Universidade do Estado do Pará

Pró-Reitoria de Pesquisa e Pós-Graduação

Centro de Ciências Naturais e Tecnologia

Pós-Graduação em Ciências Ambientais – Mestrado

Vítor Abner Borges Dutra

Análise e monitoramento de áreas de proteção ambiental através de geotecnologias: estudo de caso em duas unidades de conservação em Belém, Pará

Belém

2020

Vítor Abner Borges Dutra

Análise e monitoramento de áreas de proteção ambiental através de geotecnologias: estudo de caso em duas unidades de conservação em Belém, Pará

Dissertação apresentada como requisito parcial para obtenção do título de Mestre em Ciências Ambientais no Programa de Pós-Graduação em Ciências Ambientais.
Universidade do Estado do Pará.
Orientadora: Profa. Dra. Hebe Morganne Campos Ribeiro

Belém
2020

Dados Internacionais de Catalogação na Publicação (CIP),
Biblioteca do Centro de Ciências Naturais e Tecnologia, UEPA, Belém - PA.

D978a Dutra, Vitor Abner Borges

Análise e monitoramento de áreas de proteção ambiental através de geotecnologias: estudo de caso em duas unidades de conservação em Belém, Pará. / Vitor Abner Borges Dutra; Orientadora Hebe Morganne Campos Ribeiro. -- Belém, 2020.
45 f. : il.; 30 cm.

Dissertação (Mestrado em Ciências Ambientais) - Universidade do Estado do Pará, Centro de Ciências Naturais e Tecnologia, Belém, 2020.

1. Proteção ambiental. 2. Unidades de Conservação – Belém (PA). 3. Geotecnologias. 4. Sensoriamento remoto. I. Ribeiro, Hebe Morganne Campos. III. Título.

CDD 333.71509811

Vítor Abner Borges Dutra

Análise e monitoramento de áreas de proteção ambiental através de geotecnologias: estudo de caso em duas unidades de conservação em Belém, Pará

Dissertação apresentada como requisito parcial para obtenção do título de Mestre em Ciências Ambientais no Programa de Pós-Graduação em Ciências Ambientais.
Universidade do Estado do Pará.

Data da aprovação: 17/02/2020.

Banca Examinadora

Hebe Morganne C. Ribeiro – **Orientadora**
Profa. Hebe Morganne Campos Ribeiro
Doutora em Engenharia Elétrica
Universidade do Estado do Pará

______________________________ – **1º Avaliador**
Prof. Arthur da Costa Almeida
Doutor em Engenharia Elétrica
Universidade Federal do Pará

Kelly G. Fernandes Dantas – **2ª Avaliadora**
Profa. Kelly das Graças Fernandes Dantas
Doutora em Ciências (área: Química Analítica)
Universidade Federal do Pará

______________________________ – **3º Avaliador**
Prof. Altem Nascimento Pontes
Doutor em Ciências (modalidade Física)
Universidade do Estado do Pará

RESUMO

A Amazônia é uma das bacias hidrográficas mais importantes do planeta, pois contribui com o ciclo hidrológico, detém inúmeras espécies animais e vegetais e influencia no clima global. Assim, esforços políticos são indispensáveis para manutenção dessa floresta e seus recursos hídricos. Nesse sentido, a Agenda 2030 para o Desenvolvimento Sustentável e as políticas ambientais brasileiras, como o Sistema Nacional de Unidades de Conservação, abrangem entre suas diretrizes e seus objetivos diversos meios para proteção das águas e florestas. Logo, um dos meios para viabilizar essas metas e demais instrumentos legais são as geotecnologias, especialmente o sensoriamento remoto. Portanto, o objetivo dessa dissertação foi analisar e monitorar áreas de proteção ambiental através de geotecnologias. A metodologia englobou a aplicação de ferramentas de geotecnologias envolvendo os satélites da família Landsat e Sentinel-2 para duas áreas protegidas: Área de Proteção Ambiental da Região Metropolitana de Belém e Parque Estadual do Utinga. Os resultados indicaram que a região pode ser monitorada por sensores óticos mesmo sob a condição adversa de nuvens inerente da Amazônia. Além disso, foi possível analisar o processo de urbanização no entorno das áreas protegidas e a consequente poluição e eutrofização dos mananciais da área de estudo, em especial o Lago Bolonha. Finalmente, sugere-se a tomada de medidas efetivas para solucionar os passivos ambientais da região, dada sua importância para o abastecimento público de água de milhões de habitantes da Região Metropolitana de Belém.

Palavras-chave: Estudo Ambiental. Sensoriamento Remoto. Urbanização. Águas Amazônicas. Eutrofização.

ABSTRACT

The Amazon is one of the most important watersheds on the planet, as it contributes to the hydrological cycle, holds numerous animal and plant species and influences the global climate. Thus, political efforts are indispensable for maintaining this forest and its water resources. In this sense, the 2030 Agenda for Sustainable Development and brazilian environmental policies, such as the National System of Conservation Units, include among its guidelines and objectives various means for the protection of waters and forests. Therefore, one of the means to make these goals and other legal instruments viable are the geotechnologies, especially remote sensing. Therefore, the objective of this dissertation was to analyse and monitor environmental protection areas through geotechnologies. The methodology included the application of geotechnology tools involving both the Landsat and Sentinel-2 families satellites to two protected areas: Environmental Protection Area of the Metropolitan Region of Belém and Utinga State Park Conservation Unit. The results indicated that the region can be monitored by optical sensors even under the inherent adverse cloud conditions of the Amazon. In addition, it was possible to analyse the urban sprawl process around the protected areas and the consequent pollution and eutrophication of the study area springs, especially Bolonha Lake. Finally, it is suggested that effective measures be taken to solve the region's environmental liabilities, given its importance for the public water supply of millions of dwellers of the Metropolitan Region of Belém.

Keywords: Environmental Study. Remote Sensing. Urbanisation. Amazon Waters. Eutrophication.

SUMÁRIO

Introdução Geral

A Amazônia é uma das mais importantes bacias hidrográficas da Terra (FOLEY et al., 2002). Detentora de uma vasta rede de sistemas de água doce contendo cursos d'água e extensas planícies aluviais, a Amazônia desempenha um papel vital no ciclo hidrológico global, onde é responsável pela descarga de até 20% de água doce do mundo para o mar (FOLEY et al., 2002; SUN et al., 2019).

A Região Hidrográfica Amazônica, em conjunto com parte da Região Hidrográfica do Tocantins-Araguaia e Atlântico Nordeste Ocidental (ANA, 2018), abrange um mosaico com a maior área de floresta tropical do mundo (HANSEN et al., 2013). Essas florestas contribuem com quase 10% da produtividade terrestre e biomassa da vegetação (BRIENEN et al., 2015), além de prover habitats a inúmeras espécies animais e vegetais (FOLEY et al., 2002).

As florestas trocam grande quantidade de energia e água com a atmosfera (HASLER; AVISSAR, 2007). Esses fluxos contribuem para a convecção tropical e, possivelmente, auxiliam no desencadeamento do começo da estação chuvosa (WRIGHT et al., 2017). Sendo assim, as florestas influenciam o clima local, regional e, até certo ponto, o global (SUN et al., 2019).

Nesse âmbito, destaca-se a Agenda 2030 para o Desenvolvimento Sustentável (UN, 2015), a qual inclui 17 Objetivos de Desenvolvimento Sustentável (ODS) e 169 metas. Os ODS baseiam-se em três elementos centrais: crescimento econômico, inclusão social e proteção ao meio ambiente. Entretando, para viabilizar a Agenda 2030, é fundamental que haja lideranças políticas globais e nacionais, recursos e comprometimento com as metas traçadas (UN, 2018; OPOKU, 2019).

Desse modo, sublinham-se dois ODS expressivos no contexto Amazônico: o 6, Água Potável e Saneamento, e 15, Vida Terrestre. O primeiro objetiva assegurar a disponibilidade e gestão sustentável da água e saneamento para todas e todos. O segundo pretende proteger, recuperar e promover o uso sustentável dos ecossistemas terrestres, gerir de forma sustentável as florestas, combater a desertificação, deter e reverter a degradação da terra e deter a perda de biodiversidade (UN, 2015).

Nesse sentido, é importante frisar o empenho das políticas ambientais brasileiras para cumprir os acordos globais de proteção e recuperação das florestas e seus recursos, onde o Sistema Nacional de Unidades de Conservação da Natureza

(SNUC), Lei n. 9.985/2000, aponta dois principais tipos de unidades de conservação (UC): de proteção integral e de uso sustentável (BRASIL, 2000).

Os efeitos da aplicação do SNUC foram positivos nos últimos anos: por meio de imagens Landsat, Hansen et al. (2013) identificaram que, de todos os países do mundo, o Brasil apresentou o maior declínio anual de perda florestal, passando de valores acima de 40.000 km²/ano de 2003 a 2004 para valores mínimos abaixo de 20.000 km²/ano de 2010 a 2011. Esse fato apontou, dentro do período mencionado, o bom desempenho brasileiro em direção ao ODS 15 e suas metas. Por outro lado, tem-se o contraste da disponibilidade hídrica quali-quantitativa em território nacional, o que dificulta o cumprimento do ODS 6: apesar de 80% dos recursos hídricos brasileiros estarem concentrados na Região Hidrográfica Amazônica (ANA, 2018), as cidades do Norte possuem os piores índices de saneamento básico do país (ITB, 2018).

A problemática acima combina-se ao crescimento demográfico e aumento de atividades potencialmente poluidoras, o que gera preocupação com relação à qualidade das águas (LAMPARELLI, 2004). Os reservatórios de água são comumente absorventes de nutrientes e poluentes na escala das bacias hidrográficas e podem ser afetados pela eutrofização (ARVOR et al., 2018). Esse processo é um problema global, o qual estudos envolvendo estações de monitoramento na Europa mostraram que 40% dos seus lagos foram classificados como eutróficos ou hipereutróficos entre 2008 e 2011 (UN, 2018b). Nos Estados Unidos, o prejuízo associado as perdas por eutrofização foi estimado em $2,2 bilhões anuais (DODDS et al., 2009). No Brasil, Melo et al. (2019) identificaram que diversos córregos amazônicos estão fortemente impactados por esgoto doméstico.

Nessa perspectiva, as geotecnologias se evidenciam como importante conjunto de ferramentas que auxiliam a gestão, o monitoramento e a tomada de decisão sobre questões ambientais (RAPINEL et al., 2014). Ao abordar as geotecnologias, especial destaque deve ser dado ao sensoriamento remoto, definido como:

> [...] o registro sem contato de informações das regiões ultravioleta, visível, infravermelha e de microondas do espectro eletromagnético por meio de instrumentos como câmeras, scanners, lasers, matrizes lineares e/ou matrizes de área localizados em plataformas como aeronaves ou nave espacial, e a análise de informações adquiridas por meio do processamento de imagens visuais e digitais (JENSEN, 2014).

Assim sendo, o sensoriamento remoto pode prover dados de forma sistemática sobre áreas geográficas em diferentes escalas. Pode-se ainda afirmar que essa ciência é fundamental na modelagem de vários processos naturais (como estudos sobre eutrofização ou poluição difusa) e culturais (a exemplo de análises sobre mudanças de uso e cobertura da terra ou aumento da malha urbana) (WALSH et al., 1999; NEMANI et al., 2003; STOW et al., 2003; KARASKA et al., 2004; JENSEN, 2014).

Dessa maneira, essa pesquisa sumarizou-se da seguinte forma (PRODANOV; FREITAS, 2013):

i) Quanto à natureza: pesquisa básica, pois objetivou gerar conhecimento sobre a temática (áreas de proteção ambiental na Amazônia) e fez uso de tecnologias pré-existentes (geotecnologias) embasadas em pesquisa bibliográfica.

ii) Quanto aos objetivos: pesquisa exploratória e descritiva. Exploratória, pois a finalidade foi delinear o assunto para investigação, com posterior delimitação do tema da pesquisa e enfoque para o assunto, através de estudos de caso. Descritiva, porque os fatos foram observados, registrados, analisados, classificados e interpretados, sem interferência dos autores do estudo sobre os dados (afinal, essa é a premissa básica do sensoriamento remoto, como definido anteriormente).

iii) Quanto aos procedimentos técnicos: pesquisa bibliográfica e documental e estudo de caso. A primeira ocorreu por meio da consulta de artigos científicos, dados estatísticos e documentos oficiais sobre o assunto. A segunda decorreu pela investigação do fenômeno contemporâneo (pressão antrópica sobre a floresta e seus recursos) dentro de seu contexto real e local (YIN, 2001).

Em vista da importância da Amazônia e do cumprimento das metas globais para o desenvolvimento sustentável, levantou-se o seguinte problema: é possível monitorar, por meio de técnicas de sensoriamento remoto, unidades de conservação urbanas na Amazônia?

Nesse sentido, esse estudo objetivou analisar e monitorar áreas de proteção ambiental através de geotecnologias. Os objetivos específicos foram:

a) Analisar as condições de nuvens em imagens Sentinel-2 MSI e Landsat-8 OLI de um lago de abastecimento público em Belém-Pará-Brasil.

b) Investigar as pressões ambientais antropogênicas em unidades de conservação urbanas: um estudo de caso em Belém, Amazônia Oriental Brasileira.

Referências da Introdução Geral

ANA - AGÊNCIA NACIONAL DE ÁGUAS. **Conjuntura dos Recursos Hídricos no Brasil 2018 - Informe Anual**. [s.l: s.n.]. Disponível em: <http://www.snirh.gov.br/portal/snirh/centrais-de-conteudos/conjuntura-dos-recursos-

hidricos/informe_conjuntura_2018.pdf>.

ARVOR, D. et al. Monitoring thirty years of small water reservoirs proliferation in the southern Brazilian Amazon with Landsat time series. **ISPRS Journal of Photogrammetry and Remote Sensing**, v. 145, p. 225–237, 2018.

BRASIL. **Lei nº 9985, de 18 de julho de 2000 - Institui o Sistema Nacional de Unidades de Conservação da Natureza e dá outras providências**. Disponível em: <http://www.planalto.gov.br/ccivil_03/leis/L9985.htm>.

BRIENEN, R. J. W. et al. Long-term decline of the Amazon carbon sink. **Nature**, v. 519, n. 7543, p. 344–348, 2015.

DODDS, W. K. et al. Eutrophication of U.S. Freshwaters: Analysis of Potential Economic Damages. **Environmental Science & Technology**, v. 43, n. 1, p. 12–19, 2009.

FOLEY, J. A. et al. El Niño-Southern oscillation and the climate, ecosystems and rivers of Amazonia. **Global Biogeochemical Cycles**, v. 16, n. 4, p. 79-1-79–20, 2002.

HANSEN, M. C. et al. High-Resolution Global Maps of 21st-Century Forest Cover Change. **Science**, v. 342, n. 6160, p. 850–853, 2013.

HASLER, N.; AVISSAR, R. What Controls Evapotranspiration in the Amazon Basin? **Journal of Hydrometeorology**, v. 8, n. 3, p. 380–395, 2007.

ITB - INSTITUTO TRATA BRASIL. **Ranking do Saneamento Básico - 100 Maiores Cidade do Brasil 2018**. [s.l: s.n.]. Disponível em: <http://www.tratabrasil.org.br/images/estudos/itb/ranking-2018/realatorio-completo.pdf>.

JENSEN, J. R. **Remote Sensing of the Environment: An Earth Resource Perspective**. 2. ed. Essex: Pearson Education Limited, 2014.

KARASKA, M. A. et al. AVIRIS Measurements of Chlorophyll, Suspended Minerals, Dissolved Organic Carbon, and Turbidity in the Neuse River, North Carolina. **Photogrammetric Engineering & Remote Sensing**, v. 70, n. 1, p. 125–133, 2004.

LAMPARELLI, M. C. **Graus de trofia em corpos d'água do estado de São Paulo: avaliação dos métodos de monitoramento**. 2004. USP, São Paulo, 2004. Disponível em: <http://www.teses.usp.br/teses/disponiveis/41/41134/tde-20032006-075813/>.

MELO, M. G. et al. Sewage contamination of Amazon streams crossing Manaus (Brazil) by sterol biomarkers. **Environmental Pollution**, v. 244, p. 818–826, 2019.

NEMANI, R. R. et al. Climate-Driven Increases in Global Terrestrial Net Primary Production from 1982 to 1999. **Science**, v. 300, n. 5625, p. 1560–1563, 2003.

OPOKU, A. Biodiversity and the built environment: Implications for the Sustainable Development Goals (SDGs). **Resources, Conservation and Recycling**, v. 141, n. August 2018, p. 1–7, 2019.

PRODANOV, C. C.; FREITAS, E. C. **Metodologia do trabalho científico [recurso eletrônico]: métodos e técnicas da pesquisa e do trabalho acadêmico**. 2. ed. Novo Hamburgo: Editora Feevale, 2013.

RAPINEL, S. et al. Identification and mapping of natural vegetation on a coastal site using a Worldview-2 satellite image. **Journal of Environmental Management**, v.

144, p. 236–246, 2014.

STOW, D. et al. Irrigated Vegetation Assessment for Urban Environments. **Photogrammetric Engineering & Remote Sensing**, v. 69, n. 4, p. 381–390, 2003.

SUN, L. et al. Seasonal and Inter-annual Variation of Evapotranspiration in Amazonia Based on Precipitation, River Discharge and Gravity Anomaly Data. **Frontiers in Earth Science**, v. 7, n. March, p. 1–9, 2019.

UN - UNITED NATIONS. **Transformando Nosso Mundo: A Agenda 2030 para o Desenvolvimento Sustentável**. Rio de Janeiro: UNIC-Rio, 2015.

UN - UNITED NATIONS. **The Sustainable Development Goals Report 2018**. [s.l: s.n.]. Disponível em: <https://unstats.un.org/sdgs/files/report/2018/TheSustainableDevelopmentGoalsReport2018-EN.pdf>.

UN - UNITED NATIONS. **The United Nations World Water Development Report 2018: Nature-Based Solutions for Water**. [s.l: s.n.]. Disponível em: <http://unesdoc.unesco.org/images/0026/002614/261424e.pdf>.

WALSH, S. J. et al. Scale-Dependent Relationships between Population and Environment in Northeastern Thailand. **Photogrammetric Engineering & Remote Sensing**, v. 65, n. 1, p. 97–105, 1999.

WRIGHT, J. S. et al. Rainforest-initiated wet season onset over the southern Amazon. **Proceedings of the National Academy of Sciences**, v. 114, n. 32, p. 8481–8486, 2017.

YIN, R. K. **Case study research: design and methods**. 2. ed. São Paulo: Bookman, 2001.

Artigo publicado na Revista Ambiente & Água vol. 14 n. 4, e2375 - Taubaté 2019

Ambiente & Água - An Interdisciplinary Journal of Applied Science
ISSN 1980-993X – doi:10.4136/1980-993X
www.ambi-agua.net
E-mail: ambi.agua@gmail.com

Analysis of cloud condition on Sentinel-2 MSI and Landsat-8 OLI images of a public supply lake in Belém-Pará-Brazil

ARTICLES doi:10.4136/ambi-agua.2375

Received: 08 Feb. 2019; Accepted: 26 May 2019

Vítor Abner Borges Dutra*; Paulo Amador Tavares;
Hebe Morganne Campos Ribeiro

Universidade do Estado do Pará (UEPA), Belém, PA, Brasil
Programa de Pós-Graduação em Ciências Ambientais (PPGCA).
E-mail: vitordutra@uepa.br, paulo.tavares@uepa.br, hebemcr@gmail.com
*Corresponding author

Analysis of cloud condition on Sentinel-2 MSI and Landsat-8 OLI images of a public supply lake in Belém-Pará-Brazil

ABSTRACT

The eutrophication process leads to reduced water quality and economic losses worldwide. Furthermore, it is possible to apply remote sensing techniques for monitoring of aquatic environments. In this paper, we aimed to analyse the combined use of Sentinel-2 Multispectral Instrument and Landsat-8 Operational Land Imager data to monitor a eutrophic aquatic environment under adverse conditions of clouds, from July 2016 to July 2018. Data pre-selection was performed, and then the scenes were acquired for further investigation. After that, we created a key to the interpretation of cloud conditions for the study area and grouped each of 125 scenes in a Principal Component Analysis (PCA). The PCA grouped months with similarities in cloud conditions, highlighting their patterns in terms of the rainy and dry season for the study area. Another interesting result was that, even under the inherent adverse cloud regime of the Amazon, the combined use of both free satellite imagery data could be useful for further analysis, such as measuring of chlorophyll a, coloured dissolved organic matters, total suspended solids and turbidity. However, we highlight that, firstly, researches must be made to validate the data in situ, so that monitoring programs can be built through remote sensing applications.

Keywords: amazon waters, bolonha lake, remote sensing.

Análise das condições de nuvens em imagens Sentinel-2 MSI e Landsat-8 OLI de um lago de abastecimento público em Belém-Pará-Brasil

RESUMO

O processo de eutrofização leva à redução da qualidade da água e a perdas econômicas no mundo todo. Além disso, é possível aplicar técnicas de sensoriamento remoto para o monitoramento de ambientes aquáticos. Neste estudo, objetivou-se analisar o uso combinado dos dados Sentinel-2 Multispectral Instrument e Landsat-8 Operational Land Imager para o monitoramento de um ambiente aquático eutrofizado sob condições adversas de nuvens, de julho de 2016 a julho de 2018. Foi realizada a pré-seleção dos dados e posteriormente as cenas foram adquiridas para uma investigação mais aprofundada. Criou-se uma chave de interpretação para as condições de nuvens da área de estudo e foram agrupadas cada uma das 125 cenas em uma Análise de Componentes Principais (ACP). A ACP agrupou meses com similaridades nas condições de nuvens, destacando seus padrões em termos de estação chuvosa e seca para a área de estudo. Outro resultado interessante foi que, mesmo sob o regime adverso de nuvens inerente da Amazônia, o uso combinado de ambos dados de imagens de satélites gratuitos pode ser útil para uma análise mais aprofundada, como a mensuração de clorofila a, matéria orgânica colorida dissolvida, sólidos suspensos totais e turbidez. No entanto, destaca-se que, primeiramente, investimentos devem ser realizados de forma a validar dados in situ, para que um programa de monitoramento possa ser construído através de aplicações de sensoriamento remoto.

Palavras-chave: águas amazônicas, lago bolonha, sensoriamento remoto.

1. INTRODUCTION

Eutrophication is a process that causes water deterioration in lentic environments (LOBATO et al., 2015) and also affects the aquatic macrophytes spatial distribution (MADGWICK et al., 2011; SØNDERGAARD et al., 2010). These water vegetation contributes to primary productivity, sediment accumulation, provision of food and complex habitat for aquatic and semi-aquatic biota (POIKANE et al., 2018). Furthermore, macrophytes act as integrators of environmental conditions to which they are exposed and thus can be used as long-term indicators for water quality monitoring (PALL; MOSER, 2009; MELZER, 1999).

Studies highlighted that current water quality evaluation is limited due to three main factors: i) in-situ sampling and measurements of water quality parameters are labour demanding, time-consuming and expensive, ii) analysis of the spatial and temporal variations and water quality trends in large waterbodies is almost impractical, and iii) the collected in-situ data is not 100% accurate considering the possibility of field-sampling or laboratory error (GHOLIZADEH; MELESSE; REDDI, 2016; RITCHIE; ZIMBA; EVERITT, 2003).

In this context, remote sensing (RS) data and techniques offer a feasible means to explore spatial and temporal information, bringing a variety of insights related to tropical ecosystems (MARTINS et al., 2018; YANG et al., 2013). Among the RS possibilities for water quality monitoring, it is relevant to mention the use of open source data, such as Sentinel-2 Multispectral Instrument (S-2 MSI) and Landsat-8 Operational Land Imager (L-8 OLI) (PAHLEVAN et al., 2017, 2019), which we used in the analysis of this paper.

As a risk for future works in monitoring the environment, the US government started the processing of reviewing the data fees for Landsat family products (POPKIN, 2018). This payment would be a step backwards for Earth observation since more than 100,000 papers were produced since 2008, when the Landsat products started to be freely available. Stone (2010) reinforces the importance of the free distribution of satellite data, once it has applicability in a vast range of public and private sectors of society.

S-2 MSI is composed of two individual satellites, 2A and 2B, the first one was launched in June 2015 and the second one in March 2017. They are composed of thirteen spectral bands, four at 10 m, six at 20 m and three at 60 m of spatial resolution. L-8 OLI was launched in February 2013. The satellite is composed of nine spectral bands, which except for the panchromatic (15 m), all the other bands work at 30 m of spatial resolution. The synergetic use of S-2 MSI and L-8 OLI for monitoring provide a temporal resolution of 2.9 days (LI; ROY, 2017) and, after using image fusion techniques, a spatial resolution of 10 meters, is possible and usable for both images datasets aforementioned (BELTRÃO; TEODORO, 2018).

Applications with time series of Landsat products are a possibility of mapping and behaviour analysis of small water bodies in the Amazon (ARVOR et al., 2018). Landsat historical series also offers the opportunity to analyse the ecological regime of floating macrophyte greenness throughout vegetation indexes (TERBORGH et al., 2018). However, in Amazon, the seasonal variability of the main atmospheric constituents represents a challenge for optical RS (e.g., cloudiness regime, the high aerosol burden in the dry season, among others) (MARTINS et al., 2018).

In this perspective, we aimed to analyse the combined use of S-2 MSI and L-8 OLI data in the Brazilian Amazon, considering a eutrophic aquatic environment under adverse conditions of clouds. Our study also aimed at building knowledge related to the possibilities of monitoring aquatic ecosystems in the region.

2. MATERIAL AND METHODS

2.1. Study Area

The Bolonha and Água Preta Lakes supply nearly 63% of the drinking water of the Metropolitan Region of Belém (MRB) (PARÁ, 2013). Both lakes are refuelled by the Guamá River waters (BAHIA; FENZL; MORALES, 2008). They are located inside the Utinga State Park-Conservation Unit (USPCU) and cover 17.29% of its total area (240.85 out of 1393.088 ha) (PARÁ, 2013).

One of the main objectives of the creation of the USPCU was to ensure the water potability for the population of MRB (PARÁ, 2013). However, the pollution of Bolonha Lake due to the immoderate discharge of wastewater is causing its eutrophication and the overgrowth of water macrophytes over its surface (PARÁ, 2013; RIBEIRO, 1992). Figure 1, made in QGIS 2.18.17, shows the location of the Bolonha Lake, used as our object of study.

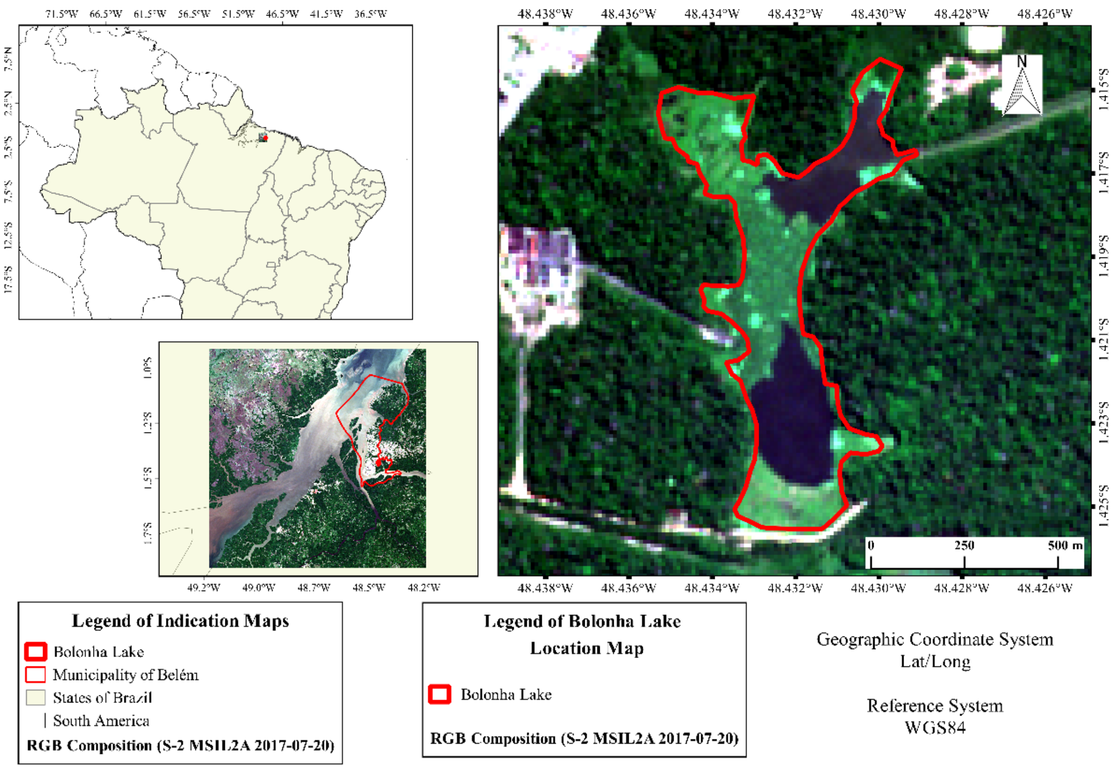
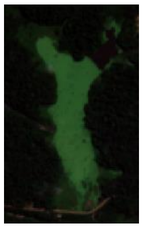


Figure 1. Location of the Bolonha Lake in Belém, Pará, Brazil. Source: Copernicus Sentinel data (2018).

2.2. Image Selection and Key of Interpretation of the Cloud Conditions

We considered all available S-2 MSI and L-8 OLI images from July 2016 to July 2018. We acquired the selected images in August 2018 in the Copernicus Open Access Hub (for S-2 MSI) and the Earth Explorer of the United States Geological Survey (for L-8 OLI). After that, we classified the collected images for the Bolonha Lake in three different cloud conditions: i) lake without cloud cover, ii) lake under partial cloud cover, and iii) lake entirely covered by cloud (Table 1). The S-2 MSI's operations phase images were excluded because the atmospheric correction could not be applied to them; hence, they are not suitable for most of the RS applications.

Table 1. Key of Interpretation applied to the study area. The S-2's coloured compositions in the example column were standardised as RGB: B4, B3 and B2. Source: Copernicus Sentinel data (2018).

Condition	Characteristics/Description	Example
Lake without cloud cover	Cloud-free images of the surface of the lake, including water mass, macrophytes and surrounding primary vegetation (e.g., S2A 20180630)	
Lake under partial cloud cover	Images that showed the lake under adverse conditions, but with a clear distinction between macrophytes and water mass (e.g., S2A 20180725)	
Lake entirely covered by cloud	Images not suitable for optical use, due to cloud obstruction of water mass, macrophytes and surroundings of the lake (e.g., S2A 20180426)	

This optical analysis was applied for all assessed images of the Bolonha Lake, scene by scene, and, even though there were scenes where the lake was under partial cloud cover condition, we distinguished which one of those scenes were optically useful for RS applications. The criterion we choose for this was the qualitative aspect of cloud fragments and shadows of cloud over the surface of the lake. With this criterion, we considered scenes as optically useful in situations where the cloud interferences could not affect the distinction of the water mass, the water vegetation and the primary vegetation around the Bolonha Lake.

We applied a quantitative approach, through PAST 3 software, to the filtered data using Principal Components Analysis (PCA) (FINKLER et al., 2015; VENKATAKRISHNAMOORTHY; REDDY, 2019) for the useful scenes of the Bolonha Lake. In this analysis, we considered the groups of images classified as "lake without cloud cover" and "lake under partial cloud cover" that surpassed the criterion from the cloud interference as useful data; the remaining scenes summed up to not suitable scene data.

3. RESULTS AND DISCUSSION

3.1 Data Classification and Characterization

In the Bolonha Lake region, most of the S-2A MSI scenes were found in operational phase until June 2016, which left us the option to analyse only the subsequent scenes – in such a way that the combination of proper S-2 MSI and L-8 OLI images were considered. After the launch and operational phase of S-2B, the number of scenes to be investigated increased considerably.

We found 125 scenes for the study area within the satellite imagery data in the period assessed, from which 77 scenes were from the S-2 MSI satellite, with an annual distribution as follows: 11 from July to December 2016, 27 from January to December 2017 and 39 from January to July 2018. For the L-8 OLI satellite, we found 48 scenes, distributed as follows: 12

from July to December 2016, 23 from January to December 2017 and 13 from January to July 2018. The S-2 MSI and L-8 OLI scenes of the Bolonha Lake were classified and quantified in terms of their suitability for RS applications, as shown in Figure 2.

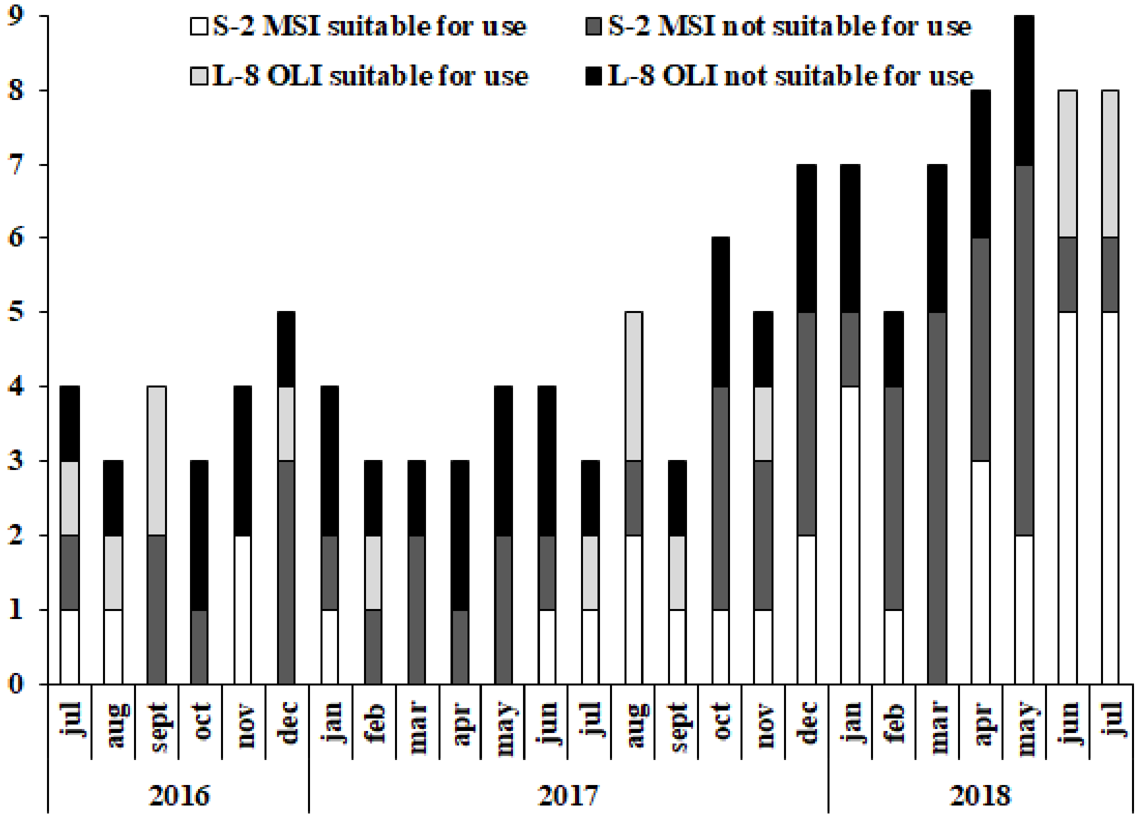


Figure 2. Classification of the suitability of S-2 MSI and L-8 OLI scenes for RS applications in terms of the cloud condition for all available data of the Bolonha Lake, from July 2016 to July 2018.

Due to its shorter revisit time (5 days) (ESA, 2015), S-2 MSI presented more available data than L-8 OLI (16 days) (USGS, 2016). The different sensing periods for the same area assisted in the selection of the optically useful images, improving temporal resolution for monitoring, agreeing with what is argued by Li and Roy (2017), e.g., in August 2017 there were four cloud-free images of the Bolonha Lake, being two of each satellite.

The gap of optically useful scenes between the months of March and May 2017 occurred because the S-2B satellite was still under the pre-launch phase (ESA, 2015). Furthermore, the L-8 OLI in the same period provided four scenes of the lake entirely covered by cloud and one scene where the Bolonha Lake was under partial cloud coverage – but with almost all pixels over the lake obstructed by clouds – i.e., those data were not suitable for RS applications.

The optical analysis and application of the key of interpretation resulted in 49 scenes of the study area suitable for RS applications, of which 34 were from S-2 MSI and 15 from L-8 OLI. We found around one useful scene per month of the Bolonha Lake (October 2016, March, April and May 2017 and March 2018 were the only months with no usable image found). This implies that the monitoring of aquatic environments using S-2 MSI and L-8 OLI imagery data is feasible even under the inherent excessive cloud regime of the Amazon (MARTINS et al., 2018).

The results of the PCA of the first (78.6%) and second (21.4%) components, suitable S-2 MSI and L-8 OLI data and total satellite available data, respectively, pointed three different groups (Figure 3). The similarities were found as follows: i) July to November 2016, January to July 2017 and September 2017 (red), ii) December 2016, October to December 2017 and February to May 2018 (green) and iii) August 2017, January 2018 and June, July 2018 (blue).

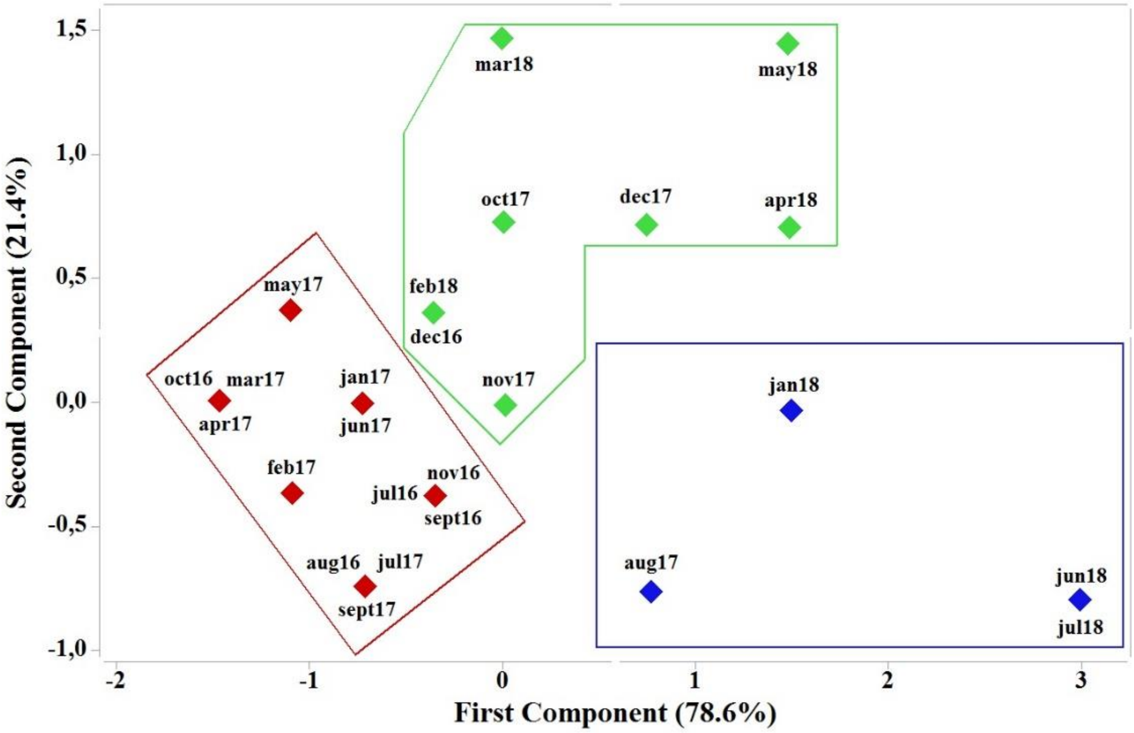


Figure 3. PCA illustrating the groups of similar months with overall cloud condition and useful S-2 MSI and L-8 OLI data for the Bolonha Lake.

The red group were assigned together due to the low availability and suitability of satellite data in these months. Prior to September 2017 (Figure 2), the S-2A was operating alone and giving a few imagery data of the study area. The temporal resolution of L-8 OLI could only delivery two scenes per month. Added to those factors, we highlight that the rainy season of USPCU occurs during December until May (INMET, 2019), which corroborates the fact that during this period the images are found covered by cloud more frequently.

The similarity of the green group, except for December 2016, was due to the launch of S-2B satellite, which increased the temporal resolution over Bolonha Lake. This group presented more suitable optical data than the red group, even during the rainy season.

Lastly, the blue group, except for January 2018, was under the dry season in the USPCU area, i.e., the formation and density of clouds over the study area was much smaller than in the rainy season. This characterised a period with high availability of satellite data, in which almost all of them are suitable for optical RS applications, e.g., June and July 2018 both presented 16 available satellite data, from them, 14 scenes were optically useful for analysis of water parameters and its surface macrophytes of the Bolonha Lake.

There are scarce studies that attempted to demonstrate the suitability of combined S-2 MSI and L-8 OLI imagery (PAHLEVAN et al., 2019). Furthermore, investigations of cloud patterns usually select bigger areas and use different satellite instruments, such as Moderate Resolution Imaging Spectroradiometer (MODIS) (GARCIA-CARRERAS; MARSHAM; SPRACKLEN, 2017).

Researches have highlighted different patterns of cloud cover over forested and deforested areas across distinct regions. Ray et al. (2003) studied the high occurrence of cumulus clouds over native vegetation areas in Southwest Australia. Teuling et al. (2017) analysed the substantial increase in cloud cover over large forest regions in Western Europe.

Wang et al. (2009) investigated patterns of shallow cloudiness over deforested areas in Western Amazon. Durieux, Machado and Laurent (2003) found increased cloud cover over deforested regions due to the enhancement of seasonal contrasts in Eastern Amazon.

Considering the data from automatic weather stations in Eastern Amazon, Germano et al. (2017) analysed the breeze circulations inside USPCU between 2003 and 2012. The cloud-correlated data were precipitation, wind speed and direction. The results showed that the effects of the sea breezes on the precipitation were more evident in Belém and other farther inland cities, which experienced a high frequency of precipitation from 15:00 to 21:00 UTC. Therefore, we can infer that the satellite data for the study area were very likely to be covered by clouds, considering the start sensing period of both S-2 MSI (13:42 UTC) and L-8 OLI (13:22 UTC).

3.2 Optically Active Water Parameters

The goal of most aquatic RS is to extract the radiance of interest from all the other radiance components being recorded by the sensor system. To identify the organic and inorganic constituents in the water column (e.g., chlorophyll a or total suspended solids), it is necessary to isolate the subsurface volumetric radiance (L_v) from the total radiance (L_t) (Equation 1). This process usually involves careful radiometric correction of the remote sensor data to remove atmospheric attenuation (L_p), surface sun-glint and other surface reflection (L_s), the radiance that entered the water column but was scattered into the upper hemisphere before reaching the bottom (L_c) and bottom reflectance (L_b). However, it is only possible to isolate and calculate L_v within a not cloud-shrouded region (LEGLEITER; ROBERTS, 2005; JENSEN, 2014).

$$L_v = L_t - \left(L_p + L_s + L_c + L_b\right) \quad (1)$$

RS data and techniques have been widely used to map the open water characteristics and their changes (ZHANG et al., 2018). Some of the water parameters optically active and the RS data used for these applications in the literature investigated are detailed in Table 2.

Table 2. Commonly measured and optically active water qualitative parameters using RS.

Water Quality Parameter	References	Satellite/Sensor Data Used
Chlorophyll a (mg L-1)	Novo et al. (2013) Watanabe et al. (2017)	L-5 TM [1] S-2 MSI, L-8 OLI
Coloured Dissolved Organic Matters (mg L-1)	Giardino et al. (2014) Ruescas et al. (2018)	MODIS, L-8 OLI, RapidEye S-2 MSI, S-3 OLCI [2]
Total Suspended Solids (mg L-1)	Umar, Rhoadsm, Greenberg (2018) Pahlevan et al. (2019)	L-5 TM S-2 MSI, L-8 OLI
Turbidity (NTU)	Rudorff et al. (2018) Sakuno et al. (2018)	L-5 TM, L-8 OLI, MODIS S-2 MSI

[1] Landsat 5 Thematic Mapper; [2] Sentinel-3 Ocean and Land Colour Instrument

Gholizadeh, Melesse and Reddi (2016) described the satellites possibilities for monitoring of water parameters. For these authors, with the use of free Landsat data, it is possible to investigate the main water parameters that have optical responses. At the release date of their paper, the S-2 MSI was recently launched, so there was not trustworthy paper released yet, so the authors did not consider it in their article. However, in Table 2, we elucidate the possibilities of also using the S-2 MSI for the main water parameters estimation. The options of the identified optically active water parameters, together with the number of images available during the year, per month, opens the opportunity of spatio-temporal monitoring the Bolonha Lake with reduced cost and for constants periods, increasing the understanding of the dynamics of this water body.

4. FINAL CONSIDERATIONS

Our study analysed the optically useful RS data for the USPCU, considering the possibility of further analysis for the study area and its qualitative water parameters. We could conclude that the synergic use of S-2 MSI and L-8 OLI surpasses the cloud issue, granting almost a monthly optical useful image data for small areas, such as Bolonha Lake. However, joint efforts of the public actors interested in the area must be made to validate the data locally during the rainy and dry seasons.

5. REFERENCES

ARVOR, D. et al. Monitoring thirty years of small water reservoirs proliferation in the southern Brazilian Amazon with Landsat time series. **ISPRS Journal of Photogrammetry and Remote Sensing**, v. 145, p. 225–237, 2018. https://doi.org/10.1016/j.isprsjprs.2018.03.015

BAHIA, V. E.; FENZL, N.; MORALES, G. P. Caracterização da qualidade das águas subterrâneas da bacia hidrográfica do Utinga/Belém (PA) - a partir de dados hidrogeoquímicos. **Anais do XV Congresso Brasileiro de Águas Subterrâneas**, p. 1–20, 2008.

BELÉM. **Mapa de localização das bacias hidrográficas do município de Belém**. Belém: Prefeitura Municipal de Belém, 2014.

BELTRÃO, N.; TEODORO, A. Evaluating the potential of Sentinel-2 MSI and Landsat-8 OLI data fusion for land cover mapping in Brazilian Amazon. **Remote Sensing for Agriculture, Ecosystems, and Hydrology XX**, p. 7, 2018. https://doi.org/10.1117/12.2325576

DURIEUX, L.; MACHADO, L. A. T.; LAURENT, H. The impact of deforestation on cloud cover over the Amazon arc of deforestation. **Remote Sensing of Environment**, v. 86, n. 1, p. 132–140, 2003. https://doi.org/10.1016/S0034-4257(03)00095-6

ESA. **Sentinel-2 User Handbook**. 1. ed. Paris: European Space Agency, 2015.

FINKLER, N. R. et al. Qualidade da água superficial por meio de análise do componente principal. **Ambiente & Água - An Interdisciplinary Journal of Applied Science**, v. 10, n. 4, p. 782–792, 2015. http://dx.doi.org/10.4136/ambi-agua.1468

GARCIA-CARRERAS, L.; MARSHAM, J. H.; SPRACKLEN, D. V. Observations of Increased Cloud Cover over Irrigated Agriculture in an Arid Environment. **Journal of Hydrometeorology**, v. 18, n. 8, p. 2161–2172, 2017. https://doi.org/10.1175/JHM-D-16-0208.1

GERMANO, M. F. et al. Analysis of the breeze circulations in Eastern Amazon: an observational study. **Atmospheric Science Letters**, v. 18, n. 2, p. 67–75, 2017. https://doi.org/10.1002/asl.726

GHOLIZADEH, M.; MELESSE, A.; REDDI, L. A Comprehensive Review on Water Quality Parameters Estimation Using Remote Sensing Techniques. **Sensors**, v. 16, n. 8, p. 1298, 2016. https://doi.org/10.3390/s16081298

GIARDINO, C. et al. Evaluation of Multi-Resolution Satellite Sensors for Assessing Water

Quality and Bottom Depth of Lake Garda. **Sensors (Switzerland)**, v. 14, n. 12, p. 24116–24131, 2014. https://doi.org/10.3390/s141224116

INMET. **Banco de Dados Meteorológicos para Ensino e Pesquisa - BDMEP**. <http://www.inmet.gov.br/portal/index.php?r=bdmep/bdmep>. Accessed: 5 feb. 2019.

JENSEN, J. R. **Remote Sensing of the Environment: An Earth Resource Perspective**. 2. ed. Essex: Pearson Education Limited, 2014.

LEGLEITER, C. J.; ROBERTS, D. A. Effects of channel morphology and sensor spatial resolution on image-derived depth estimates. **Remote Sensing of Environment**, v. 95, n. 2, p. 231–247, 2005. https://doi.org/10.1016/j.rse.2004.12.013

LI, J.; ROY, D. P. A Global Analysis of Sentinel-2A, Sentinel-2B and Landsat-8 Data Revisit Intervals and Implications for Terrestrial Monitoring. **Remote Sensing**, v. 9, n. 9, p. 1–17, 2017. https://doi.org/10.3390/rs9090902

LOBATO, T. C. et al. Categorization of the trophic status of a hydroelectric power plant reservoir in the Brazilian Amazon by statistical analyses and fuzzy approaches. **Science of the Total Environment**, v. 506–507, p. 613–620, 2015. https://doi.org/10.1016/j.scitotenv.2014.11.032

MADGWICK, G. et al. Centennial-scale changes to the aquatic vegetation structure of a shallow eutrophic lake and implications for restoration. **Freshwater Biology**, v. 56, n. 12, p. 2620–2636, 2011. https://doi.org/10.1111/j.1365-2427.2011.02652.x

MARTINS, V. S. et al. Seasonal and interannual assessment of cloud cover and atmospheric constituents across the Amazon (2000–2015): Insights for remote sensing and climate analysis. **ISPRS Journal of Photogrammetry and Remote Sensing**, n. October 2017, p. 1–19, 2018. https://doi.org/10.1016/j.isprsjprs.2018.05.013

MELZER, A. **The Ecological Bases for Lake and Reservoir Management**. 1. ed. [s.l.] Kluwer Academic Publishers, 1999. https://doi.org/10.1007/978-94-017-3282-6

NOVO, E. M. L. DE M. et al. Proposal for a remote sensing trophic state index based upon Thematic Mapper/Landsat images. **Ambiente & Água - An Interdisciplinary Journal of Applied Science**, v. 8, n. 3, p. 65–82, 2013. http://dx.doi.org/10.4136/ambi-agua.1229

PAHLEVAN, N. et al. Sentinel-2 MultiSpectral Instrument (MSI) data processing for aquatic science applications: Demonstrations and validations. **Remote Sensing of Environment**, v. 201, n. September, p. 47–56, 2017. https://doi.org/10.1016/j.rse.2017.08.033

PAHLEVAN, N. et al. Sentinel-2/Landsat-8 product consistency and implications for monitoring aquatic systems. **Remote Sensing of Environment**, v. 220, p. 19–29, 2019. https://doi.org/10.1016/j.rse.2018.10.027

PALL, K.; MOSER, V. Austrian Index Macrophytes (AIM-Module 1) for lakes: A Water Framework Directive compliant assessment system for lakes using aquatic macrophytes. **Hydrobiologia**, v. 633, n. 1, p. 83–104, 2009. https://doi.org/10.1007/s10750-009-9871-0

PARÁ. **Plano de Manejo do Parque Estadual do Utinga**. Belém: Ideflor-bio, 2013.

POIKANE, S. et al. Macrophyte assessment in European lakes: Diverse approaches but convergent views of ‘good’ ecological status. **Ecological Indicators**, v. 94, n. March, p. 185–197, 2018. https://doi.org/10.1016/j.ecolind.2018.06.056

POPKIN, G. US government considers charging for popular Earth-observing data news.

Nature, v. 556, n. 7702, p. 417–418, abr. 2018. https://doi.org/10.1038/d41586-018-04874-y

RAY, D. K. et al. Effects of land use in Southwest Australia: 1. Observations of cumulus cloudiness and energy fluxes. **Journal of Geophysical Research**, v. 108, n. 14, p. 1–20, 2003. https://doi.org/10.1029/2002JD002654

RIBEIRO, H. M. C. **Avaliação atual da qualidade das águas dos lagos Bolonha e Água Preta, situados na área fisiográfica do Utinga (Belém-Pará)**. Belém: UFPA, 1992.

RITCHIE, J. C.; ZIMBA, P. V.; EVERITT, J. H. Remote Sensing Techniques to Assess Water Quality. **Photogrammetric Engineering & Remote Sensing**, v. 69, n. 6, p. 695–704, 2003. https://doi.org/10.14358/PERS.69.6.695

RUDORFF, N. et al. Remote sensing monitoring of the impact of a major mining wastewater disaster on the turbidity of the Doce River plume off the eastern Brazilian coast. **ISPRS Journal of Photogrammetry and Remote Sensing**, v. 145, p. 349–361, 2018. https://doi.org/10.1016/j.isprsjprs.2018.02.013

RUESCAS, A. B. et al. Machine learning regression approaches for colored dissolved organic matter (CDOM) retrieval with S2-MSI and S3-OLCI simulated data. **Remote Sensing**, v. 10, n. 5, p. 1–25, 2018. https://doi.org/10.3390/rs10050786

SAKUNO, Y. et al. Evaluation of unified algorithms for remote sensing of chlorophyll-a and turbidity in Lake Shinji and Lake Nakaumi of Japan and the Vaal Dam Reservoir of South Africa under eutrophic and ultra-turbid conditions. **Water (Switzerland)**, v. 10, n. 5, 2018. https://doi.org/10.3390/w10050618

SØNDERGAARD, M. et al. Submerged macrophytes as indicators of the ecological quality of lakes. **Freshwater Biology**, v. 55, n. 4, p. 893–908, 2010. https://doi.org/10.1111/j.1365-2427.2009.02331.x

STONE, R. Earth-observation summit endorses global data sharing. **Science**, v. 330, n. 6006, p. 902, 2010. https://doi.org/10.1126/science.330.6006.902

TERBORGH, J. W. et al. Twenty-three-year timeline of ecological stable states and regime shifts in upper Amazon oxbow lakes. **Hydrobiologia**, v. 807, n. 1, p. 99–111, 2018. https://doi.org/10.1007/s10750-017-3384-z

TEULING, A. J. et al. Observational evidence for cloud cover enhancement over western European forests. **Nature Communications**, v. 8, p. 1–7, 2017. https://doi.org/10.1038/ncomms14065

UMAR, M.; RHOADS, B. L.; GREENBERG, J. A. Use of Multispectral Satellite Remote Sensing to Assess Mixing of Suspended Sediment Downstream of Large River Confluences. **Journal of Hydrology**, v. 556, p. 325–338, 2018. https://doi.org/10.1016/j.jhydrol.2017.11.026

USGS. **Landsat-8 Data User Handbook**. 2. ed. Reston: United States Geological Survey, 2016.

VENKATAKRISHNAMOORTHY, T.; REDDY, G. U. Cloud enhancement of NOAA multispectral images by using independent component analysis and principal component analysis for sustainable systems. **Computers and Electrical Engineering**, v. 74, p. 35–46, 2019. https://doi.org/10.1016/j.compeleceng.2019.01.005

WANG, J. et al. Impact of deforestation in the Amazon basin on cloud climatology. **Proceedings of the National Academy of Sciences**, v. 106, n. 10, p. 3670–3674, 2009. https://doi.org/10.1073/pnas.0810156106

WATANABE, F. et al. Remote Sensing of the Chlorophyll-a Based on OLI/Landsat-8 and MSI/Sentinel-2A (Barra Bonita reservoir, Brazil). **Annals of the Brazilian Academy of Sciences**, p. 1–14, 2017. http://dx.doi.org/10.1590/0001-3765201720170125

YANG, J. et al. The role of satellite remote sensing in climate change studies. **Nature Climate Change**, v. 3, n. 10, p. 875–883, 2013. https://doi.org/10.1038/nclimate1908

ZHANG, S. et al. Effective water surface mapping in macrophyte-covered reservoirs in NE Brazil based on TerraSAR-X time series. **International Journal of Applied Earth Observation and Geoinformation**, v. 69, p. 41–55, 2018. https://doi.org/10.1016/j.jag.2018.02.014

Artigo sob avaliação na urbe. Revista Brasileira de Gestão Urbana (submetido em 16 de outubro de 2019)

urbe. Revista Brasileira de Gestão Urbana

Anthropogenic environmental pressures in urban conservation units: A case study in Belém, Brazilian Eastern Amazon

Journal:	*urbe. Revista Brasileira de Gestão Urbana*
Manuscript ID	URBE-2019-0297
Manuscript Type:	Original Article
Keyword:	Utinga State Park, Urban sprawl, Eutrophication, Forest resilience, Remote sensing

Anthropogenic environmental pressures in urban conservation units: A case study in Belém, Brazilian Eastern Amazon

Pressões ambientais antropogênicas em unidades de conservação urbanas: um estudo de caso em Belém, Amazônia Oriental Brasileira

Abstract

More than 70% of Amazon inhabitants live in cities. Moreover, the contest between urban and green areas are historically known. In this scenario, the green areas in the Eastern Amazon cities are now beneath constant pressure and, some of its ecosystem services can be reduced due to environmental stress. Therefore, this study aimed to investigate environmental stressors in two urban conservation units located in the Brazilian Eastern Amazon. To understand how the urbanisation affected both the eutrophication process and forest resilience in the study area, we investigated the literature about the urban sprawl in Belém city and analysed, through remote sensing techniques, the responses for vegetation and built-up indices in the last 30 years. The results showed that the city expansion had not considered sustainable criteria, which ultimately intensified the anthropic eutrophication of the Bolonha Lake. Moreover, despite anthropogenic and climate pressures in the last decades over the green areas of Belém, the forest within the park showed no signal of reduced resilience. Lastly, joint efforts are necessary to improve wastewater treatment in the Metropolitan Region of Belém, so the water quality of the reservoirs improve, and its macrophytes blooming reduce gradually.

Keywords: Utinga State Park. Urban sprawl. Eutrophication. Forest resilience. Remote sensing.

Resumo

Mais de 70% dos habitantes da Amazônia vivem nas cidades. Além disso, a disputa entre áreas urbanas e verdes é historicamente conhecida. Nesse cenário, as áreas verdes nas cidades da Amazônia Oriental estão agora sob pressão constante, e alguns de seus serviços ecossistêmicos podem ser reduzidos devido ao estresse ambiental. Portanto, este estudo teve como objetivo investigar estressores ambientais em duas unidades de conservação urbanas localizadas na Amazônia Oriental Brasileira. Para entender como a urbanização afetou o processo de eutrofização e a resiliência florestal na área de estudo, investigamos a literatura sobre a expansão urbana na cidade de Belém e analisamos, por meio de técnicas de sensoriamento remoto, as respostas de índices de vegetação e área construída nos últimos 30 anos. Os resultados mostraram que a expansão da cidade não considerou critérios sustentáveis, o que intensificou a eutrofização antrópica do Lago Bolonha. Além disso, apesar das pressões antropogênicas e climáticas nas últimas décadas sobre as áreas verdes de Belém, a floresta dentro do parque não mostrou sinal de resiliência reduzida. Por fim, são necessários esforços conjuntos para melhorar o tratamento de águas residuais na Região Metropolitana de Belém, para que a qualidade da água dos reservatórios melhore e o floração de suas macrófitas diminua gradualmente.

Palavras-chave: *Parque Estadual do Utinga. Expansão urbana. Eutrofização. Resiliência florestal. Sensoriamento remoto.*

Introduction

The urbanisation is a complex socio-economic process that transforms the built environment, converting formerly rural into urban settlements, while also shifting the spatial distribution of a population from rural to urban areas. It includes changes in dominant occupations, lifestyle, culture and behaviour, and thus alters the demographic and social structure of both urban and rural areas (UN, 2019). According to Dye (2008), urbanisation has positive and negative impacts. The first one being the economic growth and development, along with a range of beneficial social outcomes. The second one comprises the increased crowd, pollution and stress compared to rural areas. Furthermore, 55% of the world population was residing in urban areas in 2018, and by 2050, 68% of the world's population is projected to be urban (UN, 2019).

Given the background, the Amazon counts with more than 70% of its inhabitants living in cities (Pontes & Cardoso, 2016). Moreover, the Eastern Amazon comprise the last portion of the Amazon Basin; this type of estuary with river deltas is a hotspot for human development and have been under continuous pressure resulted from anthropogenic activities in the last centuries (Barbosa, Atkinson, & Dearing, 2016). The human occupation in these areas was usually dispersed and scattered across the forest, dependent on river accessibility and the possibility of extractive activities (Pontes & Cardoso, 2016). Currently, the Amazon estuary is considered one of Brazil's last frontiers of development supported by the Brazilian government and is usually seen as a land of great opportunities to those pursuing new enterprises (Fortini & Carter, 2014; Steward, 2013).

In the framework of urbanisation, the city of Belém, Pará, stands out for being the biggest city in the Amazon delta and the second largest in Amazon. The often called "capital of the Amazon" also clusters up with six more municipalities (Ananindeua, Benevides, Castanhal, Marituba, Santa Bárbara do Pará and Santa Izabel do Pará) (Pará, 1995), what originates the Metropolitan Region of Belém, consisting of almost 2.5 million dwellers and being the major metropolitan region in the Eastern Amazon.

The competition for space in urban areas means smaller areas for nature, reducing the experience along with the natural world and, therefore, resulting in a reduced knowledge of (and support for) environmental issues (Cox, Shanahan, Hudson, Fuller, & Gaston, 2018). In this sense, the Ecosystem Services (ES), such as disturbance regulation, water regulation and supply, recreation and cultural activities (McPhearson, Pickett, et al., 2016) are under constant pressure in urban areas (Gong, Yu, Joesting, & Chen, 2013). Well-managed urbanisation can help maximise the benefits of agglomeration while minimising environmental degradation (UN, 2019). Therefore, it is fundamental not only to have green spaces in the cities but to manage them following sustainable criteria, such as the Sustainable Development Goals 11 (sustainable cities and communities) and 15 (life on land) (McPhearson, Parnell, et al., 2016).

Taking into account that green spaces are under continuous anthropogenic pressure in the cities (including the Amazon ones) and need to endure environmental disturbances, it is crucial to define both forest resilience and stability. The resilience determines the persistence of relationships within a system and is a measure of the ability of these systems to absorb changes of state variables, driving variables, and parameters, and yet persist (i.e., part of the ecosystem does not become extinct rapidly). Stability, on another note, is the ability of a system to return to an equilibrium state after a temporary disturbance (i.e., the more rapidly it returns, and with the least fluctuation, the more stable it is) (Holling, 1973). In this scenario, we opted for the resilience approach to investigate the environmental stress in two green areas within the Metropolitan Region of Belém. Moreover, despite forest resilience being considered a trendy environmental policy goal, it is still a challenging concept for land managers to interpret from a practical perspective (Bowditch, McMorran, Bryce, & Smith, 2019; Newton, 2016).

In the context of water regulation and supply in urban areas, one commonly noticed modification caused due to the urbanisation process is the increase of eutrophication in lentic water environments, such as reservoirs for public water supply. In these aquatic environments, the algae naturally expand its area of occupation depending on the availability of nitrogen, phosphorus, carbon dioxide and other substances resulted from the organic decomposition (Branco, 1993). However, this phenomenon can be turned into an uncontrolled process, considering that the excessive release of nutrients inside the water ultimately results in the growth of water vegetation (also called macrophytes) inside and on top of the reservoir (Lamparelli, 2004). In this situation, the stated process receive another denomination: anthropic (or cultural) eutrophication, in which the natural environment characteristics are altered, affecting the multiple uses of water and consequently the ES provided by it, such as public water supply and preservation of the aquatic life (Lamparelli, 2004; Ribeiro, 1992). Murphy et al. (2019) argue that human beings have been influencing the global movement of macrophyte species and impacting inland aquatic habitats, and this need to be assessed considering its specificities, location and intensity worldwide.

Some of the existing technological alternatives to monitor earth's natural areas are the Remote Sensing (RS) data and techniques (Haase et al., 2014; Tavares, Beltrão, Guimarães, Teodoro, & Gonçalves, 2019). Among the RS possibilities applications for ecological and urban purposes, the Land Use and Land Cover (LULC) change mapping (Xiao et al., 2006) and the execution of radiometric indices to monitor vegetation health area are some of the most common possibilities (Kwok, 2018). In the last few decades, open access RS data had made the number of its applications increase (Poursanidis & Chrysoulakis, 2017). For instance, some Amazon level works had been done in order to understand both its LULC (Almeida et al., 2016) and the forest resilience throughout vegetation indices (Anderson et al., 2018). On the other hand, it is essential that methods and data quality for each study area are selected with transparency and according to the specificities of each region (Rosa, Ahmed, & Ewers, 2014).

In this sense, the study aimed to investigate environmental stressors in two urban conservation units located in the Brazilian Eastern Amazon, specifically in the Metropolitan Region of Belém. To achieve this, we made a historical analysis, via RS, of three environmental aspects that are being altered in these green areas. Therefore, this research explores three objectives to i) investigate the urban sprawl process toward the Utinga State Park Conservation Unit; ii) interpret the water vegetation growth dynamics in the Bolonha Lake over the last 30 years; and iii) analyse the forest resilience in the study area.

Methods

Study area

The city of Belém is located in the Eastern Amazon, state of Pará, Brazil. The city has a population of approximately 1,485,732 inhabitants, living in a total area of 1059 km^2 (IBGE, 2019). In Figure 1, we present our study area and where each of the conservation units analysed is located.

The Köppen-Geiger classification of Belém is Af, i.e., the climate is equatorial with fully humid precipitation pattern (Kottek, Grieser, Beck, Rudolf, & Rubel, 2006; Yoo & Rohli, 2016). The two main occurrences of vegetation fragments in the city are the Upland (or Mainland) and Floodplain Forests (Amaral, Vieira, Salomão, Almeida, & Jardim, 2012). Furthermore, their Brazilians phytophysiognomies classifications are a subgroup of Dense Ombrophilous Forests, called *Terra Firme* and *Várzea* (or *Inundável de Igapó*), respectively (IBGE, 2012).

The city is subdivided into Urban and Natural Environment Macrozones. The first one corresponds to urbanised areas, located predominantly in the continental portion of the city. The second one prioritises the preservation, protection and recovery of natural resources in the municipality of Belém (Belém, 2008).

The Natural Environment Macrozone is subdivided into three major areas. Nonetheless, we chose only the first zone, which includes the Utinga State Park Conservation Unit (USPCU) and the Environmental Protection Area of the Metropolitan Region of Belém (EPAMRB). Both USPCU and EPAMRB areas are essential for the public water supply of the city and the conservation of the remaining Amazon rich fauna and flora. However, the unorganised urban growth and severe environmental pollution are increasing threats for these areas (Pará, 2013).

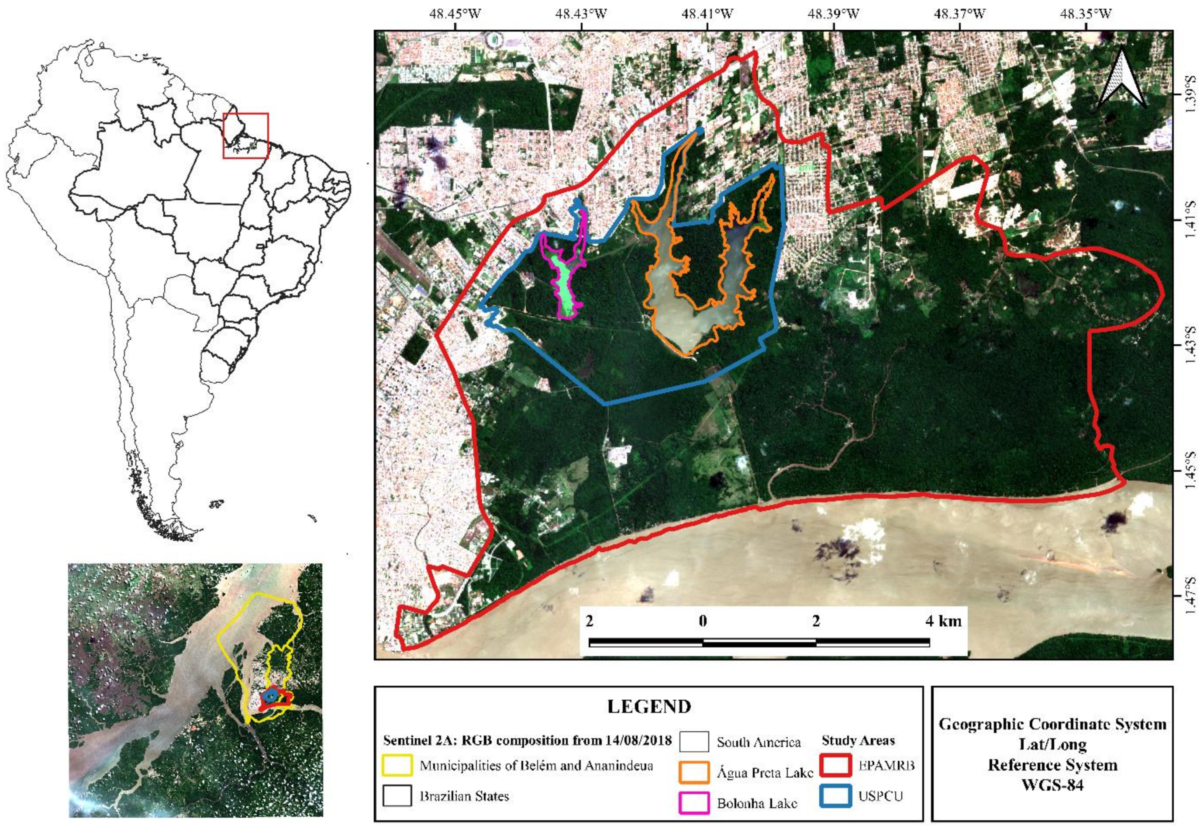


Figure 1 - Map of the study area indicating the geographic location of the Environmental Protection Area of the Metropolitan Region of Belém (EPAMRB), Utinga State Park Conservation Unit (USPCU) and both Bolonha and Água Preta Lakes.

Utinga State Park Conservation Unit

In 1993, the Pará State Government created the USPCU, whose aim is to secure public water supply through the management and recovery of degraded areas around both Bolonha and Água Preta Lakes. The total area of the USPCU is 1,393.088 ha, and its lakes are responsible for up to 63% of the public water supply of the Metropolitan Region of Belém (Pará, 2013).

The Brazilian Law classifies the USPCU as Conservation Unit of Integral Protection, which implies in the maintenance of the ecosystems free from the human interference, granted only the indirect use of the natural resources in the area (Brasil, 2000). Some of those indirect uses are the leisure to the community, the development of scientific research, cultural and educational activities, tourism, recreation and conservation of the fauna and flora (Pará, 2013).

Environmental Protection Area of the Metropolitan Region of Belém

The damping zone around the USPCU is the EPAMRB. With 5,653.81 ha, this area is classified by the Brazilian Law as Conservation Unit of Sustainable Use, i.e., it has the compatibilisation of nature conservancy with the sustainable use of a portion of its natural resources (Brasil, 2000). One of the main objectives of EPAMRB is to ensure the land use order based on ecological and urbanistic criteria (Pará, 1993).

Data acquisition

We obtained four optical satellite scenes and one digital elevation data (Table 1). Regarding the satellite scenes, three of them were Landsat 5 Thematic Mapper (L-5 TM), and the last one was a Sentinel-2 Multispectral Instrument (S-2 MSI). The L-5 TM data were acquired in surface reflectance level from the *EarthExplorer* platform of the United States Geological Survey, and the S-2 MSI data were acquired in the top of atmosphere level from the *Copernicus Open Access Hub* platform of the European Space Agency (ESA).

The Shuttle Radar Topography Mission's (SRTM) 1 arc-second Digital Elevation Model (DEM) was obtained directly from the software Sentinel Application Platform (SNAP) 6.0, through the function Add Elevation Band with bilinear interpolation resampling method. The projection of the SRTM DEM was WGS 84 Zone 22S to match both the L-5 TM and S-2 MSI data.

Table 1 - Satellite data acquired for this study.

Sensor Acronym	Sensor Type	Acquisition Date	Band Information	Spatial Resolution (m)
L-5 TM	Optical	06/07/1988 02/07/1998 13/07/2008	B3 – Red (660 nm) B4 – NIR (830 nm) B5 – SWIR (1650 nm)	30 30 30
S-2A MSI	Optical	14/08/2018	B4 – Red (665 nm) B8 – NIR (842 nm) B11 – SWIR (1610 nm)	10 10 20
SRTM	C-Band Radar	February-2000	DEM	30

Data processing

The flowchart in Figure 2 represents the data processing steps adopted for this research.

The first step implemented was the conversion of the data to surface reflectance, which is an essential step to apply to satellite data to retrieve trustworthy LULC information (Doxani et al., 2018). Furthermore, the seasonal variability of the main atmospheric constituents of the Amazon represents a challenge for optical RS, which manifests intense cloudiness regime, a high aerosol burden in the dry season and seasonal concentration of water vapour and ozone (Martins et al., 2018).

The Sen2Cor atmospheric correction processor was developed by Telespazio VEGA Deutschland GmbH on behalf of ESA (Main-Knorn et al., 2017) and showed plausible statistical results compared to other atmospheric correction processors (Warren et al., 2019). Thus, Sen2Cor v2.5.5 algorithm was applied to the S-2A Level-1C Top-Of-Atmosphere (TOA) data to achieve the Level-2A Bottom-Of-Atmosphere (BOA) reflectance product. Moreover, the L-5 TM data acquired were already available in BOA level.

After the atmospheric correction, the S-2 L2A data was resampled to 10 m spatial resolution through SNAP's S2 Geometric Resampling algorithm. The parameters used for interpolation and aggregation of the pixels' values were the bilinear upsampling and mean downsampling methods, respectively.

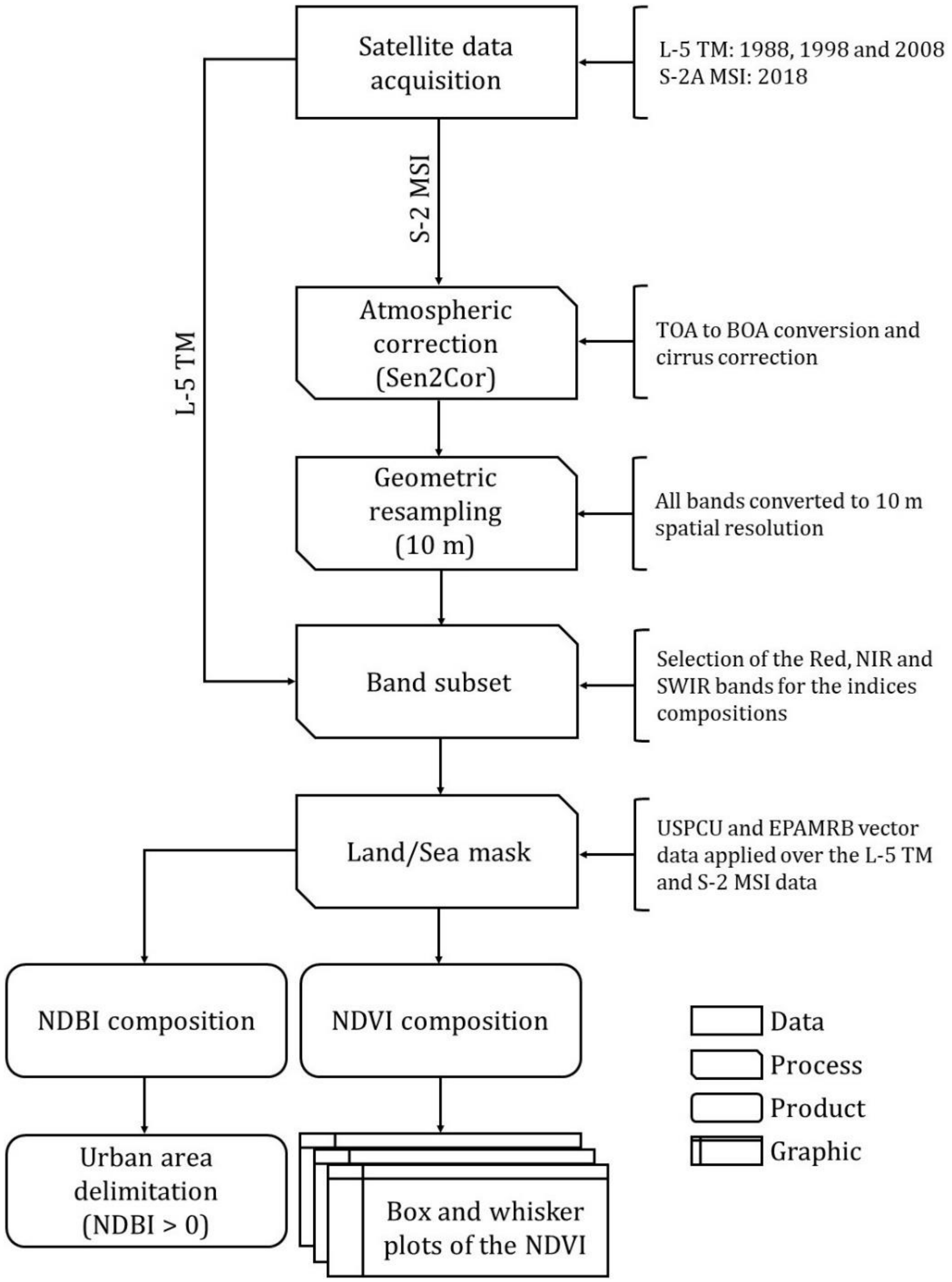


Figure 2 - Process flowchart of the data analysis.

Vegetation classes and radiometric indices

Vegetation indices are designed to enhance the contribution of vegetation properties and allow reliable spatiotemporal comparisons of terrestrial photosynthetic activity and canopy structural variations (Huete et al., 2002). In this sense, we evaluated four different classes for vegetation, considering the most prominent features in the study area, as follows: Water Vegetation (WVE), Mainland Forest (MLF), Igapó Forest (IGF) and Grassland (GSL) (Table 2).

In one previous analysis in the study area, Tavares, Dutra, et al., (2019) found that the Normalised Difference Vegetation Index (NDVI) could dissociate different types of vegetation better than other straight vegetation indices, such as the Normalised Difference Water Index (NDWI). For this reason, we adopted the NDVI to interpret the vegetation classes. The NDVI was produced through band algebra using the near-infrared (NIR) and the red bands of each satellite to create a quantitative measurement of vegetation conditions (Rouse Junior, Hass, Schell, & Deering, 1974). The expression is described in Equation 1.

$$NDVI = \frac{\rho_{NIR} - \rho_{Red}}{\rho_{NIR} + \rho_{Red}} \quad (1)$$

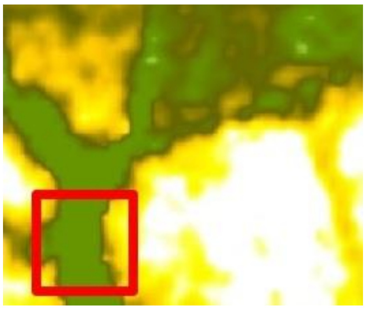
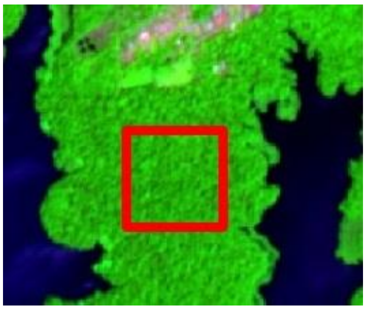
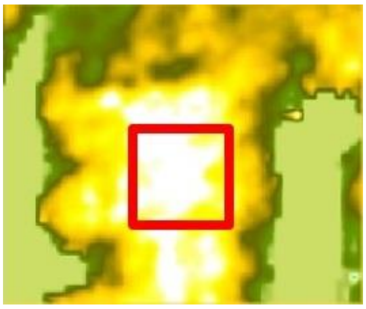
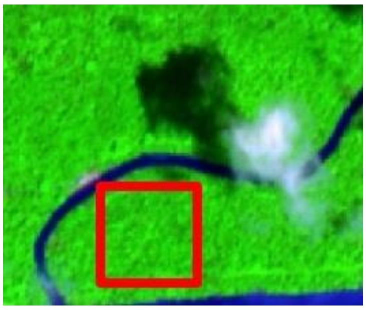
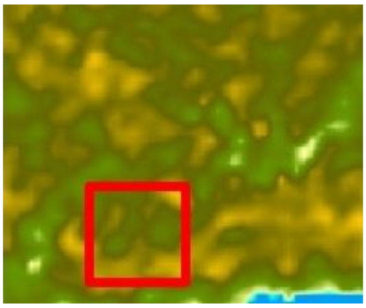
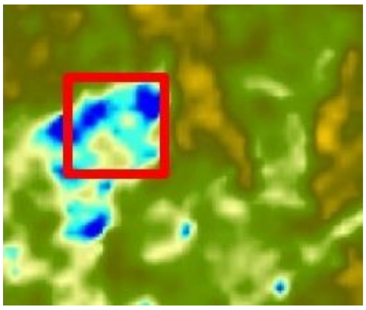
We used SNAP's Pin Manager Tool to select 20 random pixel points for each vegetation class, using the key of interpretation in Table 2 as a base to distinguish each one of them. After that, we analysed the behaviour of each pixel for each year. It was ensured, when possible, that those sampled pixels were taken from across the entire scene to avoid any bias.

Additionally, we applied the Normalised Difference Built-up Index (NDBI) (Zha, Gao, & Ni, 2003) to the data to retrieve the urban sprawl values between 1988 and 2018. The NDBI combine the shortwave infrared (SWIR) and NIR bands of the satellite to retrieve pixel values of the built-up areas in the scene (Equation 2).

$$NDBI = \frac{\rho_{SWIR} - \rho_{NIR}}{\rho_{SWIR} + \rho_{NIR}} \quad (2)$$

From the NDBI results, we select the values greater than 0, which should describe urban occupation, as they are supposed to exclude both the chlorophyll and the water spectral responses (Bhatti & Tripathi, 2014; Zha et al., 2003). However, the amount of sediment in the Amazon waters can make it mistaken respond as constructed areas (Wittmann, Oelze, Roig, & von Blanckenburg, 2018). For example, in the study of Trindade et al. (2019), the waters around Santarém city was confused with the built-up areas of the town. For this reason, after we found the values of NDBI greater than 0, we manually corrected the results to represent the urban area in our study site.

Table 2 - Key of interpretation of the different vegetation classes (highlighted in red) in the study area.

	S-2 MSI (B4; B3; B2)	S-2 MSI (B12; B8; B4)	SRTM DEM (C-Band Radar)
Water Vegetation (WVE)			
Mainland Forest (MLF)			
Igapó Forest (IGF)			
Grassland (GSL)			

Results

Figure 3 illustrates the NDVI visual representation for the years 1988 (L-5 TM), 1998 (L-5 TM), 2008 (L-5 TM) and 2018 (S-2 MSI). Some variations in the NDVI results between L-5 TM and S-2 MSI may occur due to their different central wavelength values (as displayed in Table 1). Another important factor to be considered, in terms of vegetation and urban area change analysis, is the difference in the spatial resolutions between L-5 TM and S-2 MSI satellites. Despite these disparities, the urban expansion towards the USPCU is noteworthy. Another significant detectable stressor in the conservation unit is the macrophytes bloom inside the Bolonha Lake. In the 2018 scene, the lake was entirely covered by WVE, which is why the area was recognised by the NDVI.

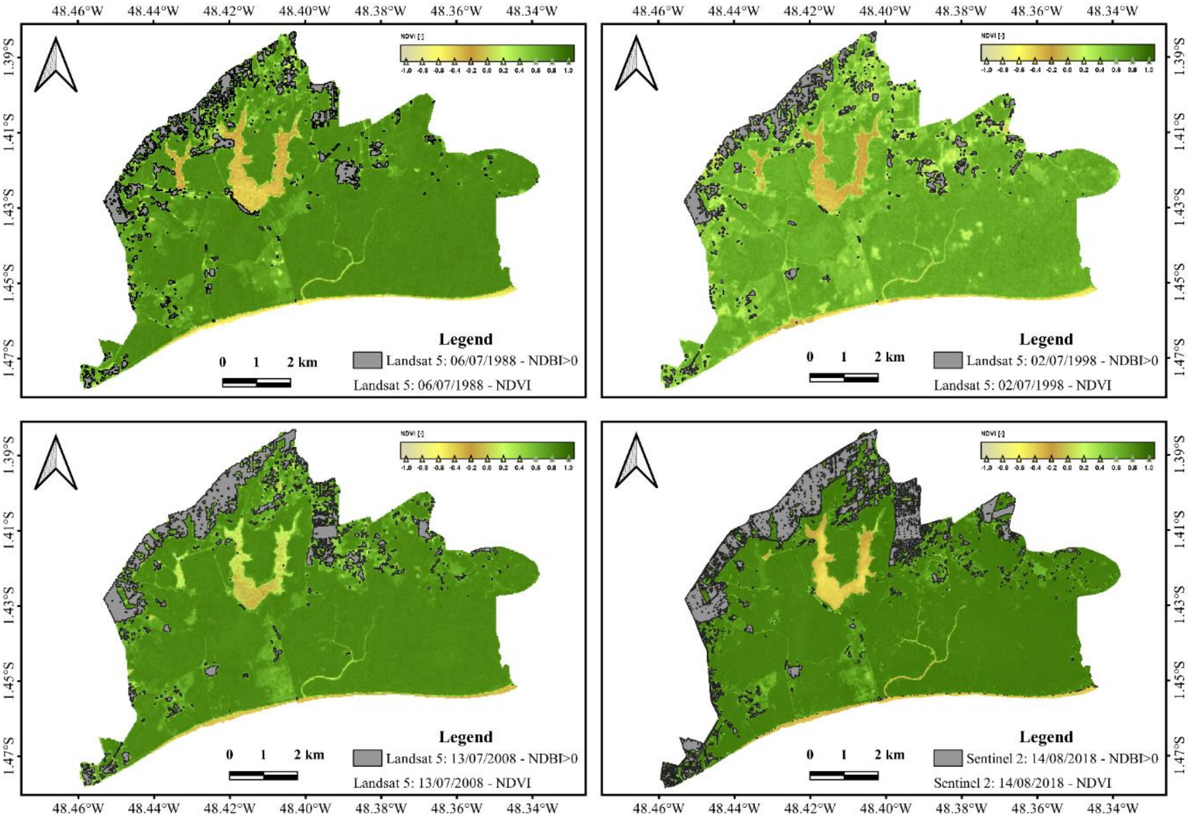


Figure 3 - NDVI variation (-1 to 1) for vegetation classes and NDBI variation (> 0) for the urban area in the last 30 years in the study area. It is noticeable the urban sprawl toward the USPCU in the period and the macrophytes coverage of the Bolonha Lake in 2018.

Regarding the different types of vegetation analysed, no significant variation was identified in the response of the inland vegetation NDVI values, such as MLF and IGF (Figure 4). Nevertheless, a significant difference was noted in the WVE values. Although we identified NDVI values greater than 0 within Bolonha Lake since 1988 (which means positive response to chlorophyll), in none of the years the values were high, and constant, as in 2018. From this perspective, it is possible that a water pollutant stressor may be acting in this lake and might be intensified in the last decade. On the other hand, it is also important to highlight that there were chlorophyll responses inside the lake, this fact, by itself, already indicates that a certain amount of organic matter is being dumped into the lake and is causing algae to proliferate inside of it.

In Figure 3, it is possible to identify that the urban area is increasing inside the EPAMRB toward the USPCU. The data extracted from the NDBI calculation, when the results were greater than 0, shows that the urban area increased from 464.42 to 905.12 ha between 1988 and 2018 (Table 3). This result indicates that the occupation of these natural areas almost doubled in the last 30 years. In 1998, the amount of clouds in the L-5 TM scene was worthy of attention, which might be one of the reasons why, in this year alone, the urban area identified was smaller than in the previous decade.

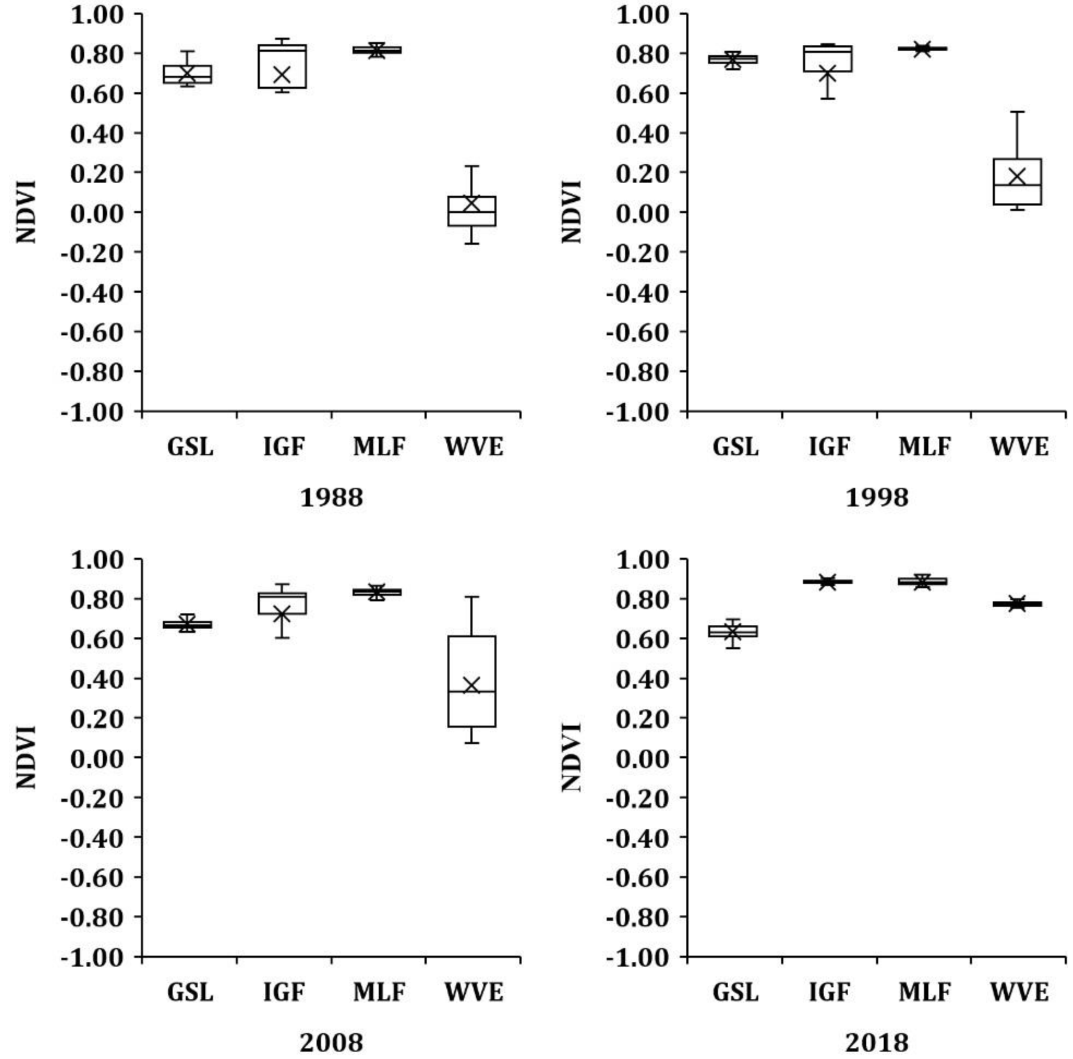


Figure 4 - Box and whisker plots of the NDVI showing mean, median, quartiles, minimum and maximum values for each (n=20) vegetation class in the last 30 years. The WVE values increased significantly in the period, pointing the worrisome consequence of pollution of the Bolonha Lake.

Table 3 - The urban area identified in the study site from 1988 to 2018, considering NDBI > 0.

Year	1988	1998	2008	2018
Urban area (ha)	464.42	436.48	665.63	905.12

Discussion

Urban sprawl

In contrast with our results for the urban area among the selected years, Gutierrez et al. (2017) found a total urban area of 1,950 ha in 2015 for the USPCU and EPAMRB. However, during their study, they used the old limits of these conservation units, in which they covered a higher portion of the urban areas of Belém and Ananindeua municipalities. Furthermore, these authors used a different type of LULC mapping methodology to define their study area.

To comprehend how this urban expansion occurred around and toward the USPCU, we assessed the historical occupation process of the city. Belém, according to Ponte (2015), until the very end of the 19th century, was still profoundly bound to the hydrography in its economic activities, public equipment and means of territorialisation. This relationship denotes the connection of the city to the water, which is often called a waterfront model. Notwithstanding, in the mid to late 20th century, the urban growth of Belém has been influenced by an urban remodel, based on the European and North American strategy of consuming (street lighting, streetcar, telephone, water pipes, machines, among others). Additionally, the hygienist logic has imposed changes in the city infrastructure and overall urbanisation, where law established, in practical terms, the rationalisation of the urban layout and the suppression of water meanders of creek beds and small urban rivers, in order to accelerate the flow of wastewater away from the city.

Corroborating the aforementioned process, the Pará State Government signed in 1945 a contract with a private company to draw up a remodelling plan for the Belém water supply services. The constructions went from 1945 to 1951, including a pump house for the Utinga area. Afterwards, in 1966, the conclusion of the BR-316 highway construction quickly increased the human occupation around the Bolonha and Água Preta Lakes. This lead to various infrastructure works in the area to secure the public water supply and, in the ’80s, both lakes were interconnected to ensure the water supply for the entire Metropolitan Region of Belém (Pará, 2013). From the late ’80s until nowadays, the local environmental laws have been trying to mitigate the effects of urban sprawl towards the USPCU.

Regardless of the environmental law effort, the occupation towards the park almost doubled in the last three decades, as seen in Table 3, which implies the higher pressure over the Bolonha and Água Preta Lakes and their surrounding vegetations (mainly MLF). One reason for part of this urban sprawl within the conservation unit is the conflict over governance of parts of the territory on the border between Belém and Ananindeua (Lima da Silva & Tourinho, 2016). Moreover, the Pará State Government started in 2013 a series of road constructions and interventions to improve both the traffic in the city and the integration of the Metropolitan Region of Belém. Controversially, they authorised the construction of a bridge over the Bolonha Lake, going against the integral protection principle of the USPCU. The infrastructure works of the bridge occurred between 2013 and 2015, upon the project entitled *Ação Metrópole*. The effects of these infrastructure work in the urban sprawl towards the USPCU are yet to be seen.

In this framework, Cardoso, Sobrinho, & Vasconcellos (2015) argue that the environmental management of urban parks depends fundamentally on land use planning and its surroundings. Moreover, they assert that, in areas with an unorganised territory, it is possible to increase the pressure over the LULC of the green areas, which ultimately cause the depredation of its natural resources (and consequently its ES). Some worrisome consequences of this unorganised urbanisation are the spread of WVE inside and on top of the reservoirs (Pall & Moser, 2009), the modification of the forest resilience characteristics in the green areas (Anderson et al., 2018), and the increased effect of urban heat island (Xue et al., 2019). Therefore, more investment in the environmental management of the green areas within the cities is required. For example, Baró et al. (2015) investigated five European cities, and the research results revealed mismatches between ES supply and demand in their study area, suggesting that further protection and restoration of urban green infrastructure is needed if ES are to play a more relevant role in meeting environmental quality standards and policy goals in cities.

Water vegetation proliferation

As displayed in Figure 3, the WVE bloom happened throughout the last 30 years. In 2018, the values of NDVI for WVE were higher than GSL (Figure 4), indicating a high photosynthetic activity of the macrophytes. Furthermore, according to the multitemporal analysis of Cardoso, Monteiro, Venturieri, & Campos (2009) over the USPCU between 1984 and 2008, this happened sometime between 2004 and 2006, where the WVE class started to be detected in the L-5 scenes. However, in the year of 2008, we did not identify a high proliferation of macrophytes, this may have occurred due to a manual removal required by the local managers of the USPCU as a palliative strategy to reduce the impacts of this vegetation in the Bolonha Lake (Araújo Júnior, 2015).

Vasconcelos & Souza (2011) presented in their paper that the water quality parameters of both Bolonha and Água Preta Lakes were above the recommended for a water supply lake in 2011. These elevated results can explain why WVE proliferation is high in these lakes. Another evidence of high chlorophyll values in these reservoirs was exposed by Dutra, Tavares, Trindade, et al. (2019) in an estimative RS analysis of the chlorophyll in the Água Preta Lake. In their paper, there was found a high concentration of chlorophyll in two parts the Água Preta Lake: the Guamá River pickup point and the adduction point for the Bolonha Lake. These pieces of evidences show that the Água Preta Lake is eutrophic, but is not yet in the same state of WVE proliferation of the Bolonha Lake due to its coverage area and water flows characteristics. Comparatively, the Água Preta Lake total area is six times bigger than Bolonha Lake, being 268.67 and 45.06 ha, respectively. Thus, Água Preta Lake has a higher self-purging capacity than Bolonha Lake.

To better comprehend the state of degradation of these lakes, it is essential to appraise the wastewater treatment situation in Belém. According to the National System of Information about Sanitation, only 2.67% of the domestic sewage was being treated in the city until 2016 (ITB, 2018). This is one of the worst values between the 100 biggest cities in Brazil. Moreover, as stated in the Management Plan of the USPCU, until 2012, there were at least 21 effluent release points inside Bolonha and Água Preta Lakes. The origin of these wastewaters is the urban areas in the EPAMRB around the USPCU (Pará, 2013).

The estimated polluting load dumped daily inside both lakes, until 2012, was 2.2 tons of Biochemical Oxygen Demand (2.2 tons of BOD/day), being 1.16 and 1.03 for Bolonha and Água Preta Lake, respectively (Pará, 2013). The dumping of wastewater inside the lakes, without any treatment, is considered one of the main stressors in the USPCU.

The aforementioned anthropic eutrophication affects the spatial distribution of WVE, increasing its growth and proliferation (Madgwick et al., 2011; Søndergaard et al., 2010). Therefore, this vegetation can be used as a long-term indicator of environmental conditions, especially water quality (Haury, 1995; Melzer, 1999; Murphy et al., 2019; Pall & Moser, 2009). For instance, Haas & Ban (2018) investigated urban LULC and ES changes in Beijing, China, based on L-5 TM and S-2 MSI data, and concluded that crucial ES, such as waste treatment, noise reduction and global climate regulation were significantly affected by landscape structural changes.

The macrophyte removal has regularly been occurring to improve the water pumping from Bolonha Lake towards the water treatment station to ensure the public water supply of the Metropolitan Region of Belém (Araújo Júnior, 2015). However, this is the only palliative method implemented, and it has a continuously cost for the Pará State Government, making it urgent to look forward to reliable solutions for Bolonha Lake.

Forest resilience

In order to identify if the primary vegetation (IGF and MLF) in the study area are losing its resilience, we captured the NDVI results from the 20 points (pixels), per class, described in the methodology (Figure 4). All of our scenes were acquired in average climatic years. Moreover, as mentioned by Anderson et al. (2018), our study area is not located within one of the zones most affected by repetitive droughts in the Amazon. However, as mentioned by these authors, the forest resilience in Amazon is being reduced due to recurring droughts, and this is usually noticed in, or close to, years of extreme events, such as the El Niño and La Niña. These events are decreasing their reoccurrence time due to anthropogenic climate-changing activities (Corlett, 2016). In this sense, our results may be explained by two facts: i) we could not find enough L-5 TM scenes to test the hypothesis at the end of the dry and wet seasons in Belém, which is a persistent problem in this sort of historical analysis in the Amazon (Asner, 2001; Dutra, Tavares, & Ribeiro, 2019); and ii) we did not test the hypothesis exhaustively in drought years.

Another difficulty related to forest resilience in the USPCU might be associated with the urban expansion in the buffer zone of the lakes. Historically, Belém has given its natural areas for urban development, and this is noted in areas such as the Cotijuba and Mosqueiro Islands, where some vast green areas have been converted into urban areas in the last 40 years (Bello & Hüffner, 2012; Sales, Borges, Pereira, Thalês, & Almeida, 2018). Other natural areas in the city, such as the Gunnar Vingren Ecological Park, is highly dependent on social participation to ensure its conservation status (Cardoso et al., 2015). Furthermore, the loss of the leading provider of ES in the city of Belém, which, as seen in Carvalho & Szlafsztein (2018) work, is already reduced in densely populated areas of the city. McPhearson, Andersson, Elmqvist, & Frantzeskaki (2015) study showed that the social-ecological resilience of an urban environment is dependent on the provision of ES through green areas. The existence of these green areas is also essential to the enhancement of the quality of life of the inhabitants of the city (Ward Thompson et al., 2012).

Gutierrez et al. (2017), who also studied the USPCU and EPAMRB, have noted the reduction of natural forests in the region as well. It is important to note that any anthropic modification in a natural area, in aggregation with the repetitive droughts, can cause uncountable (and unknown) problems in this same area. Some well-known complications are the loss of biodiversity (Barlow et al., 2018) and the increase in tree mortality (Brando et al., 2014). These problems are aggravated when it is noted that these conservation units are the only significant green areas in the continental area of Belém (Assumpção, Tavares, & Coutinho, 2019; Tavares, Beltrão, Guimarães, & Teodoro, 2019).

Conclusions

The urbanisation phenomenon is happening worldwide and, in the Amazon, it is no different. However, this process occurred in an unorganised and ravenous way in the last decades in the region, and the remaining green areas in the cities are under constant anthropic pressure. For this reason, we investigated environmental stress aspects in two fundamental conservation units within the most populated cluster of cities in the Eastern Amazon, via remote sensing, in the last 30 years. The results showed that the urbanisation process and infrastructure's works around USPCU did not consider environmental management criteria; this ultimately affected the aquatic ecosystem of the park, mainly Bolonha Lake. Another finding was that, despite the anthropic and climate pressures, the forest within the park showed no indication of reduced resilience in the period. Lastly, our findings have crucial implications for urban planning and management for the Metropolitan Region of Belém. Considering that the lakes within USPCU are accountable for 63% of water supply for almost 2.5 million urban dwellers in the Eastern Amazon, it is imperative to the local managers, along with academic institution and private initiative, to implement definitive solutions for Bolonha Lake eutrophication and macrophytes bloom. One viable solution is to improve the wastewater treatment in the city of Belém, which percentages are still very low in comparison to the biggest cities in Brazil.

References

Almeida, C. A. de, Coutinho, A. C., Esquerdo, J. C. D. M., Adami, M., Venturieri, A., Diniz, C. G., … Gomes, A. R. (2016). High spatial resolution land use and land cover mapping of the Brazilian Legal Amazon in 008 using Landsat-5/TM and MODIS data. *Acta Amazonica*, *46*(3), 291–302. https://doi.org/10.1590/1809-4392201505504

Amaral, D. D., Vieira, I. C. G., Salomão, R. P., Almeida, S. S., & Jardim, M. A. G. (2012). The status of conservation of urban forests in eastern Amazonia. *Brazilian Journal of Biology*, *72*(2), 9. https://doi.org/10.1590/S1519-69842012000200005

Anderson, L. O., Neto, G. R., Cunha, A. P., Fonseca, M. G., Moura, Y. M. de, Dalagnol, R., … Aragão, L. E. O. E. C. de. (2018). Vulnerability of Amazonian forests to repeated droughts. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *373*(1760). https://doi.org/10.1098/rstb.2017.0411

Araújo Júnior, A. C. R. (2015). Indicadores de qualidade ambiental no lago Bolonha, Parque Estadual do Utinga, Belém-Pará. *Boletim Gaúcho de Geografia*, *42*(1), 276–299. Retrieved from http://www.seer.ufrgs.br/index.php/bgg/article/view/48373/32948

Asner, G. P. (2001). Cloud cover in Landsat observations of the Brazilian Amazon. *International Journal of Remote Sensing*, *22*(18), 3855–3862. https://doi.org/10.1080/01431160010006926

Assumpção, M. P., Tavares, P. A., & Coutinho, E. de C. (2019). Balanço de Carbono em Cidades na Amazônia: Estudo de Caso em Belém, Brasil. *Urbe. Revista Brasileira de Gestão Urbana*, *11*, 1–27. https://doi.org/2175-3369.011.e20180186

Barbosa, C. C. de A., Atkinson, P. M., & Dearing, J. A. (2016). Extravagance in the commons: Resource exploitation and the frontiers of ecosystem service depletion in the Amazon estuary. *Science of the Total Environment*, *550*, 6–16. https://doi.org/10.1016/j.scitotenv.2016.01.072

Barlow, J., França, F., Gardner, T. A., Hicks, C. C., Lennox, G. D., Berenguer, E., … Graham, N. A. J. (2018). The future of hyperdiverse tropical ecosystems. *Nature*, *559*(7715), 517–526. https://doi.org/10.1038/s41586-018-0301-1

Baró, F., Haase, D., Gómez-Baggethun, E., & Frantzeskaki, N. (2015). Mismatches between ecosystem services supply and demand in urban areas: A quantitative assessment in five European cities. *Ecological Indicators*, *55*, 146–158. https://doi.org/10.1016/j.ecolind.2015.03.013

Belém - City Hall of Belém. (2008). Lei nº 8655, de 30 de julho de 2008. In *Master Plan of the Municipality of Belém* (1st ed.). Retrieved from http://ww3.belem.pa.gov.br/www/wp-content/uploads/Lei_N8655-08_Plano-Diretor.pdf

Bello, L. A. L., & Hüffner, J. G. P. (2012). Analysis of the environmental impacts of urban expansion in the Island of Cotijuba, Belém-PA. *Caminhos de Geografia*, *13*(44), 286–298. Retrieved from http://www.seer.ufu.br/index.php/caminhosdegeografia/article/view/16723

Bhatti, S. S., & Tripathi, N. K. (2014). Built-up area extraction using Landsat 8 OLI imagery. *GIScience and Remote Sensing*, *51*(4), 445–467. https://doi.org/10.1080/15481603.2014.939539

Bowditch, E. A. D., McMorran, R., Bryce, R., & Smith, M. (2019). Perception and partnership: Developing forest resilience on private estates. *Forest Policy and Economics*, *99*(December 2017), 110–122. https://doi.org/10.1016/j.forpol.2017.12.004

Branco, S. M. (1993). *Água: origem, uso e preservação* (1st ed.). São Paulo: Editora Moderna.

Brando, P. M., Balch, J. K., Nepstad, D. C., Morton, D. C., Putz, F. E., Coe, M. T., … Soares-Filho, B. S. (2014). Abrupt increases in Amazonian tree mortality due to drought-fire interactions. *Proceedings of the National Academy of Sciences*, *111*(17), 6347–6352. https://doi.org/10.1073/pnas.1305499111

Brasil. (2000). Lei nº 9985, de 18 de julho de 2000 - Institui o Sistema Nacional de Unidades de Conservação da Natureza e dá outras providências. Retrieved 9 April 2019, from http://www.planalto.gov.br/ccivil_03/leis/L9985.htm

Cardoso, S. L. C., Sobrinho, M. V., & Vasconcellos, A. M. de A. (2015). Environmental management of urban parks: the case of the Gunnar Vingren Ecological Park in Belem, Para state, Brazil. *Brazilian Journal of Urban Management*, *7*(1), 74–90. https://doi.org/10.1590/2175-3369.007.001.AO05

Cardoso, T. M., Monteiro, F. F., Venturieri, A., & Campos, G. S. (2009). Análise multitemporal da Área de Proteção Ambiental de Belém e Parque Ambiental de Belém. *Anais Do XIV Simpósio Brasileiro de*

Sensoriamento Remoto, 1283–1290. Retrieved from http://marte.sid.inpe.br/col/dpi.inpe.br/sbsr%4080/2008/11.17.22.50/doc/1283-1290.pdf

Carvalho, R. M. de, & Szlafsztein, C. F. (2019). Urban vegetation loss and ecosystem services: The influence on climate regulation and noise and air pollution. *Environmental Pollution*, *245*, 844–852. https://doi.org/10.1016/j.envpol.2018.10.114

Corlett, R. T. (2016). The Impacts of Droughts in Tropical Forests. *Trends in Plant Science*, *21*(7), 584–593. https://doi.org/10.1016/j.tplants.2016.02.003

Cox, D. T. C., Shanahan, D. F., Hudson, H. L., Fuller, R. A., & Gaston, K. J. (2018). The impact of urbanisation on nature dose and the implications for human health. *Landscape and Urban Planning*, *179*(August), 72–80. https://doi.org/10.1016/j.landurbplan.2018.07.013

Doxani, G., Vermote, E., Roger, J.-C., Gascon, F., Adriaensen, S., Frantz, D., … Vanhellemont, Q. (2018). Atmospheric Correction Inter-Comparison Exercise. *Remote Sensing*, *10*(2), 1–18. https://doi.org/10.3390/rs10020352

Dutra, V. A. B., Tavares, P. A., & Ribeiro, H. M. C. (2019). Analysis of cloud condition on Sentinel-2 MSI and Landsat-8 OLI images of a public supply lake in Belém-Pará-Brazil. *Ambiente & Água - An Interdisciplinary Journal of Applied Science*, *14*(4), 1–11. https://doi.org/10.4136/ambi-agua.2375

Dutra, V. A. B., Tavares, P. A., Trindade, A. R., Souto, J. I. de O., Beltrão, N. E. S., & Ribeiro, H. M. C. (2019). AVALIAÇÃO DO ESTADO TRÓFICO DE UM LAGO PARA ABASTECIMENTO PÚBLICO POR MEIO DE IMAGEM SENTINEL-2. *Anais Do XIX Simpósio Brasileiro de Sensoriamento Remoto*, 4. Retrieved from https://proceedings.science/sbsr-2019/papers/avaliacao-do-estado-trofico-de-um-lago-para-abastecimento-publico-por-meio-de-imagem-sentinel-2

Dye, C. (2008). Health and Urban Living. *Science*, *319*(5864), 766–769. https://doi.org/10.1126/science.1150198

Fortini, L. B., & Carter, D. R. (2014). The economic viability of smallholder timber production under expanding açaí palm production in the Amazon Estuary. *Journal of Forest Economics*, *20*(3), 223–235. https://doi.org/10.1016/j.jfe.2014.06.001

Gong, C., Yu, S., Joesting, H., & Chen, J. (2013). Determining socioeconomic drivers of urban forest fragmentation with historical remote sensing images. *Landscape and Urban Planning*, *117*, 57–65. https://doi.org/10.1016/j.landurbplan.2013.04.009

Gutierrez, C. B. B., Ribeiro, H. M. C., Morales, G. P., Gutierrez, D. M. G., Santos, L. S. dos, & Paula, M. T. de. (2017). Análise espaço-temporal do uso e cobertura do solo no interior da APA Belém e correlação com os parâmetros de água dos seus mananciais. *Revista Brasileira de Geografia Física*, *10*(1), 521–534. https://doi.org/10.5935/1984-2295.20140015

Haas, J., & Ban, Y. (2018). Urban Land Cover and Ecosystem Service Changes based on Sentinel-2A MSI and Landsat TM Data. *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing*, *11*(2), 485–497. https://doi.org/10.1109/JSTARS.2017.2786468

Haase, D., Larondelle, N., Andersson, E., Artmann, M., Borgström, S., Breuste, J., … Elmqvist, T. (2014). A quantitative review of urban ecosystem service assessments: Concepts, models, and implementation. *Ambio*, *43*(4), 413–433. https://doi.org/10.1007/s13280-014-0504-0

Haury, J. (1995). Patterns of macrophyte distribution within a Breton brook compared with other study scales. *Landscape and Urban Planning*, *31*(1–3), 349–361. https://doi.org/10.1016/0169-2046(94)01062-D

Holling, C. S. (1973). Resilience and Stability of Ecological Systems. *Annual Review of Ecology and Systematics*, *4*(1), 1–23. https://doi.org/10.1146/annurev.es.04.110173.000245

Huete, A., Didan, K., Miura, T., Rodriguez, E. P., Gao, X., & Ferreira, L. G. (2002). Overview of the radiometric and biophysical performance of the MODIS vegetation indices. *Remote Sensing of Environment*, *83*(1–2), 195–213. https://doi.org/10.1016/S0034-4257(02)00096-2

IBGE - Brazilian Institute of Geography and Statistics. (2012). Manual Técnico da Vegetação Brasileira. In L. Martins & R. Cavararo (Eds.), *Manuais Técnicos em Geociências* (2nd ed., Vol. 1). Retrieved from https://biblioteca.ibge.gov.br/visualizacao/livros/liv63011.pdf

IBGE - Brazilian Institute of Geography and Statistics. (2019). IBGE Cidades - Demographic census of the municipality of Belém. Retrieved 8 April 2019, from https://cidades.ibge.gov.br/brasil/pa/belem/panorama

ITB - Instituto Trata Brasil. (2018). *Ranking do Saneamento Básico - 100 Maiores Cidade do Brasil 2018*. Retrieved from http://www.tratabrasil.org.br/images/estudos/itb/ranking-2018/realatorio-completo.pdf

Kottek, M., Grieser, J., Beck, C., Rudolf, B., & Rubel, F. (2006). World Map of the Köppen-Geiger climate classification updated. *Meteorologische Zeitschrift*, *15*(3), 259–263. https://doi.org/10.1127/0941-2948/2006/0130

Kwok, R. (2018). Ecology's remote-sensing revolution. *Nature*, *556*(7699), 137–138. https://doi.org/10.1038/d41586-018-03924-9

Lamparelli, M. C. (2004). *Graus de trofia em corpos d'água do estado de São Paulo: avaliação dos métodos de monitoramento* (USP). https://doi.org/10.11606/T.41.2004.tde-20032006-075813

Lima da Silva, M., & Tourinho, H. L. Z. (2016). Território, territorialidade e fronteira: o problema dos limites municipais e seus desdobramentos em Belém/PA. *Urbe. Revista Brasileira de Gestão Urbana*, *9*(1), 96–109. https://doi.org/10.1590/2175-3369.009.001.ao09

Madgwick, G., Emson, D., Sayer, C. D., Willby, N. J., Rose, N. L., Jackson, M. J., & Kelly, A. (2011). Centennial-scale changes to the aquatic vegetation structure of a shallow eutrophic lake and implications for restoration. *Freshwater Biology*, *56*(12), 2620–2636. https://doi.org/10.1111/j.1365-2427.2011.02652.x

Main-Knorn, M., Pflug, B., Louis, J., Debaecker, V., Müller-Wilm, U., & Gascon, F. (2017). Sen2Cor for Sentinel-2. *Image and Signal Processing for Remote Sensing XXIII*, *10427*, 12. https://doi.org/10.1117/12.2278218

Martins, V. S., Novo, E. M. L. M., Lyapustin, A., Aragão, L. E. O. C., Freitas, S. R., & Barbosa, C. C. F. (2018). Seasonal and interannual assessment of cloud cover and atmospheric constituents across the Amazon

(2000–2015): Insights for remote sensing and climate analysis. *ISPRS Journal of Photogrammetry and Remote Sensing*, (October 2017), 1–19. https://doi.org/10.1016/j.isprsjprs.2018.05.013

McPhearson, T., Andersson, E., Elmqvist, T., & Frantzeskaki, N. (2015). Resilience of and through urban ecosystem services. *Ecosystem Services*, *12*, 152–156. https://doi.org/10.1016/j.ecoser.2014.07.012

McPhearson, T., Parnell, S., Simon, D., Gaffney, O., Elmqvist, T., Bai, X., … Revi, A. (2016). Scientists must have a say in the future of cities. *Nature*, *538*(7624), 165–166. https://doi.org/10.1038/538165a

McPhearson, T., Pickett, S. T. A., Grimm, N. B., Niemelä, J., Alberti, M., Elmqvist, T., … Qureshi, S. (2016). Advancing Urban Ecology toward a Science of Cities. *BioScience*, *66*(3), 198–212. https://doi.org/10.1093/biosci/biw002

Melzer, A. (1999). *The Ecological Bases for Lake and Reservoir Management* (1st ed.; D. M. Harper & Bill Brierley, Eds.). https://doi.org/10.1007/978-94-017-3282-6

Murphy, K., Efremov, A., Davidson, T. A., Molina-Navarro, E., Fidanza, K., Crivelari Betiol, T. C., … Urrutia-Estrada, J. (2019). World distribution, diversity and endemism of aquatic macrophytes. *Aquatic Botany*, *158*(June), 103127. https://doi.org/10.1016/j.aquabot.2019.06.006

Newton, A. C. (2016). Biodiversity Risks of Adopting Resilience as a Policy Goal. *Conservation Letters*, *9*(5), 369–376. https://doi.org/10.1111/conl.12227

Pall, K., & Moser, V. (2009). Austrian Index Macrophytes (AIM-Module 1) for lakes: A Water Framework Directive compliant assessment system for lakes using aquatic macrophytes. *Hydrobiologia*, *633*(1), 83–104. https://doi.org/10.1007/s10750-009-9871-0

Pará. (1993). Decreto Estadual nº 1551, de 3 de maio de 1993. Retrieved 9 April 2019, from State Decree website: https://www.semas.pa.gov.br/1993/05/03/9614/

Pará. (1995). Lei Complementar nº 027, de 19 de outubro de 1995 - Institui a região metropolitana de Belém e dá outras providências. Retrieved 6 August 2019, from Complementary Law website: http://www.sefa.pa.gov.br/legislacao/interna/lei/lc1995_p0027.pdf

Pará. (2013). *Plano de Manejo do Parque Estadual do Utinga*. Retrieved from http://ideflorbio.pa.gov.br/utinga/wp-content/uploads/2018/03/PMUtinga_26out2013.pdf

Ponte, J. P. X. (2015). Belém do Pará: cidade e água. *Cadernos Metrópole*, *17*(33), 41–60. https://doi.org/10.1590/2236-9996.2015-3302

Pontes, L. B., & Cardoso, A. C. D. (2016). Open spaces: windows for ecological urbanism in the Eastern Amazon. *Brazilian Journal of Urban Management*, *8*(1), 96–112. https://doi.org/10.1590/2175-3369.008.001.se06

Poursanidis, D., & Chrysoulakis, N. (2017). Remote Sensing Applications : Society and Environment Remote Sensing , natural hazards and the contribution of ESA Sentinels missions. *Remote Sensing Applications: Society and Environment*, *6*, 25–38. https://doi.org/10.1016/j.rsase.2017.02.001

Ribeiro, H. M. C. (1992). *Avaliação atual da qualidade das águas dos lagos Bolonha e Água Preta, situados na área fisiográfica do Utinga (Belém-Pará)*. Belém: UFPA.

Rosa, I. M. D., Ahmed, S. E., & Ewers, R. M. (2014). The transparency, reliability and utility of tropical rainforest land-use and land-cover change models. *Global Change Biology*, *20*(6), 1707–1722. https://doi.org/10.1111/gcb.12523

Rouse Junior, J. W., Hass, R. H., Schell, J. A., & Deering, D. W. (1974). Monitoring vegetation systems in the Great Plains with ERTS. *Third Earth Resources Technology Satellite-1 Symposium*, 309–317. Retrieved from https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/19740022614.pdf

Sales, G. M., Borges, M. da S., Pereira, J. L. G., Thalês, M. C., & Almeida, A. S. de. (2018). Cultural landscape of Mosqueiro Island: spatial-temporal evolution (1986-2016). *Caminhos de Geografia*, *19*(65), 204–217. https://doi.org/10.14393/RCG196515

Søndergaard, M., Johansson, L. S., Lauridsen, T. L., Jørgensen, T. B., Liboriussen, L., & Jeppesen, E. (2010). Submerged macrophytes as indicators of the ecological quality of lakes. *Freshwater Biology*, *55*(4), 893–908. https://doi.org/10.1111/j.1365-2427.2009.02331.x

Steward, A. (2013). Reconfiguring Agrobiodiversity in the Amazon Estuary: Market Integration, the Açaí Trade and Smallholders' Management Practices in Amapá, Brazil. *Human Ecology*, *41*(6), 827–840. https://doi.org/10.1007/s10745-013-9608-6

Tavares, P. A., Beltrão, N. E. S., Guimarães, U. S., & Teodoro, A. C. (2019). Integration of Sentinel-1 and Sentinel-2 for Classification and LULC Mapping in the Urban Area of Belém, Eastern Brazilian Amazon. *Sensors*, *19*(5), 20. https://doi.org/10.3390/s19051140

Tavares, P. A., Beltrão, N., Guimarães, U. S., Teodoro, A., & Gonçalves, P. (2019). Urban Ecosystem Services Quantification through Remote Sensing Approach: A Systematic Review. *Environments*, *6*(5), 51. https://doi.org/10.3390/environments6050051

Tavares, P. A., Dutra, V. A. B., Trindade, A. R., Souto, J. I. de O., Beltrão, N. E. S., & Ribeiro, H. M. C. (2019). APLICAÇÃO DE ÍNDICES DE VEGETAÇÃO PARA IDENTIFICAÇÃO DE VEGETAÇÃO AQUÁTICA EM LAGOS URBANOS NA AMAZÔNIA. *Anais Do XIX Simpósio Brasileiro de Sensoriamento Remoto*, 4. Retrieved from https://proceedings.science/sbsr-2019/papers/aplicacao-de-indices-de-vegetacao-para-identificacao-de-vegetacao-aquatica-em-lagos-urbanos-na-amazonia

Trindade, A. R., Dutra, V. A. B., Tavares, P. A., Souto, J. I. de O., Beltrão, N. E. S., & Ribeiro, H. M. C. (2019). APLICAÇÃO DE ÍNDICES DE VEGETAÇÃO PARA IDENTIFICAÇÃO DE ÁREA CONSTRUÍDA E VEGETAÇÃO DENSA EM ÁREAS URBANAS NA AMAZÔNIA. *Anais Do XIX Simpósio Brasileiro de Sensoriamento Remoto*, 4. Retrieved from https://proceedings.science/sbsr-2019/papers/aplicacao-de-indices-de-vegetacao-para-identificacao-de-area-construida-e-vegetacao-densa-em-areas-urbanas-na-amazonia

UN - United Nations. Department of Economic and Social Affairs. (2019). World Urbanization Prospects: Highlights (ST/ESA/SER.A/420). In *Demographic Research*. Retrieved from https://population.un.org/wup/Publications/Files/WUP2018-Highlights.pdf

Vasconcelos, V. de M. M., & Souza, C. F. (2011). Caracterização dos parâmetros de qualidade da água do manancial Utinga, Belém, PA, Brasil. *Ambiente & Água - An Interdisciplinary Journal of Applied Science*, *6*(2), 305–324. https://doi.org/10.4136/1980-993X

Ward Thompson, C., Roe, J., Aspinall, P., Mitchell, R., Clow, A., & Miller, D. (2012). More green space is linked to less stress in deprived communities: Evidence from salivary cortisol patterns. *Landscape and Urban Planning*, *105*(3), 221–229. https://doi.org/10.1016/j.landurbplan.2011.12.015

Warren, M., Simis, S. G. H., Martinez-Vicente, V., Poser, K., Bresciani, M., Alikas, K., … Ansper, A. (2019). First comparative assessment of atmospheric correction algorithms for the Sentinel-2A MultiSpectral Imager over coastal and inland waters. *Remote Sensing of Environment*, *225*(March), 267–289. https://doi.org/10.1016/j.rse.2019.03.018

Wittmann, H., Oelze, M., Roig, H., & von Blanckenburg, F. (2018). Are seasonal variations in river-floodplain sediment exchange in the lower Amazon River basin resolvable through meteoric cosmogenic 10Be to stable 9Be ratios? *Geomorphology*, *322*, 148–158. https://doi.org/10.1016/j.geomorph.2018.08.045

Xiao, J., Shen, Y., Ge, J., Tateishi, R., Tang, C., Liang, Y., & Huang, Z. (2006). Evaluating urban expansion and land use change in Shijiazhuang, China, by using GIS and remote sensing. *Landscape and Urban Planning*, *75*(1–2), 69–80. https://doi.org/10.1016/j.landurbplan.2004.12.005

Xue, Z., Hou, G., Zhang, Z., Lyu, X., Jiang, M., Zou, Y., … Liu, X. (2019). Quantifying the cooling-effects of urban and peri-urban wetlands using remote sensing data: Case study of cities of Northeast China. *Landscape and Urban Planning*, *182*(October 2018), 92–100. https://doi.org/10.1016/j.landurbplan.2018.10.015

Yoo, J., & Rohli, R. V. (2016). Global distribution of Köppen-Geiger climate types during the Last Glacial Maximum, Mid-Holocene, and present. *Palaeogeography, Palaeoclimatology, Palaeoecology*, *446*, 326–337. https://doi.org/10.1016/j.palaeo.2015.12.010

Zha, Y., Gao, J., & Ni, S. (2003). Use of normalized difference built-up index in automatically mapping urban areas from TM imagery. *International Journal of Remote Sensing*, *24*(3), 583–594. https://doi.org/10.1080/01431160304987

Conclusões Gerais

Por meio dos estudos aplicados às áreas de proteção ambiental em Belém-PA, concluiu-se que:

- É possível realizar estudos com sensoriamento remoto ótico na região, pois mesmo com as condições adversas de nuvens, há tempo de revisita suficiente para monitorar pequenas áreas, como o Lago Bolonha, um importante recurso hídrico para abastecimento público da cidade de Belém.
- Com o lançamento dos satélites da família Sentinel-2, em 2015, há possibilidade de analisar diferentes áreas de estudo com melhor resolução espacial (10 m) e temporal (5 dias). Além disso, pode-se também fazer o uso dessas cenas em conjunto com a família Landsat, melhorando ainda mais o tempo de revisita sobre um dado local.
- Por meio da análise temporal nas últimas três décadas na área de estudo, notou-se um adensamento urbano considerável no entorno da Área de Proteção Ambiental de Região Metropolitana de Belém, o que transcorreu no aumento da poluição ambiental e na eutrofização dos mananciais do Parque Estadual do Utinga.
- A realização da remoção manual desse material trata-se de uma medida mitigadora pouco eficaz e muito onerosa aos cofres públicos. Nesse sentido, a ameaça da eutrofização dos Lagos Bolonha e Água Preta deve ser levada mais a sério pelos tomadores de decisão e gestores do Parque. Deve-se, portanto, tomar medidas que solucionem definitivamente esse impacto na região.

UNIVERSIDADE DO ESTADO DO PARÁ

Universidade do Estado do Pará

Centro de Ciências Naturais e Tecnologia

Programa de Pós-Graduação em Ciências Ambientais – Mestrado

Tv. Enéas Pinheiro, 2626, Marco, Belém-PA, CEP: 66095-100