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CLIMATE CHANGE AND MEGACITIES: FLOODING ALONG THE URBANISING ATLANTIC COASTLINE OF LAGOS, NIGERIA

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ABSTRACT

The identification of risk regions is important for prioritising their risk mitigation and response efforts. In this paper, we simulate flooding and identify flood-prone as well as inundation areas between 1986 and 2023 in Lagos, Nigeria, using geospatial tools available in the Digital Earth Africa (DEA) Sandbox. By leveraging satellite imagery from Landsat and Sentinel-2 through the `Water_extent_WOFS` and `Water_extent_sentinel` notebooks, we evaluated long-term and seasonal water extent using the Modified Normalised Difference Water Index (MNDWI). A 3D terrain model was developed to assess water flow, accumulation, and coastal inundation risk. Also, through document analysis, we identified key policy options that can be strengthened within the study area. Overall, we found that some areas that were inundated with water before 2023 were revealed to be land in 2023, suggesting that water has either receded from these regions or they are being sandfilled. Meanwhile, some areas that were inundated before 2023 have remained flooded to date. These areas might have certain characteristics, such as natural depressions or poor drainage, that make them more prone to prolonged water presence. Also, we found new areas that have only become flooded in recent times, possibly due to changes in land use, climate patterns, or other factors. The implementation of the DEA sandbox geospatial resources shows the utility of the toolbox for environmental resource monitoring and city planning. With respect to the developing Lagos Megacity, our findings highlight the importance of paying attention to the flood-prone areas of the city to ensure sustainable megacity development. The paper concludes with recommendations for policy, urban planning and climate adaptation.

KEY WORDS Sea-level rise, low-lying areas, policy and planning, coastal inundation, sustainability.

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1. INTRODUCTION

Among the effects of climate change are the melting of glaciers, leading to sea-level rise and more intense storm surges, which pose a serious threat to island nations, coastal regions, and low-lying communities. In densely populated coastal cities, the effects of climate change are particularly acute. In such cases, there are serious and increasing risks due to a combination of rising sea levels, extreme weather, and flaws in current infrastructure. Lagos, Nigeria, which has rapidly grown into a coastal megacity, is one of the most affected areas in the world. Its low elevation and dense population greatly increase its susceptibility to environmental changes and associated hazards. Another significant impact of climate change is the redistribution and altered timing of water resources, resulting in recurrent floods, prolonged droughts, irregular rainfall patterns, and more intense thunderstorms, with different regions experiencing varied manifestations of these effects (Ayodele-Olajire and Olusola, 2022). For instance, the Intergovernmental Panel on Climate Change (IPCC) predicted that humid regions would generally face more intense rainfall, while arid regions could become even drier, experiencing extended droughts (Bates et al., 2008). While climate change manifests in many ways, one of the greatest concerns for scientists is the crossing of critical thresholds necessary for maintaining balance within the Earth system (Rockström et al., 2009). In 2019, thousands of scientists collectively declared a climate emergency (Ripple et al., 2020). This declaration, alongside the ongoing efforts of the United Nations Framework Convention on Climate Change (UNFCCC), has helped ensure that nations are increasingly aware of—and are potentially taking action on—the urgent issue of climate change.

Both research and lived experience point to climate change as a harbinger of numerous threats to life (Gbadegesin et al., 2011). These threats include fatalities from coastal inundation and

flooding, the spread of diseases, and security risks stemming from climate-induced migration, among others. Coastal inundation (also referred to as flooding) is one of the most frequent and costly natural disasters globally. It occurs when seawater submerges dry, low-lying coastal areas due to a combination of climatic and environmental factors. Specifically, coastal inundation can result from moderate to strong winds over water, extremely high tides, or tsunamis caused by undersea earthquakes. The impact of this hazard is further exacerbated in areas with impervious surfaces and limited vegetation cover (Ajayi et al., 2012). Additional factors that can intensify the severity of coastal inundation include inadequate stormwater drainage systems, rapid urbanisation, and poorly regulated construction in floodplains despite existing planning restrictions (Adeloye & Rustum, 2011). Defined in another way, coastal flooding is a temporary condition that leads to the partial or complete inundation of normally dry land due to tidal overflow (Jeb & Aggarwal, 2008). Low-lying coastal areas are particularly vulnerable to such events.

Lagos is known to be vulnerable to coastal flooding, but long-term studies that examine flooding trends in a way that can aid urban planning and climate adaptation initiatives are lacking. Most studies tend to either address broad climate impacts or focus on specific flooding events (Elias & Omojola, 2014; Omenai & Ayodele, 2014; Isiaka et al., 2023). To address this gap, we utilise the Digital Earth Africa (DEA) sandbox to evaluate the extent, vulnerability, and risk of coastal inundation along a portion of the Atlantic coastline by simulating flooding events and their corresponding inundation between 1986 and 2023. Understanding inundation characteristics is important for providing solutions for urban planning and climate adaptation. We also review and present policy options for developing coastal megacities such as Lagos, with respect to urbanisation and flood events, against the background of climate change.

2. CLIMATE CHANGE, URBANIZATION, AND COASTAL VULNERABILITY IN MEGACITIES

In coastal megacities, land use changes significantly as a result of urbanisation, which is fueled by population growth and economic advancement. This includes practices such as constructing densely populated structures in low-lying areas, reclaiming wetlands, and altering natural drainage systems. Although these activities can spur economic growth, they often disrupt the natural equilibrium of ecosystems and increase cities' susceptibility to climate change effects, including storm surges, rising sea levels, and altered rainfall patterns (Seto et al., 2012). Urban development in these coastal megacities is often accelerated, posing a threat to long-term sustainability and environmental preservation.

Flooding in Lagos State has increasingly become an annual occurrence, unlike in previous decades. Numerous studies attribute this growing frequency of floods to the effects of climate change (Douglas et al., 2008; Omenai & Ayodele, 2013; Elias & Omojola, 2014). Flooding poses a significant risk, affecting millions of people each year along Nigeria's coastal regions (Nimi, 2021). Lagos State is particularly vulnerable, as it experiences all three major types of urban flooding: flooding caused by poor drainage systems, flooding from inundated floodplains, and coastal flooding (Douglas et al., 2008). Each of these flood types is further intensified by the impacts of climate change, making the situation increasingly dire.

Lagos State has certain peculiarities that have made the problem of flooding almost intractable. It has the least land area among states in Nigeria but is arguably the most populated (Oyalowo, 2022). Thus, there is a high population density in most parts of Lagos on land that is either low-lying and close to the Atlantic coast, floodplains close to the lagoons and creeks, or areas with poor drainage and waste management. The

state's peculiarities extend to some of the economic activities that contribute to its GDP, for example, sand mining and land-filling to promote real estate. These activities, though profitable in an economic sense, can increase threats to life from climate-exacerbated flood risks if they are not conducted in an environmentally sustainable manner. It is troubling that, at present, these activities serve to increase the number of people vulnerable to climate change impacts and at risk of life and property losses.

Several studies in Lagos emphasise the significant threat flooding poses to communities, lives, and properties. For example, Fashae and Onafeso (2011) demonstrate that the coastal extent of Lagos decreased from 1.64 km² in 1999 to 0.89 km² in 2009, marking an annual loss of approximately 0.075 km² due to sea-level rise induced by climate change. Another study by Omenai and Ayodele (2014), which focused on the Eti-Osa and Ibeju-Lekki areas, found that approximately 83.5% of the area is highly vulnerable to climate change hazards, particularly coastal inundation and flooding, based on factors such as proximity to water bodies and elevation above sea level. More recently, Isiaka et al. (2023) suggested that nearly 70% of the total land area in Lagos is highly to moderately susceptible to flooding. In the case of Lagos State, a closer examination reveals that while certain environmental risks exist independently of climate change, they are aggravated by its effects. For example, Lagos is not inherently low-lying due to climate change; however, the threat of coastal inundation has intensified due to the predicted increase in the intensity of storm surges in the tropics, which is linked to climate change. Coastal inundation mapping is important for proper land-use planning and for identifying coastal areas at risk of inundation under extreme circumstances. Furthermore, coastal inundation mapping helps administrators and planners identify risk regions and prioritise mitigation and response efforts through charts and maps that are simple to understand and quick to access (Alemu & Belachew, 2011).

3. METHODOLOGY

3.1. Study Area

Lagos, situated at an average elevation of just 1.5 meters above sea level, is a densely populated, low-lying metropolis characterised by a flat terrain (Omenai & Ayodele, 2013; Ajibade, 2017). It is one of the world's 14 coastal megacities and ranks among the top 20 locations most vulnerable to coastal inundation (Sojobi et al., 2016). The city faces multiple environmental and developmental challenges, including deforestation, unplanned urbanisation, uncontrolled wetland reclamation, encroachment on drainage channels, and rapid population growth (Sada & Odemerho, 1988). More than 54% of Lagos's developed areas lack proper drainage networks, and existing systems are often poorly maintained (Otokiti et al., 2022). Coastal flooding has become increasingly common during both of the city's annual rainy seasons, with the heaviest rainfall typically occurring between April and July (Ikueomonisan & Ozebo, 2020). The city's vulnerability is further exacerbated by its low elevation, subsiding land, and severe drainage issues—often worsened by clogged drainage systems. These conditions result in the rapid accumulation of water following sea-level rise, heavy rainfall, or storms (Adeloye & Rustum, 2011).

As a developing megacity, Lagos continues to see development projects such as the state's transportation-network improvement initiatives, the Eko Atlantic City—a modern city within the city—the Dangote Refinery (the first privately owned refinery in Nigeria), among others. Although urban and developmental challenges such as high population density, housing deficits, and water, air, and land pollution require solutions that fulfil both the letter and spirit of sustainable development, what is often observed is an underlying "maximum" rather than "optimum" profit motive. Thus, in Lagos, it appears that the man–nature relationship aligns with the human-as-despot school of thought, combined with undefined and unrefined

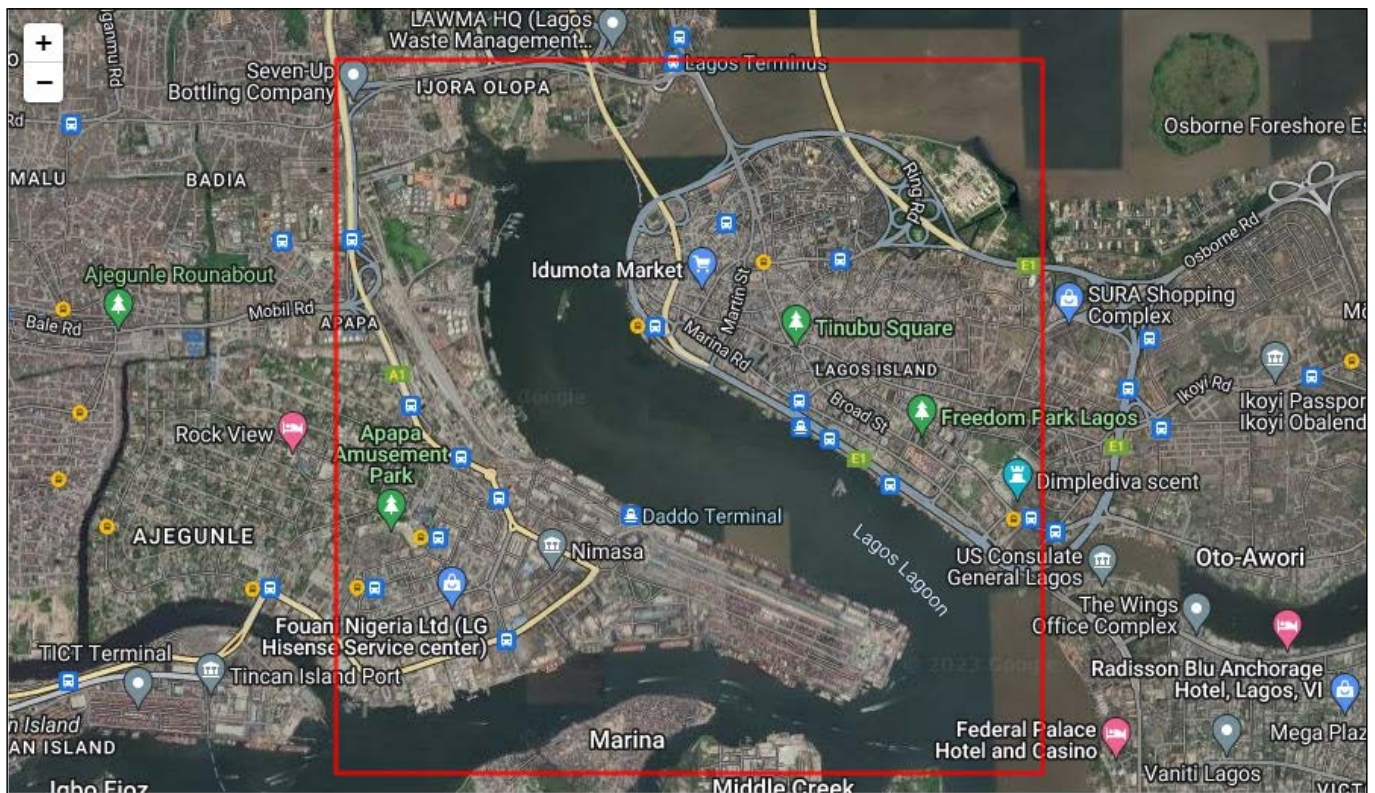
capitalism—conditions that can only serve as a time bomb for vulnerable populations.

3.2. Data Collection

This study utilises the Digital Earth Africa (DEA) sandbox technique for coastal inundation mapping to simulate floods in a controlled setting (Killough et al., 2022)—secondary data. High-resolution digital elevation models (DEMs) are integrated into the DEA analytical environment to produce a three-dimensional representation of the study area. The DEA framework requires this 3D viewpoint to assess patterns of water flow, extent, and accumulation, thereby improving the precision of coastal inundation simulations. The DEA platform was selected because of its unique advantages, which are valuable for this comprehensive long-term study. It provides easy access to decades' worth of fully analysed satellite imagery from Sentinel-2 (beginning in 2015) and Landsat (beginning in 1986). As a result, the time and computational effort required for data preparation and collection are greatly reduced. DEA is a cloud-based system that eliminates the need for powerful local computing resources while handling large geospatial datasets.

Two Python notebooks from the Digital Earth Africa Sandbox were used to evaluate the extent of inundation: `Water_extent_WOFS` and `Water_extent_sentinel`; the former uses data from Sentinel-2, while the latter uses data from Landsat. The Landsat and Sentinel data used were delineated according to the study area of interest (Figure 1). The major strength of using DEA is that it provides robust open-source tools along with long-term historical satellite data that is ready for analysis. One limitation is the possibility of cloud cover–related data gaps and the absence of precise flood depth measurements.

Documents regarding the policy dimensions of climate change and the environment within the study area context were sourced online (Lagos State Ministry of Environment, 2014; Lagos State Environmental Protection Agency, n.d.; Lagos Waste Management Authority, n.d.; FSD Africa, 2025).



Area of Interest (Lagos Island)		Park		Supermarket		Point, location		Bus, Taxi	
Civic building		Restaurant		Train, rail		Shopping Center			

Figure 1: Delineation of Study Area of Interest (AOI)¹

3.3. Data Analysis

Flood simulation was conducted to examine the extent of inundation from 1986 to 2023, analyse the Modified Normalised Difference Water Index (MNDWI), and assess seasonal water extent in the DEA Sandbox. Two notebooks in the DEA Sandbox were used: Water_extent_WOFS and Water_extent_sentinel. The former utilises data from Landsat images, while the latter uses data from Sentinel-2 satellites. Python codes were employed throughout the analysis, with Matplotlib used for visualising the results (Krause et al., 2021). Satellite imagery is used by Water Observations from Space (WOFS) to determine the locations and frequency of surface water observations. For long-term water extent analysis, this product offers a strong scientific basis. Likewise, the MNDWI is a validated spectral index that effectively distinguishes water bodies, making it especially useful for evaluating seasonal variations. The DEA Sandbox represents a relatively new technique, which has not yet been applied to the study and simulation of coastal inundation in the study area. All the codes used in the analysis are provided in the Appendix. Lastly, the policy and institutional dimension of this study was conducted through thematic analysis of policy documents relating to climate change and the environment.

In the next section, the results from the two notebooks mentioned in the previous section are presented. The notebooks have four sub-indicators, which include: spatial extent of water-related ecosystems, quantity of water contained within these ecosystems, quality of water within these ecosystems, and health or state of these ecosystems. The WOFS notebook provides insight into the longer-term extent of water bodies.

¹ Some localities at the Northern part of the study AOI include: Ijora Olopa, Idumota Market, Lagos Terminus. Some localities at the East include: Tinubu Square, Freedom Park. Some localities towards the Southern part include: Marina, Nimasa, Daddo Terminal.

This is complemented by the second notebook (Water_extent_sentinel), which focuses on more recent water extents at seasonal time intervals (Krause et al., 2021). Finally, policy and institutional responses to flooding as a climate change threat were deduced from document analysis.

4. RESULTS AND DISCUSSION

4.1. Mapping longer-term changes in water extent with Water Observation from Space (WOFs)

The results indicate a significant increase in water occurrence over time. The years 2000 and 2020 recorded the lowest and highest annual occurrences of water, respectively (Figure 2). Five images, spaced five years apart, were selected as a case study. These findings suggest a shift in water patterns and an increase in water content, which may indicate a trend of rising flooding or water-related events over time. From 1988 to 2000, the water area extent was the lowest, whereas from 2010 through 2023, the water content was notably higher (Figures 3 and 4). The water inundation observed in 1986 was relatively lower than that in 2022, highlighting a noticeable difference in the severity of flooding or water levels between these two years (Figure 5). An animated time series showing annual water extent and inundation is available on the website created for this study: <https://floodcheck.netlify.app>

The water inundation map from 1986 to 2023 illustrates changes in water distribution over time. The blue-colored areas represent locations that experienced water in both 1986 and 2023, indicating consistent water presence throughout the years. These areas may represent bodies of water or regions prone to flooding. In contrast, the yellow areas represent locations that had water in 1986 but no longer have water in 2023. This could suggest changes such as water bodies drying up or human interventions, like land reclamation, altering the natural flow of water. Lastly, the green areas represent locations that had no water in 1986 but have water in 2023. The map shows a higher concentration of green areas compared to others (Figure 6), indicating that flooding has predominantly occurred in these green areas.

Table 1: Average proportion of water coverage extents in the study area of interest from 2017 to 2023 (values range from 0 (no water) to 1 (completely covered by water))

Years	Water Coverage Extent (mean)	Minimum water extent	Maximum water extent
2017	0.38	0.00	1.00
2018	0.39	0.00	1.00
2019	0.37	0.00	1.00
2020	0.39	0.00	1.00
2021	0.39	0.00	1.00
2022	0.38	0.00	1.00

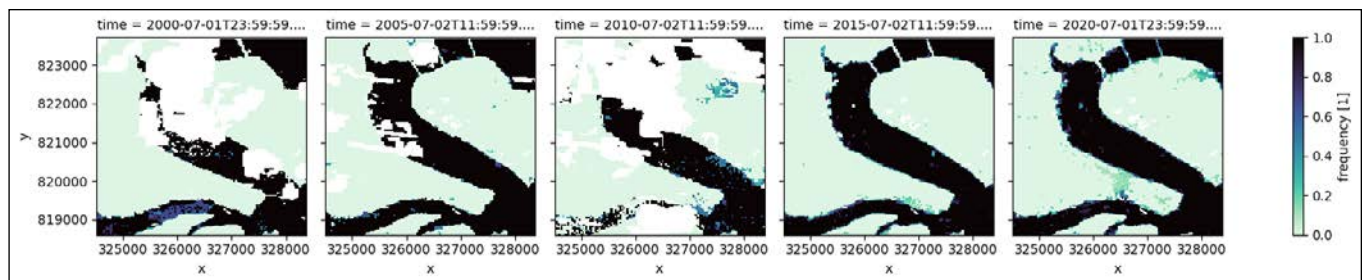


Figure 2: Annual Water Observation from Space summary (WOFs). The black areas represent areas that have been inundated with water, with the year 2020 and 2015 being the most inundated.

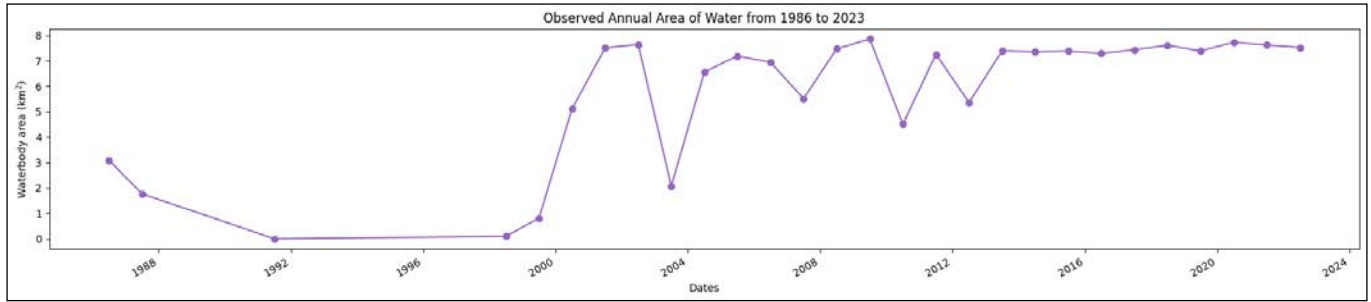


Figure 3: Observed Annual area of water from 1986 to 2023. There was a low annual area of water from 1992 to 2000 before a gradual increase occurred. There were sharp declines in the annual area of water in 2004, 2011, and 2013.

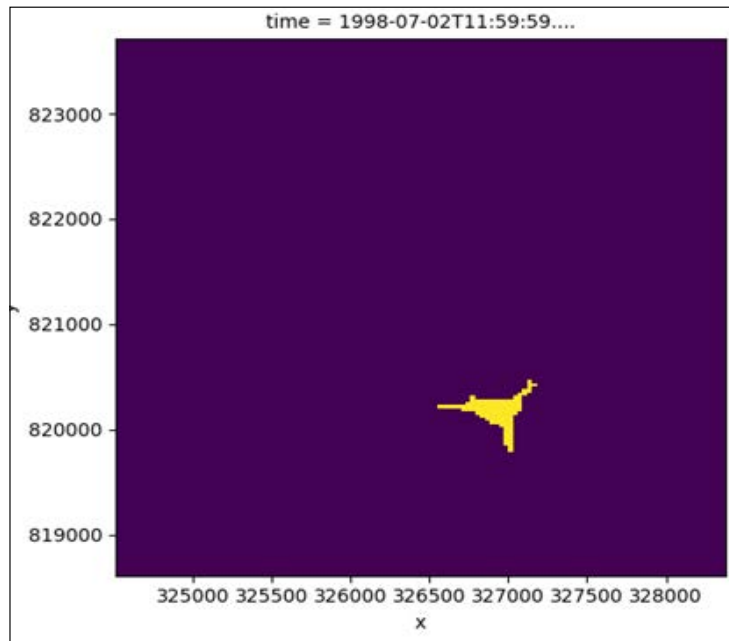


Figure 4: Minimum annual water extent (1998). The yellowish area indicates the presence of water

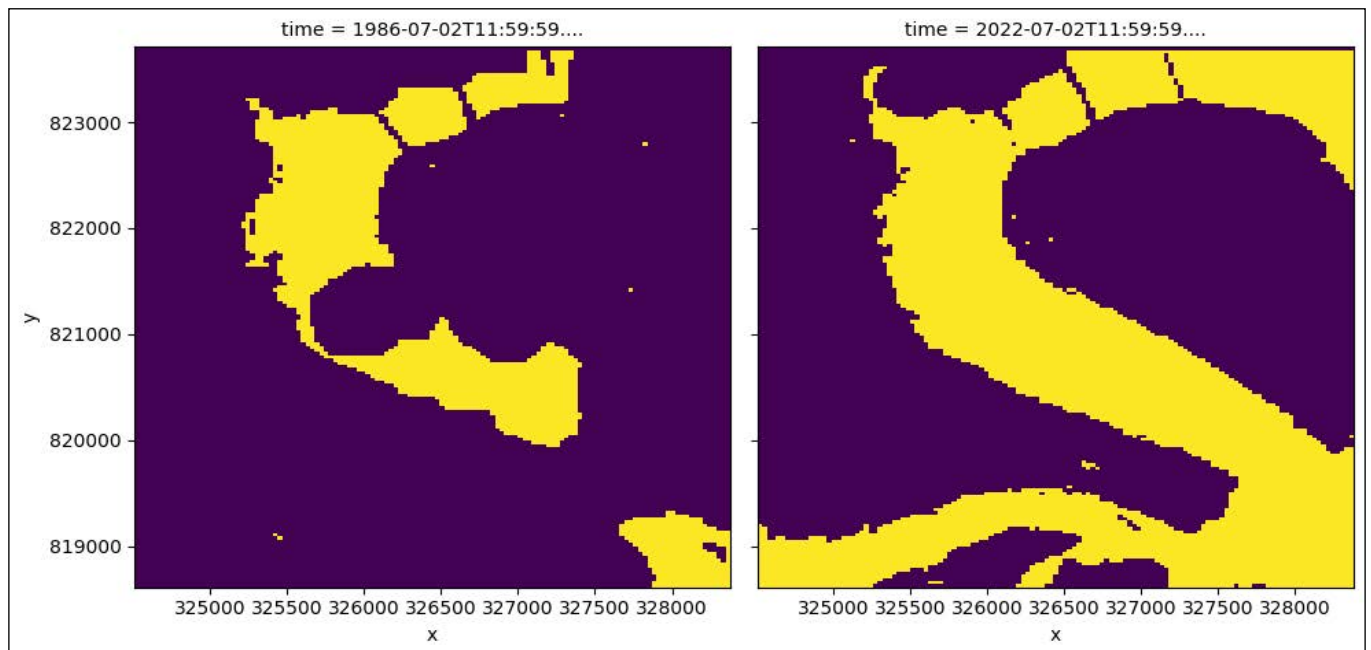


Figure 5: Annual extent of water from 1986 to 2023. There was a larger annual extent of water in 2023 compare to 1986.

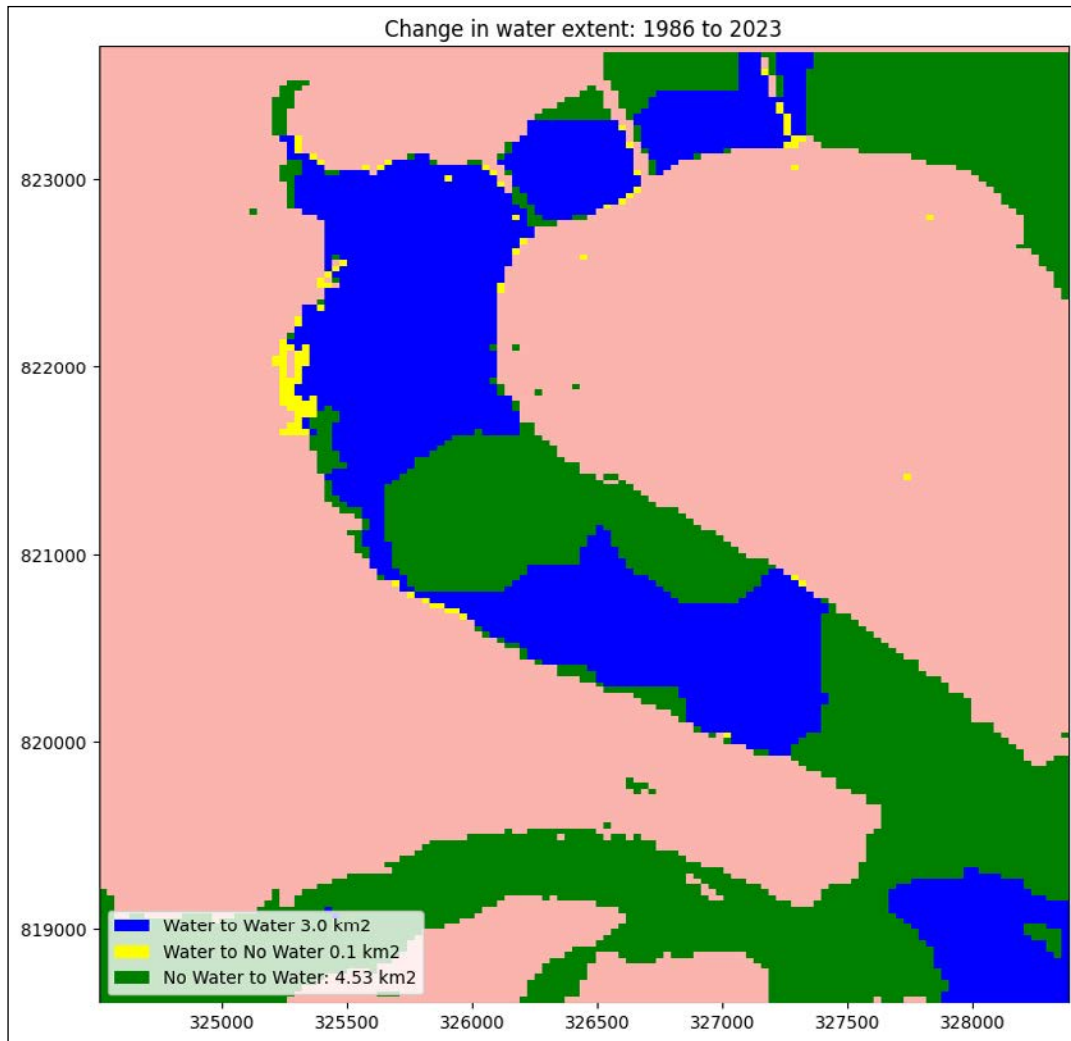


Figure 6: Change in water extent and inundation between the years 1986 and 2023

4.2. Determining seasonal extent of water bodies with Sentinel-2

The variation in seasonal water content can be observed from January 17, 2016, to December 1, 2023. Specifically, June 1, 2018, experienced the highest water inundation, while December 1, 2023, had the lowest water extent. The Modified Normalized Difference Water Index (MNDWI) seasonal time series indicates that the seasonal water area has varied over time. In 2018, the seasonal periods had the largest water area, indicating a significant presence of water (Figure 7). In contrast, the later seasonal periods of 2023 had the smallest water area, suggesting a decrease in water extent. These fluctuations in water areas may be linked to the occurrence of flooding, with 2018 experiencing higher levels of flooding compared to 2023. Figure 8 compares the years with the minimum and maximum water inundation (2023 and 2018, respectively).

In 2018, the study area was mostly covered with water, as indicated by the yellow areas. However, by 2023, these yellow areas had been replaced by land, suggesting that water had receded from these regions. On the other hand, the blue areas still contained water in 2023, meaning they had remained flooded over the years. These areas may have certain characteristics, such as natural depressions or poor drainage, that make them more prone to prolonged water presence. Interestingly, the green areas indicate flooded regions in 2023, even though they had no water presence in 2018. This suggests that new areas have become flooded over time, possibly due to changes in land use, climate patterns, or other factors. It would be worth investigating the reasons behind this new flooding to better understand the dynamics of water distribution in the study area.

The fact that the yellow areas are more extensive than the blue and green areas indicates a positive trend of water receding from certain regions (Figures 11, 12). This could be seen as a potential improvement in terms of flood mitigation or land management.

² The blue areas represent the areas where water was present in 1986 and still contain water in 2023. The yellow areas represent where there was presence of water in 1986 but do not contain water anymore in 2023. The green areas represent areas that has no water in 1986 but contains water now in 2023, these areas has been flooded over time. Increase in water extent has occurred in the North and towards the South of the study AOI.

The particular seasonal period with the highest water inundation occurred on June 1, 2018, while the seasonal period with the lowest water extent occurred on December 1, 2023 (Figure 10). Figure 12 shows more yellow areas, indicating that most of the regions covered by water in 2018 have now been replaced by land areas in 2023. The blue areas represent regions covered by water in 2018 that still contain water in 2023. The green areas represent flooded regions, as there was no water presence in those areas in 2018. The animated time series of the seasonal water extent is shown on the website created for this study: <https://floodcheck.netlify.app>.

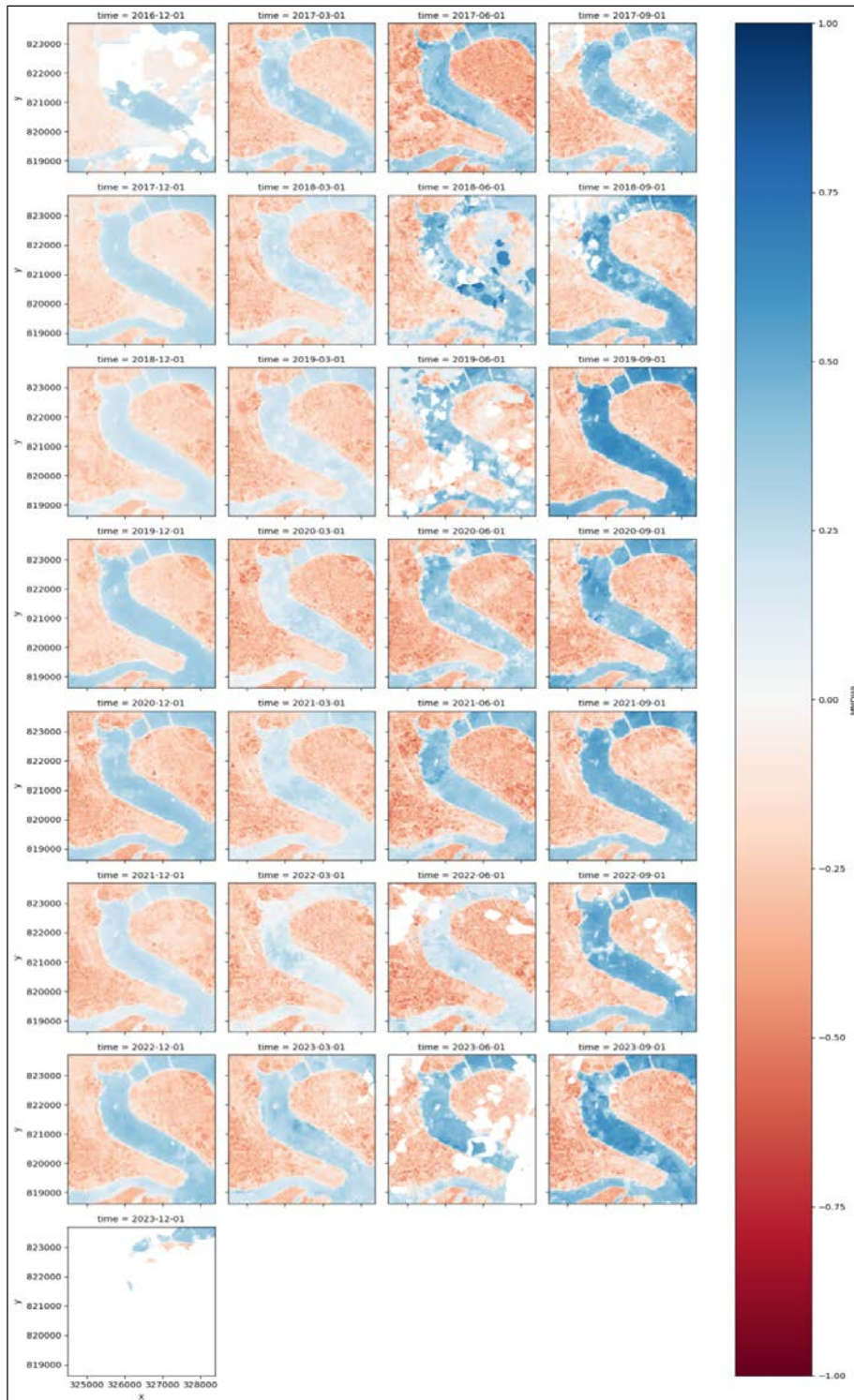


Figure 7: Modified Normalised Difference Water Index (MNDWI) Seasonal Time-series from December 2016 to December 20233

³ The blue and slightly white colored areas represent the flooded areas while the reddish areas represent places that have not been flooded. Water inundation has occurred more during the 2018 seasonal periods compared to others.

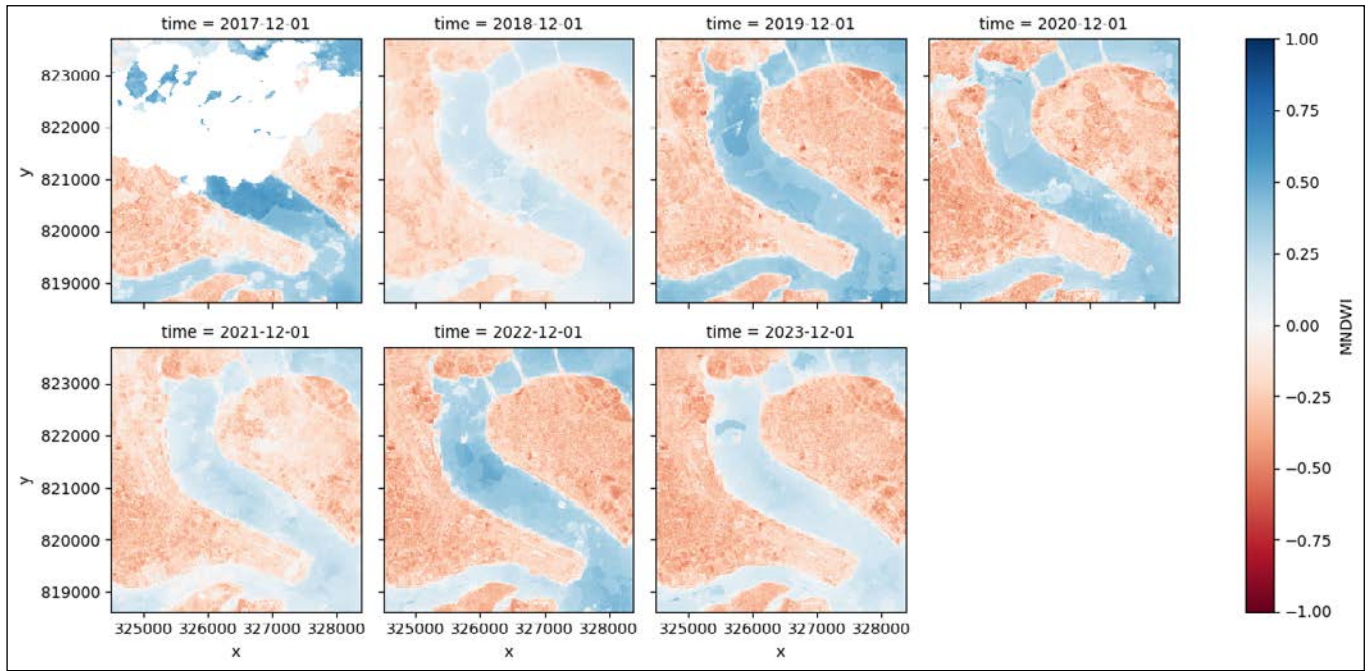


Figure 8: December's seasonal water extents from 2017 to 2023

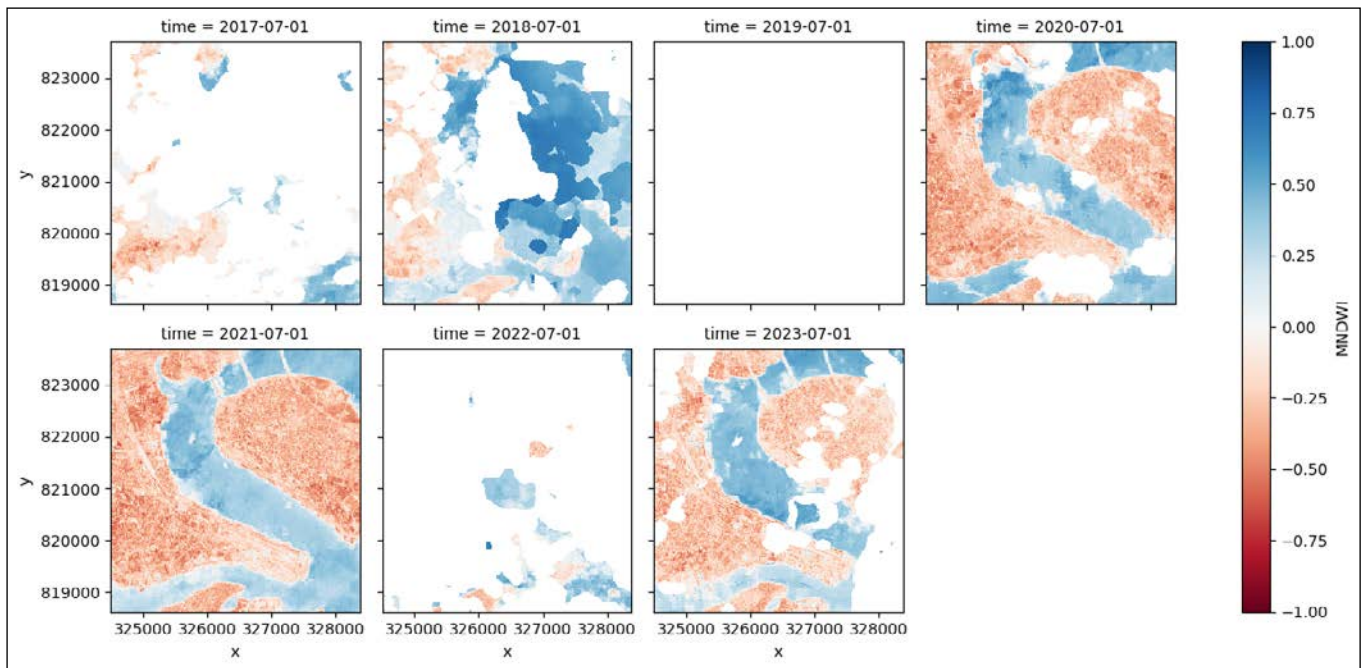


Figure 9: July's seasonal water extents from 2017 to 2023

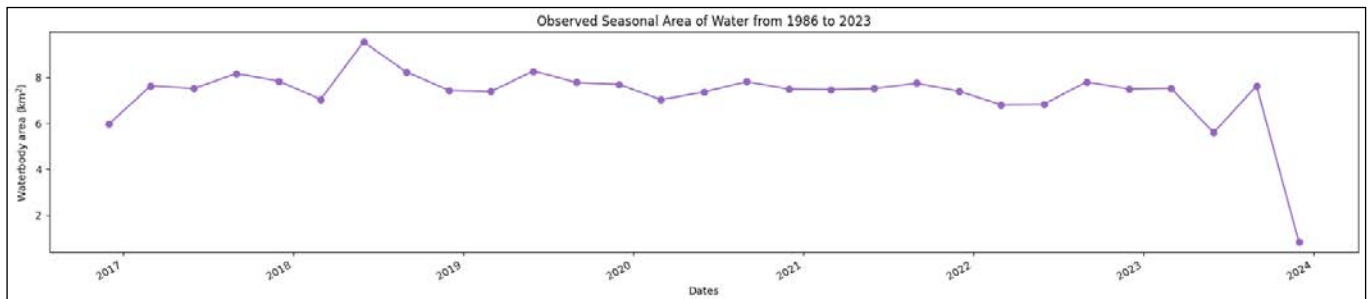


Figure 10: Plot showing observed seasonal area of water from 1986 to 2023. The year with the highest seasonal area of water is 2018, in contrast to 2023.

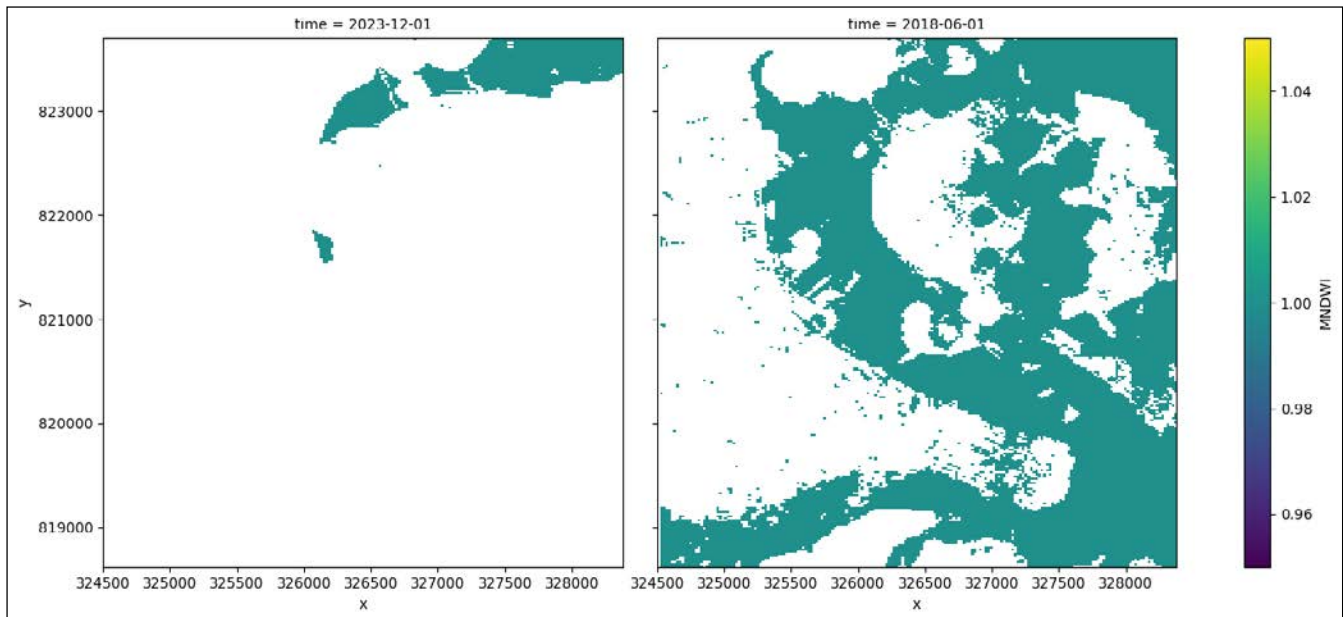


Figure 11: Plot water extent of MNDWI for the minimum and maximum seasonal periods. The year 2023 had the lowest MNDWI, while 2018 had the highest.

4.3. Enhancing Policy and Institutional Responses to Flooding as a Climate Change Threat in Lagos State, Nigeria.

Given that blocked drainage and improper waste management are non-climatic factors contributing to flooding in Lagos, reviewing the existing institutional framework could be beneficial for assessing the robustness of the current system in addressing the climate exacerbation of the problem. This section provides a review of the institutions related to climate change and waste management in Lagos, Nigeria.

4.3.1. OFFICE OF DRAINAGE SERVICES (ODS)

Lagos State Ministry of the Environment: The ODS is involved in dredging silted streams and drainage channels to combat flooding in Lagos State. Three drainage master plans were designed between 1974–1998, with Priority 1 works implemented. A total of 676,603.55 metric tons of silt were cleared from existing collector drains and canals in 2008 to improve hydraulic efficiency and carrying capacity. Between 2007–2011, 169 drainages were dredged and

124 lined with concrete, with 45 more expected to be lined by 2015. According to the Digital Earth Africa (DEA) analysis, the increasing number of water events (Figure 3) and the emergence of new flood-prone areas (Figure 6) underscore the growing difficulties the ODS is facing. While its efforts to line drains and dredge are commendable, our data from 1986 to 2023 show that flooding is becoming more frequent and intense, suggesting that these current approaches might not be sufficient to address the effects of climate change and rapid urbanisation.

Continuity from one government to another is especially important for sustaining the impacts of this institution. Canal networks across Lagos—such as the Macgregor, Achapo, and System 5 canals, among others (Filani, 2012)—need to be kept clear and properly dredged from time to time so that backed-up drains do not cause intractable flooding. This intervention is especially crucial with recent forecasts of above-average rainfall—partly attributable to climate change.

4.3.2. LAGOS STATE EMERGENCY MANAGEMENT AGENCY (LASEMA):

The Local Emergency Management Committee (LEMC) was established in 2014 under LASEMA, with 774 members from all wards, agencies, and community groups. The LEMC supports the Disaster Risk Reduction Convention of Kobe, Japan, by striving to reduce risk through knowledge, innovation, and education. The Agency’s flood preparedness efforts focus on mapping risk and hazards, collaborating with agencies such as the Nigerian Meteorological Agency (NiMet), Lagos State Environmental Protection Agency (LASEPA), Ministry of Physical Planning and Urban Development (MPPUD), and others. For flood mitigation, early warning systems are activated to educate people on emergency response. Stockpiling of resources and the building of relief camps are used for flood response. Lastly, a survey of flood victims is conducted for recovery purposes. LASEMA’s early warning systems and community-focused response efforts are critical, as evidenced by the rapid emergence of new flood-prone zones and the ongoing flooding in certain regions (shown by the blue areas in Figure 6). To address the

difficulties these areas face, prompt and targeted interventions are required.

All the foregoing activities are commendable. Specifically, bottom-up, community-based emergency response and interventions need to be promoted and prioritized for sustainable emergency management outcomes. Climate action that builds resilience, to a large extent, requires bottom-up, community-based solutions. Thus, following this approach to emergency response will help build the resilience of Lagos to climate change hazards while promoting sustainable emergency management.

4.3.3. LAGOS STATE WASTE MANAGEMENT AUTHORITY (LAWMA):

Population expansion not only leads to spatial growth but also results in the generation of waste, particularly municipal solid waste (MSW). In Lagos, approximately 10,000 tons of solid waste are generated daily, with a per capita generation rate of 0.65 kg/person/day. The rapid generation of MSW poses significant challenges to the financial and technical capacities of LAWMA in effectively managing waste in a sanitary manner. As a consequence, solid waste remains uncollected and is indiscriminately dumped in water bodies, air spaces of buildings, open lands, road verges, and public drains. The presence of littered waste becomes a permanent and unsightly feature of the urban landscape. As demonstrated by the DEA results, the overall increase in inundation and the continued presence of water in historically flooded areas (blue regions in Figure 6) suggest the effects of poor waste management.

Lagos is yet to fully resolve the problem of waste management, such as the indiscriminate dumping of waste in water bodies. Given the impact of waste in clogging drains—thereby exacerbating floods—and the release of greenhouse gases (GHGs) from dump sites (contributing to climate change), a systems approach involving a broad spectrum of stakeholders in

a solution-curating exercise may be needed. Stakeholders should include not only government and private sector representatives but also researchers, community-based organizations (CBOs), non-governmental organizations (NGOs), consultants, and the general citizenry.

4.3.4. LAGOS STATE CLIMATE CHANGE ADAPTATION STRATEGY (LAS-CCAS)

The LAS-CCAS was developed to strengthen the proactive measures already undertaken by the State Government in tackling the issue of climate change. The ultimate goal of the programme is to reduce vulnerabilities, enhance resilience, and improve adaptive capacity to climate change in Lagos State. By doing so, it aims to mitigate the detrimental impacts that disproportionately affect marginalized groups such as the poor, elderly, women, children, and persons with disabilities (PWDs).

Our results highlight the necessity of flexible planning to adjust to the shifting patterns of flooding and point to areas with increasing risks. The strategy's objective of lowering vulnerabilities and enhancing resilience in the face of these difficulties is well aligned with these findings. Similar to the approach suggested for waste management, the efforts of LAS-CCAS may need to be opened up more to include the 'people' being planned for. Also, funding for research in this area will make it possible to generate solutions that are specific and appropriate to the Lagos context.

4.4. The Pursuit of Sustainable Solutions

To address the threats to life posed by climate-exacerbated flood risks, it is crucial for Lagos State to promote climate change mitigation, adaptation, and resilience-building activities (collectively known as climate action) across its development initiatives. In order to effectively combat climate change, measures that reduce greenhouse

gas emissions—which cause global warming and sea level rise—are essential. Enforcing stronger energy-efficient regulations and improving waste management procedures are some important tactics. The state has taken commendable steps, such as instituting an annual International Climate Change Summit since 2010 and developing its second Lagos Climate Action Plan. However, there still seems to be a disconnect between development projects and sustainable outcomes in Lagos. Bolarinwa (2023), on one hand, and Solanke (2020) and ICIR (2022), on the other, provide insightful critiques of the political ecology and environmental impacts of projects such as Eko Atlantic City and the Dangote Refinery, respectively. In light of the challenges they identify, true climate action would require, for example, that the Eko Atlantic City project tangibly contribute to mitigating and adapting to climate change, particularly for the most vulnerable populations. Similarly, the Dangote Refinery should be operated in a manner that does not contribute to the increase in global temperatures, thereby exacerbating climate change.

Specifically with respect to flooding in Lagos, maintaining consistency in addressing the underlying factors is essential to achieving the desired outcome of significantly reducing flood incidents. The key word here is consistency. At the same time, it is important to tackle the specific causes of the various types of urban flooding. For example, regular clearing and desilting of drains, along with ensuring that waste does not enter the drainage systems, would help mitigate flooding caused by poor drainage. Additionally, enforcing a floodplain management plan to regulate land use, as well as encouraging the development of flood-resistant or floating structures around floodplains, could help manage floodplain inundation. Finally, adopting a multidimensional approach—integrating structural, policy-based, and community-level strategies—may be the most effective way to mitigate coastal flooding.

Pertinent to this paper are the following questions: How much environmental stewardship is incorporated into solving the city's problems and executing development projects? Taking into account that climate change exacerbates existing vulnerabilities, what would happen if current vulnerabilities (outside the influence of climate) increase? At the very least, it can be expected that climate change would worsen these increased vulnerabilities. Meanwhile, are development projects being executed solely as a reflection of humanity's dominance over nature? How should climate action be financed in the face of other important state spending priorities? How can a public-private-citizen partnership be developed to build a resilient city? How can the highlighted peculiarities of Lagos State be transformed into solutions for building a sustainable, climate-resilient city? Properly addressing these questions and revisiting the plans of ongoing projects may help the state in achieving its goals of a climate-resilient city.

5. CONCLUSION

In this paper, we utilized the Digital Earth Africa (DEA) Sandbox to evaluate the extent, vulnerability, and risk of coastal inundation in order to understand inundation characteristics in the growing megacity of Lagos, Nigeria, for urban planning and climate adaptation. Flood simulation of the study area between 1986 and 2023 reveals that some areas previously inundated with water were identified as land in 2023, suggesting that water has either receded from these regions or they have been sand-filled. Meanwhile, certain areas that were inundated prior to 2023 have remained consistently flooded. These regions may possess specific characteristics, such as natural depressions or poor drainage, making them more susceptible to prolonged water presence. Additionally, new areas have recently become flooded, possibly due to changes in land use, climate patterns, or other contributing factors. The implementation of the DEA Sandbox geospatial resources demonstrates the utility of this toolbox

for environmental resource monitoring and urban planning. In the context of the rapidly developing Lagos Megacity, our findings underscore the importance of addressing flood-prone areas to support sustainable urban development.

Overall, the study reveals a significant increase in water occurrence and inundation over time, with 2020 recording the highest annual water presence and 2000 the lowest. Analysis of five case-study images spaced five years apart highlights a shift in water distribution patterns, indicating a possible trend of increasing flood events. Between 1988 and 2000, water extent was at its lowest, whereas from 2010 to 2023, a notable rise in water content was observed. A comparison of 1986 and 2022 further underscores the intensification of water inundation in recent years. Spatial analysis of water distribution from 1986 to 2023 shows consistent flooding in some areas, water recession in others, and the emergence of new flood-prone zones, likely due to changes in land use or climate conditions. Seasonal analysis using the Modified Normalized Difference Water Index (MNDWI) indicates June 1, 2018, as the period of highest water inundation, while December 1, 2023, recorded the lowest. These seasonal fluctuations reflect the complex dynamics of flooding in the study area, with 2018 standing out as a peak flood year. While some areas have shown improvement in flood mitigation, the emergence of new flood zones highlights the need for continuous monitoring and targeted interventions. Our results offer clear, evidence-based recommendations for policymakers and urban planners in Lagos. They highlight the escalating difficulties and the urgent need for a more proactive, data-driven approach to urban development. This strategy should include effective policy implementation, sustainable land use planning, and a drive for climate-resilient development.

To effectively address flooding in Lagos—especially as climate change worsens the situation—it is crucial to assess whether existing institutional frameworks are

robust enough to manage both climatic and non-climatic drivers such as blocked drainage and poor waste management. The Office of Drainage Services has made significant infrastructural efforts, including dredging and concrete lining of drains, but maintaining continuity across administrations is key to long-term impact, especially given climate change projections of heavier rainfall. The Lagos State Emergency Management Agency (LASEMA) supports disaster risk reduction through early warning systems, hazard mapping, and community-level emergency response; however, enhancing community-based resilience strategies will better align with climate adaptation goals. The Lagos Waste Management Authority (LAWMA) faces mounting challenges from the rapid growth in solid waste, which clogs drains and worsens flooding, indicating a need for a systemic, multi-stakeholder approach that includes community participation. While the Lagos State Climate Change Adaptation Strategy (LAS-CCAS) outlines a solid framework for resilience, its effectiveness would be greatly improved by increasing public involvement and investing in localized research to ensure context-specific solutions.

Finally, to address the growing threat of climate-exacerbated flood risks in Lagos State, it is essential to integrate climate change mitigation, adaptation, and resilience—collectively known as climate action—into all aspects of development. While Lagos has made notable strides, such as hosting an annual International Climate Change Summit since 2010 and formulating a second Climate Action Plan, a strong connection between development projects and sustainable outcomes remains lacking. Regarding flooding, consistent and targeted interventions—such as clearing drains, preventing waste blockage, enforcing floodplain management, and exploring multidimensional solutions—are crucial for reducing flood incidences across the state.

6. DISCLOSURE

A version of this paper was presented at the 10th Summit of the Association of Lagos State Retired Heads of Service and Permanent Secretaries (ALARHOSPS).

7. ACKNOWLEDGEMENTS

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8. CONFLICTS OF INTEREST

The authors declare no conflict of interest.

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10. APPENDIX

Mapping longer-term changes in water extent with Water Observation From Space (WOFs)

```

First Step: Load Packages
%matplotlib inline
# Force GeoPandas to use Shapely instead of PyGEOS
# In a future release, GeoPandas will switch to using Shapely by default.
import os
os.environ[<USE_PYGEOS>] = <0>
import datacube
import numpy as np
import xarray as xr
import seaborn as sns
import geopandas as gpd
import matplotlib.pyplot as plt
from IPython.display import Image
from matplotlib.colors import ListedColormap
from matplotlib.patches import Patch
from datacube.utils.geometry import Geometry

```

```

from deafrica_tools.bandindices import calculate_indices
from deafrica_tools.plotting import display_map, xr_animation
from deafrica_tools.spatial import xr_rasterize
from deafrica_tools.areaofinterest import define_area

```

```

Second Step: Connect to Datacube
dc = datacube.Datacube(app=>water_extent)

```

```

Third Step: Select Location
# Method 1: Specify the latitude, longitude, and buffer
aoi = define_area(lat=6.4499982, lon=3.3833318, buffer= 0.02)
#Create a geopolygon and geodataframe of the area of interest
geopolygon = Geometry(aoi[<features>][0][<geometry>],
crs=>»eps:4326»)
geopolygon_gdf = gpd.GeoDataFrame(geometry=[geopolygon],
crs=geopolygon.crs)
# Get the latitude and longitude range of the geopolygon
lat_range = (geopolygon_gdf.total_bounds[1], geopolygon_gdf.total_
bounds[3])
lon_range = (geopolygon_gdf.total_bounds[0], geopolygon_gdf.total_
bounds[2])
# Define the start year and end year
start_year = <1986>
end_year = <2023>

```

```

Fourth Step: Load WOFs annual summaries
#Create a query object
query = {
    <x>: lon_range,
    <y>: lat_range,
    <resolution>: (30 ,30-),
    <output_crs>:»EPSG:6933»,
    <time>: (start_year, end_year),
}

```

```

#load wofs
ds = dc.load(product=>»wofs_ls_summary_annual»,
**query)
print(ds)

```

```

Fifth Step: Clip datasets to the shape of the area of interest
#Rasterise the area of interest polygon
aoi_raster = xr_rasterize(gdf=geopolygon_gdf, da=ds, crs=ds.crs)
#Mask the dataset to the rasterised area of interest
ds = ds.where(aoi_raster == 1)

```

```

Sixth Step: Facet subset plot of the annual WOFs summaries
ds.isel(time=[5,10,15,20,25]).frequency.plot(col=>»time», col_wrap=5,
cmap=sns.color_palette(<»mako_r», as_cmap=True));

```

```

Seventh Step: Animating time series
out_path = <annual_water_frequency.gif>

```

```

xr_animation(ds=ds,
    output_path=out_path,
    interval=400,
    bands=[<frequency>],
    show_text=>»WOFs Annual Summary»,
    show_date = <%Y>,
    width_pixels=300,
    annotation_kwargs={<fontsize>: 15},
    imshow_kwargs={<cmap>: sns.color_palette(<»mako_r», as_
cmap=True), <vmin>: 0.0, <vmax>: 0.9},
    colorbar_kwargs={<colors>: <black>},
    show_colorbar=False)

```

```

# Plot animated gif
plt.close()
Image(filename=out_path)

```

Eighth Step: Calculate the annual area of water extent

```

pixel_length = query[<resolution>][1] # in metres
m_per_km = 1000 # conversion from metres to kilometres
area_per_pixel = pixel_length**2 / m_per_km**2

```

Ninth Step: Threshold WOFs annual frequency to classify water/not-water

```

water_threshold = 0.20

```

```

#threshold
water_extent = ds.frequency > water_threshold

```

```

#calculate area
ds_valid_water_area = water_extent.sum(dim=[<x>, <y>]) * area_per_pixel

```

Tenth Step: Plot the annual area of Open water

```

plt.figure(figsize=(4 ,18))
ds_valid_water_area.plot(marker=>»o», color=>»9467#bd»)
plt.title(<»Observed Annual Area of Water from {start_year} to {end_
year}>»)
plt.xlabel(<»Dates>»)
plt.ylabel(<»Waterbody area (km$^2$)>»)
plt.tight_layout()

```

Eleventh Step: Determine minimum and maximum water extent

```

min_water_area_date, max_water_area_date = min(ds_valid_water_area),
max(ds_valid_water_area)
time_xr = xr.DataArray([min_water_area_date.time.values, max_water_
area_date.time.values], dims=[<time>])

```

```

print(time_xr)

```

Twelfth Step: Plot the dates when the minimum and maximum water extent occur

```

water_extent.sel(time=time_xr).plot.imshow(col=>»time», col_wrap=2,
figsize=(6 ,14));

```

Thirteenth Step: Compare two time periods

```

baseline_time = <1986>
analysis_time = <2021>

```

```

baseline_ds, analysis_ds = ds_valid_water_area.sel(time=baseline_time,

```

```
method =>nearest), ds_valid_water_area.sel(time=analysis_time, method
=>nearest)
```

Fourteenth Step: Plot water extent for the two chosen periods

```
compare = water_extent.sel(time=[baseline_ds.time.values, analysis_
ds.time.values])
```

```
compare.plot(col=>time,col_wrap=2,figsize=(5,10), cmap=>viridis,
add_colorbar=False);
```

Fifteenth Step: Calculate the change for the two nominated periods

```
analyse_total_value = compare.isel(time=1).astype(int)
change = analyse_total_value - compare.isel(time=0).astype(int)
```

```
water_appeared = change.where(change == 1)
permanent_water = change.where((change == 0) & (analyse_total_value
== 1))
permanent_land = change.where((change == 0) & (analyse_total_value
== 0))
water_disappeared = change.where(change == 1-)
```

```
total_area = analyse_total_value.count().values * area_per_pixel
water_apperaed_area = water_appeared.count().values * area_per_pixel
permanent_water_area = permanent_water.count().values * area_per_
pixel
water_disappeared_area = water_disappeared.count().values * area_per_
pixel
```

Sixteenth Step: Plot water variables to visualize result

```
water_appeared_color = «Green»
water_disappeared_color = «Yellow»
stable_color = «Blue»
land_color = «Brown»
```

```
fig, ax = plt.subplots(1,1, figsize=(10,10))
```

```
compare[1].plot.imshow(cmap=>Pastel1»,
add_colorbar=False,
add_labels=False,
ax=ax)
```

```
water_appeared.plot.imshow(
cmap=ListedColormap([water_appeared_color]),
add_colorbar=False,
add_labels=False,
ax=ax,
)
```

```
water_disappeared.plot.imshow(
cmap=ListedColormap([water_disappeared_color]),
add_colorbar=False,
add_labels=False,
ax=ax,
)
```

```
permanent_water.plot.imshow(cmap=ListedColormap([stable_color]),
add_colorbar=False,
add_labels=False,
ax=ax)
```

```
plt.legend(
[
Patch(facecolor=stable_color),
Patch(facecolor=water_disappeared_color),
Patch(facecolor=water_appeared_color),
Patch(facecolor=land_color),
],
[
f»Water to Water {round(permanent_water_area, 2)} km2»,
f»Water to No Water {round(water_disappeared_area, 2)} km2»,
```

```
f»No Water to Water: {round(water_apperaed_area, 2)} km2»,
],
loc=>lower left»,
)
```

```
plt.title(«Change in water extent: « + baseline_time + « to « + analysis_
time);
```

3.3.4.2. Determining seasonal extent of water bodies with Sentinel2-
First Step: Load packages

```
%matplotlib inline
```

```
# Force GeoPandas to use Shapely instead of PyGEOs
# In a future release, GeoPandas will switch to using Shapely by default.
import os
os.environ[«USE_PYGEOs»] = «0»
```

```
import datacube
import matplotlib.pyplot as plt
import numpy as np
import xarray as xr
import geopandas as gpd
from IPython.display import Image
from matplotlib.colors import ListedColormap
from matplotlib.patches import Patch
```

```
from datacube.utils.geometry import Geometry
from deafrica_tools.datahandling import load_ard
from deafrica_tools.bandindices import calculate_indices
from deafrica_tools.plotting import display_map, xr_animation
from deafrica_tools.dask import create_local_dask_cluster
from deafrica_tools.spatial import xr_rasterize
from deafrica_tools.areaofinterest import define_area
```

Second Step: Connect to data cube

```
dc = datacube.Datacube(app=>water_extent)
```

Third Step: Select Location

```
# Method 1: Specify the latitude, longitude, and buffer
aoi = define_area(lat=6.4499982, lon=3.3833318, buffer=0.02)
```

```
# Method 2: Use a polygon as a GeoJSON or Esri Shapefile.
# aoi = define_area(vector_path=>aoi.shp)
```

```
#Create a geopolygon and geodataframe of the area of interest
geopolygon = Geometry(aoi[«features»][0][«geometry»],
crs=>«epsg:4326»)
geopolygon_gdf = gpd.GeoDataFrame(geometry=[geopolygon],
crs=geopolygon.crs)
```

```
# Get the latitude and longitude range of the geopolygon
lat_range = (geopolygon_gdf.total_bounds[1], geopolygon_gdf.total_
bounds[3])
lon_range = (geopolygon_gdf.total_bounds[0], geopolygon_gdf.total_
bounds[2])
```

```
# Define the start year and end year
start_year = «1986»
end_year = «2023»
```

Fourth Step: View the area of Interest on an interactive map

```
display_map(lon_range, lat_range)
```

Fifth Step: Load cloud-masked satellite data

```

#Create a query object
query = {
  <x>: lon_range,
  <y>: lat_range,
  <resolution>: (20 ,20-),
  <output_crs>:EPSG:6933,
  <time>: (start_year, end_year),
  <dask_chunks>:{<time>:1,<x>:500,<y>:500}
}

#load Sentinel 2 data
ds = load_ard(dc=dc,
  products=[<s2_l2a>,
  measurements=[<green>,<swir_1>],
  mask_filters=[(<opening>, 3),(<dilation>, 2)], #improve cloud
mask
  group_by=>solar_day,
  **query)

print(ds)

Sixth Step: Clip the datasets to the shape of the area of interest

#Rasterise the area of interest polygon
aoi_raster = xr_rasterize(gdf=geopolygon_gdf, da=ds, crs=ds.crs)
#Mask the dataset to the rasterised area of interest
ds = ds.where(aoi_raster == 1)

Seventh Step: Calculate the MNDWI water index

# Calculate the chosen vegetation proxy index and add it to the loaded
data set
ds = calculate_indices(ds=ds, index=>MNDWI, satellite_mission=>s2,
drop=True)

Eighth Step: Resample time series
%%time
sample_frequency=>QS-DEC # quarterly starting in DEC, i.e. seasonal

#resample using medians
print(<calculating MNDWI seasonal medians...>)
mndwi = ds[<MNDWI>].resample(time=sample_frequency).median().
compute()

Ninth Step: Facet plot the MNDWI time-steps

mndwi.plot(col=>time, col_wrap=4, cmap=>RdBu, vmax=1, vmin=1-);

Tenth Step: Animating time series

out_path = <water_extent.gif>

xr_animation(ds=mndwi.to_dataset(name=>MNDWI),
  output_path=out_path,
  bands = [<MNDWI>],
  show_text = <Seasonal MNDWI>,
  interval=500,
  width_pixels=300,
  show_colorbar=True,
  imshow_kwargs={<cmap>:RdBu,<vmin>: 0.5-, <vmax>: 0.5},
  colorbar_kwargs={<color>: <black>}
)

# Plot animated gif
plt.close()
Image(filename=out_path)

Eleventh Step: Calculate the area per pixel

pixel_length = query[<resolution>][1] # in metres
m_per_km = 1000 # conversion from metres to kilometres

area_per_pixel = pixel_length**2 / m_per_km**2

Twelfth Step: Calculating the extent of water

water = mndwi.where(mndwi > 0, np.nan)
area_ds = water.where(np.isnan(water),1)
ds_valid_water_area = area_ds.sum(dim=[<x>,<y>]) * area_per_pixel

Thirteenth Step: Plot seasonal time series from the Start year to End year

plt.figure(figsize=(4 ,18))
ds_valid_water_area.plot(marker=>o, color=>9467#bd)
plt.title(<Observed Seasonal Area of Water from {start_year} to {end_
year}>)
plt.xlabel(<Dates>)
plt.ylabel(<Waterbody area (km$^2$)>)
plt.tight_layout()

Fourteenth Step: Determine minimum and maximum water extent

min_water_area_date, max_water_area_date = min(ds_valid_water_area),
max(ds_valid_water_area)
time_xr = xr.DataArray([min_water_area_date.time.values, max_water_
area_date.time.values], dims=[<time>])

print(time_xr)

Fifteenth Step: Plot the dates when the min and max water extent occur

area_ds.sel(time=time_xr).plot.imshow(col=>time, col_wrap=2,
figsize=(6 ,14))

Sixteenth Step: Compare two time periods

baseline_time = <1986>
analysis_time = <2023>

baseline_ds, analysis_ds = ds_valid_water_area.sel(time=baseline_time,
method =>nearest), ds_valid_water_area.sel(time=analysis_time, method
=>nearest)

time_xr = xr.DataArray([baseline_ds.time.values, analysis_ds.time.
values], dims=[<time>])

Seventeenth Step: Plot water extent of the MNDWI product for the two
chosen periods

area_ds.sel(time=time_xr).plot(col=>time, col_wrap=2, robust=True,
figsize=(5 ,10), cmap=>viridis, add_colorbar=False);

Eighteenth Step: Calculating the change for the two nominated periods

# The two period Extract the two periods(Baseline and analysis) dataset
from
ds_selected = area_ds.where(area_ds == 0 ,1).sel(time=time_xr)

analyse_total_value = ds_selected[1]
change = analyse_total_value - ds_selected[0]

water_appeared = change.where(change == 1)
permanent_water = change.where((change == 0) & (analyse_total_value
== 1))
permanent_land = change.where((change == 0) & (analyse_total_value
== 0))
water_disappeared = change.where(change == 1-)

total_area = analyse_total_value.count().values * area_per_pixel
water_apperaed_area = water_appeared.count().values * area_per_pixel
permanent_water_area = permanent_water.count().values * area_per_
pixel
water_disappeared_area = water_disappeared.count().values * area_per_
pixel

```

Nineteenth Step: Water variables are plotted to visualized the result

```
water_appeared_color = «Green»
water_disappeared_color = «Yellow»
stable_color = «Blue»
land_color = «Brown»

fig, ax = plt.subplots(1,1, figsize=(10,10))

ds_selected[1].plot.imshow(cmap=»Pastel1«,
                           add_colorbar=False,
                           add_labels=False,
                           ax=ax)
water_appeared.plot.imshow(
    cmap=ListedColormap([water_appeared_color]),
    add_colorbar=False,
    add_labels=False,
    ax=ax,
)
water_disappeared.plot.imshow(
    cmap=ListedColormap([water_disappeared_color]),
    add_colorbar=False,
    add_labels=False,
    ax=ax,
)
permanent_water.plot.imshow(cmap=ListedColormap([stable_color]),
                             add_colorbar=False,
                             add_labels=False,
                             ax=ax)

plt.legend(
    [
        Patch(facecolor=stable_color),
        Patch(facecolor=water_disappeared_color),
        Patch(facecolor=water_appeared_color),
        Patch(facecolor=land_color),
    ],
    [
        f»Water to Water {round(permanent_water_area, 2)} km2«,
        f»Water to No Water {round(water_disappeared_area, 2)} km2«,
        f»No Water to Water: {round(water_apperaed_area, 2)} km2«,
    ],
    loc=»lower left«,
)

plt.title(«Change in water extent: « + baseline_time + « to « + analysis_
time);
```