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Investigation of pre and post environmental impact of the lockdown (COVID-19) on the water quality of the Capibaribe and Tejipió rivers, Recife metropolitan region, Brazil

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ABSTRACT

The coronavirus pandemic has seriously affected human health, although some improvements on environmental indexes have temporarily occurred, due to changes on socio-cultural and economic standards. The objective of this study was to evaluate the impacts of the coronavirus and the influence of the lockdown associated with rainfall on the water quality of the Capibaribe and Tejipió rivers, Recife, Northeast Brazil, using cloud remote sensing on the Google Earth Engine (GEE) platform. The study was carried out based on eight representative images from Sentinel-2. Among the selected images, two refer to the year 2019 (before the pandemic), three refer to 2020 (during a pandemic), two from the lockdown period (2020), and one for the year 2021. The land use and land cover (LULC) and slope of the study region were determined and classified. Water turbidity data were subjected to descriptive and multivariate statistics. When analyzing the data on LULC for the riparian margin of the Capibaribe and Tejipió rivers, a low permanent preservation area was found, with a predominance of almost 100% of the urban area to which the deposition of soil particles in rivers are minimal. The results indicated that turbidity values in the water bodies varied from 6 mg L\(^{-1}\) up to 40 mg L\(^{-1}\). Overall, the reduction in human-based activities generated by the lockdown enabled improvements in water quality of these urban rivers.

1. Introduction

The novel coronavirus disease 2019 (COVID-19) pandemic, considered the most devastating public health crisis seen in the 21st century, has affected countries in different ways, e.g., number of cases, lockdown period, health systems, economy, among others (Montagna et al., 2021; Parida et al., 2021; Xie et al., 2021; Mandal et al., 2022). In South America, the occurrence of recorded cases by SARS-CoV-2 (severe acute respiratory syndrome coronavirus 2) was later than the spread of the disease around the world. On the other hand, cases in Brazil have grown exponentially since the first record on February 25, 2020 (Lancet, 2020). The pandemic has affected millions of human beings directly and indirectly through the effects of the virus on health and concomitantly the economy, on a global scale, with Brazil being one of the most affected countries (Brasil, 2020; Ferrante and Fearnside, 2020; Ferrante et al., 2020).

The main recommendations by the World Health Organization (WHO) to contain the spread of the coronavirus were social distance and...
the use of masks (Brasil, 2020; Farias and Araújo, 2020; Agarwal et al., 2021; Pei et al., 2021). On March 11, 2020, Brazil initiated legal distancing measures in a decentralized manner, being each state and municipal governments responsible for some determinations. Since then, in the state of Pernambuco, Northeast Brazil (NEB), the restrictive measure was adopted in all its geographical extension (Moraes, 2020).

On the other hand, the hazards or calamity humanity experienced in this pandemic showed positive side effects concerning the environment restoration, due to the reduction in the occupancy density of the urban environment (e.g., the improvement of the quality of air and water, and decrease in noise pollution), followed by the decrease in industrial and commercial activities since the beginning of 2020, as a result of restrictive measures of social isolation (Zhou et al., 2021; Benchrif et al., 2021; Cuerdo-Vilches et al., 2021; Pang et al., 2021). Some studies sought to understand better the short-term impact and improved air quality in countries such as France, Germany, Italy, Spain, and China (Nigam et al., 2021; Kovács and Haidú, 2021; Parida et al., 2021). In India during the lockdown period, more than 50% of the concentration of some toxic elements in the atmosphere was reduced (Sathe et al., 2021). Besides, recent studies also point to positive impacts of the pandemic for improvements in the quality of the environment (Tel et al., 2020; Barouki et al., 2021; Severo et al., 2021; Urban and Nakada, 2021).

The impacts of COVID-19 lockdowns on air quality around the world have received special attention (Kovács and Haidú, 2021; Sathe et al., 2021; Parida et al., 2021). In comparison, assessments of the implications for water quality are relatively rare (e.g., Muduli et al., 2021; Pesantez et al., 2022). In this context, some studies reported improvements in the quality of river waters, such as the study by Mani (2021) in the Ganges River, India, which observed significant differences in its quality after reducing industrial activity in the region imposed by the lockdown. However, water presented good quality levels in some areas, even sufficient for human consumption and the recovery of aquatic life. In another similar study carried out by Aman et al. (2020), the authors showed that water turbidity patterns of the Sabarmati River in India, before, during, and after the lockdown, period showed significant reductions after that period. Several studies point out improvements in river water quality during the pandemic period and especially during the lockdown period, due to restricted economic activities (Patel et al., 2020; Chakraborty et al., 2021; Liu et al., 2022).

Studies based on water quality analysis are commonly used in traditional methods of physicochemical analysis via field sampling and processed in laboratories (e.g., Freyberg et al., 2017; Rostom et al., 2017; Bianchi et al., 2019; Shi et al., 2019; Saha et al., 2020). However, this form of analysis becomes impractical/unsuitable for large-scale domains, such as rivers and lakes. In addition to the high cost of such procedures and required time to be spent. Therefore, a convenient and efficient alternative is the use of Remote Sensing (RS) techniques, which indirectly allow the quality characterization of extensive water bodies for different periods, making it feasible to remotely analyze water quality characteristics (Aman et al., 2020). More importantly, in-depth studies aimed at identifying and characterizing the environmental changes imposed by the reduction of human activity in the environment, followed by the assessment of the impacts generated, are essential for the development of public policies in the short and long term, in addition to raising population awareness (Santos et al., 2020a; Silva et al., 2020a, 2020b; Buck et al., 2021). Moreover, the effective use of RS techniques and satellite image geoprocessing enables the expansion of environmental studies in an effective, reliable, practical, and fast way (Silva et al., 2021a).

According to Silva et al. (2021b), the municipality of Recife is among the 10 largest urban centers in Brazil, with an unbridled expansion of industries, which promotes population growth and the formation of small centers in the metropolis, being essential to assess the impacts of anthropization on local water bodies. At present, there are relatively few studies that have performed this type of urban-environmental approach. Therefore, based on the above, this study aimed to evaluate the impacts of COVID-19 and the influence of lockdown, associated with rainfall, on the water quality of the Capibaribe and Teijiπio rivers, Recife – NEB, using cloud remote sensing on the Google Earth Engine (GEE) platform.

2. Material and methods

2.1. Characterization of the study area

The study was carried out at the Capibaribe and Teijiπio rivers located in the municipality of Recife, Pernambuco (PE), NEB. The studied areas comprise the parallels of 8°15’S and 8°7’S and, the meridians of 34°53’W and 34°57’W (Fig. 1). According to the Köppen-Geiger climate classification, the region’s climate type “Am” with predominant tropical humid or sub-humid (Silva et al., 2021b; Jardim et al., 2021).

The municipality of Recife has an estimated population of 1,653,461 inhabitants, with a territorial extension of 218.84 km² and a population density of 7555.46 inhabitants. km⁻² (IBGE, 2020). The municipality is located at the outlet of the Capibaribe and Teijiπio watersheds, under the Atlantic Forest biome. Recife is located in the Metropolitan mesoregion and comprises the municipalities that make up the coastal region of the Pernambuco State (Jardim et al., 2021). The city of Recife has 69.20% of houses with adequate sanitation; 60.50% of urban houses on public roads with trees, and 49.60% of urban houses on public roads with adequate urbanization (e.g., manhole, sidewalks, and paving), when compared with other municipalities in the state, it is in the position 20 out of 185, 107 out of 185, and 1 out of 185, respectively (IBGE, 2020; Santana et al., 2022).

The Capibaribe River is the main watercourse of the Pernambuco State, supplying 43 municipalities and 3,474,198 inhabitants, who reside along its course. The Capibaribe River has its source between the municipalities of Poço and Jataúba in Pernambuco (Upper Capibaribe River), and its mouth is in Recife, Brazil (Lower Capibaribe River). Its basin has an area of 7454.88 km² and is considered one of the most important in the state. The Capibaribe River estuary, in the city of Recife, is highly impacted by anthropogenic activities, mainly domestic effluents, deforestation, and landfills (Purificação et al., 2017; Holanda and Soares, 2019; Alves et al., 2021; Bertrand et al., 2021).

The estuarine area of the Capibaribe River begins in the municipality of Recife, close to Caxangá bridge, in the Várzea neighborhood, and continues to its mouth, in the maritime port of the city of Recife (Fig. 1). Before draining into the sea, the river divides into two branches, one heading south, currently reduced to a dead branch due to frequent landfills, and the other branch heading north, to its mouth (Chatton et al., 2016; Melo et al., 2017; Collier et al., 2019; Santos et al., 2020c; Noriega et al., 2021).

Its course to the estuary comprises 270 km, passing through three different mesoregions and climatic zones: Pernambuco Agreste mesoregion (east), between the upper and middle Capibaribe, with an “Am” climate — humid or sub-humid tropical climate, “BSH” — dry hot semi-arid, “Csa” — hot summer Mediterranean climate, “Csb” — warm-summer Mediterranean climate and BWh — hot arid climate; mesoregion of the Zona da Mata and Metropolitan Region of Recife, in the lower Capibaribe, where the climate of the “Aw” — type tropical climate, with dry winter, and “Am” — humid or sub-humid tropical climate predominates, respectively (Fig. 1) (Alvares et al., 2013; Beck et al., 2018).

2.2. Hydrological characterization of the Capibaribe and Teijiπio rivers

In the present study, we quantified the water quality changes of the two rivers, at the Recife floodplain. The Capibaribe River is the main river on the Pernambuco coast (Fig. 1). Its source is located on the slopes of the Jacararé mountain range, municipality of Poço, at an altitude of 1100 m. According to a survey by the Pernambuco State Planning and
Research Agency (CONDEPE), carried out in 1980, the hydrographic basin of the Capibaribe River covers an area of 7716 km\(^2\), equivalent to 7.85\% of the territory of the Pernambuco State. The river is divided into Upper, Middle, and Lower Capibaribe; from the source to the mouth, it runs through the mesoregions of Agreste, Zona da Mata and Metropolitana do Recife. It has about 74 tributaries and drains 42 municipalities in Pernambuco (IBGE, 2020). In addition, it has important dams used for public supply, such as the Carpina Dam, located approximately 242 km from its mouth. Therefore, the Capibaribe River suffers strong anthropogenic influences along their course, particularly in its stretch in the Metropolitan Region of Recife (MRR).

The Tejipió River makes up the hydrographic basin of the Capibaribe River, with its spring area in an Atlantic Forest reserve in the municipality of São Lourenço da Mata within the MRR, has 23 km long with an area of 93.6 km\(^2\), and it is subjected to a significant water quality loss as it crosses urban areas.

2.3. Rainfall characterization in the study region

To verify possible influences of rainfall on the studied tributaries, a rainfall survey was carried out from 01/01/2019 to 01/31/2021 (date in the ‘mm/dd/yyyy’ format), the period corresponding to the acquisition of processed images. Five random points were selected on the surface of the studied tributaries, and rainfall data were extracted. The product obtained came from the Climate Hazards Group InfraRed Precipitation with Station data (CHIRPS), a spanning 50\(^\circ\)S-50\(^\circ\)N (and all longitudes). CHIRPS incorporates indoor climatology and is available in two sets of spatial resolutions with 0.05\(^\circ\) x 0.05\(^\circ\) and 0.25\(^\circ\) x 0.25\(^\circ\), and measured rainfall data to produce time series of weather grids precipitation. This study used a higher resolution CHIRPS dataset (i.e., 0.05\(^\circ\) x 0.05\(^\circ\)) (Jardim et al., 2022). Nowadays, the CHIRPS dataset comprises precipitation data for over 35 years, starting from 1981 to the present time. In addition, the satellite has a daily periodicity, reliable dataset, and high accuracy (Funk et al., 2015).

The data were obtained from the Climate Engine platform (a platform for processing images from CHIRPS, as well as providing georeferenced data), available at the following address: https://app.climatengine.org/climateEngine. Subsequently, the data were processed, and an informative graphic was generated to analyze rainfall close to the period in which the images were obtained. The precipitation data collected served as support for comparative purposes of rainfall impact on the water quality dynamics of the Capibaribe and Tejipió rivers, thus associating anthropogenic inputs over the study region.

The CHIRPS product is fully validated for the northeast region of Brazil (NEB), based on the study by Paredes-Trejo et al. (2017) who validated CHIRPS-based satellite precipitation estimates for NEB with a correlation coefficient (r) of 0.94, from INMET meteorological stations, in which one of the stations used in the authors’ study is the Recife/Curado (station code: 82,900). Based on the validation used in the authors’ study, the CHIRPS data were used in our study to characterize the rainfall, since the rainfall dynamics at the Recife region present high spatio-temporal variability, which requires the use of more than one season for the analysis. Silva et al. (2021b), who analyzed the spatial variability of rainfall in the municipality of Recife, point out that the region has a high variability of rainfall.

2.4. Land use and Land cover (LULC) via MapBiomas Brazil and terrain slope

Land use and land cover (LULC) maps were generated to characterize the study region and investigate the potential impacts and changes that soil degradation can cause in the Capibaribe and Tejipió riverbeds. The generated product comes from the MapBiomas Brazil Platform, which details the LULC via remote sensing, geographical information systems.
(GIS), and computer science via cloud processing and automated classifiers, developed and operated from the GEE platform to generate a historical series of maps annual LULC in Brazil (MapBiomas Brazil, 2021). The LULC map developed in this study was extracted from the following link: <https://mapbiomas.org/colecoes-mapbiomas-1?cama_set_language=pt-BR>. The extracted raster file was processed in QGis software version 3.12. To identify the portion of the LULC on the rivers riparian areas, the permanent preservation area (PPA) was delimited, foreseen in the forest and environmental management legislation, following the Brazilian Forest Code (Federal Law n. 12,651, of May 25, 2012) and with CONAMA Resolution n° 303/2002. According to the legal provisions, every water body must contain a PPA protected area, covered or not by native vegetation, with the environmental function of preserving water resources, the landscape, geological stability, and biodiversity, thus facilitating the flow of flora and fauna, protecting the soil cover and ensuring the well-being of human populations (Brasil, 2012; Silva et al., 2022). The PPA was identified based on a proximity analysis (Buffer tool—creates polygons around a vector input feature to a specified distance) that considers the marginal strips proposed for each watercourse. In the analysis presented here, 500 m of protection strips were considered.

The generated LULC map was classified based on the catalog from the 6.0 collection (MapBiomas Brazil, 2021). Collection 6.0 has a catalog with 33 classes, typical of the platform, in which the following major classes were prioritized: forest, a non-forest natural formation, agriculture and livestock, urban area, and water bodies. Image processing was performed using Quantum GIS (QGis) software version 3.12. Two digital images of altimetric data from the Shuttle Radar Topography Mission (SRTM/NASA) project from the SB-25-Y-C and SC-25-V-A quadrants were used to generate the slope map. Then, with the aid of the GRASS 7.6.1 tool, available in the QGis 3.12 software and through the “Slope” application, the classification was carried out according to the class limits presented in Table 1.

2.5. 2.5. Acquisition of MSI/sentinel-2 images and SPM Algorithm

In this investigation, eight reflectance images were used at the base of the atmosphere of the Sentinel-2 satellite Multispectral Instrument (MSI) with processing level 2A (UTM/WGS84 projection), provided by the European Space Agency (ESA/Copernicus) available at https://sentinel.esa.int/web/sentinel/home. This sensor has a spatial resolution of 10, 20, and 60 m, radiometric resolution of 16 bits, revisit time 5 (in Ecuador), and 13 spectral bands, of which it has four bands in the visible and near-infrared region centered approximately at 482 nm (blue), 560 nm (green), 665 nm (red) and 833 nm (near-infrared). The identifier (ID) of each image was selected in the spatial database of the National Aeronautics and Space Administration via the United States Geological Survey platform (NASA/USGS, 2021) - (Table 2) for further processing in the GEE. Of the selected images, two were for the year before the pandemic (2019), three for the pandemic period (2020), two for the lockdown period (2020), and one for the year 2021. The selected images were considered on less than 15% cloud cover criterion.

The determination of water turbidity was made based on the algorithm Suspended Particulate Matter (SPM). The SPM is calculated from Eq. (1), proposed by Nechad et al. (2010):

\[
SPM = \frac{A' \rho_u - B'}{\rho_u / C'} + B' 
\]

where \(\rho_u\) is the reflectance of water in the red band of the Sentinel-2 satellite (665 nm), \(A'\) and \(C'\) are empirical coefficients, and \(B'\) is a correction factor established by Nechad et al. (2010). The turbidity can be caused by sedimentation, siltation, sewage disposal, metals, bacteria, and other pollutants.

Simulation based on the model established by Nechad et al. (2010) was performed via cloud processing on the GEE. After obtaining the turbidity maps for the fractions of the rivers studied, a map of the respective chosen dates was generated (Table 2) using the QGis software version 3.12.

2.6. Statistical analysis

We structured statistical analysis in two parts for this study: the first covering the descriptive statistics, and the second used cluster analysis. Initially, the temporal variability data were subjected to descriptive statistical analysis to obtain the mean, median, minimum, maximum, standard deviation (SD), and coefficient of variation (CV, %). The percentage value of the CV was categorized as low (CV < 12%); medium (for the interval from 12% to 60%), and high (when CV > 60%) - (Warrick and Nielsen, 1980); subsequently, the non-parametric Kolmogorov-Smirnov (KS) normality test was also applied, using a significance level of \(p < 0.01\) (Massey, 1951; Hassani and Silva, 2015; Yalaletdinova et al., 2019).

Next, a multivariate analysis was applied using the cluster analysis technique (Cluster Analysis – CA) via dendrogram, from Ward’s method and based on the Euclidean distance (Ward, 1963; Jardim et al., 2021) for the Sentinel-2 image dates. Cluster analysis is a technique used to identify groups of similar samples (Lyra et al., 2014). The similarities were attributed to the dates by calculating the Euclidean distance (\(d_{ij}\)) and Ward’s hierarchical method between two objects (\(i\) and \(j\)), in which the smaller the distance, the greater the quantitative similarity between individuals (Ward, 1963), as described in Eqs. (2) and (3), respectively. The descriptive statistics analysis of data and CA were performed in software R version 3.6.1 (R Core Team, 2019).

\[
d_{ij} = \sqrt{\sum_{k=1}^{n} (x_{ik} - x_{jk})^2} 
\]

where \(d_{ij}\) is the Euclidean distance; and \(x_{ik}\) and \(x_{jk}\) are the data observed at meteorological stations \(i\) and \(j\), respectively.

\[
W = \left[ \sum_{i=1}^{n} x_i^2 - \frac{1}{n} \left( \sum_{i=1}^{n} x_i \right)^2 \right] 
\]

where \(W\) is the minimum intergroup variance by Ward’s hierarchical method; \(n\) is the number of elements; and \(x_i\) is the \(i\)-th element of the group.

Table 1

| Slope Classes | Class Limits (%) |
|---------------|------------------|
| Very low      | 0 to 3           |
| Low           | 3 to 6           |
| Average       | 6 to 12          |
| High          | 12 to 20         |
| Very tall     | >20              |

Source: Chaves et al. (2008).

Table 2

| Dates          | JD  | h (CTU) | E (°)  | a (°) | Pandemic period |
|----------------|-----|---------|--------|-------|----------------|
| 01/13/2019     | 13  | 12h43min (p.m.) | 29.89 | 121.23| Before         |
| 03/19/2019     | 78  | 12h43min (p.m.) | 27.03 | 75.82 | Before         |
| 04/12/2020     | 103 | 12h43min (p.m.) | 29.46 | 55.93 | Pandemic       |
| 05/02/2020     | 123 | 12h43min (p.m.) | 32.91 | 44.81 | Pandemic       |
| 05/27/2020     | 148 | 12h43min (p.m.) | 37.15 | 37.86 | Pandemic       |
| 06/21/2020     | 173 | 12h43min (p.m.) | 39.39 | 37.08 | Lockdown       |
| 08/25/2020     | 238 | 12h43min (p.m.) | 30.55 | 53.76 | Lockdown       |
| 01/17/2021     | 17  | 12h43min (p.m.) | 28.87 | 119.35| Pandemic       |

Source: USGS/NASA (2021).
3. Results and discussion

3.1. Seasonal dynamics rivers water

The water quality dynamics of the Capibaribe and Tejipió rivers are susceptible to many environmental, climatic, and/or anthropogenic changes (e.g., rainfall, industrial waste disposal, urban waste disposal, among others) and thus rapidly change their turbidity as rivers drain the Recife municipality (IBGE, 2021). Fig. 2 shows the changes in the surface of the Capibaribe River over 1 week for April 2021.

In Fig. 2, both the dynamics and water turbidity of the Capibaribe River are extremely susceptible to changes in its hydrological components. This is because the river cuts through the Recife Metropolitan mesoregion. Therefore, it is highly vulnerable to anthropogenic pollution and degradation resulting from the reception of particles brought from the rainfall.

3.2. Rainfall characterization

Based on the five georeferenced random points of the Climate Engine platform (Fig. 1), the study region for rainfall from the CHIRPS product is presented in Fig. 3. It was found that in the period from 01/01/2019 to 01/31/2021, every day there was a rainfall event, where the minimum value observed for one day was 0.98 mm day$^{-1}$ and the maximum of 125.29 mm day$^{-1}$. It is worth noting that the CHIRPS product has already been properly validated for NEB with satisfactory results (Paredes-Trejo et al., 2017; Costa et al., 2019). Thus, the water turbidity values of the Capibaribe and Tejipió rivers had some influence from rainfall in the region, due to water dilution.

Corroborating with results obtained in this study, Solano-Rivera et al. (2019) explored the impacts of extreme rainfall on flow and turbidity dynamics in a steep, pristine, tropical volcanic drainage basin in Costa Rica, Central America. It is also noteworthy that not only rainfall but other environmental factors can influence the water turbidity when the region, in turn, refers to the urban sector, being the main route of pollution of the tributaries, the anthropic activity in its different courses of action in the urban sector. In this context, Zhou et al. (2021) studied the water turbidity dynamics via RS techniques and its potential driving factors in Wuhan, a metropolitan region of the Chinese province. The authors point out that climatic factors, such as rainfall influence the water turbidity of rivers and also anthropogenic activities, exponentially impacting the turbidity.

Still, the dynamics of rainfall in the city of Recife are associated with the seasons of the year, being Recife characterized by two well-defined seasons, being them the dry summer and the rainy winter, in which the months of May, June, and July are the ones with the highest rainfall depths, with a monthly accumulation reaching up to 450 mm (Fig. 3). Corroborating the results of this study, Silva et al. (2021b), who analyzed the spatial distribution of rainfall via geostatistical interpolation models in the mesoregion of Zona da Mata and Recife Metropolitan, highlight that the months of May, June, and July are the months of highest rainfall in the city of Recife, reaching a monthly accumulation of up to 450 mm of precipitation, directly influencing the water quality dynamics, causing flooding and, from the high polluted zones, it promotes the proliferation of diseases via contaminated water.

The results show that there are coherent relationships between rainfall. The data obtained show that the rainfall dates close to the imaged dates 01/13/2019, 03/19/2019, 04/12/2020, 05/02/2020, 05/27/2020, 06/21/2020, 08/25/2020, and 01/17/2021, to which the nearby rainfall record dates were 01/11/2019, 03/16/2019, 04/11/2020, 05/01/2020, 05/26/2020, 06/21/2020, 08/21/2020, and 01/16/2021, with daily accumulated rainfall of 25.11, 19.24, 13.06, 16.24, 55.76, 15.84, 30.51 and 3.44 mm day$^{-1}$, respectively. Except for the date of 01/16/2021 (3.44 mm day$^{-1}$), the others presented a significant rainfall record. The other dates influenced the water turbidity dynamics of the Capibaribe and Tejipió rivers. It is worth noting that the study region is close to the coastal environment and, therefore, it is influenced by local convection, sea/land breeze circulations, and Eastern Wave Disturbances (EWD) common in the east of the NEB (ENEB) - (Lyra et al., 2014; Costa et al., 2021), and also by tidal effects, which reverse their flows.

3.3. Land use and Land cover (LULC)

Fig. 4 shows the LULC for the Recife city with emphasis on the study region. The classification performed used five classes from the
MapBiomas Brazil platform, the following major classes being: forest, a non-forest natural formation, agriculture and livestock, urban area, and water bodies. Moreover, when analyzing the data on LULC for the ciliary margin of the Capibaribe and Tejipió rivers in their 500 m protection strip PPA and its immediate vicinity, it is observed that basically in the entire composition of the rivers course, there is very little forest formation or no formation, with a predominance of almost 100% of the urban area (MapBiomas Brazil, 2021).

Because of such LULC condition, it is evident that the pollution from soil particles to the river water surface is minimal. However, given the findings, the PPA, as recommended by the national constitution, is in total disagreement with the law, being the region a seriously compromised area. According to Law no 12.651, of May 25, 2012 (Brasil, 2012), the marginal strips of any perennial or intermittent natural watercourse, excluding the ephemeral ones, must present a minimum width of 30 (thirty) meters from the edge of the channel of the regular bed, for watercourses less than 10 (ten) meters wide; 50 (fifty) meters, for watercourses that are from 10 (ten) to 50 (fifty) meters wide; 100 (one hundred) meters, for watercourses that are from 50 (fifty) to 200 (two hundred) meters wide; 200 (two hundred) meters, for watercourses that are from 200 (two hundred) to 600 (six hundred) meters wide; 500 (five hundred) meters, for watercourses that are more than 600 (six hundred) meters wide.

Changes in LULC are important aspects in the process of global environmental change due to their impacts on biodiversity, climate, food security, soil, and water quality, as well as human well-being (Patel et al., 2013; Newbold et al., 2015; Song et al., 2018; Santos et al., 2020b; Salazar et al., 2021; Silva et al., 2022). These changes reflected a long history of human resource utilization in the region under study. In addition, they increased population pressure (i.e., urban sprawl,
deforestation, changes in land use, and land cover patterns), particularly related to the lack of socio-economic development policies and environmental management, which caused a disorderly growth on sloping landscapes and riparian areas (Correia Filho et al., 2021, 2022).

The results indicated that Recife’s increased anthropic activities caused an irreversible loss of forest vegetation. In our comparison, the areas previously occupied by large extensions of vegetation were converted into small isolated fragments and immersed in urban uses, where the remaining vegetation is predominantly thin or sparse. Therefore, the areas with the occurrence of native arboreal vegetation correspond to the Atlantic Forest and Mangrove ecosystems and Mangrove with human activity. However, in riparian environments with a predominance of other plant formations (secondary or introduced), the sparse vegetation corresponds to an herbaceous composition, which usually occupies degraded soils (Francisco et al., 2013; Santos et al., 2020a). In addition, the lowland vegetation associations (macrophytes and/or plant species tolerant to temporary flooding conditions) are also observed in the riparian areas.

It is important to note that this scarcity of forest fragments means the precariousness of environmental services in these areas (Tran et al., 2015; Salazar et al., 2021). On the other hand, the preservation of forest fragments in riparian areas provides ecosystem services, such as protection against storms, serving as a physical barrier to reduce surface runoff and soil erosion (Fang et al., 2012; Francisco et al., 2012; Jardim et al., 2017; Santos et al., 2020b,c), and to improve water quality, since riparian vegetation acts as a biotic filter, preventing contaminant loads from agro-industrial effluents, due to economic activities at the direct vicinity of springs and water bodies (Donato et al., 2012; Patel et al., 2013; Padonou et al., 2021).

Fig. 5 shows the slope for the Recife city with emphasis on the study region. According to Chaves et al. (2008), the study region has a slope with very low (0–3%) and low (3–6%) oscillations, which indicates that the dynamics of surface runoff and the transport of particles from the rainfall events are not the main aggravating factors that influence the dynamics of the water turbidity of the Capibaribe and Tejipió rivers. However, as a result of the low slope of the urban region of Recife (Figs. 4 and 5), it is common that during the rainy season the city suffers from flooding problems, which occur mainly at the flat region, poor management of drainage systems making them inefficient and the non-existence or almost null of PPA. Because of this, there is a sudden increase in the rivers volume, which in turn end up causing floods in the urban region. Corroborating the findings of this study, Silva et al. (2021b) studied rainfall patterns in the MRR based on a 20-year historical series of rainfall data, stating that the main agents causing floods are the high growth of the urban population associated with poor public management that implies in an inefficient drainage system, causing flooding during the rainy season.

3.4. Spatio-temporal dynamics of water turbidity

Descriptive statistics of turbidity values recorded in the Capibaribe and Tejipió rivers are shown in Table 3. In our comparison, the mean values obtained ranged from 20.85 mg. L\(^{-1}\) to 112.99 mg. L\(^{-1}\). However, the high values of the means are associated with pixels related to the presence of cloud cover and shadow, and also concrete and asphalt bridges present in Recife, mainly in the Capibaribe and Tejipió river region, which consists of the study area and by both rivers that cross Recife (IBGE, 2021). Therefore, the presence of concrete bridges and cloud cover contributes to increasing the red band’s reflectance value. On the other hand, the high incidence of clouds in Recife is common, as

| Dates          | m  | Med | Min | Max | CV | SD |
|----------------|----|-----|-----|-----|----|----|
| 01/13/2019     | 37.78 | 25.30 | 15.41 | 249.66 | 99.96 | 37.77 |
| 03/19/2019     | 112.99 | 64.00 | 18.17 | 377.71 | 88.07 | 99.51 |
| 04/12/2020     | 28.03 | 21.53 | 15.55 | 148.70 | 65.95 | 18.49 |
| 05/02/2020     | 24.43 | 22.32 | 14.41 | 162.95 | 41.27 | 10.08 |
| 05/27/2020     | 71.55 | 40.40 | 16.33 | 347.54 | 84.89 | 60.74 |
| 06/21/2020     | 26.31 | 24.44 | 18.64 | 64.47 | 24.39 | 6.42 |
| 08/25/2020     | 35.92 | 18.56 | 15.23 | 369.86 | 168.33 | 60.46 |
| 01/17/2021     | 20.85 | 16.20 | 6.20 | 132.02 | 78.17 | 16.30 |

Table 3
Descriptive statistics of turbidity values (mg. L\(^{-1}\)) were recorded in the waters of the Capibaribe and Tejipió rivers.

Figs. 4 and 5 show the percentage of the slope for the Recife city with emphasis on the study region.
the city is located on the NEB coast, and the trade winds favor the formation of clouds in the region (Lyra et al., 2014; Costa et al., 2021). Regarding the oscillation of the minimum and maximum values obtained, the minimum value observed was 6.20 mg. L\(^{-1}\) on 01/17/2021, one year after the start of the COVID-19 pandemic, date referring to the period of pre-Carnaval events, which were common at this time of year and that were suspended (Tables 2 and 3). Compared to the same period in 2019 (one year before the COVID-19 pandemic), a minimum

![Turbidity pixel frequency histogram (mg. L\(^{-1}\)) extracted from Sentinel-2 MSI images on the respective dates for the Capibaribe and Tejipió rivers and every course studied.](image)

Fig. 6. Turbidity pixel frequency histogram (mg. L\(^{-1}\)) extracted from Sentinel-2 MSI images on the respective dates for the Capibaribe and Tejipió rivers and every course studied.
value of 15.41 mg L⁻¹ was observed on 01/13/2019. Therefore, lower turbidity values are justified due to social isolation and suspension of socio-cultural events to contain the spread of COVID-19 in Brazil (Aman et al., 2020). Corroborating the results of this study, Régis et al. (2018) studied the water quality standards of the Capibaribe River, and observed an increase in the water turbidity of the river for the urban region of the municipality, due to chemical pollutants from human action, while the referring region of the forest area (Fig. 4) is due to suspended particles (e.g., organic matter, and clay). Thus, it is evident that human action in the study region directly impacts the water quality and dynamics, with the lockdown period being a determining factor in reducing river pollution (Tables 2 and 3).

The maximum value found to turbidity was 377.71 mg L⁻¹ on 03/19/2019. This high value is possibly justified by the presence of organic particles and inorganic, as well as organic debris in suspension brought to the rivers by rainfall events on previous days, which modifies the water color and brightness. Indeed, Novo et al. (2007) claim that the color and brightness of water are related to the concentration of optically active components in water. The authors cited also emphasize that the particles cause changes in the color of water due to its concentration and nature. In addition, the high incidence of clouds in the area (Fig. 1), which also carry compounds of pollutants from urban industrialization, has a direct influence on the spectral response, influencing the turbidity patterns evaluated in this study. Lebedev et al. (2018) studied semi-volatile compounds in cloud water particles using comprehensive two-dimensional gas chromatography (GC × GC) at the top of the Puy de Dôme mountain, France, pointing out that there is a high concentration of pollutant dissolved in the water particles of clouds.

The CV, in general, was high, except for days 05/02/2020 and 06/21/2020, which presented mean values of 24.39 and 41.27%, respectively, according to the classification of Warrick and Nielsen (1980). One of the factors influencing the CV measurement is the dynamics of turbidity/pollution of river waters, as this aspect is changed following uncontrollable agents, such as precipitation, festive events, pandemics, and government decrees. Corroborating the results obtained, Kim and Parinichkun (2017) studied the turbidity of the water and observed a high CV due to the dynamics of the water in the city of Changwon, South Korea, specifically in the in-drinking water treatment plant Bansong, mainly altered by human activity and natural factors such as precipitation. The lowest CV value was 24.39% (06/21/2020) since the lowest maximum value was also captured on this day, resulting in less data dispersion. It is also noteworthy that there were fewer clouds on this date. Thus, it is attested that excessively high turbidity values, for all images, were effectively interfered with by the occurrence of rainfall. It is also worth noting that poor management of the municipality’s drainage system directly impacts the dragging and deposition of pollutants in the river. According to Souza Leão et al. (2021), studying the impact of extreme climate events in the Recife city, low altitudes in the territory, the presence of flat areas, the water table close to the surface, and outcrops in the rainy season, are natural characteristics that hinder the drainage process in the municipality. This observation corroborates the results of the study. Furthermore, its urbanization process resulted in several areas susceptible to flooding, imposing severe difficulties on drainage and sanitation systems.

From the histogram in Fig. 6, it is possible to identify the highest frequencies of pixels referring to turbidity values of water bodies. However, on some dates, there are significant frequencies related to the occurrence of rainfall, as shown in Fig. 6B, and correlated with the data in Table 3 on 03/19/2019, which obtained the highest maximum value. In Fig. 4C and D, there are high frequencies for low turbidity pixel values, which is justified by reducing anthropogenic activity due to the COVID-19 pandemic. However, due to the relaxation of governmental isolation measures, an increase in the frequency of turbidity values referring to water bodies was observed in Fig. 4E and F.

Turbidity values in water bodies ranged from 6 mg L⁻¹ to 40 mg L⁻¹, as shown on the histogram in Fig. 6. Similar results of water turbidity values were obtained by Aman et al. (2020), who studied the environmental impacts of the COVID-19 pandemic in the Sabarmati River, Ahmedabad Metropolitan Region, India, where they observed a variation in water turbidity from 0 to 40 mg L⁻¹. It is worth noting that the lockdown restrictions imposed by the Indian Government significantly impacted the improvement of the water quality of the Sabarmati River.

The distribution of turbidity (mg L⁻¹) throughout the study region is shown in Fig. 7, being observed that the image of 03/19/2019 was influenced by the rainfall index of 25.11 mm, which occurred on 03/16/2019, and the image of 05/27/2020 similarly influenced by the rainfall of 55.76 mm, which occurred on 05/26/2020. It is inferred through the analysis of data obtained from the images collected in 2019 that this period, specifically, presented difficulty in selecting images due to the high incidence of clouds for that year, hindering the data acquisition and interpretation. As for the image of the date 05/27/2020, which is an image recorded in the winter season, and as observed, it is a period that was influenced by high rainfall (Fig. 2), with precipitation of 55.76 mm on the day before the recording of this image, it is natural that the water turbidity values rise as a result of the deposition of sediment brought from the rainfall runoff process, as pointed out in the study by Silva et al. (2021b), who highlight the influence of rainfall on sediment deposition in rivers in the Recife Metropolitan Region.

3.5. Cluster analysis

Based on the cluster analysis (CA), homogeneous groups with similar

Fig. 7. Spatialization of turbidity (mg L⁻¹) of the waters of the Capibaribe and Tejipió rivers - Recife based on the processing of Sentinel-2 images in the period before, between, and after the lockdown.
periods were determined, represented in Fig. 8. CA identified the formation of three groups (Cluster 1, Cluster 2, and Cluster 3, respectively) and two ungrouped pairs (NCs). The NCs presented a Euclidean distance close to 1, as they presented the lowest correlations with the groups in their vicinity. Among all groups, the NCs had the smallest differences between means, which characterizes their differences from the generated groups (Table 3).

Cluster 1 formed refers to the dates of 01/13/2019 and 08/25/2020. The similarity of this group is in the minimum values observed in Table 3, being the ones with the smallest difference between all dates (Table 3 and Fig. 8). Cluster 2 is about dates 03/19/2019 and 05/27/2020, who had the next CV (Table 3 and Fig. 8). In Cluster 3, these are the dates 05/02/2020 and 01/17/2021, the mean, median, minimum, maximum, CV, and SD values were similar between these two dates.

It was also observed that the groups formed were similar in rainfall. Cluster 1 consists of 01/13/2019 and 08/25/2020. There were rainfall events close to the mentioned dates of 25.11 and 30.51 mm, with a difference of 5.40 mm being detected. Cluster 2 is composed of dates 03/19/2019 and 05/27/2020. There was rainfall near the dates of 19.24 and 55.76 mm (difference of 36.52 mm). Cluster 3 is composed of dates 05/02/2020 and 01/17/2021, and there were rainfall events close to the dates of 16.24 and 3.44 mm (difference of 12.80 mm), respectively (Figs. 3 and 8). Cluster 1, being the group with the greatest homogeneity, was the one with the smallest difference when rainfall occurred, which justifies similar patterns of water turbidity verified (see Figs. 7 and 8, and Table 3). Such differences in turbidity among the groups are due to the seasonal variability of the meteorological systems that cause rainfall in the ENEB (Lyra et al., 2014; Costa et al., 2021).

4. Conclusions

The study highlights that immediate attention is needed to evaluate the impacts generated by the COVID-19 pandemic through the lockdown on the water turbidity dynamics of the Capibaribe and Tejipió rivers. In part, there were significant reductions in the turbidity. In addition, the reduction in anthropogenic activities generated by the lockdown enabled improvements in water quality in the study area. High efficiency of the MSL/Sentinel-2 images was verified, despite the presence of clouds and the occurrence of rainfall events. These results demonstrate the influence of human activities on the water quality of the Capibaribe and Tejipió rivers. However, sustained and targeted strategies will be required to improve water quality and reduce environmental pollutants, as the population directly depends on this water for many daily activities.

The LULC for the study region does not directly impact the water quality levels of the Capibaribe and Tejipió rivers, since the permanent preservation areas are low or almost non-existent, having a predominant domain of constructed areas (e.g., roads and sidewalks) nearby the riverbeds.

The effects of the winter season on the water dynamics in the city of Recife are evident, since this period is the one with the highest rainfall concentration, resulting in the transport and deposition of sediments in the studied rivers, as evidenced in other studies already pointed out.

The digital processing of images in the cloud on Google Earth Engine is a promising tool that maximizes results in the short term and, thus, enables the assessment of the quality of river waters during lockdown for short time and a longer time. We recommend the use of the tool in this type of assessment for existing environmental agencies in Brazil.

We recommend that local government regulations are implemented and more applicable to control water pollution from the Capibaribe and Tejipió rivers. Further research is needed to determine key variables associated with rainfall, pollution, urbanization, and vegetation connection for the Brazilian rivers.

5. Software availability

Name of the software: TbWater
Phone: +55 64 992247907.
E-mail: marcolino.114@hotmail.com.
First available: 2021.
Minimum requirements: Any device with a web browsing capability.
Platform: Any but with a web browsing capability.
Availability: Through GEE platform at: https://dicroud.users.earthengine.app/view/tbwat.

CRediT authorship contribution statement

Maria Eduarda Gonçalves de Oliveira: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. Marcos Vinicius da Silva: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. Gledson Luiz Pontes de Almeida: Writing – review & editing, Writing – original draft, Visualization, Supervision, Methodology, Investigation, Formal analysis, Conceptualization. Heliton Pandorfi: Writing – review & editing, Writing – original draft, Visualization, Software, Resources, Methodology, Conceptualization. Fabricio Marcos Oliveira Lopes: Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Formal analysis. Diego Rosyur Castro Manrique: Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Formal analysis. Anderson dos Santos: Writing – review & editing, Writing – original draft, Visualization, Methodology. Alexandre Maniçoba da Rosa Ferraz Jardim: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis. Pedro Rogerio Giongo: Writing – review & editing, Writing – original draft, Visualization, Methodology, Formal analysis. Abelardo António de Assunção Montenegro: Writing – review & editing, Writing – original draft, Visualization, Methodology, Formal analysis. Carlos Antonio da Silva Junior: Writing – review & editing, Writing – original draft, Visualization. Jose Francisco de Oliveira-Júnior: Writing – review & editing, Writing – original draft, Visualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.
Data availability

The data that has been used is confidential.

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