Theme 9

COASTAL WATER RESOURCES MANAGEMENT

INVESTIGATING THE STRONG CORRELATION BETWEEN SALINITY AND SUBMARINE GROUNDWATER DISCHARGE WITH GROUNDWATER POTENTIAL ALONG A TROPICAL COASTLINE

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The present study explores the relationship between salinity, thermal anomalies in sea surface temperature (SST), hydrogeochemical characteristics, and groundwater availability along a tropical coastline, focusing on the factors influencing these interactions and potential mitigation approaches. The study focuses on the coastal plains of Odisha, covering an area of approximately 20,000 km² and encompassing five coastal districts: Balasore, Bhadrak, Kendrapara, Jagatsinghpur, and Puri. Odisha's coastal length spans around 485 km, featuring a fragmented shoreline with islands and deltas formed by the Mahanadi, Brahmani, Baitarani, and Suvernarekha rivers, which flow into the Bay of Bengal. The geographical extent of the study area lies between 21° 54′ 19.86″ N to 19° 37′ 19.28.59″ N latitude and 87° 02′ 48.50″ E to 85° 25′ 25.80″ E longitude. The region is characterized by a low-lying terrain with a gentle slope and is predominantly composed of fluvial-deltaic sediments such as sand, gravel, and pebbles, which progressively thicken toward the coast, forming significant groundwater reservoirs. Notable natural resources in the region include Chilika Lake, Asia's largest brackish water lagoon, and extensive mangrove forests that contribute to ecological sustainability. The region experiences an average annual precipitation of 1400 mm and has a subtropical climate with three distinct seasons: summer, monsoon, and winter. The coastal aquifers, despite their groundwater storage potential, face significant challenges, including saltwater intrusion in littoral zones.

Hydrogeochemical data were collected from 137 groundwater samples in 2021, sourced from the Central Ground Water Board (CGWB). Groundwater availability was assessed through recorded water table levels, with data spanning 2009 to 2021, obtained from the India Water Resources Information System (India-WRIS) website (indiawris.gov.in) and the CGWB reports for Odisha. The data was employed to examine the average groundwater level fluctuations during the specified period. The groundwater recharge zone was calculated using the groundwater table fluctuation method, as outlined by the CGWB (CGWB, 2017) for the year 2021. This method, particularly effective for shallow aquifers, estimates recharge by considering the specific yield of the aquifer and the peak water level rise or fall observed during the recharge period. An average groundwater fluctuation map was generated using the Inverse Distance Weighting (IDW) interpolation method in ArcGIS 10.8.2 software. The meteorological data for the years 2015 to 2021 was obtained from the POWER Data Access Viewer on the NASA website (https://power.larc.nasa.gov/data-access-viewer/). Salinity in the region was evaluated using electrical conductivity and chloride concentration, which serve as key indicators of salinity levels. Additionally, satellite-derived SST data from MODIS and LANDSAT-8 were imported and processed in ArcGIS to identify thermal anomalies. These anomalies were calculated by comparing the current SST readings from LANDSAT-8 images captured at 4:37:45 UTC with the baseline (average) SST values from April to August 2021. Raster analysis tools were used to generate anomaly maps, highlighting areas with significant temperature deviations, which could indicate SGD or other thermal influences. Statistical analyses were conducted to examine correlations among salinity, thermal anomalies, and groundwater levels.

The analysis provides a comprehensive view of the hydrogeochemical dynamics impacting coastal aquifers along Odisha's coastline. The 12-month lag Standardized Precipitation Index (SPI) map highlights regions with abundant rainfall, with rainfall intensity increasing from 839 mm to 2000 mm during the period from 2015 to 2021. This trend highlights the presence of high groundwater recharge zones (GWRZ) in the area. Despite a high GWRZ, groundwater levels (GWL) continue to decline due to excessive extraction. Groundwater levels typically range from 0 to 2 meters below ground level (mbgl), and this over-extraction exacerbates the issue by intensifying seawater intrusion (SWI), particularly in the upper parts of the aquifers and along the coastal regions. The GWL and SST anomalies suggest probable zones of submarine groundwater discharge (SGD) in the southern and central regions, with lower GWL confirming SGD-prone areas. Hydrogeochemical parameters reveal that regions with high SGD exhibit lower TDS, Na^+, and Cl^- concentrations due to fresher water influx, while areas affected by SWI show significantly elevated levels. The GWL and temperature trends highlight probable SGD zones with declining GWL and lower temperatures. A strong correlation between GWL decline and salinity increase, indicating deep saline upconing due to extensive over-extraction. The ROC curve between SST and MODIS SST further validates SST-derived data reliability, confirming the reliability of the SST map. This multi-tiered analysis effectively identifies regions vulnerable to SWI and SGD, providing essential insights for sustainable groundwater management strategies in coastal aquifers.

This study underscores the significant vulnerability of Odisha's coastal aquifers to SWI and SGD, primarily driven by excessive groundwater extraction despite favorable recharge conditions. The identification of SGD-prone zones, supported by SST anomalies and validated through MODIS data, confirms the reliability of SST mapping for detecting such areas. Hydro geochemical analysis reveals distinct patterns, with lower salinity in regions affected by SGD and increased salinity and conductivity in areas influenced by SWI, highlighting the complex interactions within coastal aquifers. The impact of groundwater salinization is particularly severe in the eastern and upper southern regions, compromising freshwater quality and creating substantial challenges for coastal communities. Furthermore, SGD along the Odisha coast contributes to freshwater depletion and potentially introduces land-derived pollutants into the coastal-marine ecosystem, with implications for ecological balance. These findings emphasize the urgent need for sustainable groundwater management practices to mitigate salinization risks, ensuring water resource protection and ecosystem health. This multi-proxy approach provides a valuable framework for effective targeted interventions to preserve and manage coastal water resources.

Keywords: *Groundwater recharge zone, groundwater level, sea surface temperature, submarine groundwater discharge, seawater intrusion*

APPLICATION OF MULTI-SPECTRAL ANALYSES FOR ASSESSING HYDROLOGICAL CHANGES IN COASTAL AREAS OF SOUTHERN WEST BENGAL, INDIA

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The process of seawater encroachment and its impact on the behaviour of coastal aquifers has been well documented and assessed through various hydrogeological and geophysical techniques. However, with a universal emergence of irregular groundwater abstraction patterns in sea-side areas and unreliable climatic behaviour affecting the coastal environments at the global level, this correlation can no longer be characterized merely through conventional methods. Moreover, with such drastic changes in the hydrogeological environment, the possibility of sub-regional variations in the same coastal aquifer system would require an impetus of newer and more flexible methods to distinguish groundwater fluctuations and quality patterns at a local level. In this context, the study presented here tried to highlight the use of multi-spectral analysis in understanding the changes in coastal areas and its subsequent impact on regional aquifers systems associated with it. This assessment covered parts of South 24 Parganas and Purba Medinipur districts (Diamond Harbour, Nandakumar and Haldia blocks) in West Bengal, India. In addition to this, it also tries to correlate the impact of other factors such as the extent of cyclone vulnerability and human intervention in the form of urbanization and industrialization on persisting groundwater resources. The study includes a general hydrogeological assessment of spatiotemporal water table changes and hydrochemical facies variation to establish the current settings. Additionally, the changes in the coastal areas were explored through a multi-spectral analysis using different indices (Normalized Difference Vegetation Index or NDVI, Modified Normalized Difference Water Index or MNDWI, Normalized Difference Salinity Index or NDSI, Enhanced Water Index or EWI, and Soil-Adjusted Vegetation Index or SAVI) between 2018 and 2022. These indices were then used as proxies to indirectly assess groundwater conditions by analysing changes in salinity, open water, and vegetation as indicators of broader environmental shifts. The observations from these two aspects of the study were then evaluated simultaneously to give relevant inferences.

The NDVI ranges from -1 to +1, with negative values indicating non-vegetative areas like water, snow, or barren land, while higher values reflect denser vegetation. NDVI is essential for monitoring vegetation health, detecting deforestation, and assessing environmental disturbances, providing valuable insights into changes in vegetation patterns, structure, and extent. It is especially useful in coastal environments for tracking vegetation such as mangroves and salt marshes, which play a vital role in stabilizing shorelines and enhancing resilience to coastal hazards. The MNDWI also ranges from -1 to +1, with positive values signifying water bodies and negative values indicating non-water regions. Unlike the NDWI, MNDWI minimizes the influence of vegetation by utilizing the green band, making it more effective for distinguishing water from dense vegetation. This enhanced capability makes MNDWI particularly useful in coastal areas, where it aids in mapping land-water interfaces and monitoring shoreline dynamics, reducing misclassification errors that often occur in vegetated regions. The NDSI is a valuable remote sensing tool for mapping salt concentrations in coastal and inland saline environments. With positive values indicating higher salinity, NDSI provides a reliable means for assessing salinity levels and monitoring the spatial distribution of salinized soils in coastal regions. The EWI improves water body detection, especially in complex coastal environments, by incorporating additional spectral information. It enhances sensitivity to water bodies, enabling the detection of smaller features and improving accuracy in areas with dense vegetation or complex land-water interfaces. Finally, the SAVI adjusts for soil brightness in regions with sparse vegetation or high soil reflectance. It is particularly useful in coastal areas, where soil types vary, as it improves the sensitivity to vegetation changes, helping monitor vegetation health and detect environmental stress.

The initial observations from the study showed that while the changes associated with these processes have affected its fragile coastal aquifer system were noticed in general, the minor changes in water levels and a peculiar trend of hydrochemical facies variations seem to refute the possibility of extensive regional-wide seawater intrusion in recent years. The impact of seawater encroachment on the groundwater quality is minimal and highly localized. Furthermore, the declining water table is likely attributed to scanty rainfall in the Diamond Harbour part, while in Nandakumar and Haldia, the impact of groundwater abstraction through human interventions had a stronger role in it. The general observations from the spectral analysis of the region showed an overall decrease in NDVI and SAVI and an increase in MNDWI, NDSI, and EWI values for the period between 2018 and 2022. This could be attributed to a variety of factors, including the growth of urban areas and rapid industrialization, the apparent rise of sea level and deforestation. Thus, it was observed that even though these indices provide little direct evidence of the relationship between the changes in coastal environments and groundwater systems, they did hint towards changes in coastal hydrogeology in the study area. In retrospect, the study highlights the scope of these analytical methods for hydrogeological characterization in complementing traditional methods, especially in areas with major upheaval in coastal processes and groundwater systems associated with them.

Keywords: *Coastal areas, groundwater, spectral indices, seawater intrusion, diamond harbour, Haldia*

SALTWATER INTRUSION DRIVING GROUNDWATER SALINIZATION IN COASTAL AQUIFERS OF GUJARAT: A HYDROCHEMICAL-ISOTOPIC ANALYSIS

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The present study focuses on understanding the causes and impact of saltwater intrusion and groundwater salinization in the coastal aquifers of Gujarat, specifically in the Kachchh and Anand districts, with the goal of providing practical recommendations for improving groundwater management and conservation efforts. Groundwater samples (n = 59) were collected from coastal aquifers in Kachchh and Anand districts, representing diverse hydrogeological settings. Samples were stored in high-density polypropylene bottles and categorized for cation, anion, and isotopic analysis. To ensure sample integrity, proper labelling and transport in insulated boxes were conducted. On-site measurements included pH, electrical conductivity (EC), and total dissolved solids (TDS), using a multi-parameter instrument. Carbonates and bicarbonates were quantified through titration following APHA guidelines. Major cations and anions were analyzed via ion chromatography, while stable isotopic compositions ($\delta^{18}O$ and δD) were determined at the Physical Research Laboratory, Ahmedabad. Hydrochemical data were analyzed to identify major geochemical processes, including weathering, ion exchange, and mineral dissolution, influencing groundwater composition. Isotopic data were compared to the Local Meteoric Water Line (LMWL) to trace salinity sources and assess evaporation effects on recharge. GIS mapping was employed to integrate spatial data, visualizing the extent and distribution of salinization.

The groundwater in the study area exhibited alkaline characteristics, with pH values ranging from 8.1 to 10.5, indicative of semi-arid to arid conditions. TDS ranged from 413 mg/L to 9850 mg/L, reflecting significant salinity variations. EC values varied between 1870 µS/cm and 15,900 µS/cm, with approximately half of the samples showing moderate salinity (1500–5000 µS/cm) and the remainder displaying high salinity (>5000 µS/cm). The ionic composition followed the order: $Na^+ > Ca^{2+} > Mg^{2+} > K^+$ for cations and $Cl^- > HCO_3^- > SO_4^{2-} > NO_3^-$ for anions, indicating a dominance of Na-Cl water facies. This distribution highlights the impact of salinization and geochemical interactions within the aquifer system. Geochemical analysis revealed that silicate weathering and ion exchange were the primary processes controlling groundwater composition. Scatter plots of Ca^{2}+ Mg^{2+}versus HCO_3^-+ SO_4^{2-} indicated that most samples were below the 1:1 equiline, suggesting reverse ion exchange and carbonate dissolution.

The relationship between (Na^++ K^+) and Cl^- pointed to significant contributions from soil salt dissolution and silicate weathering, demonstrating the complex interplay of geological and hydrochemical processes affecting groundwater quality. Stable isotopic analysis revealed $\delta^{18}O$ values ranging from -1.48‰ to -6.06‰ and δD values from -46.04‰ to -17.83‰ in Kachchh, while in Anand, $\delta^{18}O$ ranged from -0.61‰ to -3.0‰ and δD from -7.13‰ to -20.8‰. Regression analysis of δD versus $\delta^{18}O$ yielded slopes of 5.33 (±0.45) and 4.48 (±0.5) for Kachchh and Anand districts, indicating significant evaporation during recharge,

influenced by high temperatures and low rainfall. The $\delta^{18}O$ versus Cl^-scatter plot showed most samples aligned along the regression line, suggesting a common origin. Samples with high Cl^- concentrations also exhibited enriched $\delta^{18}O$ values, indicating evaporative enrichment of saline water, particularly near coastal sampling points where rivulets facilitated saline intrusion. The integrated hydrochemical and isotopic analysis provides critical insights into the salinization processes affecting coastal aquifers in Gujarat. Key findings include:

Groundwater quality is primarily governed by natural geochemical processes such as weathering, ion exchange, and mineral dissolution, alongside anthropogenic factors including overexploitation and land-use practices. Saltwater intrusion is primarily driven by the upconing of underlying saline water, exacerbated by excessive groundwater extraction and coupled with evaporative enrichment during recharge. The study underscores the importance of employing integrated approaches that combine hydrochemistry, isotopic analysis, and GIS to unravel complex groundwater systems. There is an urgent need for sustainable groundwater management practices to mitigate salinization and preserve water resources in coastal regions. These findings offer critical insights for formulating effective management strategies aimed at mitigating salinization and ensuring the long-term sustainability of coastal aquifers on a global scale. Priority should be given to implementing policies that reduce groundwater overexploitation, enhance natural and artificial recharge, and establish robust monitoring systems to track and manage saltwater intrusion. Such integrated approaches are essential for preserving coastal aquifers as vital resources for future generations.

Keywords: *Coastal Gujarat, coastal aquifers, saltwater intrusion, groundwater salinization, hydro-chemical analysis, GIS,* ionic ratio, *geochemical processes, stable isotopes*

CONTRIBUTION OF GROUNDWATER DISCHARGE IN LOW FLOW SUSTENANCE OF THE BAITARANI RIVER BASIN

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Low flow is vital in catchment hydrology as it fulfils the non-rainy season water demand and is essential for ecosystem functioning. The World Meteorological Organisation states low flow as the streamflow observed during prolonged dry weather. It is seasonal and is part of the flow regime. Contrary to floods, the impacts of the decline in the low flows are creeping in nature and could have a long-lasting consequence. Aquifers recharged during monsoon contribute to streamflow during non-monsoon periods. Similarly, reservoir release also contributes to non-monsoon streamflow. Land use land use-land cover (LULC) determines the fractionation of precipitation to different components such as infiltration, recharge, evapotranspiration, and surface runoff. In addition to LULC change, erratic monsoons have declined recharge and reservoir storage. Consequently, the lean season flow is declining in many rivers worldwide, such as in the Baitarani Riven in eastern India. Hence, a detailed analysis of the conditions favoring sustained low flow would aid in better water management considering increased water demand, changing land use, and climatology. In this context, we performed hydrologic simulation to identify the fractional contribution of aquifer storage, surface runoff and reservoir release to streamflow of the Baitarani River basin in eastern India.

The study area selected is the Baitarani River basin in eastern India, within 20.67-22.28°N latitude and 85.16-86.89°E longitude. It originates from the Gonasika Hills towards the northern part of the basin at an altitude of 900 m above the mean sea level (MSL) and drains in the Bay of Bengal in the East, traversing about 350 km. The area can be physio-graphically divided from north to southeast as eastern ghats, central table land, and coastal plains. Tropical monsoon climate prevails over the study area, with 80% of precipitation occurring during June-September. It has been observed that the non-monsoon streamflow of the Baitarani River is declining, posing difficulty for water managers in water distribution to agriculture, domestic, and industry sectors. To perform the hydrological modelling and subsequent analysis, we selected the open-source model SWAT. The data procured for the model setup are the Digital Elevation Model (DEM) from the USGS Earth Explorer, meteorological observations of rainfall and temperature from the India Meteorological Department, LULC and soil from the Odisha Remote Sensing and Application Centre, and time series of discharge observation from the Central Water Commission. Based on the freely available 30 m resolution DEM, the entire basin was first delineated into 23 subbasins. Further, a total of 107 hydrological response units (HRUs) were derived based on the existing soil, LULC, and topography of the area. These HRUs behave similarly to any external forcing. The publicly available SWAT calibration and uncertainty (SWAT-CUP) program was used for model calibration. The Sequential Uncertainty Fitting 2 (SUFI-2) algorithm of SWAT-CUP was used to calibrate the model. For calibration, out of the available parameters, 12 parameters were identified based on expert knowledge and after conducting a literature review on the application of the SWAT model to identical basins. The parameters can be broadly categorized as surface response (e.g., CN2.mgt, CH_K2.rte, CH_N2.rte, ESCO.hru, OV_N.hru, SOL_K.sol, SOL.AWC.sol, and HRU_SLP.hru), sub-

surface response (e.g., ALPHA_BF.gw, GW_DELAY.gw and GWQMN.gw), and basin response (SURLAG.bsn) types. Sensitivity analysis was carried out to rank the selected parameters in the order of sensitivity. The Nash Sutcliffe model efficiency Coefficient (NSC) was chosen as the objective function while reproducing the discharge during calibration (1995 to 2007) and validation (2008 to 2013) at three gauging stations, representing headwater catchment, mid-reach, and delta regions.

Analysis of historical LULC shows that barren and built-up areas have increased by 145% and 70%, respectively, whereas the forest land cover has decreased by 13%. The agricultural land use has not been affected much. SWAT reproduced the observed discharge at the Akhuapada gauging station with an NSC of 0.64 and R2 of 0.68. As it is not economical to have gauging stations at the outlet of each sub-basin, the discharge simulated by the calibrated SWAT setup at the outlet of each sub-basin was assumed to be the observed discharge of that sub-basin. It was observed that the sub-basins draining to different river reaches contributed differently. The sub-basins of the headwater region contributed initially after the monsoon withdrawal, whereas the subbasins draining to the mid-reach contributed significantly throughout the year. Similarly, the subbasin-wise (LULC) data was analyzed to check the LULC type aiding in delayed low-flow. The contribution of aquifer in low flow is ≥ 90%. The outcome of this study would help the water managers understand the cause of the decline in low flows and its possible remedy through appropriate land management.

Low flow plays a vital role in lean season water supply. From this study, it was observed that barren land and built-up areas have increased after 1990. Consequently, the non-monsoon streamflow has decreased. Further, it was observed that groundwater discharge contributes ≥ 90% of streamflow during the lean season.

Keywords: *Low-flow, hydrological modelling, SWAT, baseflow, e-flow*

COMPARATIVE ASSESSMENT OF GROUNDWATER VULNERABILITY MODELS IN COASTAL ANDHRA PRADESH, INDIA: DRASTIC, SINTACS AND GOD APPROACHES

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This study compares three groundwater vulnerability models DRASTIC, SINTACS, and GOD—to determine which provides the most accurate assessment of groundwater vulnerability in coastal Andhra Pradesh, considering the region's specific conditions. Groundwater vulnerability models assess the risk of contamination by utilizing various hydrogeological parameters. Notable models include DRASTIC, uses seven parameters such as depth to water and hydraulic conductivity. Although comprehensive, its adaptability to local conditions can be enhanced by adjusting parameter weights. The SINTACS model, a DRASTIC adaptation, offers greater flexibility for Mediterranean environments and specific pollution risks, especially in coastal areas affected by agriculture and industry. Lastly, the GOD model simplifies assessments with three parameters: Groundwater confinement, overlaying lithology, and Depth to groundwater, making it efficient for rapid evaluations but potentially lacking detail for complex coastal regions. The primary objectives of the study include: (1) Compare the effectiveness of the DRASTIC, SINTACS, and GOD models for groundwater vulnerability assessment in coastal Andhra Pradesh. (2) validate model performance using observed groundwater quality data (e.g., nitrate levels, salinity). (3) Identify the most reliable model for predicting groundwater vulnerability in coastal regions with similar hydrogeological characteristics. (4) Provide recommendations for groundwater management based on the comparative results.

The study area includes Coastal Andhra Pradesh with an areal extent of 86,297 Sq.km. It spans between 78.5^0 E and 84^0 E longitudes and 13.5^0N and 19^0N latitudes approximately. This paragraph includes the method adopted in the study to obtain data and their inputs into GIS. The study integrates data on various hydrogeological parameters, including,1-Depth to water 2-Recharge 3-Aquifer media: 4-Soil type 5-Topography 6-Vadose zone impact.7-Hydraulic conductivity. Additionally, data on land use, climate, and pollutant sources are gathered to provide context for regional contamination risks. Groundwater quality data, such as nitrate levels and salinity concentrations, are collected for validation. Secondly, GIS-Based Data Integration, wherein GIS tools are used to map and integrate the collected data layers for each model. This allows for spatial analysis of groundwater vulnerability and the generation of vulnerability maps. Thirdly, Model Application, the three models. the DRASTIC SINTACS model, and GOD model. The Vulnerability Mapping is carried out with each model that generates a vulnerability map that visualizes areas of high and low contamination risk based on the integration of hydrogeological data. For validation and comparison, the model outputs are validated by comparing the predicted vulnerability zones with observed groundwater quality data. Statistical analyses, such as R^2 value computation, are performed to evaluate the accuracy of the models by measuring the correlation between model predictions and actual contamination levels.

The results of this study include the comparative analysis that reveals that the SINTACS model provides the most accurate vulnerability assessments for coastal Andhra Pradesh, as it incorporates region-specific factors, such as local soil types and pollution sources, which the DRASTIC and GOD models overlook. The SINTACS model's flexibility in adjusting parameter weights makes it more adaptable to the region's complex hydrogeological conditions, such as varying salinity levels and differing recharge patterns. The GOD model, while useful for quick assessments, lacks the detail required to capture the region's vulnerability accurately. In contrast, the DRASTIC model, though comprehensive, tends to overestimate vulnerability in this region when used without modification. A well location map was created and overlaid onto the GOD, DRASTIC and SINTACS maps. Nitrate concentrations were used as a direct indicator of groundwater contamination. The correlation between groundwater vulnerability risk levels and nitrate concentrations served as a measure of the reliability and accuracy of the applied methods. The positive correlation existed between both GOD, DRASTIC & SINTACS and nitrate value as shown in the R^2-values of 0.53, 0.64 & 0.67. For example, an R^2-value of 0.64 means that 64% of the variance in nitrate concentration can be explained by the DRASTIC index. However, the 36% unexplained variance suggests there are other factors (e.g., land use, agricultural practices, local geology, or additional hydrogeological conditions) influencing nitrate concentrations. Including such variables in future models might improve the prediction. Upon application of SINTACS method, nearly 54.91 % of study area is highly vulnerable and 40.81% is in moderate vulnerable range, and only 4.28% of the study area falls under low vulnerability. Upon application of DRASTIC method, nearly 49.46 % of study area is highly vulnerable and 39.98% is in moderate vulnerable range, and only 10.56% of the study area falls under low vulnerability. Upon application of GOD method, nearly 45.56 % of study area is highly vulnerable and 44.78% is in moderate vulnerable range, and only 9.66% of the study area falls under low vulnerability. The study concludes that the SINTACS model is the most effective for groundwater vulnerability assessment in coastal Andhra Pradesh, providing the most accurate predictions when compared to observed groundwater quality data. The findings suggest that SINTACS, with its flexibility and adaptability, is well-suited for coastal areas with complex hydrogeological conditions. For effective groundwater resource management in such regions, it is crucial to select a vulnerability assessment model that considers local conditions and pollution sources. This study provides valuable insights that can guide water resource management strategies in coastal areas facing similar challenges.

Keywords: *DRASTIC, SINTACS, GOD, groundwater, vulnerability, Andhra Pradesh*

SEAWATER INTRUSION ASSESSMENT FOR A COASTAL AQUIFER USING MESHLESS LOCAL PETROV-GALERKIN (MLPG) METHOD

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Seawater intrusion (SWI) is a significant environmental challenge that threatens freshwater resources in coastal aquifers worldwide. This phenomenon, driven by factors such as excessive groundwater (GW) pumping, urbanization, and sea-level rise, disrupts the availability and quality of freshwater essential for human and ecological needs. Coastal aquifers, particularly those with stratified structures, are highly vulnerable due to their inherent heterogeneity in hydraulic conductivity and porosity. Traditional approaches for modelling and mitigating SWI often rely on simplified empirical models or data-driven techniques that fail to account for the complex, non-linear interactions governing GW flow and solute transport. To address this gap, advanced numerical methods are necessary to accurately simulate these processes and provide actionable insights for GW management. Among these, the Meshless Local Petrov-Galerkin (MLPG) method has emerged as a powerful and flexible tool for GW modelling, offering computational efficiency and adaptability for complex scenarios. The MLPG method eliminates the need for structured grids or meshes, a significant advantage when dealing with systems characterized by irregular geometries or abrupt transitions in properties, such as stratified aquifers. This mesh-free framework uses radial basis functions (RBF) to construct trial and test functions for discretizing the governing equations of GW flow and solute transport. The method employs local weak forms derived from these equations, ensuring accurate representation of spatial variations across heterogeneous aquifer systems. Integration over local subdomains provides the foundation for assembling a global system of equations, which incorporates boundary conditions and is solved numerically. This study applies the MLPG approach to simulate variable-density flow and solute transport in stratified aquifers, characterized by distinct layers with varying hydraulic conductivities and porosities, to model the dynamics of the freshwater-saltwater interface under different stress scenarios.

In this study, the MLPG framework is implemented to simulate one-dimensional (1D) and two-dimensional (2D) aquifer systems. The study area, located along the coastal region in Chennai and Kanchipuram District, Tamil Nadu, India, is a critical zone for groundwater resources. It faces challenges like overexploitation and seawater intrusion due to sea level rise and anthropogenic pressures. The prepared models are defined with specific parameters, including porosity, hydraulic conductivity, and dispersivity. Boundary conditions are set to represent coastal interfaces and variable flux scenarios, such as groundwater (GW) pumping or recharge. The models are validated against established analytical solutions to ensure accuracy and reliability. Preliminary results demonstrated the method's capacity to resolve the sharp freshwater-saltwater interface with high accuracy, capturing the effects of aquifer heterogeneity on intrusion patterns. Sensitivity analyses revealed that high permeability contrasts between aquifer layers significantly influence the depth and shape of seawater intrusion, underscoring the need for precise aquifer characterization in GW modelling. The MLPG simulations showed good agreement with finite difference results, with an error margin of ±10%, further validating its potential as a robust numerical method.

Stratified aquifers pose unique challenges for SWI modelling due to their non-uniform flow patterns caused by spatial variability in hydraulic properties. Conventional grid-based methods often struggle with the complexities of these systems, as they require fine discretization to accurately capture transitions between layers, leading to high computational costs. In contrast, the MLPG method’s flexible node placement enables efficient modelling of sharp gradients and irregular boundaries. By discretizing the governing equations locally, the method reduces computational overhead while maintaining accuracy. This makes it particularly well-suited for modelling variable-density flow in heterogeneous aquifers, where seawater intrusion is influenced by interactions between layers with differing properties. For example, in the simulated scenarios, layers with high permeability facilitated greater intrusion depths, highlighting the critical role of layer-specific hydraulic conductivity in controlling SWI dynamics.

The study also explored the influence of GW pumping rates on SWI, revealing a direct correlation between excessive pumping and increased intrusion. Variable flux boundaries are used to simulate hypothetical pumping scenarios, demonstrating the exacerbation of SWI as withdrawal rates intensified. These findings provide actionable insights for GW managers and policymakers, emphasizing the need for sustainable pumping practices and the importance of monitoring and managing withdrawal rates to mitigate SWI. Additionally, the research examined the impact of recharge rates, suggesting that enhanced recharge can act as a buffer against intrusion, further supporting strategies for artificial recharge in vulnerable regions. Despite its advantages, the MLPG method is not without challenges. The accuracy and stability of its solutions depend on the appropriate distribution of nodes, the selection of support domain parameters, and the formulation of trial and test functions. Further research is needed to establish standardized guidelines for these aspects to enhance the method’s resilience and applicability to large-scale problems. The choice of RBF and the integration schemes used also play a crucial role in determining the method's performance, highlighting areas for potential refinement in future studies.

The results of this study underscore the potential of the MLPG method as a powerful tool for GW modelling, particularly in addressing complex challenges such as SWI in stratified aquifers. Its flexibility, computational efficiency, and ability to handle heterogeneous systems make it a valuable addition to the suite of numerical methods available for GW research. By providing detailed insights into the dynamics of variable-density flow and solute transport, the MLPG approach supports the development of sustainable management strategies for coastal aquifers. These strategies are essential for preserving freshwater resources in the face of growing environmental pressures, including urbanization, population growth, and climate change.

Keywords: *Seawater intrusion, groundwater, Meshless Local Petrov-Galerkin (MLPG) method, numerical methods, modelling*

SALTWATER INTRUSION MODELING AND GROUNDWATER DYNAMICS IN THE COASTAL AQUIFER SYSTEM OF THE MAHANADI DELTA, ODISHA: A CYCLONE-PRONE REGION OF INDIA

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Coastal aquifers play a crucial role in supplying freshwater to densely populated regions that depend on groundwater for agriculture, domestic needs, and industrial activities. Their significance is especially pronounced in deltaic areas like the Mahanadi delta, where they support local economies and livelihoods. However, these aquifers are highly vulnerable to seawater intrusion due to their proximity to the sea, heavy groundwater extraction, and changing climate patterns. Jagatsinghpur district, covering approximately 1,600 km^2, is part of the Mahanadi Delta on India's eastern coast near the Bay of Bengal. The region faces rising groundwater salinity due to seawater ingress and human activities, which alter the hydrochemical composition of aquifers and pose a threat to freshwater availability. Several factors, including over-extraction, reduced recharge, and aquifer geology, contribute to this phenomenon. Cyclones, common in this region, worsen seawater intrusion by pushing saline water inland, temporarily raising aquifer salinity. Post-cyclone conditions, such as disrupted surface water supplies and increased groundwater extraction, create favourable conditions for intrusion. Additionally, changes in river discharge and reduced recharge further intensify the risk. This study explores the hydrogeochemical evolution of groundwater in the Mahanadi delta, using geochemical tools and numerical modeling to understand the dynamics of seawater intrusion in this cyclone-prone region. The research aims to inform sustainable water resource management in vulnerable coastal aquifers.

A total of 30 groundwater samples from the Mahanadi delta revealed a wide range of electrical conductivity (EC), indicative of varying salinity levels. Freshwater zones exhibited EC values as low as 146 µS/cm in the northwest, whereas saline zones near the coastline recorded values as high as 33,900 µS/cm. The ionic composition followed distinct trends, with cations dominated by $Na^+ > Ca^{2+} > Mg^{2+} > K^+$ and anions by $Cl^- > HCO_3^- > SO_4^{2-}$. These variations reflect the progressive mixing of seawater and freshwater, with hydrochemical facies transitioning from Ca-Mg-Na-HCO_3 types in the upper delta to Na-Cl types near the coast. Ion exchange processes were identified as key drivers of these transitions. A robust correlation ($r > 0.9$) between chloride and major ions, including Na^+, Ca^{2+}, Mg^{2+}, SO_4^{2-}, and K^+, highlighted the significant influence of seawater on groundwater chemistry. Ionic ratios such as Na^+/Cl^-, HCO_3^-/Cl^-, Mg^{2+}/Ca^{2+}, and SO_4^{2-}/Cl^- provided further evidence of salinity ingress. The stable isotope composition ($\delta^{18}O$ and δ^2H) ranged from -1.86‰ to -6.87‰ for $\delta^{18}O$ and -10.79‰ to -45.42‰ for δ^2H, indicating a mixing trend between saline and freshwater in the coastal zones.

Using PHREEQC, the saturation indices of carbonate minerals such as calcite and dolomite were calculated. Negative indices (<1) in the upper delta indicated fresh groundwater conditions, supported by calcium-rich water with Mg^{2+}/Ca^{2+} ratios below 1. The proportion of seawater in groundwater was estimated to vary from 0% in the upper delta to 72% near the coast. A conceptual model was developed to illustrate the spatial variability in salinity and ion concentrations across the coastal aquifer system. Shallow wells near the Bay of Bengal exhibited lower Na^+ and Cl^- concentrations and lower EC values, suggesting minimal seawater influence. In contrast, deeper coastal wells displayed elevated ionic concentrations, indicating pronounced seawater intrusion.

Numerical modeling was conducted using Visual MODFLOW to simulate the dynamics of groundwater flow in the Jagatsinghpur coastal district. The hydraulic head ranged from 1 m to 15 m above mean sea level (MSL), with an average of 6 m in low-lying coastal areas. These areas were found to experience significant groundwater abstraction for agricultural purposes, leading to overdraft conditions. Aquifer properties, including horizontal hydraulic conductivity (40–45 m/day) and specific yield (0.05–0.07), were determined using the Parameter Estimation Technique (PEST). The model was calibrated using data from 2004 and 2007 and validated against observations from 2008 to 2009. Results indicated that net recharge to the coastal aquifer ranged from 247.89 to 262.63 million cubic meters (MCM) during the study period. River inflow was estimated at approximately 34 MCM during pre- and post-monsoon seasons, while aquifer discharge to the river system during monsoons ranged from 23 to 27 MCM. Water level contour analysis revealed significant hydraulic gradients, steep in the upper delta and sluggish in the lower regions. These gradients were influenced by seawater intrusion, which reduced groundwater movement in the lower delta. Overextraction and urbanization further exacerbated the decline in hydraulic head, intensifying salinity ingress.

The findings underscore the dual challenges posed by natural and anthropogenic factors in managing coastal aquifers. The Mahanadi delta's aquifer system is under pressure from declining recharge rates, excessive abstraction, and salinity ingress due to seawater intrusion. Hydrochemical analysis highlights the critical role of ion exchange and mixing processes in determining groundwater quality. Stable isotope signatures provide robust evidence of saline-freshwater interactions, crucial for demarcating vulnerable zones. Numerical modeling offers insights into groundwater flow patterns and their implications for aquifer sustainability. By estimating recharge, discharge, and hydraulic properties, the model aids in identifying regions at risk of seawater intrusion. These findings are vital for formulating targeted interventions, including controlled groundwater pumping, artificial recharge, and sustainable water use practices. This research integrates hydrochemical and numerical modeling approaches to comprehensively analyze seawater intrusion in the Mahanadi delta. The study demonstrates the importance of combining ionic, isotopic, and geochemical tools with groundwater flow modeling to unravel the complexities of coastal aquifer systems. The Ersama block of Jagatsinghpur district, the most affected area during the 1999 Super Cyclone, exhibits the highest groundwater salinity, indicating significant seawater intrusion. Fluctuations in hydraulic head suggest that seawater ingress is a temporal phenomenon, predominantly occurring during the pre-monsoon period. The findings provide a framework for managing seawater intrusion not only in the Mahanadi delta but also in similar coastal regions worldwide. As coastal aquifers continue to face growing threats from seawater intrusion and overexploitation, implementing sustainable management practices is imperative. Strategies such as restricting groundwater abstraction, enhancing recharge through managed aquifer systems, and monitoring salinity dynamics can help mitigate the adverse impacts of seawater intrusion. By addressing these challenges, this study contributes to safeguarding freshwater resources & ensuring the long-term resilience of coastal aquifers.

Keywords: *Mahanadi delta, saltwater intrusion, groundwater dynamics, hydrochemical composition, numerical modelling, MODFLOW, isotopes*

APPLICATION OF ADVANCE SCIENTIFIC INNOVATIONS AND POLICY REGULATIONS FOR SUSTAINABLE COASTAL GOVERNANCE AND RESOURCE MANAGEMENT FOR COASTAL INDUSTRIALIZATION TO AIM TOWARDS VIKSIT BHARAT @2047

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This paper seeks to define how the following scientific innovations: AI monitoring, Minimum Support Price (MSP) and eco-coasts for industrialisation policy designs interact. This paper aims to analyse the involvement of scientific innovation and policy regulation in effective coastal management. Now technological innovation in marine sector in combination with the legislative steps like Coastal Regulation Zone (CRZ) norms and ICZM has made available opportunities for synchronized development. This research is in consonance with the concept of Viksit Bharat@2047 and means the transition for sustainable industrialisation from exploitative constructional models. Through the use of such modern concepts as geospatial applications and predictive analysis with the application of governance frameworks, this research has the objective of providing recommendations on the management of coastal resources. This research uses both quantitative and qualitative methods to assess sustainable coastal governance practices. Primary data is collected from face-to-face interviews with policymakers, industry representatives and environmentalists. Secondary data comprises of reports of good experience in implementing coastal management methods in India and other parts of the world. A range of expert resources supported by GIS and marine research indices work to evaluate resource availability and the industrial footprint. The nature of policy evaluation emphasizes the comparison of existing policies to the benchmark of the best practices. Using policy simulations based on intelligent agents, future effects of policy actions on coastal environments are modelled. The work also uses cost-benefit approaches to examine the consequences of implementing new technologies within the industrialization of coastal areas.

The study highlights that promoting the introduction of newer scientific advances into the strategies used to regulate the industrialisation process, strongly contributes to making the industrialisation of the coastal regions more sustainable. It reveals a 25% efficiency of AI-based tools in supervising ecological consequences while geospatial tools enhance the marine spatial planning minimizing resource contradictions 30%. The analysis shows drawbacks of the current policy, including deficits in the practical application of policies, specifically the absence of sufficient ways to enforce proposed policies and the lack of involvement of the local population in the policies' formulation. Carrying out of the ICZM practices alongside the use of the advanced technologies the emission of carbon by the coastal industries can be brought down to as low as 40%. Economic evaluation outcomes show a high economic benefit for developing an eco-friendly innovation, which supports the idea that it is feasible to implement these solutions on a large scale. In all, these findings highlight the role of harmonised innovation and policy in measuring and achieving sustainable coastal governance.

This paper identifies the cross-hybridization of innovative technology with policy laws to be a major foundation for a sound and sustainable coastal Rican governance- Sustainable coastal Rican governance" deals with the way that coastlines in Costa Rica – often called "Rica" in this country's name, "Costa Rica" – should be run in order to be sustainable in terms of using energy sources, having fair rights distribution and economic stability. This covers the conservation and sustainable use of coastal and marine biological diversity, as well as taking care of the welfare of coastal inhabitants and developmental interests, not forgetting the protection of coasts from factors such as over fishing, pollution and climate change through policies informed by science. Coastal sustainability management is an approach to sustaining the coastal environment and resources, supporting growth of sustainable economic activities and developing policies that enables the involvement of coastal users in policy making for ultimate benefit of future generations. Tools such as AI or geospatial analysis do act as tools for monitoring but also solutions to enable effective decisions. Consequently, eight overall conclusions were extracted from the analysis of literature on ICZM by the authors: The findings emphasize the involvement of stakeholders in the application of ICZM practices. There are still many issues in reconcile various interests, especially while promoting the development of industry and preserving the environment. The lessons from the Netherlands' Delta Program reveal that India needs more synergy between science and policy to effectively respond to flood risks. Cognizant of the complexity of coastal problems, policy suggestions focus on such aspects as the development of appropriate human and institutional capital, decentralized management, and organized learning. This discussion strengthens the idea of Viksit Bharat@2047, that calls for an efficient coastal industrialization plan for an inclusive India.

As such, hurricane, science, and policy analyses have central perspectives in understanding the future and future success of sustainable coastal governance. Applying technologies, which include, but are not limited to, artificial intelligence and geospatial technologies, while incorporating diverse elements of marine biodiversity monitoring into the adaptive governance of structures that Industrial Development Corporation of Odisha (IDCO) employs to foster coastal industrialization, can guarantee sustainable development of the coast. Outcomes confirm that mutually complementary policies can contribute to the future-oriented consideration of the factors for the development of both nature protection and economic development. Policy implications mean increased rigor of enforcement changes in stakeholder engagement, and increased spending towards environmentally friendly technologies. This research forms a guideline for achieving sustainable coastal management and foster India's vision of Viksit Bharat 2047. Therefore, in the future development of structural and economic security of the coastal regions, there will be need to encourage cooperation between the government, industry, and the local people. Recommended sustainable agenda for coastal governance and resource management under Viksit Bharat@2047 the next two decades should be implemented in the following steps. Solutions in the timeframe of one to five years cover all aspects of regulation and pilot initiatives. Mid-term (6-15 years) promotes scaling innovations, and the long-term (16-20 years) ensures the reassessment of nationwide sustainable practices.

Keywords: *Coastal governance, marine biodiversity, Viksit Bharat, economic security, AI, fishing, aquaculture*

DELINEATION OF AQUIFER GEOMETRY AND FRESH SALINE INTERFACE IN COASTAL PARTS OF KASAI - SUVARNAREKHA BASIN, EASTERN INDIA

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Water is regarded as the origin and sustainer of life and held sacred by most of ancient races. The accelerated growth in population, industrialization and urbanization is leading to increasing demand for water in several sectors. The groundwater is the major source of water for irrigation, domestic and industrial uses resulting in scarcity of resources. Water being the life line of all living being, is noteworthy for research purpose to uplift socio economic factors. The present study is mainly focused on the alluvial tracts of the Kasai-Suvarnarekha (KS) basin. Despite the average rainfall of the area being medium to high (~1234-4136 mm), the area experiences acute scarcity of groundwater, especially during summer as the area is an agrarian, have created conflicts between various stakeholders in the coastal area. Waterlogging during the rainy season affects and results in loss of crops in the area. Due to unscientific drilling and improper identification of the aquifer zone, failure of wells, reduction in discharge rate, and saline water up coning is a common phenomenon in the area.

This study demonstrates a practical approach to delineating the fresh and saline water interface and its geometry in a coastal alluvial plain. The combined geophysical integrated and coupled with EC of formation water samples of respective aquifer zones has been attempted to accomplish this goal. The accurate determination of aquifer groups will allow a proper groundwater management plan and well field design to abstract the fresh water resource judiciously and saline water aquifers to be utilized for industrial development in the area to conserve and protect the freshwater system. Geophysical logs play a unique role in synthesizing the lithology and defining the marker horizons. The present study attempts on a regional scale to provide the hydro-stratigraphy and aquifer groups in alluvial parts of KS basin, eastern India, using in-situ electrical and gamma properties using all the available boreholes. The logs have helped in identifying the aquifer groups in alluvial parts of the Kasai-Suvarnarekha basin. The in-situ electrical and gamma properties were used using 58 geophysical logs and 126 lithologic logs, which have penetrated the aquifer system's base to correlate the geophysical markers and determine their relation to significant stratigraphic boundaries at a wider scale. For a meaningful hydrogeological study, a hydro stratigraphic unit on a regional scale is defined covering both the area of recharge and discharge zone, i.e., up to the coast. The hydro stratigraphic cross-section of the area reveals five distinct hydro stratigraphic features according to their vertical distribution and lithological composition. Regionally three aquifer groups namely Aquifer-I, Aquifer-II and Aquifer-III have been delineated in the area. Pinching out of individual sand and clay layers within the single aquifer group are not ruled out. The major clay groups intervening between these aquifer groups extend regionally and pinch out at the alluvial area's extreme northern boundary. The presence of three different potentiometric surfaces generated from hydraulic heads measured through various wells in the area also confirms three regionally extensive aquifer groups. The thickness of sediments varies from 100 m in the North to more than 450 m in the southern part. The aquifer group-I extends all over the basin with varying thicknesses. It is composed generally of coarser sediments as compared to other groups. It is underlain by an extensive clay group that is about 10 to 15 m thick and separates the aquifer group-II. It is also inferred that the deeper aquifer i,e., the Aquifer-III is more than 300 m thick in the southern part forming a single aquifer system. Iso-conductivity maps were prepared showing variation of EC of respective aquifers. The fresh and saline water interface map shows that in the northern part of the basin, groundwater is fresh at all levels. In the southeastern part of Kasai River, there is no groundwater prospect in shallower zone (Aquifer-I). The groundwater of Aquifer-II in this section is mostly saline. However, Aquifer-III in this section is mostly fresh. But there is a thin saline water bearing sand exists just below the grey clay horizon. Care must be taken while designing the well, so that the deeper fresh water zone is tapped and there should not be any leakage from the upper saline water part. The upper saline part needs to be sealed properly in order to avoid mixing of the water. It is further suggested to tap the Aquifer-III in general as there is limited groundwater development at this level. The upper two zones are mostly exploited and there will be risk of further movement of interface towards the land. The geo-electric sections revealed that the area near to the coast has been intruded by saline water. Attempt has been made to demarcate freshwater and saline water zone, both vertically and laterally through resistivity method. The saline water ingression in this aquifer cannot be ruled out. Deeper aquifer which is yet to be exploited needs to be explored for sustainable development of the area in the coastal part.

The results presented in this research work show the effectiveness, reliability and usefulness of available geophysical, lithological and hydrogeological data that results to a complete and realistic aquifer model prior to drilling that can lead to reduction of drilling failure and to solve environmental issues alluvial areas and coastal areas in particular. The combined study of electrical logging with lithological variation is in fair correlation with chemical quality of formation water. From the study, it is possible to integrate geophysical data to define salinity, thickness of various granular zones forming the aquifer and the intervening clay layers. The establishment of hydro stratigraphy and aquifer groups along with its characteristics in these alluvial parts of the Kasai-Suvarnarekha basin will help minimize the risk related to resource availability, deliverability, impact on the environment and conflict with the stakeholders. In turn, efficient water wells design will further reduce the operational issues, drilling, and lower the risk of saline water up coning. Detailed mapping in GIS will help policy makers to minimize risk in water resource planning. This study is meant to develop a robust multilayer hydro stratigraphic model prior to groundwater modeling experiment which is an important step in the overall process that leads to understanding a ground system. The findings of present study will help national, local policy makers and various water user agencies in planning and management of water resources.

Keywords: *Grey clay, aquifer groups, marker clay, up coning, Kasai-Suvarnarekha*