From Surface to Subsurface: Evaluating Wetlands as Groundwater Recharge and Filtration Systems

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Abstract: Wetlands play a vital role in groundwater recharge and filtration, yet their mechanisms remain poorly understood in the context of subsurface hydrology. This review synthesizes the current body of research, focusing on the physical, chemical, and biological processes that enable wetlands to serve as effective groundwater recharge systems. We explore various methodologies such as hydrological monitoring, vadose zone characterization, hydrochemical and isotopic analysis, and numerical modelling to assess the contribution of wetlands to groundwater systems. Additionally, we identify research gaps and propose future directions for wetland hydrology, emphasizing the need for a holistic, systems-based approach to groundwater management.

Keywords: Wetlands, Groundwater Recharge, Filtration, Isotopic Analysis, Hydrochemical Analysis, Numerical Modelling

I Introduction

Wetlands, often referred to as nature's kidneys, are dynamic ecosystems that provide numerous ecosystem services, including water purification, flood regulation, and biodiversity support (1). Across various regions, such as the East Kolkata Wetlands, Sundarbans Mangrove Wetlands, Rasik Beel Wetland Complex, Purbasthali Oxbow Lake (Chupi Char), Santragachi Jheel, Kanwar Taal (Mithila Wetland), Nalban Wetlands, and Patlakhawa Wetlands, these ecosystems play a vital role in groundwater recharge and filtration (2).

Notably, wetlands like the Sundarbans, with their vast mangrove forests, protect coastal regions while aiding in water filtration (3), while the East Kolkata Wetlands are celebrated for their role in treating urban wastewater (4). Similarly, the Rasik Beel Wetland Complex and the Purbasthali Oxbow Lake serve as crucial recharge zones in their respective regions, showcasing unique hydrological interactions (5). Santragachi Jheel and Nalban Wetlands exemplify the importance of peri-urban wetlands in maintaining ecological balance and groundwater quality (6). Kanwar Taal and Patlakhawa Wetlands highlight the diversity of wetland ecosystems in supporting water recharge in agricultural and semi-arid landscapes (7).

Groundwater recharge in wetlands occurs when surface water infiltrates through the soil and percolates into the underlying aquifer (8). This process can be influenced by numerous factors, including soil permeability, vegetation cover, water table dynamics, and hydrological connectivity between surface water and groundwater systems (9). The interaction between these elements forms the basis of the wetland's ability to filter out contaminants, including nutrients, heavy metals, and organic pollutants (10).

This review aims to provide an overview of methodologies for evaluating wetland groundwater recharge and filtration, highlighting the critical processes involved. Additionally, recent advancements in research and a framework for future studies are examined, building upon previous work in wetland hydrology (11) and ecohydrological modeling (12).

II Case Studies of Wetlands

East Kolkata Wetlands: The East Kolkata Wetlands are a Ramsar site known for their dual role in wastewater treatment and groundwater recharge. The combination of natural filtration processes and human intervention enhances their effectiveness. However, urban encroachment and pollution pose significant challenges.

Sundarbans Mangrove Wetlands: Located in the Ganges-Brahmaputra delta, the Sundarbans Mangrove Wetlands contribute to groundwater recharge through tidal dynamics and sediment deposition. The salinity gradient and its impact on subsurface water quality are key areas of ongoing research.

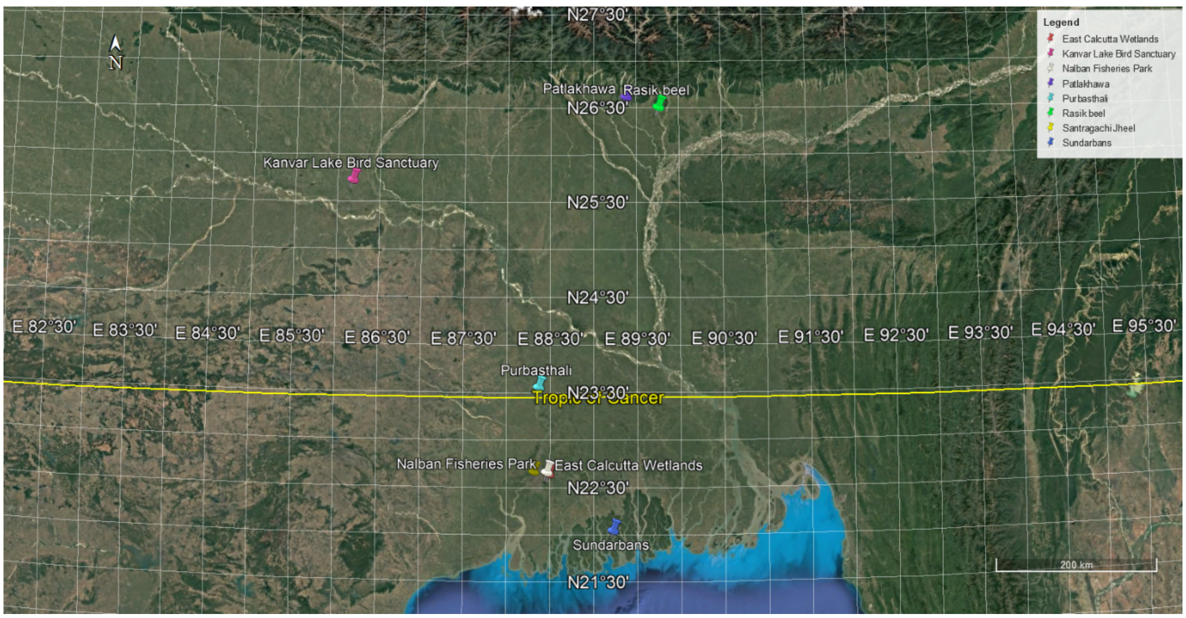

Figure 1: **Area of interest showing the location of wetlands in and around West Bengal**

Rasik Beel Wetland Complex: This complex in West Bengal serves as a critical recharge zone for the surrounding agricultural landscape. Seasonal hydrological studies suggest significant recharge during the monsoon season, though data on subsurface dynamics are limited.

Purbasthali Oxbow Lake (Chupi Char): This oxbow lake demonstrates the interaction between surface and groundwater systems. Studies emphasize its role in seasonal recharge, but the impact of agricultural runoff and eutrophication requires further investigation.

Nalban Wetlands: Located in the urban sprawl of Kolkata, the Nalban Wetlands face challenges from pollution and urban development. Despite these pressures, they provide critical groundwater recharge and filtration services.

Santragachi Jheel: Primarily known for its biodiversity, Santragachi Jheel also plays a role in urban groundwater recharge. However, rapid urbanization and reduced catchment area threaten its hydrological functions.

Kanwar Taal (Mithila Wetland): One of Asia's largest freshwater oxbow lakes, Kanwar Taal is vital for groundwater recharge in the Mithila region. Seasonal variations in water levels and their influence on aquifer recharge are key research topics. **Patlakhawa Wetlands:** Situated near the India-Bhutan border, these wetlands are integral to local groundwater dynamics. Limited research highlights their potential, but comprehensive hydrological studies are needed.

III Methodology

III.a Hydrological Monitoring

It is fundamental to understanding how wetlands interact with groundwater systems. Two primary components are involved:

III.a.1 Water Table Dynamics

Piezometers and monitoring wells are installed at various depths within and around the wetland to measure spatial groundwater head gradients. These measurements allow for the assessment of hydraulic conductivity and the potential for groundwater recharge. By using pressure transducers with data loggers, high-frequency monitoring is possible, which is particularly useful for analyzing recharge events triggered by rainfall (13). This real-time data can be critical for understanding temporal variations in groundwater flow and recharge rates.

III.a.2 Surface Water-Groundwater Interaction

The interaction between surface water and groundwater is assessed using synoptic streamflow measurements and dye tracer studies (14). These methods quantify seepage rates, which directly influence the recharge process. Hydrograph separation is also used to distinguish between baseflow (groundwater contribution) and stormflow (surface runoff), thus identifying the groundwater contribution to wetland hydrology (15).

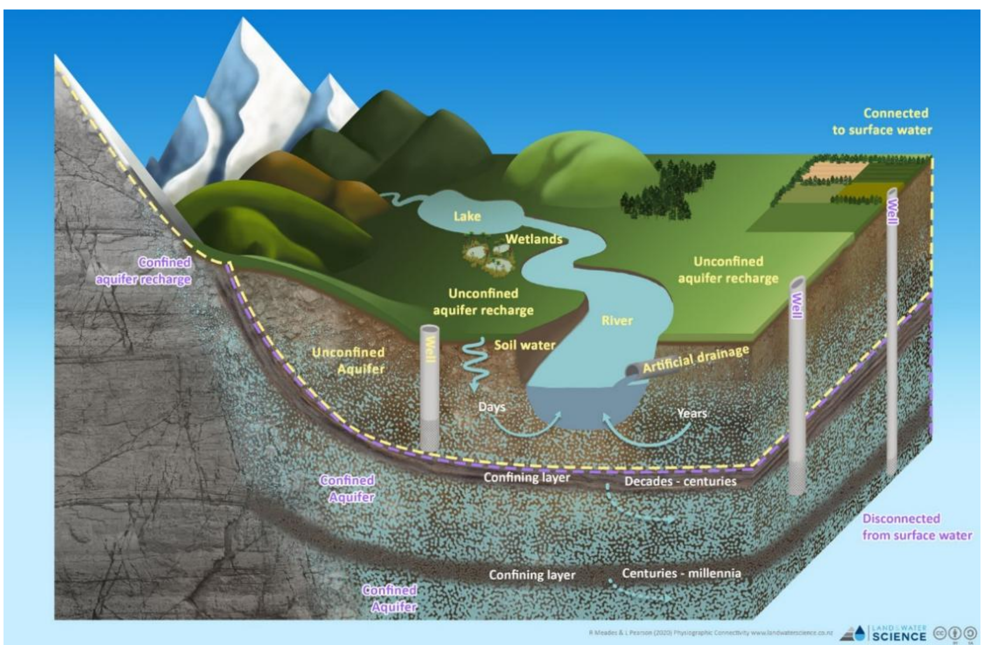

Figure 2: **Wetland influencing groundwater environment (Source: Land, Water, Science)**

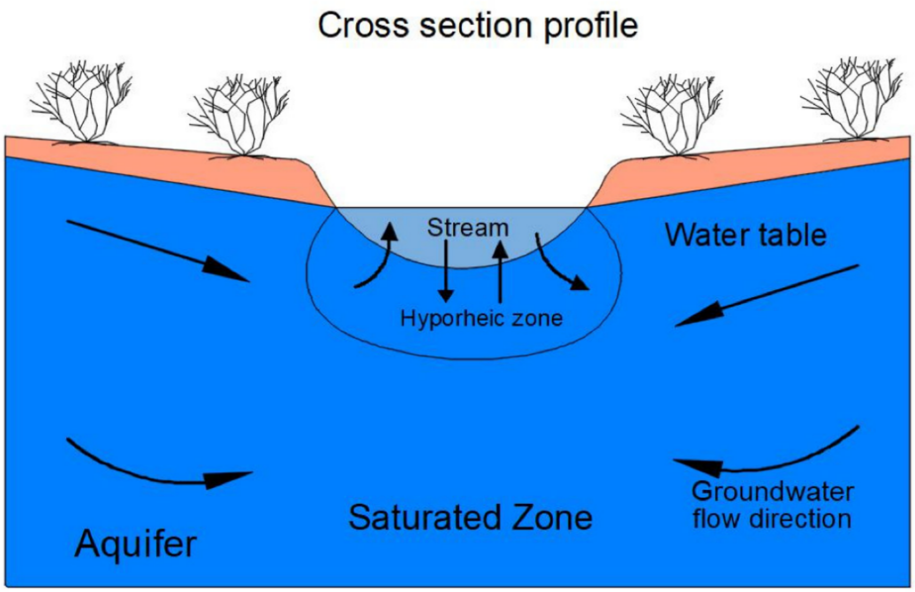

Figure 3: **Groundwater system in a vertical plane (Source: (16))**

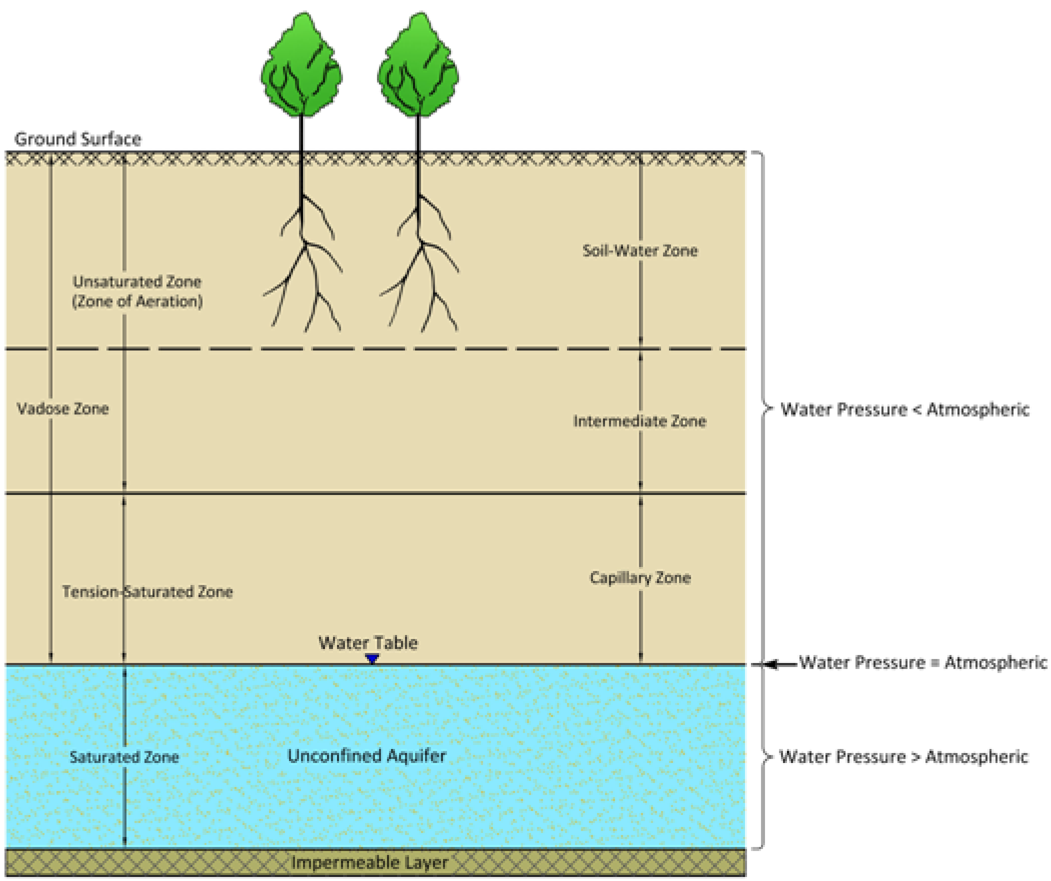

Figure 4: **Hydrologic zones below the ground.**

III.b Vadose Zone Characterisation

The vadose zone, which lies between the ground surface and the water table, is crucial for understanding the infiltration and filtration capacity of wetlands.

III.b.1 Infiltration and Permeability Tests

In-situ tests, such as constant and falling head permeameter tests, provide essential data on the hydraulic conductivity of wetland soils. These tests can be conducted in areas with varying vegetation cover to assess the impact of plant roots on soil permeability (17). In addition, inverse modelling techniques can be applied using soil moisture data to estimate vertical water fluxes through the vadose zone (18).

III.b.2 Soil Physical Properties

Soil samples are collected for analysis of texture, bulk density, porosity, and matric potential. These properties are crucial for understanding how water moves through the soil and the potential for contaminant filtration. Additionally, mineralogical analysis using X-ray diffraction (XRD) can identify minerals that affect soil permeability and its ability to filter pollutants such as heavy metals (19).

III.c Hydrochemical and Isotopic Analysis

Hydrochemical and isotopic analysis are key tools for studying the chemical processes occurring within wetlands and their influence on groundwater recharge.

III.c.1 Hydrochemical Profiling

Ion chromatography and inductively coupled plasma mass spectrometry (ICP-MS) are employed to analyze major ions, trace metals, and nutrients in wetland water. These analyses help determine the chemical composition of groundwater recharge and assess how wetlands attenuate pollutants (20).

III.c.2 Stable Isotope Technique

Stable isotopes, such as $\delta^2 H$ and $\delta^{18}O$, are powerful tools in hydrological studies, particularly for tracing water movement and interactions within wetlands. These isotopes help scientists identify the sources of water—whether from direct rainfall, surface runoff, or groundwater—and understand how water flows through the wetland system. By analyzing their ratios in water samples, we can track recharge pathways and seasonal variations in water sources. Similarly, isotopes like $\delta^{15}N$ and $\delta^{13}C$ play a crucial role in studying the biogeochemical processes within wetlands. For instance, $\delta^{15}N$ can be used to trace nitrogen cycling, shedding light on processes such as denitrification or nitrate uptake by plants. On the other hand, $\delta^{13}C$ provides insights into the decomposition of organic matter and carbon cycling, which are essential for understanding how wetlands remove nutrients and improve water quality. Together, these isotopes provide a comprehensive understanding of both the hydrological and biochemical functions of wetlands, making them invaluable for evaluating groundwater recharge and pollutant filtration mechanisms.

III.d Numerical and Reactive modelling

Numerical and reactive transport modeling plays a critical role in understanding the movement of water and contaminants within wetland-soil systems, offering profound insights into groundwater recharge processes and pollutant attenuation mechanisms. These models use computational techniques to simulate hydrodynamic processes such as infiltration, percolation, and the interaction between surface and subsurface water. By solving complex equations that describe the flow of water and the transport of solutes, numerical models provide a detailed picture of water dynamics, while reactive transport models go a step further to incorporate chemical and biological interactions influencing contaminant fate. Key processes such as advection, diffusion, dispersion, sorption, desorption, biodegradation, and redox reactions are captured to predict how pollutants like nutrients, heavy metals, and organic compounds behave and transform within the system. Additionally, these models simulate the recharge process by accounting for variables like hydraulic conductivity, seasonal variations, and aquifer-wetland interactions, which are crucial for estimating groundwater sustainability. They also help identify critical zones with high pollutant attenuation capacity, optimize wetland design to enhance natural filtration, and forecast the long-term impacts of human activities or climate change on wetland ecosystems. By offering a comprehensive framework to evaluate and predict the hydrological and chemical dynamics of wetlands, numerical and reactive transport modelling supports effective environmental management, aids in policy development, and ensures the conservation of these vital ecosystems.

III.e Recharge Modelling

MODFLOW and HYDRUS-1D/2D are widely utilized numerical modeling tools that effectively simulate water movement through the unsaturated and saturated zones, providing critical insights into groundwater recharge processes. MODFLOW, a modular finite-difference flow model developed by the U.S. Geological Survey, is primarily used to simulate groundwater flow in the saturated zone. It allows users to model aquifer systems, predict groundwater levels, and assess flow dynamics under varying hydrological and geological conditions. On the other hand, HYDRUS-1D and HYDRUS-2D excel in simulating water, heat, and solute movement in the unsaturated zone, offering fine-grained analyses of infiltration, evaporation, and root water uptake processes. Together, these models can be calibrated with field data, such as soil moisture content, hydraulic conductivity, and groundwater levels, to accurately estimate groundwater recharge rates. Moreover, the integration of temporal climatic data, including rainfall patterns and evapotranspiration rates, enables these models to capture the variability in recharge under different climatic and land-use scenarios. For instance, by incorporating changes in rainfall intensity and frequency, as well as alterations in vegetation cover or land management practices, these models can predict how recharge rates fluctuate in response to natural or anthropogenic influences. This capability is particularly valuable in regions vulnerable to climate change, where understanding the interplay between precipitation and evapotranspiration is essential for sustainable water resource management. By offering a robust framework to evaluate the impact of temporal and spatial variability, MODFLOW and HYDRUS-1D/2D provide a reliable foundation for designing water management strategies, conserving groundwater resources, and mitigating the effects of land-use changes and climate variability on recharge processes.

III.f Reactive Transport Modelling

PHREEQC, a powerful geochemical modelling software, is extensively used to simulate the complex chemical reactions and contaminant attenuation processes occurring within a wetland's subsurface environment. It is particularly effective in modelling the interactions between water chemistry and subsurface materials, enabling researchers to understand and predict the fate of pollutants as they traverse through the wetland-soil system. Reactive transport models like PHREEQC incorporate a range of processes, including adsorption, where contaminants such as heavy metals and organic compounds bind to soil or sediment particles, thus reducing their mobility and bioavailability. The software also accounts for microbial activity, a critical component of natural attenuation in wetlands, where microorganisms catalyse the breakdown of organic pollutants, nitrogen compounds, and other contaminants through processes such as denitrification and sulphate reduction. Furthermore, PHREEQC can simulate mineral precipitation and dissolution reactions, which play a vital role in immobilizing pollutants like phosphates and heavy metals by forming stable mineral phases. These capabilities allow for a detailed assessment of the biogeochemical processes that regulate contaminant attenuation, helping to evaluate the efficiency and long-term sustainability of wetlands as natural filtration systems. Additionally, PHREEQC can model the dynamic interplay between hydrological conditions, such as water flow and saturation, and chemical reactions, providing insights into how changes in environmental factors influence the wetland's filtration capacity. By simulating these intricate processes, PHREEQC enables researchers

and environmental managers to predict the long-term performance of wetlands under varying pollutant loads, climatic conditions, and land-use changes, supporting the development of strategies for wetland conservation, pollution control, and sustainable water management.

IV Research Gaps and Future Directions

Long-Term Hydrological Monitoring: Most studies focus on short-term data, overlooking long-term variations due to climate change and urbanization. Long-term, high-frequency monitoring in wetlands like East Kolkata and Santragachi Jheel is essential to capture seasonal and inter-annual groundwater recharge dynamics.

Soil Heterogeneity and Subsurface Hydrology: Wetland soils exhibit significant spatial variability in permeability and composition, yet this is often underexplored. Comprehensive vadose zone characterization in regions like East Kolkata and Nalban Wetlands is needed to understand soil dynamics and pollutant filtration capacities.

Real-Time Data on Temporal Variation: Availability of real-time hydrological data for wetlands such as East Kolkata Wetlands, Sundarbans, and Kanwar Taal is insufficient. This data would allow for the analysis of temporal variations in groundwater flow and recharge.

Tidal and Seasonal Impacts on Recharge: The role of tidal dynamics in groundwater recharge in coastal wetlands, such as the Sundarbans, remains poorly understood, particularly in relation to salinity gradients and seasonal freshwater influx. More research is needed on groundwater salinization and its impact on recharge potential.

Pollutant Filtration in Agricultural Wetlands: The mechanisms of nutrient and pesticide attenuation in agricultural wetlands like Purbasthali Oxbow Lake are insufficiently studied. Understanding the role of wetland vegetation and microbial activity in filtering agricultural runoff is crucial for effective groundwater management. **Reactive Transport and Contaminant Modelling:** Limited studies use reactive transport modelling to predict long-term pollutant dynamics in wetland soils. Tools like PHREEQC should be used to simulate contaminant movement and assess the long-term sustainability of filtration processes in wetlands like East Kolkata.

V Conclusion

Wetlands play a critical role in groundwater recharge and filtration, offering a natural solution to the growing challenges of water scarcity and contamination. In regions like West Bengal, where urbanization, agricultural runoff, and tidal dynamics influence wetland functioning, understanding the hydrological processes is crucial for sustainable groundwater management. Without a comprehensive understanding of wetland-soil-water interactions, groundwater recharge rates, and pollutant attenuation mechanisms, we risk undermining the very ecosystems that support water security. Failure to monitor and address key factors such as long-term hydrological cycles, soil heterogeneity, and the impact of urbanization will likely lead to a decline in wetland effectiveness. Inadequate management of these systems could result in reduced groundwater quality, exacerbating water scarcity issues, particularly in areas where groundwater is a primary water source. Additionally, unsustainable land use changes and pollution could degrade wetland ecosystems, reducing their ability

to filter contaminants, such as nutrients and heavy metals, thus worsening water quality. In the near future, neglecting these critical monitoring and research areas could lead to more frequent water shortages, contamination of groundwater supplies, and loss of biodiversity. This could exacerbate socio-economic challenges, particularly for communities reliant on groundwater for agriculture and drinking water. Therefore, it is imperative to take immediate, coordinated steps to integrate long-term monitoring, advanced hydrological modelling, and socio-economic considerations into wetland management strategies. By doing so, we can ensure the continued role of these ecosystems in sustaining groundwater resources and securing water availability for future generations.

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References

[1] William J Mitsch and James G Gosselink. *Wetlands*. John Wiley & Sons, 5th edition, 2015.

[2] Debashis Ghosh and Bappaditya Ghosh. East kolkata wetlands: A multifunctional urban ecosystem. *Journal of Urban Ecology*, 6(1):1–12, 2020.

[3] Abhijit Mitra. *The Sundarbans of India: A development analysis*. IUCN, 2005.

[4] Partha Chatterjee and Harm Vogtmann. Wetland treatment of urban wastewater: The east kolkata model. *Ambio*, 42(2):151–163, 2013.

[5] Shreya Malik and Subodh Chandra Pal. Groundwater recharge potential of floodplain wetlands in eastern india. *Environmental Earth Sciences*, 80(3):1–15, 2021.

[6] Sudeshna Banerjee and Priyabrata Santra. Urban wetlands of kolkata: Challenges and conservation strategies. *Journal of Environmental Management*, 246:334–343, 2019.

[7] Rakesh Kumar Singh and Anil Kumar Sharma. Wetland ecosystems in semi-arid regions: A case study of kanwar taal, bihar. *Ecological Indicators*, 115:106382, 2020.

[8] Marios Sophocleous. Interactions between groundwater and surface water: the state of the science. *Hydrogeology Journal*, 10(1):52–67, 2002.

[9] Richard W Healy, Thomas C Winter, James W LaBaugh, and O Lehn Franke. *Water and watersheds: An integrated approach*. CRC Press, 2010.

[10] K Ramesh Reddy and Ronald D DeLaune. *Biogeochemistry of wetlands: science and applications*. CRC press, 2005.

[11] William R Wright and Kent S Novakowski. Hydrogeology of wetlands. *Groundwater*, 49(5):645–652, 2011.

[12] Hao Wang, Yongqin David Chen, and Ming Ye. Wetland ecohydrological modeling: Current challenges and perspectives. *Water Resources Research*, 54(8):5201–5216, 2018.

[13] Grey R Evenson, Heather E Golden, Charles R Lane, Daniel L McLaughlin, and Ellen D'amico. Depressional wetlands affect watershed hydrological, biogeochemical, and ecological functions. *Ecological Applications*, 28(4):953–966, 2018.

[14] Ronald Baker, Kátya Abrantes, and Ilka C Feller. Stable isotopes suggest limited role of wetland macrophyte production supporting aquatic food webs across a mangrove-salt marsh ecotone. *Estuaries and Coasts*, 44(6):1619–1627, 2021.

[15] Alexandra Tietz, Alexander Kirschner, Günter Langergraber, Kirsten Sleytr, and Raimund Haberl. Characterisation of microbial biocoenosis in vertical subsurface flow constructed wetlands. *Science of the Total Environment*, 380(1-3):163–172, 2007.

[16] Dolon Banerjee and Sayantan Ganguly. A review on the research advances in groundwater–surface water interaction with an overview of the phenomenon. *Water*, 15(8):1552, 2023.

[17] Daniel Hillel. *Introduction to environmental soil physics.* Elsevier, 2003.

[18] Thomas W Gardner. *Surface hydrology, sediment transport dynamics, and remote sensing of disturbed watersheds in a humid temperature region*, volume 9109. PennState, Environmental Resources Research Institute, 1991.

[19] Qixiang Wu, William H. Hendershot, William D. Marshall, and Ying Ge and. Speciation of cadmium, copper, lead, and zinc in contaminated soils. *Communications in Soil Science and Plant Analysis*, 31(9-10):1129–1144, 2000.

[20] Bernard Ladouche and Philippe Weng. Hydrochemical assessment of the rochefort marsh: Role of surface and groundwater in the hydrological functioning of the wetland. *Journal of hydrology*, 314(1-4):22–42, 2005.