Understanding the Exchange Process of Surface and Sub-surface Hydrological System for Safe and Sustainable Water Security Plan in Shilabati River Basin: Associated Risks and Eco-friendly Remediation

Synopsis

Submitted by

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(Registration Number: D-7/ISLM/79/18)

For the fulfillment of

Doctor of Philosophy

(Science)

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Kolkata, India

2023

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SYNOPSIS

The population explosion and environmental degradation are closely intertwined, exerting a dual impact on the Earth's surface. The rivers, which are vital sources for sustaining human life, are under threat, necessitating immediate action. The watershed, which refers to the hydrologic unit drained by a specific river system, is plagued by numerous ecological and environmental issues (Khanduri et al. 2023). It encompasses physical, biological, socio-economic, and socio-political aspects and aims to plan and implement resource management activities. Integrated watershed management involves the execution of action plans that assess both natural and human-made resources, while considering social, economic, and political factors to achieve specific ecological and socio-economic objectives. Rivers are natural hydro-ecological units, subject to human intervention and modifications to meet our needs. Human activities such as constructing hydro-power plants, dams, and reservoirs not only disrupt the normal flow regime but also have far-reaching implications on the surrounding and neighboring watersheds. The imposition of dams, barrages, and reservoirs on major rivers, along with diverting flow from smaller rivers, creates water stress in the latter. Therefore, it is crucial to assess the hydrogeology and hydro morphology of these small watersheds to ensure their capacity for flow augmentation.

In this context, the following research proposal aims to analyze and evaluate the watershed fed by the Shilabati River in West Bengal. The Shilabati River serves as a pick barrage for the Kangsabati reservoir project, initiated in 1956. This diversion of water from the Shilabati to the Kangsabati river basin intensifies the criticality and vulnerability of the former, particularly during non-monsoonal periods, when it fails to adequately serve its own ailing watershed. Hence, it is essential to assess and implement a sustainable watershed management program, specifically evaluating the groundwater and surface water potentiality (Halder et al. 2020).

The Shilabati River is a significant river basin in eastern India and a contributing factor to the formation of the Rupnarayan River. It originates from the La para village of the Puncha block near the Shilabati Mandir in Puruliya and flows into the Rupnarayan River near Srirampur village in the Ghatal block of Paschim Medinapore. The general slope of the region is in a southwest direction. The basin's geographical coordinates range from 22^{o}32'N to 23^{o}15'N latitude and 86^{o}40'N to 87^{o}46'E longitude (Fig.1). The river traverses through three distinct blocks of West Bengal, namely Puruliya, Bankura, and Paschim Medinapore, encompassing a basin area of 3880 km^{2}. The river exhibits varying geology, with hard crystalline rock in the upper reach, older alluvium and laterite in the middle reach, and younger alluvium in the downstream. Additionally, the river experiences a combination of flash floods in the upstream and monsoonal and tidal floods in the downstream stretches. Its main tributaries include Joypanda, Silai, Kubai, Parang, Purandar, among others. Major towns such as Taldanga and Simlapal in Bankura, and Garbeta, Salboni, and Chandrakona in Paschim Medinapore are situated along the basin. There are a few artesian aquifers and artesian wells along the banks of the Shilabati, which facilitate agricultural irrigation. However, these sources are showing a decreasing trend due to growing water demand. **The key concerns regarding the river basin are highlighted below (Fig.2).**

I. The upper basin has been experiencing severe drought conditions, resulting in a decrease in crop yields in recent years, with temperatures surpassing 47°C.
II. The downstream region, particularly in the Ghatal block of Paschim Medinapore, is subjected to high flood discharges, aggravated by poor management of groundwater and surface water resources.
III. The occurrence of extensive embankment breaches and bank erosion is prevalent during periods of high-water flow.
IV. Forest distortion, desertification, and an increase in exposed bare soil are contributing to higher surface runoff, posing challenges to the ecosystem.
V. The basin faces significant issues of high runoff and excessive sedimentation, especially in the Garbeta block, which disrupts the normal ecological flow of the river.
VI. Along the basin, there is a notable problem of water-induced rill and gully erosion, indicating inadequate groundwater recharge.
VII. Unsustainable extraction of groundwater resources due to the deteriorating condition of the river channels has led to a decline in the groundwater levels in nearby aquifers.
VIII. Upstream sections exhibit evidence of skeletal fluorosis and bone deformation due to elevated fluoride content in the groundwater.
IX. The middle and downstream sections of the basin have considerably higher concentrations of phosphate and iron, leading to recurrent reports of health-related issues.
X. Groundwater sources, such as tube wells and dug wells, have undergone qualitative degradation, with frequent reports of foul smells and the presence of dirt particles during pumping.

Index map of the study area

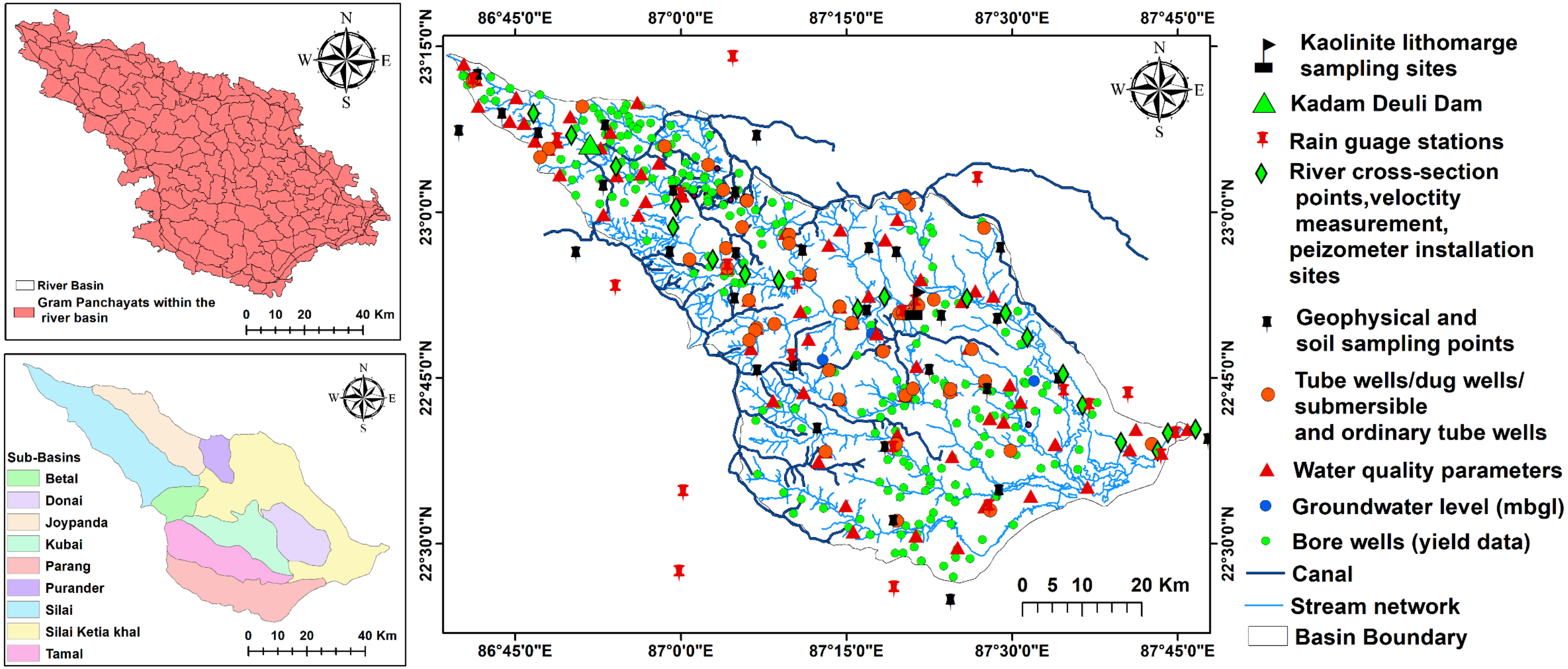


Fig. 1. Index Map of the Study Area

Fig. 2 (a) Dying condition of Shilabati river channel; (b) condition of dug well used of domestic purpose and (c) evidences of Skeletal fluorosis and bone deformation within the river basin.

Research Gap of the study

- Investigating the interaction between ground and surface water in complex terrain conditions within a river basin.
- Assessing the recharge patterns of groundwater in different sections of the river.
- Evaluating the impact of climate change on groundwater availability and developing a groundwater level index to assess drought conditions.
- Applying the MIKE-FEFLOW modeling software to simulate groundwater flow under changing climate conditions and analyze the influence of drought intensity on groundwater resources.
- Integrating new machine learning (ML) and Fuzzy MCDM techniques into groundwater research.
- Incorporating field-based factors to estimate potential zones for groundwater resources.
- Examining the efficiency of low surface area biochar and cost-effective earth materials for removing contaminants such as iron, phosphate, and fluoride.

Objective of the study

The primary goal of the study is to achieve sustainable watershed management by analyzing the interaction between groundwater and surface water flow, estimating recharge potential zones, and implementing contaminant remediation techniques using natural adsorbents.

Scope of work

- Hydro-meteorological, hydro-geological, and hydro-geomorphic conditions of the study area will be documented comprehensively.
- Water budget of the study area will be carefully calculated, and an estimation of groundwater resources will be made.
- Through the utilization of modeling techniques and the installation of piezometers, the continuous flow of groundwater and its interaction with the river channel will be identified.
- Various landscape and channel patterns will be examined in relation to their impact on recharging the subsurface aquifer.
- The analysis of groundwater flow in the study area will involve estimating aquifer characteristics using the Dar Zarrouk Parameters at specific locations.
- A comprehensive assessment of the study area's groundwater resource will be conducted, considering multiple factors, including groundwater quality for irrigation and suitability for drinking water purposes.
- By employing field-based conditioning factors, standard formulae, and advanced machine learning techniques, the potential zones for groundwater recharge will be estimated.
- A holistic approach will be taken to develop an integrated watershed strategy plan, which will include the identification of Managed Aquifer Recharge (MAR) Sites and the provision of recommendations for areas affected by water scarcity.
- An environmentally friendly and enhanced treatment method will be implemented to address the presence of three major groundwater contaminants: iron, phosphate, and fluoride. This treatment will involve the use of biochar and natural clay.

Novelty of the study

- A comparative analysis will be conducted on four MCDM models in the field of environmental studies.
- The application of Fuzzy DEMATEL will be utilized in the context of environment and climate studies.
- A novel estimation method will be employed to assess groundwater drought and establish a groundwater level index, which has not been previously undertaken.
- This study presents an innovative methodological framework that compares fuzzy MCDM and machine learning techniques, incorporating field-based conditioning factors.

- A novel methodological framework will be introduced in this study to gain insights into the exchange process, utilizing MIKE-FEFLOW and piezometer installation.
- The FSE-GVI model will be employed as a novel approach to identify groundwater vulnerable zones.
- The focus of this study is to identify a river basin suitable for agriculture and determine priority areas for management using a novel clustering tool that combines fuzzy logic techniques in R and Geographical Information System.
- The study will explore the application of a low-cost, natural, and eco-friendly adsorbent for the enhanced removal of iron, phosphate, and fluoride.

Methodology of the study

- ❖ Delineation of the study area with help of remote sensing/ GIS and collection of topographical maps of the study area from Survey of India.
- ❖ The preparation of a land use/land cover map, assessment of drainage density, and geological mapping of the study area are conducted using remote sensing/GIS. Basin properties such as form ratio and elongation ratio are measured.
- ❖ Various physical and non-physical datasets are collected from different government and non-government organizations for analysis.
- ❖ Meteorological data is collected from IMD and statistically analyzed using modern statistical software. A water budget model of the study area is prepared using the Soil Water Assessment Tool model and calibrated and validated through field study.
- ❖ The study area includes a questionnaire survey among locals to estimate water demand and identify water-related problems during different seasons.
- ❖ Cross-sections are selected along the river, considering different channel patterns at the upstream and downstream parts, to measure river velocity using current meters.
- ❖ Soil samples are collected from each horizon to determine soil permeability, hydraulic conductivity, and conduct grain size analysis in the soil laboratory. Statistical representation is made based on the results using Origin Pro.
- ❖ Dar Zarrouk parameters are determined through Vertical Electrical Sounding (VES) using the Schlumberger arrangement to identify groundwater potential zones.
- ❖ An aqui-potential map of the basin is prepared to understand groundwater flow and head using the MIKE-FEFLOW model.
- ❖ Recharge potential zones are identified based on field-based parameters, and machine learning techniques (XGBoost, Random Forest, and Naïve Bayes) as well as Fuzzy MCDM techniques are applied.
- ❖ The study involves investigating the exchange process between ground and surface water using mini drive point piezometers and mathematical models to identify suitable Managed Aquifer Recharge sites.

- ❖ Recharge potential zones are identified based on field-based parameters, machine learning techniques (XGBoost, Random Forest, and Naïve Bayes), and Fuzzy MCDM techniques.
- ❖ The study focuses on assessing drinking water suitability and developing a groundwater vulnerability index using the FSI-GVI model.
- ❖ Groundwater irrigation suitability is evaluated using the Fuzzy EDAS technique, and clustering of sampling sites is performed using the Fuzzy C mean clustering technique.
- ❖ The study aims to enhance fluoride removal from groundwater by using red and white kaolinite lithomarge to develop a low-cost, eco-friendly defluoridation unit in rural areas of the Shilabati river basin, West Bengal.
- ❖ The study examines the adsorption efficiency of low surface area hardwood biochar and explores modifications for enhanced removal of cationic (Fe+) and anionic (PO_4^{3-}) nutrients from aqueous solution.
- ❖ The study involves selecting suitable sites for Managed Aquifer Recharge using Fuzzy MCDM techniques and validating those using statistical approaches and pumping tests for designing infiltration galleries and radial collector wells, aiming for sustainable groundwater management of the river basin.

Brief notes on the results and discussion of the research

The present research concentrates on addressing the water supply challenges and highlighting the importance of groundwater resources in the Shilabati River basin. It explores various aspects, including both micro and macro perspectives. Additionally, this study delves into comprehending the physical and non-physical attributes of groundwater contamination, as well as the behavior of pollutants and their fate within the sub-surface environment of the river basin.

The Shilabati River originates from the geological structure of the Chotonagpur gneissic complex, which experiences poor groundwater recharge and suffers from annual drought scenarios, resulting in prolonged water scarcity. This research aims to address this issue by employing various statistical techniques and multi-criteria decision-making approaches (MCDM). To achieve the research objectives, the morphometric characteristics of nine sub-watersheds within the Shilabati River basin, covering a total area of 3881 km^2, was estimated. Principal Component Analysis (PCA) was utilized to group these characteristics into three components, and K-means clustering was used to categorize the sub-watersheds into three clusters based on morphometric asymmetry. The prioritization of the basins, considering recharge and infiltration capacity, was carried out using three MCDM techniques: Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS), Complex Proportional Assessment (COPRAS), and VlseKriterijumska Optimizacija I Kompromisno Resenje (VIKOR). Among these techniques, TOPSIS has been identified as the most effective model based on the Spearman rank correlation coefficient test. According to the TOPSIS model, the Donai sub-watershed ranks first and exhibits a higher amplitude in recharging its aquifer, with well yields ranging from 200-400 LPM (Liters per Minute). On the other hand, sub-watersheds like Betal and Joypanda require sustainable management at a priority level, as validated by groundwater yield data, with well yields ranging from 10-100 LPM. The methodology employed in this research provides decision-makers with valuable insights to implement groundwater management and planning strategies effectively.

In this study, drought risk zones within a river basin were identified by analyzing Landsat images from three specific years with precipitation deficits (2000, 2009, and 2018). A comprehensive evaluation of seven parameters, including the Standard Precipitation Index (SPI), Long-term Temperature Condition Index (TCI), Long-term Vegetation Condition Index (VCI), Vegetation Health Index (VHI), Long-term Soil Moisture Index (SMI), Long-term Soil Adjusted Vegetation Index (SAVI), and Long-term Normalized Difference Water Index (NDWI), was conducted. The Fuzzy DEMATEL model was employed to classify the causative and effective groups, which were represented more effectively through a causal diagram, thereby facilitating the identification of drought risk zones. Summarizing the results, the study found that VHI, SPI, and TCI were the three most influential indicators of drought. To validate the findings, a Yield Anomaly Index (YAI) was calculated, and the cropping pattern was mapped to provide additional insights.

The groundwater system within the river basin is currently facing a severe crisis due to the unsustainable extraction of groundwater for agricultural, industrial, and domestic purposes by the rapidly growing population (Garg et al. 2022). To investigate the degradation of groundwater resources, a study was conducted in a river basin located in West Bengal, selecting 20 wells. The seasonal trend of groundwater levels in these wells from 1996 to 2018 was analyzed using the Mann Kendall test statistics. The results indicate that 60% of the wells showed a decline in water levels, particularly during the post-monsoon season. It is worth noting that these wells are predominantly situated near agricultural lands, where extensive groundwater extraction through submersible pumping wells was observed during the socio-economic survey. Agglomerated Hierarchical Cluster analysis was performed to classify the wells based on the magnitude of their fluctuation. The wells were grouped into four clusters, with cluster I comprising the majority, encompassing approximately 15 wells exhibiting fluctuations ranging from 1.8 meters to 4.33 meters below groundwater level (mbgl). Additionally, the Standard Groundwater Level Index (SGWI) was applied to identify years of groundwater drought. Specific well locations, such as Simlapal, Bheduasol, and Neradeul, experienced a higher frequency of drought years. The recharge potential of these wells is progressively diminishing over time. Studies of this nature are essential in highlighting the need for sustainable management of this valuable water resource, providing valuable insights for stakeholders to focus on implementing effective measures.

The primary aim of the forthcoming research was to generate groundwater potential maps by comparing machine learning techniques with a Fuzzy MCDM model, exclusively utilizing field-based conditioning factors. The research followed a stepwise approach: first, 285 wells were identified, with 70 percent allocated for training and 30 percent for model validation. Next, 13 field-based conditioning factors, including longitudinal conductance (SC), longitudinal resistance (ρl), transverse resistance (TR), coefficient of electrical anisotropy (λ), resistivity of formation (ρm), fracture porosity (φf), reflection coefficients (r), hydraulic conductivity (K), transmissivity (Tr), bulk density, porosity, permeability, soil moisture content, and water holding capacity, were analyzed to understand their association with groundwater occurrences. Subsequently, XGBoost, Random Forest, Naïve Bayes, and Fuzzy Analytical Hierarchy Process models were developed using the training dataset, and weights were calculated through the Extent analysis method. To assess and compare the performance of the four models, ROC curves, AUCs, MCAs, and correlation plots were utilized. Overall, all four models demonstrated success in evaluating groundwater occurrence potential. Notably, the XGBoost technique exhibited the highest AUC values (0.79) and the strongest correlation (0.78) among the machine learning and MCDM models. Geophysical surveys further revealed the aquifer's transmissivity and hydraulic conductivity within the river basin ranged from 1.55-440.11 m/day and 10.15-2253 m^2/day, respectively, indicating a moderate to good hydrodynamic potential.

The generated groundwater potential maps can be valuable tools for planners and engineers in effectively managing water resources. Subsurface characteristics within the complex formation of the Shilabati basin was estimated using a cost-effective piezometer and the MIKE FEFLOW package, utilizing a steady-state numerical model. The pore size and fine particle content of streambeds are influenced by opposing flow conditions, which can impact the hydraulic conductivity of the streambed. However, the documentation of hydraulic conductivity (K_h) analogies for losing and gaining streams in recent times has been limited. The piezometer measurements indicated the highest K_h value at the Dakshin Pairachali site (6.765 m/day), where the stream gains water from the discharge of the local aquifer. Through the analysis of stream-aquifer interaction using the FEFLOW model, the groundwater water head within the basin was observed to range from 160.33-0.32 m.a.s.l (Metres above sea level). This study also marks the first attempt to identify suitable sites for implementing Manage Aquifer Recharge (MAR) technology in West Bengal, India, specifically to manage extreme drought events. The identification of suitable sites was accomplished using three fuzzy multi-criteria decision analysis methods based on nine criteria: river discharge, moisture content, porosity, drainage type, rainfall, land use type, geology, aquifer material, and hydraulic conductivity. To design a radial collector well and infiltration gallery for the selected site, a pumping test was conducted in an anisotropic, homogeneous, unconfined, and semi-infinite aquifer located near a fully penetrating stream. The objective was to optimize a safe yield of 12.096 MLD (Megaliters per day).

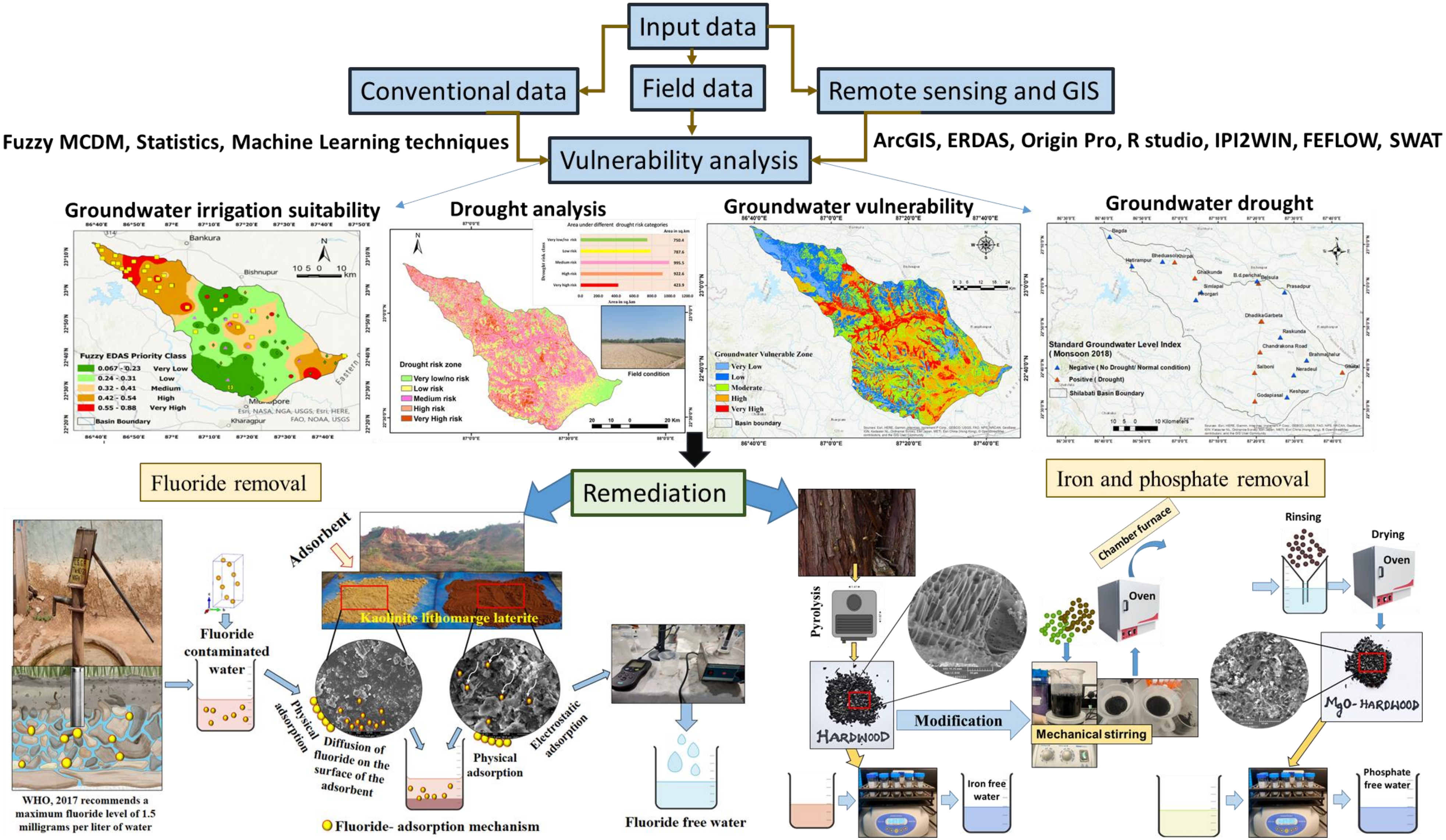
This research also introduces a novel approach for identifying groundwater vulnerable zones by combining Fuzzy Shannon Entropy (FSE) with a decision support algorithm, offering an alternative to conventional methods such as DRASTIC and GOD. The proposed "FSE-GVI" framework expands and enhances the original seven geological and hydrogeological parameters by incorporating geochemical and anthropogenic factors. Thirteen factors related to the geo-environment and hydrogeology (e.g., slope, soil, pH, recharge, etc.) as well as anthropogenic factors (e.g., land use/land cover, population density, groundwater-based irrigation schemes) were optimized with appropriate weights. Based on the computed map, the groundwater vulnerability was categorized into very high (10.82%), high (23.20%), moderate (29.29%), low (25.02%), and very low (11.64%) zones. The groundwater quality of the river basin was assessed on a scale ranging from excellent to unfit for consumption. Comparing the model to 74 groundwater quality data points, the findings revealed a strong correlation between the water quality index (r=0.84) and various parameters such as Total Dissolved Solids (70%), iron (72%), hardness (85%), and alkalinity levels (75%). The research highlights that approximately 27.3% of the sampled sites (villages) exhibit poor water quality, while 23.21% fall within the very highly vulnerable zone. These results underscore the need for effective planning, development, and management strategies to safeguard groundwater resources.

In the current research the derived fuzzy C-mean clustering (FCM) outperformed other available hard computing techniques like Hierarchical Clustering (HCA), K-means clustering, Agglomerative Clustering, etc. It successfully divided the sampling sites into two clustering groups (FCM I & FCM II), which were validated using fuzzy silhouette index (0.85), the partition coefficient (0.76), the partial entropy (0.68), and the modified partition coefficient (0.52). Hydrogeochemical analysis confirmed the prevalence of rock-water interaction, chemical weathering, and ion exchange processes in the aquifer system of the study area. Correlation plots indicated that the studied groundwater samples largely fell into categories such as Ca^{2+}- HCO_3^-, Mixed Ca^{2+}- Mg^{2+}- Cl^- types, and HCO_3^-–Ca^{2+}types. Spatial distribution mapping and hydro chemical analysis revealed significant fluoride (>1.0 mg/l) and high iron (>0.3 mg/l) contamination in groundwater, rendering it unsuitable for both drinking and irrigation purposes. A Fuzzy EDAS priority map was developed based on all irrigation suitability parameters, highlighting that the upstream and downstream sections of the basin require the highest attention for management. Five zones were delineated based on priority levels: very high (5.98%), high (22.31%), medium (16.39%), low (32.30%), and very low (23.02%). The findings of this study will serve as valuable insights for planners and policymakers, enabling them to develop strategies to address similar issues across the country.

In the Shilabati River basin of West Bengal, India, high concentrations of fluoride (> 2 mg/l) have been detected, leading to numerous cases of skeletal fluorosis and bone deformation in recent years. This study focused on investigating the adsorption of fluoride on kaolinite lithomarge (red and white laterite) from Paschim Medinapore, West Bengal, through kinetic and equilibrium analysis using batch tests and a fixed-bed column study with natural water. X-ray Powder Diffraction analysis revealed that the Alpha SiO_2 and Alpha Al_2O_3 present in this natural adsorbent, with their trigonal and hexagonal structures respectively, played a crucial role in the fluoride absorption mechanism. Experimental findings indicated that, at pH values relevant to fluoride-enriched groundwater, the red-type kaolinite lithomarge exhibited the highest efficiency, with an effective removal rate of 98.32% at pH 6.58, while the white type demonstrated a removal efficacy of 95.31% at pH 6.51. Breakthrough curves were successfully modeled, showing good agreement with the corresponding experimental data. Water samples collected from 11 sites within the fluoride-contaminated zone of the river basin were filtered using red-type kaolinite lithomarge, resulting in a removal capacity of 97.13% within 30 minutes, for an initial concentration of 2.37 mg/l. The laboratory-tested prototype demonstrated promising contaminant removal as a cost-effective and time-saving natural filtration option, providing one liter of fluoride-free water at a cost of 0.0015 USD.

The utilization of low surface area and cost-effective biochar as an adsorbent shows great promise for the recovery of iron and phosphate from aqueous solutions, presenting an alternative to commonly used high surface area and expensive biochars such as rice straw, wheat straw, and corn straw (Priya et al. 2022). However, there has been a lack of research regarding optimal preparation procedures and the adsorption mechanisms of iron uptake with plant-based biochars. In this context, a novel low-cost ($4.46/kg) and low surface area (6.87 m^2/g) biochar derived from hardwood wastes (HW) and modified with magnesium impregnation (MgO-HW) has been developed for the efficient removal of iron and phosphate from aqueous solutions. The HW and MgO-HW biochars exhibited exceptional Dubinin-Radushkevich isotherm (D-R) maximum adsorption capacities for iron (289.45 mg/g) and phosphate (828.82 mg/g), respectively. This excellent performance can be attributed to well-developed pore structures in MgO-HW with high magnesium content and abundant oxygen-containing functional groups in HW biochar. The kinetic study revealed that the adsorption of iron and phosphate followed the pseudo-second-order model. The HW biochar and MgO-HW biochar demonstrated remarkable iron adsorption (98.25%) at a pH of 10 and phosphate removal (96.22%) at pH 6, respectively. These findings highlight the potential of HW biochar, particularly in iron removal, and the cost-effective MgO-HW biochar in phosphate removal. This work signifies new possibilities in utilizing HW biochar for efficient iron and phosphate removal at a low cost, thereby opening avenues for eco-friendly pollutant separation from aquatic environments using environmentally friendly materials.

Graphical abstract



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