Gross Freshwater Availability and Accessibility in the Delta Plain of Indian Sundarbans

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Abstract

The Indian Sundarbans Delta is experiencing severe water scarcity that has affected 4.5 million people due to increased salinity levels, restricting access to drinking and irrigation water. Areal surface-water coverage has been obtained through use of MNDWI from Landsat with subsequent classification and determination of zonal-statistics estimation, surface-water quality data (2019–2022) from the NWMP portal and groundwater levels-reports and groundwater quality data from current CGWB reports then used to prepare surface and groundwater quality maps employing Empirical Bayesian Kriging. The central part of the delta had better water quality than Sagar Island, which was observed to have WQI values in the range of 203.98–255.6 in the Water Quality Map produced in this study. Groundwater levels diminished from 3.3 meters BGL in 1996 to 7.67 meters BGL in 2022. Freshwater scarcity and seawater intrusion are affecting agriculture and food security.

Keywords: water demand, ground water availability, water quality, salinity, green economy

1. Introduction

Groundwater is a vital source of water worldwide, with an estimated 25% of water consumption globally that relies on groundwater sources (although this varies by region and development) (Mishra, 2023). As to Southeast Asia and the Pacific, in particular, groundwater supplies drinking water to 66% of urban households and 60% of rural households, or 79% of the populations in those countries (Carrard et al., 2019).

In the Sundarbans region, access to fresh drinking water is a critical issue due to the predominance of brackish water. Despite receiving abundant rainfall, the region fails to adequately utilize it to meet the needs of its 4.43 million residents across 19 administrative blocks (Bhadra & Hazra, 2012). The region's terrain frequently changes due to floods, cyclones, beach erosion, and sea level rise, causing significant disruptions to local livelihoods (Mondal & Bandyopadhyay, 2014).

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After Cyclone Aila in 2009, water quality measurements at three stations in the Sundarbans showed sharp increases in COD, BOD, nitrate, and phosphate levels (Bhattacharya et al., 2014). Six blocks close to river estuaries (Gosaba, Hinjalganj, Patharpratima, Basanti, Namkhana, and Sagar) face severe water problems in agricultural areas due to high salinity. Despite surface water supply, potable water availability is nearly nonexistent, forcing reliance on groundwater located below 300m (Zaman & Gayen, 2008).

During the COVID-19 pandemic, surface water quality in rivers improved by 40-50%, with notable decreases in TDS and BOD levels, demonstrating the potential for natural water quality recovery (Chakraborty et al., 2021). The urgent need for a fresh water supply to protect the Sundarbans' landscape and mangrove ecosystem is evident, considering the region's high salinity levels(Saha, 2024; Wahid et al., 2025). Mangrove forests play a crucial role in providing habitat, preventing erosion, and protecting against natural disasters, making the assessment of surface water quality and temporal changes essential (Rahman et al., 2013).Sagar Island, with its numerous tidal creeks, presents opportunities for large-scale aquaculture. Studies have been conducted to investigate the surface water quality in these creeks, revealing the potential for sustainable aquaculture practices (Basu et al., 2021). In low-lying areas like Sagar and Basanti blocks, fish farming ponds are vulnerable to saltwater flooding, prompting farmers to raise the height of pond dikes to reduce salinity intrusion (Chand et al., 2012).

Global climate patterns such as the El Niño Southern Oscillation (ENSO) and the Indian Ocean Dipole (IOD) significantly affect water quality and recharge patterns. Continuous monitoring and adaptation strategies are necessary to mitigate these impacts (Das, Mukherjee, et al., 2021). Studies have modelled the Water-Energy-Food (WEF) nexus in India using various data sources, including the Community Land Model v4.0, to estimate groundwater storage changes and validate satellite-derived groundwater data (Barik et al., 2017).Research has also explored nexus modelling of water, energy, and food subsystems, considering variables such as agricultural water withdrawal and electricity consumption. This approach underscores the importance of integrated resource management to ensure sustainable development (Ravar et al., 2020).Given the high population pressure in the Sundarbans, it is crucial to assess water availability and production for aquaculture and agriculture, alongside addressing the knowledge gap regarding dry season irrigation (Humphreys et al., 2014). The urgent need to improve water management practices in the Sundarbans is clear. This includes enhancing rainwater harvesting, developing sustainable aquaculture practices, and implementing integrated water resource management (IWRM) approaches. Addressing these challenges requires a comprehensive understanding of the region's hydrology, climate impacts, and socio-economic conditions.

The Sundarbans region's water scarcity issues are multifaceted and require a holistic approach to address. By leveraging scientific research, technological advancements, and community engagement, it is possible to develop sustainable solutions that ensure water security for the region's residents. This will not only improve their quality of life but also contribute to the resilience and sustainability of the Sundarbans' unique ecosystem.

2. Study area

The Sundarbans are situated in the lower Gangetic delta (≈21°43′–21°55′N, 88°42′–89°04′E), comprising a complex estuarine system of tidal channels that is supported by seven major rivers draining southward into the Bay of Bengal. Tidal channels and channel banks, along with the dynamic tidal processes, help regulate freshwater–saltwater exchange, sediment deposition, and the patterns of salinity throughout the landscape (Das, Mishra, et al., 2021).

Salinity is the most important driver of hydrological and ecological change: research and monitoring reports illustrate that salinity levels have increased throughout the Sundarbans from north to south, and have accelerated amid storm surges and sea level rise. Studies report episodic salinization following cyclones (e.g. Sidr 2007, Aila 2009, Amphan 2020). Sea-surface temperature and estuarine temperatures have also increased in the region (0.019 °C yr^{-1} in the Bay of Bengal and ~0.06 °C from 1980–2007), further adding stress to freshwater species and biogeochemical processes Ghosh, 2015; (Abul & Mallik, 2016; Ghosh, 2015). The submergence of mangroves and salinization of agricultural lands has already led to reductions in paddy cultivation and sharp declines in freshwater fish catches and hatchling survival in some areas (Ghosh, 2015).

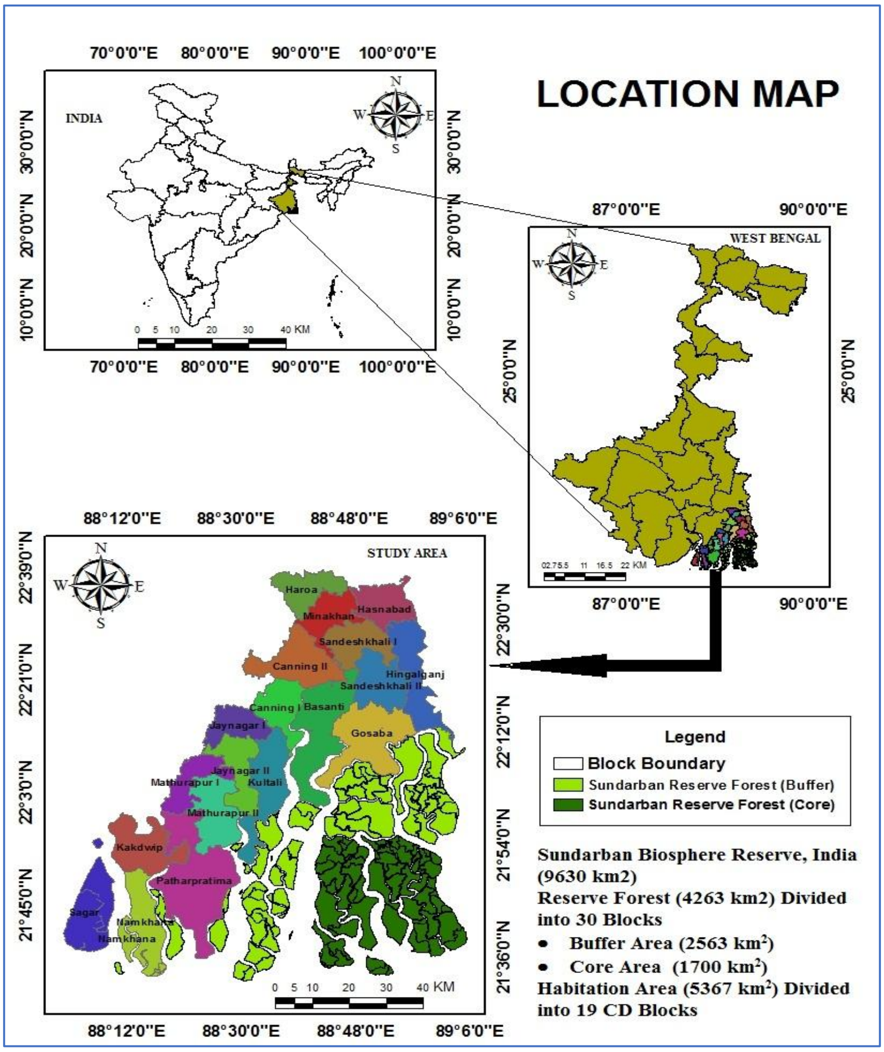

Fig. 1: Study area of Indian Sundarbans (West Bengal)

The availability of groundwater is highly limited: useable fresh groundwater is reported only at significant depth (~160–400 m) in many parts of the Sundarbans, beyond the capability of shallow wells for potable supply, while communities are left relying on limited surface freshwater sources and deep aquifers (Abul & Mallik, 2016; Bhadra et al., 2020; M. Mondal et al., 2024). Collectively, the estuarine salinity regime, disrupted surface-water quality after extreme events, and deep, spatially variable aquifers will create significant challenges to drinking-water security, irrigation, and aquaculture. Because of this, hydrological responses will depend on controlling freshwater inputs (capture and storage), limiting saltwater intrusion, and continuous monitoring of channel dimensions, salinity gradients, and aquifer recharge.

3. Methodology

A map of the available water resources and their accessibility was produced by combining four essential parameters that defined the water supply, the water quality, the ground water levels and the ground water quality. The four parameters described above were combined into one composite layer by using the Weighted Overlay Method. The surface water supply was calculated from MNDWI values that were generated from Landsat images that were pre-processed. The mapping of the surface water quality was completed by using a combination of weighted overlays and spatial interpolation from secondary data from the CPCB. Ground water levels were mapped using interpolation from data collected by the Central Ground Water Board (CGWB). The assessment of the ground water quality was completed with weighted overlays and spatial interpolations from datasets of CGWB. The temporal range of the analysis encompasses the period from 2019 through 2022 (Figure 2).

Surface water, which includes rivers, canals, ponds, wetlands, and other bodies, is assessed and quantified using the Modified Normalized Difference Water Index (MNDWI). The MNDWI formula is (Green – SWIR)/(Green + SWIR) (Xu, 2006). MNDWI values greater than zero indicate the presence of water, while negative values denote non-water features in the Sundarbans region.

Surface water quality is evaluated by computing the Water Quality Index using a weighted averaging method that includes parameters such as pH, salinity, dissolved oxygen (DO), turbidity, and chlorophyll (CHL). Groundwater quality and level data are obtained from the Central Ground Water Board report and the Global Groundwater Information System (GGIS) developed by the International Groundwater Resources Assessment Centre. Parameters for groundwater quality assessment include pH, electrical conductivity (EC), carbonate (CO3), bicarbonate (HCO3), chloride (Cl), sulfate (SO4), nitrate (NO3), phosphate (PO4), total hardness (TH), calcium (Ca), magnesium (Mg), sodium (Na), potassium (K), fluoride (F), and total dissolved solids (TDS). Continuous surface maps for both surface water and groundwater quality and levels are generated using spatial interpolation techniques, specifically the Empirical Bayesian Kriging method and the Inverse Distance Weighting (IDW) method, selected based on their accuracy reports. These spatial continuous surfaces are then used to assess water availability and accessibility on a zonal or block-wise basis. Finally, a Consumable Water

Availability and Accessibility Map has been produced using the weighted overlay method, incorporating all four previously mentioned parameters of water availability and accessibility. All the parameters have been assigned equal weightage.

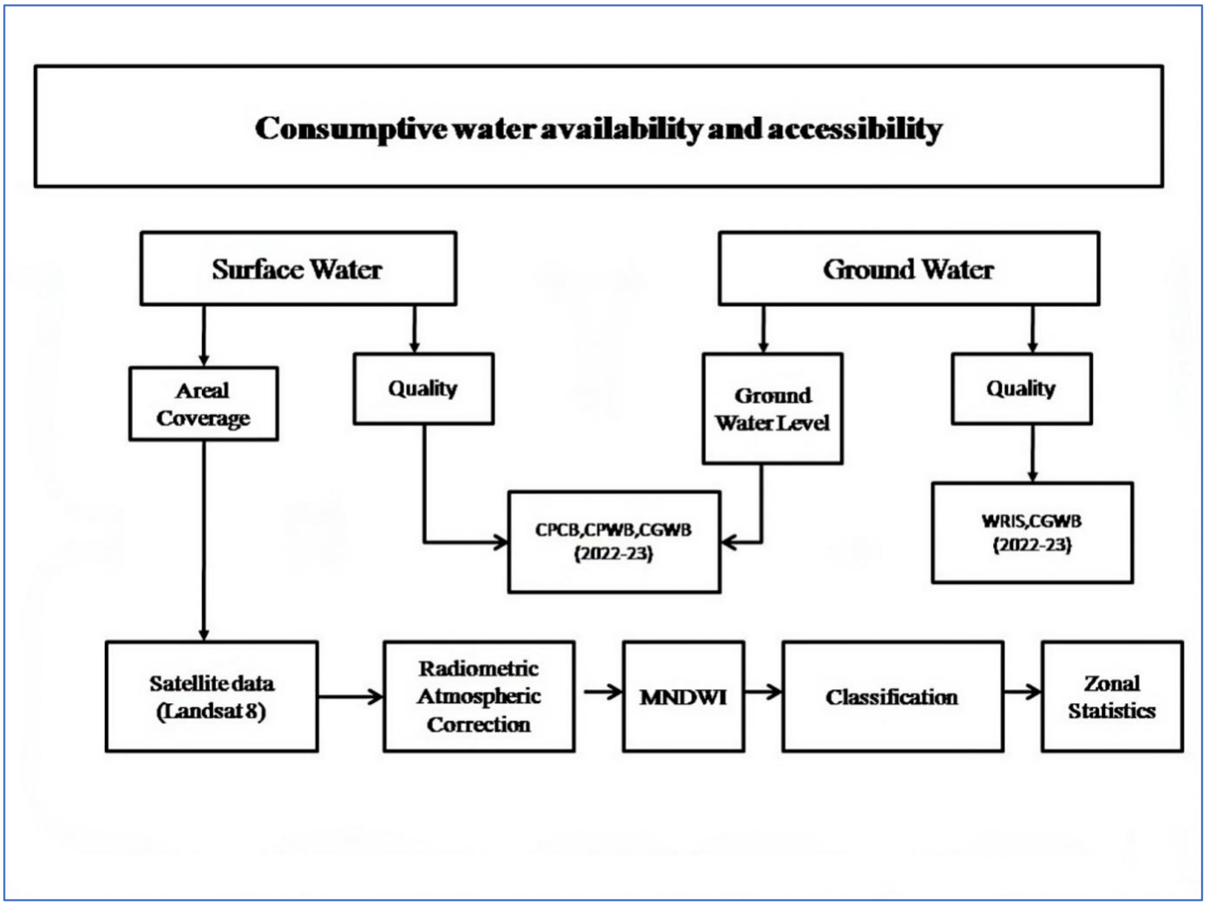

Fig. 2: Methodological framework

4. Results and Discussion

The result and discussion section is presented in three main segments: the assessment of surface water, the assessment of groundwater and Consumable Water availability and accessibility mapping.

a. Assessment of surface water:

A comprehensive study of surface water quality was conducted across 19 blocks in the Sundarbans region during pre-monsoon, monsoon, and post-monsoon periods (Figure 3). The analysis focused on ten parameters, of which five—pH, Salinity, Dissolved Oxygen (DO), Turbidity, and Chlorophyll (CHL)—showed continuous variation. Data primarily from the post-monsoon period (August) were utilized for consistency. The pH levels ranged from neutral to alkaline (pH > 7.0) during the post-monsoon period. Salinity in the Sundarbans varied, with the highest recorded at 29.7 ppm and the lowest at 7.4 ppm. The region's ambient temperature during this time (28°C - 31°C) influenced salinity, which generally increased post-monsoon.

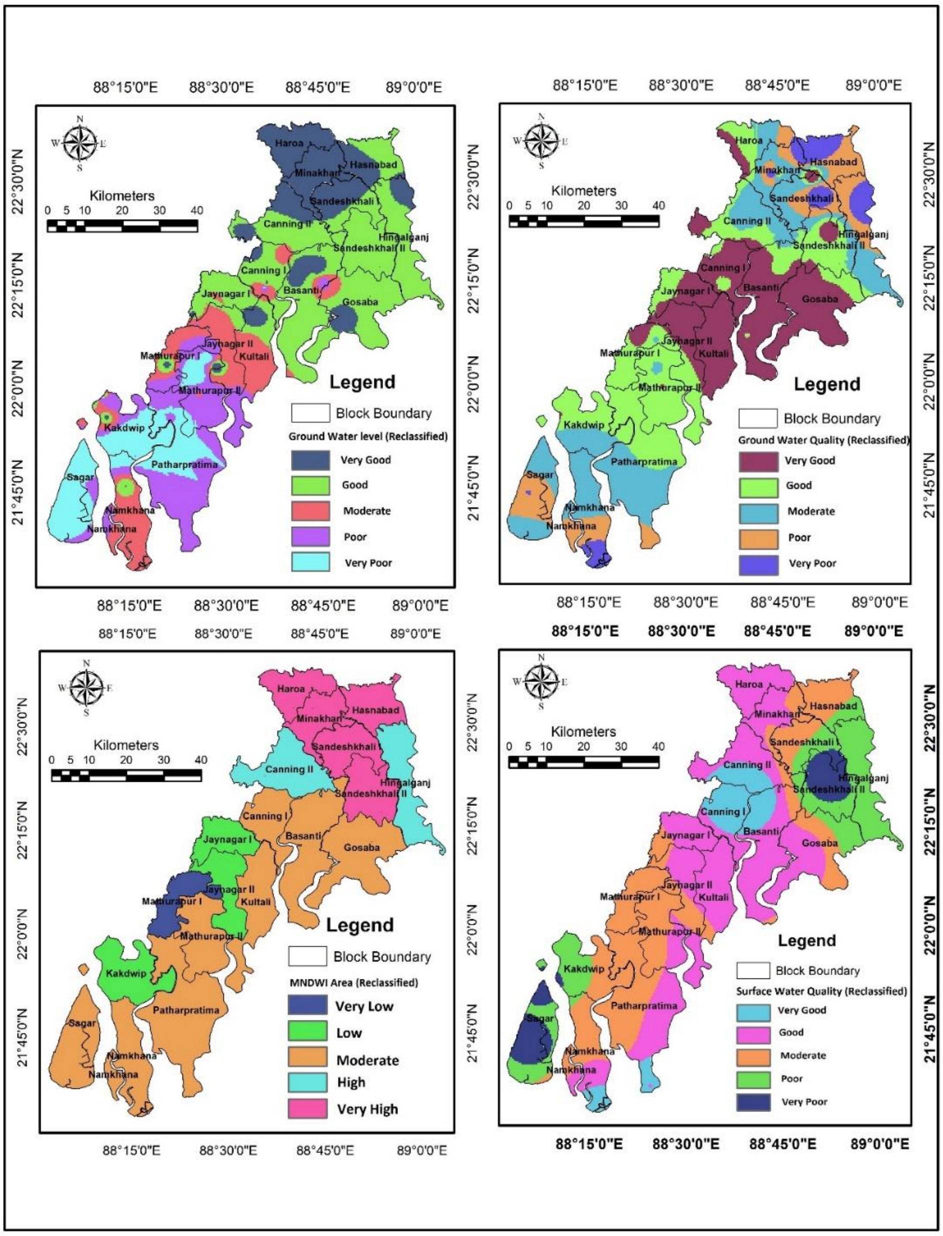

Fig. 3: Reclassified parameters of consumable water availability and accessibility map

Areas between 115.54 to 166.62 WQI are classified as Good. The surface water quality in Canning I & II and Vasanthi blocks is relatively good, indicating limited pollution and adequate natural recharge. Areas of 166.63 to 203.97 WQI are in the Medium category. Canning II, Vasanthi, Gosaba, Jaynagar I & II, Mathurapur I & II, Kultali, Sandeshkhali I, Lebukhali, Malancha, Bakkhali and Hemnagar fall under this category. Moderate levels of surface water pollution are observed in these areas, which may be due to agricultural runoff, gravel-mud transport, tidal effects, and waste runoff from residential areas.

Areas between 203.98 to 255.6 are in the Poor category. Surface water is highly polluted in Sagar, Kachuberia, Sandeshkhali II, Hingalganj and Bhagwatpur areas. Industrial effluents, tidal mixing, organic pollution and increased sediment load may be responsible for these values. Surface water in these areas is not safe for use without treatment.Surface water availability is highest in Haroa, Minakha and Sandeshkhali blocks as per the MNDWI zonal statistics values. These blocks having MNDWI values between 0.03 and 0.21indicating the presence of open water bodies, river/canal networks and adequate surface water storage. These areas are generally wetland-rich, tidally dependent and close to riverine areas, so water availability is relatively high. Hasanabad, Basanti, Canning, Gosaba, Patharpratima and Namkhana have MNDWI values ranging from 0.17 to 0.02. Although water availability in this region is moderate, the natural water holding capacity varies from year to year. Mathurapur I block has MNDWI value of 0.40 to 0.18, which is significantly lower. It indicates that the amount of open water bodies is extremely low, most of the land is used for agriculture or settlement, and Surface water capacity is limited due to geological conditions. (Figure 4 & 5).

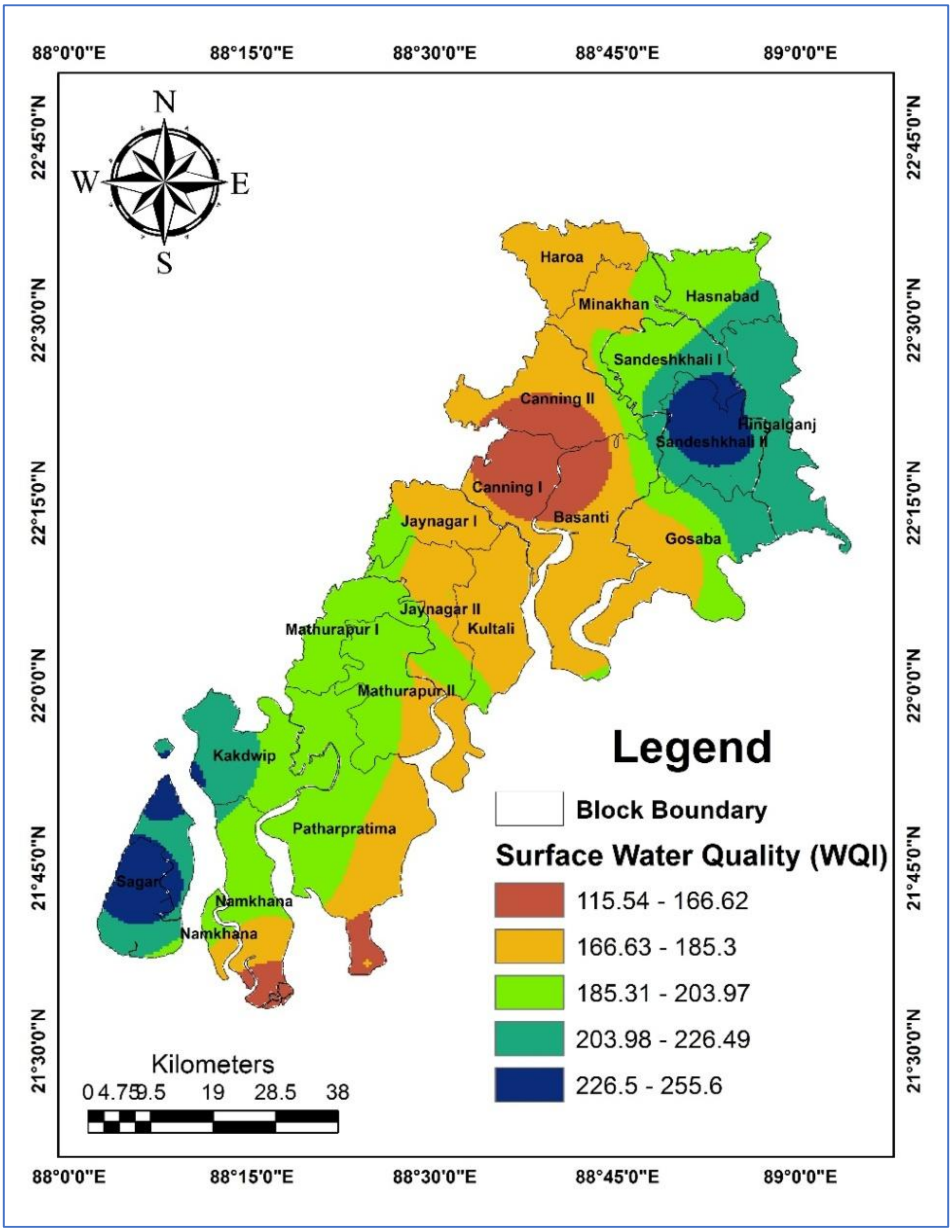

Fig. 4: Surface water quality

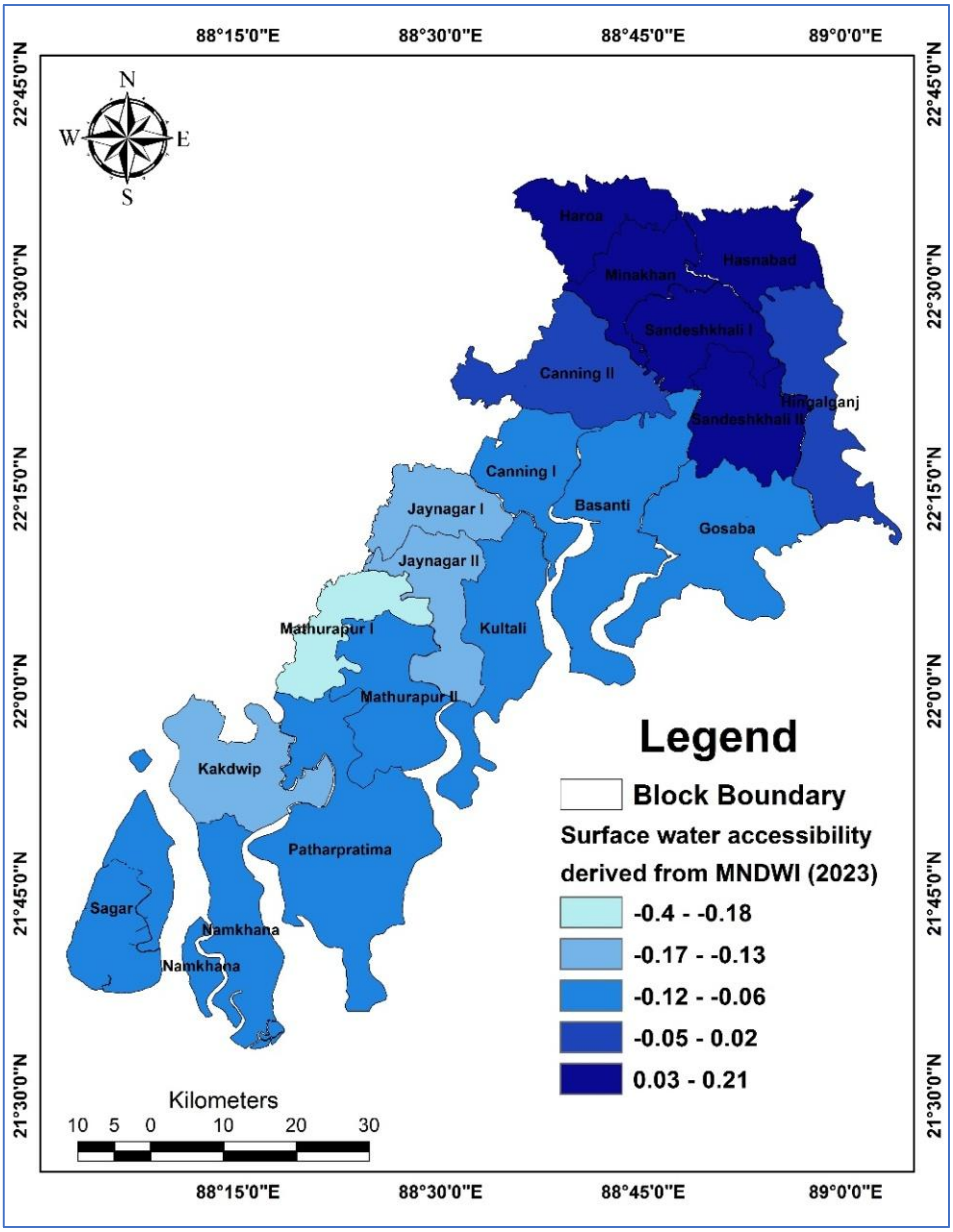

Fig. 5: Spatial distribution of surface water

b. Assessment of Groundwater:

The groundwater quality assessment focused on both deep and shallow water during the post-monsoon period, considering various parameters (pH, EC, CO3, HCO3, Cl, SO^3, NO3, PO^3, TH, Ca, Mg, Na, K, F, and TDS). Shallow water exhibited higher salinity compared to deepwater due to significant sea water intrusion. Deep water was more alkaline (pH > 7.0) due to higher bicarbonate concentrations. These values indicated that shallow water, affected by seawater intrusion, was unsuitable for drinking. Some deeper groundwater sources were found suitable for drinking.

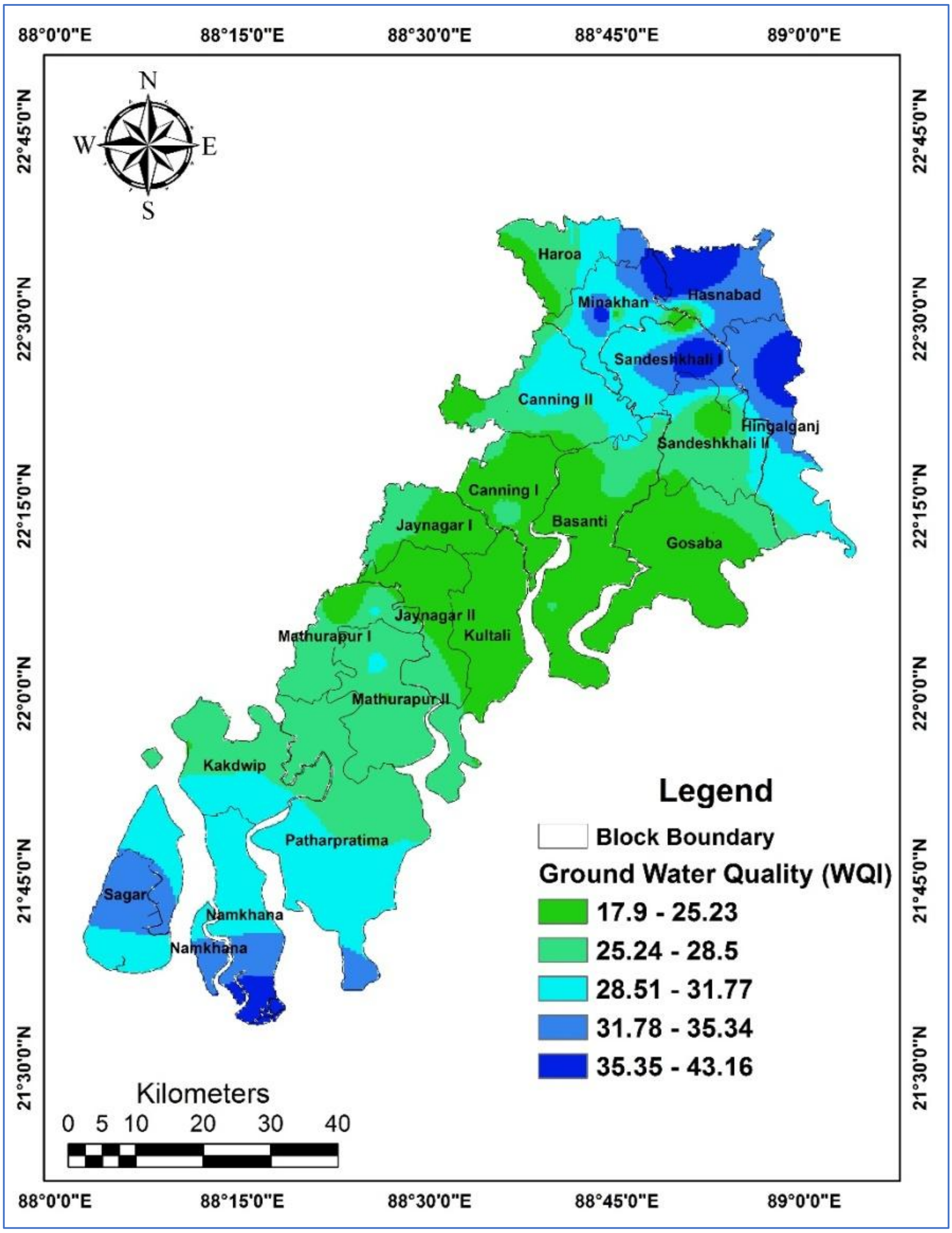

Fig. 6: Groundwater quality

Qualitative differences between regions are clearly discernible in terms of WQI values for groundwater. Areas between 17.9 to 25.23 WQI are classified as Good. Jayanagar I and II, Kultali, Canning I, Sandeshkhali II, Vasanthi and Gosaba belong to this category. Groundwater contamination in these areas is relatively low and water quality is within acceptable limits, indicating safe drinking. 25.24 to 31.77 WQI populated areas fall into the Medium category. Hasnabad, Meenkhan, Patharapratima, Kakdwip, Sandeshkhali II, Hingalganj, Canning II and Mathurapur I and II fall under this category. The pollution pressure in these areas is moderate and the water quality is somewhat compromised but can still be usable with minor purification.Areas between 31.78 to

43.16 WQI value are of Poor category. Water quality is poor in Sandeshkhali I, Meenakh, Hasnabad, Hingalganj, Namkhana and Sagar blocks. High levels of contamination are present, which may pose a health hazard and the water is not suitable for direct consumption without proper purification. The depth of the groundwater sampled in this study indicated the average groundwater depth in each respective year. The year by year average depth of groundwater was 3.3m bgl in 1996 and decreased to 6.5m in 2017 and again down to 7.67m bgl in 2022.(Das, Mishra, et al., 2021).This suggests that the groundwater level decreased by about 3 m between 1996 and 2017 and approached near-normal conditions by 2022. Observations indicate that groundwater levels in the Sundarbans drop markedly during the pre-monsoon period, rise during the monsoon, and stabilize to normal levels in the post-monsoon period. The temporal pattern of groundwater-level (GWL) fluctuations is similar in both shallow (15 mbgl) and deep (115 mbgl) aquifers. Shallow groundwater level (below 0.33-4.54 m) in the study area includes the following blocks: Haroa, Meenakhan, Sandeshkhali I, Hasnabad, Basanti and Canning I. Blocks designated as shallow groundwater level indicate maximum availability of groundwater in these areas and these "natural zones" are the most "efficient". Where groundwater is between 4.55 and 10.52 m below ground level, these represent groundwater conditions for medium to high groundwater levels. The following blocks are found within this range of groundwater levels: Basanti, Mathurapur I, II, Hingalganj, Canning II, Namkhana, Kakdwip, Jayanagar I In Gosaba and Basanti, many residents must travel long distances to collect drinking water using the Vat system.

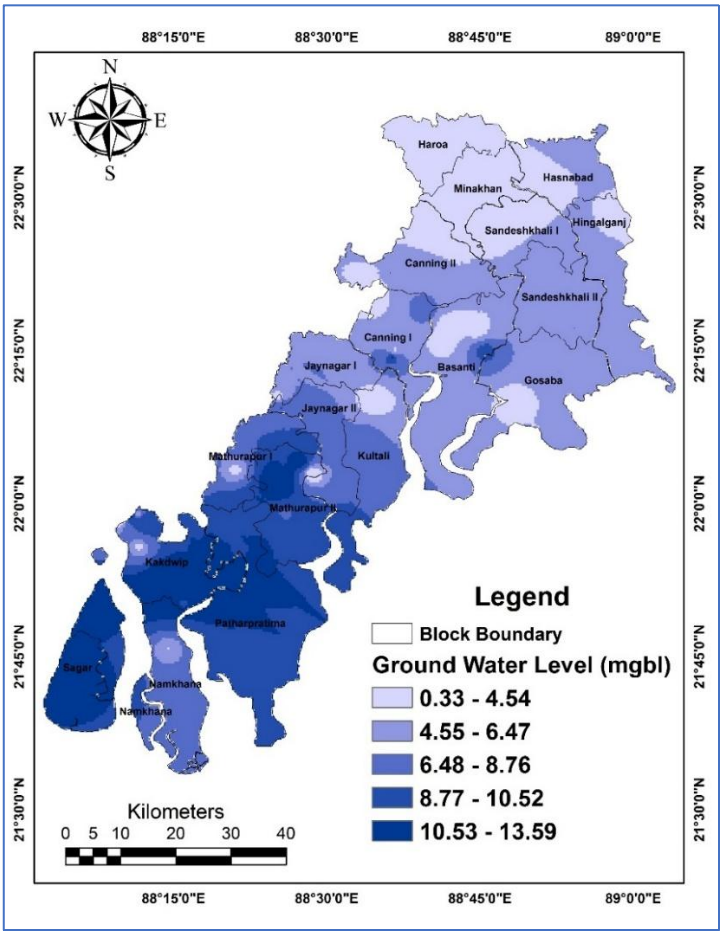

Fig. 7: Spatial distribution of groundwater level

5. Consumable Water Availability and Accessibility Mapping

The comprehensive assessment of surface and groundwater quality in the Sundarbans region highlights significant variations in water quality and availability across different periods and locations. The post-monsoon data revealed trends and regional disparities, emphasizing the need for targeted water resource management strategies to address the challenges posed by salinity, alkalinity, and water accessibility in both surface and groundwater sources.The areas with good freshwater availability and accessibility (red) are primarily concentrated in the northern and central parts of the district comprising Canning I, Basanti, Gosaba, Jaynagar I& II, Kultali, Mathurapur I blocks. This suggests that these regions have a better water supply infrastructure and natural resources compared to other areas. A significant portion of the district, particularly in the southern and eastern regions, falls under the category of moderate freshwater availability and accessibility (yellow) comprising Haroa, Minakhan, Canning II, Kakdwip, Mathurapur II, Patharpratima, Namkhana blocks. These areas may face challenges in meeting their water needs during certain periods or for specific uses.The areas with low freshwater availability and accessibility (green) are scattered throughout the district, but they are more prominent in the southern and western regions comprising the Hasnabad, Sandeshkhali I & II, Hingalgunj, And Sagar. These areas may experience water scarcity and have limited access to clean drinking water.

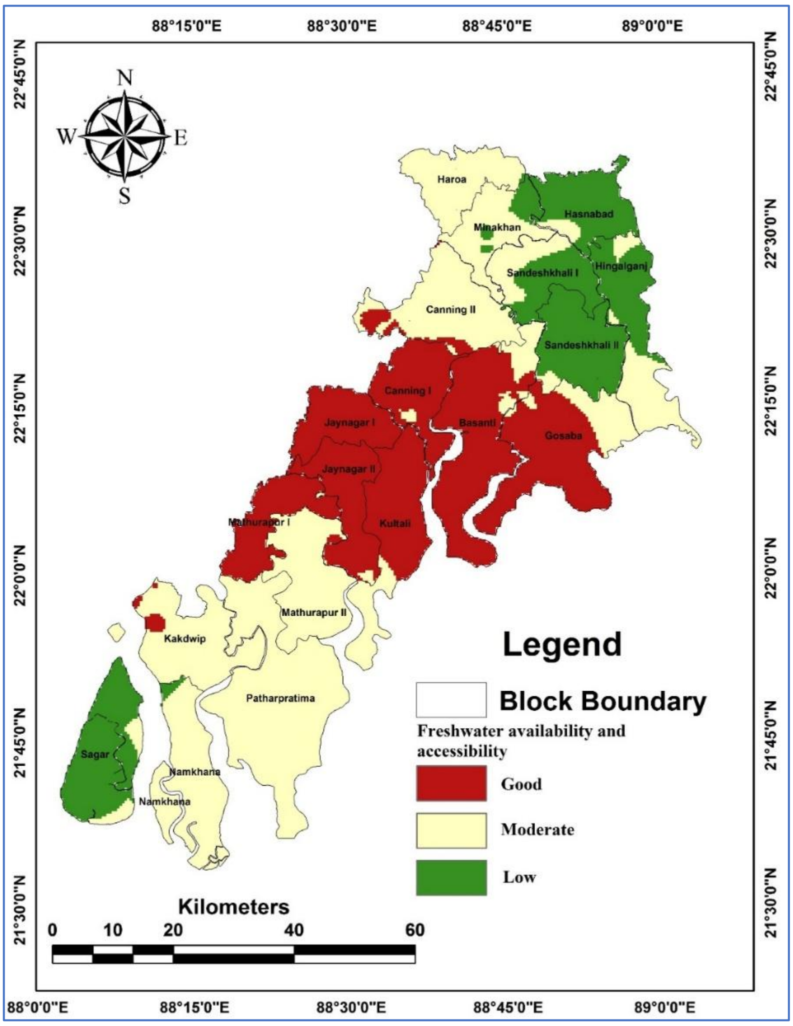

Fig. 8: Consumable fresh water availability and accessibility map

6. Discussion

Water scarcity in the Sundarbans region of India is a significant issue primarily due to high salinity levels in surface and groundwater sources along with variability caused by seasons and climate change. Our research on water quality and availability mapping through remote sensing and GIS approaches was helpful in describing the contemporary situation of water resources in this area.

In our evaluation of water surface quality over 19 blocks of the Sundarbans, we found marked seasonal and spatial variability. For pH, salinity, dissolved oxygen (DO), turbidity, and chlorophyll (CHL), there was continuous variability in pre-monsoon, monsoon, and post-monsoon periods. In particular, we saw the pH levels in post-monsoon were neutral to alkaline, so the water should not show an acidic challenge. Salinity was a prominent context with certain pockets of the study area, where salinity ranged from 7.4ppm -29.7ppm. Vacillations with references to ambient temperatures where temperatures varied between 28°C and 31°C during the time of our collection. In general, the central zone of the Sundarbans had a better quality of water than to the northern and southern zones with better management practices and less salt intrusion from the sea.

Specific areas including Sagar Island, Kachuberia, Bhagabatpur, and Namkhana were found to have poorer overall water quality, likely a result of increased salinity and pollution levels. Areas that demonstrated moderate water quality included Gosaba, Hemnagar, Sandeshkhali, Lebukhali, Malancha, and Bakkhali and suggests that localized management of water uses may be more feasible in these locations. There is also a clear distinction between shallow vs deep groundwater quality in the Sundarbans with depth being particularly relevant in post monsoon systems. Shallow water sources had elevated salinity level from strong seawater intrusion, which made them unsuitable for consumption. On the other hand, deeper groundwater sources were more alkaline, found higher concentrations of bicarbonate, and some sources were considered suitable for consumption. Still, there are distinct regional differences in the quality of groundwater. Specifically, both northern and southern locations in the Sundarbans faced poorer groundwater quality from increased salinity and seawater intrusion. These areas also had unsafe consumption from shallow and deep groundwater sources. The central parts, though also affected by seawater intrusion, had better deep-water quality, making it a more viable option for potable use.

Groundwater quality was not acceptable in certain places, such as Hasnabad, Minakha, Sandeshkhali, Hingalganj, Namkhana, and Sagar Island, requiring different types of interventions for managing water. Other blocks, like Jayanagar, Kultali, Basanti, and Gosaba, had reasonably good groundwater quality. However, the accessibility of water in these blocks was less than optimal because of the Vat system and fewer drinking water tube wells, making effective distribution difficult. Using the Modified Normalized Difference Water Index (MNDWI), we assessed surface water accessibility between blocks, and there were substantial differences:

- High Surface Water Accessibility Zones: Haroa, Meenakha, and Sandeshkhali exhibited high accessibility with MNDWI values ranging from 0.03 to 0.21.

- Moderate Surface Water Accessibility Zones: Hasanabad, Basanti, Canning, Gosaba, Patharpratima, and Namkhana had moderate accessibility with MNDWI values between -0.17 and 0.02.
- Low Surface Water Accessibility Zones: Mathurapur I block had low accessibility with MNDWI values between -0.4 and -0.18.

These findings are significant for the comprehension of water resources spatial availability and the sustainable use of the water resources. The zonal detailed statistics allow for a better understanding of the area that requires immediate attention and intervention. The analysis has highlighted alarming trends of groundwater levels. The average groundwater levels decreased from 3.3 meters below ground level (mbgl) in the year 1996 to 7.67 mbgl in 2022. The decrease in groundwater levels is sharp and is an indication of over-extraction and insufficient recharge, and seasonal fluctuations have also contributed. There is a rapid decline in groundwater level from pre-monsoon to monsoon, followed by some stabilization of levels post-monsoon. Groundwater levels showed similar fluctuations in shallow (15 mbgl) and deep (115 mbgl) regions in the study area. Importantly, the northwestern slice of Sundarbans with arsenic pollution, has very low groundwater levels. The other blocks have medium to high groundwater levels, although saline groundwater is also present.

The limited availability of freshwater supply both in terms of surface and sub-surface water storage facilities is one of the important determinants of agriculture and food security in the Sundarbans. Blocks like Gosaba, Canning, Patharprotima, Kakdip, Sagar and Namkhana are especially relevant here. For example, residents of blocks such as Gosaba and Basanti sometimes have to travel long distances to collect drinking water based on the Vat system indicating the need for improved water management and infrastructure.

7. Conclusion

The accessibility of groundwater varies spatially across the study area. There are six blocks with shallow groundwater levels (groundwater level of < 4.54 M below ground level) – these are: Haroa, Meenakhan, Sandeshkhali I, Hasnabad, Basanti and Canning I, accounting for 33% of all blocks surveyed (33%). Therefore, these six blocks represent the most concentrated area of groundwater accessibility. Eight blocks contain groundwater located at an intermediate depth (between 4.55 and 10.52 M) – these include Basanti, Mathurapur I & II, Hingalganj, Canning II, Namkhana, Kakdwip and Jayanagar I (44% of study area). They also provide moderate to high levels of groundwater accessibility for extraction, generally requiring intermediate levels of technological intervention.

In contrast to its spatial variability with respect to accessibility, the quality of groundwater exhibits a high degree of spatial deterioration, necessitating urgent attention. The classification of WQI indicates three separate ranges or classifications of groundwater quality: Groundwater of Good Quality (17.9 – 25.23 WQI) has limited availability (six blocks only; comprising 33% of surveyed blocks), and provides drinking water that is free of harmful contaminants. Groundwater of Medium Quality (25.24 – 31.77 WQI) can be found in eight blocks (comprising 44% of surveyed blocks) and is suitable for human consumption with some degree of treatment. Groundwater classified as Poor Quality (31.78 – 43.16 WQI) contains extremely high amounts of contaminants that render it unsafe for direct human consumption, thus posing a serious threat to human health.

The availability of surface water demonstrates a strong spatial pattern consistent with the deltaic and estuarine nature of the district. The areas of highest surface water availability are located within three blocks, constituting a total area of 17% of the study area (MNDWI = 0.03–0.21), where large water bodies and extensive river networks exist in wetland-rich and tide-influenced environments. The broader region of moderate surface water availability (MNDWI = 0.02–0.17) comprises six blocks and comprises 33% of the area. For this region, natural storage capacity varies greatly depending upon the season. Mathurapur I block displays very little surface water (MNDWI = 0.18–0.4) due to its large agricultural and settlement population.

Surface water quality is similarly poor. Good quality surface water (WQI = 115.54–166.62) is limited to three blocks (17% of the area). Medium quality surface water (WQI = 166.63–203.97) exists in eleven blocks (61% of the area), where pollution from agricultural runoff and urban waste diminishes the usability of water. Poor quality surface water (WQI > 203.98–255.6) exists in five blocks (28% of the area), where industries release high levels of pollutants accompanied by organic matter that require extensive treatment before any potential use.

In general, the analysis of the data presents a clear distinction between the total number of blocks with access to groundwater (77% of total blocks) and that of those maintaining good groundwater quality (33% of total blocks). In addition, we know that 83% of the surface water in blocks classified as mid/poor surface water has experienced degradation to levels considered as poor (WQI > 166.63), demonstrating the widespread extent of surface water contamination.

Regarding water systems and contaminated areas, there are some specific areas of concern. These blocks have specific aspects to consider regarding their performance, such as the Hindalganj, Sandeshkhali I, Sandeshkhali II and Meenakhan areas, where both surface water and groundwater quality deteriorate concurrently; or there may be blocks with fewer issues but better quality, such as Jayanagar I, Jayanagar II and Vasanthi blocks (where both quality systems are relatively better than the comparison zones). Thus, they can serve as model areas for protocols related to management techniques.

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