

# Analyzing Climate Change Impacts on Louisiana's Water Resources Using GIS Techniques

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## Abstract

Louisiana possesses a bountiful groundwater reserve, an invaluable and noteworthy asset. Despite extensive literature on climate change implications in Louisiana, there is limited academic research focused on its effects on the state's water resources. Therefore, this study addresses that gap by using GIS to spatially analyze water usage trends from 1960 to 2014, to examine climate-induced consequences and determine the susceptibility of water utilities' functions and facilities. This study utilized various online sources to gather data on water withdrawals, temperature trends, and climate impacts in Louisiana. Water usage data from the Lower Mississippi Gulf-Water Science Centre and temperature trends from Meteoblue covering 2023 were also analyzed to assess the state's water resource challenges. The water withdrawal data was linked to a shapefile within ArcMap, using graduated color symbology to visualize regional variations in water usage. This method highlighted significant water withdrawals across Louisiana from 1960 to 2014, clearly illustrating the differences between regions. Based on the data sources, the results show that groundwater levels in Louisiana have steadily declined over time. For instance, water levels in the Jasper Aquifer in St. Tammany dropped from approximately 125 feet to 50 feet, while levels in the Sparta Aquifer in Lincoln fell from 30 feet to -25 feet. Similarly, the Chicot Aquifer in Acadia experienced a decline from -25 feet to -50 feet. These reductions indicate a concerning trend of groundwater depletion, exacerbated by high temperatures and current drought conditions affecting roughly 73% of the state. To ensure sustainable water management in Louisiana, investing in water storage, transfer infrastructure,

and conservation practices are needed to protect surface and groundwater sources. More so, the state's Reservoir Priority and Development Program (RPDP), which includes the construction of reservoirs, is a key initiative that can address water scarcity, improve water supply, and enhance long-term water security.

## Keywords

Aquifer, Climate Change, Drought, Groundwater, Surface Water

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## 1. Introduction

Louisiana is often perceived as being a water-rich state but ironically faces significant threats, including declining water levels, saltwater intrusion, and external pressures from neighboring states to access its water resources. Louisiana's water resources are increasingly vulnerable to climate change, necessitating immediate action essential to ensure sustainable water management. Key measures include protecting both surface and groundwater sources, investing in water storage infrastructure, and expanding policies that address the growing impacts of climate change on water resources. However, despite the increasing efforts in research on climate change implications in Louisiana, there remains a gap in research focused specifically on how climate change affects the state's water resources. Essentially, this study aims to fill that gap by using Geographic Information Systems (GIS) to analyze water usage trends from 1960 to 2014, providing critical insights into the present and future climate-induced consequences for Louisiana's water utilities and infrastructure. Geographic Information System (GIS), which offers powerful tools for understanding, analyzing, and managing spatial data is one of the key applications used in sustainability and the analysis of land cover data [1]. To assess the impact of climate change on a geographical location, Geographic Information Systems (GIS) modeling plays a critical role in understanding these climate change impacts by allowing for the spatial analysis of environmental data over time. For instance, GIS enables the mapping of flood-prone areas, allowing for the development of risk management plans and the implementation of measures to minimize the impact of potential flooding [1]. In Louisiana, where approximately 11% of the total surface area is composed of water bodies, GIS modeling plays a pivotal role in understanding the impacts of climate change on these critical resources, enabling detailed analysis of changes in water levels, usage patterns, and environmental stressors over time. With extensive marshes, islands, native prairies, and diverse coastal and interior forests and savannas, Louisiana's waters support an enormous variety of fish and wildlife habitat [2]. According to the [3], a substantial amount of water supply is derived from groundwater stored in aquifers. Water usage is projected to increase by up to 30 percent by 2050, owing to overpopulation, economic growth, and shifts in consumption habits [4]. Increased water

consumption has resulted in some areas of the country drawing groundwater from aquifers quicker than they can be replenished ordinarily. Droughts in some locations have expedited this downturn. Droughts may become more likely as temperatures rise due to climate change, particularly in the West [3]. Similarly, [5] explains that Louisiana has a water shortage issue. This challenge is embedded in aquifers buried beneath Louisiana's marshlands, where groundwater that roughly sixty-five percent of the state's residents consume is rapidly depleting.

According to the [6], climate change is already causing severe significant issues to water and sanitation systems worldwide. Conflicts surrounding water usage and political turmoil are on the increase. Climate change is exacerbating the problem by fueling floods and droughts, changing rainfall patterns, and accelerating rising sea levels [4]. Based on data from the U.S. Geological Survey, the decline in groundwater levels in Louisiana and its surrounding areas is occurring at a pace faster than that of most other regions in the country [5].

Climate Change encompasses a broader range of alterations that occur in conjunction with the rise in the earth's surface temperature. These changes involve modifications in weather conditions, ecosystems, and oceanic environments, including the melting of ice and snow. Climate change is also responsible for variations in precipitation patterns, which means that numerous areas that presently receive adequate rainfall for drinking, energy, and agricultural purposes may experience a scarcity of water in the future [7]. Studies by [8] state that changes in the hydrological cycle as a result of climate change are predicted to increase over the next generation. Thus, the impact of climate change on water resources is inevitable since river hydrology is closely linked to climatic variables and in recent times, the warming trend has led to changes in the hydrologic cycle. According to [9], changes in climatic indices, including precipitation and temperature have a direct impact on streamflow which indirectly contributes to the modifications in the flow regime. There are numerous studies discussing the possible causes of climate change on water resources. For example, research by [10], indicates that changes in climate indices, such as the intensity of extreme events affect water availability and quality.

Given the inseparable relationship between climate change and the accessibility of enough water to fulfill our needs, it is essential for Louisiana to adopt measures that safeguard both our planet and its water resources [7]. As climate change impacts increasingly stress natural resources, water quality requires additional attention, as long-term strategies for preserving environmental services and public health fail to gain traction [11]. These extreme and recurrent climate events faced by the State have shown the need for an adaptive and comprehensive strategic plan to inform and assist the cities in identifying potential alternatives, in the face of climate change. This paper aims to utilize innovative models, such as GIS to identify current and future climate impacts. By this, this research will focus on assessing the temperature trend and water levels in Louisiana project future climate-related changes. Research findings will contribute to the sustainable

management of water resources by (a) developing a comprehensive water resource strategic plan; (b) training students in water resource assessment research, (c) invariably aiding in the achievement of the UNs' Sustainable Development Goal (SDG) 6, and (d) equipping researchers and students in the 1890 institutions, as well as other countries to adapt to the models developed in order to aid in minimizing the rate of water crisis faced in the world.

## 2. Problem Statement

Water-related issues have persisted throughout history, and the current combination of rising population growth and climate change exacerbates the risks to water resources, posing a serious threat [12]. That is, climate change is poised to shift precipitation patterns and increase glacial melt, thereby altering water supplies and intensifying floods and droughts in different parts of the world. Changes in precipitation spatially and temporally are difficult to avoid as climate change intensifies and this contributes to the increase in susceptibility to droughts and water shortages [13]. According to [14], the International Panel on Climate Change (IPCC) estimates that the global average surface temperature will increase from 1.8°C, to 4.0°C, while precipitation will increase from 5% to 20% between 1990 and 2100. The world's water resources are facing formidable threats, and according to [4], more than a billion people who live in water-scarce regions and many more could experience water scarcity by 2025. For several years, the development of water resources for consumption and industrial purposes in Louisiana took place without much consideration for the possibility of water shortage [15]. According to [15], Louisiana's water resources (*i.e.*, both above and below ground) will continue to be inextricably linked to the State's economy, culture, wildlife and aquatic resources. More so, the state of Louisiana is currently facing several water-related challenges, including declining water levels and saltwater intrusion due to excessive groundwater extraction [16].

For instance, [17] highlights that the Louisiana coastline is undergoing subsidence into the Gulf of Mexico, resulting in a loss of land equivalent to about one football field per hour (equivalent to 18 square miles per year). However, amidst this sinking area, two river deltas are expanding. The Atchafalaya River and its diversion channel, the Wax Lake Outlet, are gaining fresh land at a rate of roughly one football field every 11 and 8 hours, respectively (which equates to 1.5 and 2 square miles per year). Also, the issues associated with land loss in Louisiana have far-reaching consequences that affect a diverse range of stakeholders, from the oyster industry, farmers, and the economy, to the livelihoods of residents residing near the mouth of the Mississippi River. The coastal environmental systems paint a vivid picture of the challenges we faced by the State, and the state is at a crucial juncture in history where it will experience the impact of a retreating coastline [18]. [15] argues that if the unregulated development of surface water and groundwater resources persists, it is anticipated that the effects will become more widespread and severe, with potential repercussions on economic growth prospects in

the state. Although there has been an increase in the amount of literature discussing the overall effects of climate change in Louisiana, there are very few scholarly works that focus specifically on the impact of climate change on water resources in the state. Agreeably, researchers have focused more on the state's land loss, rising sea levels, and coastal erosion which are key issues contributing to the environmental and economic strain. However, there are still limited studies on how Geographic Information Systems (GIS) can be used as an effective tool to analyze the specific impact of climate change on water resources, especially in Louisiana. That is, in a state where water is a critical resource, GIS has the potential to provide valuable insights into the spatial and temporal patterns of water availability and usage in the context of changing climate conditions. This gap, therefore, reinforces the need for more comprehensive research using GIS to address water resource challenges in relation to climate change. By this, the research hypothesis posits that applying GIS modeling has the potential to uncover significant spatial and temporal variations in Louisiana's water resource availability, driven by climate change factors such as rising temperatures, drought and increased groundwater, surface water withdrawals. This research study also emphasizes on the need for an adaptive and comprehensive strategic plan comprising of modelling and predicting future consequences. This is to inform and assist the cities in identifying potential alternatives, in the face of climate change. Hence, this study aims to bridge the current gap in knowledge on the subject by utilizing advanced models, including GIS, to identify both current and future climate-related impacts and evaluate the vulnerability of water utilities' operations and infrastructure.

### **3. Literature Review**

#### **3.1. Water Resources and the Issue of Drought in Louisiana**

Louisiana serves as the destination for the world's largest capacity inland waterway system, which is The Mississippi River and its Tributaries. It is also the point where this navigation artery connects with the Gulf Intracoastal Waterway system. Groundwater, containing fresh and abundant water of excellent quality, underlies a significant portion of the state [19]. Water flows from Louisiana to the Gulf of Mexico at a rate of approximately 577 million acre-feet per year (MAFY) or 188 trillion gallons per year, with approximately 80% (459 MAFY) originating upstream of the state. More than 98% of the 459 MAFY enters Louisiana via the Mississippi River system (over 448 MAFY) (including Mississippi, Red, Ouachita, and Tensas rivers and their tributaries) [19]. According to [20], around 15% of Louisiana's total water supply comes from groundwater, with half of that being used for public supply and most of the rest for irrigation and aquaculture. Louisiana shares its borders with Texas, Arkansas, Mississippi, and the Gulf of Mexico. The neighboring states all have shared water basins and groundwater with Louisiana. The state has several smaller rivers, primarily along the coast, that flow directly into the Gulf of Mexico [15]. Louisiana has an abundance of surface water, which can be attributed to two geographic factors. Firstly, its location at the end

of the Mississippi River watershed contributes to its water resources. Secondly, its location in the humid southeastern region of the United States also plays a role in its water availability [15].

Louisiana is primarily located within the Mississippi River basin, which spans approximately 1,245,000 square miles and encompasses all or parts of 31 states. The state receives 50 to 65 inches of rain per year on average [15]. At present, the region that is most severely impacted by the drought is situated in southwestern Louisiana, where an extreme drought is currently ongoing. The drought's extent and severity are rapidly spreading eastward towards southeastern Louisiana and Mississippi along the Mississippi River and have now been classified as a severe drought area [21]. The Mississippi River's current water level is at its lowest point in ten years, primarily due to a dearth of rainfall upstream of Louisiana. The Mississippi River's watershed encompasses all or a portion of thirty-two states and two Canadian provinces [22]. In recent weeks, the southern region has faced dry weather conditions, which are expected to worsen with rising temperatures. Between November and February, Louisiana encountered its second-driest four-month period since 1895, with less than 10 inches of rainfall measured across the state [15].

### 3.2. Impact of Climate Change on Water Resources

It is undeniable that climate change is the most significant environmental issue that the world faces in the 21<sup>st</sup> century due to its extensive effects on human society. Human actions lead to a substantial increase in the emission of significant quantities of greenhouse gases (GHGs), such as carbon dioxide (CO<sub>2</sub>), into the atmosphere [23]. [24] reported that the global surface temperature has increased by 0.74 °C in the past century. This rise in temperature has affected the hydrological cycle and is expected to increase the occurrence and intensity of extreme climate events such as floods and droughts [25] [26]. As global temperatures continue to rise, the hydrologic cycle is intensified as more water evaporates into the atmosphere. This, in turn, is expected to lead to more frequent and intense precipitation events, such as heavy rain showers and storms, in the years ahead [27].

Similarly, [28] explains that climate change is already causing significant impacts on water availability for people worldwide, resulting in more severe floods and droughts. One of the key drivers of this issue is the rise in global temperatures. Climate change affects the water cycle by altering the timing, location, and amount of precipitation. It also results in more frequent and intense extreme weather events. The warming climate accelerates the evaporation of water, leading to increased atmospheric water vapor and more intense and frequent heavy rainfall in the future [28]. [29] notes that certain elements in the air, such as water vapor, carbon dioxide, methane, and ozone, act as a sort of insulating layer around the planet. These are known as greenhouse gases and make up less than 1% of the atmosphere. Despite their small quantity, they have a significant impact by preventing heat energy from escaping into space, creating what's called

the “greenhouse effect”. This effect is responsible for maintaining Earth’s average surface temperature about 30°C warmer than it would be without it [29].

Recent research has been utilizing statistics to analyze long-term data series in order to predict the impact of possible climate changes [29]. [30] conducted an analysis of fifty years of historical data in the American River basin to gain insights into winter storms that cause flooding. His findings suggested that the risk of flooding in the American River is significant. Meanwhile, [4] developed a methodology to evaluate the connection between climate variability and changes in hydrologic time series in the southwest United States. They examined six hydrologic time-series from the Mojave River Basin in California and discovered that climate variability exists in all the data types, and partially overlaps with known climate cycles like the Pacific Decadal Oscillation and the El Niño–Southern Oscillation [29].

According to a study by the National Oceanic and Atmospheric Administration (NOAA) and the World Weather Attribution (WWA) group, scientists modeled the probability of Louisiana’s historic rainfall and assessed how those odds have shifted over the past century as human activity has altered the climate. The study found that climate change has raised the probability of the event by a minimum of 40%, and it could even have doubled the likelihood of its occurrence [31]. According to scientists who are knowledgeable about the latest UN climate science report, climate change presents a dire threat to south Louisiana in the next 50 years. This threat includes causing human suffering, requiring migration to the north, and disrupting both the state’s economy and infrastructure [32].

## 4. Methodology

### 4.1. Study Area—Louisiana

Louisiana has been blessed with a copious amount of groundwater, which serves as a dependable resource. This resource is consistently restored by an annual rainfall of approximately 56 inches [33]. About 61% of the state’s population, which equates to 4.4 million individuals, rely on groundwater as their main source of drinking water. Moreover, a considerable number of industrial and rural users, as well as half of the state’s irrigation users, depend on groundwater [34]. Groundwater accounts for 15% of Louisiana’s total water supply, accounting for roughly half of the public supply and the majority of irrigation and aquaculture. The state has thirteen primary and secondary aquifer systems that are used as groundwater supply sources [19]. Groundwater is the primary source of drinking water for approximately half of Louisiana’s population [35]. The Chicot, Mississippi River Alluvial, Sparta, and Southern Hills (which includes the Jasper Equivalent) aquifer systems are the most heavily used in the state. However, with the exception of the Mississippi River Alluvial aquifer, all of these aquifer systems have seen a decline in groundwater levels in recent decades [19] (**Figure 1**).

Louisiana is divided into nine primary surface water basins based on topographic



**Figure 1.** Louisiana lakes, rivers and water resources [19].

features. These basins may contain headwater areas from upstream states. It should be noted that surface water basins do not always coincide with parish boundaries [19]. Around 50% of Louisiana's significant agencies are involved in safeguarding or managing the state's water resources. These agencies include Agriculture and Forestry, Culture, Recreation and Tourism, Economic Development, Environmental Quality, Health and Hospitals, Natural Resources, Public Service Commission, Transportation and Development, and Wildlife and Fisheries. Besides, various regional and local governmental organizations, such as levee districts, water management districts, municipalities, and police juries, are actively engaged in developing Louisiana's water resources [36].

#### 4.2. Data Sources

This study drew from a range of online resources to collect and analyze relevant information. Data on water withdrawals in Louisiana was sourced from [37], offering detailed insights into groundwater and surface water usage across different regions. This information is crucial for understanding how water is being extracted for agricultural, industrial, and residential purposes. Temperature data for

Louisiana was gathered from sources such as [38] and [39], which provided temperature trends over time. These trends are important because they influence evaporation rates, water demand, and overall water availability. Rising temperatures can increase the strain on water resources, making this data key for evaluating water management strategies. Additionally, various reports and publications supplemented the study: [40] offered insights into climate-related issues, [22] and [41] contributed geological and environmental data. [15] provided studies specific to Louisiana's environment and [42] supplied broader climate trend analyses and data. By incorporating multiple data sources, the study took a comprehensive approach to understanding Louisiana's water resource challenges.

### 4.3. Methods

The methods section is particularly important as it explains how the data was processed, analyzed, and presented. Geographic Information Systems (GIS) are powerful tools for spatial analysis, enabling researchers to visualize, interpret, and understand patterns across different geographic regions. In this study, GIS was used to spatially analyze water usage trends in Louisiana from 1960 to 2014. This period was chosen to provide a comprehensive view of Louisiana's water usage trends over more than five decades. Thus, the chosen time frame of 1960 to 2014 allowed for a long-term assessment of water usage patterns and climate trends. By spanning more than 50 years, the study could capture both short-term fluctuations and long-term trends. This temporal scope also allowed the researchers to see how events such as droughts, industrial growth, or policy changes impacted water resources over time.

The attribute table within ArcGIS stored water withdrawal data that was linked to a shapefile, which contains geographical features (such as state boundaries or water bodies). The linking of these two datasets allowed for visual representation on maps. The graduated color symbology tool was employed to distinguish areas based on water withdrawal amounts. This approach involves coloring regions on a map with different shades (typically from light to dark) based on the quantity of water withdrawn. For example, areas with high water withdrawals might be shaded darker, while areas with lower withdrawals would be lighter. This visual distinction made it easier to understand water consumption patterns across the state and identify regions with higher or lower water usage. Three distinct maps were generated using the GIS data, each reflecting different aspects of water withdrawals. These maps served as a visual tool to compare changes in water use across regions and over time. This is crucial for identifying trends, such as increasing or decreasing water withdrawals, and for making data-driven decisions regarding water management.

To complement the GIS analysis, tables were used to track changes in temperature and groundwater levels. This enabled the study to make connections between temperature fluctuations (likely influenced by climate change) and groundwater depletion. For example, higher temperatures may lead to increased water

demand and evaporation, putting stress on groundwater reserves. Groundwater levels are particularly important because they serve as an indicator of water availability. Over time, excessive withdrawal of groundwater can lead to depletion, making it harder for regions to meet water demands. By analyzing groundwater levels, the study could assess the sustainability of current water usage practices in Louisiana.

GIS technology is especially valuable for this type of study because it allows for spatial analysis—that is, it helps to see how different geographic regions are affected differently by water withdrawals, climate changes, and other factors. In the case of Louisiana, where water use patterns can vary greatly between coastal regions, agricultural areas, and urban centers, GIS was crucial for breaking down and analyzing these variations visually. The combination of GIS-based mapping, temperature analysis, and groundwater level assessments provided a multi-faceted approach to understanding water usage in Louisiana. By integrating data from a variety of credible sources and using sophisticated analysis tools, the study was able to offer a comprehensive overview of how Louisiana's water resources have been used and how they may be affected by ongoing climate changes.

## 5. Results

### 5.1. Temperature Changes in Louisiana

According to the State Climate Summaries (SCS), Louisiana's climate is characterized by relatively short and mild winters, hot summers, and year-round precipitation. The Gulf of Mexico helps moderate the climate in the southern portion of the state, while temperatures and precipitation are more variable in the north [43]. Additionally, Louisiana is noted for recording extreme temperatures that range from a record high of 114°F at Plain Dealing (August 10, 1936) to a record low of -16°F at Minden (February 13, 1899). Temperatures in Louisiana have risen by 0.5°F since the beginning of the 20<sup>th</sup> century, less than a third of the warming for the contiguous United States, but the warmest consecutive 5-year interval was the most recent, 2016-2020 [43]. Temperatures during the 20<sup>th</sup> century were also highest in the first half of the century, followed by a substantial cooling of almost 2°F from the 1950s to the 1970s. Temperatures have risen since that cool period by more than 2°F, such that the first 21 years of this century have been about as warm as or warmer than early 20<sup>th</sup>-century levels, with 17 of the 21 years since 2000 being above average [43]. Notably, temperature changes in Louisiana show distinct seasonal variations, with a trend toward increasing extremes. Summers are characterized by intense heat, with average high temperatures frequently exceeding 30 degrees Celsius, especially in July and August. Winters are milder, though cold spells occasionally bring temperatures below freezing, particularly in January and February. Over time, there has been a gradual rise in overall temperatures, contributing to more frequent heatwaves. This warming trend is consistent with broader climate change patterns, which are expected to exacerbate extreme temperatures, particularly during the hottest months of the year. For instance, in a

high-emissions scenario, Louisiana could see average temperatures rise more than 10 degrees Fahrenheit by 2100 (compared to 1901-1960 average) which can easily take a toll on humans and the systems that are depended on [40].

### 5.1.1. Average Annual Temperatures in Central and North Louisiana

The data in the tables below represent the standard or average temperatures for the highest and lowest values that occur each year, as determined by the US National Centers for Environmental Information using weather data collected between 1991 and 2020. **Table 1** and **Table 2** shows average yearly temperature for Central and North Louisiana respectively.

**Table 1.** Central Louisiana-Average yearly temperature [39].

Place	High (degree Celsius)	Low (degree Celsius)
Alexandria	25	14
Leesville	26	13
Natchitoches	26	14
Winnfield	25	12

**Table 2.** North Louisiana-Average yearly temperature [39].

Place	High (degree Celsius)	Low (degree Celsius)
Lake Providence	23	13
Monroe	25	12
Ruston	25	12
Shreveport	25	13

According to data from **Table 1** and **Table 2**, central and north Louisiana have experienced high temperatures reaching 20 degrees Celsius or higher, with no recorded temperatures below 10 degrees Celsius. Specifically, between 1991 and 2020, the highest temperature recorded in central Louisiana's Natchitoches and Leesville was 26 degrees Celsius, as shown in **Table 1**. On the other hand, the lowest temperatures (12 degrees Celsius) were recorded in north Louisiana's Monroe and Ruston (**Table 2**), as well as Winnfield in central Louisiana (**Table 1**).

### 5.1.2. Historical Temperature Data for Louisiana (2006-2013)

**Table 3** displays the average temperatures in Louisiana from 2006 to 2013. In July, the highest mean daily maximum temperature is recorded at 33 degrees Celsius, making it one of the hottest months with a maximum temperature of 38 degrees Celsius on extremely hot days. Conversely, January shows the lowest mean daily minimum temperature at -3 degrees Celsius, and the lowest temperature on cold days at -13 degrees Celsius. Remarkably, on hot days, temperatures above 20 degrees Celsius were observed in ten out of the twelve months, with six of those months experiencing temperatures of 30 degrees Celsius or higher, which indicates

extreme heat conditions.

### 5.1.3. The Daily Maximum and Minimum Temperatures Recorded in Louisiana

**Table 4** reveals that the number of days with temperatures surpassing 30 degrees Celsius exceeds the count of days with temperatures lower than  $-10$  degrees Celsius across the months. Specifically, July and August are the two months with

**Table 3.** Average temperatures in Louisiana [38].

Month	Mean daily maximum (degrees Celsius)	Hot days	Mean daily minimum (degrees Celsius)	Cold days
January	4	15	-5	-16
February	7	18	-3	-13
March	13	24	2	-9
April	20	28	7	-3
May	20	32	12	2
June	30	35	17	8
July	33	38	19	12
August	32	38	18	10
September	27	35	13	2
October	21	30	8	-3
November	13	23	2	-8
December	6	16	-3	14

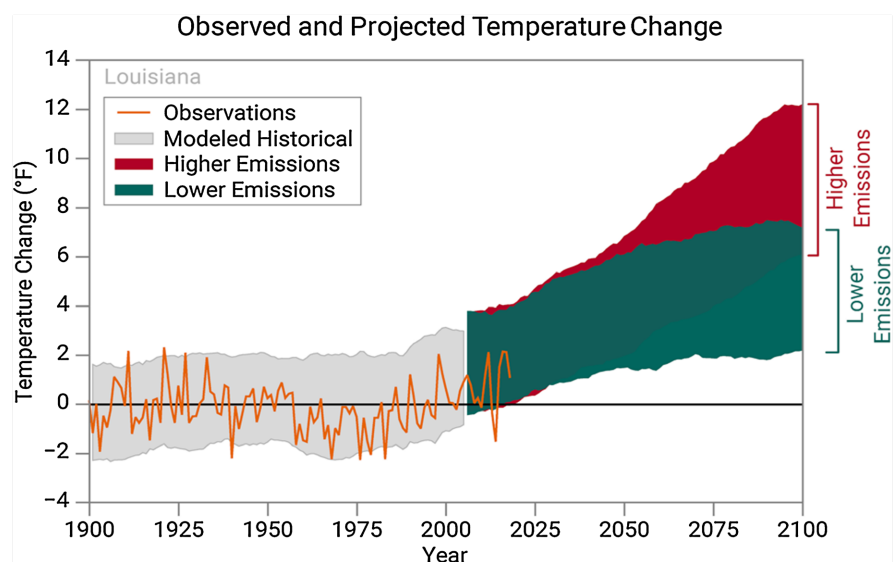
**Table 4.** Daily Maximum and Minimum temperatures in Louisiana [38].

Month	Maximum temp (>30 degrees Celsius)	Minimum temp (<-10 degrees Celsius)
January	0	0.5
February	0	0.2
March	0	0
April	0	0
May	0.1	0
June	1.3	0
July	7.6	0
August	6.8	0
September	1	0
October	0	0
November	0	0
December	0	0.2

the highest number of days with temperatures over 30 degrees Celsius, totaling 7.6 and 6.8 days respectively. Notably, in nine out of the twelve months, temperatures never dropped below  $-10$  degrees Celsius.

#### 5.1.4. Observed and Projected Temperature Change in Louisiana

From **Figure 2** below, it is evident that the observed and projected temperature change in Louisiana keep fluctuating. Temperature has been increasing and decreasing over the years. Historically, Louisiana has experienced a fairly stable temperature in the past. It is projected that higher emissions will keep increasing in many years to come. The climate crisis is already a part of Louisiana residents' daily lives, especially when it comes to issues like hurricanes, flooding, and sea level rise. Louisiana has the highest vulnerability to flooding of any state in the United States. Floods in the state are expected to become more frequent and intense as the climate continues to change. Climate change is expected to cause rising sea levels in the Gulf of Mexico and along the Louisiana coast. Storms in the region have also become more frequent and severe. Coastal Louisiana is threatened by both relative sea level rise and land subsidence. This double vulnerability implies that flooding will take place at higher altitudes and at a quicker pace, worsening the state's flood risk [40].



**Figure 2.** Observed and Projected temperature change in Louisiana [40].

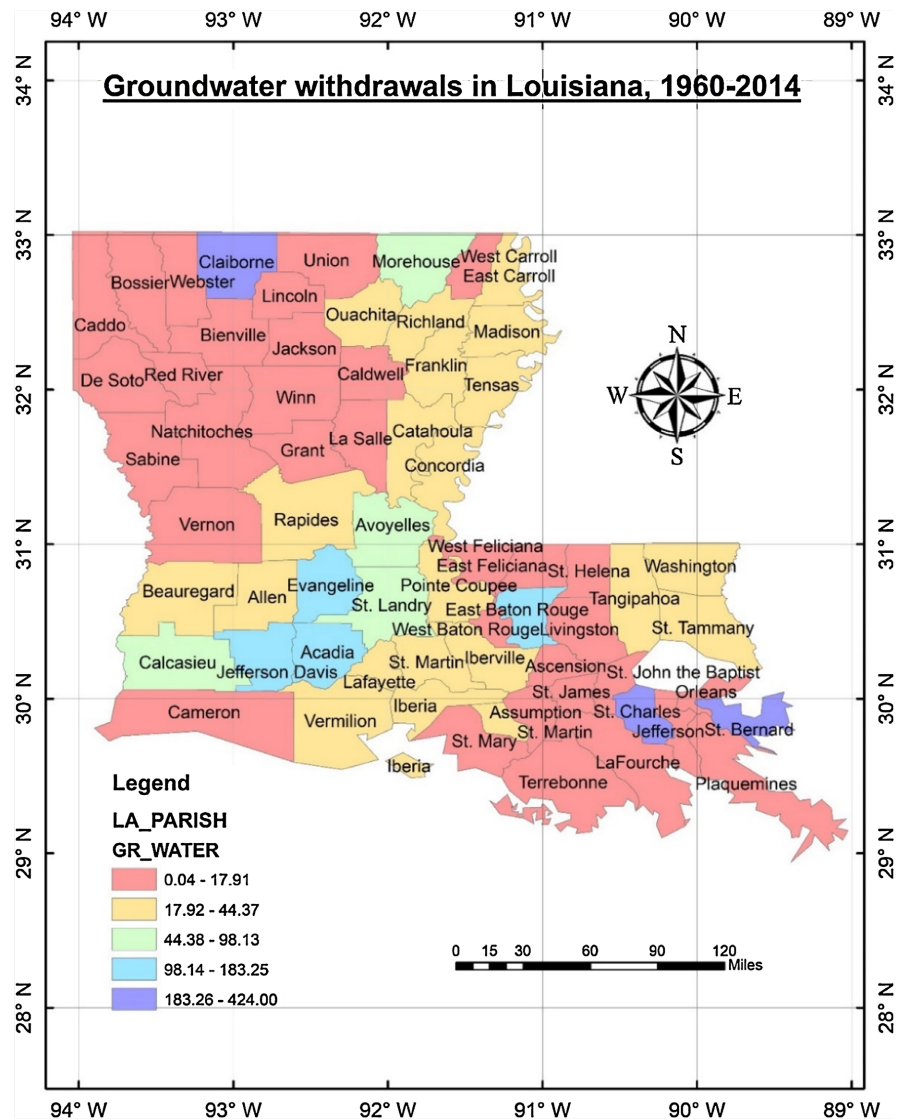
## 5.2. Groundwater, Surface Water and Total Water Withdrawals in Louisiana between 1960 and 2014

Groundwater is a valuable resource both in the United States and throughout the world which supplies many of the hydrologic needs of people [44]. Particularly in the United States, groundwater is the source of drinking water for about half the total population and nearly all the rural population, and it provides over 50 billion gallons per day for agricultural needs. Groundwater depletion, a term often defined as long-term water-level declines caused by sustained groundwater

pumping, is a key issue associated with groundwater use [44]. In Louisiana for instance, water is essential for various purposes, such as drinking, irrigation, livestock operations, aquaculture, industrial facility operations, and cooling for power generation facilities [16]. However, excessive groundwater withdrawals have resulted in several negative consequences, including aquifer depletion, land subsidence, reduced water quality, and ecological impacts on nearby surface water bodies and wetlands. Even though water removed from the ground is constantly replaced in Louisiana, this stresses aquifers and areas of concern which gives the state a pause for examination of how to conserve water for sustainable consumption [45].

**5.2.1. Groundwater Withdrawals in Louisiana, 1960-2014**

With reference to **Figure 3**, the highest groundwater withdrawal was observed in St. Charles, St. Bernard in the southeastern part of Louisiana and Webster in the

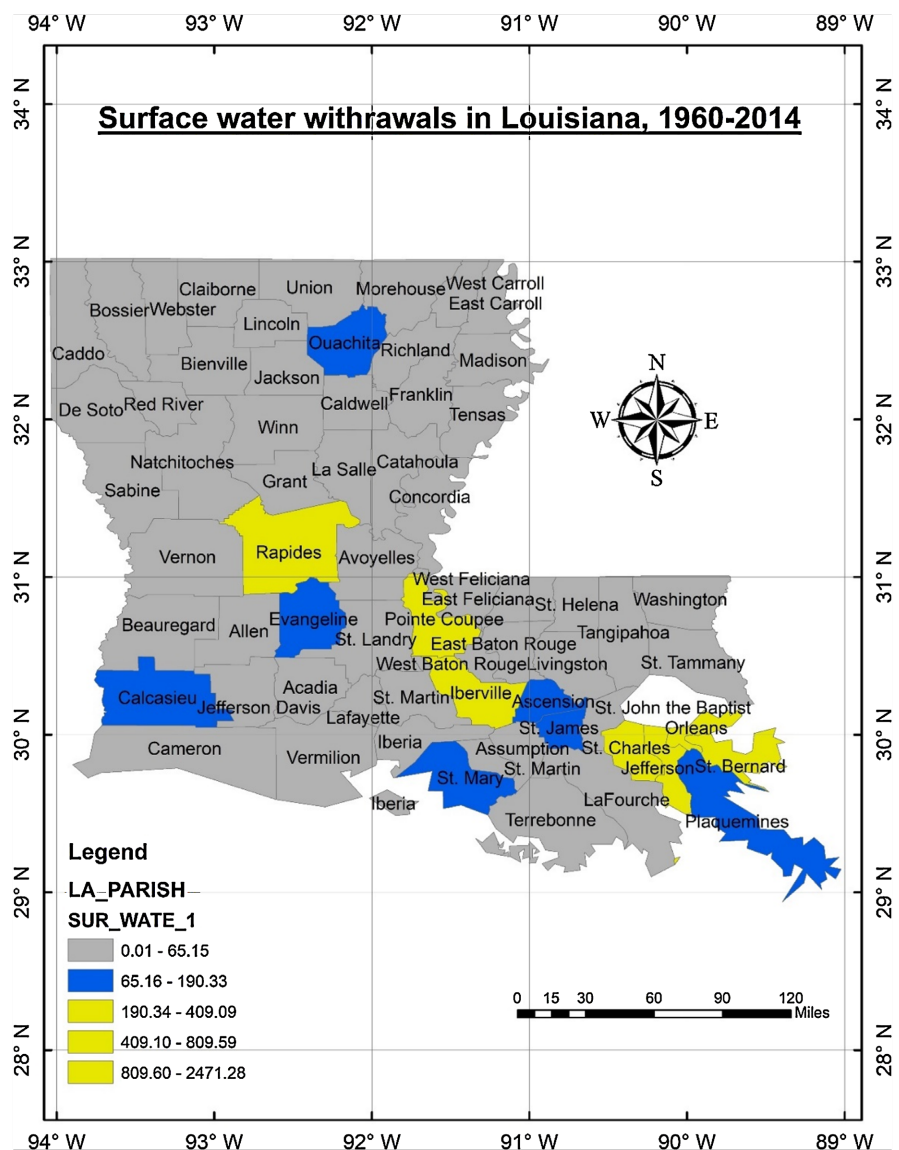


**Figure 3.** Groundwater withdrawals in Louisiana, 1960-2014.

north. These regions that experienced the highest groundwater withdrawals likely reflect a combination of industrial, agricultural, and population pressures in those areas [16]. For instance, southeastern Louisiana, including parishes like St. Charles and St. Bernard, is home to significant industrial activity, including petrochemical plants and refineries that require large amounts of water for operations. On the other hand, groundwater was least withdrawn in parishes such as Vernon, Grant, La Salle, Cameron, Winn, Caddo, Catahoula, Concordia, among others which is attributed to these regions having less industrial activity or smaller populations, leading to less demand for groundwater resources.

### 5.2.2. Surface Water Withdrawals in Louisiana, 1960-2014

With reference to **Figure 4**, Rapides, Pointe Coupee, Iberville, Orleans and St. Charles, located in the southeastern part of Louisiana recorded the highest

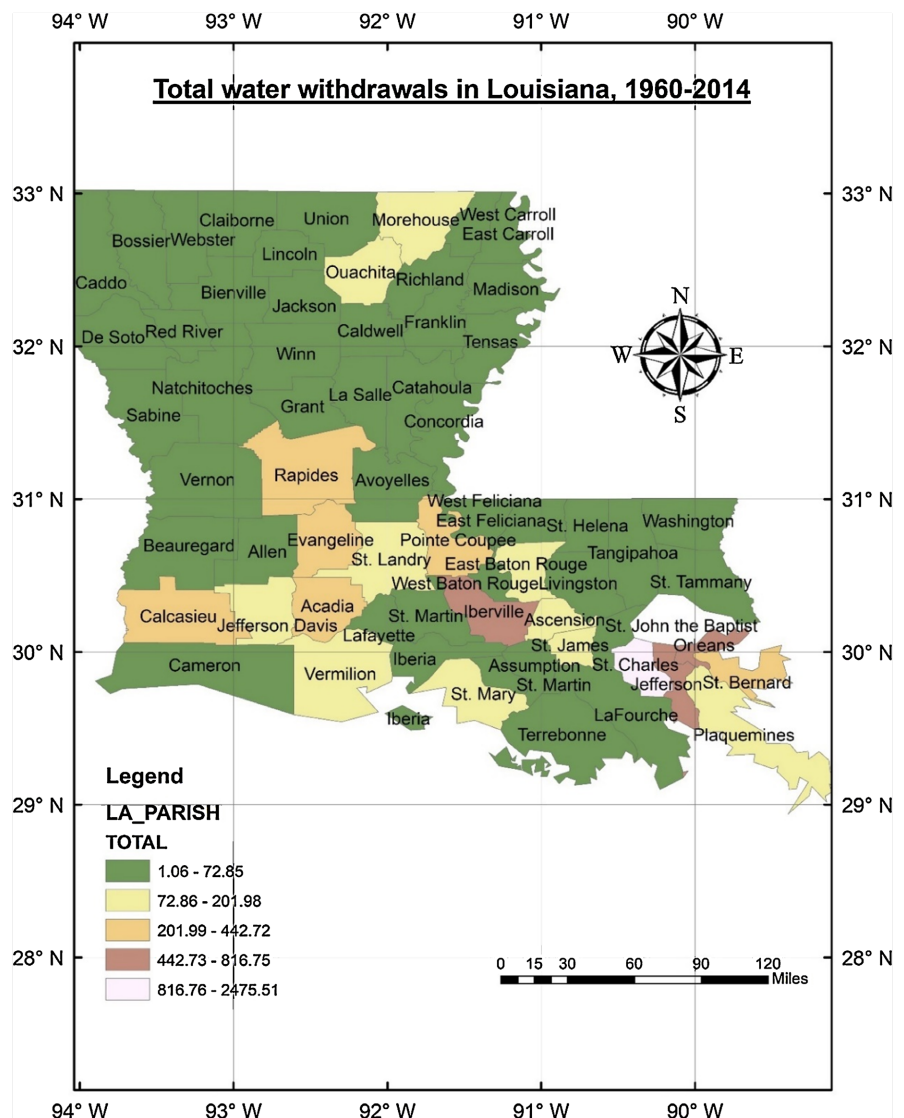


**Figure 4.** Surface water withdrawals in Louisiana, 1960-2014.

amounts of surface water withdrawals. Considering the various threats to Louisiana’s water resources, a decline in water levels in these regions is related to drought or over-pumping, which in turn have resulted in low surface water flows as well as impaired surface water quality [16]. In contrast, parishes such as Terrebonne, Beauregard, Allen, Vernon, Sabine, which may experience less drought seasons, recorded the lowest amounts of surface water withdrawals between 1960 and 2014.

**5.2.3. Total Water Withdrawals in Louisiana, 1960-2014**

Louisiana’s water resources include 10 principal surface water basins and 11 aquifers and aquifer systems underlying most areas of the state which are currently under [16]. Overall, **Figure 5** portrays that total water withdrawals in Louisiana is the highest in St. Charles and John the Baptist whereas groundwater was withdrawn the least in most parishes.



**Figure 5.** Total water withdrawals in Louisiana, 1960-2014.

#### 5.2.4. Levels of Water in Three Aquifers in Louisiana

From 1960 to 2010, it is observed that the groundwater levels in Louisiana, relative to mean sea levels keep decreasing over the years. **Table 5** highlights that the water level in the Jasper Acquirer in St. Tammany dropped from approximately 125 ft to 50 ft whereas the water level in the Sparta Acquirer in Lincoln dropped from approximately 30 ft to -25 ft. Finally, the water level in the Chicot Acquirer of Acadia was estimated to have dropped from -25 ft in 1965 to -50 ft.

**Table 5.** Groundwater levels in three aquifers in Louisiana [41]

Year	Sparta Aquifer- Lincoln	Chicot Aquifer- Acadia	Jasper Aquifer-St. Tammany
1960	-	-	125
1965	-	-25	100
1970	30	-25	75
1975	0	-25	70
1980	0	-25	70
1985	5	-10	60
1990	10	-10	50
1995	15	-5	50
2000	25	-25	50
2005	-25	-50	50

#### 5.2.5. Groundwater Levels in Sparta Acquirer in Louisiana

Morehouse Parish Well 350, Ouachita Parish Well 401, and Ouachita Parish Well 444 are all located within the Sparta Aquifer in Louisiana. In recent years, management strategies have resulted in a decrease in groundwater use, resulting in an increase in groundwater levels in some parts of the Sparta Aquifer, particularly in the region beneath Arkansas [20].

The USGS and the Sparta Ground Water Conservation District collaborated on a study to track changes in groundwater levels and quality, including saltwater intrusion. Furthermore, the Sparta Ground Water Conservation District collaborated with a consultant to develop a groundwater model that indicated that a 50% reduction in Louisiana's groundwater consumption would likely stabilise, if not recharge, the Sparta Aquifer [46]. From **Table 6**, groundwater levels in the Sparta Acquirer in Louisiana continued to drop more rapidly in the Ouachita Parish Well 444 from 200 ft to 250 ft below the ground whereas the water level drop in the Morehouse Parish Well 350 and Ouachita Parish Well 401a was not very significant. However, there was a sharp rise in the Union well from 2003 to 2007 and above.

#### 5.2.6. United States of America Drought Monitor in Louisiana in 2022

Louisiana is currently experiencing a drought in approximately 73% of its area.

**Table 6.** Groundwater levels in Sparta Aquifer in Louisiana [15].

Year	Morehouse Parish Well 350	Ouachita Parish Well 401	Ouachita Parish Well 444	Union County AR, Monsanto
1980	105	100	200	350
1983	100	90	200	325
1986	100	100	200	320
1989	100	100	210	350
1992	100	100	210	-
1995	100	100	220	-
1998	105	110	225	-
2001	110	115	230	-
2004	115	120	240	350
2007	115	120	250	300

Source: (Zahir & Bill, 2010).

This was a predicted event, with forecasters warning in early October that the entire state would be affected by drought by December due to weeks of no rain [22]. In Orleans and St. Tammany parishes, there is a moderate drought, and some areas in Jefferson, Plaquemines, and St. Bernard parishes are experiencing abnormally dry conditions. This follows a drought from January to June this year, which resulted in local river levels being at least 2 feet lower than the previous summer of 2021 [22].

## 6. Discussion

### 6.1. Groundwater Decline in Louisiana

In northern Louisiana, parishes have experienced recurring droughts and systemic declines in multiple aquifer systems, while southeastern areas like the Southern Hills' Baton Rouge region face challenges with decreasing supply and saltwater intrusion [16]. Thus, drought-prone regions see reduced surface water availability, and increasing dependence on groundwater resources. For instance, North Louisiana faced a significant drought beginning in 2010, which severely strained groundwater resources, particularly in southern Caddo Parish [16]. During this period, aquifers like the Carrizo-Wilcox and Upland Terrace saw steep declines in water levels, leading to local wells running dry by the summer of 2011 [16]. This trend highlights the urgent need for policymakers to prioritize sustainable water management strategies. Managing the balance between surface and groundwater usage is essential to preventing depletion and maintaining water quality. More so, adequate time must be allowed for aquifers to replenish, in addition to careful management which will help prevent water-soluble pollutants from contaminating underground supplies. Based on the state's growing reliance on groundwater, driven by population growth, agricultural demands, and

industrial needs, the water consumption continues to rise, placing increased stress on available water supplies and distribution systems [45] [47]. Despite these challenges, Louisiana has made progress in addressing water quantity and quality issues. For instance, the state has expanded its water resource monitoring network, which has been in place since the 1940s through a cooperative agreement between the United States Geological Survey (USGS) and the Louisiana Department of Transportation and Development [16]. This network includes groundwater and surface water monitoring sites that track water levels, stream flow, and chloride concentration, helping to guide future water management strategies. However, considering the limitations in the data, such as uncertainties in long-term climate projections and water usage patterns, mean that policymakers must remain adaptable in their approaches.

## 6.2. Climate Change Impacts on Water Resources in Louisiana

Louisiana's weather patterns have been significantly impacted by climate change, resulting in a surge of extreme weather events such as hurricanes, floods, and heatwaves. As global temperatures continue to escalate, sea levels have been steadily increasing, which poses an imminent threat to coastal regions like Louisiana. With reference to **Table 4**, frequency of days with temperatures above 30 degrees Celsius surpasses the occurrence of days with temperatures below -10 degrees Celsius across the months. Over the past few decades, Louisiana has witnessed a rise in the frequency and severity of heatwaves, which can result in several health issues such as heat stroke and dehydration. Hurricanes have also become more frequent and intense, causing considerable damage to homes, businesses, and infrastructure.

Being a "water-rich" State, Louisiana's water resources also face challenging threats, including declining water quantity and quality [48]. The Southwestern region of the United States is facing drought, and reduced snowfall, resulting in added stress on water resources. Furthermore, climate change is expected to increase water demand while decreasing water supply in many areas [3]. The intensity of hurricanes is projected to rise, and droughts similar to those experienced between 1999 and 2002 are expected to occur more frequently and for longer durations. As a result, planning for future water needs must factor in a greater degree of variability than what has been witnessed in the past.

In August 2016, heavy rainfall caused by a slow-moving storm system resulted in extensive flooding and loss of life in southern Louisiana. The storm deposited over 24 inches of rain in certain areas, which led to the evacuation of tens of thousands of people. An analysis has shown that the frequency and severity of extreme rainfall events like this have increased due to global warming caused by greenhouse gas emissions. The analysis further indicates that the statistical return period for extreme rainfall events of this magnitude has decreased from an average of 50 years to 30 years. Additionally, the amount of rainfall that would have fallen during a typical 30-year event in 1900 would have been 10% lower than a comparable event today. This event underscores the urgent need to address climate

change and reduce greenhouse gas emissions to mitigate the impact of extreme weather events in Louisiana [42].

Due its location along the Gulf of Mexico, Louisiana is especially vulnerable to the effects of climate change, such as rising sea levels that cause coastal flooding, erosion, and saltwater intrusion into freshwater sources. These changes have the potential to have a negative impact on the state's economy, including key industries such as fishing and oil and gas, as well as the overall well-being of its residents. As a result, in order to protect the environment, public health, and safety, policymakers and citizens in Louisiana must take proactive measures to mitigate and adapt to the effects of climate change.

## 7. Conclusions

Climate and water are crucial factors in ensuring food security, human health, economic progress, industrial growth, urban and rural development, and thriving ecosystems. However, the growing population will lead to an increase in demand for water and food, which will further strain water resources and harm the environment [49]. To manage both surface water and groundwater resources effectively in Louisiana, a comprehensive strategy is needed to meet the current and future needs of various sectors, including municipalities, agriculture, industry, rural water users, and the environment, while also ensuring sustainable use of groundwater resources and promoting economic and ecological sustainability [15].

As [49] argues, it is crucial to implement effective water resource management strategies while also preserving biodiversity and freshwater ecosystem sustainability. This involves engaging in water conservation practices such as integrated planning and use of water wisely, protecting water sources as well as investing in the right infrastructure to ensure long-term water availability and ecosystem health. To address the increasing demand for water and cope with the irregular replenishment of urban water supply systems, water source protection, including surface and groundwater, and investment in storage and water transfer infrastructure will be necessary. [15] reveals that the DOTD Public Works and Water Resources Division is developing a priority program for state-funded surface water reservoirs called the Reservoir Priority and Development Program (RPDP) to address current and emerging water resources issues and needs in Louisiana. This program is based on existing information, previous studies conducted in Louisiana, and best practices used in other parts of the United States. It has the potential to reduce the impacts of climate change on Louisiana's water resources. However, additional policies must be implemented to combat the root cause of the issue, which is climate change.

To sustainably manage Louisiana's water resources while preserving biodiversity and freshwater ecosystems, it is vital to adopt holistic water management approaches. Given the increasing water demand and inconsistent replenishment of urban water supplies, safeguarding both surface and groundwater sources is

essential. This effort should be supported by substantial investments in water storage and transfer systems to maintain a reliable supply. The state's Reservoir Priority and Development Program (RPDP), focused on developing surface water reservoirs, is a promising step in addressing water resource challenges. However, additional policies aimed at tackling climate change are necessary to ensure the long-term sustainability of Louisiana's water resources.

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## Conflicts of Interest

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

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