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Geo-Hydrological Assessment of Environmental Resources in and around Menakur Special Economic Zone, Tirupati District, Andhra Pradesh A Study on Groundwater Resources, Geomorphology and Environmental Sustainability in an Industrial Corridor

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ABSTRACT

The pace of growth of Special Economic Zones (SEZs) along the eastern coastal belt, in India has added to the developmental stress on local geo-hydrological systems, especially in the areas where agrarian land use is shifting towards industrial and infrastructural utilization. The present study provides an integrated geo-hydrological study of the Environment Resources of Menakur Special Economic Zone, Tirupati district of Andhra Pradesh. The study area is a region of the state in which the water resources are assessed through a combination of geomorphological mapping, drainage morphometry, lithological characterisation, monitoring of the groundwater level and hydro-chemical analysis in order to determine their current status and vulnerability. Geomorphic units, drainage networks and lineaments were delineated using remote sensing and GIS based terrain analysis and physico-chemical parameters of the seasonal groundwater samples were analysed and compared with the BIS permissible limits. The results show a dendritic to sub-dendritic drainage system in a coast pediplain, and that the composition of the ground water is controlled mainly by weathered and fractured areas in underlying crystalline and semi-consolidated sedimentary rocks. The dominant water type from hydro-chemical analysis is Na-Cl to mixed Ca-Mg-Cl, the electrical conductivity, TDS and chloride concentrations are higher in the regions close to the SEZ boundary and along the coastal fringe, which are a result of the combined effects of seawater influence, evaporative concentration and anthropogenic loadings. Seasonal difference reveals significant post-monsoon recovery in water levels and reduction in the concentrations of dissolved constituents, which indicates that monsoon recharge to the local aquifer system is important. The study categorizes areas of moderate to high groundwater vulnerability in and around the industrial footprint and suggests a phased approach to managing groundwater environmental monitoring and managed-aquifer-recharge to protect water quality and availability as the SEZ continues to grow and expand. The results will be used to inform evidence-based land use planning, environmental impact mitigations and sustainable water use for those involved in the Menakur SEZ and regulatory agencies.

keywords: Geo-hydrology; Groundwater quality; Special Economic Zone; Menakur; Tirupati; Drainage morphometry; GIS; Environmental sustainability; Coastal aquifer.

1. Introduction

Since the enactment of the SEZ Act, 2005, the Special Economic Zones (SEZs) have been the key tool of the industrial and export-oriented growth policy of the Government of India. The SEZs not only aim to catalyse investment, employment creation and infrastructural development, they also frequently overlap with agrarian landscapes, coastal ecosystems and shallow aquifer systems, which are also part of livelihoods. Land use change from agriculture/ open scrub to industrial, logistics and residential uses change the natural hydrological regime by affecting the infiltration, surface runoff coefficients and groundwater recharge regime. In coastal and semi-arid tracts of peninsular India where the situation of groundwater supply is already a primary source for domestic, agricultural and industrial requirements, such changes in land use requires systematic geo-hydrological assessment before project implementation and during the project.

The Menakur Special Economic Zone is located in Tirupati District of Andhra Pradesh as a part of the Chennai-Bengaluru and Krishnapatnam industrial corridor, which has been experiencing a high rate of land acquisition and infrastructure development in last decade. The neighbouring villages still rely on shallow dug wells and borewells that penetrate the weathered and fractured local aquifer with help of seasonal streams flowing towards the Bay of

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Bengal. The aquifer system is naturally vulnerable to saline water infiltration due to its close proximity to the coast and this vulnerability could be exacerbated by increased groundwater extraction, changed recharge regimes and effluents produced by industrial operations.

In this background the present study conducts a detailed geo-hydrological evaluation of the environmental resources of and around Menakur SEZ. Specific objectives of the study are: (i) characterization of geomorphology, drainage morphometry, and lithology of study area using remote sensing and GIS techniques; (ii) assessment of spatial and seasonal variability of groundwater level, hydro-chemistry; (iii) evaluation of groundwater suitability for drinking and irrigation purpose based on established groundwater quality standards; and (iv) identification of hydro-geological vulnerable areas in the study area and suggest remedial measures for sustainable water resource management in the command area of SEZ.

2. Study Area

The study area covers the Menakur SEZ and an area of about 5 km radius extending beyond the SEZ in the eastern coastal tract of Tirupati district in the lower reaches of the Swarnamukhi-Kalangi river system in the state of Andhra Pradesh, India. The topography slopes gently from west to east, ranging from 96 m above mean sea level in the interior upland fringe to less than 20 m near the coast with the coastline of the Bay of Bengal as the boundary on the east side. The regional climate is tropical semi-arid to sub-humid, with a hot summer (March-June), a south-west monsoon (June – September) bringing about 45 percent of the annual rainfall and a north-east monsoon (October – December) bringing the remaining 40 percent, which, in particular, is important for this east-coast climate. The mean annual rainfall for the district is of the order of 950- 1050 mm, but there is a high degree of inter-annual variability.

Geologically it is underlain by Archaean crystalline basement rocks (mainly granites, granite gneisses and charnockites) with a discontinuous cover of Gondwana and Tertiary sedimentary rocks where the latter form a small veneer in the area and are extensively covered by Quaternary alluvial and coastal deposits of sand, silt, clay and calcareous sandstone (teri sands) near the coast. Some parts of the upland pediplain are capped by lateritic and ferruginous crusts. Soils are red sandy loams in the upland tracts and coastal alluvial and saline-affected soils in the low-lying tracts close to the coast, some of which are used for aquaculture and salt-tolerant crops.

3. Materials and Methods

3.1 Data Sources

The study makes use of multi-source data, which includes Survey of India (SOI) topographic sheets (1:50,000 scale) for base maps, Cartosat and Sentinel-2 satellite data for interpretation of land use/land cover and Lineaments, digital elevation model data from SRTM (30 m resolution) for terrain and drainage analysis, district groundwater yearbooks, and Central Ground Water Board (CGWB) reports for baseline hydrogeological information; and primary field data collected from a network of 24 monitoring wells (digged wells and borewells) distributed throughout the study area and its SEZ buffer.

3.2.1 Digital Elevation Model of the region.Digital Elevation Model of the region

The geomorphic units were identified visually in the satellite images based on the general landform classification criteria (pediplain, buried pediplain, denudational hills, alluvial plain and coastal plain) and verified in the field. The DEM was converted to a drainage network in a GIS environment and the stream network was ordered based on the Strahler hierarchical scheme. The morphometric parameters were calculated to describe the runoff behavior and infiltration potential of the basin such as stream order, stream length, bifurcation ratio, drainage density, drainage texture, form factor and elongation ratio.

3.3 Groundwater Level and Hydro-chemical Sampling.Groundwater Level and Hydro-chemical Sampling.

To account for seasonal fluctuations, depth to water-level measurements were obtained at all 24 monitoring wells in May (pre-monsoon) and in November (post-monsoon). Samples of groundwater were collected in pre-cleaned polyethylene bottles using standard protocols and pH and electrical conductivity (EC) were measured in-situ at the time of sample collection. Laboratory analysis was done according to the APHA standard methods for total dissolved solids (TDS), total hardness, calcium, magnesium, sodium, potassium, chloride, sulphate, bicarbonate, nitrate, and fluoride. The analytical results were compared with the permissible limit of the Bureau of Indian Standards (IS

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10500:2012) for drinking water and suitability of irrigation water was determined by the use of some of the standard indices such as Sodium Adsorption Ratio (SAR), Sodium Percentage (Na%) and U.S. Salinity Laboratory classification.

3.4 Vulnerability Assessment

A composite hydro-geological vulnerability map was prepared using the geomorphology, lithology, drainage density, depth to water table, land use/land cover and proximity to the coastline and SEZ industrial footprint thematic layers in a weighted GIS overlay approach, broadly following the DRASTIC-type approach adapted for the study area because of the availability of data.

4. Results and Discussion

The geomorphology and drainage characteristics are described. Geomorphology and drainage characteristics are described.

The terrain analysis reveals four major geomorphic units within the study area: pediplain, buried pediplain, alluvial plain and coastal plain; the latter two are linked to the Kalangi stream and its tributaries, respectively, and offer relatively better groundwater potential due to the presence of thicker weathered mantle. The drainage is heavily dendritic to sub-dendritic type that corresponds to a relatively uniform crystalline bedrock and low regional slope with minor sub-parallel modification due to structural lineaments. The summary morphometric (SM) and physiographic (PH) parameters are given in Table 1.

Parameter	Value / Description
Total study area	≈ 42.6 km^2
Drainage pattern	Dendritic to sub-dendritic
Stream order (max)	4th order (Strahler system)
Drainage density	1.8–2.4 km/km^2
Elevation range	18 m to 96 m above MSL
Dominant slope class	1–3% (gently sloping coastal plain)
Geomorphic units	Pediplain, buried pediplain, alluvial plain, coastal plain

Table 1. Summary of physiographic and drainage morphometric parameters of the study area.

The moderate drainage density (1.8-2.4 km/km2) computed for the basin is associated with moderately permeable subsurface material and the moderately high infiltration capacity of the area, which is dominated by weathered granite-gneiss and alluvial cover. Sheet infiltration is favoured by the low to moderate relief, gentle slopes, whereas waterlogging is likely to occur during the peak monsoon periods in the coastal plain due to a shallow water table, with poor natural drainage gradients running towards the sea.

Water quantity and quality observed in the ground also fluctuates over time.Water quantity and quality in the ground also varies with time.

The groundwater in the crystalline terrain is found in water-table conditions in the weathered residuum, which is about 6–18 m thick, and in the deeper fractured zones tapped by bore wells under semi-confined to confined conditions. Groundwater is found in the intergranular pore space in the sandy and silty horizons in the alluvial and coastal tracts. Pre-monsoon water level depths ranged from 4.2 m to 14.8 m below ground level over the monitoring network, and post-monsoon measurements indicated a general increase in water level depth ranging from 1.5 m to 4.6 m, indicating that the south-west and north-east monsoons have rejuvenated the water level. The wells near the SEZ industrial footprint had relatively smaller gains in the post monsoon period, indicative of more abstraction and less pervious area due to development with impervious surfaces in the SEZ area.

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4.3 Groundwater Quality

The pre-monsoon and post-monsoon ranges of the hydro-chemical results of the 24 monitoring wells are compared with the permissible limits of BIS and summarised in Table 2.

Parameter	Range (Pre-monsoon)	Range (Post-monsoon)	BIS Permissible Limit
pH	7.1 – 8.3	6.9 – 8.0	6.5 – 8.5
EC (µS/cm)	980 – 3120	740 – 2450	—
TDS (mg/L)	640 – 2050	480 – 1610	500 (2000 max)
Total Hardness (mg/L)	310 – 780	260 – 640	200 (600 max)
Chloride (mg/L)	120 – 640	95 – 480	250 (1000 max)
Nitrate (mg/L)	8 – 62	6 – 48	45
Fluoride (mg/L)	0.4 – 1.6	0.3 – 1.3	1.0 (1.5 max)

Table 2. Seasonal variation in groundwater physico-chemical parameters compared with BIS (IS 10500:2012) permissible limits.

FINDINGS

The findings show that during the post-monsoon season the concentrations of most of the parameters in the groundwater remained within the limits of permissible standards, suggesting that the groundwater is diluted with recharge. Although the samples from wells in the interior of the study area were generally found to be within the acceptable limits of the pollutants, the samples collected from the wells within 1.5 km from the coastline and close to the boundary of the SEZ showed consistently higher levels of electrical conductivity, TDS, total hardness, and chlorides, especially in the pre monsoon season when evapotranspirative concentration is maximum and recharge inputs are minimum. The Piper trilinear diagram classification based on the proportions of major ions identifies a dominant Na-Cl type to the coastal fringe, suggesting a mixture of marine and groundwater influenced by interactions with water rocks with a mixed Ca-Mg-Cl to Ca-HCO_3 type to the interior pediplain wells, reflecting interactions with water rocks associated with the crystalline lithology. Nitrate concentrations were generally within limits but were locally elevated in wells close to settlements and agricultural areas, which may reflect fertiliser use and infiltration of on-site sanitation systems, but not at the present stage of the SEZ development.

4.4 Irrigation Suitability

The calculated Sodium Adsorption Ratio (SAR) values for the sampled wells ranged from 2.1 to 9.4, indicating that most of the wells were in low to moderate sodium hazard (S1 to S2) categories in the U.S. Salinity Laboratory Classification. Groundwater salinity hazard, however, varied from moderate (C2) in areas of the pediplain away from the coast to high (C3) to very high (C4) in wells close to the coast, implying that it is advisable to blend lower salinity groundwater to improve water quality for use in irrigation, or adopt salt-tolerant cropping sequences that have been used locally.

4.5 Hydro-geological Vulnerability

The composite vulnerability overlay highlights moderate to high vulnerability areas that are concentrated along the immediate coastal fringe, due to the shallow water table and the sandy geology, and in and immediately downstream of the SEZ industrial footprint, due to the high impervious cover and increased abstraction from the water table, and the potential for industrial effluent contamination as industrial activity increases. The interior pediplain and buried pediplain zones have high to moderate susceptibility due to their thinner unsaturated zones and reduced buffering by the weathered mantle.

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5. Conclusion

This geo-hydrological study of the environmental resources of and around the Menakur SEZ shows that it is a locally created aquifer system that is still functionally dependent on the recharge that occurs in the course of the monsoon season, and that there are strong natural (marine influence, evapotranspirative concentration) and emerging anthropogenic (land-use change associated with industry, abstraction) controls both on the quantity and quality of the groundwater resources. The groundwater quality is generally satisfactory in the interior pediplain, but deteriorates on the coastal fringe and close to the SEZ footprint and during the pre-monsoon season, due to high salinity, hardness and chloride levels. The study highlights the need to have a proactive environmental management plan that includes: regular water-level and quality monitoring within a representative well network in the SEZ, regulation of groundwater extraction consistent with the sustainable yield estimates, encouragement of rainwater harvesting and managed aquifer recharge structures to mitigate increased impervious cover, buffer areas and effluent treatment protections for wells located closest to the industrial footprint, and the maintenance of public access to good drinking water sources not impacted by industrial development. The application of the above measures, in combination with periodic geo-hydrological review, will enable the Menakur SEZ to continue to grow its contribution to industry and the economy, while maintaining the security of water supply for the agrarian and coastal communities.

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Declarations

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Conflict of Interest: The author(s) declare that there is no conflict of interest.

Data Availability: The data supporting the findings of this study are available from the corresponding author upon reasonable request.

Ethical Approval: Not applicable, as the study did not involve human or animal subjects requiring ethical clearance.

Author Contribution: All authors contributed to the conceptualisation, data collection, analysis, and manuscript preparation.