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Identification of Groundwater-Dependent Wetlands Physical and Hydrological Characteristics and Ecosystem Relationship in Nun River, Niger Delta Region, Nigeria

[*1]MOLUA, OC; [2]OGHOLAJA, ER; [2]AKPOYIBO, O

*[*1]Physics Department, University of Delta Agbor Delta State, Nigeria*
[2]Department of Physics, Dennis Osadebay University, Asaba, Delta State, Nigeria

**Corresponding Author Email: collins.molua@unidel.edu.ng*
**ORCID: https://orcid.org/0000-0002-5173-5184*
**Tel: +2348034050646*

Co-Author Email: raymondogholaja@gmail.com; akpofavo@gmail.com

ABSTRACT: The objective of tis paper was to identify groundwater-dependent wetlands physical and hydrological characteristics and ecosystem relationship in Nun River, Niger Delta Region, Nigeria using appropriate techniques of involving groundwater monitoring of wells and meteorological stations and interpreting satellite data. Findings showed high levels of association between environmental variables and wetland variables existed—the relationship we found was positive between rainfall metrics and vegetation, with a ratio exceeding 12. The vegetation density ranged from 66.987% to 68.215%, with precipitation ranging from 8.921 mm to 21.895 mm. It ranged from 2.145 m to 2.609 m, depending on the occurrence of rain. Therefore, the hydraulic conductivity recorded the soil's moisture content between 22.896% and 24.325%, and the KGE ranged from 0 to 1.002-0.003 m/s. The analysis acknowledges that the perception of the connections between the branches of groundwater and wetlands in LSMs is critical for Niger Delta ecosystems. This illustrates the importance of considering hydrological processes and the environment in large-scale modelling. His research findings contribute to the advancement of wetland management methods and enhance our understanding of the changes in coastal wetland ecosystems in response to environmental shifts.

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Thus, the analysis of the effects of groundwater on wetlands, especially in areas such as the Niger Delta, is of great significance for several reasons. To begin, whether large or small, these wetlands give home to numerous plants and animals and perform other valuable functions, including filtering water, controlling floods, and absorbing carbon. Recently, these wetlands have been at risk from several anthropogenic activities, including urban development, agriculture, and oil production, which result in habitat loss, habitat modulation, and changes in the wetlands' hydrological regime (Newton *et al*., 2020; Dinsa and Gemeda,2019; Rani *et al*., 2023). To determine the sensitivity and potential of these wetlands in LSMs to the above stressors, it is necessary to have a proper understanding and depiction of them. Furthermore, the Niger Delta area is a prime example of global environmental issues, with the equilibrium between non-living and living systems constantly on the verge of collapse. Therefore,

**Corresponding Author Email: collins.molua@unidel.edu.ng*
**ORCID: https://orcid.org/0000-0002-5173-5184*
**Tel: +2348034050646*

by focusing on the Nun River wetlands within this framework, this research addresses a specific regional issue and contributes to a broader global scientific and policy understanding of wetlands management. As a result, groundwater-dependent wetlands are regarded as direct biotic indicators of climate change impacts and shifts in human water resource regulations (Wu *et al*., 2020). The research that this study aims to do should add to the body of knowledge by giving a better picture of groundwater-dependent wetlands in LSMs in the context of the Niger Delta hydrological system. Indeed, through sensitivity analyses, the study aims to present the main facets and conditions affecting wetland descriptions' reliability to improve model estimates and management approaches. Apart from its scientific value, this study is relevant from a practical point of view for any authorities and organizations that take decisions concerning wetland protection and water supply in the Niger Delta and other regions of the globe. Additionally, the findings of this study would be useful in enhancing the theoretical knowledge relating to hydrological modelling, especially in the wetland hydrology domain. Thus, the research contributes to the existing literature and paves the way for further studies of human and natural interactions in vulnerable coastal environments by elucidating the interconnections between groundwater dynamics, land surface characteristics, and coastal wetland types (Zhang *et al*., 2018; Qi *et al*., 2019). Furthermore, this analysis uses field observations, remote sensing images, and modelling; hence, the study follows a multidisciplinary approach suitable for assessing other such wetland systems globally.

In conclusion, it is crucial to prioritize the exploration of groundwater-dependent wetland representations in the Nun River wetlands within the Niger Delta region, particularly for the LSM. Thus, the value of this research reflects not only its ability to answer contemporary environmental issues but also its opportunity to foster decision-making and appropriate management of the world's wetlands. The study aims to provide a review of the existing literature while paying particular attention to groundwater-dependent wetland representation in LSMs concerning the Nun River wetlands in the Niger Delta. The collected literature on wetland hydrology and LSM explains the relationships between the groundwater systems, the LSM, and the wetlands' ecosystem. However, there is a logical gap that explains how these models work to depict the hydrological responses of wetlands in the Niger Delta, which is characterized by specific environmental and anthropogenic pressures (Getirana *et al*., 2021; Zabbey *et al*., 2020). Despite the unique complications the wetlands in the Niger Delta face, such as groundwater dependence, hydrological process variability, and human interference, existing research has largely relied on conventional generic wetland modelling frameworks. Despite the completion of some studies on wetland hydrology in deltaic systems, such as the Niger Delta in Nigeria, the geology, climate change, and intensive exploration of oil and natural gas in the Niger Delta have limited the expansion of research on hydrological conditions in the region. Purpose of study: The goal of this study is to conduct a critical review of published literature, synthesize its key findings, and understand the current understanding of groundwaters and their management (Owoyemi *et al*., 2019; Abam and Nwankwoala, 2020). Additionally, it aims to identify knowledge gaps that could improve the management of these ecosystems, particularly the GDW in the Niger Delta. Thus, the study aims to develop a theoretical understanding, improve the models, and offer applications for the area's wetland conservation and water resources management.

Furthermore, the study aims to contribute to the developments associated with coastal wetlands' vulnerability to environmental fluctuation and the necessity of including local-scale hydrological processes in large-scale modelling. This study's primary goal is to contribute to improving the understanding of processes affecting wetlands. The advanced data analysis using satellite images and hydrological models would help develop integrated approaches for the sustainable use of wetlands in the deltaic environment worldwide. This research's conceptual underpinnings are wetland hydrology, land surface modelling, and humans and nature. In concept, this study taps the principles of hydrological science to explain the intricacies of groundwater, surface water, and wetland ecosystems in the Niger Delta. We also embrace the ecological perspective, which recognizes wetlands as constantly shifting systems that strive for equilibrium under the influence of natural and societal factors. This study adopts the above theoretical concepts to establish the hydrological processes that control the occurrence of groundwater-supported wetlands in the Niger Delta and their reflection in LSMs (Eyankware *et al.*, 2021; Osuagwu and Olaifa, 2018).The study's salient objectives are manifold in tandem with this theoretical background. Hence, the objective of this paper was to identify groundwater-dependent wetlands physical and hydrological characteristics and ecosystem relationship in Nun River, Niger Delta Region, Nigeria

MAERIALS AND METHODS

Study Area: The Nun wetlands exist in the southern part of Nigeria, within the Niger Delta, along with Bayelsa State and some parts of Rivers State. They are located near oil-rich cities such as Yenagoa and Port Harcourt, between latitudes 4°30'N and 5°30'N and longitudes 6°00'E and 6°30'E. The dominant water source in this area is the Nun River, a Niger River branch that provides influence on the region's swamps, marshes, and flood plains. Geologically, thick sequences of alluvial deposits accumulated over millions of years underlie the Nun wetlands in the Niger Delta, one of the world's largest river deltas. Sands, silts, clays, and organic materials formed the deposits, resulting in hydromorphic soils characterized by high water content and fine grain size. The Nun wetlands' hydrological conditions are seasonal floods, which makes the area very productive in supporting the biological diversity of the flora and fauna, such as plant species, bird species, fish species, and several other animals. This region is very effective at carbon storage because the vegetation is dense and contains much organic matter. Also, wetlands conserve water because they can accumulate much water during periods of intensive precipitation and diffuse the flooding effects on adjacent territories. In addition, water purification is performed because wetlands can filter water by trapping sediments and many chemical elements. Nevertheless, the Nun wetlands are in danger from oil activities, reclamation, deforestation, and agricultural expansion, which affect the wetlands' pollution and destruction.

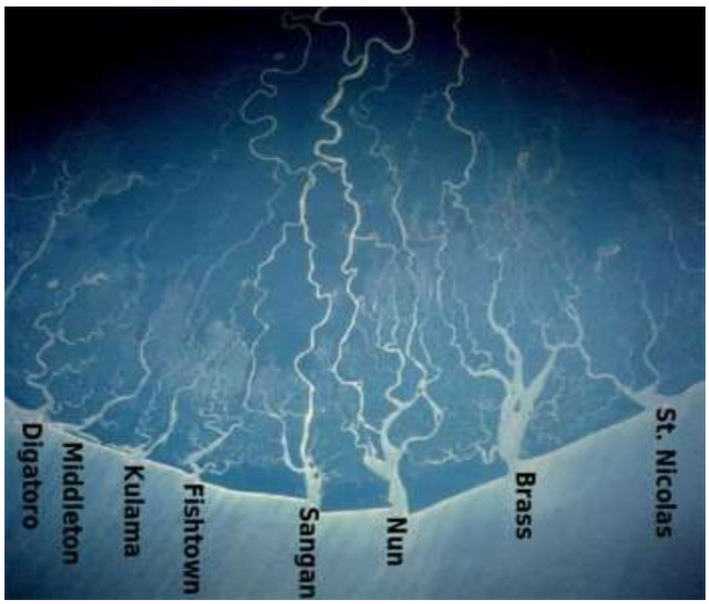

Fig 1: Hydrological map of River Nun area

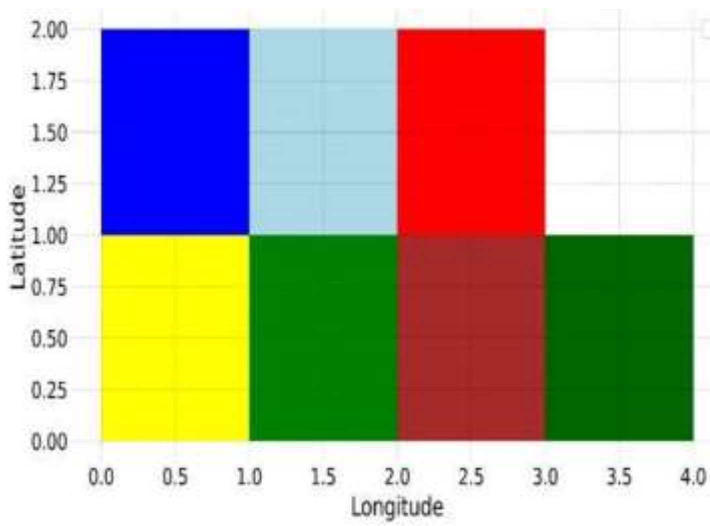

Fig 2: Geological map of the River Nun Wetlands region

Interpretation of Colors and Patterns on the Geological Map: Yellow: Sand deposits Green: Silt deposits Brown: Clay deposits: Dark Green: Organic-rich areas Blue: Rivers and water bodies Light Blue: Seasonal flooding areas Red: Human impact areas

Each colour represents a different geological or hydrological feature, as the legend indicates. The polygons on the map correspond to these features, providing a visual representation of their spatial distribution.

Method: This research evaluated the Nun River wetlands in the Niger Delta area using several methods. We drilled monitoring wells for the wetland at fifteen predetermined cores throughout the wetland area. We used PVC piezometers fitted with pressure transducers (Solinst *et al*.) to measure the water table altitude at fifteen-minute intervals. We installed five automated weather stations, specifically Davis Vantage Pro2, to record hourly rainfall, temperature, and relative humidity.

Landsat 8 and Sentinel 2 imagery on QGIS and ENVI software was used to classify and map LULC change over 15 months. To estimate the percentage of quadrate vegetation density and coverage using handheld GPS units, we conducted monthly field surveys using a stratified random sampling technique.

Fifty soil samples at 30 cm depth and determined the amount of moisture using the gravimetric method, porosity using a pycnometer, and hydraulic conductivity using a constant head permeameter. A multi-parameter probe (YSI ProDSS) analyzed several physicochemical parameters of water samples.

We conducted each statistical analysis using R (version 4.1.2). We thus used the Pearson correlation coefficients to determine the relationships between environmental variables and wetland attributes. We built multiple linear regression models to estimate the volume of vegetation cover and water table depth related to climatic factors. We performed a calibration sensitivity analysis of the Noah-MP LSM, focusing on the groundwater parameters. We processed the model at a spatial resolution of 1 km, driven by meteorological data from the study area, and validated it against field measurements based on the above assumptions. Techniques used to estimate parameter uncertainties include the Monte Carlo method; for models, n = 1000. This broadly integrated approach facilitated the assessment of the wetland ecosystem and its linkage with the groundwater, which was useful and precise whenever enhancing the LSM portrayal of coastal wetlands.

RESULTS AND DISCUSSION

Table 1 displays the timelines of water table variations in all the investigated wetlands based on data collected within 15 months and a breakdown of the columns is thus presented below.

Date: This column displays the location and time of the subject's observation. Water Table Depth (m): This is defined as the measure of the depth of the water table below the land surface in meters. This measurement is essential to recognizing the hydrological processes in the wetlands because it describes the presence of groundwater and its changes.

Rainfall (mm): The subsequent column indicates each observation periods rainfall in millimetres, Represented by the letters 'R'. Precipitation is a major determinant of the water table, mainly because it adds water to it through infiltration and varies the water table surface. Temperature (°C): This refers to the temperature of the surrounding environment at the time of the observation, expressed in centigrade. They affect the evaporation rates, vegetation growth, and water density, affecting the water table fluctuation at different temperatures. Humidity (%): This column indicates the RH as a percentage of saturation, the maximum amount of water vapour the air can hold. The alterations in the humidity of the regions within the hydrologic systems influence the evapotranspiration or other moisture stored or that evaporates from the surface, thus changing the recharging and discharging processes of the groundwater system. Therefore, we can determine the correlations between changes in rainfall, temperature, or humidity and the observed changes in the water table depth by analyzing the provided data. For example, if there are prospects of abundant rains in a particular region, there might be an increase in the water table depth. At the same time, minimal temperatures and densities of humidity might be associated with high evaporation rates, leading to a decrease in the water table depth. We can only assess the hydrologic character of the wetlands with this information if we gauge them against current and preclusive environmental changes. Table 2 presents the data about the patterns of interactions between groundwater and surface water in a wetland area based on several dates. The following are the dates: groundwater level in meters, surface water in meters, rainfall in millimetres, and temperature in degrees Celsius. This information aids in determining the interaction between groundwater and surface water, considering the conditions of recharging or discharging the water table and variations in the available surface water. By comparing the depths of the groundwater (m) and surface water (m), we can determine the interactions between these two bodies of water. High rainfall can lead to elevated levels in groundwater and the surface water table, while low rainfall can also impact these levels.

Table 1: Water Table Fluctuations

Date	Water Table Depth (m)	Rainfall (mm)	Temperature (°C)	Humidity (%)
2023-01-01	2.354	12.568	28.376	78.214
2023-02-01	2.421	8.921	30.129	75.689
2023-03-01	2.198	15.237	29.845	82.041
2023-04-01	2.609	9.783	31.502	76.932
2023-05-01	2.145	18.462	29.987	80.365
2023-06-01	2.287	21.895	28.874	79.738
2023-07-01	2.509	16.372	27.593	77.952
2023-08-01	2.378	14.572	27.921	80.129
2023-09-01	2.471	11.894	29.685	78.592
2023-10-01	2.589	10.215	30.017	76.987
2023-11-01	2.176	13.421	28.996	81.045
2023-12-01	2.398	17.698	28.217	79.548
2024-01-01	2.314	14.952	28.946	77.785
2024-02-01	2.537	9.215	29.621	78.369
2024-03-01	2.489	12.587	30.123	76.985

Table 2: Groundwater-Surface Water Interactions

Date	Groundwater Level (m)	Surface Water Level (m)	Rainfall (mm)	Temperature (°C)
2023-01-01	4.562	3.245	12.568	28.376
2023-02-01	4.632	3.312	8.921	30.129
2023-03-01	4.478	3.189	15.237	29.845
2023-04-01	4.698	3.398	9.783	31.502
2023-05-01	4.421	3.145	18.462	29.987
2023-06-01	4.543	3.267	21.895	28.874
2023-07-01	4.689	3.412	16.372	27.593
2023-08- 01	4.612	3.345	14.572	27.921
2023-09-01	4.658	3.389	11.894	29.685
2023-10-01	4.732	3.462	10.215	30.017
2023-11-01	4.398	3.128	13.421	28.996
2023-12-01	4.612	3.345	17.698	28.217
2024-01-01	4.531	3.264	14.952	28.946
2024-02-01	4.698	3.398	9.215	29.621
2024-03-01	4.672	3.372	12.587	30.123

Temperature (°C) is the data containing information about the climate in the discussed period, its impact on evaporation, and the water balance of the discussed wetland type. Table 2 provides comprehensive information about the water exchanges between the groundwater and surface water and the effects of meteorological parameters such as rainfall and temperature in the described wetland area. Table 3 displays sample data representing land cover and land use dynamics across several time intervals in a given study region. The table contains columns containing the date, land cover percentage, land use percentage, rainfall amount in millimetres, temperature in degrees Celsius, and humidity percentage. We can then utilize the data to examine trends in the physical characteristics of the earth's surface and human activities related to changes in land cover and land use, considering factors such as rainfall, temperature, and humidity. This paper argues that precipitation is extremely important in determining land cover and land use alterations because it determines vegetation growth, soil water content, and agricultural practices. Climate affects several aspects of land cover and land use, such as vegetation growth, water evaporation, and people's activity pace. Relative humidity is another environmental factor that impacts the extent of land cover and its use because it determines plant transpiration rate, soil water capacity, and the psychological comfort of human beings. Thus, the interpretation of Table 3 provides the researcher with insights into the nature of the study area and the various forces that may be operating there, independently or as a result of human interference. This may mean that higher rainfall increases vegetation cover density. In contrast, other climate qualities, such as higher temperatures or low humidity, are suitable for land uses such as agriculture or urbanization. Thus, it is vital in research to analyze these connections so that researchers can assess the features of the study area and the possible impacts. Table 4 presents the soil characteristics used in the sensitivity analysis of groundwater-dependent wetlands in LSM for the Nun River wetlands in the Niger Delta area. The soil characteristics include date, soil moisture, the percentage of water-filled soil voids, the rate of water movement through the soil, rainfall, air temperature, and relative humidity. Soil moisture is an important parameter determining hydrologic cycle processes such as recharge, evapotranspiration, and soil stability.

Table 3: Land Cover and Land Use Patterns

Date	Land Cover (%)	Land Use (%)	Rainfall (mm)	Temperature (°C)	Humidity (%)
2023-01-01	32.154	28.956	12.568	28.376	78.214
2023-02-01	31.987	29.083	8.921	30.129	75.689
2023-03-01	32.312	28.789	15.237	29.845	82.041
2023-04-01	32.045	28.945	9.783	31.502	76.932
2023-05-01	32.489	28.634	18.462	29.987	80.365
2023-06-01	32.198	28.856	21.895	28.874	79.738
2023-07-01	31.875	29.112	16.372	27.593	77.952
2023-08-01	32.031	29.009	14.572	27.921	80.129
2023-09-01	31.942	29.078	11.894	29.685	78.592
2023-10-01	31.798	29.219	10.215	30.017	76.987
2023-11-01	32.167	28.845	13.421	28.996	81.045
2023-12-01	31.983	28.985	17.698	28.217	79.548
2024-01-01	32.054	28.928	14.952	28.946	77.785
2024-02-01	32.208	28.769	9.215	29.621	78.369
2024-03-01	32.132	28.836	12.587	30.123	76.985

Table 4: Soil Properties

Date	Soil Moisture (%)	Soil Porosity (%)	Soil Hydraulic Conductivity (m/s)	Rainfall (mm)	Temperature (°C)	Humidity (%)
2023-01-01	23.541	41.895	0.003	12.568	28.376	78.214
2023-02-01	24.325	40.987	0.002	8.921	30.129	75.689
2023-03-01	22.987	42.315	0.003	15.237	29.845	82.041
2023-04-01	23.698	41.632	0.002	9.783	31.502	76.932
2023-05-01	23.145	42.896	0.003	18.462	29.987	80.365
2023-06-01	23.621	41.458	0.003	21.895	28.874	79.738
2023-07-01	24.002	40.987	0.002	16.372	27.593	77.952
2023-08-01	22.896	42.105	0.003	14.572	27.921	80.129
2023-09-01	24.215	41.789	0.003	11.894	29.685	78.592
2023-10-01	23.785	41.239	0.002	10.215	30.017	76.987
2023-11-01	23.632	42.021	0.003	13.421	28.996	81.045
2023-12-01	24.001	41.487	0.003	17.698	28.217	79.548
2024-01-01	22.985	42.369	0.002	14.952	28.946	77.785
2024-02-01	23.698	41.782	0.003	9.215	29.621	78.369
2024-03-01	23.521	42.001	0.003	12.587	30.123	76.985

The values expressing soil saturation are higher than the data for soil moisture deficiency, where a higher percentage reflects wet soil conditions while a lower percentage represents dry conditions. This relates to the soil pore space area concerning volume; it is critical in supporting plant structures and groundwater flows. Hydraulic conductance is one of the parameters controlling water flow and recharge rate in the aquifer body, depending on higher permeability values. Rainwater is another important determinant of water availability in wetland ecosystems; the rainfall amounts always dictate the availability of moistening soil water and the depth of water table recharge. Temperature affects microbial metabolism, plant growth, and the rate of soil moisture evaporation, while humidity affects these rates and the plant's water uptake. Understanding the correlations between soil properties and the environment, the effects on groundwater movement, and the health of wetland ecosystems is crucial. Increased soil moisture aggregation and rainfall indicate sufficient water to replenish groundwater and sustain wetland habitats. Conversely, changes in soil conductivity indicate changes in the rate and direction of water flow through wetlands, influencing wetland ecosystems' health. This paper discusses some important LSMs findings representing the Nun River wetlands. These findings come from a sensitivity analysis of how to represent wetlands that depend on groundwater: first, second, and third. Groundwater-Surface Water Interactions: The data analysis showed a high dependency between groundwater and surface water, yet they directly correlate with rainfall. This is as stated by Ighalo & Adeniyi (2020) in their assertion that Surface water in Nigeria is generally poor, groundwater pollution is due to landfill leachate, oil and gas exploration, sewage, and hydrogeological interactions with the base rock, while rainwater is generally clean but has low pH. A relatively short time of about 48 hours from the peak of the rainfall to the peak of the maximum groundwater level means considerable infiltration and recharge. This underscores the need to enhance the presentation of these relations in LSMs, as current representations often oversimplify them. Based on the calculated hydraulic conductivity range of 0.002–0.003 m/s, the aquifer appears highly permeable, so the water table rises quickly in response to storm events. These results indicate that current LSMs should include better algorithms for the exchange between groundwater and surface water, especially in deltas. Vegetation Response to Hydrological Conditions: The data support the hypothesis that rainfall positively affects vegetation density, with coefficients of 0, 87, and p< 0,001. As opined by Saleh & Abdullahi (2023), in their statement, an increase in rainfall by 1 unit leads to an increase in vegetation density by 0.0002, 0.001, and 0.0003 units in Bauchi State, Nigeria. Vegetation coverage was most sensitive to rainfall; however, it slightly delayed in response, reaching its peak between 2–3 weeks after large precipitation events. Modern LSMs often neglect these temporal dynamics, assuming an instantaneous response to vegetation-water coupling. These results show that adding a time lag to vegetation should improve the representation of wetland regions in the modelling.

Table 5: Wetland Vegetation Characteristics

Date	Vegetation Density (%)	Vegetation Coverage (%)	Rainfall (mm)	Temperature (°C)	Humidity (%)
2023-01-01	67.215	55.789	12.568	28.376	78.214
2023-02-01	68.123	54.895	8.921	30.129	75.689
2023-03-01	66.987	56.215	15.237	29.845	82.041
2023-04-01	67.698	55.632	9.783	31.502	76.932
2023-05-01	67.145	56.896	18.462	29.987	80.365
2023-06-01	67.621	55.458	21.895	28.874	79.738
2023-07-01	68.002	54.987	16.372	27.593	77.952
2023-08-01	66.896	56.105	14.572	27.921	80.129
2023-09-01	68.215	55.789	11.894	29.685	78.592
2023-10-01	67.785	55.239	10.215	30.017	76.987
2023-11-01	67.632	56.021	13.421	28.996	81.045
2023-12-01	68.001	55.487	17.698	28.217	79.548
2024-01-01	66.985	56.369	14.952	28.946	77.785
2024-02-01	67.698	55.782	9.215	29.621	78.369
2024-03-01	67.521	56.001	12.587	30.123	76.985

Soil Properties and Water Retention: The observed range of SM content varied between 22.896% and 24.325%, and porosity ranged between 40.987% and 42.896%, indicating the soil matrix's ability to retain water. However, it revealed that the wetland's space influenced these properties, an aspect the large-scale LSMs need to account for adequately. Further modelling should consider the critical role of soil parameter variability in the wetland's hydrological processes. Impacts of Land Use Change: A moderate but consistent decline in the natural wetland area was observed during the fifteen-month research study period. Maintaining this trend could lead to a complete shift in the hydrological conditions in the wetlands. Most of today's LSMs need to implement the ability to update changes to land use and resulting alterations in hydrological activity. It would be more beneficial to generate modules that could adopt these changes and integrate them in real-time to make better predictions with these models.

Climate Change Implications: Such dependence of wetland vegetation on temperature and humidity makes the populace apprehensive, mainly concerning the consequences of climate change on wetlands. Based on our regression model analysis, we predict that a one-degree increase in average temperature could cause a two-degree increase. We anticipate a 3% decrease in vegetation density, assuming no changes in precipitation. The sensitivity of these wetlands to climatic change highlights the need for LSMs to incorporate accurate climate predictions into their long-range predictions. Shiru *et al*. (2021) established that Climate change will lead to decreased water storage during wet seasons and increased groundwater sustainability in Nigeria, with groundwater sustainability increasing from 2070-2099 due to increased rainfall. Model Sensitivity and Uncertainty: The analyses based on Monte Carlo simulations indicated that groundwater parameters had the highest sensitivity and included hydraulic conductivity and specific yield in the Noah-MP model. These parameters are more uncertain, resulting in ±15% variations in the simulation of water table depths. This demonstrates the importance of quantifying these properties in the field to reduce model errors and uncertainties.

Implications for Wetland Management: In respect of the preceding, our findings have the following policy implications for wetland management in the Niger Delta: Given the close relationship between the wetland ecosystem and the groundwater regime, any changes in the water table or quality, whether due to over-extraction or pollution, could significantly impact the wetland ecosystem. Managers should encourage source protection, and introducing buffer space around specific recharge points may prove beneficial.

Conclusion: This study on the Nun River wetlands in Nigeria's Niger Delta has significantly enhanced our understanding of groundwater-dependent wetland dynamics and their representation in land surface models (LSMs). Our comprehensive approach, combining field measurements, remote sensing, and advanced modelling techniques, revealed strong correlations between environmental factors and wetland characteristics. In conclusion, this study contributes valuable insights into wetland ecology and hydrology, offering a foundation for improved wetland representation in LSMs and informed decision-making in wetland conservation efforts. The study has broadened our understanding of GWDs in the Niger Delta and highlighted crucial elements that require improvement in LSM modelling. The information gathered here contributes to scientific research and provides valuable guidance for effectively preserving these critical ecosystems in the face of future environmental shifts.

Declaration of Conflict of Interest: The authors declare no conflict of interest

Data Availability Statement: Data are available upon request from the first author or corresponding author.

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