This review identified the terminology adopted, types of GBI techniques, benefits, quantity and geographic coverage of case studies included in each article.

Table 8.2 – Review studies searched in the Scopus and Web of Science databases about the quantification of multiple benefits of multiple urban GBI techniques

Source	Terms	Benefits	Other variables	Number of studies and geographic cover (if defined)	Techniques									
					bioretention	green area	infiltration	pavement	pond	rain garden	roof	swale	tank	waterbody
Jayasooriya and Ng (2014)	GI	Stormwater quality and quantity, economics	Spatial scale, data inputs and outputs, models	20 modelling tools	x	x	x	x	x	x	x	x	x	x
Botzat et al. (2016)	GI	Biodiversity, supporting, provisioning, regulating and cultural ecosystem services	Geographical range, greenspace types, cultural scales	200 studies		x			x		x			x
Prudencio and Null (2018)	Green stormwater infrastructure	Stormwater control, provision of food and energy, climate regulation, food control, carbon sequestration, recreation, education, biodiversity	Number of publications, metrics to quantify each benefit	170	x	x	x	x	x	x	x	x	x	x
Zinia and McShane (2018)	Green adaptation strategies, GI	Climate regulation, air quality, aesthetics, recreation, flood prevention, biodiversity, pollination, noise, food, social activities, soil	Social acceptance and economic feasibility	115		x		x		x	x		x	x
Badiu et al. (2019)	GI	Water management, climate regulation, biodiversity, health, well-being, economic, and social	Authors' affiliation, spatial scale, methods	490		x		x		x	x			x
Kim and Song (2019)	GI	Economic capacity, educational opportunity, aesthetics, runoff control, noise, increase and social capital, health, community cohesion, UHI, air and water quality	Type of facility; Cost,-Features-techniques, Green area, Project type	447 project case studies; USA and Canada	x	x		x		x	x	x	x	x
Parker and Zingoni de Baro (2019)	GI	Health, wellbeing, carbon sequestration, biodiversity, air quality, food provision, climate, energy use, cost, social cohesion	Geographic, climate zone, focus area	171		x	x				x			x
Venkataraman an et al. (2019)	GI, NBS, BMP, LID	Health, wellbeing, flood prevention, property values, aesthetics, recreation, education, awareness	Field of research, geographic, methods, analytical method	18	x	x	x	x	x	x	x	x	x	x
Xu et al. (2019)	LID, sponge city, BMP	Cost, water quality, air quality, carbon sequestration, energy	Life Cycle Assessment, scale	89	x	x	x	x	x	x	x	x	x	x
Zhang and Chui (2019)	GI	Hydrological benefits, water quality, biodiversity, soil fertility, air quality, temperature regulation	Spatial scale, methodological approach	100	x			x			x			x
Dick et al. (2020)	NBS	Economic, health, wellbeing, educational, social cohesion	Geographical, method approach, scale	115		x			x	x	x			x
Felappi et al. (2020)	GI	Health, biodiversity, wellbeing	Scale, geographical, method, trade-offs and synergies	72		x				x	x			x
Venkataraman an et al. (2020)	GI	Flood protection, aesthetics, health, recreation, biodiversity, costs, home price	Scale, method, source of data, demographic characteristics	85	x	x	x	x	x	x	x	x	x	x
Abellán García et al. (2021)	SUDS, UGI, GBI	Hydrology, energy efficiency (GR), economic performance (RH)	Climatology, methods and parameters	137; Spain	x		x	x	x		x	x	x	
Liu, Jay, et al. (2021)	NBS, GI	Biodiversity, carbon sequestration and storage, health and wellbeing	Countries, terms, scope, challenges	52	x	x	x	x	x	x	x	x	x	x
Shah et al. (2021)	GBI	Food provision, stormwater runoff, water quality and supply, energy, UHI, carbon storage/sequestration	Food-energy-water nexus framework used as approach, methods	873		x		x		x	x	x	x	x
Shakya and Ahiablame (2021)	GI	UHI, aesthetics, health, air quality, job creation, water quality, social cohesion, agriculture, noise	Methods, locality	16 cities	x	x		x		x	x			x
Teotónio et al. (2021)	Green roofs and walls, GI, NBS	Costs, flood control, energy consumption, noise, air and runoff quality, UHI mitigation, health and wellbeing, biodiversity, food, wood	Economic methods, year, location, indicators, scale, time horizon, discount rate	79	x	x	x	x	x	x	x	x	x	x
Veerkamp et al. (2021)	GBI, NBS	Temperature and stormwater regulation, water and air quality, pollination, recreation, aesthetics	GBI type, geographic, year, type of contrast, indicators, study type	850	x	x	x	x	x	x	x	x	x	x
Ying et al. (2021)	GI	Health, wellbeing, energy, water quality, biodiversity	Countries, institutions, disciplines, terms	2194	x	x	x	x	x	x	x			x
Stroud et al. (2022)	NBS, UGS	Air pollution, temperature, soil protection, carbon, water quality, property values, health, wellness	Geographic, temporal and spatial scales, methods	684		x				x	x			x

Some of these review studies offered a broad and interdisciplinary summary of the research field, assessing methods used to quantify multiple benefits of multiple GBI (Jayasooriya & Ng, 2014; Liu, Jay, et al., 2021; Prudencio & Null, 2018; Teotónio et al., 2021; Veerkamp et al., 2021; Venkataramanan et al., 2020; Venkataramanan et al., 2019; Xu et al., 2019). Nevertheless, after reading and collecting valuable results and conclusions from these publications, a comprehensive and systematic mapping of interests, benefits, and methods tp study multiple GBI was still missing.

Veerkamp et al. (2021) addressed this gap by synthesising multiple methods applied in 850 papers that assessed regulating, maintenance, and cultural ecosystem services provided by urban GBI. The authors recommended that future research should focus on less studied GBI types, especially blue infrastructure small-scale solutions such as rain gardens, green walls, and green roofs, despite their water-related potential benefits. They also found that the less studied geographical regions are in the Global South, especially in African and South American cities, covered by just 5% of the studies. Their final calls were to studies that quantify GBI benefits compared to the social supply and demand, and to the effectiveness of grey infrastructure.

Although there are many review studies about the benefits and ecosystem services provided by urban green infrastructure, the studies with broader geographical cover commonly highlight the lack of robust evidence on GBI benefits considering the different stages of urban development and the great inequalities between Global South and North (du Toit et al., 2018; Liu, Jay, et al., 2021; Veerkamp et al., 2021; Ying et al., 2021). So, the state-of-the-art panorama calls for future research on quantifying GBI benefits to support its implementation, especially in Global South cities. An additional recommendation is shared among the reviews: it is necessary to consider the synergies and trade-offs among the benefits provided by GBI, reinforcing the challenge for interdisciplinary studies (Amorim et al., 2021; Dick et al., 2020; Venkataramanan et al., 2019; Zhang & Chui, 2019).

8.3.2 Objective

In this context, this study aims to contribute to the shared effort of evidencing the potential of GBI to improve the resilience of cities against impacts of climate change and urban development, as well as in the provision of many ecosystem services and their contribution to increasing the wellbeing and cities liveability, with a focus from and to Global South reality. The specific objectives of this review are to explore how the benefits of Green and Blue Infrastructure are being quantified, analysing: 1) the time evolution of interests in benefits, terms, and methods; 2) the geographic distribution of research topics and methods; 3) the most frequently quantified benefits for each GBI type; 4) methods and indicators applied for the study of each benefit; 5) spatial scale of studies according to methods and benefits studied.

8.4 Methods

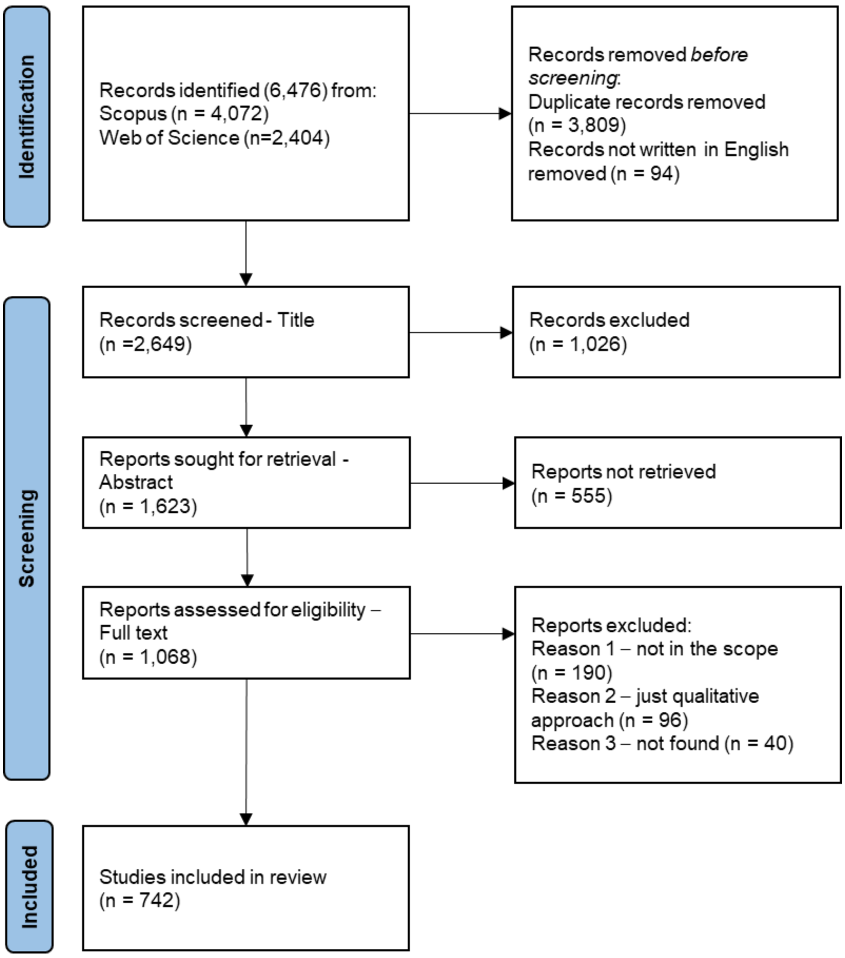
The systematic review followed an adapted version of the guidelines proposed in PRISMA 2020 – "Preferred Reporting Items for Systematic Reviews and Meta-Analyses" (Page et al., 2021). The keywords indicated in Table 8.3 were searched in Scopus and Web of Science databases on 14 June 2022, and the selected studies consisted solely of peer-reviewed works published in English and available using institutional access.

Table 8.3 – Keywords searched in the Scopus and Web of Science databases, with no restriction of the year of publication, and considering the keyword "urban"

Terms		Benefits		Methods
"green and blue infrastructure" (GBI) ***or*** *"green infrastructure" (GI)* ***or*** *"best management practices" (BMP)* ***or*** *"integrated urban water management" (IUWM)* ***or*** *"low-impact development" (LID)* ***or*** *"source control" (SOC)* ***or*** *"stormwater control measures" (SCM)* ***or*** *"sustainable urban drainage system" (SUDS)* ***or*** *"water-sensitive urban design" (WSUD)* ***or*** *"urban canopy" (UCAN)* ***or*** *"urban green areas" (UGAS)* ***or*** *"green corridors" (GCOR)* ***or*** *"sponge city" (SPC)* ***or*** *"green roof" (GR)*	***and***	*"heat island"* ***or*** *"climate regulation"* ***or*** *"temperature regulation"*	***and***	*"quantitative"* ***or*** *"ecosystem services"* ***or*** *"evaluation"* ***or*** *"quantification"* ***or*** *"value"* ***or*** *"valuation"* ***or*** *"cost-benefit"*
		"air quality" ***or*** *"air pollution"* ***or*** *"ozone"* ***or*** *"particulate matter"*		
		"carbon emission" ***or*** *"carbon sequestration"* ***or*** *"carbon storage"* ***or*** *"greenhouse gas"*		
		"health" ***or*** *"social"* ***or*** *"leisure"* ***or*** *"activity"* ***or*** *"recreation"*		
		"agriculture" ***or*** *"food production"*		
		"water quality" ***or*** *"water pollution"* ***or*** *"diffuse pollution"* ***or*** *"non-point source solution"*		
		"water quantity" ***or*** *"runoff"* ***or*** *"infiltration"* ***or*** *"flood"* ***or*** *"water security"* ***or*** *"water supply"* ***or*** *"stormwater"*		

With these combined terms, 6,476 studies were initially identified, from which 3,809 were duplicated and 94 ere not written in English, excluded before the screening stage. Following the screening of title, abstract, and full text, 742 studies were included in this review, fulfilling the interest in the quantification of benefits promoted by any GBI type in urban areas (Figure 8.1). The list of the 742 selected references is available in the Supplementary Data.

Figure 8.1 – Flow diagram for the systematic review based on Prisma 2020



Six classes of information were extracted from the selected studies: geography, spatial scale, terminology, techniques, benefits, method, and indicators. During the last screening stage, if the full text's content fitted the scope of the review, data on each information class were extracted and recorded textually in a spreadsheet for the first 200 papers read. This corpus created a common categorisation and codification to describe the information classes (Table 8.4), accelerating the full-text reading process focused on extracting the codified information.

Table 8.4 – Categories and codes defined for analyzing the 742 selected papers

Classes	Categories	
	Code	**Description**
Geographic location	Affilliation Case	Country of affiliation of the 1st (and other identified) author(s) City or country of study case
Spatial scale (average order of the magnitude of the studied area, when it is the case)	Pilot Building Block Subcatchment Neighbourhood City Catchment Region Metropolis State Country Continent	(10^1 m²) (10^3 m²) (10^4 m²) (10^5 m²) (10^1 km²) (10^2 km²) (10^3 km²) (10^4 km²) (10^5 km²) (10^6 km²) (10^7 km²) (10^7 km²)
Terminology	ADAPT BMP GBI GI GR IUWM LID NBS SCM SOC SPC SUDS UAGR UCAN UGAS WSUD	Climate Adaptation Strategies, Ecosystem-Based Adaptation Best Management Practices Green and Blue Infrastructure, Blue and Green Infrastructure Green Infrastructure, Natural Infrastructure Green Roof Integrated Urban Water Management Low Impact Development Nature-Based Solutions Stormwater Control Measures, Stormwater Management Practice Source Control Sponge City Sustainable Urban Drainage Systems Urban Agriculture Urban Canopy, Urban Trees Green Areas, Green Spaces, Open Spaces, Parks, Forests Water-Sensitive Urban Design
Technique	bioret green infilt pave pond rgard roof swale tank water	Bioretention cell Green space, parks, open areas, trees, forests, riparian areas, etc. Infiltration trench, pit, strip Permeable and porous pavement Detention and retention pond or basin, wetland Rain garden Green roof, blue roof, green wall, green façade Vegetative swale Rain barrel, cistern, rainwater harvesting tank Waterbody, watercourse
Benefits	access aesthe air biodiv carbon cost cultural econo food health recrea social soil sound temp wqual wquan	Human access, accessibility Aesthetics and landscape improvement Air quality improvement Biodiversity protection and enhancement, habitat creation Carbon storage, sequestration or other GHG emissions avoided Cost reduction with infrastructure investment Cultural services, espiritual inspiration, educational opportunities Economic development of real estate, job creations, productivity growth Food provision, urban agriculture Health (physical and mental) improvement and wellbeing Recreation opportunities Social cohesion, community health Soil protection, erosion control Sound insulation, reduced noise pollution Temperature or local climate regulation, Urban Heat Island mitigation Water quality improvement Water quantity: runoff control, infiltration increase, flood reduction

Table 8.4(cont.) – Categories and themes for analyzing the selected papers

Classes	Categories	
	Code	**Description**
Methods	LCA	Life Cycle Assessment
	ModWater	Modelling water cycle and quality (SWMM, SWAT, MUSIC, etc.)
	Monitoring	Monitoring (field measurement – primary or secondary source)
	Climate	Climate modelling (ENVI-met, CFD, WRF, etc.)
	Review	Literature review
	CBA	Cost-Benefit Analysis
	Qualita	(Semi-)Qualitative multicriteria index and Analytic Hierarchy Process
	GIS	Geographical Information System, remote sensing, spatial analysis
	Survey	Survey, questionnaire, interview, public or expert consultation
	BEST	B£ST, TEEB, InVEST, and other ecosystem service assessment tools
	i-Tree	i-Tree model (Eco, Canopy, Hydro, etc.)
	Contingent	Contingent valuation, discrete choice experiment
	Hedonic	Hedonic price analysis
	Experimental	Experimental (pilot experiment with field or laboratory analysis)
	Statistical	Statistical analysis, regression, and correlation tests
Indicators	Runoff	Runoff volume or flow
	Wpollut	Water pollutant load or concentration (TSS, COD, nutrients, etc.)
	Apollut	Air pollutant load or concentration (PM, O_3, CO, NOx, etc.)
	Temp	Surface or air temperature, thermal comfort, heat flux, etc.
	Carbon	Carbon mass or volume emitted, stored, sequestrated, etc.
	WTP	Willingness To Pay, Willingness To Accept, etc.
	PropValu	Property values
	Cost	Cost (capital, maintenance, operation, etc.)
	IndicQual	(Semi-)Qualitative indicators and indexes
	GIS	GIS variables (NDVI, landscape metrics, vegetation cover, etc.)
	AvoidCost	Avoided costs (travel cost, damage cost, energy cost, etc.)
	SocioEcon	Socioeconomic indexes (HDI, income, minority, age, Gini, etc.)
	Frequency	Frequency of occurrence (visits, use, restrictions, cases, etc.)
	Distance	Distance (Euclidean distance, walking distance, buffer)
	Bibliometric	Bibliometric and scientometric factors (scale, methods, values, etc.)
	Diversity	Diversity (species richness, number of species, Shannon index, etc.)
	HealthData	Health data (mortality, morbidity rate, disability-adjusted life years)

After the codification-focused reading of the 742 studies, the total number of studies included in each category was calculated. The less frequent categories were joined into other more frequent categories according to their similarity, so each class was reclassified into ten categories. Then, the percentage of co-occurrence between pairs of all ten categories in the six classes was calculated and sorted in a heat map according to the co-occurrence frequency.

The authors' countries of affiliation were identified and counted, grouped into regions and continents, and differentiated between Global North and South. The geographic location of the case study was listed and represented in maps with the geographic coordinates of the centroid of world cities or countries, depending on the scale of the study.

Finally, VosViewer software was used to produce the network maps presented in the sequence (van Eck & Waltman, 2010). Those visual representations of frequency and connections among the keywords will help synthesise this work's main findings.

8.5 Results and discussions

For the six information classes, the number of studies corresponding to each of the ten reclassified categories is presented in Table 8.5. The total number of papers is not constant among the classes because a study can refer to more than one category. In the case of spatial scale, not every paper included case studies or referred to the geographic scale of the study, so the number of papers is smaller than the total amount of reviewed papers (742).

The terminology adopted in the searched keywords potentially affected the research results, such as the decision to restrict the search to English language terms. This can reduce the number of papers selected from non-English speaking countries such as France and Brazil, where terms *"techniques alternatives"* and *"técnicas compensatórias"* have been frequently used to refer to stormwater management approaches included in the scope of this research (Fletcher et al., 2014). Adopting the premise of English as a *lingua franca* in research and science has been discussed by linguistic scholars (Monteiro & Hirano, 2020; Wilkinson et al., 2021), and it can be further examined in the context of the impacts of GBI-related studies in the local reality.

'Green infrastructure' was the most used term and was present in 46% of the papers, many times associated with others. The broadest use of GI is related to the fact that it is a concept used beyond the stormwater research field, such as in landscape architecture and ecology, which agrees with findings from other reviews (Benedict & McMahon, 2000; Fletcher et al., 2014). The last group, 'ETC', which aggregated all the terms with the lowest frequency, included many expressions – such as WSUD, IUWM, SCM, sponge city and source control – relatively restricted to water-related subjects.

Table 8.5 – Most frequent categories and themes, reclassified into 10 codes

Classes	Papers	Categories	
		Code	Description
Terminology	344	GI	GI
	141	UGAS	UGAS
	92	GR	GR
	61	NBS	NBS
	54	LID	LID
	41	GBI	GBI
	35	BMP	BMP
	35	SUDS	SUDS
	33	UCAN	UCAN
	91	ETC	WSUD, SPC, ADAPT, SCM, UAGR, SOC, IUWM
Technique	495	green	Green space, parks, open areas, trees, forests, riparian, etc.
	231	roof	Green roof, blue roof, green wall, green façade
	91	pave	Permeable and porous pavement
	84	pond	Detention and retention pond or basin, wetland
	65	biore	Bioretention cell
	62	tank	Rain barrel, cistern, rainwater harvesting tank
	56	swale	Vegetative swale
	54	infil	Infiltration trench, pit, strip
	52	rgard	Rain garden
	51	water	Waterbody, watercourse
Benefits	296	temp	Temperature or local climate regulation
	285	soci	Social, health, recreation, access, aesthetics, cultural
	256	wquan	Water quantity regulation (runoff, infiltration, evaporation, etc.)
	200	air	Air quality improvement
	176	wqual	Water quality regulation
	168	econ	Cost reduction, economic
	147	carbon	Carbon storage, sequestration, reduced emission
	138	biodiv	Biodiversity protection
	77	agri	Urban agriculture, food, soil, and raw products provision
	39	sound	Sound and noise regulation
Methods	217	GIS	GIS, remote sensing, spatial analysis, multicriteria index
	145	Monitor	Monitoring (field measurement – primary or secondary)
	131	Review	Literature Review
	124	Survey	Survey, hedonic price analysis, contingent valuation
	108	CBA	Cost-Benefit Analysis, Life Cycle Assessment
	96	BEST	Existing ES assessment tools (B£ST, TEEB, i-Tree, etc.)
	80	ModWater	Model water (SWMM, SWAT, MUSIC, etc.)
	77	Climate	Climate model (ENVI-met, CFD, WRF, etc.)
	36	Statist	Statistical analysis, regression, and correlation tests
	29	Experim	Experimental (pilot experiment with field or laboratory)
Indicators	219	Money	WTP, WTA, Property Values, travel cost, damage cost
	216	GIS	GIS variables (NDVI, landscape metrics, etc.), distances
	196	Temp	Surface or air temperature, thermal comfort, heat flux, etc.
	170	Runoff	Runoff volume or flow
	155	SocioData	Socioeconomic indexes (HDI, income, etc.), health data
	128	Apollut	Air pollutant load or concentration (PM, O_3, CO, NOx)
	114	Carbon	Carbon and GHG emission, storage, sequestration, etc.
	99	Wpollut	Water pollutant load or concentration (TSS, COD, etc)
	96	Diversity	Diversity (species richness, Shannon index)
	66	Bibliometri	Bibliometric factors (scale, methods, values, etc.)
Spatial scale (average order of magnitude)	21	Country+	(10^7 km²)
	39	Metropolis	(10^5 km²)
	27	Region	(10^4 km²)
	66	Catchment	(10^3 km²)
	207	City	(10^2 km²)
	106	Neighbourhood	(10^1 km²)
	41	Subcatchment	(10^5 m²)
	39	Block	(10^4 m²)
	55	Building	(10^3 m²)
	23	Pilot	(10^1 m²)

The most frequently studied GBI techniques were included in the code 'green': two-thirds (67%) of the studies evaluated some type of green spaces, open areas, parks, trees, urban forests, riparian vegetation, etc. The study of the ecosystem services provided by urban green areas is a long-standing and broad research topic, especially in urbanism and landscape ecology. Interestingly, the research on ecosystem services provided by the urban 'blue infrastructure' (watercourses and waterbodies) was the least frequent. Among the built techniques, the group 'roof' was the most frequently studied in interdisciplinary approaches (31% of the selected papers).

GBI impact in temperature regulation was the most frequently studied benefit (40%), notably referring to the mitigation of the urban heat island effect or the impacts of global warming. Urban afforestation is applied to improve urban thermal comfort even before the development of microclimate models, as trees provide shade and dissipate heat through evapotranspiration. The second code (38%) includes the GBI social-related benefits to improve community and citizen's health, and the collapse of many benefits in one code was justified by the difficulty of disconnecting the improvement of mental and physical health related to the creation of opportunities for leisure and contact with nature. The starting point of this research, the water cycle regulation, was the third most frequent (35%) GBI benefit in interdisciplinary studies.

GIS tools for the spatialisation of GBI benefits were the most frequent methods (29%) applied in interdisciplinary research, followed by monitoring studies (20%) using data collected in the field or measurements available in public databases. Computational models were less frequently applied to quantify GBI benefits in interdisciplinary research – existing tools for quantification of ecosystem services were applied in 13% of the studies, water-related models in 11%, and climate models in 10%.

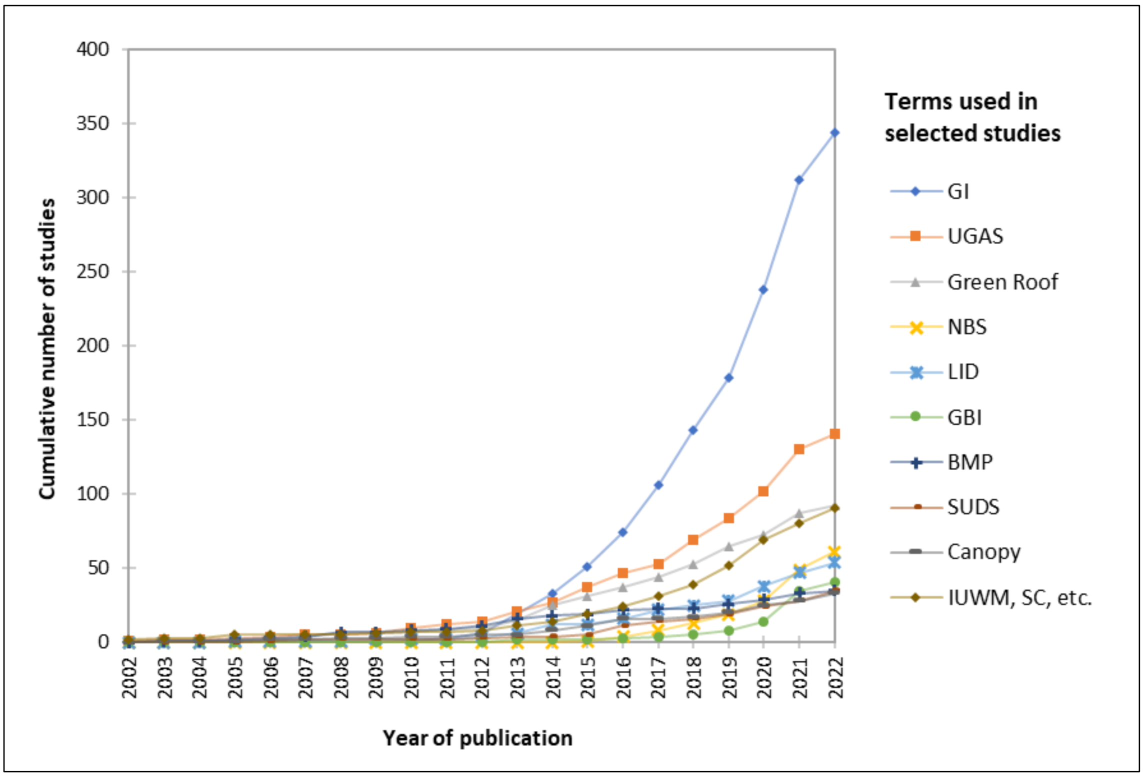
The most frequent quantitative indicator of GBI benefits was monetary value (30% of the studies), while a notable 70% quantified the benefits without furthering their monetisation. GIS indicators were the second most common (29%) among interdisciplinary studies. Case studies were developed more frequently in the scales of administrative unities, such as cities (28%) and neighbourhoods (14%), or within natural boundaries of catchments (9%) and subcatchments (6%).

8.5.1 Time evolution

The graphs presented in this section indicate the research interests in quantifying GBI benefits, showing the cumulative number of papers published over the last two decades. The total number of studies increased cumulatively from 3 in 2002 to 54 in 2012, 273 in 2017, and 742 until 14 June 2022.

Figure 8.2 presents the terms used in the selected studies over time. Until 2012, UGAS was the most used term, after succeeded by GI. Since 2020, the frequency of the terms NBS and GBI has increased more intensely compared to other terms.

Figure 8.2 – Cumulative number of papers published per year according to the terms used



Concerning the types of GBI studied, there is no expressive change in research focus, as green areas and green roofs remain the most frequently studied GBI over the last 20 years (see Figure 8.3). Figure 8.4 presents the cumulative number of studies about GBI benefits over time.

Figure 8.3 – Cumulative number of papers published according to the studied GBI types

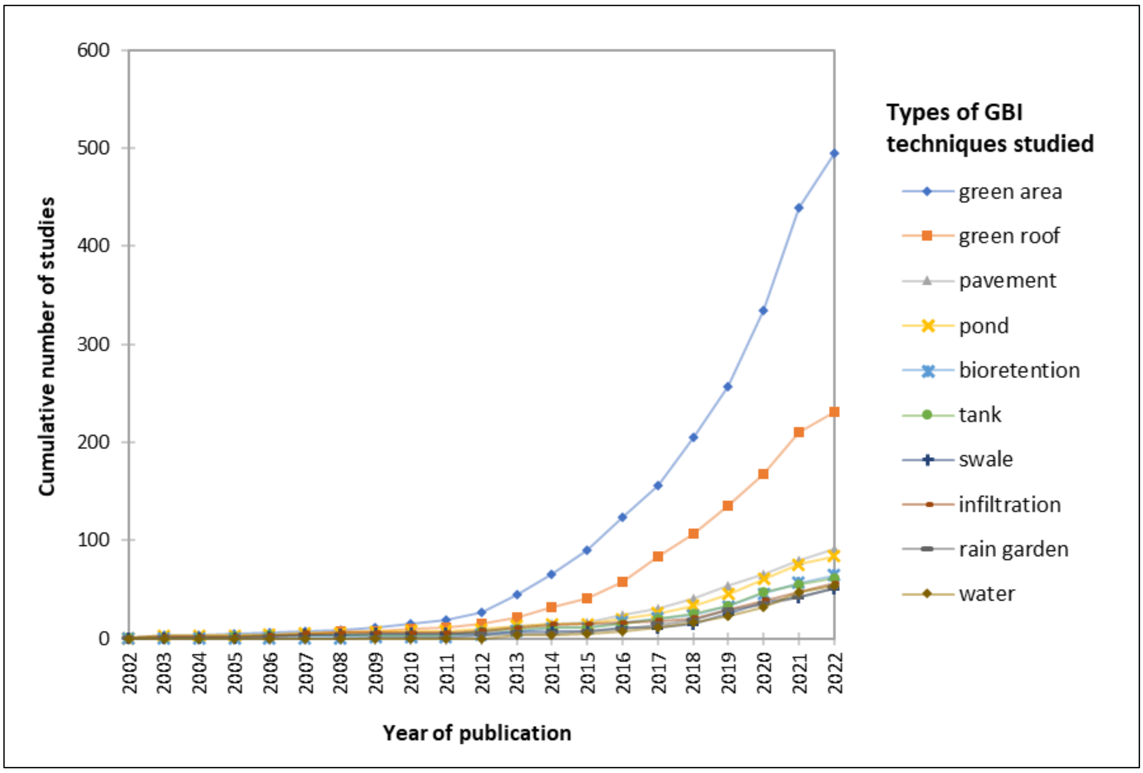
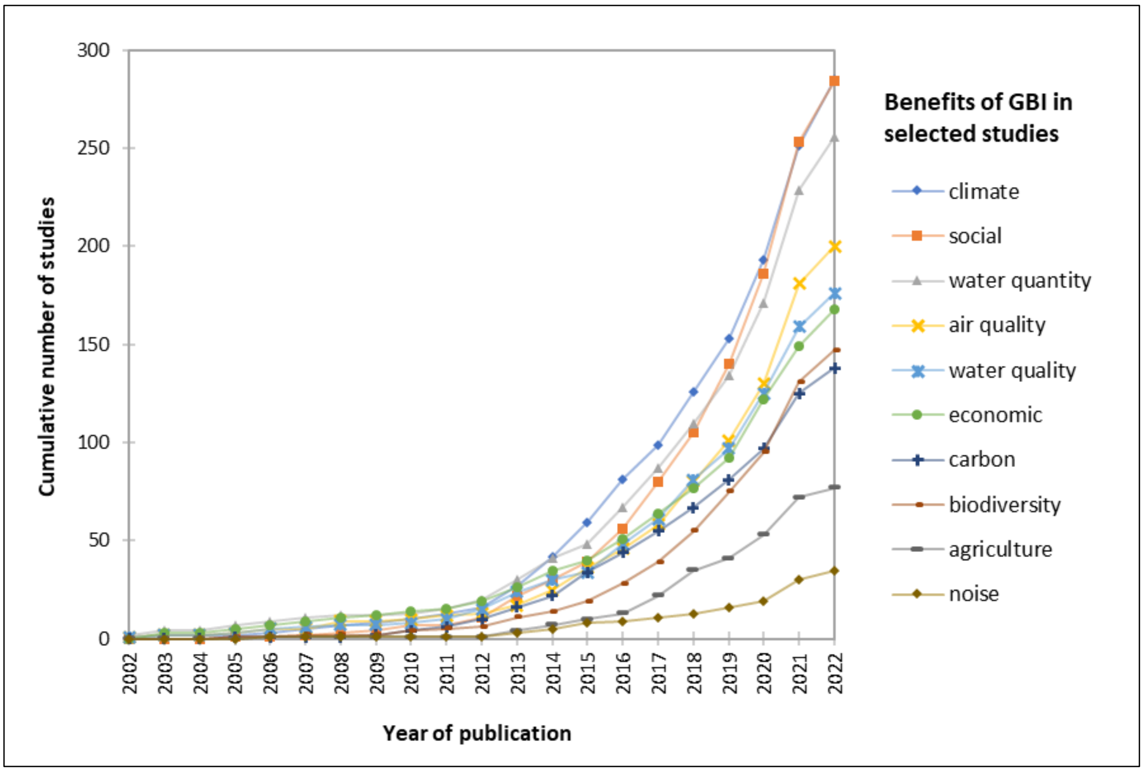


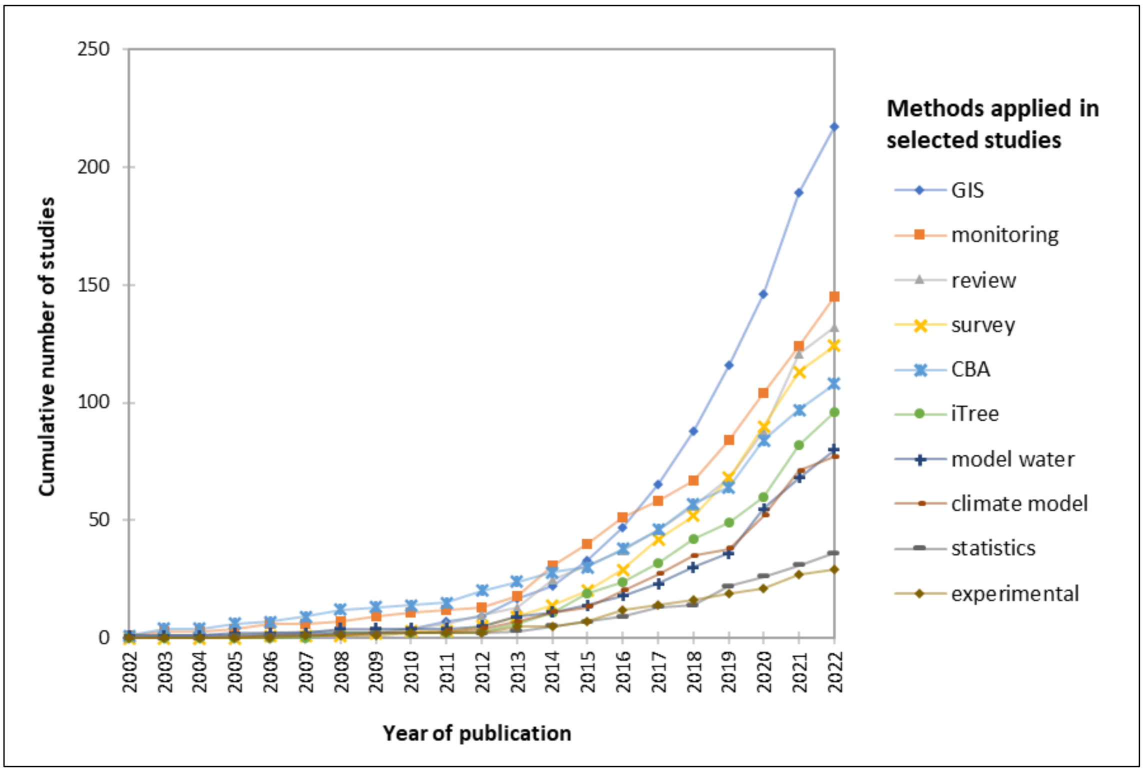
Figure 8.4 – Cumulative number of papers published according to the studied GBI benefits



Until 2012, water-related and economic benefits were the main focus of the selected studies. In 2014, climate-related benefits became the most quantified among the selected studies, being succeeded by social-related as the most studied benefit in 2021. GBI benefits to air and water quality improvement are also more frequently studied than the economic benefits since 2018.

Concerning the methods most frequently applied to quantify the multiple GBI benefits, Cost-Benefit Analysis was the most common until 2013, when monitoring studies became the most frequent. With the mainstreaming of spatial databases and an increased variety of available platforms, GIS tools have become the most frequently applied method to quantify GBI benefits since 2017 (see Figure 8.5).

Figure 8.5 – Cumulative number of papers published per year according to the methods applied to quantify the GBI benefits



8.5.2 Co-occurrence of categories

The percentage of co-occurrence among the ten categories and six classes was calculated and classified in a heat map according to its frequency (most intense colours indicate the greatest co-occurrence) and represented in the matrix of Figure 8.6.

Figure 8.6 – Matrix of co-occurrence (percentage of studies in a row category which co-occurred with a column category) – the more intense the colour, the greater the co-occurrence between the pairs of terms, techniques, benefits, methods, indicators, and scale

The main insights from the co-occurrence analysis (Figure 8.6) are:

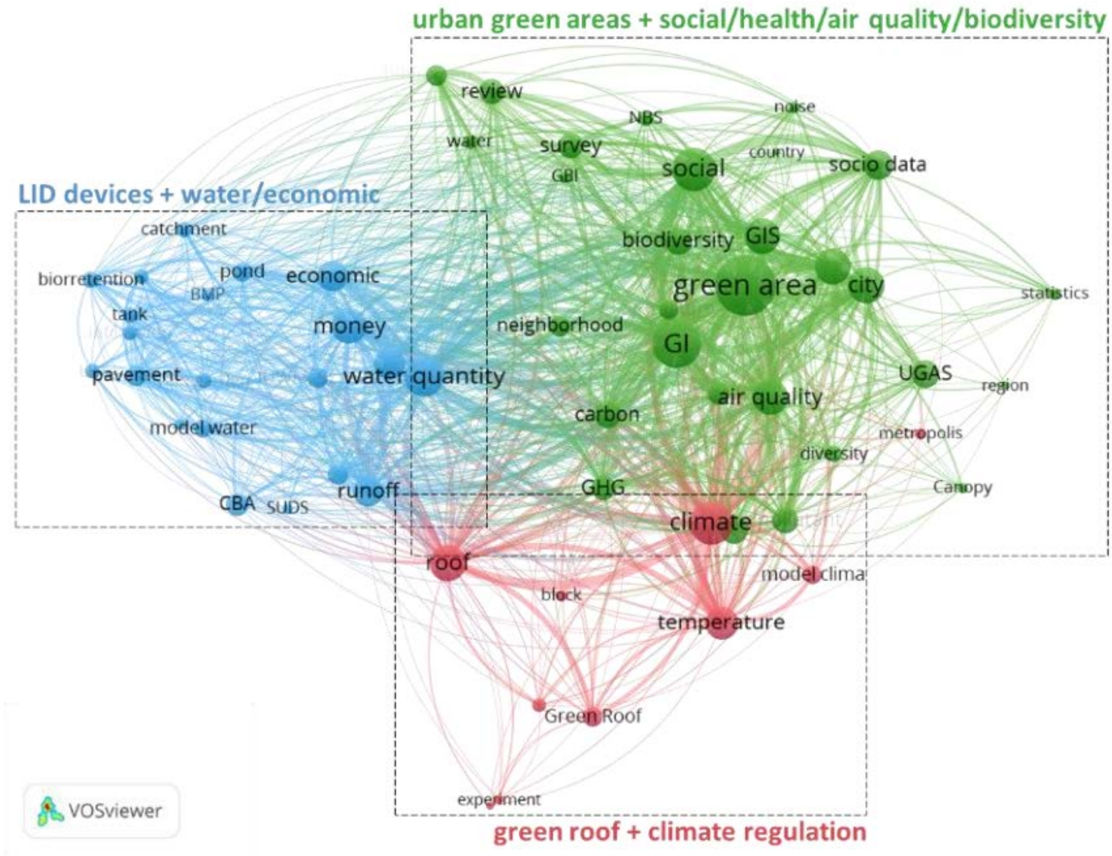
- Most studies about green areas, rain gardens, and water used the term GI, while studies about drainage techniques (permeable pavements, ponds, bioretention, tanks, swales and infiltration practices) frequently used the terms LID, BMP, and SUDS, besides GI.

- Drainage techniques (permeable pavement, pond, bioretention, tank, swale, infiltration, and rain garden) were frequently studied together, mostly focusing on assessing water quantity, quality, and economic benefits throughout water modelling and CBA. In those assessments, the most frequent indicators were monetary value, runoff and water pollutants, studied in the spatial scale of catchment, city and subcatchment. Studies about drainage techniques frequently included green roofs in their assessment.
- Studies about water (rivers, lakes, wetlands) almost always also studied green areas, most frequently assessing social-related benefits by applying GIS methods and indexes.
- Some topics are substantially applied to study green areas: social, air quality, biodiversity, food provision, and noise benefits; GIS and statistical methods, followed by monitoring, survey, i-Tree models and climate models; GIS index, socio data, diversity and air pollutant as indicators; large spatial scales (country, metropolis, region, and city);
- GIS was the most frequently adopted method for quantifying climate, social, air quality, biodiversity, and agriculture benefits, most frequently in the metropolis, region or city scale, and frequently associated with statistical analysis.
- Experimental studies were mostly developed on the pilot or building scale, assessing green roofs' climate benefits, frequently associated with water-related benefits.

In summary, the co-occurrence analysis shows that there is a gap in the combined assessment of the benefits of GBI conceived for stormwater management (permeable pavement, pond, bioretention, tank, swale, infiltration, and rain garden) and the urban green infrastructure not primarily designed for that. In this sense, there is great potential for holistic methodological approaches that contemplate the spatialisation of multiple GBI benefits in different scales. Some of the methods frequently applied for estimating the ecosystem services provided by green areas can be adapted to study the social and environmental co-benefits of the stormwater-oriented GBI types, such as methods based on GIS and geostatistical analysis, i-Tree Eco model and open-source climate models.

The network map in Figure 8.7 represents the frequency (size) and connections (line width and distance) between codes extracted from the selected studies. Three clusters can be identified in the cloud of topics and their connections.

Figure 8.7 – Network map between terms, techniques, benefits, methods, indicators and spatial scale (using classified data)



The biggest cluster (green colour, top-right) is the most interdisciplinary group of studies focused on quantifying multiple benefits related to urban green areas. The interests of this group include the social-related benefits (social, health, recreation, access, aesthetics, cultural), the air quality improvement, and biodiversity protection associated with urban green areas (green space, parks, open areas, trees, forests, riparian vegetation). Those studies were mainly published in multidisciplinary journals such as 'Urban Forestry & Urban Greening', 'Sustainability', 'Forests', 'Ecosystem Services', and 'Landscape and Urban Planning'. These studies are usually developed on medium to macro-scale, considering political-administrative limits as cities, metropolises and regions.

The second cluster (blue colour, left) comprises the group of studies interested in quantifying the water-related and economic benefits of GBI types usually associated with stormwater management (permeable pavements, detention ponds, bioretention cells, rainwater harvesting tanks, vegetative swales, infiltration trenches, and rain gardens). Their relatively isolated position illustrates that those GBIs are rarely considered in multidisciplinary studies. Though evidence about their benefits to water cycle regulation is becoming more robust, a clear gap exists about their combined effects with UGAS in providing multiple ecosystem services. Those studies were mainly published in journals such as 'Water', 'Sustainability', 'Journal of Environmental Management', and 'Science of the Total Environment'. These studies usually consider physiographic limits such as catchment and subcatchment scales, frequently applying cost-benefit analysis and hydrological modelling methods.

The third cluster (red colour, bottom) includes studies focused on quantifying the benefits of green roofs in regulating temperature and mitigating the urban heat island effect, reducing energy consumption, and sometimes including the related benefits of rainwater control and avoided carbon emissions. Those studies frequently apply climate modelling and experimental measurements on the pilot or building scales. They are mainly published in journals such as 'Building and Environment', 'Journal of Cleaner Production', 'Ecological Engineering', and 'Urban Forestry & Urban Greening'.

The evident preference for the term 'green infrastructure' was already identified in previous systematic review studies (Bartesaghi Koc et al., 2016; Ersoy Mirici, 2022; Matsler et al., 2021; Parker & Zingoni de Baro, 2019). Although it is the most frequent term in this systematic analysis of quantitative studies, GI is often used in studies that do not define its concept (Matsler et al., 2021). In the screening process, hundreds of studies were excluded because they did not clearly explain to which functional structures (here classified as different techniques) the term refers. Considering the urban-water-management context from which this research is derived, and with the intention of approximating these still separated groups of drainage techniques and urban green areas (see Figure 8.8), the choice of terms GBI and NBS is deliberate (and apparently shared, as indicated by the late increase of their use). In sequence, Figure 8.9 presents the network map between techniques, benefits, and methods.

Figure 8.8 – Network map between terminology, techniques, and benefits

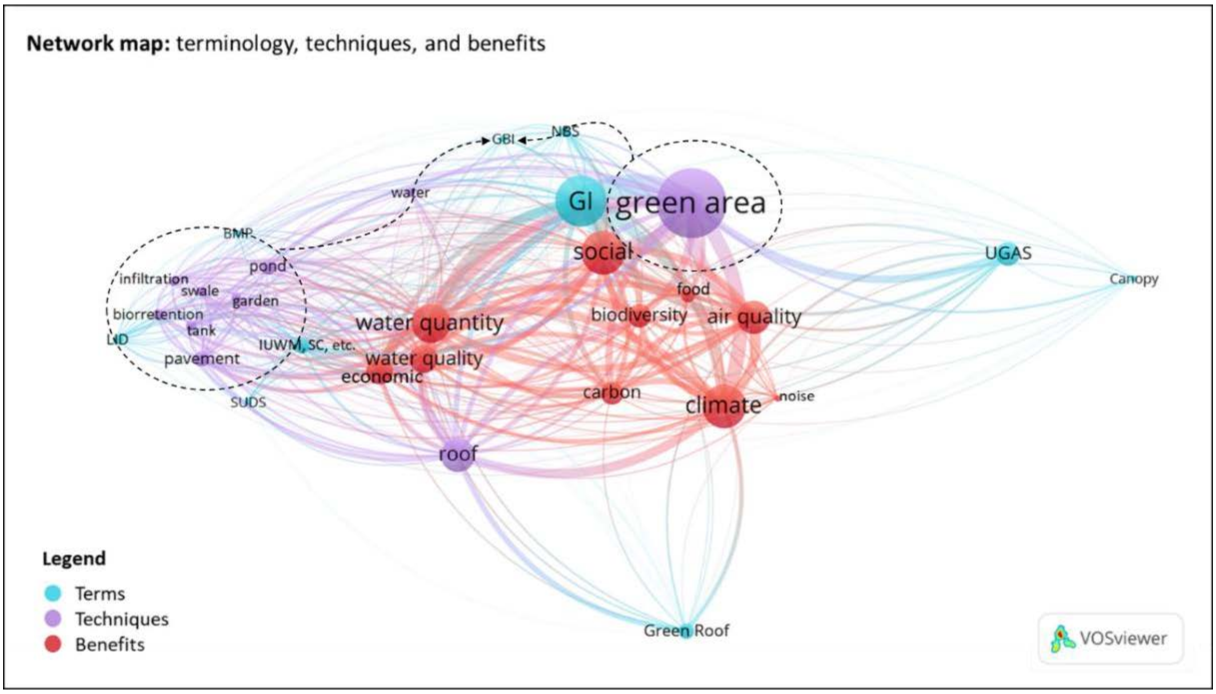
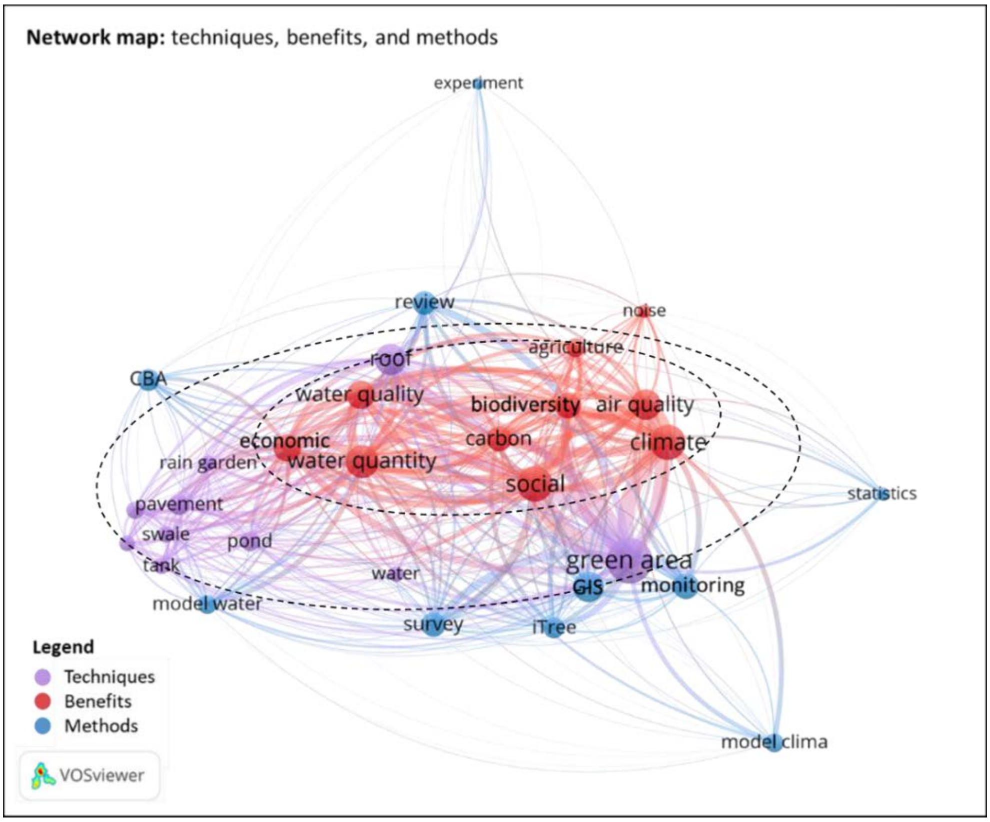


Figure 8.9 – Network map between techniques, benefits, and methods



Although the central importance of the multifunctionality (indicated by the interconnected group of benefits inside the inner ellipse in Figure 8.9) seems clear for mainstreaming GBI-NBS implementation, the selection of the best-fitted techniques (the intermediate ellipse in Figure 8.9) is still open to be explored. GIS-based methodological approaches, coupled with other spatial-oriented models, have the potential to integrate diverse research areas and can contribute to clarifying the evidence in favour of GBI adoption. These results agree with what Nieuwenhuijsen (2020) observed in their review and reinforce the need for a multidisciplinary approach to obtain optimal benefits. An integrated evaluation is also needed to consider synergies and trade-offs between the multiple benefits (Amorim et al., 2021).

Furthermore, free and available data and models are feasible methods that can allow the development of further research about the less studied geographic areas and benefits in the context of the Global South (Veerkamp et al., 2021).

8.5.3 Geographic distribution

The geographical distribution of the number of studies published per country of affiliation of the first author is illustrated in the map of Figure 8.10. The top ten countries with the greatest number of affiliated authors were the United States of America (144 studies), China (86), Italy (57), the United Kingdom (53), Australia (43), Germany (34), Spain (32), Brazil (24), South Korea (17), and Portugal (14). The concentration of studies in countries from the Global North is evident, as authors from Europe published 40% of the studies, 21% by authors from North America, and 6% from Oceania. Authors from Eastern Asia (China, Korea, Japan, Hong Kong, and Taiwan) published 17% of the studies, and the other 16% were published by authors from other Asian countries (7%), Latin America (6%) and Africa (2%). The map of Figure 8.11 illustrates the geographical distribution of case studies, where each dot represents one study developed in that location (city or country).

Figure 8.10 – Geographical distribution of countries of affiliation of the first authors, distinguishing countries from Global North (pink) and South (green), and highlighting the number of papers for the top ten countries with the highest productivity

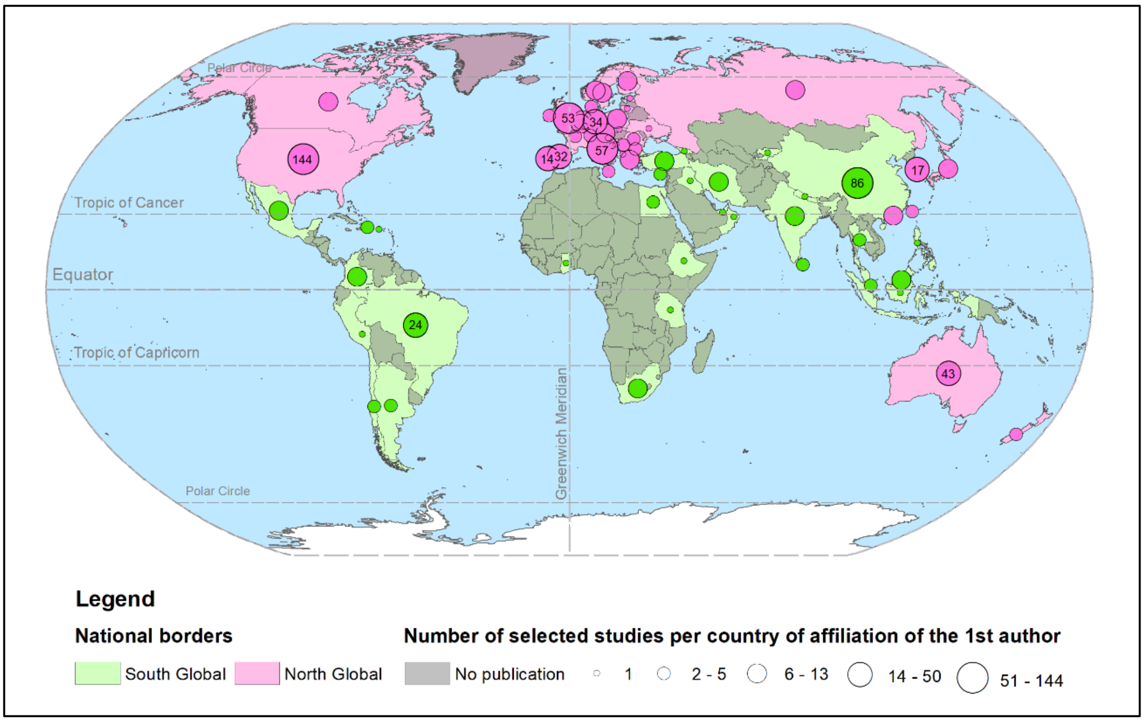
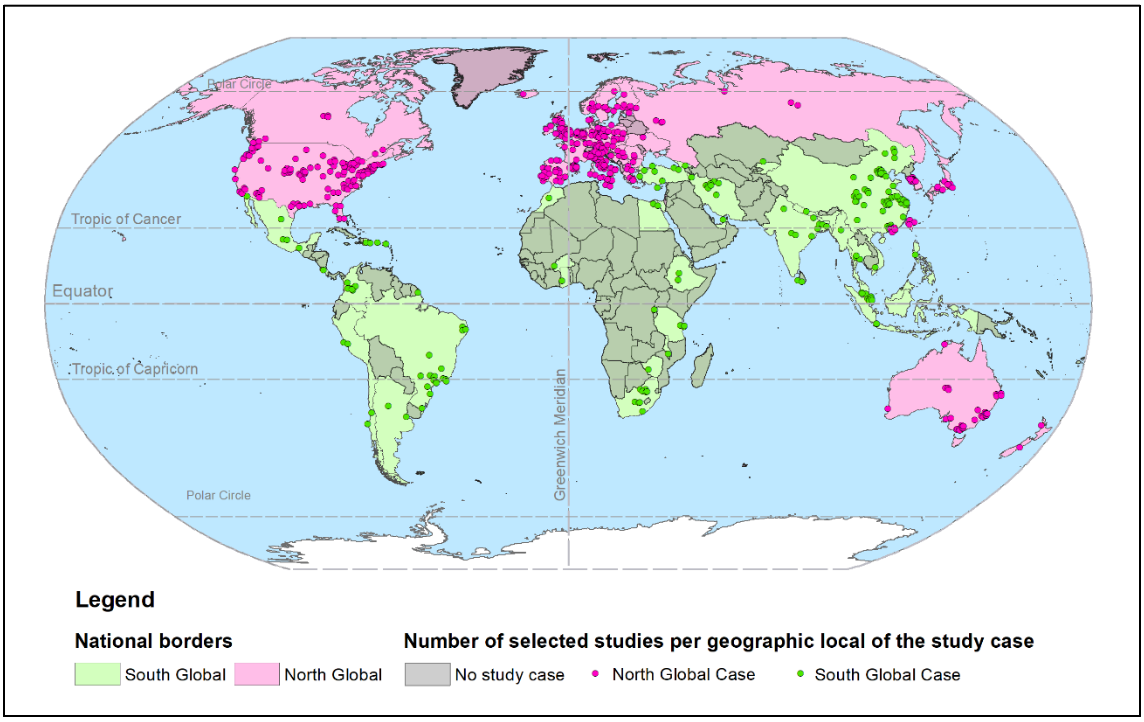


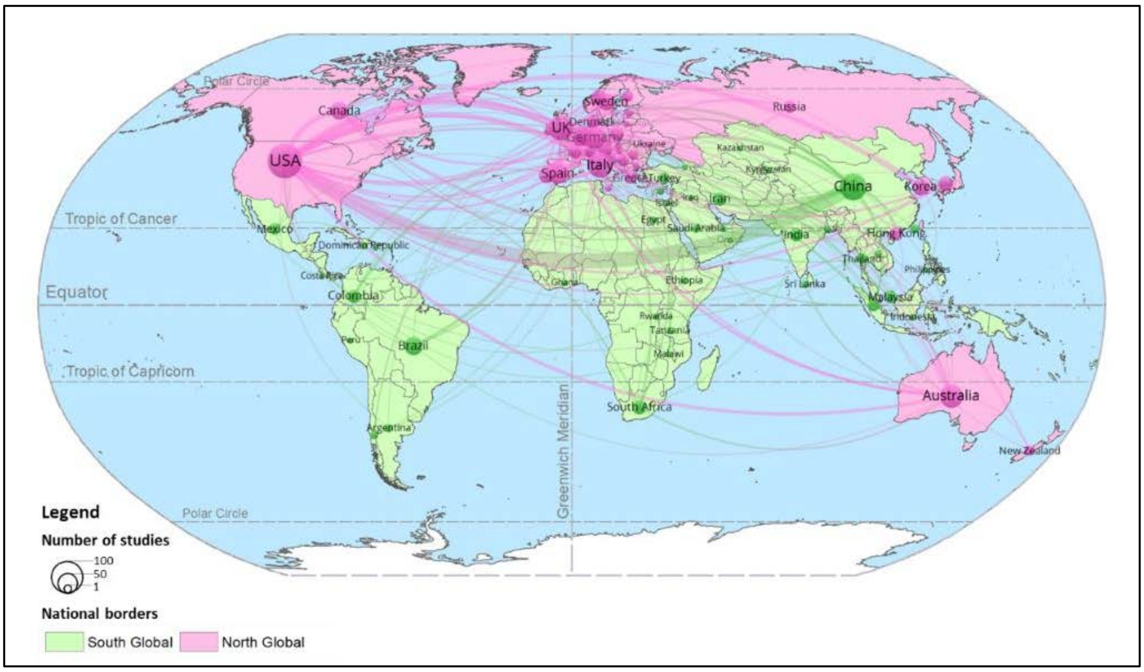
Figure 8.11 – Geographical distribution of case studies (1 dot per case study in the centroid of the city or country), distinguishing countries from North (pink) and South (green colour)



The unequal geographical distribution of the studies is even more evident in the map of Figure 8.11, with the European continent almost entirely covered by dots. Other areas with a high density of case studies are also marked on the East United States Coast and the Northern portion of the West Coast. Apart from those areas, a great concentration of studies can be identified in the biggest cities of large countries such as China, Brazil, Australia, South Africa, and Iran, or covering small countries with big cities such as Korea, Japan, Malaysia, Hong Kong, Taiwan, and Singapore.

Finally, Figure 8.12 shows a map of connections indicating the frequency of collaboration among authors from different nations. The wider the line, the greater the number of studies developed in collaboration by authors affiliated to institutions in the connected countries.

Figure 8.12 – International collaboration in publication (wider lines indicate greater collaboration), distinguishing countries from Global North (pink) and South (green colour)



Most studies were developed in collaboration between countries from the Global North, and the map highlights the great exchange between North America and Europe. China is the greatest South Global research partner with institutions from the Global North. However, there is a clear gap in research comparing North-South realities and discussing similarities and specificities of developing countries, especially tropical countries in Latin America, Africa, and South and Southeast Asia. Few differences between the Global South and North were identified in the frequency of themes and interests. The term ‘Green Infrastructure’, for example, is used more frequently in Global North (53% of studies) than in Global South (31% of studies); and the benefits related to ‘water quantity’ are more frequently studied in Global South (43%) than Global North (32%); while ‘air quality’ is more frequently studied in North (34%) than in South (17%).

These results are mainly aligned with the obtained by Veerkamp et al. (2021), though these authors found even fewer publications from the Global South outside China. Other reviews with limited scope did not find publications from Latin America and Africa (Parker & Zingoni de Baro, 2019), while others focused on searching for studies developed in the same regions (du Toit et al., 2018). The prominence of European countries and the United States as the main places where GBI research is based is evident and was already identified in previous review studies (Badiu et al., 2019). Since 2019, however, Eastern Asia has become the most productive region of research about GBI benefits, especially with the elevation of China as the country with the highest research production in the area. Northern and Western Europe were already identified as the frontrunner in GBI studies (Hegetschweiler et al., 2017), but in the selection made for this review, Southern Europe was the most productive region in the continent, with the contribution of Italy, Spain, and Portugal.

8.5.4 Summary of main quantified benefits

This item presents a non-exhaustive summary of results extracted from the studies that numerically quantified benefits, indicating measurement units and spatial references that allow comparison between different contexts and areas of study. At this stage, the summary focuses on presenting the quantitative results of studies that compiled evidence in the literature to provide references for future comparisons.

Table 8.6 presents the summary of results extracted from 17 studies that assessed the potential of GBI in temperature reduction.

Table 8.6 – Summary of GBI efficiency in temperature reduction

Reference	Case study	Method	Temperature reduction (°C) Mean [Min-Max]			
			Green areas	Rain gardens	Green roofs	Water-bodies
Al-Kayiem et al. (2020)	-	Review of 128 studies	0	0	1.25 [0.2-4.2]	0
Bartesaghi Koc et al. (2018)	-	Review of 165 studies	1.5 - 9.5	0	1.0-15	2.0 - 6.0
Francis and Jensen (2017)		Review	0	0	0.03 - 3	0
Chen (2013)	Taiwan	Review	0	0	0.3 - 1.2	0
Chow and Bakar (2019)	-	Review	0	0	4.0 to 8.1	0
Getter and Rowe (2006)	-	Review	0	0	3 to 4	0
Berardi et al. (2014)	-	Review	0	0	2 [0.3 - 3]	0
Jamei et al. (2021)	-	Review	0	0	1 - 3	0
Jia and Wang (2021)	Hong Kong	ENVI-met	4.23	00.36		0
Kasprzyk et al. (2022)	Gdansk, Poland	Monitoring	0	0.94 - 1.15	0	0
Liu, Kong, et al. (2021)	-	Review	0	0	0.09 - 4.2	0
van Oorschot et al. (2021)	The Hague, Netherlands	GIS	2.7	0	0	2.3
He et al. (2022)	Wuhan, China	Estimation from literature	0.5 - 2.1	0	0	4.03
Williams et al. (2021)	Australia	Review	0	0	0.06 - 1.4	0
Yenneti et al. (2020)	Australia	Review (33)	1.08 [0 - 2]	0	0.78 [0.25 - 1.5]	4 - 13
Zardo et al. (2017)	-	GIS	1 - 6	0	0	0
Wang et al. (2014)	-	Review of 148 studies	2.8 - 4.5	0	0.5 – 4.3	0

Most studies focused on the effects of green roofs (12) and green areas (6) on climate regulation, and review was the most common method. Few studies assessed the microclimate impacts of waterbodies (4) and rain gardens (2), and no quantitative evidence about the other GBI types was found in the selection. In general, most studies were developed in micro scales, and the main gap indicated by the reviews was related to the lack of research focused on tropical and semi-arid climates, especially concerning the effects of irrigation and the adequate vegetation in the different GBI

(Bartesaghi Koc et al., 2018). The most viable methods recommended for future research in places with scarce data and resources are the use of open climate models (e.g. ENVI-met) powered by remote sensing data (e.g. Landsat images with spatial resolution from 15 to 100 m).

Table 8.7 presents the summary of studies on the GBI benefits in terms of air pollutant removal.

Table 8.7 – Summary of GBI efficiency in air pollutants removal per unit area

Reference	Case study	Scale	Method	Pollutant	Air pollutant removal ($g/m^2/year$) Mean [Min – Max]		
					Green Roofs	**Green Areas**	**Infiltra-tion**
Gourdji (2018)	-	City	Review of 3 studies	PM10 O3 NO2 SO2	1.33 [0.36 - 3.21] 1.88 [0.52 - 4.40] 1.02 [0.27 - 2.28] 0.29 [0.10 - 0.59]	-	-
Francis and Jensen (2017)	-	City	Review of 4 studies	PM10 SO2 NO2 O3	0.42 - 9.1 0.1 - 1.01 0.37 - 3.75 1.24 - 7.17	-	-
Zhu et al. (2022)	Beijing, China	Region	LCA, LCC	NO2 O3 SO2 PM10	1.9 3.7 1.6 0.6		
Wang et al. (2014)	-	-	Review of 148 studies	NO2 O3 SO2 PM10 CO		0.4 - 2.88 1.1 - 7.6 0.2 - 2.73 1.1 - 17.3 0.1 - 0.57	
Tan et al. (2021)	Kyoto, Japan	City	i-Tree Eco Model	NO2 O3 PM2.5 SO2		0.24 0.93 0.08 0.11	
Derkzen et al. (2015)	Rotterdam, Netherlands	City	GIS and literature review	PM10		1.9 [0.82-3.97]	
He et al. (2022)	Wuhan, China	City	Estimation according to literature	SO2		0.24-1.55	
De Valck et al. (2019)	Antwerp, Belgium	Park	Estimation according to literature	PM10	0.043	3.893	6.881

Most studies were developed on the city scale, usually indicating the GBI efficiency in the removal of particulate matter (PM2.5 or PM10), ozone (O3), nitrogen dioxide (NO2), sulphur dioxide (SO2), and carbon monoxide (CO). Some open-source models, such as the i-Tree Eco and the Urban Forest Effects (UFORE), can be used to estimate the air pollutant removal by the vegetation present in GBI (Wang et al., 2014).

Table 8.8 presents the results of studies that estimated the carbon sequestration in annual CO2 mass per unit area. Similar to air pollutant removal, the i-Tree Eco Model can estimate the potential carbon sequestration but requires data collected in the field to calculate the volume of plant biomass (e.g. tree crown and trunk dimensions).

Table 8.8 – Summary of GBI capacity for carbon sequestration per unit area

Reference	Case study	Method	Carbon sequestration (g CO2/m²/yr)				
			Green roof	Bioretention	Green area	Pond	Swale
Zhan and Chui (2016)	Hong Kong	LCA, LCC	510				
Chenoweth et al. (2018)	Surrey, Canada	Review				310	
González-Méndez and Chávez-García (2020)	-	Review	162-1259				
De Valck et al. (2019)	Antwerp, Belgium	Estimation from literature	64.3		380.0	619.1	
Moore and Hunt (2013)	-	Review	13	633	5 - 200	160	57
Smith et al. (2021)	-	Review			11.5 - 13.5		
Warwick and Charlesworth (2012)	-	Review	1387.5		4218		
Wang et al. (2014)	-	Review			77.7 - 747.4		
Tan et al. (2021)	Kyoto, Japan	i-Tree Eco Model			117.8		

8.6 Conclusion

This study is part of a greater research whose main objective is to support public discussion and decision-making on adopting GBI, providing evidence about its economic viability and social support, considering all the ecosystem and environmental services it provides. The systematic review presented in this article brings many insights about the state of the art and the global interests in the topic, highlighting the geographical inequality and the gap in comparative studies between different realities. At the same time, it underlines the potential for collaboration and exchange of technology and knowledge among different countries and contexts. The following steps of this research are the discussion on valuing traditional and local knowledge about nature-based solutions in urban land and water management context, as well as the presentation and dissemination of evidence on the multiple benefits of GBI, especially for managers and local governments.

As this analysis intends to be interdisciplinary, besides the most common types of GBI studied in the stormwater management subject (bioretention cells, infiltration trenches, permeable pavements, retention ponds, rain gardens, green roofs, vegetative swales, rain barrels, and their variations), other GBI elements were comprehended in the research scope (urban green spaces, open areas, urban forests, trees, riparian vegetation, wetlands, water bodies, water courses). Therein lies part of the innovation of this work, to include in the GBI concept both sustainable stormwater techniques and green areas, riparian buffers and other nature-based solutions, usually studied separately (Zhang & Chui, 2019).

The concept of green connectivity is more explored in the literature on parks, urban forests, and green corridors than on small devices such as green roofs or rain gardens. The recent consideration of urban trees as part of the urban infrastructure for stormwater management and intensive green roofs may offer a perspective on connectivity and its benefits for the urban environment.

The interdisciplinary aspect of this study opens frontiers for exchanges among research areas that could be more connected to improve the adoption of GBI to address the increasing demand for ecosystem services in the developing world. For example, researchers from the urban water management field can be inspired to test the application of methods usually employed in studies about urban green areas in their stormwater-designed GBI. In this sense, GBI is particularly strategic to help Global South cities increase resilience to the climate emergency and address the deficit of basic infrastructure for urban water management, flood control, sanitation, and treatment of diffuse pollution.

8.7 Appendix

Table 8.9 – Review studies searched in the Scopus and Web of Science databases about the quantification of multiple benefits of green roofs

Source	Terms	Benefits	Other variables	Number of studies and geographic cover (if defined)
Getter and Rowe (2006)	Extensive green roof	Volume and quality of stormwater runoff, energy conservation and UHI, biodiversity, air pollution, aesthetic, noise	Discussion about challenges for USA adoption	-; Mainly USA and Europe
Oberndorfer et al. (2007)	Green roof	Stormwater management, roof longevity, cooling, UHI, habitat, community	-	-
Rowe (2011)	Green roof	Air quality, energy conservation, carbon sequestration, water quality	Influence of roof material	-
Chen (2013)	Green roof	Water quantity and quality, thermal regulation	-	-
Berardi et al. (2014)	Green roof	Reduction of energy consumption, mitigation of UHI effect, air quality, water management, sound insulation, and ecological preservation	Influence of technical aspects of roof design	-
Li and Babcock (2014)	Green roof	Water pollution, carbon sequestration, UHI	-	52
Hashemi et al. (2015)	Green roof	Water quality, thermal regulation, energy consumption	Performance variation with grass species	Tropical areas
Mahdiyar et al. (2015)	Green roof	Energy saving, carbon reduction, UHI, air quality, water quality, stormwater control, noise, recreation	Challenges for developing countries	-
Francis and Jensen (2017)	GR, GI	UHI, air quality, energy consumption	"Level of evidence": number of studies providing evidence for each benefit	62 studies
Zivkovic et al. (2018)	Green living systems	Energy savings, UHI, stormwater treatment, air quality, carbon sequestration	Roof type, research type	-
Chow and Bakar (2019)	Sustainable urban development	Stormwater management, UHI, energy consumption, noise, increase life expectancy of building, aesthetics, air quality, biodiversity	Types and components of green roofs	-
Joshi and Teller (2021)	Green roof	Water management, UHI mitigation, biodiversity, air quality, energy savings, costs	Scale, roof type, species, influencing factors on effectiveness, lifespan	158
Liu, Kong, et al. (2021)	GR	Water quantity and quality, thermal environment, air quality	Citations, climate, location, area	1623
Nguyen et al. (2021)	GR, WSUD	Runoff reduction, thermal comfort, energy use, runoff quality, air quality, noise reduction	Geography, scale, climate, methods	102
Williams et al. (2021)	GR, GI, NBS	UHI, stormwater retention, energy, wellbeing, biodiversity, air quality	Substrates and plants, barriers and policy development	Australia
Zhang and He (2021)	GR	Energy efficiency, UHI, roof longevity, air quality, runoff control, water purification, noise reduction, biodiversity, recreation and aesthetics, property value and employment improvement	Year, geographic (developed and developing countries), drivers, barriers, stakeholders	192
Alim et al. (2022)	GR, WSUD	Runoff quantity and quality, temperature regulation, energy savings, costs	Roof area, payback period	129
O'Hara et al. (2022)	GR, GI	Health and wellbeing, education, UHI, biodiversity, stormwater mitigation, air quality, carbon sequestration, energy cost, long-lasting infrastructure	Considerations for designing GR in hospitals	100
Ode Sang et al. (2022)	GR, GI, NBS	Health and wellbeing, temperature regulation, air quality, noise regulation	Type of study, focus, type, scale, species used	69

Table 8.10 – Review studies searched in the Scopus and Web of Science databases about the quantification of multiple benefits of urban forests and green areas

Source	Terms	Benefits	Other variables	Number of studies and geographic cover (if defined)
Jorgensen and Gobster (2010)	GI, UGS	Human health and wellbeing, biodiversity	Preference, area, distance, perception	182
Hirokawa (2011)	Urban forest, GI	Air quality, carbon, runoff, water quality	-	-
Cameron et al. (2012)	Domestic gardens	Temperature regulation, energy conservation, carbon balance, runoff, health, and wellbeing	-	-
Cilliers et al. (2012)	UGS	Supporting, provisioning, regulating and cultural ecosystem services	-	-
Cook-Patton and Bauerle (2012)	UGS	Temperature regulation, rainwater retention, water and air quality, biodiversity	Discussion about plant diversity and services provided	-
Gómez-Baggethun and Barton (2013)	GI	Air quality, urban cooling, runoff mitigation, recreation, climate regulation	Economic values	-
Clapp et al. (2014)	GI, conifers canopy	Air quality, rainwater control, UHI, health	Investment return ratio, discussion about the species	-
McPhearson et al. (2014)	GI	Food production, water quantity, water quality, air pollution, carbon, temperature, aesthetic, recreation, educational	Scale of production, management and planning	-
Wolch et al. (2014)	UGS	Public health, aesthetic, recreation, property values	Environmental justice and gentrification	-
Bowen and Lynch (2017)	Gi, UGS	Health, economic	Standards methodology to calculate monetary estimates	-
Hegetschweiler et al. (2017)	GI, UGS	Cultural, aesthetics, access, noise, health, wellbeing	Linking demand (user needs, preferences) and supply (area, biodiversity, recreational infrastructure) factors	40
du Toit et al. (2018)	UGS, GI	Temperature regulation, runoff, air quality, carbon storage, erosion prevention, pollination, noise reduction, provision of food and raw material, recreation, aesthetic, social cohesion, education	Number of studies, countries, year of publication, barriers and challenges to Sub-Saharan context	68
Krajter Ostoić et al. (2018)	Urban forest, GI, UGS	Human health, climate regulation, biodiversity, economic, education	Year of publication, country, research theme, methods	408
Chen (2020)	GI, urban nature	Health, economic, air quality, physical activity, recreation, human access, social cohesion, mental health	Monetised health-related benefits	10
Singh et al. (2020)	GI	Air quality, carbon sequestration, moderation of temperature and mitigation of climate change, stormwater management, biodiversity, economic	Annual monetary benefit per tree	-
Farinha et al. (2021)	UGA	Health, wellbeing, UHI, carbon sequestration, biodiversity, water management	Year, country, co-authorship	29
Kolimenakis et al. (2021)	UGA and parks	Aesthetic, property values, health, wellbeing, carbon sequestration	Study type, location, method	14
Kong et al. (2021)	NBS, urban forests and trees	Flood mitigation, UHI, health and wellbeing, economic benefits	Scale, methods, typologies, country, keywords	493
Wiesel et al. (2021)	Urban afforestation, urban trees, GI	UHI, air quality, rainwater runoff quality, biodiversity, property value, health, and social cohesion	Year, countries, research area, key terms	8367

Table 8.11 – Review studies searched in the Scopus and Web of Science databases about the quantification of multiple benefits of 2 or 3 urban GBI techniques

Source	Terms	Benefits	Other variables	Number of studies and geographic cover (if defined)	Techniques									
					bioretention	green area	infiltration	pavement	pond	rain garden	roof	swale	tank	waterbody
Hop and Hiemstra (2013)	Urban green	Air quality, rainfall treatment and retention, UHI, noise, food, energy, health, employment, real state value, biodiversity	-	347		x					x			
Wang et al. (2014)	GI	Indoor thermal comfort, air quality, health, education, aesthetics, noise	Spatial and time scales, project and geographical influencing factors	148		x					x			
Breed et al. (2015)	GI	Supporting, provisioning, regulating and cultural ecosystem services	Geographic, scale, vegetation type,	655 articles and 255 projects; South Africa		x				x				
Derkzen et al. (2015)	Urban green spaces	Air purification, carbon storage, noise reduction, runoff retention, recreation	Vegetation types	Rotterdam, Netherlands		x				x				x
Raymond et al. (2017)	NBS, GI	Carbon sequestration, air quality, stormwater quantity and quality, biodiversity, human access, wellbeing, economic	Trade-offs and synergies, potential for citizen's engagement	500 articles and 1200 policies		x				x	x			
Russo et al. (2017)	NBS, GI	Food provisioning, carbon sequestration, medicinal resources, wellbeing, air quality, biodiversity, runoff reduction, costs	Edible green infrastructure types, risk of contamination and other disservices	80		x				x	x			
Soga et al. (2017)	GI	Health, wellbeing, physical activity, human access	Health of gardening practice	22		x				x				
Cilliers et al. (2018)	GI, gardens	Health, food provision, education, recreation, social interaction, aesthetic	Ownership, management scale, stakeholders, indigenous knowledge	75; Sub-Saharan Africa		x				x				
Van Oijstaeijen et al. (2020)	GI	Carbon storage and sequestration, climate regulation, stormwater quantity and quality, air quality, health and wellbeing	Time and expertise requirement, adaptability, scalability, uncertainty, type of GI	10		x				x	x			
Amorim et al. (2021)	GI	Carbon sequestration, local climate regulation, runoff regulation, air quality, noise attenuation, wellbeing, accessibility, physical activity, recreation, health, pollen emission and allergies, costs	Method, spatial and time scale, geographical distribution	90; Nordic countries		x				x	x			
Smith et al. (2021)	NBS	GHG reduction, food production, biodiversity, flood protection, soil protection, social cohesion, heatwave mitigation, aesthetics, water quality, education, recreation	Type of intervention, nature of outcomes, methods	56; Bangladesh		x			x					x
Sunita et al. (2021)	Urban blue-green spaces	Health, flood management, wellbeing, costs, temperature mitigation, air quality	Year, subjects, funding agency, country	165		x				x				x
Ersoy Mirici (2022)	GI	Economic benefits, cultural benefits, biodiversity	Year, keywords frequency	22		x					x			
Evans et al. (2022)	GI	Aesthetics, recreation, health, food, fibre and fuel provision, carbon sequestration and storage, soil protection, climate regulation, air quality, noise, pollination, biodiversity, nutrient cycling	Urban agriculture areas, type of growing spaces, geographic	157		x				x	x			
Iftekhar and Pannell (2022)	WSUD	Biodiversity, recreation, water quantity, aesthetics, costs, health, heat reduction	-	180		x								x

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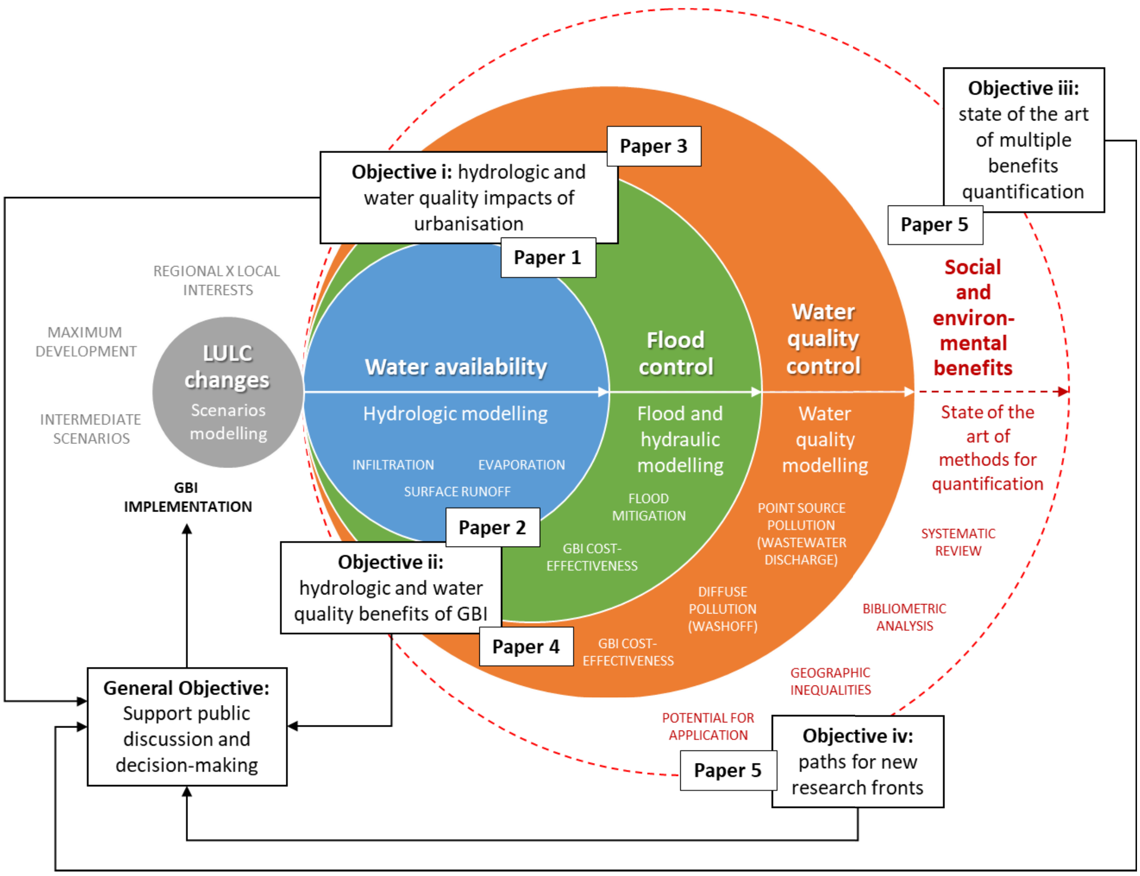
8.9 *Summary*

This chapter was the latest contribution to comprehend the contemporary research methodologies in evaluating the multiple functions and benefits of Green and Blue Infrastructure across urban and peri-urban areas. Expanding beyond the hydrological and water quality benefits addressed in prior chapters, this literature review offered a more comprehensive insight into how GBI's socioenvironmental ecosystem services can be effectively quantified (Figure 8.13).

Figure 8.13 – Summary diagram of the developed research and objectives – Paper 5



This comprehensive review followed a systematic approach and is broader than the one featured in Chapter 2, underlining that monetary value is just one among many other quantitative indicators that can be used to evidence multiple GBI benefits. The results of the review contextualise the findings from previous chapters within a broader framework and offer directions for future investigations into the multifunctional benefits of GBI. By indicating methodological approaches that are more feasible and require less resource investment, this article seeks to contribute to advancing the ongoing development of knowledge concerning GBI's potential benefits, especially in the context of the Global South.

The assessment of GBI's quantitative benefits, methodologies used, and the identified gaps underscored the need for an interdisciplinary and integrative evaluation approach. The systematic review also highlighted the disparities in research focus and geographical distribution, especially between the Global North and South. Moreover, the findings of this systematic review emphasize the need to explore and understand the specificities of developing countries, especially in tropical regions of Latin America, Africa, and South and Southeast Asia.

This article addressed the third and fourth specific objectives of the thesis. The conclusion is, however, open – the research of GBI benefits is extensive but still significantly fragmented, especially regarding integrating stormwater management techniques with other green infrastructures such as urban green spaces, reinforcing the need for more holistic assessments.

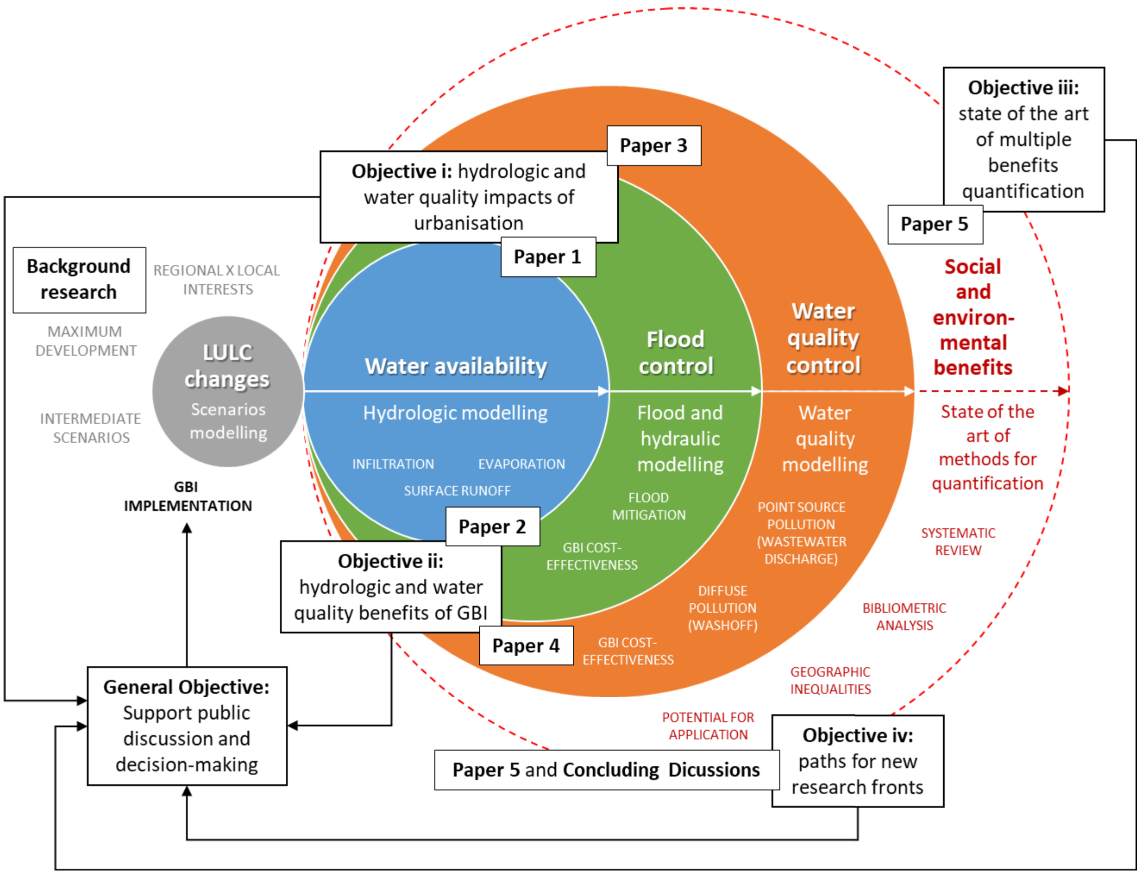
9 CONCLUDING DISCUSSIONS

"Quem abre a torneira	*"Who opens the faucet*
convida a entrar	*invites to enter*
o lago	*the lake*
o rio	*the river*
o mar"	*the sea"*

Ana Martins Marques, 'Torneira' [Faucet],
in 'Da arte das armadilhas' [The art of traps]
(Marques, 2011)

The path of the research described in this PhD thesis can be synthesised by the diagram in Figure 9.1.

Figure 9.1 – Summary diagram of the developed research and perspectives



9.1 Overview of the research journey

In the first chapters, the research was framed within the context of the slow adoption of Green and Blue Infrastructure in Brazil, despite its potential to address many impacts of land use and climate changes. It was mentioned that the adoption is even slower in small and medium cities, which frequently lack adequate conventional infrastructure for flood control and normative and institutional instruments to manage urban stormwater.

As presented in the background research, the lack of political support is a crucial reason for this slow adoption of GBI, especially when the alternative is investing in conventional grey infrastructure for flood control. Political commitment is essential for wide GBI deployment, either by governments and decision-makers or through broad civic support and community engagement (Wouters et al., 2016). In this sense, one of the persistent arguments that limits the political support for large-scale applications of GBI is the supposed economic unfeasibility (Vincent et al., 2017). However, GBI has become more attractive compared to conventional urban drainage techniques, mainly when the multiple benefits they can promote are taken into account (Wilker & Rusche, 2013). Considering the criticisms of monetisation because of its inability to encompass social and ethical concerns (Harvey, 1996), the research followed a methodological approach of modelling alternative future scenarios to explicit impacts of 'business as usual' urban development and GBI potential to mitigate and compensate those impacts.

9.1.1 Impacts of urban development 'business as usual'

Chapters 4 and 6 addressed the first specific objective of evaluating "the hydrological and water quality impacts of land use and land cover changes associated with urban development in a peri-urban catchment in the Belo Horizonte Metropolitan Region". It was necessary to adopt strategies to overcome the limitations in data availability to prepare and calibrate the land use and cover change, the hydrological and the water quality models. Even without high-frequency monitoring systems, the dataset was assembled with data provided by the sanitation company Copasa and collected in open and public databases from local (Contagem and Betim municipalities), regional (FJP and Metropolitan Agency), state (IDE-Sisema, Cemig) and federal (Cemaden, Inmet, MapBiomas) scales.

Mapping past urban expansion processes made it possible to forecast future urban developments following "business as usual" trends, and the consequent hydrological and water quality impacts. Results of the first article confirmed that the progressive urban expansion in the studied area led to decreasing infiltration volumes and groundwater flow, increasing runoff volumes, peak flows and flooding downstream of the reservoir. In the third article, the model was adjusted to adequately represent the past variations on pollutant loads associated with sewage contribution, and the impacts of urban expansion on increasing the diffuse pollution transported to the watercourses by the runoff.

At this stage, Vargem das Flores catchment served as a typical case study to illustrate challenges commonly faced in the developing world, where persistent issues of inadequate sanitation and the need for flood control infrastructure coexist with the urgent need to manage diffuse pollution and increase the metropolis water security against climate change. In the last decades, infrastructure investments in the region have reduced sewage discharge into the catchment watercourses and increased the hydraulic capacity of the downstream channels to transport the flow of extreme events. Even so, this thesis found that the urbanisation process may resume the reservoir's water quality degradation with an increase in diffuse pollution. Simultaneously, the increase in sediment contribution can accelerate the reservoir's silting up and the loss of useful life. With all this, the urban development 'business as usual' is a pessimistic future for the catchment, threatening the reservoir's water source and flood control functions.

With these two articles, the specific objective of this thesis of representing the impacts of urbanisation on the quantity and quality of water in the case study was fully achieved.

9.1.2 Impacts of an alternative sustainable future

Considering the evident impacts of 'business as usual' urbanisation, an alternative future scenario guided by the Green and Blue Infrastructure principles was studied in Chapters 5 and 7, addressing the second specific objective of this thesis.

The alternative future scenario was proposed to allow further urban development but not compromise the regulating ecosystem services provided by the existing forest fragments and the reservoir. In this alternative scenario, multiple GBI combinations were considered, and their construction and maintenance costs were estimated and compared to their potential hydrological and water quality impacts simulated using the SWMM model. The cost detailing of GBI techniques based on the cost composition of their construction elements presented in the second article (Item 5.7.2) addresses one of the gaps found in the literature review. With that, the most cost-effective techniques to treat future impervious areas were identified: rooftop disconnection and vegetative swales were the optimal GBI for runoff volume and peak flow control, while bioretention cells were the optimal for diffuse pollution control.

These different results provide valuable information that can support decision-making regarding which GBI should be deployed to mitigate multiple impacts of new urban areas in the catchment. While rooftop disconnection and vegetative swales presented the lowest cost and greatest peak flow reduction (67.8%) and runoff volume reduction (54.8%) compared to the other alternatives, the effectiveness of those structures on diffuse pollution control could not be assessed. Rooftop disconnection is a limited solution, as it requires a great pervious area within the lot to infiltrate the runoff conducted from the rooftop. Although most new urban areas in the GBI scenario would have lots with low impervious rates and large areas, lots near the existing urban areas would have 360 m² and impervious rates up to 70%. Vegetative swales could be designed to fit in the urban parcelling project but also require land availability. Apart from the area availability required for these techniques to reduce runoff effectively, their design does not consider the subsurface soil and storage layers. Because of that, rooftop disconnection and vegetative swale water quality treating capacity can not be assessed in SWMM.

In this sense, this thesis found that although the bioretention cell presented a higher cost than the rooftop disconnection and vegetative swale combination (2.65 greater cost), it became the most advantageous alternative when considering its effectiveness in treating diffuse pollution. Bioretention cells also present the advantage of being more effective regarding area requirement, as the proportion of treated impervious area per technique area of bioretention cell is 26:1, while rooftop disconnection has a proportion of 1:1 and vegetative swale 10:1. Lastly, the effectiveness of bioretention cells to reduce runoff peak flow (66.2%) and volume (52.0%) is sufficiently close to rooftop disconnection and vegetative swales effectiveness to be considered as a feasible alternative.

Lastly, this thesis confirmed the potential of GBI to mitigate flood risks and reduce the impacts of urban expansion on the water cycle. Results from the fourth article demonstrated the GBI's potential to control diffuse pollution in new urban areas, decreasing the contribution of suspended solids and nutrients, slowing down the eutrophication and silting processes of the reservoir and protecting its function as a water source for 600,000 people. In this sense, this research recommends that further urban development in the catchment must guarantee the protection of remnant forest fragments, reforestation of riparian areas, and treatment of new impervious surfaces with bioretention cells. The fact that GBI principles could significantly mitigate the hydrological impacts of soil sealing while maintaining water security is aligned with the overarching hypothesis of the thesis, supporting the argument for adopting GBI in urban planning for multiple benefits.

With these two articles, the specific objective of this thesis of evaluating GBI benefits on the quantity and quality of water in the studied catchment was fully achieved.

9.1.3 How are the other GBI benefits quantified?

In order to expand the quantification of GBI benefits beyond those related to water, a systematic review was conducted and presented in the fifth paper (Chapter 8), addressing the third specific objective of studying "the state-of-the-art methods to quantify ecosystem services and other benefits of GBI implementation, such as improvement of surface water quality, heat island mitigation, carbon sequestration, improvement of air quality, creation of opportunities for leisure, social interaction, urban agriculture and landscape improvement".

Moving beyond the analysis in the preceding chapters, this literature review provided a more extensive understanding of how GBI's socioenvironmental ecosystem services can be effectively measured (Figure 9.1). The comprehensive nature of this review adopted a systematic approach, surpassing the scope of the one outlined in Chapter 2.

The findings of this review contextualised insights from previous chapters within a broader framework and suggested possibilities for future investigations of the multiple benefits of GBI. This thesis found that the term Green Infrastructure is predominant and frequently applied in studies beyond stormwater research, including landscape architecture and ecology. In general, studies are predominantly focused on evaluating the benefits of green spaces, open areas, parks, trees, and urban forests, and the most studied benefit is temperature regulation (urban heat island effect and global warming). GIS tools were the most frequently used method for spatializing GBI benefits in interdisciplinary research, among which open source data and models such as Landsat images, i-Tree Eco Model and the Urban Forest Effects (UFORE) stand out.

By highlighting methodological approaches that require open and accessible data and models, this article aimed to contribute to the ongoing development of knowledge on the potential benefits of GBI, particularly in the Global South. The evaluation of GBI's quantitative benefits, methodologies employed, and identified gaps underscored the necessity for an interdisciplinary and integrative assessment approach. The systematic review also brought attention to disparities in research focus and geographical distribution, particularly between the Global North and South. Additionally, the results underscored the importance of exploring and understanding GBI specificities in developing countries, especially in tropical regions of Latin America, Africa, and South and Southeast Asia.

These findings addressed the fourth specific objective of indicating "possible paths for new research fronts and collaboration opportunities for assessing the multiple GBI benefits in different geographical realities".

9.1.4 Where to go now?

The methodological approach of this research started with a focus on the catchment scale, where the water-related impacts of past and future LULC changes and alternative scenarios with GBI implementation were evaluated. At this scale, the study was conducted by the application of a toolset of open-source software to model the

LULC changes (Dinamica EGO), the hydrologic cycle (SWMM), floods hydraulic (HEC-RAS), and water quality (SWMM). As mentioned, to estimate the input parameters and adjust all those models, monitoring data relative to LULC, land use controls, population, sanitation cover, rainfall, water level, and water quality were obtained from open databases, public institutions, and state-owned companies.

The emphasis on 'open-source' tools and 'open' and 'public' databases is justified by the intent that this research could be scalable, transferable, and replicable in other cities from the Global South. Beforehand, the priceless contribution of so many people and institutions in making valuable monitoring and existing data available is the first acknowledgement of this research. Besides that, most of these datasets are much larger than the Vargem das Flores Reservoir catchment, so this study can work as a pilot experiment replicable in other strategic water source areas.

In the diagram of Figure 9.1, the arrow that indicates the research progress points to the (continuous) expansion of the scope. Nevertheless, a PhD Thesis needs an end, but research does not. In this last move towards estimating the co-benefits of GBI, the systematic review of the literature on urban ecosystem services indicated many insights into methods, indicators, and possible data sources for future work.

The systematic review highlighted the increasing global interest in GBI and the potential for collaboration among different countries and contexts, especially in the Global South. Future research should consider the potential association of sustainable stormwater techniques with green areas and riparian buffers as nature-based solutions for urban climate change adaptation. This is the next step of the research to be developed after the doctorate: incorporating precipitation and temperature time series obtained from climate change downscaling models to study the combined risks of climate and land use changes in the Vargem das Flores catchment and surroundings.

This research only started to address the gap identified by all review studies consulted in the systematic review: there is still little rigorous evidence on the environmental and social benefits of GBI in the Global South, especially for the infrastructure designed for stormwater and flood management. The interdisciplinary aspect of the study opens frontiers for exchanges among research areas to improve the adoption of GBI in addressing the increasing demand for ecosystem services in the developing world. The systematic literature review reinforced the understanding that robust evidence about the multiple benefits of GBI needs to be provided by studies oriented to the local reality to be politically compelling for decision-makers. As the example of Vargem das Flores's case study, open-source models can be applied, adapting the analysis to make the most of the available local data and looking for the large amount of free data being available worldwide.

The overview of the research approaches applied worldwide inspires the expansion of the focus for the metropolis spatial scale. After exploring some of the tools and databases suggested in the literature review and promising to be applied in future endeavours, it is worth returning to the initial objective of this research to evaluate the work done.

9.2 Answering the research question

"Can the research provide sufficient evidence to guide decision-making towards a water-sensitive city with intergenerational equity?"

The set of tools adjusted and applied in the case study area made possible the verification that the adoption of GBI principles in the land use regulation and its implementation in further urban development can protect the reservoir from the LULC change impacts and can support future studies to assess the impact of climate change on the multiple functions of the reservoir. These results prove the main hypothesis of the MOMA-SE research project of which this thesis is part (MOMA-SE, 2019):

> "It is possible to increase the resilience of strategic water sources to anthropic pressures and climatic changes, through measures of land use regulation, adoption of soil and water conservation techniques based on concepts of green and blue infrastructure".

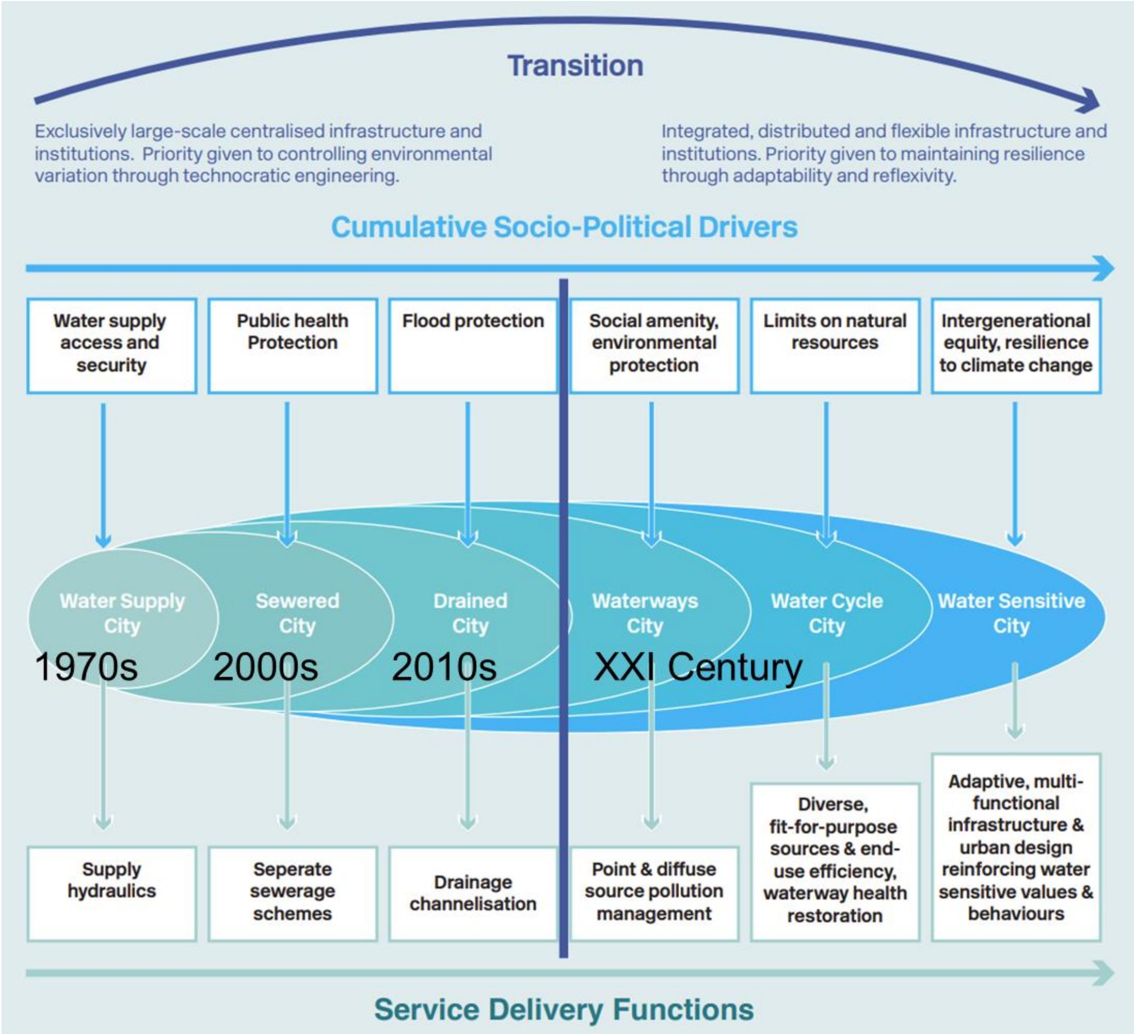
Results presented in Chapters 4 to 7 evidenced the expected impacts of LULC changes in regulating functions of the reservoir, such as the increased frequency and gravity of floods downstream, the reduced capacity of the reservoir to recover its volume during the dry season, the degradation of its water quality, accelerating the reservoir's silting and eutrophication. The proposed GBI scenarios effectively mitigated all these impacts, even allowing the development of an area equivalent to the existing (in 2020) urban area in the catchment. All results were presented to several stakeholders in Betim and Contagem municipalities and to the sanitation company responsible for the reservoir management. These results supported the arguments of the groups and institutions that defend the protection of the reservoir and presented alternatives for further water-sensitive development, where GBI would be capable of regulating runoff volume and quality, extending the reservoir's service life.

The main methodological approach of this work is based on modelling and the use of secondary data. As in every modelling effort, all the premises adopted in its construction restrict extrapolation and direct transfer to other realities. Although this is a quantitative study, numerical results should always be interpreted cautiously and, where appropriate, in a non-deterministic or even qualitative manner. Models are simplifications of reality, subject to uncertainties and inaccuracies, but with the use of a series of steps that make up good modelling practice (calibration, validation, performance metrics, comparative graphs), it is possible to guarantee robust results. Despite the efforts that can complement the analysis carried out (increasing the spatial and temporal resolution of the monitoring, for example), the results are consistent, and the scenario-based modelling can be very supportive for decision-making.

9.2.1 Framing Vargem das Flores catchment situation

Resuming the framework (Figure 9.2) proposed by Brown et al. (2009) and considering all the arguments presented in this document, it is possible to locate the evolution of Vargem das Flores catchment towards the timeline.

Figure 9.2 – Urban water management transition framework proposed by Brown et al. (2016)



The first stage (Water supply city) corresponds to the 1970s, when the dam was built, the reservoir was conceived for the main function of supplying water for the metropolitan area to develop with reliable supply sources during the dry season. The transition to the second stage (Sewered city) occurred with spatial inequality for decades. Until the decade of 2000s, multiple efforts from the sanitation company to collect and transpose the sewage from the formally built areas of Vargem das Flores catchment to a neighbouring catchment (in the subcatchment of Betim stream) partially avoided further degradation of the reservoir's water quality. Parts of the catchments remained unattended by the sewage collection system, and just in the 2010s, the sewage treatment plant was built in the catchment to cover the area of Nova Contagem, in the subcatchment of Água Suja ("dirty water") stream. At this point, it could be said that the UN Sustainable Development Goal 6 (Clean water and sanitation) was close to being achieved locally.

Stretches of the watercourses were channelised in the upstream region of Contagem city centre and downstream the reservoir, in Betim, to avoid flood in occupied areas of those municipalities. The reservoir function of regulating the Betim stream's flow prevented floods in its margins, so the downstream area was densely developed, and avenues were built. In that sense, the urban landscape is of a “Drained city” (Stage 3).

The recent changes in land use regulation have brought the catchment to a crossroads. While the ‘Green and Blue Network’ proposed in the metropolitan master plan could lead the catchment to further stages on the transition framework, the last Contagem's land use legislation could regress the area to cope with issues that seemed relatively overcome. Results from the first and third papers identified that further development following the municipal master plan could threaten the use of the reservoir as a water source, degrade the water quality of streams and the reservoir, and increase the frequency and intensity of floods downstream of the reservoir.

On the other hand, the alternative proposed scenario with GBI implementation could catalyze the transition towards a water-sensitive city. Firstly, the set of LID techniques aligned with protecting existing forest fragments and recovering riparian zones could treat the diffuse pollution, slowing down the reservoir's silting and eutrophication. With that, the service life of the reservoir could be extended, guaranteeing its usability to the next generations (intergenerational equity). Protecting the reservoir storage capacity increases the resilience of the metropolitan water supply system to long dry periods and the resilience of the downstream municipality's macro-drainage system to extreme precipitation events, both expected effects of climate change in the rainfall regime. In other words, the GBI scenario could be the key to achieving UN SDG 11 (United Nations Sustainable Development Goal 11: Sustainable Cities and Communities) in the region.

The potential of Vargem das Flores reservoir for recreation and cultural practices remains underexplored despite its strategic location and historic destination as low-income leisure equipment. Public engagement in the discussion about the future of

Vargem das Flores is also an opportunity to educate the metropolitan community about the multifunction of the waterbody and the multiple interests and conflicts related to the catchment land use. In the last decades, decisions that impact the future of the reservoir were made in a more or less democratic way (the metropolitan master plan *versus* the 2018 municipal master plan) in several instances (local and metropolitan). Decisions made with less social participation were, and are, widely questioned by social movements in defence of the reservoir. The most recent was the state government's decision to build a highway that crosses the catchment in areas of consolidated occupation and areas with forest cover, further fragmenting the local landscape.

Comparing the possible futures of Vargem das Flores with the neighbouring catchment of the Pampulha reservoir can be an appealing awareness strategy. The lake was built in the 1930s to supply water for the growing capital Belo Horizonte. Decades later, its banks became one of the most valued areas of the city, with an important cultural and architectural heritage. The rapid population growth in the catchment and the release of sewage and sediments in its contributors degraded the ecological status of the reservoir, which lost a significant part of its volume due to silting and is in a hypereutrophic state, representing a threat to public health and a sink of public resources for its de-pollution and recovery (Coutinho, 2007).

9.2.2 Future perspectives for Vargem das Flores catchment

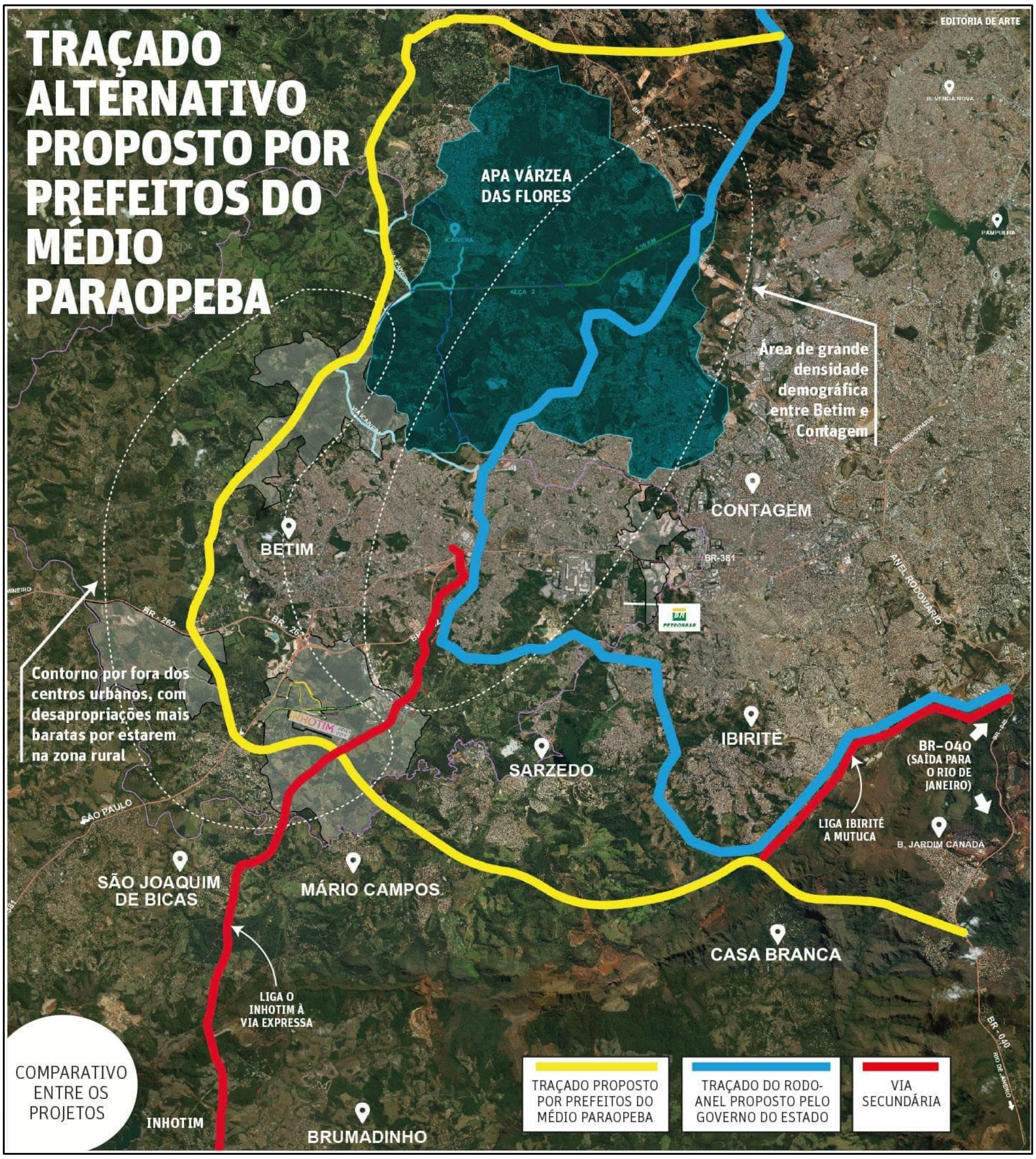
The historical context of urban development and land use changes in the region highlights the challenges related to the coexistence of urban expansion and environmental protection. Since the reservoir construction, legal frameworks, including land use controls and the creation of conservation units, have tried to protect the catchment environment to guarantee the water supply function. Even so, political and economic pressures to develop new urban areas in the catchment showed that no regulatory framework is immutable and legal protection can be revoked. Between 2016 and 2020, when a right-wing government managed Contagem municipality, a new master plan with poor participatory process eased the restrictions, allowing the urbanisation of previously protected areas in the catchment. The impacts rapidly became evident, with many new parcelling projects submitted to Contagem municipality in a few months after the new law's approval (Carvalho, 2021). However, the impacts of changes in political direction on municipal government were not restricted to formal processes of urban occupation.

In addition, Vargem das Flores's case study illustrates the contrast between normative protections on paper and the realities of "Business as Usual" development. In Brazil, the existence of land use plans and protective laws does not guarantee their effective implementation. The disparity between established normative instruments and their practical implementation is evident, often yielding to prevailing customary practices on the ground. Besides the frequent ineffectiveness of normative regulation to control the urban occupation, Vargem das Flores's history illustrates how institutionalised and participatory processes in land use planning are vulnerable to changes in the balance of political and socioeconomic forces. Despite efforts to create protective measures, these are consistently threatened by dominant political and economic interests, evident in the fluctuating stances of different governmental bodies over the years.

Given all this, the extension of the results of this research may be at an impasse. While elucidating the benefits of environmental preservation is crucial for public awareness, the practical complexities often render this awareness insufficient in driving actual change. The debate regarding whether research can effectively drive real-world change remains uncertain, particularly given the deep-rooted political and economic complexities of those decisions. Scientific evidence, though valuable, might not always be impactful in the face of powerful interests.

The future of Vargem das Flores remains open. In 2021, a new Contagem government concerned with protecting Vargem das Flores conducted a new participatory process to elaborate a new municipal Master Plan. The recently approved instrument indicates more restrictions to urbanisation and protection for the catchment. However, the current state government proposed a mega infrastructure project crossing the catchment: the Metropolitan Rodoanel, a highway that would improve urban mobility and attract cargo transport. The route planned by the State Government crosses the catchment, while Betim and Contagem municipalities proposed an alternative route outside the catchment (Figure 9.3).

Figure 9.3 – Massive transport infrastructure investment threats Vargem das Flores protection: the Metropolitan Rodoanel would cross the catchment in the state government proposal, while Betim and Contagem municipalities propose an alternative route for the



Source: O Tempo (2021).

After all, science will continue to make its contribution to the public debate. Vargem das Flores is a strategic water source for the Belo Horizonte metropolis. Furthermore, in the critical tension between environmental preservation and urban development, community involvement and activism play a significant role, and science can provide powerful fuel for change towards a sustainable future.

9.3 Education and social impact

One important contribution intended by this work is related to its popularisation. This is a frequent recommendation across GBI-benefits studies to engage "public, planners and decision-makers regarding the desirability of green infrastructure and nature conservation within urban areas" (Singh et al., 2020). The primary means used so far for this has been the participation and presentation of the results of the work about Vargem das Flores reservoir to the public and planners. Part of the results was presented in meetings with managers and land use planners in Betim (February 2021), in a public hearing at the State Parliament (November 2021), and in several meetings with representatives from the sanitation company Copasa and Contagem municipality (starting from December 2021).

A transcription of one of the last presentations was published on the Manuelzão Project's website, a Federal University of Minas Gerais project that seeks to revitalize the Velhas river basin. The following steps will be translating the articles into accessible text (in Portuguese) to be made available to the public and planners in Brazil. It is important to consider the language barrier as a condition for the social impact of this research. All the outputs are being published in English to participate in and exchange with the global scientific community. However, it is indispensable to have a translated version of the studies in Portuguese to be accessible to stakeholders and the public in general in Brazil.

9.4 Future research perspectives

The first front of work to be done beyond the limits of this thesis is the evaluation of the combined impacts of urbanisation and climate change on water quantity and quality. Future precipitation patterns can be obtained from downscaled climate change models and compared with the long-term past precipitation and reservoir's water levels time series. Those datasets can be used to simulate the summed impacts of future changes in land use and rainfall in the stormwater runoff and in the pollutant load affluent to the reservoir.

The interdisciplinary research of GBI co-benefits is as complex as the challenges presented by its time, so this work is situated at the beginning of a longer research journey, opening up several fronts for further analysis based on the modelling tools and robust databases built throughout the PhD:

- Water security: probabilistic analysis of hydrological impacts on the reservoir volume, considering variations in its initial states, now possible with the constitution of a rainfall and water level time series of 20 years;

- Economic evaluation: opportunity costs considering land price changes with urban development, avoided costs with water treatment, flood impacts, costs with operation and management of the reservoir in the case of its water becoming unfit for consumption;

- Ecological: the output of the hydrologic and water quality model of the catchment can be used as input for modelling the thermodynamics, sedimentation and ecological status of the reservoir;

- Institutional: assessment of normative alternatives for incentives and investment, economic tools such as financial compensation and payment for environmental services to compensate for more restrictive land use regulation.

Furthermore, the research is also coming back to the context of the Moma-se project at the metropolis scale, "Modelling strategic metropolitan water sources as an input for water and land management in the face of climate change", including Serra Azul catchment in the analyses and comparing with the other case studies developed in the Universidade de Brasília, Universidade de São Paulo, Brazil, and the École de Ponts ParisTech, in France.

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10 FINAL REFLECTIONS

"É feia. Mas é uma flor.
Furou o asfalto, o tédio, o nojo e o ódio."

"It is ugly. But it is a flower.
It broke through the asphalt, the tedium, the disgust, and the hatred."

Carlos Drummond de Andrade,
'A flor e a náusea' em 'A rosa do povo' (Andrade, 1945)
'Nausea and the Flower' in 'Rose of the People' (Andrade, 2016)

Green and Blue Infrastructure has been increasingly studied and deployed around the world. Developing countries, including Brazil, have recently been more interested in this topic, as demonstrated by the growing number of research and implementation cases. Sometimes, they are presented as a panacea for social and environmental issues because of the many benefits and ecosystem services they provide. However, the broad GBI implementation in the real world is more complex and naturally political (Meerow, 2020). For this very reason, the decision-making process on urban planning and water management needs to be well grounded in technical-scientific arguments that consider all the socio-environmental and economic aspects.

This is the context of this work, whose ambition is to contribute scientifically and socially to the construction of water-sensitive cities. Especially in the case of the Brazilian metropolis, a community of which the author is a part and to which he wishes to contribute to social and environmental enhancements. The results obtained in this research will be presented to all stakeholders involved in urban planning and water management in Vargem das Flores catchment, especially in the municipalities of Contagem and Betim. In addition to the expected publications in scientific journals, it is important that the results are also presented to society in more accessible means, so that Green and Blue Infrastructure would be considered in the public debate as alternatives for metropolitan development.

This thesis aims to contribute to breaking the cycle that prevents the wide adoption of GBI, especially in the context of most Brazilian cities. As discussed in the text, there is a scarcity of resources and capability to trigger the adoption of GBI on the scale of municipal and local governments, where flood control investments are still concentrated in conventional “grey” infrastructure. So, evidencing the multiple benefits of GBI implementation, and publicising them, is one contribution of this thesis. However, on the local government scale, there are still limited capacity and institutional incentives to quantify the multiple GBI benefits. In this context, not knowing if GBI solutions are more cost-effective or economically efficient, there is no way for the institutions responsible for stormwater management to budget for the supposedly additional social and environmental benefits.

However, even with quantified benefits, there is still the challenge of overcoming the inertia to change these institutional arrangements and the permanence in the paradigm of conventional infrastructure. In this sense, the second contribution of this thesis is the effort to educate and promote social awareness about the effectiveness of sustainable alternatives for urban stormwater management and planning. This contribution may be especially crucial for the Vargem das Flores catchment, given that this thesis was developed and written during the ongoing public debate on the new land use and land cover legislation in Contagem municipality.

“O povo sabe o quer,
mas o povo também quer o que não sabe.”

“The people know what they want,
but the people also want what they do not know.”

Gilberto Gil, in ‘Rep’ (1998)

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