Theme 6

GROUNDWATER MODELING AND MANAGEMENT

ANALYTICAL SOLUTION TO MODEL FLOW BEHAVIOR IN UNCONFINED DUAL PERMEABILITY AQUIFERS

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Groundwater is a key resource that is crucial in supplying water for drinking, agriculture, and industrial activities. The unconfined dual-permeability aquifers are particularly important because of their unique structures, consisting of two continua namely a porous matrix continuum that stores water and exchanges it with the fracture continuum, and a fractures continuum with higher permeability. This framework permits dual-permeability models to simulate preferential flow, where fracture networks respond more rapidly than the porous matrix to external disturbances such as pumping wells, rainfall infiltration, and river flooding. The flow behavior in such systems is complex and is significantly influenced by various factors like precipitation patterns, land use changes, pumping rates, and boundary conditions. Unconfined aquifers are crucial for controlling water exchange between surface and subsurface sources, as well as in the recharge of confined aquifers, and the contaminants attenuation processes. They serve as key freshwater resources but are highly vulnerable to surface pollution. Understanding the interactions between the matrix and the fracture zones is crucial for effective management of groundwater. Comprehensive analytical solutions incorporating critical factors like precipitation, unsaturated flow, water table variation and variable pumping rates are limited in the existing literature, notwithstanding their importance. Such model developments and incorporation of these challenges into analysis necessitate the use of analytical models that describe the flow behavior in unconfined dual-permeability aquifers with good accuracy. This paper addresses these gaps through the development of an analytical model using the Laplace transform method together with GITT. This is expected to go a long way in enhancing predictions and management strategies of groundwater resources toward sustainable water management practices.

The present study develops an integrated approach to analytically and numerically model the dynamics of groundwater flow in unstressed dual-permeability aquifers. An analytical solution for the pressure head is developed in both the porous and fracture matrices by applying GITT, coupled with the Laplace transform that generally leads to a framework for solving complex boundary value problems. The analytical solution developed for a dual-permeability model has excessive contrasts of hydraulic properties in the interaction of fracture and matrix. GITT projects complicated governing equations with critical boundary conditions representing source and sink terms standing for precipitation and variation of the water table in the aquifer. The solution of the auxiliary problem for the homogeneous boundary condition is used by GITT, while the filtered or steady-state solution is used for the nonhomogeneous boundary. In the Laplace transform, the time dependence is considerably simplified, the equations are converted into algebraic form, and then the application of the Inverse Laplace Transform obtains the solution in the original time domain. The numerical-analytical framework provides, in an effective way, the heterogeneity of the system. It ensures that the obtained results are representative of real conditions with greater accuracy than numerical approaches. Numerical simulations are performed to compare the numerical results with the model in question through the application of the finite difference method by

means of MATLAB software. It is a tool utilized as a numerical solution to compare with the analytical result in order to assess its accuracy and reliability. The FDM discretizes the spatial and temporal domains so that scrutiny of groundwater flow dynamics in detail for different scenarios can be performed. The numerical method gives a good insight, but emphasis is laid on the analytical solution due to its precision in predicting flow behavior under various conditions: All values of various parameters and coefficients like hydraulic conductivity, specific liquid capacity, and transfer coefficient of liquid are borrowed from the available literature for the solution. These parameters are basically required to assess the impact of precipitation, fluctuating water table, unsaturated flow, and variable pumping rates in groundwater flow.

The various results from the analytical model describe the interaction between fracture and matrix with dual-permeability in unconfined dual-permeability aquifers. Hereby, the model takes into account variable boundary conditions, fluctuating water tables, source/ sink terms, and pumping rates essential for the management of groundwater. A comparison is carried out between pressure head profiles obtained from the GITT analytical solution to numerical simulations using the finite difference method in MATLAB. These solutions are in excellent agreement with each other, especially for longer times, hence confirming the reliability of the GITT approach coupled with the eigenvalue problem. For higher values of the exchange term coefficient, pressure head equalization between the porous matrix and fracture continuums occurs more rapidly.

This present research provides substantial insight through a comprehensive analytical methodology that can be used to explain the behavior of groundwater flow in unconfined dual-permeability aquifers. The incorporation of these key factors-precipitation, unsaturated flow, fluctuating water table, and pumping rate into the analytical solutions hints at the limitation of previous models. The solution, by the GITT technique, the Laplace transform method, etc., allows for analytical solution and thus gives a very good model of the interaction between matrix and fracture systems with essential handling of complex boundary conditions. The developed analytical model provides an accurate prediction of groundwater behavior and hence emerges as a reliable tool for practical application to environmental and geotechnical engineering. These numerical solutions, by the finite difference method using MATLAB, would be used for comparison with the analytical results, so that this model can perform well in different scenarios and be stable and adaptable. This research will contribute to enhancing the prediction capability of the response of aquifers under various factors, such as precipitation, which in turn will be vital in improving strategic groundwater management. Additionally, the outcome will form the foundation for further analysis into more complicated aquifer systems, promote understanding of the dynamic nature of groundwater flow, and serve as a basis for sustainable management of water resources.

Keywords: *Analytical solution, dual-permeability model, generalized integral transform technique, finite difference method, laplace transform, matrix-fracture interaction*

ASSESSMENT AND PREDICTION OF CIPROFLOXACIN ANTIBIOTIC IN GROUNDWATER DUE TO PHARMACEUTICAL WASTE DISPOSAL IN MUSI RIVER, HYDERABAD

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Groundwater is a major water source for domestic, agricultural, and industrial purposes. The quality of groundwater is crucial for its several uses. However, expanding industrial sectors is causing severe environmental issues to surface and sub-surface water bodies. Their contamination by industrial effluents is one of the major issues. These effluents include untreated discharge from industries. In the present study, the impact of pharmaceutical discharge in surface water and its effect on groundwater is examined. For this, the study area of Greater Hyderabad is chosen. In Hyderabad, several industries are located near the bank of Musi River and these industries are responsible for its contamination. The available studies show that the river is heavily polluted with pharmaceutical waste. It leads to an overabundance of antibiotics in the river water. The presence of these antibiotics is also a threat to the groundwater bodies in the vicinity of the Musi River. The excessive antibiotics in the water promote the spread of antimicrobial resistance bacteria (AMR). It affects aquatic fishes and as a result, humans become resistant to antibiotics. Ciprofloxacin antibiotic contamination in groundwater is a major health concern. In this study, groundwater contamination due to ciprofloxacin antibiotic is predicted using MODFLOW and MT3DMS models. To conduct this study, initially, 26 water samples at different locations of Musi River were collected and these samples were tested in the laboratory to estimate the ciprofloxacin contamination using UV-Visual spectrophotometer at 278 nm wavelength. The laboratory results showed that the river water is heavily polluted by active pharmaceutical ingredients (API) and the average ciprofloxacin concentration is 6 ppm in the river water. Moreover, soil samples were collected using the reverse rotary drilling technique from every 0.6 m of depth to obtain stratigraphy modeling data and to determine the distribution of soil in the study area. The hydraulic conductivity of soil was determined using the falling head permeability test. For various input parameters of the model, hydrological data was taken from CGWB (Central Groundwater Board) and WRIS (Water Resource Information System) reports. Further, ciprofloxacin transport in the groundwater of the study area is modeled in the GMS (Groundwater Modeling System) software. For this, a conceptual model of Hyderabad city is set up in the GMS. To conduct groundwater flow modeling, MODFLOW model and for contaminant transport, MT3DMS model were used. The double-beam spectrophotometer was used to quantify the concentration of ciprofloxacin antibiotic for 26 river water samples. The spectra of ciprofloxacin show maximum absorbance at 278 nm wavelength. Similarly, all collected samples were analyzed precisely in a UV-visual spectrophotometer. Absorbance values were noted for each sample. The concentration of contaminant was computed by using a straight-line equation from the calibration curve. Average ciprofloxacin concentration was computed as 6 ppm from all 26 samples. The hydraulic conductivity of sediments was determined by using the falling head permeability test. The initial water level (h1) was marked and the valve was open for 2 min 15 seconds. Reading of the final water level (h2) was noted down, and then the hydraulic conductivity (k) was calculated by the using falling head permeability equation. A Conceptual model is created for the study area using GIS shape file and by delineating its boundaries with all source and sink. Various coverages were added for respective feature objects (viz. boundary of feature object, Sources and sink, Recharge and Layer Properties). Thereafter, the model was converted to MODFLOW. A steady-state conceptual model approach was used to develop contaminant transport plumes across the river concerning different stress periods and to predict further groundwater contamination in the next upcoming years. The sources for input data were collected from authentic Govt. organizations. The origin coordinates for Hyderabad district, study area was covered between 17°23'11" N and 78°30'12" E.The developed flow models show the present groundwater flow direction, i.e. from Hussain Sagar Lake. The depth of the water table is higher in the northern part (Hussain Sagar Lake) and sequentially lower down towards the southeast (Peerzadiguda) side. Hence, the groundwater is flowing from the north to southeast direction. Four different scenarios were taken at a regular interval of 10 years, starting from 2022. To develop the flow model, the hydraulic conductivity (0.275 m/day) and transient values for recharge were added to simulate the results. The results of the study show that the groundwater regions is likely to get contaminated with ciprofloxacin in the future. This case study not only highlights the complexities associated with antibiotics pollution but also serves as a model for assessing similar risks in other regions. Given the alarming trends in antibiotics contamination and its potential health implications, our findings advocate for enhanced regulatory frameworks and community awareness programs to mitigate the risks associated with the contaminated groundwater. It also emphasizes the need for stricter regulations to control the discharge of antibiotics into the environment, particularly from sources like pharmaceutical industries and hospitals. Additionally, it calls for community-level awareness programs to educate the public on safe disposal practices, pollution prevention measures, and the importance of protecting groundwater resources.

Keywords: *API (Active Pharmaceuticals Ingredients), GMS (Groundwater Modeling System) Ciprofloxacin, MODFLOW, MT3DMS*

GIS-BASED GROUNDWATER POTENTIAL ANALYSIS FOR SUSTAINABLE EXTRACTION AND RECHARGE PLANNING: A CASE STUDY FROM NORTH CHENNAI, TAMIL NADU, INDIA

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Water is one of the basic requirements for living. Out of all the earth's water resources, only 3% is present as fresh water. While the majority of freshwater is present in the form of ice, nearly 30% is present in groundwater, and less than 1% is present as surface water in the form of lakes and rivers. Around the world, groundwater provides a reliable source for water supply systems. It is one of the primary sources of irrigation and ecological support in addition to drinking water. Generally, groundwater is considered less polluted than other sources of available water due to lack of direct contact. Still, in recent decades, groundwater quality has been decreasing due to its high demand. Water scarcity is also a growing concern nationally and internationally, with regions depending on groundwater facing considerable pressure from population growth, industrial demand, and over-extraction.

The study area combines five zones in Chennai Corporation, Tamil Nadu, namely Thiruvottiyur, Manali, Madhavaram, Tondirapet, and Royapuram, called North Chennai. It lies within the boundaries of 13.0483° N to 13.2460° N latitudes and 80.2574° E to 80.3521° E longitudes, covering an area of 68.33 km^2. It is a residential zone within the Chennai Metropolitan area. It is characterised by its vibrant port activities, dense population, and extensive industrial establishments like significant power plants, refineries, and factories, making it a pivotal contributor to the region’s economy. The urban sprawl and heavy industrial activity in the North Chennai region have significantly strained local natural resources, particularly groundwater, often outpacing natural recharge rates. This over-reliance on groundwater, combined with limited surface water availability, alongwith fluctuating monsoon-dependent recharge rates, puts tremendous pressure on its groundwater resources. Due to industrial emissions and wastewater discharge, the region is susceptible to air and water pollution, making pollution control and sustainable resource management essential for its future.

In this study, the Groundwater Potential Zone has been identified through a spatial data model of QGIS (quantum geographic information system) using different primary thematic layers like soil map, geology, land use land cover, slope map, relative relief, dissection index, geomorphology, drainage density, drainage frequency and drainage texture. First of all, various data or maps were collected like LULC (land use land cover) map from ESRI (environmental system research institute), DEM (digital elevation model) with a resolution of 30 metres from USGS (United States Geographical survey), soil map from FAO (food and agriculture organisation), geology and geomorphology maps from BHUKOSH. It takes a combination of datasets, plugins, and tools to create thematic layers in QGIS, such as soil maps, geology, land use/land cover (LULC), and others. While QGIS's Raster Calculator or SAGA GIS Terrain Analysis can determine slope and relative relief by processing elevation data (DEM), the Semi-Automatic Classification Plugin (SCP) helps with LULC classification by processing satellite images. A Raster Calculator can be used to combine slope and relative relief data to create a Dissection Index.

The Geomorphometry and Gradient Metrics plugin in QGIS can be used to evaluate geomorphology layers. After digitizing stream networks or performing hydrological research using Hydro tools, users can utilize Line Density tools to determine drainage density, frequency, and texture. Hence, these operations collectively enable the creation of the above-mentioned 10 primary thematic layers. The various thematic layers have been classified into 4 categories, namely: Drainage (density, frequency, texture), Slope (relative relief, dissection index, slope), Natural resource (geology, geomorphology, soil map), and LULC. In this study, a GIS approach termed weighted overlay analysis has been used to evaluate several spatial parameters by giving each one a proportionate priority. In order to make spatial judgments, this strategy incorporates multiple layers, each of which represents a unique criterion (such as soil type, elevation, or land use). Based on its applicability or impact on the analytical goal, each layer has been classed into a common scale (e.g., 1 to 10). Each layer has then been given a weight to represent its significance or impact in relation to the other layers. After classification, suitable weights have been assigned to them according to their importance in groundwater potential zones. All thematic layers have not been superimposed at a time but done in the above-mentioned categories, thus obtaining 4 intermediate thematic layers. This has been done so that errors can be pointed out accurately. Next, the 4 thematic layers have been superimposed to form a groundwater potential map.

The study produced a detailed map identifying zones of low, medium, and high groundwater potential across North Chennai. Areas with a high potential for recharging and those appropriate for sustainable groundwater extraction have been highlighted on the map. The study is expected to assist initiatives to decrease water table loss, lessen saline intrusion, and sustainably balance groundwater resources by identifying regions susceptible to over-extraction and emphasizing possible recharge zones.

Keywords: *Groundwater potential, North Chennai, QGIS, extraction and recharge planning*

RIVER AQUIFER EXCHANGE DYNAMICS IN VARUNA RIVER THROUGH DIFFERENTIAL FLOW GAUGING AND NUMERICAL GROUNDWATER MODELLING

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Thomas C. Winter explained that the connection between groundwater (GW) and surface water (SW) bodies in various landscapes is dynamic. This interaction between rivers and aquifers is referred to as River Aquifer Exchanges (RAE). The exchange processes are bidirectional and depend on the hydraulic gradient between the surface water bodies and the adjacent aquifer. There are several methods to quantify River Aquifer Exchanges (RAE), ranging from field techniques to analytical and numerical approaches. At the point scale, RAE is typically measured using seepage meters, temperature loggers, and mini piezometers. For small segment scale measurements, the hydraulic gradient is used to calculate Darcy's flux, and geochemical tracers may be employed. At the reach and larger scale, measurements are usually conducted through water balance calculations between two gauged stations. However, available research on determining RAE through numerical modeling is primarily limited to a regional scale and often overlooks small-scale dynamics. Field-based methods can be exhaustive and require extensive data collection. To address this gap, this research examines River Aquifer Exchanges (RAE) in a small groundwater-fed river by integrating Differential Flow Gauging (DFG) observations into a calibrated groundwater flow model.

In this study, a comprehensive local scale model has been developed to simulate a 34.6 km stretch of the Varuna River Basin (VRB) using the MODFLOW-NWT software. This model employs a parent-child modeling approach, allowing for a detailed representation of groundwater interactions within the specified area. To establish accurate boundary conditions for this localized model, a regional scale model of the lower middle Ganga Basin was utilized. This broader model provided the necessary hydrological context and data to ensure precise simulations. The river itself has been modeled using the Streamflow Routing (SFR2) package, which effectively integrates the hydrological fluxes generated by the area's hydrological model. This integration is crucial as it allows for the assessment of how surface water and groundwater interact within the basin. To calibrate the model accurately, transient groundwater observations were collected from 36 strategically placed open wells throughout the river section. These observations provided valuable data regarding the aquifer parameters and riverbed conductivities. In addition, transient data from eight specific cross-sectional areas were gathered to support the calibration process. Measurements of the groundwater table were taken meticulously with a measuring tape, supplemented by precise positioning data obtained from a Differential Global Positioning System (DGPS) unit (Sokkia GRX2). The assessment of river discharge at the eight cross-sections was conducted using an Acoustic Doppler Current Profiler (ADCP) (Sonotek-M9), a sophisticated instrument that measures water velocity and discharge in rivers. This data is essential for understanding the hydrodynamics of the river and its relation to the surrounding groundwater system. To refine the aquifer parameters and achieve a high level of accuracy, the particle swarm optimization algorithm was applied. This advanced computational technique helped minimize the root mean squared error between the observed data and the simulated results, thereby enhancing the overall reliability of the groundwater model within the Varuna River Basin.

Analysis of the data indicates that during the lean flow period, the average groundwater (GW) table in the study area is consistently measured at approximately 10.2 meters below ground level. This depth reflects variations in groundwater levels that experience increases between 0.05 meters and 0.3 meters in response to heightened aridity in the region. Additionally, it has been observed that the stage of the Varuna River exhibits a downward trend as temperatures rise, suggesting a correlation between higher air temperatures and decreasing river stages. In June, the Varuna River recorded its lowest stage, with measurements ranging from 68.279 meters above sea level (m asl) down to 62.805 m asl. This significant drop indicates a substantial reduction in water availability during a critical period. Correspondingly, measurements from nearby wells revealed fluctuating water levels between 66.16 m asl and 71.45 m asl, which highlights a pronounced hydraulic gradient during the pre-monsoon season. Such gradients are indicative of the dynamic interactions between surface water and groundwater during this time.

The alluvial deposits in the Varuna River Basin (VRB) demonstrate a significant heterogeneity, which is particularly evident in the calibrated properties of the aquifer, including hydraulic conductivity and storage coefficients. These variations affect not only the movement of water through the soil but also the overall water retention capabilities of the aquifer. Average losses or gains at each river section exhibit variability, ranging from 6.9% to 12.06% of the total inflow from preceding sections. Interestingly, there is an overall average gain of approximately 9.92%, indicating that, on average, more water enters the aquifer than exits it during the dry flow period in the monitored sections. As the measurement periods unfolded, the contribution from RAE became increasingly significant, particularly during the intervals from May to June 2022 and from January 5 to February 17, 2023. This trend underscores the aquifer's reliance on base flow during the dry season, whereby groundwater replenishes surface water sources to maintain flow levels in the river.

Further analysis of simulated RAE data illustrates a complex and dynamic interaction between surface water (SW) and groundwater (GW) within the region. Notably, most sections of the river exhibit a pattern of losing water to the aquifer during the rainy season. After the monsoon, the rate of interaction at these losing reaches begins to diminish, while the contribution of groundwater to the river in the lower reaches increases, indicating a shift in the hydrological dynamics post-rainy season. Ultimately, the overall patterns of RAE dynamics witnessed in the Varuna River are characterized by losing reaches that experience low seepage rates, signifying the need for careful management of this valuable water resource. In the Varuna basin, the River Aquifer Exchange (RAE) is particularly noticeable in the lower reaches of the river, especially after the confluence of its two tributaries. The upper reaches of the river system are shallow and often disconnect from the groundwater during the pre-monsoon season. In contrast, the lower reaches primarily receive groundwater from the adjacent aquifer. However, the exchange rate is relatively low due to the reduced hydraulic conductivity of both the shallow aquifer and the riverbed. Additionally, the calibrated hydraulic conductivity of the riverbed indicates significant heterogeneity.

Keywords: *Varuna River basin, river aquifer exchanges, MODFLOW, differential flow gauging, particle swarm optimization, parent-child models*

ASSESSMENT AND PRIORITIZATION OF GROUNDWATER QUALITY PARAMETERS USING MCDM TECHNIQUES

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Groundwater is crucial for drinking, domestic, industrial, and agricultural needs. The rapid growth of population and urbanization reduces the water recharge areas. The over-drafting of groundwater may increase the chance of water contamination due to deeper layers having different geological formations and it also increases the cost of water usage. The decline of water level promotes deeper excavation due to poor groundwater recharge. The groundwater development has reached more than 70 per cent in most parts of the country and now moving to the dark zone, which indicates the decline of groundwater level, to fulfil the demand. This overdevelopment exposes different aquifer layers, degrading water quality, and resulting in contamination that can be harmful to health, crop yields, and ecosystems directly or indirectly. So, there is a need to evaluate the groundwater quality and suggest remedies to minimize the wastage of groundwater based on qualitative evaluation. It supports sustainable water use, helps to assess compliance with regulatory standards, and also helps in the prevention of health risks. Regular groundwater quality assessments are essential for maintaining agricultural productivity and effective water resource management, thus safeguarding the overall integrity and safety of water resources. The qualitative evaluation of groundwater is a comprehensive process, conducted to measure the physical parameters such as pH, Ec, turbidity, total dissolved solids, ions and other parameters such as heavy metals etc. Previous studies on groundwater quality in Varanasi reveal significant concerns regarding water contamination due to anthropogenic and natural factors. High concentrations of parameters like total dissolved solids (TDS), nitrate (NO_3^-), fluoride (F^-), and heavy metals such as lead (Pb) and arsenic (As) have been reported, often exceeding permissible limits set by the WHO and BIS. Rapid urbanization, unregulated industrial discharge, and improper waste management are primary contributors to groundwater pollution. In various studies it was found that the Ganga River system and fluctuating water tables, influence the groundwater quality of Varanasi, leading to spatial variability across the region. Evaluating the water quality of Varanasi now becomes crucial due to rapid urbanization, industrial discharge, and agricultural runoff, which degrade groundwater. Ensuring safe water becomes vital for public health, sustainable development, and addressing contamination risks of this densely populated region. In this study, the water quality of the study region was evaluated by developing a water quality index and ranking the site of observation well for evaluating the potential area of water contamination. The study also aims to identify the factors contributing to the variation of groundwater quality parameters, determine the sources of contamination, and assess the impact of specific drivers. These findings emphasize the need for robust water quality management strategies to safeguard public health and sustainable water use in Varanasi. This research considered 15 physical parameters of water quality to develop an index using different MCDM techniques, to evaluate the water quality. The water quality was analyzed through AHP, TOPSIS and Fuzzy AHP MCDM techniques. These techniques, help in developing the Water Quality Index (WQI) by assigning weights to key parameters (water quality) based on their significance. They prioritize locations by ranking groundwater quality across sites, offering a systematic, objective, and efficient approach compared to traditional methods. These MCDM technique-based models have been developed to identify the impacts of different influencing parameters on the overall WQ potential. Techniques like TOPSIS and Fuzzy TOPSIS help in ranking the well (location) and others (AHP, Fuzzy AHP and Entropy) are used to develop the water quality index. Ranking of wells helps in prioritizing for management and the water quality indices (WQIs) give a numeric value to summarize the overall quality status compared to quality standards by aggregating multiple physicochemical data into a single value. Results of analysis carried under the study highlight that nitrate (NO_3^-) and TDS are the most critical parameters determining the water quality of the study area, with weights of 0.15 and 0.13, respectively. The wells near urban clusters and industrial zones, such as the Varuna River basin and Cantonment regions, fall under 'moderate to poor' water quality category and southern Varanasi, indicates better water quality. Water quality index developed under the study are expected to help in the design and monitoring of water conservation structure. The results indicate varying degrees of water quality across different areas of Varanasi, highlighting regions with critical quality concerns. The observed variations in groundwater quality across the region highlight the significant impact of human activities, such as untreated wastewater, agricultural runoff, and unregulated industrial discharge. The use of AHP-TOPSIS methods for evaluating the Groundwater Quality Index (GWQI) has effectively identified priority areas for intervention and provided a valuable approach to developing sustainable groundwater management strategies. This study underscores the need for regular monitoring and management strategies to ensure safe drinking water and sustainable groundwater use.

Keywords: *WQI, AHP, TOPSIS, Fuzzy AHP, Fuzzy TOPSIS*

GROUNDWATER CHARACTERIZATION THROUGH MODELING EXERCISE IN THE UPPER PART OF AJOY-DAMODAR INTERFLUVE OF WEST BENGAL, INDIA

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The study focuses on simulating groundwater flow in the shallow aquifer zone beneath the upper part of the Ajoy-Damodar interfluve in the state of West Bengal. This region is of significant hydrogeological interest as it encompasses the renowned Raniganj Coalfield, where mine dewatering remains a critical challenge in numerous open-cast mines. The study area includes the Gondwana group of rocks in the west and extends to the older alluvium deposits in the east. The aquifer system is primarily composed of Gondwana sandstone horizons interspersed with shales and overlaid by laterites. The simulation aims to better understand the groundwater dynamics of this region, particularly in relation to mining activities. To develop the conceptual groundwater flow model, the study area was bounded by three major rivers: Barakar River to the west, Ajoy River to the north, and Damodar River to the south. The eastern boundary is defined by a transition from older to younger alluvial deposits. The model was constructed using the MODFLOW computer code, which is widely used for simulating groundwater flow. Boundary conditions were incorporated to account for the hydrological inputs from the rivers, and relevant hydrogeological parameters, including hydraulic head data from both central and state government agencies, were used. The model has been run in both steady-state and transient-state conditions to simulate varying groundwater flow scenarios. The groundwater flow model was successfully calibrated and validated, providing insights into the flow dynamics within the shallow aquifer zone. The model accurately represented the regional groundwater behavior and responded to changes in boundary conditions. The results showed the influence of the Barakar, Ajoy, and Damodar rivers on groundwater flow, as well as the impact of lithological transitions in the east on the groundwater regime. However, the lack of detailed micro-level water data, particularly around the coal mining pockets, posed a limitation in fully capturing the groundwater flow dynamics in these localized areas. The developed groundwater flow model serves as a valuable tool for understanding the groundwater dynamics in the Ajoy-Damodar interfluve, especially in the context of coal mining activities in the region. While the model has been calibrated and validated successfully, the absence of high-resolution, micro-level water data around the coal mining areas remains a significant limitation. Further studies incorporating more detailed hydrogeological data would enhance the accuracy of the model and its applicability in addressing mine dewatering challenges and other groundwater management issues in the region.

Keywords: *Groundwater characterization, groundwater flow model, boundary conditions and MODFLOW computer code*

EVALUATING STATUS OF GROUNDWATER DYNAMICS USING GEO-SPATIAL WATER LEVEL FLUCTUATION MAPPING FOR DINDI WATERSHED

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In Telangana region, during the last few decades, there was a steep decline in the area irrigated under tanks and the negligible increase in irrigation under Major and Medium irrigation projects which led to over exploitation of ground water. One such case study is the Dindi watershed where the groundwater status is over exploited. A new Lift irrigation project is in pipeline called the Sri Ramaraju Vidyasagar Rao Dindi Lift Irrigation Project (SRVR DLI Project) which envisages to provide irrigation and drinking water to the most severely affected areas by fluoride and the drought prone areas of Devarakonda and Munugodu constituencies of Nalgonda District.

Groundwater has become the sole source of irrigation in non-command regions due to frequent failures of the hydrological cycle. Because to the hydrogeological complexity and lack of understanding of the aquifer systems, groundwater availability has been overstated. The groundwater table fluctuation technique is one of the effective approaches for evaluating groundwater availability in India's hard rock regions. Water table maps are essential tools for managing water resources in arid and semi-arid regions. Due to the numerous observation wells, it might be difficult to spatially evaluate water table oscillations and determine time series changes in static groundwater levels at the watershed scale. Furthermore, a spatial framework analysis of the data with reference to a global datum is required in order to comprehend the groundwater dynamics of the watershed. In this context, a case study has been carried out in one of the watersheds in the hard rock areas of Telangana state (Dindi watershed, Nalgonda district) with a purpose to analyze dynamics and interaction aspects of aquifer system. The study area falls under semi-arid class, and is covered mostly by hard rocks, feasible for bore wells. As groundwater irrigation is common in the study area, it may cause groundwater level decline due to over exploited stage of groundwater development. Extensive extraction of groundwater for irrigation and other uses is exerting stress on the resource. Therefore, formulation of a robust groundwater management policy is essential for long term sustainability of aquifer systems in this region. To facilitate this, initially the dynamics of groundwater aquifer systems need to be understood. For the purpose, analysis of long-term groundwater levels has been carried out in one of the watersheds known as the Dindi watershed. Long term groundwater level and quality data from this watershed for thirty-five well-locations have been analyzed in time and space for any trends or fluctuations. Based on elaborate analyses, useful inferences on groundwater trends and water quality fluctuations in the study area are identified and presented in the paper.

In the previous few decades, the Telangana region has seen a sharp decrease in the area irrigated under tanks and a small growth in irrigation under Major and Medium irrigation projects, which has resulted in overuse of ground water. An instance of this can be found in the Dindi watershed, where the overexploitation of groundwater has occurred. There's a new lift irrigation project in the works called the Sri Ramaraju Vidyasagar Rao Dindi Lift Irrigation Project (SRVR DLI Project). Its goal is to supply drinking water and irrigation to

the areas of Nalgonda District that are most vulnerable to drought as well as the area's most severely affected by fluoride. The Telangana state groundwater department with NIH has considered the area of Dindi to study the impact of LIS on groundwater status of the region. Specific objectives are developed to study the issues of micro-basins as representative studies in Krishna River basins of Telangana. The objectives are achieved with the use of various statistical tools and designing case-based data products to prepare ground water model development for Dindi micro-basin in Krishna River basin. Therefore, the objectives of this study are to assess the long-term changing pattern of rainfall using statistical analysis; to study the declining water levels in aquifers based on observed Groundwater levels; and to identify the sectors under water-stressed regions for planning sustainable groundwater development and management.

The study area is a command watershed which has an area of 2334 km^2. The study area falls under semi-arid regions of the country. The South-West monsoon season is from June – September, Winter is from January – February, Pre-Monsoon is from March – May, Post-Monsoon (North-East Monsoon) is from October – December. The Piezometric static Groundwater level observations of 35 monitoring stations have been used for statistical analysis of groundwater dynamics for Telangana State Groundwater Department. Rainfall data has been collected from concerned department and utilized. In this study, AGHW modelling has been used to prepare dynamic piezometric surfaces to categorize the study area into different zones based on transient water level measurements. Trend is analyzed for these zones based on change detection concept where the areas are observed to be expanding or reducing in a particular Groundwater level zone.

The changes in rainfall trend can have a significant effect on the watershed conditions and groundwater availability. Hence, for the watershed considered the rainfall trend analysis is carried out to check the changes in the long-term rainfall. If there are significant changes then it is quantified by the statistical tests performed. The Aquifers largely gets recharged in the monsoon season and aided to some extent in the post-monsoon season. Hence, to analyze the behavior of groundwater levels AHGW tool have been used to observe the distribution of transient groundwater levels in study area for Pre-Monsoon, Monsoon and Post-Monsoon seasons for the year 2015 – 2018 having consistent data. The groundwater aquifers are classified based on water level variation characteristics into 8 classes. 150-180 m, 180-210 m, 210-240 m, 240-270 m, 270-300 m, 300-330 m, 330-360 m, 360-390 m above MSL. 360-390 m range are shallowest aquifers and 150-180 m range are deepest aquifers. Use of geospatial applications such as ArcHydro Groundwater tools can effectively help in visualizing the categorization of Piezometric heads of aquifers. The dynamics of groundwater stressful regions can be identified by long term aquifer information mapping. The spatial rainfall distribution using iso-hyetal procedures can help in understanding the variations and trend in rainfall pattern and its impact on groundwater recharge. It is found through this study that although monsoon rainfall trend is towards above normal, there is a decline in post-monsoon recharge. This may be attributed to the decreasing rainfall trend along with the extensive groundwater exploitation in post-monsoon season for agricultural and drinking purposes. This is evident from the results of AGHW modelling which shows that the zones with shallow groundwater levels (300-390 m above MSL) is decreasing and the zones with deeper groundwater levels (150-240 m above MSL) is expanding over past few years.

Keyword: *Groundwater, Arc-Hydro, trend analysis, GIS, watershed,*

EFFECTS OF WATER EXTRACTION ON MAXIMUM LONGITUDINAL PLUME LENGTH: A NUMERICAL INVESTIGATION FOR CONTAMINANT SITE REMEDIATION

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Contaminated sites pose significant threats to groundwater resources. In India, 240 such sites have been identified in the year 2022, and the number is likely to increase owing to increasing crude oil consumption and its storage facilities. Globally, non-aqueous phase liquids (NAPLs), including petroleum hydrocarbons and chlorinated solvents, have been thoroughly investigated through extensive projects. Due to their persistence and potential to form long contaminant plumes that degrade groundwater resources, NAPLs pose significant challenges. However, subsurface modelling of NAPLs in India remains limited, with most studies focusing only on pollutants near the groundwater table. While many studies have examined contaminant transport under natural conditions, few have analysed the impact of external stresses such as water extraction on subsurface conditions. Groundwater extraction, commonly practiced for water supply, can significantly alter hydraulic gradients and flow patterns within an aquifer, potentially affecting the migration of contaminant plumes. Addressing this research gap, this study numerically investigates the effects of water extraction on the maximum longitudinal plume length ( ) of a contaminant plume generated by a contaminant source. By simulating various scenarios of groundwater extraction, we aim to provide insights into how water extraction effects the contaminant plume dynamics.

A three-dimensional numerical model was developed using MODFLOW-2005 for simulating groundwater flow and MT3DMS for modelling contaminant transport. The model represents a homogeneous, isotropic, and fully saturated aquifer with uniform hydraulic properties, consistent with the analytical model. The domain dimensions were selected to capture the full extent of the contaminant plume under steady-state conditions. To ensure computational efficiency, several model domains with different grid discretization were tested. The final model employed a refined grid in the vicinity of the contaminant source and extraction wells to accurately capture steep concentration gradients, flow velocities. Boundary conditions were specified as constant head boundaries to maintain a uniform flow across the domain. Model validation was performed by comparing the numerical plume length estimates ( ) with the analytical solution. Our numerical model demonstrated 97.3% accuracy with the analytical solution, validating its suitability for scenario analysis. Simulation scenarios were devised to quantify changes in by varying three main parameters: 1) Spatial locations of extraction wells: Wells were placed at different positions along and perpendicular to the groundwater flow direction, both inside and outside the analytical plume extents; 2) Extraction rates: Pumping rates were varied from low to high values to assess the sensitivity of to the intensity of water extraction, and 3) Number of extraction wells: Scenarios included single well extraction and multiple wells operating simultaneously, with total extraction rates kept constant for comparison. These scenarios aimed to assess the direct and indirect impacts of water extraction on plume dynamics and to identify optimal strategies for plume management. The simulation results demonstrate that the placement and operation of extraction wells significantly influence the contaminant plume length ( ). When extraction wells are located within the plume specifically along the centre of the model domain where they directly intersect the contaminant plume decreases exponentially with increasing pumping rates. This reduction is attributed to the direct removal of contaminants through pumping and the enhanced dispersion caused by increased groundwater velocities near the well.

In contrast, extraction wells situated outside the plume, particularly those positioned farther from the contaminant source, have a minimal effect on reducing . In some instances, a slight increase in plume length was observed, likely resulting from alterations in the hydraulic gradient that promote downstream migration of the plume. These wells primarily influence groundwater flow patterns without effectively removing contaminants, leading to negligible or even adverse effects on plume length. Additionally, the use of multiple extraction wells resulted in a smaller reduction in compared to a single well operating at an equivalent total extraction rate. The reduced effectiveness is attributed to the distribution of pumping rates among multiple wells, which leads to lower individual well capacities and decreased contaminant capture due to lower contaminant concentrations at each well location. This finding suggests that consolidating extraction efforts into a single, strategically placed well within the plume may be more effective for plume reduction than dispersing the extraction across multiple wells.

Our findings categorize the impacts of water extraction on into two types: 1) Direct contaminant extraction: Significant reduction in plume length occurs when wells are strategically placed within the plume and operated at sufficient pumping rates to capture and remove contaminants, and 2) Indirect mixing effects: Wells located outside the plume primarily influence groundwater flow patterns, inducing mixing but not effectively removing contaminants, resulting in negligible changes to . In some cases, these mixing effects led to slight increases in plume length, indicating potential unintended consequences of poorly placed extraction wells.

This study highlights the critical importance of well placement and pumping rates in controlling contaminant plume migration. Integrating water extraction into contaminant transport modelling is essential for accurately predicting plume behaviour and designing effective remediation strategies. The numerical models developed in this research serve as powerful tools for preliminary assessments, enabling stakeholders to evaluate various remediation scenarios before committing to costly field interventions.

Strategic placement of extraction wells within the contaminant plume can significantly reduce plume length, mitigating risks to downgradient water users and environmental receptors. Conversely, poorly planned groundwater extraction may fail to control plume migration and could exacerbate contamination spread. While pump and treat remediation methods are extensive and expensive, the insights gained from this study facilitate more targeted and cost-effective remediation efforts. By precisely determining the extent of subsurface contamination and optimizing well configurations, practitioners can enhance the efficiency and effectiveness of remediation programs.

***Keywords**: Contaminant transport, groundwater extraction, plume length, numerical modelling, MODFLOW, MT3DMS, NAPLs, contaminated site modelling*

3-D GROUNDWATER FLOW MODELING IN YAMUNA MICRO-WATERSHED USING FEFLOW

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Over the period, northwest India has emerged as one of the most groundwater (GW) overexploited regions due to its geological, climatic, and anthropogenic complexities. Over-pumping of resources to meet the enhanced agricultural, domestic, and industrial demands, coupled with continuously changing climatic patterns, has amplified the GW scarcity and deepened the water table in the region unexpectedly. The GW estimations have been studied using the in-situ and GRACE estimations, flux-based numerical models, and data-driven modeling techniques. Spatial and temporal coarse resolution and noise contamination, data-oriented results, and being a more complex physical system, the GW balance assessment poses a great challenge to acquire a real picture of its variability and flow patterns. Numerical models have demonstrated their efficacy in modeling by employing complex mathematical algorithms to represent the GW flow intricacies and dynamics. Over time, various models (e.g., FEFLOW, MODFLOW, GMS) have been developed to simulate GW flow and solute transport within aquifer systems. The robustness and reliability of these models are defined by their ability to incorporate geological heterogeneity, address boundary conditions, and their governing equations.

The current study utilizes the finite element modeling approach using FEFLOW (version 8.1). FEFLOW provides the ability to create finite element unstructured grids which helps to represent the complex and irregular geometries of the natural system with its multidimensional modeling capabilities. For regions with complex hydrogeological characteristics such as fractured rock systems, layered aquifers, or areas with significant heterogeneity and anisotropy—FEFLOW’s precision in handling spatial variability offers an advantage. Hence, this study aims to develop a 3-D finite element GW model for a micro watershed in the Yamuna sub-basin to simulate the transient GW flow and its budget in the region. The study area, with an area of 4,418 km^2, has an aeolian-alluvium dominance with the presence of silt-sand and quartzite with predominant quaternary formations.

A 3-D transient state finite element model is developed for the multilayered aquifer system containing four major aquifers. The GW is abstracted from ten blocks represented administrative boundary-wise accessed from CGWB while monitored through 237 monitoring wells over the period from 2015 to 2024 from state and central GW stations. The 2-D model domain was generated based on the hydraulic gradient in the watershed region, with the river boundary on the east side of the boundary. A high-resolution 2-D finite-element mesh is generated using triangular prism discretization and projected to 3-D with 11 layers using their available elevation (X, Y, and Z) to effectively capture the complexity of the geological structures. Borehole log data are incorporated to achieve accurate vertical discretization of model layers. The rivers and lineaments are refined more with the local refinement property for intricate analysis.

The model includes 18,918 nodes and 37,085 elements per layer. The top elevation of the model varies from 287.0 m to 438.5 m from the mean sea level. After meshing, the model properties were assigned as an unconfined phreatic first and other dependent layers with a fully saturated water table. The top unconfined layer was assigned a default residual water depth of 0.5 m to avoid any dry cells in the first slice during simulation. The western no-fluid flux boundary is likely chosen due to geological constraints or the absence of significant flow across this boundary. Meanwhile, the eastern fluid transfer (3^{rd} kind flow Cauchy) boundary conditions (BC), align with the Sahibi River's water level at 238.99 m, simulating a controlled, consistent exchange with surface water that can impact local hydraulic gradients and flow paths near this boundary. The north and south boundaries are assigned constant head (first kind flow Dirichlet) BC.

Constant zone material properties were provided for every layer with four aquifers in 2^{nd}, 3^{rd}, 4^{th}, and 5^{th} (aquifer 1), 7^{th} (aquifer 2), 9^{th} (aquifer 3), and 11^{th} (aquifer 4) layers. Horizontal hydraulic conductivity (Kx=Ky) values were assigned based on the transmissivity values provided by the authorities, divided by the thickness of the aquifers. The vertical conductivity (Kz) is given a factor of 1/10 of the horizontal values. Average precipitation and evapotranspiration data were acquired from satellite data Global Precipitation Measurement (GPM) and MODIS respectively for around 200 points in the model domain from 2015 to 2024 and were calculated as inflow-outflow, applied on the top layer using the inverse distance interpolation method. The lack of pumping well information has motivated to calculate the source-sink property for selected elements in different depths with the pumping volume information provided block-wise by CGWB authorities.

The model is simulated for the steady and transient conditions. To simulate the reliable GW flow, model calibration is important, hence FEPEST is used. Since the model is most sensitive to permeability, K values were chosen for the calibration along the X, Y, and Z axes. The parameter definition is provided for the Kx, Ky, and Kz layerwise with the Kriging (internal) interpolation technique. The model is optimized with 20 iterations with a regularization setting for the high-parameterized model. The model is calibrated by assigning the pilot points across the model, presenting the spatial heterogeneity in the K values. The model is calibrated to achieve the least root mean square error and best fit the observed and simulated heads. The model is validated from 2015 to 2024 under transient conditions, employing the calibrated conductivities and heads from steady state as initial conditions. The transient data for other boundary conditions were employed and simulated for the transient state. The model aims to gain accuracy with a 95% confidence interval and simulate the hydraulic heads and GW imbalance in the watershed region.

Keywords: *Groundwater, numerical modeling, finite element, simulations, flow dynamics*

EFFECTIVE GROUNDWATER MONITORING NETWORK FOR MODELLING AND MANAGEMENT AT MICRO-WATERSHED SCALE

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Effective groundwater monitoring networks are essential, as comprehensive information obtained from observation wells offers critical insights into the dynamics of hydrogeological systems and serves as a foundation for numerous applications such as modeling, and management. The network design, namely the selection of positioning and number of monitoring wells, is crucial in any study that involves modeling and prediction utilizing geographical data. It is essential to comprehend the variability of groundwater levels, specifically the depth to groundwater (DTW) across various scales, as this knowledge will aid in developing policies for the effective planning and management of the deteriorating groundwater resource at several levels. Moreover, the efficacy of a groundwater model is contingent upon the quality of the input data utilized. Consequently, inadequately distributed monitoring wells may result in erroneous conclusions or a distortion of the regional perspective. This study focuses on efficient groundwater monitoring network capturing the spatiotemporal variability at micro-watershed level for intensive hydrologic monitoring and evaluation for science-based management and planning, with a focus on groundwater extraction and recharging.

The study area consists of the Illirsinga, Kodhibhanga, and Rasol micro-watersheds in the Hindol region. It is situated 30 kilometers to the west of Dhenkanal Urban in the state of Odisha, India. The region is bounded by south-western mountains, that form a watershed between the Brahmani and Mahanadi rivers, with a narrow intermountain valley in the west, a perennial drainage ditch, in the north, and undulating plain in the south-east. It exhibits diverse topography, ranging from 90 to 630 meters above sea level, and lacks perennial streams. The region has a semi-arid climate that is influenced by the recurring appearance of the monsoon, which brings rainfall from mid-June to mid-October. The average annual precipitation is approximately 1300 mm, with over 80% occurring during the monsoon season. The average yearly temperature is 31.5˚C. However, during the summer months of March to May, the daily maximum temperature can reach up to 48˚C. Currently, the study area contains only one well, named Rasol National Hydrological Stations (NHS) within the long-term groundwater monitoring network of NHS in India, captured from the India Water Resources Information System. Henceforth, it was necessary to enhance the groundwater monitoring network to focus on groundwater recharge and extraction for micro-watershed planning and management. The dynamics of groundwater flow has been captured via a preliminary observation well network with a cluster of 13 wells, distributed enough to ensure sufficient spatial coverage, and, utilized to monitor groundwater levels to investigate the effectiveness of the current groundwater network. The measurement of the depth below an arbitrary place and the groundwater level is conducted in meters using a Groundwater Level Indicator. Additionally, the elevation of that arbitrary point above the mean sea level (msl) is measured using a Handheld GPS device.

Geostatistical sampling is a method for creating a sample network that employs statistical and spatial analysis to identify ideal sampling sites. To determine where to place more sampling points, a geostatistical model called the model variogram is employed. These are chosen according to the established selection criteria by minimizing the maximum kriging variance. It is contingent upon the covariance model and the arrangement of data and unaffected by the actual values in data. The geostatistical sampling design relies on the predicted standard error as a selection factor for choosing the location of additional points of sampling. Regardless of the data, two identical sample location distributions will yield the same kriging variance for a given covariance model. The mathematical-statistical description and numerical analysis of two-dimensional Gaussian distributed realizations demonstrate the validity of kriging variance. The prediction error variance is independent of the data values; hence the kriging variance remains an accurate evaluation of local uncertainty, even when fluctuations in particular regions are greater or lesser than in others. Nonetheless, these conclusions are inapplicable to the non-Gaussian scenario. Additionally, the results are compared with stratified, and cluster sampling to assess the heterogeneity in the DTW variability, consequently distinguished as an internally homogenous cluster.

The Geostatistical Sampling Design is executed in the Esri Environment using an ArcGIS Tool "Densify Sampling Network." The semi-variogram is revised at each densification phase, resulting in varying outcomes based on the consecutive addition of points. Consequently, it led to monitoring efficient network with the lowest average standard error. Additionally, this network also captures the distinctness of each well and its seasonal DTW variability. This study aimed to establish a groundwater level monitoring network to determine if an extensive design can provide valid spatial estimates of groundwater levels, capturing spatiotemporal variability in the micro-watershed scale. We examined the geostatistical sampling by densifying the network by placing additional sites depending on the semi-variogram model. This methodology resulted in verifying the spatiotemporal variability of DTW. The seasonal fluctuations in the water levels of groundwater demonstrate the potential variations in the specific yield within this study region by examining the distinctness of each well. This monitoring network provides information that offers valuable insights into the spatial variability of evapotranspiration and recharge fluxes over the aquifer system. Such a monitoring network can assist in the intervention emphasis on groundwater recharge and extraction.

Keywords: *Groundwater, monitoring network design, geostatistical sampling, spatiotemporal variability*

PARTICIPATORY GROUNDWATER MANAGEMENT TOWARDS SUSTAINABLE DEVELOPMENT OF AN AQUIFER – A CASE STUDY AQUIFER FROM SATARA DISTRICT, MAHARASHTRA, INDIA

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Groundwater is an essential shared resource, critical for various user groups, yet its depletion is becoming a major concern in Maharashtra due to erratic monsoons and over-exploitation of aquifers. In response, a participatory groundwater management initiative was launched in a portion of the BM-85 watershed in Satara district. The project developed an Integrated Groundwater Management Action Plan (GWMAP), utilizing a comprehensive approach that incorporated remote sensing, hydrometeorological, hydrological, hydrogeological, hydro-chemical, and geophysical analyses. The study area, located in the basaltic Deccan Trap formations, experiences a semi-arid climate with an average annual rainfall of 367.5 mm, and the aquifers are predominantly unconfined. This case study describes the methodology used for aquifer delineation, employing geospatial tools, multi-criteria analysis, and hydrogeological surveys. The implementation of the GWMAP was guided by scientific data alongside a deep understanding of the local social structure, integrating both natural and social sciences in a community-based groundwater management program. A base map was created using the Survey of India topographic map (47K/5 at 1:50,000 scale), and spatial analyses—such as slope and precipitation maps—were performed using GIS software. Other key analyses, including geomorphology, drainage patterns, and groundwater potential, were also carried out using GIS tools. A baseline survey was conducted to gather demographic data, assess the status of domestic water supply, identify agricultural practices, and evaluate existing water conservation structures. Social science surveys, in collaboration with local support organizations, assessed the community's social and economic conditions. Hydrogeological surveys helped determine groundwater potential and informed management strategies. Historical data, combined with field surveys, enabled the development of hydrogeological maps that identified high-potential groundwater zones and evaluated aquifer controls. Aquifer characteristics, including specific yield (0.0015 to 0.03) and transmissivity (77.62 to 232.26 m^2/day), were derived from aquifer pumping tests (Theis, 1935; Cooper & Jacob, 1946). The occurrence and distribution of groundwater in the area were analyzed through a detailed study of well inventories. The average well density is 4.7 wells per square kilometer. Of the 412 open wells, 389 are used for irrigation, with 294 equipped with electric motors and 48 with diesel engines. Additionally, 70 wells are no longer in use, while 23 wells serve domestic and drinking water needs. Well depths range from 5 m to 21 m below ground level (bgl), and diameters vary between 6 m and 13 m. Water levels fluctuate between 0.5 m and 17 m bgl during winter and 3.5 m to 20.5 m bgl during summer. Seasonal water level variations from pre-monsoon to post-monsoon were observed to range from 2 m to 13 m. Water level fluctuations indicate the seasonal regeneration of groundwater, with variations ranging from 5 to 8 m over the last decade. Wells fully penetrating the aquifer yield between 40 to 100 m^3/day in winter, with a decrease to 0 to 40 m^3/day in summer. Groundwater exists under unconfined water table conditions, with aquifer depths limited to 15 meters below ground level. The region has 97 irrigation borewells, whose yields vary from 5 to 60 m^3/day in winter and 0 to 30 m^3/day in summer. Approximately 30% of the wells yield high quantities, while 40% of borewells become defunct annually due to groundwater depletion. Vertical Electrical Soundings (VES) at 68 locations revealed the aquifer is predominantly occupied by vesicular zeolitic basalt, with resistivity values ranging from 20 to 40 Ωm, followed by fractured basalt with resistivity values between 40 and 70 Ωm. Chemical analysis of water samples was performed, and a Piper diagram was used to interpret water quality. The results indicated that groundwater in the area is suitable for drinking, with Total Dissolved Solids (T.D.S.) and other constituents within permissible limits. All data were geo-referenced and integrated into a GIS platform, facilitating the creation of thematic maps for aquifer management. The study identified two primary aquifer types: phreatic aquifers in weathered vesicular basalt and fractured massive basalt, with the former being dominant. A water balance was computed for the aquifer using 75% dependable rainfall, alongside cropping data from the agricultural department. The water account indicated a deficit of 54 million cubic meters (ham), with the aquifer's development stage at 112%. To address this deficit and ensure sustainable groundwater use, the GWMAP integrates both supply-side and demand-side strategies, such as water-saving technologies, improved irrigation practices, crop planning, and local regulations to reduce overuse. Ongoing monitoring of groundwater levels and rainfall provides the community with vital data to track aquifer status. Demand-side measures, such as crop diversification, efficient irrigation practices, and self-regulation, are gradually being adopted by farmers. While the changes are beginning to show positive results, continued collective efforts will help achieve long-term groundwater sustainability. A holistic approach to groundwater management is crucial, considering factors such as slope, geomorphology, lineaments, soil, and land use. Long-term planning must also address future irrigation and drinking water needs. The success of this initiative hinges on effective demand management, including participatory groundwater management, community-based monitoring, water budgeting, and self-regulation. This case study highlights the importance of integrating both supply-side and demand-side measures, alongside active community involvement, for successful groundwater management. It also recommends sharing groundwater resources among neighbouring villages and promoting the conjunctive use of groundwater and surface water to ensure sustainability in the long term.

Keywords: *Groundwater management, aquifer, remote sensing, water budgeting, participatory groundwater management*

A FINITE VOLUME METHOD-BASED NUMERICAL MODEL FOR COUPLED SUBSURFACE FLOW AND CONTAMINANT TRANSPORT DYNAMICS

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Groundwater is a critical resource for agriculture, industry, and human consumption. However, it is facing continuous threats of contamination and overexploitation, under the complexities of the changing climatic scenarios. Effective management of this essential resource relies heavily on our ability to model subsurface flow and transport dynamics accurately. Mathematical models are essential for predicting the flow dynamics and contaminant migration under various hydrodynamic conditions and developing remediation and disposal policies for contaminants to ensure the long-term sustainability of groundwater systems. These models are indispensable tools in groundwater contaminant hydrology for forecasting the impacts of various extraction scenarios, assessing contamination risks, and planning remediation strategies. Despite significant advancements, the existing coupled subsurface models often fail to achieve mass conservation while simultaneously simulating the flow and transport mechanisms. Partially coupled models handle flow and transport sequentially, using the output from the flow models to drive the transport model. This approach can lead to inaccuracies where the interactions between flow dynamics and transport mechanisms are dominant. Fully coupled models, which solve the flow and transport equations simultaneously within a single framework, often suffer from high mass balance errors and computational inefficiencies. To address these limitations, it is necessary to develop a mass-conservative, fully coupled subsurface flow and transport model, incorporating advanced computational techniques like an adaptive time-stepping algorithm for computational efficiency.

In the present study we have developed a robust, adaptive, and mass-conservative, one-dimensional (1D) coupled model to simulate the complex subsurface flow and transport phenomena. The Finite Volume (FV) method is used to discretize the governing equations of flow and transport for the developed modeling framework. The FV method ensures mass conservation across the computational domain thereby, enhancing the applicability of the developed model for accurate predictions. The nonlinearity of the flow and transport equations is handled using the modified Picard iteration scheme in the mathematical formulation of the developed modeling framework. Within the unsaturated zone of the subsurface media, the non-linear relationship between the pressure head and the soil-water characteristics parameters - moisture content ( ), hydraulic conductivity ( ), and specific moisture capacity ( ) are expressed using the empirical van Genuchten-Mualem model. An adaptive time-stepping algorithm is implemented in the modeling framework to address the computational challenges associated with fully coupled models. This algorithm dynamically adjusts the time-step size during the simulation based on the evolving behavior of the solution, thereby ensuring smooth convergence of the Picard iteration scheme and significantly enhancing the computational efficiency without compromising accuracy.

The integration of a contaminant transport model with a density-dependent flow model in the present research work aims to predict the complex interactions between groundwater flow dynamics and contaminant migration in variably saturated subsurface media. Application of the FV method for the coupled 1D modeling framework ensures minimum mass balance errors as the FV discretization scheme is inherently mass-conservative. The developed 1D model is validated against the standard benchmark problems from the literature which confirms its applicability for accurate modeling of complex subsurface flow and contamination transport phenomenon. The present model is deemed crucial for developing effective strategies for groundwater management under increasing extraction activity and contamination risks. In the future, we aim to extend the applicability of the developed model to three-dimensional domains for solving practical problems on complex subsurface phenomena, including saltwater intrusion, contaminant flow and transport, and nutrient leaching.

Keywords: *Coupled models, finite volume method, subsurface flow, contaminant transport, mass conservation, picard iteration scheme, adaptive time-stepping algorithm*

A STUDY OF PRE- AND POST-MONSOON WATER LEVEL AND WATER LEVEL FLUCTUATION OF NORTHERN PART OF WRJ-2 WATERSHED, NAGPUR DISTRICT, MAHARASHTRA STATE

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A majority of water problems in India are related to groundwater as India is the largest consumer of groundwater in the world. Groundwater is a major source of irrigation and industrial uses in India. It is the main source of water for agriculture, municipal and industrial use. A total of 93% geographical area of Maharashtra State is covered by hard rocks, out of which the Deccan basalt constitutes about 82% of the geographical area. Due to its hard and compact nature, the *occurrence* and *storage* of groundwater in the Deccan basalt is very limited, which is a reason for its poor to moderate yield. The groundwater in the basaltic terrain occurs in the multi-layered sequence of lava flows. Aquifers in the Deccan basaltic terrain generally occur as (i) aquifers in which storage space exists by virtue of weathering and porphyritic and vesicular zones. (ii) aquifer in which storage space exists due to the structural features such as columnar joints, fractures, faults, etc., and (iii) aquifer which occurs at relatively greater depth, where groundwater occurs under confined state. The heterogeneous nature of the Deccan Trap is responsible for the variable occurrence and distribution of groundwater. The present study area is the WRJ-2 Watershed, which is included in Survey of India toposheets 55K/11 and 55K/7 and bounded by latitude 21°17'30" - 21°29'00" N and longitude 78°30'00"-78°59'15" E. The WRJ-2 watershed has a total area of 219.86 km^2 and is included in the critical category, after groundwater assessment. The entire area of watershed WRJ-2 is covered by the Deccan basaltic lava flows of Upper Cretaceous to lower Eocene age. The study area has been drained by the Jam River and its tributaries. The overall pattern of drainage is dendritic which testifies the presence of hard rock in the area. The general slope of the ground is towards the south. The northern part of the watershed WRJ-2 falls mostly in the runoff zone. A percolation tank is also present in the Northern part of the study area. Stratigraphically this area comprises eight lava flows of Sahyadri Group, which is further categorized as Karanja Formation. Out of the eight lava flows exposed in the area, seven flows are massive and one flow is unclassified basalt.

A detailed hydrogeological study has been carried out in the area and regular pre- and post-monsoon water level monitoring has been carried out. The average static water levels in the post-monsoon season range between 2.1 to 20.50 m bgl, whereas in pre-monsoon season it varies between 5.2 to 20.50 m bgl. The seasonal water level fluctuation ranges between 2 to 4 m. The average yield of the dug wells ranges between 60 and 100 m^3/day during post-monsoon, while it ranges between 18 and 50 m^3/day during pre-monsoon season. The geomorphology of the area is suitable for groundwater management and provides a scope for further groundwater management as the population in the area is growing enormously thus posing an increased demand for groundwater extraction. As the shallow aquifers are dried in summer, the dependability on the deeper aquifers has increased. The present study would help to analyze the pre- and post-monsoon water levels and their fluctuation in the northern part of the watershed. The study area comprises of vast belt of orange and citrus cultivation, resulting in over-exploitation of groundwater in the area. The study incorporates, the water level fluctuation and water level trends in the northern part of watershed WRJ-2, concerning the growing over-exploitation of groundwater due to citrus cultivations in the area.

Geographic information system is used as a tool to identify and study the groundwater fluctuation, geology, and hydrogeology of the area. Preparation of geological and geomorphological maps based on field observations and existing data has been done. A detailed study of the yield and water level fluctuation of the monitoring stations is carried out during pre-monsoon and post-monsoon periods in the study area. The groundwater management of the study area is carried out on a ridge to valley-based concept. Also, the data from the actual field survey has been collected after studying various irrigation and public wells in the study area. For the effective groundwater management of the study area, the area should be thoroughly investigated considering geological, hydrogeological aspects, and aquifer parameters, in the Deccan basaltic terrain of multi multi-layered aquifer system in the present area. The artificial recharge measures suitable in the area are suggested to arrest surface water and soil runoff.

Keywords: *Groundwater, Deccan trap, watershed, over-exploitation, heterogenous, critical, water level*

UNVEILING THE HIDDEN WATERS: INTEGRATING SWAT-MODFLOW FOR MAHANADI RIVER BASIN'S WATER DYNAMICS

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Climate change aided with rapid urbanization has significantly impacted the regional water table. This has altered the water dynamics and intensified water scarcity across the globe. With dwindling resources and untimely rains, as cities expand and populations grow, the demand for water increases, often outpacing the available supply. This situation is further complicated by the alteration of natural hydrological cycles due to climatic changes, which can lead to reduced groundwater recharge, increased surface runoff, and pollution of water sources. Consequently, there is an urgent need for a comprehensive hydro-climatological assessment of all components of the hydrological cycle, including precipitation, evaporation, infiltration, and runoff. Such an assessment is crucial for developing sustainable water resources management strategies that can ensure a reliable water supply, and predict drought and flood events, while also protecting the environment and maintaining the balance of natural ecosystems. By understanding and managing the intricate dynamics of regional hydrology, policymakers, and water managers can implement effective measures to mitigate the impacts of climate change on water resources and promote long-term sustainability.

Understanding the interaction between surface water and groundwater is crucial to deciphering the complexity of the hydrological cycle. SWAT-MODFLOW is a widely employed integrated model to effectively couple surface water with groundwater to simulate their interaction processes. In this study, SWAT-MODFLOW has been applied to the mighty Mahanadi River basin, located on the eastern coast of India to simulate the Surface water groundwater dynamics. For the development of the SWAT (Soil and Water Assessment Tool) model, a variety of data sets have been utilized to ensure a comprehensive and accurate representation of the study area. These datasets include the Digital Elevation Model (DEM), stream density, soil characteristics, Land Use and Land Cover (LULC), and slope. The integration of these diverse data sources allowed for the detailed classification of the entire basin into 30 sub-basins and 806 Hydrologic Response Units (HRUs). This classification was crucial for understanding the spatial variability and hydrological processes within the basin.

Climate data played a significant role in the simulation of surface runoff. The climate data included parameters such as rainfall, maximum and minimum temperatures, wind speed, solar radiation, and relative humidity. These parameters were used to simulate surface runoff over a 23-year period, from 2000 to 2023. The initial two years, 2000 and 2001, were designated as a warm-up period to stabilize the model and ensure accurate simulations for the subsequent years. In addition to the SWAT model, a groundwater model (MODFLOW) was developed to simulate groundwater flow and interactions within the basin. The MODFLOW model was constructed using aquifer characteristics, including aquifer thickness, hydraulic conductivity, and specific yield data. These characteristics were essential for accurately representing the groundwater system and its dynamics. The entire basin was discretized into a grid with a spatial resolution of 1000 x 1000 meters, which provided a detailed representation of the groundwater flow system. To understand the linkage between surface water and groundwater processes, the HRUs of the SWAT model were linked to the grid cells of the MODFLOW model. This linkage was crucial for capturing the interactions between surface runoff and groundwater recharge. The outputs of both the SWAT and MODFLOW models were validated using observed data. Surface runoff data from 18-gauge stations and groundwater recharge data from various wells were used for this validation process. The validation ensured that the models accurately represented the hydrological processes within the basin. The analysis of LULC changes over time was a significant aspect of this study. Using MODIS (Moderate Resolution Imaging Spectroradiometer) data, the time-dependent trend in LULC was analyzed from 2001 to 2020. The analysis revealed notable changes in the LULC within the basin. Water bodies and urban areas showed an increase of 2% and 3%, respectively, indicating urban expansion and changes in water management practices. Conversely, barren land decreased by 14%, suggesting a shift towards more vegetated or developed land uses.

The water balance analysis of the basin provided insights into the overall hydrological dynamics. The analysis indicated a negative soil water content of -1133.61 mm, which suggested net water loss through runoff and evapotranspiration. This negative balance highlighted the importance of understanding and managing water resources to mitigate water scarcity and ensure sustainable water use. One of the key findings of the study was the higher water discharge observed in sub-basin 22, where the Hirakud dam is located. The discharge rate in this sub-basin was 227 mm in 2002, which increased significantly to 614 mm in 2023. This substantial increase in discharge rate indicated that sub-basin 22 had become a flood-prone zone. The construction of the Hirakud dam and subsequent changes in land use and hydrological processes likely contributed to this increased flood risk. Largely, the study provided valuable insights into the hydrological processes and changes within the basin over the 23-year period. The integration of SWAT and MODFLOW models, along with comprehensive data sets and validation, ensured a robust analysis of surface and groundwater interactions. The findings highlighted the importance of continuous monitoring and adaptive management to address the challenges of water resource management in the face of changing climate and land use patterns. This integrated approach will provide a detailed understanding of groundwater recharge and stream flow dynamics, allowing them for the estimation of key hydrological cycle components. These results will offer insights into water storage dynamics within the concerned basin, providing crucial information to support policymaking and ensure the sustainable management of water resources in the future.

Keywords: *Mahanadi river basin, SWAT-MODFLOW, hydrological cycle, surface runoff, groundwater recharge*

FLOW MODEL FOR GROUNDWATER RECHARGE POTENTIAL

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Groundwater is a vital freshwater resource globally, equally important as surface water. Over-exploitation due to increasing water demand from population growth has led to water stress in several regions. This paper focuses on delineating the recharge potential of an area using advanced technologies such as GIS, remote sensing, and modeling. The primary factors contributing to groundwater depletion include improper land use and land cover, hydrogeology, lithology, salinity constraints, and water pollution. To address these challenges and implement appropriate measures, it is crucial to assess the recharge potential of specific areas. The Analytical Hierarchy Process (AHP) model, integrated with GIS, is employed for decision-making to identify high-risk areas experiencing rapid depletion, suitable for artificial recharge. In this study, various thematic layers have been developed using satellite imagery to analyze factors such as slope, drainage density, and geomorphology for zoning areas with low recharge potential. These methods facilitate the collection of historical data to predict and estimate future groundwater level fluctuations in the region.

Keywords: *Analytical Hierarchy Process, GIS, remote sensing, groundwater*

PRIORITIZING GROUNDWATER POTENTIAL AND SOIL EROSION-PRONE ZONES USING MORPHOMETRIC, HYPSOMETRIC AND COMPOUND FACTOR APPROACHES IN THE BEAS BASIN, HIMACHAL PRADESH

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One of the most crucial techniques for evaluating drainage and sub-watershed prioritization for groundwater potential and soil erosion of watersheds is the use of remote sensing and GIS. This study focuses on the Beas River Basin, from its origin up to Pong Dam (Kangra district), Himachal Pradesh, covering an area of 12,370 square kilometers. This study uses morphometric, hypsometric, and compound factor techniques to identify zones that are prone to groundwater potential and erosion using digital elevation models (DEM) and Arc GIS tools. Using remote sensing and GIS techniques, morphometric measurements that is, linear, areal, and relief features were assessed for a thorough analysis of the Beas River Basin. The USGS earth explorer provided the SRTM- DEM with a 30 m resolution for the Beas River Basin morphometric investigation. Linear, bifurcation ratio (Rb), mean bifurcation ratio (Rbm), stream length (Lu), stream numbers (Nu), stream order (So), and mean stream length. Overland flow length (Lg), circulatory ratio (Rc), form factor (Ff), shape factor (Bs), elongation ratio (Re), compactness coefficient (Cc), drainage density (Dd), stream frequency (Fs), drainage texture ratio (Rt), and infiltration number (If) in the Areal aspects Relief (Rf), relative relief (R), relief ratio (Rh), ruggedness number (Rn), mean relief (Hm), maximum relief (Hmax), minimum relief (Hmin), and hypsometric integral (HI) are among the morphometric parameters reviewed in this study. There are five sub-watersheds within the watershed i.e. SW1, SW2, SW3, SW4, SW5 and SW1, SW2, SW3, SW4 and SW5 having areas of 3175.13, 2367.64, 1795.0.72, 1775.53 and 3256.18 km^2 and having perimeter for sub-watersheds 352.73, 269.00, 221.47, 259.82 and 367.98 km. For the estimation of the ranking technique for soil erosion calculate the Linear aspect and areal aspect for calculating the compound factor after the calculation of the compound factor prioritize the ranking for soil erosion. Similarly for the estimation of prioritizing groundwater potential zones calculate the Linear aspect i.e. Mean bifurcation ratio (Rbm), in the areal aspect, circulation ratio (Rc), drainage density (Dd), stream frequency (Fs), drainage texture ratio (Rt), form factor (Ff), shape factor (Bs), and elongation ratio (Re) infiltration Number (If) and relief aspects i.e. relief ratio (Rh) and ruggedness number (Rn) with Compound factor ranking technique approaches to determine and prioritize the groundwater potential zones. The morphometric, compound factor (CF), and hypsometric integral (HI) parameters were all effectively calculated. The ground water potential and soil erosional susceptibility of the basins were evaluated using the hypsometric integral (HI) and compound factor (CF) ranking approaches. The methodology for this study is STRM Data, GIS software, study area extraction, stream networks, sub-basins, morphometric analysis i.e. (Linear aspect, areal aspect, relief aspect) and then compound factor for analysis of both groundwater potential zoning and soil erosion prone zone areas. Results for this study depend upon two factors i.e. compound factors and the hypsometric integral approach. Following the evaluation of factors, priority zones are allocated to each sub-watershed for areas susceptible to groundwater potential and soil erosion-prone areas. This study using ArcGIS tools and different methodologies showed as a result that all of the sub watersheds i.e. SW1, SW2, SW3, SW4 and SW5 having high or low infiltration, high or low groundwater potential zones, high or low erosive levels of soil and also having high or low permeability. The average of all these parameters for each watershed is calculated to determine the priority. To better planning and management, the study shows that remote sensing data and geographic information systems are viable for analyzing and estimating the stage and rate of soil erosional processes and groundwater potential zones in a Himalayan watershed. To manage groundwater zones and soil erosion-prone area activities at the appropriate locations within the study area, the results have aided in the qualitative discussions and prioritizing the sub-watershed for sustainable groundwater potential zones and soil erosion-prone area zones and management. We are able to establish the priority ranks and categorize the sub-watershed into three groups based on the calculated results: low, moderate, and high priority. The distribution of its natural resources and the identification of major watersheds or sub-watersheds must be prioritized to implement effective and sustainable watershed management strategies. A key methodology approach for a better understanding of hydrological challenges and efficient catchment management planning is the use of RS and GIS for morphometric evaluation and prioritizing sub-catchments according to their groundwater capacity and susceptibility to soil erosion. The study's findings can be used to inform plans for flood prevention, watershed management, and water resource conservation.

Keywords: *Catchment, morphometric analysis, hypsometric analysis, compound factor, Beas River basin, ground water potential, soil erosion, sub basin prioritization*

MATHEMATICAL MODELLING OF GROUNDWATER FLOW IN HETEROGENEOUS SOIL USING THE FINITE DIFFERENCE METHOD

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Modelling the groundwater flow is a key requirement of proper water resource management in arid and semi-arid regions, where groundwater is the principal source for irrigated agriculture. The goal of the paper is the establishment of a mathematical model simulating the process of flow of groundwater in heterogeneous soils using the Finite Difference Method. Variability in hydraulic soil properties plays a significant role in the groundwater flow pattern, making this complexity appear necessary to incorporate it into modelling efforts. Groundwater is an essential resource supporting ecosystem functions, agricultural activities, and human endeavours; hence, understanding the dynamics of its flow is fundamental to its sustainable management. The study aims to create a robust three-dimensional (3D) groundwater flow model that incorporates spatial variations in hydraulic conductivity and evaluates how these variations, alongside different boundary conditions, affect groundwater flow behavior. The governing equations for steady-state groundwater flow are derived from the fundamental principles outlined in the continuity equation and Darcy's law, which serve as the basis for the model. Using the Finite Difference Method, the research successfully discretizes such governing equations in a manner that allows a three-dimensional simulation of groundwater flow. There are three different cases for hydraulic conductivity variations: constant, linear, and exponential variations, each representing distinct realistic real-world scenarios common to the field of subsurface hydrology. Simulations under different boundary conditions, such as Dirichlet and Neumann types, are run to ensure the reliability of the model. These are important in defining how the outer boundaries of the system affect the flow of groundwater. From the study, there are significant insights into hydraulic head distribution across the modelled area. It is noticed that the hydraulic heads have a wide range of distributions based on the imposed boundary conditions. For example, the hydraulic head values on the boundaries may be given through Dirichlet boundary conditions. The Dirichlet boundary conditions may tend to yield a relatively uniform hydraulic head distribution over the model domain. The Neumann boundary conditions are flux inputs on the boundaries and usually lead to higher hydraulic head variability in terms of influences of flux-based factors. Furthermore, the study highlights the impact of heterogeneity in soil properties on groundwater flow dynamics. By introducing spatially variable hydraulic conductivities into the model, the researchers uncover notable changes in flow patterns. When applying linear variations in hydraulic conductivity, gradual shifts in groundwater flow patterns are observed, indicating a smoother transition in flow dynamics. Alternatively, the inclusion of exponential functions implies a steeper variation that identifies certain zones that can dry out or have their groundwater accumulate. Such discovery is essential in determining changes due to soil property variations impacting groundwater availability and movement with better management practices. The study emphasizes that soil heterogeneity needs to be incorporated into the groundwater flow models; in fact, such factors may improve predictive capabilities in the simulations considerably. The Finite Difference Method simulates the complex groundwater scenario effectively; however, there are limitations with the study regarding computational efficiency when model complexity increases. This aspect emphasizes the demand for realistic modelling approaches that reflect the complex nature of subsurface hydrological systems. In this regard, the study becomes invaluable in advancing the understanding of groundwater flow in heterogeneous soils, as any consideration in variations of hydraulic conductivity determines overall flow dynamics. The developed FDM model turns out to be a useful tool for predicting groundwater behaviour, which is important for the sustainable management of water resources, especially in areas facing problems related to variable soil conditions. Therefore, this research has significant implications for water resource management strategies, as it gives a better understanding of how groundwater systems behave under different scenarios. Future research efforts should look forward to further extending the model to incorporate additional complexities, such as interactions with various soil properties and the incorporation of seasonal variations in groundwater recharge. Testing the applicability of the model in different geographical contexts would also be important since it would enhance the utility of the model in addressing a wide range of water resource management challenges faced globally. Overall, this study is a testament to the importance of mathematical modelling in understanding and managing groundwater resources, contributing valuable insights that can aid decision-making processes in sustainable water management practices.

Keywords: *Groundwater flow, heterogeneous soil, Finite Difference Method, hydraulic conductivity, water resource management*

TEMPORAL ANALYSIS AND PREDICTIVE MODELING OF GROUNDWATER DYNAMICS IN SAMBHAL DISTRICT, UTTAR PRADESH, INDIA

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Groundwater constitutes an indispensable resource pivotal for sustaining agricultural productivity, potable water supply, and industrial operations. Understanding its dynamics is essential for sustainable resource management and mitigation of water scarcity challenges. The current investigation targets the dynamics of groundwater in Bahjoi, situated within the Sambhal District of Uttar Pradesh, India (latitude: 28.41, longitude: 78.63). The study spans from 2001 to 2022, encompassing key variables such as rainfall, minimum and maximum temperatures, and groundwater levels during the pre-monsoon season. The overarching objective is to elucidate trends and predict groundwater levels employing advanced statistical techniques and machine learning methodologies. Analytical tools such as the Mann-Kendall test, Sen's slope estimator, and a random decision forest model were deployed. The dataset underwent rigorous preprocessing, including the handling of missing values using Inverse Distance Weighted (IDW) interpolation in ArcGIS and the application of Kalman smoothing for noise reduction.

Rainfall and temperature datasets were sourced daily from the Indian Meteorological Department (IMD) and aggregated to seasonal averages. Employing reliable methods for data aggregation ensures the precision of the analysis and provides an accurate basis for subsequent modeling. The IDW interpolation method was utilized to estimate missing values based on spatial proximity, enhancing the dataset's reliability. Kalman smoothing was applied to mitigate data noise and refine temporal patterns. Correlation analyses using Pearson and Spearman coefficients provided insights into interdependencies among variables. Temporal trends were assessed through the Mann-Kendall test and Sen's slope estimator, while the Innovative Trend Analysis (ITA) method augmented the trend identification process. A random decision forest model was implemented to forecast groundwater levels, integrating rainfall, maximum temperature (Tmax), and minimum temperature (Tmin) as predictors. The model's efficacy was gauged using metrics such as R-squared (R^2), Root Mean Squared Error (RMSE), and Mean Absolute Error (MAE).

The correlation analysis revealed varied degrees of association among the parameters under investigation. This step is integral for delineating the interplay between climatic variables and groundwater levels, forming the groundwork for robust predictive modeling. Rainfall exhibited a weak positive correlation with groundwater levels, with Pearson's coefficient recorded at 0.12 and Spearman's rank correlation at 0.15, implying a limited direct influence. Tmax demonstrated a more substantial positive correlation, with Pearson's coefficient at 0.31 and Spearman's rank correlation at 0.29, underscoring its influence on groundwater dynamics through processes such as evaporation and aquifer recharge. Conversely, Tmin showed negligible correlation, with coefficients approximating zero, indicating a minimal role in groundwater fluctuations. Trend analysis yielded significant insights into long-term variability. Identifying trends over decades is crucial for planning adaptive measures and understanding the impact of climatic variations on groundwater systems. Rainfall displayed a

marginally declining trend, as evidenced by a Mann-Kendall Z-score of -0.42 and a Sen’s slope of -0.0028 mm/year. Tmax exhibited a decreasing trajectory with a Z-score of -0.22 and a Sen’s slope of -0.0150 °C/year, suggesting potential climatic shifts. In contrast, Tmin presented an upward trend, marked by a Z-score of 0.32 and a Sen’s slope of 0.0016 °C/year. Groundwater levels showed a pronounced increasing trend, with a Z-score of 4.76 and a Sen’s slope of 0.3581 m/year, indicative of substantial recharge mechanisms or reduced abstraction pressures. The ITA method corroborated these findings, highlighting consistent increases in groundwater levels alongside relatively stable rainfall and temperature dynamics.

The study period exhibited considerable variability in groundwater levels, ranging from a minimum of 8.65 meters below ground level (mbgl) in 2002 to a maximum of 15.95 mbgl in 2021. This variability underscores the complex interrelations among climatic inputs, recharge mechanisms, and human activities affecting groundwater. This variability reflects a complex interplay of factors, including recharge rates, water extraction practices, and prevailing climatic conditions. Lower levels during the early 2000s likely resulted from elevated extraction rates and suboptimal recharge, whereas higher levels in recent years suggest improved water resource management practices or favorable natural recharge conditions. The random decision forest model demonstrated robust predictive capabilities, achieving an R^2 value of 0.78, RMSE of 0.81 mbgl, and MAE of 0.58 mbgl. These results signify the potential of machine learning frameworks in decoding intricate environmental systems and providing actionable predictions. These metrics underscore the model’s ability to effectively capture the intricate relationships between groundwater levels and influencing variables. The model forecasted a groundwater level of 13.92 mbgl for 2023, aligning well with observed trends and validating its reliability. The relatively weak correlation between rainfall and groundwater levels emphasizes the significant role of non-rainfall factors, such as soil characteristics, aquifer properties, and anthropogenic activities, in shaping groundwater dynamics.

This investigation underscores the efficacy of integrating statistical and machine-learning approaches for groundwater analysis and prediction. Such integration paves the way for comprehensive strategies to address pressing water resource challenges in a changing climatic scenario. The Mann-Kendall test and Sen’s slope estimator provided robust tools for identifying temporal trends, while the random decision forest model delivered reliable predictions. The findings illuminate the critical role of temperature and non-rainfall variables in influencing groundwater levels. The upward trend in groundwater levels during the pre-monsoon season suggests enhanced recharge conditions or moderated abstraction, offering valuable insights for sustainable water resource management strategies. Future research could incorporate additional parameters, such as land use changes, aquifer properties, and socio-economic factors, to further refine the understanding of groundwater system dynamics and improve predictive accuracy.

Keywords: *Random Decision Forest, Mann-Kendall Test, Sen’s slope, inverse distance weighted*

GROUNDWATER PUMPING INDUCED STREAMFLOW DECLINE

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The Ganga and Indus River basins, which support a significant portion of the global population and are intensively irrigated, have emerged as a hotspot for groundwater depletion. These regions supply essential groundwater and surface water resources that underpin food production, irrigation, and drinking water. Groundwater, in particular, helps stabilize river flows during dry seasons, ensuring that water is available even when rains are scarce. However, over the past few decades, a troubling trend has emerged: groundwater levels and streamflow in these basins are falling alarmingly, threatening water supplies, food production, and the ecosystems that depend on the rivers.

The situation is especially dire in the Ganga River Basin (GRB). Summers before the monsoon, once a time of relief, now bring record-low water levels. The cause? Over-extraction of groundwater, where it is being pumped out faster than it can be replenished. This is not just draining underground aquifers but also disrupting the natural flow of groundwater into streams, which is crucial for keeping rivers flowing during dry seasons. As groundwater contributions dwindle, streams are drying up, creating significant water management challenges, particularly during the dry season when rivers rely heavily on baseflow—the part of streamflow fed by groundwater. This drop in water availability has enormous consequences: millions face water shortages, and river ecosystems are at serious risk.

Unfortunately, many large-scale hydrological models do not fully capture the complex interactions between groundwater and surface water, especially lateral groundwater flow, which moves sideways and feeds rivers. To address this gap, we used the ParFlow-CLM model. This advanced hydrological model stands out for its ability to simulate groundwater and surface water dynamics in great detail, down to a 5 km resolution. It can simulate water movement above and below ground, capturing the complex relationships between groundwater, soil moisture, evapotranspiration, and surface water.

In our study, we applied the ParFlow-CLM model over 50 years (1970–2021) to explore a range of hydrological variables—stream discharge, evapotranspiration, soil moisture, total water storage, and water table depth. We ensured our model was reliable by validating it against real-world data: streamflow records from the Central Water Commission (CWC), groundwater level data from the Central Ground Water Board (CGWB), and GRACE satellite measurements that track changes in groundwater storage. We also used data from the Minor Irrigation Census to understand how human activities, especially groundwater pumping for irrigation, have contributed to these trends. Bringing all this data together helped us better understand how water systems are changing in the Ganga and Indus basins.

Our main goal was to uncover how declining streamflow is directly linked to reduced river groundwater contributions. The results are precise: human activities, particularly unsustainable groundwater pumping for irrigation, significantly deplete groundwater levels and reduce river flow during dry periods. Since the 1970s, when large-scale groundwater extraction ramped up for agriculture, baseflow has steadily dropped. This decline disrupts the natural balance between streams and aquifers, putting many rivers at risk of becoming "losing streams," where, instead of groundwater flowing into rivers, river water is absorbed back into the ground, further draining both surface and groundwater resources. Our study highlighted specific sections of the Ganga River and its tributaries that are either gaining or losing water, showcasing the uneven and complex nature of groundwater-surface water interactions.

Although climate change plays a significant role in determining the contribution of groundwater to streamflow variability, the primary driver of the decline in groundwater discharge is the excessive pumping of groundwater for irrigational practices. The steady drop in baseflow undermines the long-term stability of river systems. It highlights the urgent need for a more integrated approach to managing water resources, considering both surface water and groundwater systems. This is especially important in areas where groundwater depletion is accelerating due to human activity and increasing climate stress. Our research offers a pathway for more sustainable water management in two of the world's most critical river basins, aiming to secure water resources for future generations.

If these trends continue, the Ganga and Indus basins face the risk of severe water crises and potentially devastating impacts on food security, economic stability, and the health of ecosystems. Our research underscores the urgent need for policies that integrate surface and groundwater resources management and consider the spatial variability of groundwater-surface water interactions. In short, to protect the future of water in these basins and the millions of people who rely on them, we must act now, rethinking how we manage this precious resource in the face of mounting pressures from humans and the environment.

Keywords: *Groundwater depletion, Streamflow variation, Ganga River Basin, Groundwater discharge, Groundwater-surface water interactions, Integrated groundwater modelling.*

NUMERICAL MODELING ON THE TRANSPORT OF BENZENE UNDER VARIABLE-DENSITY FLOW

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Benzene, a volatile and toxic aromatic hydrocarbon, is a persistent environmental pollutant with significant consequences for human health and ecological stability. Because of its carcinogenic characteristics, even minimal concentrations of benzene in soil and groundwater can present significant threats to public health, requiring effective predictive models to evaluate and alleviate its effects. This study examines the intricate mechanisms of benzene transport in variable-density flow systems, particularly those affected by seawater intrusion in coastal aquifers. Coastal habitats, where freshwater and seawater mix together, display unique density gradients, creating more complexities for modeling pollutant transport. The transport of benzene in subsurface environments is influenced by many physical and chemical processes, including dissolution, sorption, retardation, and volatilization. These processes collectively influence the mobility and bioavailability of benzene in groundwater. Comprehending these transport mechanisms are essential for creating efficient numerical models that can forecast the behavior of benzene and suggest successful remediation approaches. Numerical modeling is an effective instrument for simulating intricate relationships among flow dynamics, pollutant transport, facilitating thorough risk assessment and the development of corresponding remedies.

This study investigates the transport dynamics of benzene in variable-density flow systems by integrating the governing equations of flow with benzene's advection-dispersion mechanisms. The model integrates density gradients produced by fluctuations in benzene concentration, facilitating more precise simulations of actual scenarios, where seawater intrusion influences groundwater density. Coastal aquifers are particularly influenced by density-driven flows resulting from the interaction between freshwater and intruding seawater. These interactions establish distinct transport conditions for toxins such as benzene, which must be considered to forecast contamination plume dynamics effectively. The foundation of the current numerical modeling technique relies on the finite volume method, which is utilized to discretize the governing equations for flow and transport. The flow model is coupled with the transport model, indicating that the flow field calculated from density variations due to seawater intrusion and benzene concentration gradients directly affects benzene transport. The velocity field obtained from the flow model functions as an input for the transport model, further connecting the physical and chemical mechanisms that regulate benzene transportation. This connection is crucial for precisely capturing the interactions between flow dynamics and contaminant transport under a variable-density flow.

Boundary conditions are carefully defined to represent the intricacies of the natural system. A constant head boundary condition is established at the upper boundary of the flow model, simulating a steady-state flow condition driven by external hydrological inputs. No-flow boundary restrictions are imposed on the left, right, and bottom boundaries of the model to restrict the system and facilitate a concentrated examination of transport processes within a specified area. In the benzene transport model, a temporally variable boundary condition is assumed at the source zone at the upper boundary. All remaining boundaries for the transport model are assumed to be Neumann boundary conditions, signifying impermeable or reflective obstacles that limit the passage of benzene beyond the model region. The model development of the study integrates hydrodynamic processes, including advection and dispersion, and chemical interactions under hydro-geochemical settings pertinent to benzene transport. In the study, a series of simulations are performed to analyze the impact of density variations on benzene transport, exploring scenarios with varying levels of seawater intrusion and benzene concentration. These simulations illustrate the influence of density gradients on dispersion and advection, affecting benzene plume expansion and the efficacy of natural attenuation. The findings suggest that elevated density gradients, either by intensified saltwater intrusion or benzene levels, augment the advection-dispersion of benzene, potentially resulting in more broad contaminated plumes. This finding directly impacts risk assessment and the formulation of remediation solutions, highlighting the necessity of considering density-driven flow mechanisms in the evaluation of pollutant transport within coastal aquifers.

Although prior studies have investigated benzene transport in freshwater environments, research on variable-density systems is still scarce. This study addresses a gap in the field and establishes a framework for future research on pollutant transport in coastal aquifers affected by seawater intrusion. The results elucidated herein augment the comprehension of benzene behavior in variable-density settings and contribute to the formulation of predictive models that can direct environmental management and policy. The study's findings about the interaction of flow dynamics, benzene transport, and natural attenuation mechanisms can enhance the development of more efficient monitoring and remediation strategies in coastal areas susceptible to pollutant intrusion. This study illustrates the effectiveness of numerical modeling in explaining the complex relationship between variable-density flow and benzene transport. The study presents a comprehensive tool for simulating benzene dynamics in density-driven flow environments by coupling flow and transport models. This research enhances the understanding of contaminant transport in coastal aquifers, improving predictions and mitigation strategies for harmful compounds such as benzene on human health and the ecosystem.

Keywords: *Numerical modeling, variable-density flow, benzene, finite volume method, advection-dispersion*

GROUNDWATER MANAGEMENT USING COUPLED MESHLESS NUMERICAL MODELS AND MACHINE LEARNING TECHNIQUES

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Groundwater is under increasing stress due to population growth, climate variability, and rising demand, making effective assessment and management essential, and necessitating advanced predictive tools for sustainable management. Current groundwater assessment heavily relies on numerical models to predict groundwater level and flow. The numerical models are based on solving partial differential equations to represent aquifer physical processes, and need intensive meshing, complex data inputs, and substantial computational resources, restricting their ability to represent complex geometry. Further, the meshing process in the traditional models requires high preprocessing and finetuning efforts. Meshless methods are more flexible numerical methods that use scatter points in the domain boundary instead of grids, which simplifies handling complex geometries, reduces preprocessing, and improves boundary representation. However, issues such as the requirement for extensive field data and accurate measurements are not alleviated in meshless methods. The present study aims to overcome traditional numerical methods' limitations by combining the strengths of numerical models with emerging artificial intelligence (AI) techniques to create robust predictive models for groundwater quantity modeling.

The simulation model is developed by coupling the Meshless Radial Point Collocation Method (RPCM) with Long Short-Term Memory (LSTM) networks to predict Groundwater Levels (GWL) accurately. RPCM is a strong-form meshless method with the advantages of simpler adaptive analysis, direct discretization, a straightforward modeling approach, and computational efficiency. RPCM is proven to be reliable for spatial prediction of groundwater levels. LSTM is a form of deep learning AI technique suited for time-series predictions, retaining sequential dependencies using memory cells and gates, making them ideal for predicting groundwater levels over time. The proposed RPCM-LSTM hybrid model leverages the spatial modeling capabilities of meshless methods alongside the temporal forecasting power of LSTM, which captures nonlinear patterns and long-term dependencies in groundwater systems, where the meshless methods are known for their flexibility in handling complex geometries and boundary conditions.

The Multi-Quadric Radial Basis Function (MQ-RBF) is used as the approximating technique in RPCM to derive the shape functions. The Neumann boundaries are handled using the direct approach. The groundwater flow equations are formulated using RPCM for heterogeneous confined aquifer. The RPCM model is developed in MATLAB and is well-validated. The model is applied to a real aquifer in Surat, Gujarat, India. This aquifer has an area of 4.5 km^2 and is highly heterogeneous with 11 transmissivity zones. The aquifer is discretized into 986 nodes, with the nodal arrangement representing the recharge zone in detail. The nodes lying on the boundary are assigned the values as per the Dirichlet or Neumann boundary conditions. The stiffness matrix is formed by looping over the nodes. For every support domain, the values of the shape function, and its first and second derivatives concerning nodes are calculated and incorporated into global stiffness matrices. After the global matrix is created, the head values at all nodes are approximated. This results in the steady state head distribution from the RPCM model. The traditional Finite Difference

Method (FDM) based MODFLOW model, with the same configuration, is developed to compare the results of RPCM.

After computing the steady state head distribution from RPCM and verifying the results with MODFLOW, the RPCM is coupled with LSTM for temporal forecasting to reduce the computational demands while providing accurate groundwater forecasts. Along with the head distribution, various recharge and extraction scenarios and their influence on future groundwater heads are generated to train LSTM networks on the input and output of RPCM to mimic the numerical model simulation. Thus, the temporal simulations by the LSTM model are trained with simulated data from RPCM to capture the temporal dependencies in GWL influenced by recharge and demand changes. The hybrid RPCM-LSTM model is finally used to evaluate the change in groundwater level in the future due to changes in recharge and extraction rates.

The results indicate that the meshless approach provided flexibility with complex boundary conditions and demonstrated high accuracy and adaptability in groundwater flow simulations. The average percentage difference between the groundwater heads estimated by RPCM and MODFLOW is 0.85%, which indicates that RPCM can simulate the flow phenomenon with good accuracy. Thus, RPCM is the best alternative approach to traditional mesh-based methods and has the advantages of computational efficiency, simpler fine-tuning, lower preprocessing, and the ability to handle complex geometries. Using simulated data, the LSTM accurately learned and predicted patterns in groundwater levels, effectively addressing long-term dependencies like changes in recharge rates and demand, thereby successfully mimicking the numerical model. LSTM significantly reduces the computational cost and becomes very adaptable when new information is introduced.

Thus, the hybrid RPCM-LSTM model offers robust solutions for more accurate groundwater level prediction. Through the meshless RPCM simulation, the model achieves flexibility in handling complex geometries and boundaries, while the LSTM network captures essential temporal patterns, providing flexibility and addressing the key challenges in groundwater modeling, such as computational complexity and data scarcity. The obtained results can be used for various groundwater management scenarios and applications such as location of wells, desired pumping, quantity of groundwater that can be extracted etc. Therefore, the hybrid numerical-AI models are valuable tools for decision-makers to balance groundwater use with increasing demand and mitigate the risks of over-extraction and resource depletion.

Keywords: *Meshless method, LSTM, groundwater level predictions, spatial-temporal prediction, groundwater flow*

SIMULATING GROUNDWATER LEVELS AND POLLUTION IN PUNE, INDIA

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Groundwater is perhaps the most useful resource in nature. From agricultural to industrial to residential, the use of groundwater is infinite. But its sources are not. Over 50% of urban water usage is dependent on groundwater. Most of the groundwater comes from rainwater absorption with seepage from rivers and canals contributing a little. However, with urbanization, rainwater absorption is on the decline. Moreover, groundwater resources are being contaminated day after day. Many studies discuss the implications of groundwater pollution on public health. Polluted groundwater has been known to cause a severe decline in immunity levels in children. Contaminated groundwater is a major source of cholera, typhoid, hepatitis, and other similar waterborne diseases. Consumption of groundwater having heavy metals and industrial waste water can cause cancer and neurological disorders. Polluted groundwater can also loss agriculture and aquatic life. The purpose of this study is to find out different factors affecting groundwater levels and quality in the Pune district. By analyzing historical rainfall data, industrial waste output, urban population and water usage statistics, we aim to create a simulation model capable of predicting groundwater usage, contamination, and recharge. This model will assist to know the activities would be best for reducing pollution, enriching recharge channels, and evolving optimal strategies for sustainable groundwater management, that safeguards clean and abundant groundwater resources for the region.

We are collecting data from various government approved sources and other relevant publications. Government agencies like the Maharashtra Pollution Control Board and the Central Pollution Control Board stake water pollution levels and measurements timely. These periodic reports are valuable as they support to compile comprehensive data mapping both surface water and groundwater pollution across the region. Agencies like the Indian Meteorological Department collect and document rainfall statistics every day. This data is crucial for constructing rainfall patterns. Understanding these patterns will be influential in assessing groundwater recharge rates, which are critical for maintaining sustainable water resources. The Groundwater Surveys and Development Agency conducts regular groundwater level surveys. This data can be used to map past and existing groundwater levels. Analysis of this data will allow us a better understanding of the activities taking place as recharge rates of groundwater and the level of pollution within the groundwater. This all collected data will also help to the development of an LSTM-based model predicting the future availability of groundwater and groundwater pollution over time. This work will present a thorough understanding of patterns and trends of water quality and availability. This will contribute making decisions toward water management and environmental protection. All the data collected will be treated and then merged. Preprocessed data will be fed to the LSTM model. The LSTM model is chosen to incorporate both current and previous data giving more accurate results. Since we are working with natural phenomena, previous data plays a vital role in forecasting other related factors (i.e. we will need Y_{t-1} and X_t both). This makes the LSTM model a significant choice due to its integration of the internal current data point (X_t) and the historic one (Y_{t-1}), which has been strong in delivering estimated accuracy compared to others.

Upon training, LSTM will be subjected to multiple scenarios. This will help us simulate different usage, recharge, and pollution conditions in order to find out how we can boost groundwater sources, reduce groundwater pollution, and promote sustainable usage of groundwater. We will also be using other GRU-based architectures to confirm and cross check our findings. This will help strengthen the validity of the LSTM architecture for groundwater simulation tasks. The output of this study would be a model capable of simulating groundwater usage, recharge, and pollution levels against various input conditions. This study would also help us determine the most optimal usage conditions for ensuring sustainability in groundwater levels in Pune district. This work is aimed at identifying the various factors governing both the levels and quality of groundwater in the Pune district. This can be achieved by analyzing historical rainfall data, industrial waste output, and statistics on the urban population and their utilization of water. This paper will try to obtain a simulation model that may predict the dynamics of the region's groundwater resources. Such a model is essential to understanding the complexity involved with the several factors that affect the groundwater resources and their quality. We will also implement some more complex modeling techniques, including Long Short-Term Memory (LSTM) and Gated Recurrent Unit (GRU) architectures. These are relevant methods for this study as they emphasize the importance of sample data in accurate prediction. We will thus be able to validate the importance of our research by examining how different influences affect groundwater resources over time. This way, it will not only add to the existing knowledge but will also help formulate appropriate sustainable groundwater management strategies for the Pune district.

Keywords: *Groundwater, LSTM, GRU, simulation, sustainability*

QUANTITATIVE INSIGHTS AND GROUNDWATER FLOW MODELING IN OPEN-PIT MINES

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Agriculture, industry, domestic purposes and other sectors are dependent on groundwater resources due to the limitations in availability of surface water resources especially in semi-arid and arid regions. The limited groundwater resources are severely affected by open-pit mining operations in many ways which includes inflow into mine pits, depletion in groundwater level, change in regional hydrogeology etc. We have conducted a quantitative analysis study and applied a groundwater flow modelling approach in an open-pit mine in Chittorgarh, Rajasthan, having geology characterized by limestone, granite, gneiss and weathered shale. We have monitored groundwater levels at 15 locations in our study site within 10 km buffer zone surrounding the mine. Both pre- and post-monsoon levels within the buffer zone were measured for understanding the seasonal variations in groundwater level. Electrical Resistivity Tomography (ERT) method was applied in addition to understand the subsurface strata of the region. We conducted infiltration tests in five sites in the study area for determination of hydraulic conductivity. A spatial heterogeneity referring to the variation of hydraulic conductivity within the range of 7.41 to 21.33 cm/day was found as the result of the tests. We also conducted pumping tests and recovery tests for computations of two more parameters, i.e., transmissivity and storativity, for understanding the aquifer's capacity to transmit and store water respectively. The value of transmissivity came out was 142.63 m^2/day and storativity was found 0.000905. We used an advanced groundwater modelling software, Visual MODFLOW Flex, to integrate Geographic Information Systems (GIS) data for enhanced visualization and management. Geological, hydrological, topographical parameters and the groundwater dynamics under transient conditions were simulated holistically by the conceptual model. Recharge from precipitation, interactions with rivers & drains and few more boundary conditions were defined based on the observed data and hydrological characteristics of the region. We used rainfall intensity, infiltration capacity and land use patterns for calculation of the recharge rates. We divided our study area into grids assigning specific hydrogeological properties, e.g., hydraulic conductivity, porosity and storage coefficient to each cell. Estimation of seepage into the mine pit and simulation of the groundwater flow patterns were the primary objectives of our research. Partial Differential Equations (PDE) representing groundwater flow is used by this model, solved using the finite difference approach. Model evaluation, i.e., calibration is done using observed groundwater levels from the field data during pre- and post-monsoon periods. The temporal variations in groundwater levels were accounted for the model using the transient state approach. We used analytical methods for estimation of seepage in addition to numerical modelling. Different analytical equations, provided by renowned scientists and researchers, were used to get initial seepage flow. Though these assumptions offer a simplified approach to seepage estimation, they often fail to capture the complexities of heterogeneous aquifers and dynamic groundwater systems. To overcome these limitations, numerical models account for site-specific data, variations in geology for better understanding of groundwater flow dynamics and seepage. Our results came up with the demonstration of significant groundwater inflow towards the mine-pit for development of the strategies for sustainable dewatering. For better understanding of groundwater behaviour, the integration of geophysical data, ground observations as well as advanced modelling techniques become important. Minimization of environmental impacts and maximization of economic benefits, i.e., ensuring the economic feasibility of mining are the objective functions. Future research will focus on improvement of model by calibrating it with hydraulic conductivity and storage related parameter and validation of the model will be done from the field data. The results of this study will help us in many ways, firstly it will provide a detailed understanding of groundwater flow dynamics and seepage pattern in mining region. It will help us in developing a sustainable mine dewatering plan, ensuring that groundwater extraction is optimised to minimize the environmental impacts. The study will also help in developing regional water management strategies by providing relation between mining activities and groundwater resources. The methodology adopted in this research will not only address short term changes but also help us analysing long term changes. By using techniques like Self organising Maps this study can be enhanced and used for long term monitoring. We will also focus on the application of emerging technologies, e.g., artificial intelligence (AI) and Remote Sensing (RS) for management of groundwater resources in regions where mining takes place. The multidisciplinary approach for management of groundwater resources and its significance is the focus of the research. The primary result from simulation of Visual MODFLOW Flex shows that the flow of groundwater converges towards the mine-pit due to hydraulic gradient. The impacts of mining activities are lightened using velocity distribution maps. The initial results show a difference between the estimated seepage inflow from two different analytical equations used for seepage estimation, having higher value for the second one. The results from Visual MODFLOW Flex estimate seepage value which matches the result of the first analytical equation. These discrepancies refer to the limitations of the analytical equations.

Keywords: *Groundwater flow, seepage estimation, open-pit mining, hydrogeology, numerical modeling, mine dewatering plan*

FLUORIDE CONTAMINATION AND ASSOCIATE HEALTH RISK ACROSS THE STATE OF MAHARASHTRA, INDIA

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This study aims to examine fluoride contamination in groundwater across Maharashtra state and its associated health hazards. To conduct this study, we have collected 1,278 groundwater samples data from CGWB water quality data base. The results indicate that fluoride concentrations ranging from 0 to 4.93 mg/L, with an average of 0.59 mg/L (±0.56). The data indicate significant regional variability, with inland districts exhibiting higher fluoride levels and corresponding health risk values compared to coastal districts demonstrating lower contamination and risk. Mostly the eastern region of Maharashtra has fluoride concentration exceed the maximum (1.5 $mg.L^{-1}$) permissible limit indicating the high vulnerability of dental and skeletal fluorosis. However, the coastal district of state have concentration less that lower permissible limit (0.5 $mg.L^{-1}$) in groundwater depicts the high vulnerability towards health issues causes due to deficiency of fluoride. Our findings underscore the importance of identifying and addressing the sources of fluoride in these regions and implementing effective public health strategies to minimize exposure. Additionally, the study highlights the need for ongoing monitoring of groundwater quality and the development of policies aimed at managing fluoride levels in affected areas. By providing insights into the spatial distribution of fluoride contamination, this research serves as a crucial step toward safeguarding public health in the Maharashtra state and informs future initiatives to combat environmental contaminants. The results emphasize the critical need for comprehensive risk assessments and community education regarding the implications of fluoride exposure.

Keywords: *Groundwater, contamination. Fluoride, Health risk, Maharashtra*

ASSESSMENT AND FORECASTING OF GROUNDWATER TRENDS IN THE BUNDELKHAND REGION: IMPLICATIONS FOR WATER SCARCITY AND RESOURCE MANAGEMENT

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The Bundelkhand region, known for its susceptibility to drought and water scarcity, has been facing a persistent decline in groundwater levels due to over-extraction, limited rainfall, and ineffective water management practices. This study was conducted to analyze groundwater level trends in Bundelkhand, predict future changes, and identify critical areas vulnerable to severe water shortages. These insights aim to assist policymakers, environmentalists, and engineers in designing effective water resource management and conservation strategies for sustainable water availability in the region.

The study involved time-series analysis of groundwater levels collected from over 40 observation wells across Bundelkhand. These wells include both confined and unconfined aquifers, providing a comprehensive view of groundwater distribution and variations within the region. Data analysis was performed using the Mann-Kendall test to detect monotonic trends, Sen's slope estimator to quantify the rate of change in water levels, and the Exponential Smoothing Method (ESM) to forecast groundwater levels for the year 2030. In addition to statistical analyses, spatial analysis software was employed to create isobath maps, offering a visual representation of groundwater levels and helping to identify areas at greater risk of depletion.

Results of the Mann-Kendall and Sen's slope analyses revealed significant groundwater level trends in 23 observation wells during the pre-monsoon season and in 14 wells during the post-monsoon season. Among piezometric wells, which measure water pressure in confined aquifers, significant trends were observed in 12 wells during the pre-monsoon season and 9 wells post-monsoon. The observed groundwater level changes in unconfined aquifers showed a consistent trend, ranging from a decline of -0.541 m per year to an increase of 0.395 m per year during the pre-monsoon period, while post-monsoon levels fluctuated from -0.385 to 0.239 m per year. Similarly, confined aquifers displayed a range of changes in piezometric levels, with variations from -0.341 to 0.870 m per year in the pre-monsoon season and -0.401 to 1.148 m per year in the post-monsoon season. Spatial analysis through isobath mapping provided further insights into the geographical distribution of groundwater levels, highlighting areas of severe decline. Maps generated for both confined and unconfined aquifers identified significant spatial variability in water levels across the region. Areas with the greatest declines in groundwater levels were primarily in Mahoba, Banda, and Jhansi, where water scarcity has been particularly severe in recent years. These areas, identified as "hotspots," are at a heightened risk of water shortage, which could impact local agriculture, industry, and community water supply, if not managed effectively. The Exponential Smoothing Method (ESM) was utilized to predict short-term groundwater level changes for the year 2030. The forecasted scenarios indicate a critical drop in the water table during the pre-monsoon period in several locations across Bundelkhand. Projections suggest a potential reduction in water levels by as much as 11 m in Mahoba and 8.2 m in Banda pre-monsoon. Post-monsoon declines are projected to reach up to 7.9 m in Mahoba and 8.7 m in

Chhatarpur. Additionally, in confined aquifers, a drastic decline in piezometric levels is anticipated, with a maximum drop of 22.15 m predicted in Jhansi. These forecasts emphasize the urgency for immediate intervention and the adoption of sustainable groundwater management practices to prevent further depletion and ensure water security for the region. Given these findings, the study proposes several mitigation strategies tailored to Bundelkhand’s hydrological and socio-economic context. One key recommendation is to strengthen water recharge initiatives, particularly in high-risk areas identified through isobath mapping. Implementation of artificial recharge structures, such as check dams, percolation ponds, and rainwater harvesting systems, could help enhance groundwater replenishment during the monsoon season and alleviate stress on water resources. Another critical strategy involves regulating groundwater extraction rates, especially for agricultural purposes, which constitute a major portion of water usage in Bundelkhand. Adoption of efficient irrigation techniques, such as drip irrigation, could significantly reduce water usage and limit further groundwater depletion. The study also emphasizes the importance of community engagement and awareness programs to foster a culture of water conservation within local populations. Education campaigns can help inform residents of sustainable water usage practices and the benefits of rainwater harvesting at household and community levels. Additionally, integrating traditional water management practices, which have historically been effective in arid regions, with modern techniques could provide more resilient solutions to water scarcity in Bundelkhand. Finally, this research underscores the need for continuous groundwater monitoring and policy support to address the ongoing water crisis in Bundelkhand. Regular monitoring of groundwater levels, with data-driven analysis and forecasting, is essential for effective water management. Policymakers are encouraged to utilize findings from this study to implement region-specific regulations that safeguard groundwater resources. By adopting a comprehensive approach that combines scientific analysis, spatial mapping, and local involvement, sustainable groundwater management in Bundelkhand is achievable, providing a blueprint for other water-stressed regions across India.

In conclusion, the groundwater depletion trends and forecasts for Bundelkhand underscore the severity of the water crisis in the region. This study offers valuable insights into groundwater behaviour, potential scarcity zones, and actionable strategies for sustainable water management. With these findings, water resource engineers, environmentalists, and policymakers can better understand the extent of groundwater depletion in Bundelkhand and work toward long-term solutions that secure water availability for future generations.

Keywords: *Groundwater, time Series data, Mann-Kendall’s test, Sen’s slope estimator, exponential smoothing method.*