Estimation of aquifer vulnerability to groundwater pollution using an entropy-based model: a case study from the Musi River Sub-Basins, Southern India

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The present study evaluates uncertainties in decadal rainfall (RF), groundwater level (GWL), and total dissolved solids (TDS) into an entropy-based model to determine aquifer vulnerability across eight sub-basins of the Musi River Basin, Southern India. Transinformation, T(RF, GWL, TDS), is utilised to estimate the reduction in TDS uncertainty in groundwater, H(TDS), due to the knowledge of rainfall information, H(RF), and groundwater level, H(GWL). Results indicate slightly increasing annual RF (2007–2023), with an average of 1047 mm/year and dominance of monsoonal RF during June to September. GWL has shown notable spatial and temporal variation, with recovery in most sub-basins except Hussain Sagar, and also reflected variable recharge efficiency. The TDS concentrations have been observed to exhibit distinct spatial variability, and fresh to highly saline groundwater with higher salinity in the Muchkunda and Paleru sub-basins. Entropy-based analysis of RF-GWL interactions has shown groundwater recharge averaging about 14.96% of the monsoon RF, the highest (21.68%) in Ibrahimpatnam and lowest (12.06%) in Hussain Sagar sub-basins. The interactions of RF, GWL, and TDS have revealed strong groundwater-hydrochemical linkages. The elevated aquifer vulnerability is identified in the Paleru, Muchkunda, Shamirpet, and Ibrahimpatnam sub-basins, with the T(RF, GWL, TDS) values ranging from 0.0287–2.2886 bits across the Musi River Basin. The present study provides an understanding of aquifer vulnerability for sustainable groundwater management and guides future research.

Keywords: Aquifer vulnerability, groundwater level, Musi River Basin, rainfall, total dissolved solids, transinformation.

GROUNDWATER recharge plays a pivotal role in sustaining water reserves, as it governs storage and availability through a complex balance of recharge and discharge processes. Recharge occurs primarily from rainfall (RF), with additional contributions from irrigation return flows, surface water bodies (i.e., rivers, ponds, and lakes), and artificial structures, while discharge takes place via evapotranspiration, groundwater extraction, and base flow from rivers[1]. Accurate estimation of natural recharge is fundamental to groundwater management, especially under changing climatic conditions where RF variability strongly influences aquifer replenishment. Various techniques and empirical approaches have been introduced for recharge estimation, including groundwater balance[2], base flow separation techniques[3], and hydrogeological, geophysical, and hydrochemical techniques[4–11]. Among these, environmental tracer techniques, notably tritium (^3H) with piston flow model[4,5,10], have provided robust estimates. However, these approaches are often data-intensive, costly, and imitated in spatial coverage, making them less practical for large-scale regional studies in developing countries[12]. Recent advancements have integrated tracer techniques with remote sensing (RS) and numerical modelling, thereby enhancing the accuracy of recharge estimates to some extent[13].

To overcome such limitations, an entropy-based statistical model has been proposed for estimating natural groundwater recharge using minimal datasets, such as RF and groundwater level (GWL) fluctuations[14]. This model, grounded in Shannon's entropy[15], quantifies the uncertainty and variability of hydrological processes and has been successfully applied in various geological settings[16], including the granitic terrains of Southern India[14,17], basaltic provinces of Central India[18], and the sedimentary basin of the Ganga River plains in Northern India[19]. Their strength lies in bypassing the need for detailed hydrogeological characterisation, thereby providing a rapid and cost-effective means of estimating natural groundwater recharge.

Parallel to this recharge estimation, the concept of aquifer vulnerability due to the natural recharge has evolved as a critical framework for assessing susceptibility to groundwater contamination. First introduced by Marget[20], aquifer vulnerability refers to the intrinsic characteristics that determine how easily a pollutant introduced at the land surface can reach the aquifer[21]. Vulnerability

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