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Assessing the Impact of Population Growth in Louisiana on Diminishing Water Quantity and Quality within the State

Yaw A. Twumasi[1]*, Edmund C. Merem[2], Zhu H. Ning[1], Harriet B. Yeboah[3], Jeff D. Osei[1], Priscilla M. Loh[1], Dorcas T. Gyan[1], Esi Dadzie[1], Vanessa Ferchaud[1], Matilda Anokye[4], Recheal N. D. Armah[1], Janeth E. Mjema[1], Lucinda A. Kangwana[1]

[1]Department of Urban Forestry, Environment and Natural Resources, Southern University and A&M College, 110E Fisher Hall, Baton Rouge, Louisiana, USA
[2]Department of Urban and Regional Planning, Jackson State University, 101 Capitol Center, Jackson, Mississippi, USA
[3]Department of Geography and Tourism Studies, Brock University, St. Catharines, Ontario, Canada
[4]Department of Built Environment, North Carolina A&T State University, Greensboro, NC, USA
Email: *yaw_twumasi@subr.edu, *yaw.twumasi@gmail.com

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Abstract

This study explores the intricate relationship between population growth and water resource management in Louisiana, emphasizing the spatial distribution of water quality. Human activities, particularly urbanization, have significantly impacted the state's water resources, with population growth driving increased water withdrawals for public supply, industry, and power generation. By employing a Geographic Information System (GIS)-centered approach, this research utilizes Louisiana's census data from 1999 to 2020 to illustrate population shifts and their effects on water resource distribution. The study also incorporated advanced remote sensing techniques, using Sentinel 2 imagery to assess the water quality through the Trophic State Index (TSI). The TSI, calculated based on the near-infrared (NIR) and Red bands of Sentinel-2 imagery, provided a nuanced understanding of the nutrient levels and clarity/quality of water bodies across the state. The study reveals a significant correlation between population density and water withdrawals, with higher populations leading to greater extraction from both groundwater and surface water sources. For instance, densely populated parishes like East Baton Rouge and Orleans showed substantially higher water withdrawals for public supply, industry, and power generation compared to less populated areas. The water quality analysis indicated that many water bodies in Louisiana are experiencing high levels of nutrient enrichment, with rivers and streams accounting for 86% of the impaired water bodies, and lakes, reservoirs, and coastal waters showing hypereutrophic conditions in up to 96% of cases. These results underscore the significant impact of human activities on Louisiana's water resources, highlighting the need for effective water management practices that consider both quantity and quality. The study therefore advocates for the implementation of water conservation measures, responsible consumption, and pollution prevention strategies to ensure the sustainable use of water resources and the preservation of water quality across Louisiana.

Keywords

Groundwater, Surface Water, Trophic State, Water Resources, Climate Change, Urbanization

1. Introduction

Water quality degradation has emerged as a significant factor in a variety of global issues, including the availability of safe drinking water for humans and the survival of species. Currently, approximately 1.1 billion people worldwide do not have access to safe drinking water, and 2.6 billion do not have access to proper sanitation services. Water pollution is a leading cause of death worldwide, as it transmits or promotes the spread of a variety of debilitating diseases among populations forced to drink contaminated water. [1] [2] argue that despite covering 71% of the earth's surface, only 0.3% of water is available for human consumption as fresh water. Furthermore, the quality of fresh water in both underground and surface systems is a major concern because drinking water requires the proper mineral composition. Natural processes as well as human activities have an impact on the quality of ground and surface water in rural and urban areas. As a result, as the world's population grows, water scarcity becomes a pressing issue (ibid).

According to [3], Louisiana is known for its abundant and vital water resources, with over 40,000 miles of rivers, streams, and bayous, as well as 400 miles of coastline. Despite having abundant water reserves, Louisiana's water resources face significant challenges, including diminishing quantity and quality. [4] [5] argue that human activities have had a significant impact on the ecological environment, owing primarily to the rapid process of urbanization. Human utilization and contamination of freshwater have now reached an unprecedented level, with water scarcity expected to limit food production, ecosystem functioning, and urban water supply in the near future. This scarcity is primarily due to population growth, which has outpaced food production in recent years and is expected to add approximately 3 billion more people by the middle of the twenty-first century, primarily in impoverished countries facing water scarcity [1].

Anthropogenic activities can potentially alter urban groundwater's hydrogeological and hydro chemical properties [6]. For instance, Malaysia's population growth has contributed to significant consumption of water resources. While water quality has received some attention, its relationship with water quantity and water system operation has been largely overlooked. Human activities frequently threaten the quantity and quality of water in Malaysian water resources. These activities include direct use of river water, such as irrigation, as well as land-based practices that introduce nutrients and pollutants into their respective catchments while altering runoff patterns. The growing population puts increasing strain on water resources, straining their ability to maintain adequate standards of water quantity and quality [7]. Growing human and livestock populations in Malaysia, a developing country, have put additional strain on land, forest, and water resources, leading to mismanagement and neglect. Forests are being overexploited, land is being misused, and overgrazing is occurring [8].

[9] accentuates that human activities significantly risk river water quality when pollution exceeds the defined limit. Urban operations have been identified as a significant contributor to surface water contamination in Asian countries. To maintain healthier freshwater ecosystems while also pursuing national development goals, it is critical to assess sustainable human population capacities within river watersheds. Small-scale human activities have far-reaching consequences for an entire drainage basin. Furthermore, significant variations in climate and water flow exist at the local, regional, and global levels, resulting in a variety of effects of human activities on land and water quality and quantity. These effects are affected by factors such as geology, biology, physiographic characteristics, and climate, as well as their specific location within a watershed. These natural characteristics, on the other hand, exert significant control over human activities, which in turn can modify or influence the natural composition of water [10]. The primary goal of this study is to investigate the relationship between population changes in specific parishes of Louisiana and their impact on the quantity and quality of water resources using advanced modeling techniques, specifically Geographic Information System (GIS). Specifically, the paper's objectives are as follows: 1) To assess the influence of climate change on water resources in Louisiana; 2) To evaluate the impact of land use and climate change on Louisiana's water resources; 3) To investigate the potential relationship between Louisiana's population and sea level rise; 4) To predict the current and future climate change effects and vulnerability of Louisiana's water utilities and facilities; and 5) to analyze the patterns in climatic indices that may impact Louisiana's hydrology.

2. Problem Statement

Estuaries, which are considered highly productive ecosystems, are under severe threat and are listed as endangered on a global scale. Pollution, eutrophication, urbanisation, changes in land use and reclamation, overfishing, and unsustainable exploitation of natural resources all pose ongoing threats to estuaries' long-term viability. Human populations face a critical challenge today in effectively managing coastal ecosystem utilisation while ensuring the preservation and availability of their visual, cultural, and ecological resources for future generations to enjoy [11]. According to [12], among the contiguous 48 states, Louisiana has a significant proportion of vegetated wetlands (25 percent) and tidal wetlands (40 percent). However, the coastal region of Louisiana has the fastest erosion rate of any coastal area in the world. Louisiana loses up to 40 square miles of land each year, an area roughly the size of Washington, D.C. While some of this land loss can be attributed to human activities, a significant portion is due to natural forces such as land subsidence caused by sediment compaction in the Mississippi River Delta and frequent powerful storms that occur every five years.

Urbanisation has resulted in an increase in impervious surfaces such as roads and buildings, which significantly reduce groundwater infiltration. As a result, the availability of areas for groundwater recharge has decreased significantly, resulting in a significant depletion of groundwater resources. This depletion has emerged as a major issue associated with urbanization [13]. Land use is a major contributor to pollution in the landscape. The need for housing, food production, and the development of infrastructure to facilitate transportation all contribute to changes in land use, ultimately promoting urbanization and agricultural activities. The expansion of impermeable surfaces such as parking lots, rooftops, roads, and sidewalks is aided by urbanization. As a result, surface runoff increases, and an additional pathway for pollutants to be transported from the landscape to water bodies is created [14].

Agricultural activities play a significant role in the introduction of fertilizers, pesticides, herbicides, and dairy manures into croplands to meet the human population's growing food demands. Unfortunately, some of these substances end up in nearby bodies of water. The direct and indirect effects of urbanization and agricultural practices contribute to the degradation of water quality, which is a direct result of land use changes [15]. This degradation causes an increase in algal blooms and phytoplankton biomass, as well as changes in water taste and odor, resulting in higher drinking water purification costs [16]. These negative consequences affect both terrestrial and aquatic ecosystems [17]. Uncontrolled discharge of untreated sewage and the presence of polluted urban runoff have caused significant pollution in surface water bodies, rendering them unsuitable for meeting urban regions' freshwater needs [18]. Improper sewage and leachate management and disposal at solid waste landfill sites have also resulted in significant contamination of urban groundwater. As a result, the impact of urbanization on water quality has emerged as a pressing issue that requires immediate attention [13]. Surface waters are susceptible to pollution due to their utilization for wastewater disposal in many countries. The quality of surface water in a particular area is influenced by a combination of natural processes and human activities [19].

The complexity of global water challenges, according to [20], is exacerbated by interconnected stressors such as population growth, rising consumption, demographic shifts, land use changes, urbanization, and climate change. While there is a growing body of literature exploring the general factors influencing Louisiana's water resources, there is a dearth of scholarly research specifically focusing on the impact of population growth on the state's water resources. This study aims to fill this knowledge gap by examining how population changes in Louisiana's select parishes have influenced the quantity and quality of water resources using advanced models, including GIS. The study aims to contribute valuable insights into the relationship between population dynamics and water resource management by filling this research gap.

3. Literature Review

3.1. Population Growth in Louisiana

The rate of population growth in the United States has slowed. The population increased by 7.4% between 2010 and 2020, the slowest rate since the 1930s. Several factors, including declining birth rates, an aging population, and decreased immigration, are all contributing to this historically slow growth [21]. Louisiana, located in the southern United States, is known for its rich history and vibrant culture, which is centered primarily on its largest city, New Orleans. Despite being overshadowed by its larger neighbor, Baton Rouge is the state capital. Over the years, Louisiana has shown consistent growth [22]. Louisiana has a land area of 51,839 square miles, making it the 31st largest state by land mass. The population density, on the other hand, remains low. There are approximately 105 people per square mile of land (40.5 people per square kilometer) (ibid).

Between 2010 and 2021, Louisiana's population increased in six of the eleven years. The greatest annual population growth occurred between 2010 and 2011, at a rate of 0.7%. The most significant decline occurred between 2020 and 2021, resulting in a 0.6% population decrease. Between 2010 and 2021, Louisiana experienced annual growth of 0.2% on average [23]. According to [24], four parishes in Louisiana ranked among the top ten in the country in terms of population decline between 2021 and 2022. Estimates place St. John the Baptist Parish, Terrebonne Parish, Plaquemines Parish, and St. Charles Parish second, third, fourth, and eighth in terms of population loss, respectively. St. John the Baptist Parish lost 5.1% of its population, Terrebonne Parish lost 3.9%, Plaquemines Parish lost 3.3%, and St. Charles Parish lost 2.7% of its population. These figures were based on parishes and counties with populations greater than 20,000. Hurricane Ida, which hit the state's southern region in August 2021, severely impacted all four of these Louisiana parishes [25].

Despite the overall low population density, there are some areas with higher concentrations of residents, mostly around major cities [22]. The southern region of Louisiana experienced the greatest population growth. The Greater New Orleans Area experienced the most significant growth, increasing by 6.9%, followed by the Greater Baton Rouge Area, which increased by 5.9%. Southwest Louisiana, centered around Lake Charles, saw a 5.1% increase in population, while Acadiana saw a 0.6% increase. It's important to note that the census data reflects the situation as of April 2020, before Hurricanes Laura and Delta wreaked havoc in Southwest Louisiana, forcing many residents to relocate [26].

3.2. Water Resources in Louisiana

A sizable proportion of the population in Louisiana, approximately 61%, or 4.4 million people, rely on groundwater as their primary source of drinking water.

Furthermore, a significant number of industrial and rural users, as well as half of the state's irrigation users, rely on groundwater [27]. Groundwater is the primary source of drinking water for roughly half of the state's population [28]. Louisiana is divided into nine primary surface water basins based on topographic characteristics. These basins may contain headwater areas from neighboring states. It is critical to recognize that surface water basins do not always coincide with parish boundaries (ibid). The presence of a saltwater-freshwater interface reduces the availability of groundwater in Louisiana's coastal aquifers. These coastal aquifers, like the Mississippi River Alluvial Aquifer in Northeast Louisiana and Southeast Arkansas, have high salinity levels in the groundwater. This is most likely due to the upward migration of deeper brines, which renders groundwater unfit for use [29].

[11] notes that the Mississippi Delta, which covers 25,000 square kilometers, is North America's largest and most productive coastal ecosystem. However, it has shrunk significantly over the last century as a result of human activities and disruptions to its natural hydrologic system. Levees and other man-made influences have resulted in the loss of approximately 25% of the delta's coastal wetlands. This decline emphasizes the importance of habitat restoration in ensuring the delta's ecological future. The United States Geological Service has been studying the water quality of the Mississippi River in Louisiana since 1905. These studies' findings have been used by federal, state, and local agencies, as well as environmental organizations, to identify pollutants coming from nonpoint sources in river water. Furthermore, the studies look at the potential impact of these contaminants on drinking water sources and aquatic ecosystems in areas that rely on Mississippi River water for coastal restoration [12]. According to [11], To accomplish this, it is critical to understand the delta's original state prior to human intervention, identify the factors causing its decline, and assess the feasibility and desirability of halting further degradation.

3.3. Impact of Population Increase on Water Quantity and Quality

According to [2], domestic use, agriculture, industry, mining, power generation, and forestry practices, all contribute to water quality and quantity degradation. This not only has an impact on the health of the aquatic ecosystem but also makes it difficult to obtain safe drinking water for human consumption. Although water quality and quantity are inextricably linked, they are frequently assessed separately rather than concurrently. Rising population demands for food, housing, and energy place significant strain on water resources, particularly in terms of water quality. Water quality is deteriorating globally, primarily as a result of intensive agricultural practices associated with rapid urbanization [30]. Hydrological monitoring stations typically measure water quantity by recording parameters such as water level, discharge, and velocity. Water quality, on the other hand, is assessed through the collection and analysis of water samples obtained from these monitoring stations on a regular basis. Water quality monitoring results are critical for understanding the spatial and temporal patterns in surface water and groundwater. Important characteristics of aquatic environments can be identified, as well as the positive and negative impacts of human activities on water quality, using local, regional, and global assessments of water quality data. A thorough understanding of water quality is essential for various water assessments [2].

[31] contends that the increasing demand for high-quality water for domestic use and economic activities has resulted in a scarcity of water resources. Precipitation patterns have become unpredictable as a result of climate change. Water quality is critical for human health and has an impact on grain crop quantity and quality because it affects soils, crops, and the environment [32]. Since people are concentrated in small areas, urbanization creates ongoing environmental pressures. This process results in significant changes in land use patterns, extensive withdrawal of surface and groundwater, expansion of built-up areas, solid waste disposal, and sewage discharge. The expansion of urban areas necessitates the removal of vegetation, the conversion of wetlands, and the use of open spaces for construction purposes. These urbanization-related activities add to environmental stress [13].

According to [7], water quality and quantity are inextricably linked, as poor water quality reduces the amount of usable water for specific users and can increase the costs associated with water treatment. Poor water quality has a direct impact on water supply availability, limiting its usability and necessitating additional treatment methods. As a result, it is critical to prioritize water quality preservation in order to ensure a sufficient and economically viable water supply for a diverse range of users. In Louisiana, groundwater systems frequently have elevated bicarbonate levels in comparison to chloride concentrations. This type of water, distinguished by sodium and bicarbonate dominance, is thought to result from carbonate dissolution and subsequent ion exchange, in which sodium replaces calcium in clay minerals. As a result of the modification of groundwater chemistry during interactions with the surrounding rock formations, the specific conductance (SC) of groundwater may be higher, while chloride concentrations may be lower than expected [29].

To achieve sustainable management of freshwater resources, both water quality and quantity must be considered. Water availability is being strained globally as a result of climate change, population growth, and increased agricultural and industrial demands. Simultaneously, pollutants associated with population growth, changes in land cover, and the discharge of irrigation and industrial effluents are threatening water quality. These difficulties highlight the importance of implementing comprehensive measures to ensure the sustainable use and preservation of freshwater resources [33].

4. Methodology

4.1. Data Sources

This study's primary data collection and analysis method was primarily based on online resources. [34] was used to obtain population census data for Louisiana in 1999 and 2020. [35] provided information on the distribution of Louisiana's surface and groundwater resources. Supplementary data from [36] and [37] were also incorporated to enhance the study.

4.2. Methods

A holistic methodological approach was used to explore the possible implications of human activities, and global climate change on the hydrological ecosystems of Louisiana's watershed. The study used a Geographic Information System (GIS)-based approach to visualize Louisiana population census data between 1999 and 2020. Using ArcGIS software, population data from various parishes in Louisiana were combined into an attribute table and linked to a shapefile. To depict the population distribution, two separate maps were created in the symbology tool using the graduated color option, representing the population in Louisiana in 1999 and 2020. An overlay analysis was also applied using ArcGIS to examine the distribution of lakes and rivers in the most and least populated areas in Louisiana. Tables were also used to examine the use of groundwater and surface water in Louisiana parishes with the highest and lowest populations. A bar chart was also created to show the resident population of Louisiana from 1960 to 2020. Finally, a pie chart was used to portray the percentage of impaired water bodies in Louisiana in 2020.

Mapping the Spatial Distribution of Water Quality in Louisiana State

Using the Trophic State Index (TSI), the water quality of Louisiana was computed using Equations (1)-(3) in Google Earth engine using Sentinel 2 imagery. TSI was calculated based on the near-infrared (NIR) and Red bands of Sentinel-2 imagery, which are sensitive to water quality parameters such as chlorophyll-a and suspended matter. Before the sentinel 2 image with a spatial resolution of 10m was used, Rayleigh scattering correction was performed to remove the influence of atmospheric scattering on the measured radiance, allowing for a more accurate estimation of the water-leaving radiance [38]. Water-leaving radiance is essential for deriving various water quality parameters, such as chlorophyll-a concentration, turbidity, and dissolved organic matter. TSI is a numerical scale used to classify the trophic status of water bodies based on their nutrient levels, primarily phosphorus and nitrogen. TSI provides insight into the nutrient enrichment of water bodies, which can indicate eutrophication [39]. High TSI values suggest nutrient-rich conditions, often leading to algal blooms and degraded water quality. This calculation was performed using Google Earth Engine (GEE). The TSI was reclassified into four (4) discrete classes for easier interpretation and analysis as shown in **Table 1**.

$$\mathrm{TSI} = 30.6 + 9.81\log\left(\mathrm{Chlor_a}\right) \tag{1}$$

$$\text{Chlorophyll-a estimation}\left(\mathrm{Chlor_a}\right) = 14.039 + 86.115\left(\mathrm{NDCI}\right) + 194.325\left(\mathrm{NDCI}^2\right) \tag{2}$$

$$\text{Normalized difference Chlorophyll index}\left(\mathrm{NDCI}\right) = \left(\frac{\mathrm{Blue} - \mathrm{Red}}{\mathrm{Blue} + \mathrm{Red}}\right) \tag{3}$$

Where:

The TSI is a numerical scale used to classify the trophic state of a water body based on its nutrient levels, particularly phosphorus and nitrogen. Higher TSI values indicate higher nutrient concentrations, often associated with eutrophic (nutrient-rich) conditions that can lead to algal blooms and degraded water quality. Chlorophyll-a is a pigment found in phytoplankton and algae that is used as a proxy for the number of algae in a water body. The concentration of Chl-a is commonly used to assess the trophic state of a water body, as it reflects the primary productivity and potential for eutrophication. log (Chl-a) is the logarithm of the chlorophyll-a concentration which is used in the equation to account for the non-linear relationship between Chl-a and the trophic state. This transformation helps in scaling the Chl-a values to fit the TSI scale. NDCI (Normalized Difference Chlorophyll Index) is an index used to estimate chlorophyll-a concentration from satellite imagery. It is derived from the reflectance of different spectral bands (typically the red and near-infrared bands) and is sensitive to the presence of chlorophyll-a and other pigments in the water [39]. Blue represents the reflectance in the blue spectral band. In remote sensing, the blue band is typically sensitive to water properties, including turbidity and chlorophyll concentration. Red represents the reflectance in the red spectral band. The red band is also sensitive to the absorption of light by chlorophyll, making it useful in estimating algal concentrations [38].

Table 1. TSI Classification [39].

Class code	TSI Range	Description
1	TSI < 30	Oligotrophic (low nutrient, high clarity)
2	30 ≤ TSI < 40	mesotrophic (moderate nutrient, moderate clarity)
3	40 ≤ TSI < 50	eutrophic (high nutrient, low clarity)
4	50 ≤ TSI < 60	hypereutrophic (very high nutrient, very low clarity)

5. Results

5.1. Population Growth in Louisiana

Figure 1 and **Figure 2** depict the distribution of Louisiana's total population in 1999 and 2020.

According to the 1999 Louisiana census data, the parishes with the highest populations were New Orleans (461,304), Jefferson (449,913), and East Baton Rouge (394,579), while Cameron (9162) and Tensas (6558) had the lowest populations. Remarkably, these parishes retained their positions with the highest and lowest populations in the 2020 census (**Figure 3**). However, substantial shifts in the recorded data became evident. In comparison to the 1999 census, the populations of Jefferson and Orleans decreased by 9132 and 77,307 residents, respectively, reflecting significant demographic changes. Conversely, East Baton Rouge experienced substantial growth, adding 62,202 people to its population. Similarly, Tensas and Cameron saw declines of 2411 and 3545 people, respectively, underscoring the dynamic nature of Louisiana's population distribution over the years.

Figure 3 illustrates the population of Louisiana's residents spanning the years from 1960 to 2020.

As of 2022, Louisiana's projected population of approximately 4.59 million signifies a slight dip from the preceding year's count of roughly 4.63 million, suggesting a subtle but noteworthy shift in demographic trends. This marginal decline may be influenced by a combination of factors, including fluctuations in birth rates, migration patterns, and economic conditions. In stark contrast, when reflecting on Louisiana's population in 1960, estimated at 3.26 million residents, one observes a remarkable historical growth trajectory over the past six decades, which can be attributed to natural population increase, in-migration, and economic opportunities. These shifting population dynamics underscore the ever-evolving nature of Louisiana's demographic landscape, carrying implications for various aspects of the state's social, economic, and political fabric.

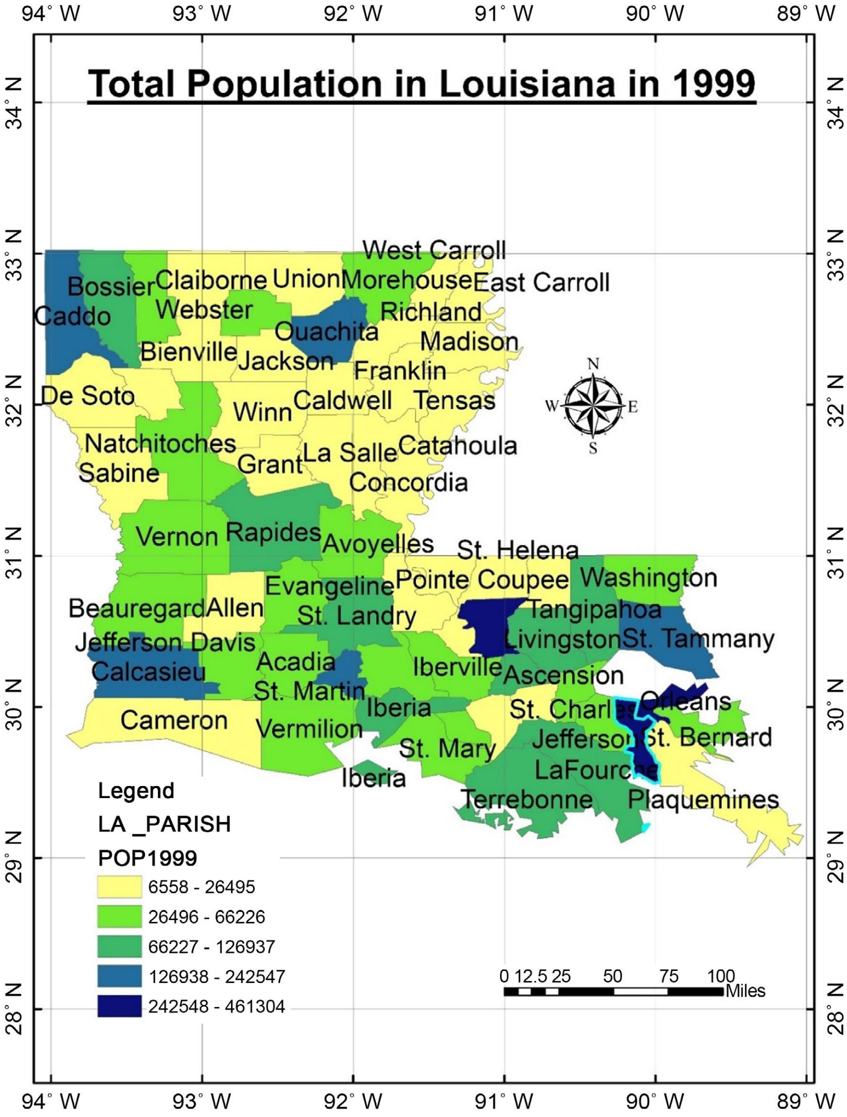


Figure 1. 1999 Population map of Louisiana [40].

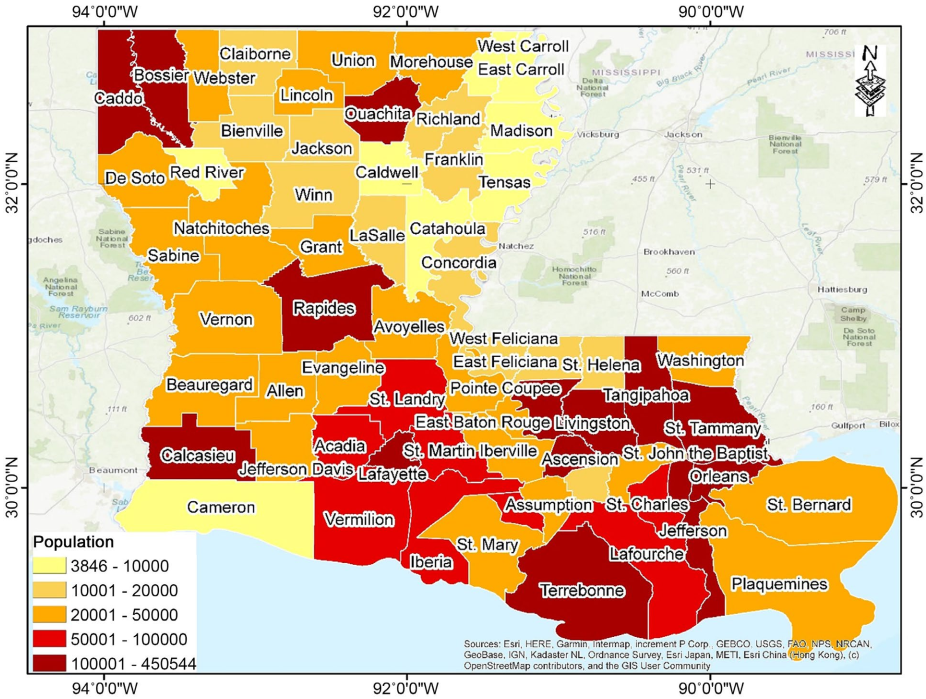


Figure 2. Total population in Louisiana in 2020 [34].

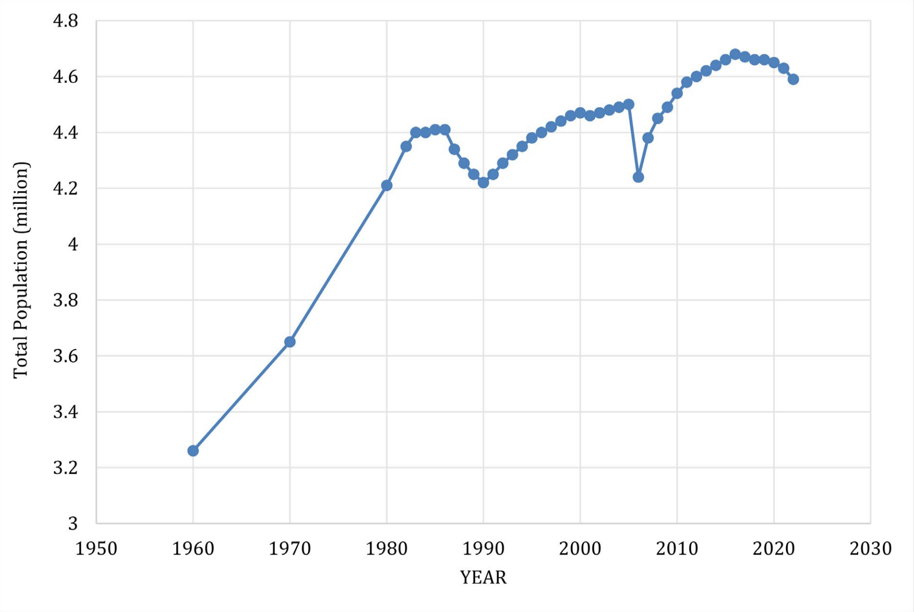


Figure 3. Resident population in Louisiana from 1960 to 2020 [36].

5.2. Distribution of Groundwater and Surface Water Resources among Parishes with the Highest Population in Louisiana in 2015

5.2.1. Distribution of Groundwater and Surface Water Resources in East Baton Rouge in 2015

Table 2 presents the allocation of groundwater and surface water resources in East Baton Rouge in the year 2015.

Table 2. Total groundwater withdrawals in million gallons per day in 2015 in East Baton Rouge [35].

Use Category	Total
Public supply	72.2089
Industry	72.5853
Power generation	7.3953
Rural development	0.2388
Livestock	0.0725
General irrigation	0.3883
Aquaculture	0.2249

Table 3 displays the total daily surface water withdrawals in East Baton Rouge for the year 2015, measured in millions of gallons.

Table 3. Total surface water withdrawals in million gallons per day in 2015 in East Baton Rouge.

Use category	Total
Industry	16.6797
Livestock	0.0055

Source: [35].

5.2.2. Distribution of Groundwater and Surface Water Resources in Jefferson in 2015

Table 4 provides data on the overall daily groundwater withdrawals in Jefferson for the year 2015, quantified in millions of gallons.

Table 4. Total groundwater withdrawals in million gallons per day in 2015 in Jefferson.

Use category	Total
Industry	1.625
Power generation	4.79
Rural domestic	0.033
General irrigation	0.0184

Source: [35].

Table 5 showcases the complete daily surface water withdrawals in Jefferson for the year 2015, measured in millions of gallons.

Table 5. Total surface water withdrawals in million gallons per day in 2015 in Jefferson.

Use category	Total
Public supply	61.7922
Industry	4.8254
Power generation	739.9842
Livestock irrigation	0.0372
General irrigation	0.0038

Source: [35].

5.2.3. Distribution of Groundwater and Surface Water Resources in New Orleans in 2015

Table 6 exhibits the aggregate daily groundwater withdrawals in New Orleans for the year 2015, quantified in millions of gallons.

Table 6. Total groundwater withdrawals in million gallons per day in 2015 in New Orleans.

Use category	Total
Industry	0.8904
Power generation	10.87
Rural domestic	0.2068
Livestock	0.0011
General irrigation	0.048

Source: [35].

Table 7 displays the overall daily surface water withdrawals in New Orleans for the year 2015, measured in millions of gallons.

Table 7. Total surface water withdrawals in million gallons per day in 2015 in New Orleans.

Use category	Total
Public supply	140.8988
Power generation	261.1933
Livestock	0.0094

Source: [35].

5.3. Distribution of Groundwater and Surface Water Resources among Parishes with the Lowest Population in Louisiana in 2015

5.3.1. Distribution of Groundwater and Surface Water Resources in Cameron in 2015

Table 8 outlines the total daily groundwater extractions in Cameron for the year 2015, quantified in millions of gallons.

Table 8. Total groundwater withdrawals in million gallons per day in 2015 in Cameron.

Use category	Total
Public supply	1.5031
Industry	0.5196
Rural domestic	0.0737
Livestock	0.042
Rice irrigation	9.0157
Aquaculture	0.1785

Source: [35].

Table 9 illustrates the complete daily surface water withdrawals in Cameron for the year 2015, measured in millions of gallons.

Table 9. Total surface water withdrawals in million gallons per day in 2015 in Cameron.

Category use	Total
Industry	8.7455
Livestock	0.126
Rice irrigation	13.5236
General irrigation	0.1589
Aquaculture	0.739

Source: [35].

5.3.2. Distribution of Groundwater and Surface Water Resources in Tensas in 2015

Table 10 presents the overall daily groundwater withdrawals in Tensas for the year 2015, quantified in millions of gallons.

Table 10. Total groundwater withdrawals in million gallons per day in 2015 in Tensas.

Use category	Total
Public supply	0.5401
Rural domestic	0.0186
Livestock	0.0025
Rice irrigation	5.1226
General irrigation	15.7404
Aquaculture	1.0414

Source: [35].

Table 11 demonstrates the aggregate daily surface water withdrawals in Tensas for the year 2015, measured in millions of gallons.

Table 11. Total surface water withdrawals in million gallons per day in Tensas in 2015.

Use category	Total
Public supply	0.6153
Livestock	0.0076
Rice irrigation	1.7075
General irrigation	1.7489

Source: [35].

Notably, the parishes with the highest population also recorded the highest water withdrawals from both groundwater and surface water sources in 2015. Conversely, parishes with lower populations had comparatively lower water withdrawal rates. For instance, according to **Table 2**, East Baton Rouge, a highly populated parish, withdrew 72.21 mgal/d of groundwater for public supply and 72.58 mgal/d for industrial use in 2015. Although the quantity of water withdrawn from surface water sources was relatively lower than groundwater, the overall water withdrawal volume can be attributed to the higher population in the parish. Similarly, Orleans and Jefferson, both densely populated parishes, had significant water withdrawals. Table 5 and Table 7 show that Jefferson withdrew 739.98 mgal/day from aquifers for power generation, while Orleans withdrew 261 mgal/day for the same purpose to meet the needs of their populations. On the contrary, it is evident that parishes with lower populations had lower water withdrawal volumes for economic activities. Tables 8-11 demonstrate that the water withdrawals in such parishes did not exceed 16 mgal/d, in contrast to the parishes with higher populations. Overall, the categories with the highest water withdrawals were public supply, industry, and power generation.

5.4. Assessing the Quality of Water in Louisiana

Figure 4 illustrates the proportion of impaired water bodies in Louisiana in the year 2022.

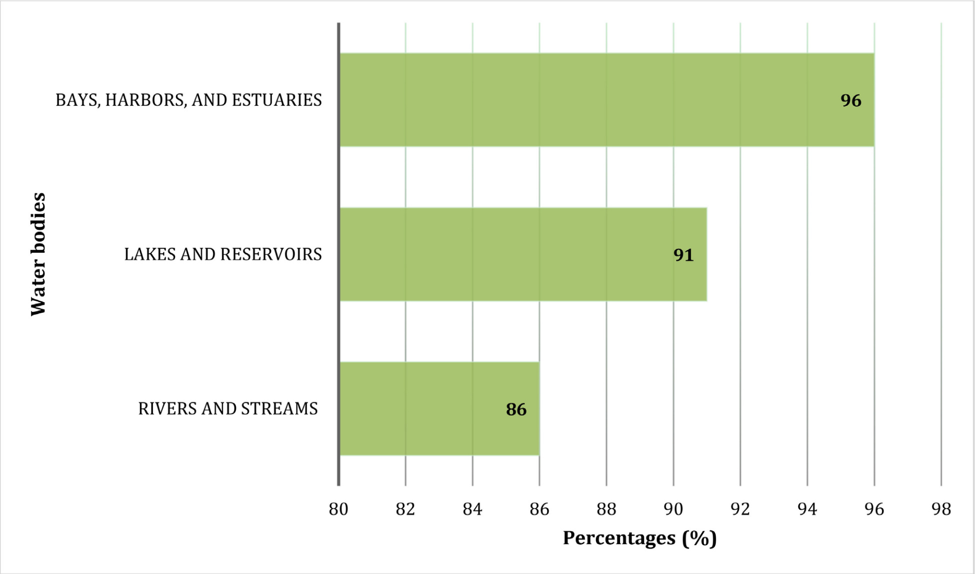


Figure 4. Percentage of impaired water bodies in Louisiana in 2022 [37].

The chart presented provides a comprehensive view of the distribution of polluted and low-quality water bodies in Louisiana. It highlights a significant disparity in the sources of impairment across different types of water bodies. Rivers and streams emerge as particularly vulnerable, with 86% of the polluted rivers in the state falling into this category. This finding underscores the importance of addressing pollution sources that impact on these freshwater systems, given their critical ecological and societal roles. On the other hand, the chart reveals that lakes and reservoirs, as well as bays, harbors, and estuaries, make up the majority of impaired water bodies in Louisiana as shown in Figure 4 and Figure 5, accounting for 91% and 96%, respectively. This suggests that efforts to improve water quality should prioritize these specific types of water bodies, likely requiring targeted interventions and regulatory measures [37].

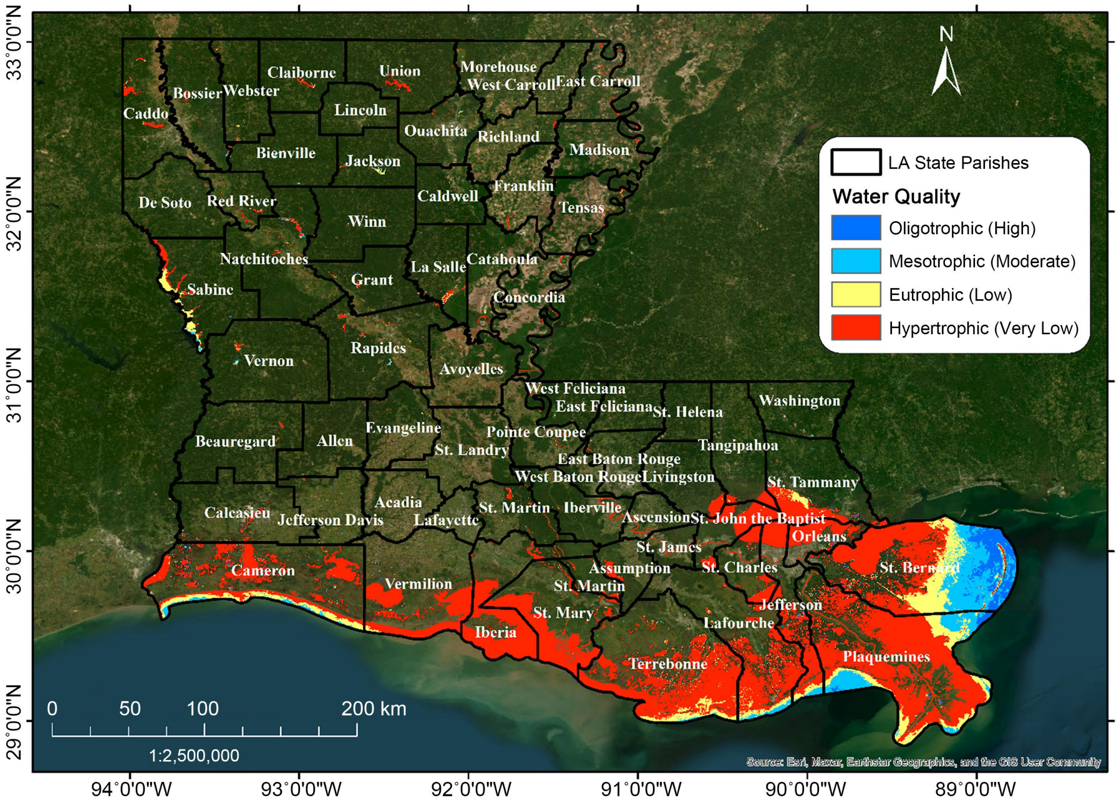
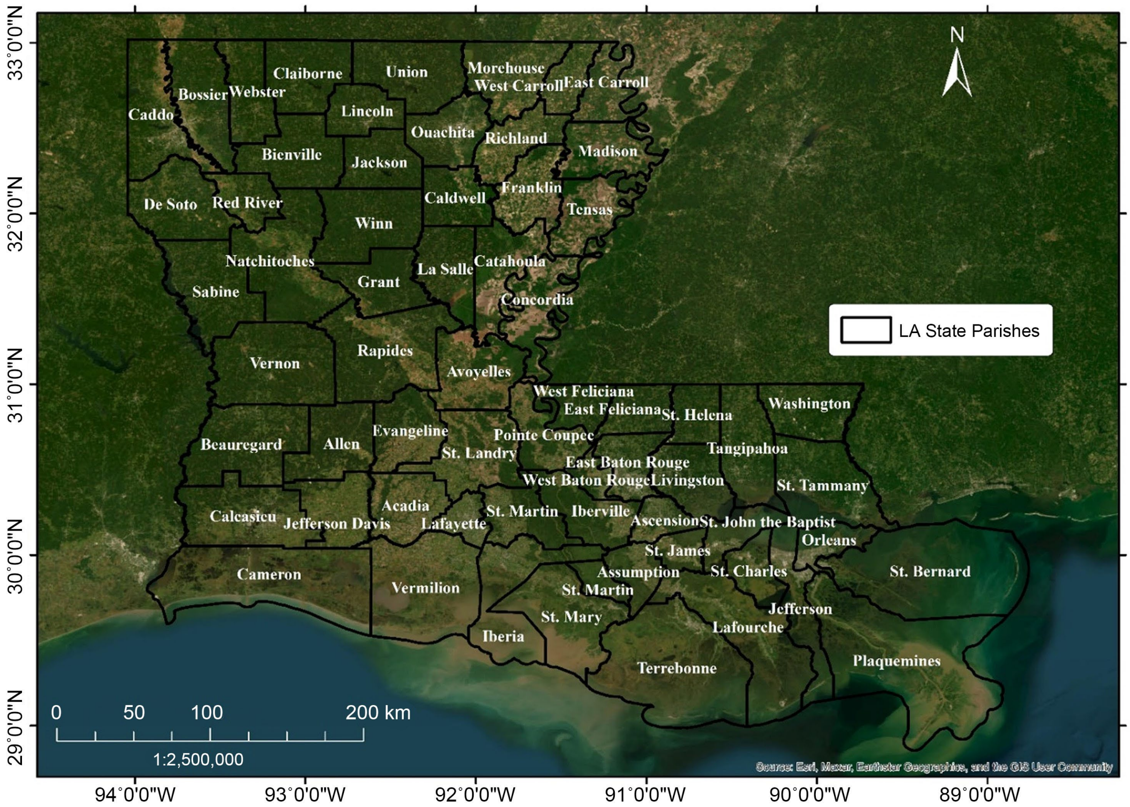


Figure 5. Spatial Distribution of water quality in Louisiana 2022.

5.5. Spatial Distribution of Water Quality in Louisiana State

The spatial distribution of water quality across Louisiana as shown in **Figure 5** with its corresponding true colour composite, as shown in **Figure 6**, reveals significant disparities in the condition of water bodies, with distinct patterns of impairment observed in different regions and types of water bodies.

According to Parker [37], a considerable portion of Louisiana's water bodies are classified as impaired, with rivers and streams, lakes and reservoirs, and bays, harbors, and estuaries being the most affected (**Figure 5**). Rivers and streams in Louisiana are particularly vulnerable to pollution, with 86% of these water bodies categorized as impaired (**Figure 5**). This high percentage indicates that a significant portion of the state's freshwater systems suffer from poor water quality (eutrophic and hypereutrophic). The primary sources of impairment in rivers and streams are likely agricultural runoff, industrial discharges, and urbanization, all of which contribute to the degradation of water quality [37]. The ecological and societal importance of rivers and streams makes their impairment especially concerning, as these water bodies support diverse ecosystems, provide drinking water, and are crucial for recreational activities [41].



Source: Esri, Maxar, Earthstar Geographics, and the GIS User Community

Figure 6. Sentinel 2A Water masked areas in Louisiana (True color composite).

Lakes and reservoirs in Louisiana also face substantial water quality challenges, with 91% of these water bodies classified as impaired (**Figure 5**). The primary issues in these water bodies include eutrophication, characterized by high nutrient levels leading to algal blooms, decreased oxygen levels, and reduced water clarity. The eutrophic and hypereutrophic conditions found in many lakes and reservoirs result from nutrient runoff from agricultural lands, sewage discharge, and stormwater runoff from urban areas. These conditions not only degrade the aesthetic and recreational value of lakes and reservoirs but also threaten aquatic life by creating hypoxic conditions, where oxygen levels are too low to support most forms of life.

Bays, harbors, and estuaries represent some of the most impaired water bodies in Louisiana, with 96% classified as impaired. These coastal water bodies are critical for both the environment and the economy, serving as habitats for marine life, supporting commercial and recreational fishing, and providing areas for shipping and transportation. The high level of impairment in these areas is often due to nutrient loading, industrial pollution, and sedimentation, which can lead to the deterioration of water quality and the loss of biodiversity. The hypereutrophic conditions prevalent in many of these areas indicate extremely high nutrient levels, which promote excessive algal growth and lead to severe oxygen depletion, further exacerbating the decline in water quality.

The spatial distribution of impaired water bodies in Louisiana (**Figure 5**) shows that most of the water quality issues are concentrated in areas with high levels of agricultural activity, industrial operations, and urban development. Regions with extensive agricultural lands, such as those in the northern and central parts of the state, are more likely to experience eutrophic and hypereutrophic conditions (Very low quality) due to the heavy use of fertilizers and pesticides [42]. Industrial areas, particularly along the Mississippi River and in coastal regions, contribute to the impairment of water bodies through the discharge of pollutants and the alteration of natural hydrological processes [42].

The prevalence of impaired water bodies in Louisiana highlights the need for targeted interventions and regulatory measures to address the sources of pollution and improve water quality. Efforts should focus on reducing nutrient runoff from agricultural lands, regulating industrial discharges, and implementing best management practices in urban areas to minimize stormwater pollution. Additionally, restoration projects aimed at improving the ecological health of impaired water bodies, such as wetland restoration and the creation of buffer zones, can help mitigate the impacts of pollution and enhance water quality.

Figure 7 illustrates a map that displays how lakes and rivers are distributed in both the highly populated and the sparsely populated areas of Louisiana. **Figure 8** visualizes the fluctuations in sea levels occurring in Louisiana between 1980 and 2020.

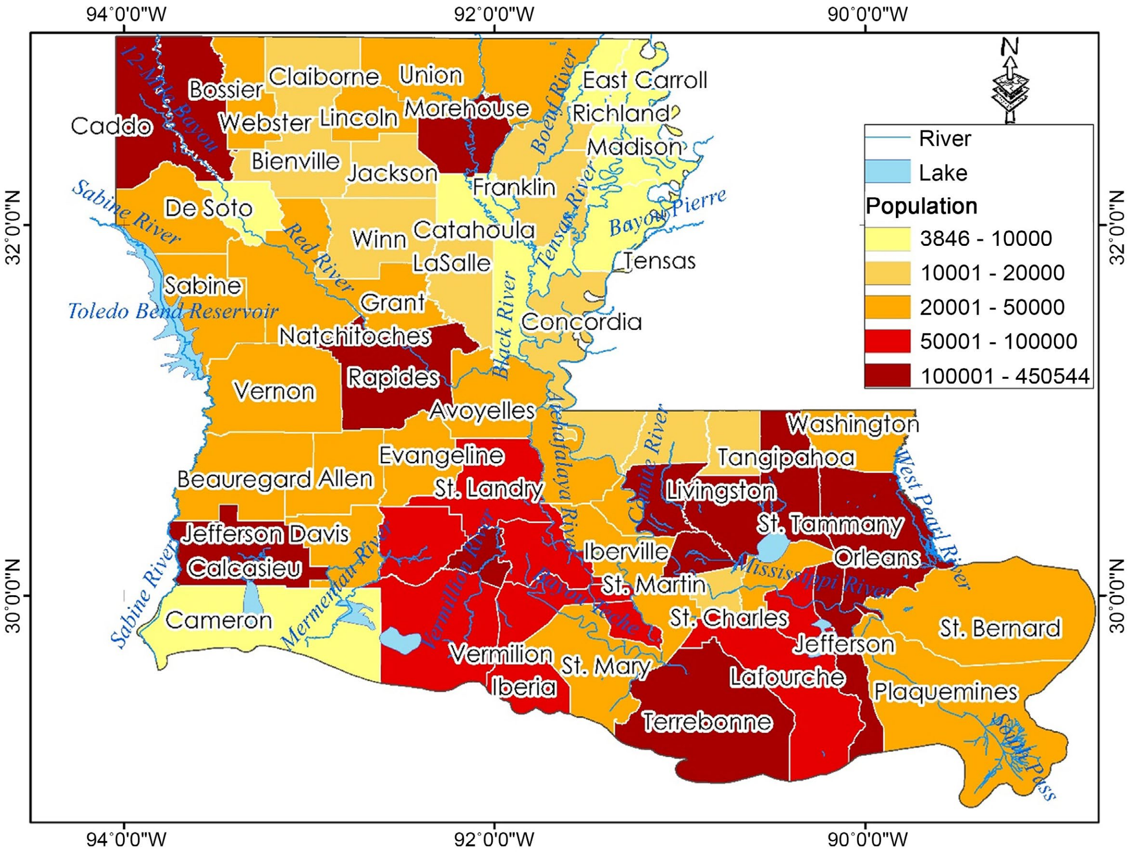


Figure 7. A map showing the distribution of lakes and rivers in the most and least populated areas in Louisiana.

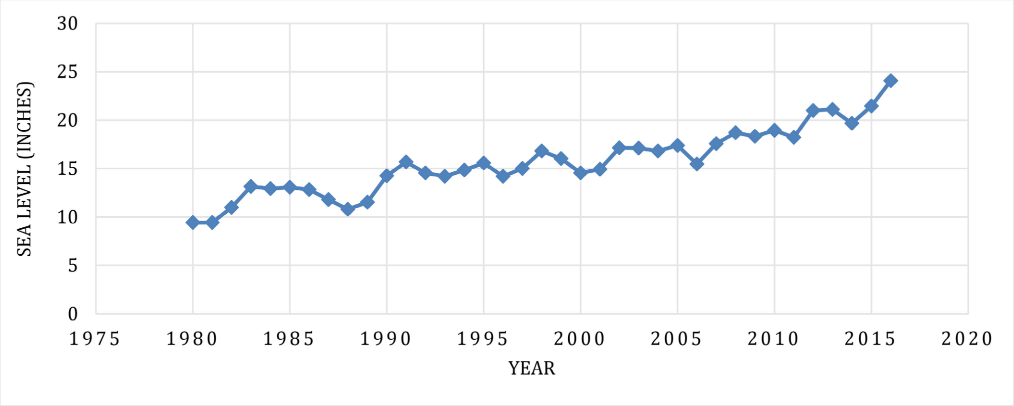


Figure 8. Sea level changes in Louisiana from 1980 to 2020 [43].

6. Discussion

6.1. The Distribution of Lakes and Rivers in the Most and Least Populated Areas in Louisiana

The majority of parishes in Louisiana are intersected by lakes and rivers. According to **Figure 7**, parishes like St. Tammany, Vermilion, Sabine, Jefferson, and Cameron are characterized by the presence of lakes. On the other hand, major rivers such as the Red River flow through parishes like Rapides, Grant, De Soto, Natchitoches, and the Sabine River passes through Cameron, Beauregard, Vernon, Sabine, De Soto, and Caddo. Parishes in Louisiana with numerous bodies of water, such as lakes, rivers, and wetlands such as Cameron, Vermilion, Sabine, Orleans, and Plaquemines, among others, may exhibit varying population trends. In general, areas with abundant water resources may entice residents due to the scenic beauty, recreational opportunities, and economic opportunities such as fishing and tourism. In such cases, these parishes may see an increased population as people flock to the benefits of water-rich environments. Parishes with abundant water bodies, on the other hand, may face challenges such as flooding and environmental concerns, which could stifle population growth or cause shifts in residency. Due to inadequate infrastructure and increased vulnerability to natural disasters, these areas may experience lower population levels in some cases.

The disparity in water consumption between Louisiana's densely populated and sparsely populated parishes has serious implications for the state's water resources, both in terms of quality and quantity. The significant water consumption in parishes with high population densities indicates that existing water sources are under increased strain. This increased usage can put a strain on local water systems, potentially affecting both water availability and quality in the region. Also, there is a greater risk of depleting groundwater reserves and putting pressure on surface water bodies in parishes with high population densities and significant water withdrawals. By 2020, more than 90% of Louisiana's assessed water bodies had failed to meet the required water quality standards for wildlife habitat and recreational activities. This troubling statistic places Louisiana among the worst-affected states in terms of water quality. Furthermore, the state has the most polluted estuaries in the country. While industrial pollution has contributed to the degradation of water quality, as shown in **Figure 5**, agricultural pollution, characterized by an abundance of nutrients, is the primary culprit. This nutrient-rich pollutant helps to form harmful algal blooms on the water's surface, depleting oxygen levels and endangering the health of fish and wildlife [37].

Irrigated agriculture in Louisiana is centered on the cultivation of soybeans, rice, aquaculture (specifically crawfish), corn, and cotton. The southwest region is primarily focused on rice and aquaculture, whereas the northeastern region, within the Mississippi Valley, is heavily focused on soybeans and mixed crops. The proximity of brackish surface water near the coast, made possible by canals, channels, and estuaries, makes accessing surface water for irrigation purposes difficult [12]. According to a recent study conducted by the Environmental Integrity Project, a nonpartisan watchdog group, the primary threat to Louisiana's waterways is the runoff of land-based pollutants from farms and home sewage systems. This finding emphasizes the significant impact of agricultural and domestic activities on the state's water quality [37]. Furthermore, the coastal aquifers in the area have a saltwater-freshwater interface, limiting groundwater availability. The Mississippi River Alluvial Aquifer in northeastern Louisiana (and Southeast Arkansas) contains zones of high-salinity groundwater, which is likely influenced by the upward migration of deeper brines [12].

Additionally, extensive groundwater extraction for public supply, industry, and power generation can deplete aquifers, potentially reducing water availability and compromising water quality. Furthermore, population density can amplify pollution risks because greater volumes of wastewater and pollutants are discharged into water bodies, increasing the potential for contamination and degradation. Low-population parishes such as Tensas and Cameron, on the other hand, consume less water, which can have a positive impact on water resources. Reduced demand for water in these areas can help to relieve pressure on aquifers and surface water sources. As the burden on natural water systems is reduced, this can contribute to the preservation of water quality and the sustainable management of water resources.

6.2. Spatial Patterns and Implications of Water Quality in Louisiana

The spatial distribution of water resources and the quality of water bodies in Louisiana reveals significant disparities driven by population density and human activities. In heavily populated parishes like East Baton Rouge, Orleans, and Jefferson, water withdrawals are substantial, primarily for public supply, industrial use, and power generation. These high levels of water consumption correlate with the demands of urban populations and industrial activities. In contrast, less populated parishes like Cameron and Tensas show markedly lower water withdrawals, primarily for agricultural purposes. The data highlights the pressing need for sustainable water management practices as population growth in urban areas continues to increase water demand. Moreover, the widespread impairment of water bodies across the state, with rivers, streams, lakes, reservoirs, and coastal waters facing significant challenges from pollution, underscores the urgent need for comprehensive water quality improvement strategies. The primary sources of impairment, including agricultural runoff, industrial discharges, and urban stormwater, contribute to conditions such as eutrophication and hyper eutrophication, which threaten aquatic ecosystems and human health [10].

Addressing these water quality and resource distribution challenges requires a multi-faceted approach. Key measures include promoting water conservation in urban areas, implementing best management practices to reduce pollution, and restoring ecosystems to improve water quality [44]. Stricter regulations on agricultural runoff and industrial discharges, along with targeted interventions in urban stormwater management, are crucial for mitigating the sources of pollution that impair water bodies. Additionally, ongoing monitoring and public awareness campaigns are essential to track progress and ensure that water quality issues are addressed effectively. By adopting these strategies, Louisiana can work towards the sustainable management of its water resources, ensuring the health of its aquatic ecosystems and the well-being of its communities for the future.

6.3. Population Growth and Seal Level Rise

Louisiana, a state prone to hurricanes and storm surges, is feeling the effects of rising water levels. According to a recent report published by various federal agencies in the United States, sea levels along the Gulf Coast near Lafitte are expected to rise by 1.5 to 2 feet by the year 2050. Furthermore, by the year 2100, these levels could rise by another 2 feet [45]. Louisiana's coastal regions have lost approximately 5000 km^2 of wetlands over the last century. This loss raises concerns about the resilience and preservation of the remaining wetlands, especially given that the area is experiencing some of the highest rates of relative sea-level rise (RSLR) in the world [46]. Louisiana has been losing approximately 25 square miles of land per year over the last few decades. If temperatures continue to rise, sea levels could rise by one to three feet over the next century, according to projections. Because rising sea levels have similar effects to sinking land, climate change is expected to hasten coastal erosion and land loss. While federal, state, and local governments are working to reduce land loss in Louisiana, these efforts may face new challenges if sea levels rise faster in the future [47] [48].

Although population growth does not cause sea level rise directly, it does have indirect consequences. The growing population places additional strain on coastal areas, necessitating the construction of infrastructure such as levees, dams, and canals. These man-made structures disrupt natural water flow, impede sediment deposition, and limit wetlands' ability to provide natural protection from storms and rising sea levels. Furthermore, population growth increases the demand for resources and energy consumption, resulting in higher greenhouse gas emissions. These emissions contribute to global climate change, which causes sea level rise. The primary cause of this rise is thought to be land subsidence, which has serious consequences. New Orleans is the most prominent urban area in the United States facing the risks associated with sea level rise. It is currently experiencing one of the fastest rates of sea-level rise in the world. Louisiana is losing approximately 25 square miles of land per decade due to ongoing sea level rise, posing a threat to its coastal marshes [43].

The rise in sea levels not only causes increased storm surges during hurricanes but also increases the risk of flooding even on days when there are no extreme weather events, especially when tides are high. According to a recent study published in Nature Climate Change, flood-related losses in the United States total approximately $32 billion per year, and this cost is expected to rise further in vulnerable coastal communities like ours [49].

The rapid expansion of Louisiana's population presents significant challenges to its water resources, potentially resulting in water scarcity and declining water quality. To tackle these concerns, the state should adopt a diverse range of sustainable approaches. Implementing educational initiatives targeting residents, schools, and businesses can heighten awareness about water conservation practices, including fixing leaks, using water-efficient appliances, and adopting responsible water usage habits.

Furthermore, integrating smart water management techniques that leverage technology and data, such as deploying smart irrigation systems based on weather conditions or detecting leaks in real time, can prove highly effective. Encouraging rainwater harvesting at both individual and community levels can supplement water supplies during dry periods and reduce dependence on conventional sources. Moreover, investing in advanced wastewater treatment facilities to purify water for safe reuse in non-potable applications, like irrigation and industrial processes, can help alleviate the strain on freshwater resources. Through the implementation of these sustainable measures, Louisiana can effectively and prudently manage its water resources, preserving water quality and establishing a resilient and sustainable water future amid population growth and evolving environmental circumstances. The success of these initiatives heavily relies on the collaborative efforts of government agencies, private sectors, communities, and individuals working together.

7. Conclusions

In conclusion, the significant water consumption in highly populated parishes and the minimal water consumption in low-population parishes in Louisiana indicate that water consumption has a significant impact on the quality and quantity of water in the state. The disparities in water consumption patterns between densely populated and sparsely populated parishes highlight the significant influence of water usage on water quality and quantity in Louisiana. Moreover, addressing spatial disparities in water quality, as revealed by Sentinel-2 imagery and Trophic State Index (TSI) analysis, is crucial. The study showed that hypereutrophic conditions (Very Low quality) were prevalent in lakes, reservoirs, and coastal waters, particularly in densely populated areas. Implementing pollution control measures, supported by stricter environmental regulations, monitoring, and enforcement, can mitigate these effects. Recognizing the interdependence between human activities and water quality and quantity along hydrologic pathways is critical for effective resource management. Policies alone are insufficient to address degradation issues. Instead, a comprehensive strategy encompassing policy implementation, education, scientific understanding, careful planning, and law enforcement is required [10]. For instance, in the agricultural sector, organizations such as the Natural Resource Conservation Service work with farmers to encourage the use of best management practices. These practices, such as planting cover crops to prevent soil erosion and improve soil health, as well as erecting fences to keep livestock out of waterways, aim to mitigate the negative effects of agricultural activities on water quality [37].

To address the pressing issue of impaired water quality and the diminishing water quantity in Louisiana due to population growth, a multi-pronged policy approach is imperative. First, investing in comprehensive water management strategies that prioritize conservation and efficient use of water resources is essential. Implementing strict water-use regulations, promoting water-efficient technologies, and incentivizing water conservation practices among residents and industries can help mitigate the strain on available water supplies. Additionally, focusing on pollution control measures through stricter environmental regulations, monitoring, and enforcement can alleviate water quality degradation. Supporting sustainable urban planning that incorporates green infrastructure and reduces impervious surfaces can help manage stormwater runoff and prevent contamination. Furthermore, fostering public awareness and education campaigns on responsible water use and pollution prevention can empower communities to actively participate in preserving water resources. Collaboration among government agencies, stakeholders, and communities is crucial for the success of these policies to ensure a sustainable and resilient water future for Louisiana.

To address the issues posed by sea level rise in Louisiana, it is critical to employ holistic approaches that include coastal restoration, sustainable land-use practices, and greenhouse gas emission reductions. The preservation and rehabilitation of coastal wetlands, the implementation of effective flood management measures, and the promotion of sustainable development are all critical components of mitigating the negative effects of sea level rise on Louisiana's coastal areas. The state can work to protect its vulnerable coastal regions by implementing comprehensive strategies.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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