Theme 12

VADOSE ZONE HYDROLOGY AND AGRICULTURE WATER MANAGEMENT

SIGNIFICANCE OF SOIL MOISTURE PROBES IN CALIBRATING HYDROLOGICAL MODELS

Arivoli E.[1], Saravanan Subbarayan[1*] and Chandrasekar K.[2]

[1]Department of Civil Engineering, National Institute of Technology, Tiruchirappalli, India
[2]Water Resources Group, National Remote Sensing Centre, Hyderabad, India
[*]Corresponding author e-mail: ssaravanan@nitt.edu

Soil Moisture in vadose zone plays a crucial role in a hydrological cycle and determines the water availability for vegetation especially for crop growth in rainfed agriculture areas. During the cropping period the soil moisture varies between the state of saturation to permanent wilting point depends on the crop stage and the effect of preceding rainfall events. Precise estimation of soil moisture helps to project the seasonal irrigation demand and optimize the water allocation at respective stages of crop growth. Hydrological models are often found as an effective tool for assessing the hydrological cycle and helps in partitioning the rainfall into surface and subsurface components. Calibrating the model parameters is considered as the important step for simulating the actual scenario which directly defines the performance of the model. Hence the objective of this study is to identify the sensitive parameters through calibrating the hydrological model with respect to the data obtained from permanent soil moisture station and understand the subsurface hydrology in a better way. This study is an attempt to make use of soil moisture data measured from soil moisture instruments installed at field for the model calibration and to identify the sensitive parameters of the model as well the local boundary conditions impact the soil sensor.

In this study, Variable Infiltration Capacity (VIC) hydrological model is chosen as it estimates the subsurface soil moisture values at user defined depths up to 1.5 m below the surface level. The data from permanent soil moisture station installed at GB Pant agricultural university is taken for calibration and for identifying the sensitive parameters in the model. The reason for point scale calibration and validation of Soil Moisture is to identify the field soil moisture response to local boundary conditions and to narrow down the specific parameters which are sensitive for model calibration. VIC model is a macroscale semi distributed hydrological model which simulates grid wise water balance components in terms of Evapotranspiration, Runoff, Root zone and Deep zone soil moistures. VIC model includes the grid wise input parameters in terms of meteorological data like Rainfall, Temperature (Min and Max), land class information like area of each land class in a grid, root fraction/root distribution, Leaf Area Index (LAI), Albedo, soil hydraulic properties like permeability, bulk density, saturation, field capacity and permanent wilting point. Here meteorological data (Rainfall, MinT and MaxT) from India Meteorological Department (IMD) is taken, National Bureau of Soil Survey and Land Use Planning (NBSSLUP) soil data is used, MODIS-MOD 15 LAI is used for defining monthly vegetation properties and further validated using secondary data and literatures. MODIS-MOD 43 is taken for monthly Albedo data. Secondary data were used for defining root fraction/root distribution beneath the surface of the selected crop. Single grid simulation approach is used, the grid resolution is considered as 3” (~5.5 Km) and a homogenous vegetation cover is defined for each crop stage for the entire grid as collected from field and the properties of the subsurface soil profile were defined in the model. The data from permanent soil moisture (PSM) instrument installed at G. B. Pant University of Agriculture and Technology by National Remote Sensing Centre (NRSC) is used for calibrating and assessing the performance of the VIC hydrological model. The soil moisture data was taken from *https://bhuvan.nrsc.gov.in/nhp/vic-soil-moisture-dashboard* for the Layer 1 from 0 - 15 cm and Layer 2 from 16 – 30 cm for a period between February 2022 to December 2022. The PSM was installed in the rainfed area. Two types of vegetation cover were observed during the study period namely Green Peas and Medium to Tall grass respectively. The model run was made during February 2022 to December 2022 using daily meteorological data, monthly LAI and root fraction distribution in the subsurface layers for the respective vegetation covers. The initial state of soil moisture and root fraction distribution was updated for each crop stage and the model was calibrated and validated for its best fit using statistical performance indicators.

The observed soil moisture obtained from PSM is compared with the VIC simulated soil moisture at the subsurface layers. The boundary conditions are updated at each crop stage and the calibration process was carried till its best fit. It is observed that root fraction definition in the model plays a significant role in subsurface soil moisture variation along with the antecedent moisture conditions which is influenced by local meteorological conditions. Since the vegetation cover in the selected site has a shallow root fraction distribution, the influence of variation is observed more in the layer I soil moisture i.e., up to 15 cm during initial stage. As the vegetation growth proceeds further in the season, the monthly LAI defined in the model along with the root fraction influences the variation of soil moisture in layer II i.e., up to 30 cm. It is observed in the results that the variation of subsurface soil moisture has a strong agreement with the Evapotranspiration as it is witnessed during the crop growth stage. The performance was assessed through the statistical indicators like R^2, Nash Sutcliffe Efficiency (NSE) and Kling Gupta Efficiency (KGE) yields an agreement between observed and simulated as 0.89, 0.69, 0.21 in Layer I and 0.81, 0.03, 0.23 in Layer II respectively. Hence the study concludes that soil moisture variation in the hydrological model is a function of root fraction distribution, LAI definition in the model and the meteorological conditions. Thus, the optimized root fraction distribution could be used for simulating the similar vegetation/crop types and soil type in the hydrological model. It is proven from this study that PSM instruments are significant in calibrating and validating the hydrological models at micro level and upscaling the same into macro framework for its application in various hydrological studies with similar crop and soil conditions.

Keywords: *Calibration, modeling, root zone, soil moisture, vadose zone*

ESTIMATING SOIL EROSION USING RUSLE MODEL TECHNIQUE IN AMBA RIVER BASIN, MAHARASHTRA, INDIA

Rajat kumar[1]*, Avinash kumar[2], Prachi[2], Umesh Kumar Singh[1] and Richa Pandey[1]

[1]*National Institute of Hydrology, Roorkee, India*
[2]*Delhi Technological University, Delhi, India*
[*]*Corresponding author e-mail: rajatkumar.nihr@gov.in*

About 175 million hectares of land in India require soil and water conservation measures to address the increasing issue of soil erosion. Among the different types of erosion, sheet and rill erosion are the most significant, leading to substantial decline in agricultural productivity. Soil erosion in developing countries like India is primarily driven by raindrop spray energy and various human activities, which collectively trigger land degradation. Soil erosion is a three-phase process involving the detachment of soil particles, their transport by agents such as water or wind, and eventual deposition when the transporting energy diminishes. Factors contributing to soil erosion include intensive agricultural practices, soil degradation, and changing global climatic conditions. The consequences are profound and far-reaching including the loss of fertile topsoil, reduced soil fertility, soil compaction, eutrophication, groundwater contamination, and, adverse impacts on agriculture, water quality, ecosystems, and landscapes. Floods, in particular, intensify soil erosion. High water volume and velocity during floods dislodge and transport soil, stripping nutrient-rich topsoil essential for fertility and agricultural productivity. This eroded soil is often deposited downstream, resulting in sedimentation that alters landscapes and disrupts ecosystems. Predicting soil erosion is crucial to mitigate these challenges and implementing effective conservation strategies. This study focuses on estimating soil erosion in the Amba River Basin for 2018, a year marked by severe floods in the region. The research aims to evaluate the soil erosion using the Revised Universal Soil Loss Equation (RUSLE) model integrated with Geographic Information Systems (GIS) and remote sensing tools. The Amba River Basin, spans 929.75 km^2. The river originates in the Sahyadri ranges near the Khopoli-Khandala road at an elevation of approximately 554 meters. The region exhibits diverse geomorphological features, including mangrove vegetation in the lower basin, extensive agricultural zones along the riverbanks, and mudflats that support a rich variety of seabirds. The basin experiences a tropical climate, with an average annual rainfall of 3157 mm, 95% of which occurs during the southwest monsoon. The RUSLE model was employed to estimate the average annual soil loss in the basin. This model integrates five key factors: rainfall erosivity (R), soil erodibility (K), slope length and steepness (LS), crop cover (C), and conservation practices (P). By combining these parameters, the RUSLE model provides a comprehensive understanding of the soil erosion processes and potential risks in the region. The R factor measures the erosive force of rainfall and was calculated using long-term rainfall data. In the Amba River Basin, R values ranged from 1266.35 to 1553.02 MJ mm/ha/h/year, with higher values observed in Sukeli and Karjat due to abundant rainfall. The K parameter depends on the physical and chemical properties of the topsoil. The K values in the region ranged from 0.018 to 0.021 t h ha/MJ/ha/mm, with lower values indicating reduced permeability and antecedent moisture content. LS factor reflects the influence of topography on erosion, with values increasing up to 645.98 as slope and flow accumulation rise. Using NDVI (Normalized Difference Vegetation Index), the C values ranged from 0.027 in dense forested areas to 0.053 in rocky terrains. Lower values indicate better soil protection due to vegetation cover. The P factor values ranged from 0.55 to 1, with higher values representing poorly managed areas more susceptible to erosion. The RUSLE model estimated that the average annual soil loss in the Amba River Basin is approximately 765.88 tons/year. Analysis of erosion severity maps revealed that 24% of the basin's area experiences high or very high erosion, underscoring the urgent need for targeted conservation measures. The study also identified a strong correlation between increased agricultural activity and high erosion risk, emphasizing the challenges posed by unsustainable agricultural practices. The findings highlight the importance of integrating empirical soil erosion models like RUSLE with GIS and remote sensing tools for effective resource management. This integration facilitates the creation of erosion severity maps, which are vital for regional planning and prioritizing conservation efforts. By identifying erosion-prone areas, policymakers and land managers can implement adaptive strategies tailored to mitigate the adverse impacts of soil erosion. Additionally, the study underscores the interplay between agricultural expansion and soil erosion risk, emphasizing the need for sustainable land management practices. Future research should focus on developing and evaluating adaptive conservation strategies that address the unique characteristics of the region's land use and topography. Such efforts will not only help mitigate soil erosion but also contribute to the long-term sustainability of the region's natural resources. In conclusion, the Amba River Basin study demonstrates the efficacy of using models like RUSLE in conjunction with GIS and remote sensing for assessing soil erosion. The insights gained from this study can inform soil conservation initiatives, promote sustainable land use practices, and guide future studies aimed at addressing soil erosion challenges.

Keywords: *Amba River Basin, GIS, NDVI, RUSLE, Soil erosion*

ROAD MAP FOR WATER EFFICIENT FARMING IN INDIAN HIMALAYA

Anil K Srivastva*

ICAR-VPKAS, Almora
Central Soil Conservation Inst., Dehradun
ICAR Consultant-Int. Farming Systems, Dehradun, Uttarakhand
**Corresponding author e-mail: aksrivastva4@yahoo.com*

Water is core natural resource in farming, facing several challenges for the present and future including availability at source and sink. Age-old edict venerating the river systems *"Oum Gange cha Jamunechaive Godavari, Saraswati, Narmade Sindhu, Kaveri Jaleusminsannidhi Kuru"* highlights the cultural thrust on water in India. It contributes to Environment, Food, Livelihood security along with ensuring economic wellbeing and resilience to climate change. The Indian Himalaya is grouped under AER (Agro-Eco Region) 1: Western Himalaya Cold Arid Ecoregion, AER 14: Western Himalaya Warm sub-humid to humid with inclusion of per-humid eco-region, AER 16: Eastern Himalaya Warm sub-humid eco-region and AER 17: North eastern Hills Warm per-humid eco-region. Majority of small holding farmers in Himalaya practice farming under widely diverse agro-ecosystems. Hill farming has a major role in maximizing water efficiency and productivity. The knowledge and experiences gained in India over a century in soil conservation and watershed management have provided a strong base for water efficient farming. Summarizing the task and road map for future needs, a comprehensive management could well provide roadmap for future.

In mountain ecosystem, seasonal extremes and gaps in precipitation, vanishing vegetation cover, slopy terrains along with poor sink due to depth and gravels present major management issues. The criticality of water resource is well recognized. There is limited possibility of tube wells and canal irrigation, which may be compensated by conservation and harvesting of water. Availability of water for farm sector has to be on a time and volume specific. Major concerns for this sector are storage, efficient use of water sources, increasing wastage, pollution and degradation. The decisions and operations of farming have to be synchronized with the nature and availability of water resource. The pattern of receding water in the storage is an important tool. The inclusive research includes management of water, eco-system and meticulously scaled-up to farm holding to watershed to region, thereby targeting the regional and global opportunities. The watershed management approach is advocated for regions with lack of water conservation and storage, over exploitation of vegetation cover, water losses due to inefficient water conveyance and application aggravating the stress. Comprehensive and water centric management is needed under watershed approach.

Watershed is inclusive of ecosystem, natural resources, inhabitants, production systems along with on- and offsite implications. Degradation, loss of sink, fine particles, organic fraction, higher cost due to energy needs and applied resources severely affect productivity and viability of hill farming. Watershed management components include natural resources, their utilization, conservation and aggradation, humans and livestock and market and associated infrastructure, environment and climate. Development of water resources is another approach. Under this approach harnessing the available water into usable form on grid basis is adopted as inclusive approach. Conservation and ponding of rain water, diverting flowing water to farm fields and water bodies, surface and sub-surface water storage, along with appropriate conveyance and application systems forms the core management. The rainfall intensity moderated by vegetative cover, terrain and soil conditions, provides the balance available for crop growth. Integrated farming, protected cultivation and operational management is another option. Agro-Ecosystem approach is perceived as logical basis for optimum use and management of resources by several research workers. It involves management of an ecological unit, having similarities of natural resources, micro-climate, energy and production systems. Diversified hill cropping and Farming Systems Families is also an important approach. The primary aspects include production systems planning which involves demand, ecosystem potential, resources, skill and capacity based and policy links that are closely dependent on market intelligence. Agro-ecosystems are characterized and quantified. These include orientation to sun, landscape positioning, field slope, soil depth, texture and gravel content. Landscape forest cover whether up-stream or downstream is also included. Productivity is grouped under high, medium and low level. Emerging scenario-life-style purchasing capacity and consumers' awareness are the other factors that are considered along with farming practices.

Hill Terrain limits large scale use of canal or tube well irrigation. Whereas, small irrigation channels (Guls or Kuhls) face perpetual problem of repairs due to unstable terrains. Development of water harvesting ponds was appropriate. Protected cultivation is a suitable technology because of small holding size of around 0.4 to 0.6 ha/family. It has distinct advantage of 3 to 4 times higher production per year. It facilitates year-round cropping even during harsh winters. The physical damage to fruits and plants due to hail storm and excess rains are also prevented. It works as excellent tool for carbon sequestration. Apiary associated with poly house adds to the advantages. Grid based water harvesting ponds entail due emphasis to perennial vegetation, giving thrust to sustainable water resource development will. The improved vegetative cover will not only reduce splash erosion but also result in reduced tillage. This will positively influence soil erodibility. In turn will impart climate resilience to farming system. Inclusive advantage of Watershed management was highlighted by IPCC in improving the ecosystem resilience to climate change. Strategy consisted of runoff control, moisture conservation and vegetative cover as highlighted in the Hydrologic cycle.

To summarize, augmentation, conservation and multiple utilization of water resources, inclusive of entire cause and effect relationship has to be primary intervention towards water secured future. Water conservation in both non-arable and arable land, recycling in protected cultivation and harvested water fisheries are highly successful. The secondary interventions have to be water efficient farming and other sectors appropriately matching the defined objectives. The third intervention involves long term on-farm and on-station comprehensive, need based and problem-solving research, useable technology and skill development. Both these interventions were implemented on on-farm eco-systems, linked to market factors. The fourth equally crucial is enabling policies, investment both in human resources, infrastructure and realistic costing. The fifth important intervention has to be strong incentives and dis-incentives towards maximizing efficient use of water. Stage-wise involvement of stake holders was key to success. Wider adoption of the technologies is expected to contribute to Water Secured Future.

Keywords: *Water security, watershed management, water conservation, farming, hilly terrain*

ASSESSMENT OF AGRICULTURAL WATER AND LAND PRODUCTIVITY USING WATER ACCOUNTING PLUS FRAMEWORK FOR LUNI RIVER BASIN, INDIA

Dilip Barman[1*], Malkhan Singh Jatav[1], Akshay V. Dahiwale[1], Sudesh Singh Choudhary[1], Sourabh Nema[1], Anupma Sharma[2], M.S. Rao[2] and P.K. Mishra[2]

[1]North Western Regional Centre, Jodhpur (Rajasthan), National Institute of Hydrology, India
[2]National Institute of Hydrology, Roorkee, India
[*]Corresponding author e-mail: dilip14.nihr@gov.in

In India, ensuring food security amidst limited water resources will become a growing concern in the coming decades. The agricultural sector is the major freshwater consumer in India, accounting for more than 80 percent. Besides, low water use efficiency and crop productivity are major challenges for developing countries like India. Furthermore, spatial and temporal information regarding water productivity and land productivity remains a significant challenge due to limitations in data availability. This study aims to address these critical gaps by analyzing water consumption patterns, Land Productivity (LP), and Water Productivity (WP) for both irrigated and rainfed crops in the Luni River basin, Rajasthan over an 18-year period, from 2001-02 to 2018-19.

The Luni River, the longest river in Rajasthan, originates in the Naga Hills (Nag Pahar) of the Aravalli Range in Ajmer district at an elevation of 550m (MSL) and traverses 495 kilometers in a south-westerly direction, ultimately disappears into the marshy land of Rann and Kutch region in Gujarat. It spans a geographical area of 72,000 km^2, traversing seven districts of Rajasthan: Ajmer, Nagaur, Jodhpur, Pali, Barmer, Jalore, and Sirohi. The geographical area of the basin spans arid to semi-arid conditions and encompasses three distinct agro-climatic zones: the northeastern upper part falls within the western dry region, the northwestern lower part lies in the central plateau and hills region, and the southernmost part extends into the Gujarat plains and hill region. The annual rainfall across the basin varies significantly, ranging from 1,048 mm in the western region to 221.5 mm in the southwestern area, with an average rainfall of 320 mm. Mostly 95% of the annual rainfall occurs during the monsoon months from July to September. The analysis is conducted using the Water Accounting Plus (WA+) framework, a Python-based tool that entirely relies on globally available remote sensing data. The study was focused on assessing the water and land productivity of a major cereal (Bajra), which is a key crop in the study area. WA+ framework is fully based on the remote sensing datasets, following geospatial datasets have been used in this study: Gridded rainfall from India Meteorological Department (IMD) with spatial resolution of 0.25°×0.25°, Actual Evapotranspiration (ET) from Simplified Surface Energy Balance (SSEBop), Leaf Area Index (LAI) from MODIS, Potential Evapotranspiration (PET) from Global Data Assimilation System (GDAS), Gross Primary Products (GPP) and Net Primary Products (NPP) from MODIS. These geospatial datasets were collected from the period 2000 to 2019 to assess the WP and LP for the Luni River basin. WA+ framework categorize the land use land cover into Protected Land Use (PLU) as designated for conservation and protection, where human activities are restricted, Modified Land Use (MLU) that have been significantly altered by human intervention for agricultural and other productive purposes, Utilized Land Use (ULU) engaged in various ecosystem services that typically exhibit limited human alteration, and Managed Water Use (MWU), where the natural water cycle has been artificially modified, particularly for agricultural and urban applications. These four major

land-use covers are further subdivided into 80 classes based on distinct open-source geospatial inputs. To prepare the WALU land use land covers for the study area, various geospatial datasets i.e., land use land cover from NRSC, Rainfed and irrigated crop area from MIRCA, Irrigated crop map from IWMI, Population from WorldPOP, Water bodies information from JRC-EU, protected areas information from WDPA, and ESA Globcover map have been used.

The results of the study were verified with field data, Crop Cutting experiments (CCE) were conducted to assess the yield and productivity of crops. In this study, CCEs were conducted at multiple locations across the basin to collect productivity data for major Kharif crops in the Luni basin, including guar, bajra, jowar, and groundnut. A 1 m × 1 m sampling frame was utilized for the CCEs, within which crops were harvested and their yields were precisely measured to determine the productivity of these major Kharif crops.

The analysis differentiated between rainfed and irrigated conditions, providing insights into how these different agricultural practices impact productivity. The result of the study reveals land productivity for the major cereal in the basin varies from 175 to 596 kg/ha/year from 2001-02 to 2018-19 under rainfed conditions, whereas, under irrigation, it varies from 201 to 900 kg/ha/year. The total land productivity of the basin varies from 482 to 1369 kg/ha/year with an average land productivity of 870.11 kg/ha/year. The spatio-temporal results of the study also reveal a significant increasing trend of land productivity under irrigation conditions. Similarly, the water productivity of the basin varies from 0.83 to 1.64 kg/m^3 with an average WP of 1.19 kg/m^3 during the study period. In conclusion, this study demonstrates the effective application of the Water Accounting Plus (WA+) framework in analyzing and mapping spatio-temporal water consumption patterns, Land Productivity (LP), and Water Productivity (WP) for irrigated and rainfed crops in the Luni River basin.

Keywords: *Irrigated and rainfed crops, land productivity, Luni River basin, water accounting plus, water productivity*

INTENSIVE IRRIGATION AFFECTING GROUNDWATER QUALITY: A CASE STUDY FROM PUNJAB, INDIA

Parth Sarthi*

RGNGWTRI, Central Groundwater Board, India
**Corresponding author e-mail:* sparth8771@gmail.com

Agriculture in Punjab is heavily reliant on groundwater, with more than 70% of irrigation demands met through tube wells. The region's groundwater quality has become a major concern due to its direct linkage with extensive agricultural practices, especially in the context of intensive irrigation. Punjab’s agro-ecological landscape exhibits significant variations in groundwater quality, driven by diverse hydrogeological conditions. The very high evapotranspiration rate in Punjab accelerates sodium accumulation in soil which enhances sodicity of top soil and vadose zone soil. The natural rainfall recharge and irrigation return flows drag sodium from these sodic layers while infiltrating through top soil and leaching through vadose zone. The percolating water eventually joins the groundwater table in unconfined aquifers, imparting salinity known as inland salinity, which significantly contributes to Punjab's severe groundwater quality issues. The fine-textured soils prevalent in regions with shallow unconfined aquifers such as Malwa and parts of the Siwalik ranges in western, southwestern, and northern Punjab are especially prone to water-logging and high salinity issues due to excessive irrigation, which is further aggravated by long groundwater residence time and high evaporation rates. These regions are characterized by a thin vadose zone (<2mbgl). Presence of such a shallow water level often leads to a condition exacerbating issues of nitrate contamination, soil degradation through sodium accumulation (increasing Sodium Adsorption Ratio) and structural loss.

Conversely, regions like Majha, Doaba, and Sirhind in central and southeastern Punjab are characterized by sandy loam to loamy soils with semi-confined to confined aquifer systems and a thicker vadose zone reaching up to 70 mbgl. This geological setting makes these areas prone to secondary salinization and accelerated groundwater depletion, which significantly reduces agricultural productivity. The challenges stem from excessive irrigation and deep percolation, which enhance capillary rise and lead to salt accumulation in the root zone. Additionally, over-extraction of groundwater disrupts the hydrological balance, causing aquifer compaction and, in severe cases, land subsidence, further exacerbating the region’s agricultural and ecological vulnerabilities. This study examines the relationship between groundwater quality and irrigation practices, highlighting the impacts of varying vadose zone thickness on groundwater salinity, as well as variations in aquifer geometry, water table depth, soil composition, and rainfall, and their implications for agriculture. Additionally, it addresses the challenges posed by groundwater over-exploitation.

The methodology for this study includes a combination of hydrogeochemical analyses and vadose zone profiling. Groundwater analysis data such as Total Dissolved Solids (TDS) measurements and isotopic analysis provide a comprehensive overview of regional groundwater quality and its variations. TDS, a critical indicator of groundwater salinity, reveals high concentrations exceeding 2000mg/L in southwestern Punjab, marking the groundwater as unsuitable for both agricultural and domestic use. This is often associated with high Sodium Adsorption Ratio (SAR), which further deteriorates soil and groundwater quality. The poor water quality conditions, which vary spatially, can be attributed to factors like irrigation return flows, inland salinity, water logging and excessive fertilizer use. The regions with thicker vadose zones, including central and southeastern Punjab, although exhibiting lower TDS values, are vulnerable to secondary salinization caused by excessive irrigation return flows. These return flows contribute to the accumulation of salts in the soil and groundwater, especially in areas where episodic recharge from rainfall or canal seepage is insufficient to flush the salts. The study also integrates groundwater isotopic analysis data (δ18O and δ2H) from published reports to trace recharge sources and mechanisms. Isotopic signatures suggest that precipitation contributes minimally to recharge in the water-logged regions of southwestern Punjab, where over-irrigation dominates. In contrast, the groundwater in central and southeastern Punjab reflects a significant contribution from canal seepage and irrigation return flows. The varying regional conditions present a complex hydrogeological landscape in Punjab, where both salinization and depletion are intertwined with the vadose zone's thickness and the intensity of irrigation practices. The study concludes that the depth to the water table, the thickness of the vadose zone, and the hydrogeological properties of the aquifer system play critical roles in determining groundwater quality. As a response to the dual challenges of salinization and depletion, this research recommends adopting a set of sustainable groundwater management practices. For the regions experiencing salinity due to water-logging, such as southwestern Punjab, measures such as subsurface drainage systems, alternate cropping patterns, and salt-tolerant crop varieties can be beneficial. Additionally, deficit and precision irrigation techniques should be promoted to optimize water use and minimize the adverse effects of excessive irrigation. Managed Aquifer Recharge (MAR) schemes, tailored to specific regional conditions, could play a pivotal role in enhancing groundwater recharge and mitigating the long-term salinity problem in over-exploited regions. The ideal vadose zone thickness of 10 to 50 mbgl provides balanced capillarity and drainage, facilitating optimal soil aeration, nutrient cycling, and water availability for sustainable agricultural production. Beyond this range, the soil's buffering capacity to manage salinity and retain moisture decreases, impacting crop yield and long-term soil health.

The study also emphasizes the importance of a comprehensive groundwater monitoring framework, integrating geophysical surveys, remote sensing, and GIS-based mapping. This framework will help in identifying vulnerable zones and tracking temporal changes in groundwater quality. The integration of groundwater modeling, calibrated with field data, can provide predictive insights into the potential impacts of various management strategies, facilitating better policy formulation. Furthermore, public awareness campaigns and policy interventions, aimed at regulating fertilizer use and encouraging water-use efficiency, are critical for ensuring sustainable groundwater management in Punjab. In conclusion, this study underscores the critical linkages between vadose zone characteristics, aquifer hydrogeology, and intensive irrigation practices in determining groundwater quality. By addressing these factors, and with the implementation of scientifically informed management practices, Punjab can work towards balancing agricultural productivity with the long-term health of its groundwater resources.

Keywords: *Vadose zone, salinity, sustainable groundwater management, water logging, groundwater extraction*

DETERMINATION OF SOIL HYDRAULIC PROPERTIES USING PEDOTRANSFER FUNCTIONS FROM SOIL TEXTURE PROPERTIES IN LUNI RIVER BASIN, INDIA

Satendra Kumar*, L. Surinaidu, Pintu K. Gupta, Nitesh Patidar and Anupma Sharma

National Institute of Hydrology Roorkee, India
**Corresponding author e-mail:* satendrakr.nihr@gov.in

Luni basin is the largest river basin in the northwest India, having arid to semi-arid climate. The region receives a very low rainfall of order 400 mm annually, major portion of which is received in the monsoon season. It is located in south-western part of Rajasthan. The Luni River basin is covered mainly by rocks belonging to the Pre-Cambrian rocks to Aeolian and Fluvial deposits of Recent to Sub-Recent age. The region has scarce surface water sources and brackish groundwater sources. Hence, management and utilization of available water resources becomes important. Soil hydraulic properties play important role in modelling and simulation of water movement process (infiltration, conductivity, storage and plant water relationships). Soil hydraulic properties are very much dependent on the textural composition of a soil, and can be predicted with the help of textural information along with other optional data. Texture of soil is an import information, which affects many soil characteristics such as: water holding capacity, aeration, erosion, soil workability, soil productivity and infiltration characteristics. Soil texture is a very stable characteristic which influences saturated hydraulic conductivity and other hydraulic parameters. Soils dominated by larger sand fractions tend to have higher porosity having higher K_{sat} values and have lower water retention content. Soils dominated by larger clay fractions tend to have relatively smaller pore spaces having lower K_{sat} values. Determination of hydraulic properties such as water retention characteristics and K_{sat} is rigorous and time taking exercise. Soil texture information, can aid in the determination of these properties using pedo-transfer functions (PTFs). PTFs are multiple linear regression equations relating the soil hydraulic properties to the texture, bulk density, retention water content at field capacity and retention water content at permanent wilting point. More the information is available closer are the predictions. There are several PTFs developed by various researchers for soils of different regions. Present analysis shows the prediction of K_{sat} and water retention parameter values using Rosetta PTFs with the textural properties of soil samples collected in the Luni River basin. The Rosetta PTFs are ANN based relations between the soil hydraulic functions and textural composition of soil samples.

A total of 54 disturbed soil samples were collected from different locations and depths varying from 10 to 100 cm, and were analysed for textural composition. Texture analysis was performed by Electromagnetic Sieve Shaker for coarse fractions (gravels and sand) and by Master Sizer (MICROTRAC S3500) for fine fractions (silt and clay). Finally, the entire distribution of soil particles is obtained by combining the results of both the analysis. The textural compositions for each soil sample so obtained are partitioned into clay, silt, sand and gravel compositions as per USDA soil texture classification. The compositions obtained are fed into PTFs, which yields the soil hydraulic parameters. The results of the electromagnetic sieving (coarse particles) and particle size analysis (fine particles) yields the particle size distribution of the soil samples analysed. The analyses yield the fractional presence of Gravels, sand, silt and clay particles in the soil sample. The result show that gravel composition varies from 0 to 35.5 % with a mean value of 4.47 %, sand composition varies from 28.45 to 92.33 % with a mean value of 28.45 %, silt composition varies from 4.23 to 57.19 % with a mean value of 4.23 %, and clay composition varies from 0.07 to 9.55 % with a mean value of 1.84 %. The results show that samples collected vary texturally and comprises soil textures as: Sand, loamy sand, sandy loam, loam and silt loam as per the USDA soil classification, showing the predominance of sand followed by silt with trace presence of clay minerals.

The obtained fractional compositions of each sample analysed are fed to the Rosetta PTFs for the determination of K_{sat} and water retention parameters. The obtained value of K_{sat} varies from 28.13 cm/day for loamy soil to 839.35 cm/day for sandy soil with an average value of 12.75 cm/day which correspond to the loamy sand texture. The value of water retention parameters viz: θ_r, θ_s, α_v and n_v are also obtained which are important for modelling of flow process in the unsaturated zone. The variation in the textural composition along the river path show an increasing trend in sand and silt percentage, while clay shows a decreasing trend for a 10 and 20 cm depth of sampling. At 50 and 100 cm depth of sampling locations the sand % shows an increasing trend and silt shows a decreasing trend. The presence of sand along with silt fraction is predominant in surface soil. These estimates of hydraulic properties obtained by PTFs provide predictions of hydraulic conductivity and water retention parameters which are otherwise time taking and require rigorous lab and in-situ experiments. Spatial information of hydraulic properties is a valuable information in the determination of water retention characteristics and higher K_{sat} regions as potential recharge zones in the Luni basin.

Keywords: *Soil texture, hydraulic properties, pedo-transfer functions, saturated hydraulic conductivity, water retention parameters*

GRAVITY OPEN-CHANNEL IRRIGATION SYSTEMS IN HILL AREAS: A FIELD STUDY IN ANDHRA PRADESH, INDIA

Venkata Ramamohan Ramachandrula*

Water and Livelihoods Foundation (WLF), Hyderabad, Telangana
**Corresponding author e-mail: ramamohan.ramachandrula@gmail.com*

Natural springs and streams that originate on the hill tops and flow down the slope are the major sources of drinking water as well as irrigation in the hilly areas. A natural spring is defined as the water source which oozes out the groundwater onto the surface, typically at the point of sudden reduction of hill slope or in the foothill regions. On the contrary, a natural stream is fed by both upstream springs, often multiple of them, as well as the direct runoff from the rainfall. The eastern ghat areas in Alluri Sitarama Raju (ASR) district of Andhra Pradesh, India are replete with number of such natural springs and streams. While the yield of a spring is relatively low, such as 2-10 litres per second (lps), the streams comparatively carry larger flows, such as, 100 to 500 lps. Further the spring water is cleaner and free from dust and soil, unlike the surface water streams. Therefore, spring waters are protected, tapped and distributed for drinking purpose in the tribal habitations. On the other hand, the hill streams are abundant source of water for irrigation, particularly to cultivate crops like paddy and vegetables.

Gravity irrigation by diverting stream water from hill tops is a common practice in Dumbriguda and Hukumpeta *mandals* of ASR district. In a typical gravity open-channel irrigation system (GOIS), a check dam diverts the stream water into a cement-lined or earthen open channel and distribution channels finally carrying water to farmlands for irrigation. A reconnaissance study was done on 13 GOISs in association with the Water Resources Department, Government of Andhra Pradesh and three of them were taken up for the detailed study. The reconnaissance study of 13 GOISs found that: there is a general trend of reduction in the flow in the hill springs and streams. Some streams completely dry up during dry period. Shift to coffee cultivation by farmers on the hill slopes in recent years might have influenced the base flows in the streams. Depleted flows in the streams resulted in water shortage in the tail-end of the command areas, leading to failure of paddy crop in the GOISs. This problem is prominent in the GOISs which have predominantly earthen unlined main channels. The bed of the cement-lined main channel got eroded at locations with higher flow velocities. This particularly happened at the take-off location of main channel from the check dam and the segments of main channel with steeper bed slope. Water leakage from the bottom of concrete sidewalls is widespread in most of the GOISs. These leakages are resulting in water not reaching tail-end farmlands and in unequal distribution of water in the command area.

The detailed study was limited to three GOISs located in Ukurba, Panthalachintha and Podili villages in Hukumpeta *mandal*, ASR district. All these systems were about 8-10 years old. Since, Ukurba and Podili are neighbouring villages, there is some overlap in terms of villages benefited. However, these two GOISs provide water to mutually exclusive command areas. The detailed study was carried out using various methods such as groups discussions with farmers, transect walks to different channel locations and visit to the water diversion check dams on the hill tops. Information related to functioning of the systems for the past years, current water distribution and cropping practices, major problems faced by the systems were

gathered through discussions with farmer's groups. The problems identified from the discussions were listed and field study of each of them was done by visiting those specific locations. Major functional problems in the three GOISs were enumerated broadly dividing them as source-related and distribution-related. Reduction of dry period flows or complete drying up of perennial streams were observed in all the three GOISs studied. Water leaks from the join between side walls and the bed is a wide-spread problem noticed across GOISs. These problems had ultimately resulted in water shortages and crop failures at the tail-end of the command areas. Bed erosion of cement-lined channels, due to higher flow velocities, were found to be common at the channel take-off from the diversion check dams and segments with steeper bed slopes.

Few of the solutions identified were prioritized for carrying out the renovation works. The renovation works are mainly of three types, viz., augmenting the water diversion from the source to the main channel, arresting the leakage of water from the main channel, and ensuring equitable distribution of water. There were also few works that are not directly related to the functional performance of the GOISs, such as, laying of deck slabs on the main channel at the road-crossing points to facilitate smoother vehicular movement. Further, a novel silt-water separation structure (SWSS) was designed and built in Podili reviving the silted-up pipeline, that is taking-off from the end of a cement-lined main channel. While LAYA, with grants from Ajim Premji Foundation (APF), spent financial resources for the renovation works, the authors provided technical support in designing and guidance in proper implementation of the identified improvement works. These interventions need to be observed for longer time to confirm their performance. Measures to augment base flow to the hill streams needs to be integrated for sustainability of gravity irrigation systems.

Keywords: *Gravity irrigation, open channel, silt separation, hill streams, base flow augmentation*

PERFORMANCE EVALUATION OF GLOBAL ET DATASETS USING THE GOOGLE EARTH ENGINE FOR GROUNDWATER AND WATER RESOURCES APPLICATIONS

Richa Pandey*, Sukant Jain, Manish K. Nema and Ajay Ahirwar

National Institute of Hydrology, Roorkee, India
Corresponding author e-mail: richapandey018@gmail.com

Groundwater is the largest freshwater resource, available globally. It is vital for supporting food production and population sustenance. However, groundwater levels are declining in many arid and semi-arid regions, and climate change is likely to exacerbate these declines by increasing evapotranspiration and reducing precipitation, further depleting soil moisture. Several studies highlight the strong link between evapotranspiration (ET) and groundwater recharge, particularly in water-scanty regions to explain how altering ET statistics can influence groundwater recharge in semi-arid climates. Accurate quantification of ET is essential, as groundwater recharge often hinges on the small difference between rainfall and ET. ET directly affects groundwater levels by influencing soil moisture and recharge rates, directly linking atmospheric conditions to groundwater fluctuations. Recent advances in satellite and reanalysis-based datasets have enabled unprecedented improvement in ET assessments at a finer spatial and temporal resolution, though achieving reliable ET estimates requires careful selection of appropriate datasets and methodology.

This study aims to focus on the utilization and accuracy assessment of global ET datasets, available on Google Earth Engine (GEE) through site-pixel evaluation with the conventional Penman-Monteith approach in the semi-arid environment of the northern part of India. Long-term daily historical records of various climatic parameters for 31 years (1990–2020) at the research farm of the Indian Agricultural Research Institute (IARI), New Delhi were used to estimate reference evapotranspiration (ET_0) using the Penman-Monteith equation to serve as ground observations. Many of the remote sensing and reanalysis-based datasets are offered by many global agencies and are useful in detecting spatial and temporal variability in meteorological variables at a finer scale. The global evapotranspiration products viz. Global Land Data Assimilation System (GLDAS) V2.2, Penman-Monteith–Leuning Evapotranspiration V2 (PML_V2), the Terra Moderate Resolution Imaging Spectroradiometer (MODIS, MOD16A2GF) V6.1, Famine Early Warning Systems NETwork (FEWS NET) Land Data Assimilation System (FLDAS) ET and TerraClim ET available on Google Earth Engine (GEE) platform were used for the analysis. Performance evaluation is facilitated through the application of five statistical performance evaluation indices viz., Root Mean Square Error (RMSE), Coefficient of Determination (R^2), Bias (PBIAS), Nash-Sutcliffe Efficiency (NSE) and Index of agreement (d).

The results of this study revealed significant variations in the performance of global evapotranspiration datasets when compared to Penman-Monteith-based estimates in the semi-arid context of central Delhi. Among the ET datasets assessed - GLDAS, PML_V2, MODIS, FLDAS, and TerraClim, statistical indices showed varying levels of accuracy. PML_V2 dataset demonstrated the highest consistency with ground observations, as reflected by higher R^2 values and lower RMSE, making it the most reliable ET product for this region. MODIS-ET estimates generally overestimated ET, particularly during the peak summer months when temperatures are highest. This overestimation suggests that MODIS-ET is less accurate in

extreme heat conditions, possibly due to its spatial resolution limitations and sensitivity to temperature changes. The TerraClim ET dataset performed reasonably well during non-monsoon months, but it showed some discrepancies in periods of high evapotranspiration, primarily due to temperature sensitivity and its limited ability to capture evapotranspiration peaks accurately. This indicates that TerraClim is less reliable during the summer or when ET is at its highest. The GLDAS ET estimates showed good overall performance with a moderate NSE score. However, it tended to underestimate ET during the monsoon period when evapotranspiration is influenced by both rainfall and temperature fluctuations. The GLDAS dataset is less sensitive to rapid changes in ET, which might be due to its reliance on modeled rather than observed data for certain atmospheric variables. The FLDAS-ET dataset also performed relatively well, showing good agreement with observed data during the non-monsoon period. However, the FLDAS dataset struggled during peak evapotranspiration periods, especially in late spring and early summer, where it consistently underestimated ET rates. This discrepancy could be attributed to FLDAS's model configuration, which might not fully apprehend the intensity of seasonal evapotranspiration variability.

The study highlights that while global ET datasets, PML_V2, MODIS, GLDAS, FLDAS, and TerraClim, provide valuable tools for estimating evapotranspiration in arid and semi-arid regions, their accuracy can vary significantly. The PML_V2 dataset emerged as the most reliable for the study area, followed by GLDAS, which performed well but showed few underestimations during monsoon periods. FLDAS and TerraClim also provided useful information but demonstrated limitations during extreme evapotranspiration phases. MODIS overestimated ET, particularly in the hot season, due to resolution limitations. The outcomes from the present study can serve as a guiding document for researchers and investigators in selecting appropriate datasets for various water resource-related applications, including groundwater fluctuation patterns, drought monitoring, hydrological modelling, agricultural water management, and other related studies in semi-arid climatic zones of India.

Keywords: *Global ET products, GEE, groundwater resources, Penman-Monteith Equation, GLDAS*

EVALUATION OF IMPACT OF SHIFTING SOWING DATE ON GROUNDWATER BEHAVIOR IN RICE-WHEAT PLAIN OF NORTH-WEST INDIA

Pavan Kumar Harode[1]*, Satyendra Kumar[2], Vinod Kumar Tripathi[1], Deepak Kumar[1] and Vivekand[3]

[1]Department of Agricultural Engineering, I.A.S., BHU Varanasi, India
[2]ICAR-Central Soil Salinity Research Institute, Karnal, India
[3]McGill University, 21111 Lakeshore Road, Ste-Anne-de-Bellevue, QC H9X 3V9, Canada
**Corresponding author e-mail: pavankuharode@gmail.com*

Groundwater is one of the important components of hydrologic cycle, which is stored in aquifers, rock formations, and beneath soil. Particularly in areas with limited surface water supplies, it is an essential resource for industrial, agricultural, and drinking water uses. Its availability is affected by increasing industrial water demand, a change in land use, and weather patterns. In the dominant agricultural regions such as North-western Indo-Gangetic Plain region, increasing irrigation water demand is a major cause of steady decline of groundwater. In the region, approximately 85% of the land is used for crop cultivation, mostly for rice and wheat production. To ensure groundwater availability for future, development of sustainable agriculture water management practices is crucial to prevent groundwater over-extraction. In this study, four major rice-wheat dominant districts (Karnal, Kaithal, Panipat, and Kurukshetra) of Haryana were selected to evaluate impact of different planting dates on groundwater resources. The study used meteorological data from the ICAR-Central Soil Salinity Research Institute, Karnal, and CCSHAU RRS Kaul weather observatories for the period 2013–2021. Digital elevation model was collected from BHUVAN, while groundwater level data was received from the Groundwater Cell, I&WRD, Panchkula. Cropping pattern information was taken from the Land Use/Land Cover (ERIS) dataset, while hydrogeological and lithological data were obtained from the Central Ground Water Board (CGWB). Three rice-wheat crop planting dates scenarios that correspond to different sowing periods throughout the *Rabi* and *Kharif* season were studied: SWD-1 (sowing from June 15 to November 5), SWD-2 (June 15 to November 15), and SWD-3 (June 15 to November 25). Impact of these crop planting dates scenarios were assessed in the four districts using the AquaCrop model and MODFLOW model. AquaCrop Model was used for estimating irrigation demand and deep percolation for rice-wheat system. The estimated rice-wheat growing season irrigation depth and deep percolation was considered groundwater draft from crop land. Whereas groundwater demand and groundwater recharge from other land uses (forests, residential areas, water bodies, and barren lands) was estimated using the standard methodology (GEC, 2009).

Total groundwater recharge and draft from all land uses were calculated by considering the entire study area as a single hydrological unit. The Visual MODFLOW 6.1 model, a 3D tool, was used to examine the impact of different sowing dates on groundwater dynamics in unconfined aquifer systems. The aquifer depth in the study region ranges from 90 to 180 m, with an average hydraulic conductivity of 22 m per day and a storativity of 0.12. Boundary conditions, including specified flux and head-dependent parameters (e.g., river borders), were integrated into the model. No-flux conditions were applied to the northern, southern, and western boundaries due to the absence of physical boundary features. The aquifer system spans a geographical area of 7,736.18 km², divided into 7,496 cells with a uniform cell size of

1 km × 1 km. Data from 205 observation wells, representing the entire study region, were used for model calibration (2013–2017) and validation (2018–2021). Model calibration, conducted using the PEST auto-calibration tool, involved defining hydraulic conductivity zones and adjusting specific yield values. The calibrated hydraulic conductivity ranged from 15.75 to 110.28 m/day across the region.

The model demonstrated strong agreement between simulated and observed hydraulic heads, with a coefficient of determination (R^2) of 0.97 and a root mean square error (RMSE) of 4.72 m during the calibration period. During the validation period, the model maintained strong performance, with $R^2 = 0.93$ and RMSE = 7.20 m. In 2013, the average water table depth was 23.5 m of the region, which decreased by 2.55 m, 3.88 m, and 5.58 m under crop planting scenarios SWD-1, SWD-2, and SWD-3, respectively, by 2021. Corresponding annual water table decline rates were 28.38 cm, 43.13 cm, and 62.05 cm. Among the scenarios, SWD-1 rice-wheat crop planting scenario (June 15 to November 5) proved to be the most effective in sustaining groundwater resources and agricultural productivity. The study concludes by underlining the importance of sustainable crop management to manage groundwater in agriculturally dominated regions. The findings provide a strong scientific basis for formulating crop management strategies and policies that ensure sustainable groundwater use while maintaining agricultural productivity.

Keywords: *Modflow, groundwater, variable sowing date, aqua crop*

EVALUATING METEOROLOGICAL AND GROUNDWATER DROUGHTS IN BIHAR STATE, INDIA

Shubham Shaurabh[1*] and Sachidanand Kumar[2]

[1]Centre for Flood Management Studies, Patna, National Institute of Hydrology, India
[2]Karnpura Construction Private Limited, Jharkhand, India
[*]Corresponding author e-mail: sshubham.nihr@gov.in

The study examines the dynamics of drought and groundwater responses in ten cities of Bihar by employing meteorological and groundwater drought indices. Using the Standardized Precipitation Index (SPI) and Standardized Precipitation Evapotranspiration Index (SPEI), drought conditions were analyzed for the historical period from 1981 to 2023. Future projections for 2025–2100 were explored under two Shared Socioeconomic Pathway (SSP) scenarios: SSP245, representing a moderate climate change trajectory, and SSP585, indicating a severe trajectory. To complement this analysis, the Standardized Groundwater Level Index (SGI) was derived from groundwater depth data collected from 15 observation wells, with data sourced from the Bihar State Groundwater Board and the Central Ground Water Board (CGWB). The study further investigates the relationship between meteorological drought indices and groundwater levels to understand how droughts influence groundwater resources across Bihar. The historical analysis reveals a clear increasing trend in drought severity, particularly after 2015, with notable changes observed on a 12-month time scale. Among the indices, SPEI consistently indicates more severe drought conditions compared to SPI across all studied locations. This difference is attributed to SPEI's ability to incorporate evapotranspiration, making it more sensitive to temperature-driven changes in drought severity. The findings show that the frequency and intensity of drought events have escalated in recent years, highlighting a growing vulnerability to drought in Bihar. Projections under the SSP scenarios provide valuable insights into the future evolution of drought conditions in the region. Under the severe SSP585 scenario, drying trends are dominant up to 2050, with several locations experiencing prolonged and intensified drought periods. However, a noticeable shift towards wetting trends is projected for the post-2050 period in some locations, with extreme wet conditions (SPI > 2) becoming increasingly prevalent towards the end of the study period. In contrast, SSP245 projects milder drought conditions throughout the future period, suggesting that moderate climate action could significantly mitigate the severity of drought impacts. Both SPI-12 and SPEI-12 indices suggest that most locations will face mild drought conditions in the near future (2023–2050), transitioning to prominently wet conditions in the far future (2051–2100). This shift in hydrological conditions underscores the importance of adapting water management strategies to cope with both drought and extreme wet events. Trend analysis, conducted using the Mann-Kendall test and Sen's slope estimator, confirms the observed changes in drought severity and frequency. These robust statistical tools provide reliable evidence of the increasing trend in drought conditions during the historical period and the complex patterns projected under future climate scenarios. The analysis emphasizes the need for proactive measures to address the impacts of these changing trends on water resources and agricultural systems in Bihar.

The spatial and temporal distribution of SGI highlights areas within Bihar that are particularly prone to critical groundwater drought conditions. These locations exhibit significant declines in groundwater levels, reflecting the combined impact of reduced precipitation, increased evapotranspiration, and over-extraction of groundwater. Groundwater depletion in these areas poses a severe challenge to water security, particularly during prolonged drought periods when dependence on groundwater resources intensifies. The integration of SGI with meteorological drought indices enables a comprehensive understanding of the interaction between drought and groundwater resources, providing a valuable framework for monitoring and managing groundwater in drought-prone regions. Establishing the relationship between groundwater levels and meteorological drought indicators is a significant contribution of this study. By correlating SPI, SPEI, and SGI, the study demonstrates how readily available meteorological drought indices can be used to estimate groundwater levels during drought conditions. This relationship offers a practical tool for water managers and policymakers to anticipate groundwater stress based on drought forecasts, enabling timely interventions to mitigate the impacts of water scarcity. Moreover, the study highlights the critical role of groundwater level monitoring in understanding the broader implications of drought on water resources. The findings also address a critical gap in the current understanding of drought-groundwater interactions. While meteorological drought indices provide a broad overview of precipitation and evapotranspiration trends, their impact on groundwater resources is influenced by several region-specific factors, including aquifer characteristics, land use patterns, and water extraction practices. This study underscores the need for region-specific investigations to accurately capture the dynamics of groundwater response to drought. Such insights are essential for developing effective groundwater management strategies that are tailored to the unique conditions of each region. Additionally, the research emphasizes the importance of long-term monitoring of groundwater levels and the integration of hydrological data with climate projections. As climate change intensifies, the frequency and severity of extreme weather events, including droughts, are expected to increase, posing significant risks to water security. This study provides a framework for understanding how groundwater resources are likely to respond to these changes, offering valuable guidance for sustainable water management in Bihar and similar regions. In conclusion, this study provides a comprehensive assessment of drought dynamics and groundwater responses in Bihar State, integrating historical trends and future projections under different SSP scenarios. The findings reveal an alarming increase in drought severity in recent years and highlight the potential for extreme wet conditions in the future, particularly under SSP585. By linking meteorological drought indices with groundwater levels, the research offers practical tools for water resource management and underscores the need for region-specific strategies to address the complex challenges posed by climate change. The insights gained from this study can inform policies aimed at enhancing the resilience of water resources and agricultural systems in Bihar, contributing to sustainable development in the face of a changing climate.

Keywords: *Drought assessment, SPI, SPEI, groundwater dynamics, climate change*

EVALUATION OF SPATIO-TEMPORAL VARIABILITY OF GROUNDWATER QUALITY FOR IRRIGATIONAL SUITABILITY AND ITS RELATION WITH CLIMATOLOGICAL PARAMETERS IN PONDICHERRY REGION, INDIA

Reshma Susan Jacob[1], Joji V.S.[1*], M. Sivakumar[2] and Divya A.S.[1]

[1]*Department of Marine Geology and Geophysics, School of Marine Sciences, CUSAT, India*
[2]*Central Ground Water Board, South Eastern Costal Region, Chennai, Tamil Nadu, India*
[*]*Corresponding author e-mail: jojivsdeepam@gmail.com*

Water is essential for all life on Earth, but only a tiny of portion about 2.5% of the world's total water supply is freshwater that can be used for drinking, agriculture, and industry. Many densely populated coastal regions worldwide struggle with freshwater shortages and are heavily dependent on groundwater. Climate change is worsening the pressure on these limited freshwater resources, leading to potential social conflicts as a result of erratic rainfall, rising demand, and overuse of scarce supplies. The current study centres on Pondicherry (293 sq.km), a Region that depends heavily on groundwater for drinking and agricultural needs and is increasingly exploiting deeper aquifers (over 60 meters below ground level). The primary objective is to assess the suitability of groundwater for irrigation by using graphical techniques and calculating index values. The study also graphically compares the past agricultural scenario of the Pondicherry region. The rainfall frequency and atmospheric temperature play a significant role in the present stage of development of the groundwater and its movement. This includes employing visual tools like Wilcox diagrams and US Salinity Laboratory diagrams to interpret water quality data, providing a comprehensive evaluation of its irrigation potential.

To evaluate the spatio-temporal variability of groundwater during the year 2022, a total of 62 samples were collected from various places that encompassed the entire study area with depth ranging from 2 to 104 mbgl. The pH, EC, and TDS values were determined by pH meter, EC meter and TDS meter respectively. Major cations (Ca, Mg, Na, K) were analysed using an ICP-mass spectrometer. The sulphate (SO_4) was analysed by spectrophotometric approach, nitrate (NO_3) ion chromatography, chloride (Cl) volumetric titration and carbonate (CO_3) were assessed using Portamess through titration techniques involving HCl, phenolphthalein, and methyl orange. The irrigation suitability was determined using Sodium Absorption Ratio (SAR), Percent Sodium (%Na), Residual Sodium Carbonate (RSC), Magnesium Ratio (MR) and Kelley's Index (KI). The temperature and rainfall data from 2010 to 2022 of Pondicherry Region was correlated with hydrochemistry of the ground water samples. The temperature and rainfall data were obtained from the Central Groundwater Board, South Eastern Coastal Region, Chennai.

Water and soil characteristics are crucial for plant growth. Using poor-quality water for irrigation can negatively impact crop yield. Intensive agricultural practices like the use of fertilizers, pesticides, and insecticides, can significantly affect groundwater quality. According to the USSL salinity diagram, most samples fell within the C3S1 (low SAR, high EC) and C2S1 (low SAR, medium EC) categories. Based on SAR classification, the majority of the water samples are considered excellent for irrigation. In the study area, 46.1% of samples (from Kariyamanikkam, Kalmandapam, and Kurumbapet) fall within good to acceptable levels for agricultural use based on % Na, while 30.2% are rated as exceptional (from Parikkalpattu, Kirumampakkam, and Kaduvanur). About 12.4% of samples from

Netaji Nagar, Thengaithittu, and Thuthipet are either unsuitable or questionable for agricultural practices, and 3.4% are entirely unsuitable (from Thirukkanur and Sellipet). As per Doneen's Permeability Index, most samples fall into Classes 1 and 2, indicating that the water is only marginally suitable for agricultural use. Most samples (98%) showed negative RSC values, suggesting a low risk of sodium accumulation. With a maximum MAR value of 38 meq/L, the water falls within the optimal range for irrigation. Regarding KI, 11.1% of samples are unsuitable for irrigation in the study area. Spatially, 35%, 50%, and 25% of the area is classified as good, moderate, and poor respectively. When comparing pre- and post-monsoon seasons (PRM and POM), about 52% of the area remains in the good category, with noticeable declines in the moderate (50-40%) and poor (15-8%) categories after the monsoon. Rainfall is the primary source of groundwater recharge in Pondicherry, with 63% of the rainfall contributing from the northeast monsoon (October to December) and 29% southwest monsoon (June to September). It is noticed that the maximum temperature (32°) experienced in PRM with minimum rainfall of 41mm. The maximum rainfall experienced during POM (1102.8mm) with a minimum temperature of 29°C. The higher rainfall and lower temperature cause groundwater dilution, making it more suitable for irrigation. The study also found a good correlation (correlation coefficient, r=0.93) between Cl^- and Na^+, particularly in the Muthialpet area, which covers about 8% of the total area, indicating the presence of marine water intrusion.

The study reveals that groundwater quality in the Pondicherry region is generally suitable for agricultural purposes, with most samples falling within good to acceptable ranges for irrigation. The majority of water samples, classified based on SAR and RSC, indicate minimal risk of sodium accumulation, and a significant area (46.1%) is ideal for agricultural purposes. The study also highlights spatial variability, with 35% of the area classified as good, though this improves during the POM. The PRM temperature peaks at 32°C with 41mm of rainfall, while the POM experiences 29°C with 1102.8mm of rain. The increased rainfall and lower temperature in the POM enhance groundwater dilution, making it better for irrigation. However, a notable concern is the marine water intrusion in the Muthialpet area, which affects approximately 8% of the region. Overall, the findings underscore the importance of managing groundwater resources to ensure their sustainability for agriculture, particularly in light of seasonal fluctuations and potential contamination. These results highlight the need for targeted management practices to address localised issues like high bicarbonate levels and saline water intrusion, to maintain the viability of groundwater for agricultural and potable purposes.

Keywords: *Deeper aquifer, irrigational suitability, climatological parameters, spatio-temporal variability, Puducherry*

A MULTI-INDICATOR RETROSPECTIVE ANALYSIS OF GROUNDWATER DROUGHT DYNAMICS IN CENTRAL INDIA

Ruchir Patidar[1,2*], Santosh M. Pingale[1], Deepak Khare[2] and Sourav Choudhary[2]

1National Institute of Hydrology, Roorkee, India
2Department of Water Resources Development and Management, Indian Institute of Technology Roorkee, India
**Corresponding author e-mail: ruchirp.nihr@gov.in*

Groundwater drought is an intricate phenomenon arising from the interplay of multiple factors, including climate variability, terrestrial water storage (TWS) anomalies, and land-use dynamics. Unlike surface water droughts, which are often visible and more immediate, groundwater droughts are subtle and can persist for years due to the slow response of aquifers to climatic and anthropogenic stresses. This complexity underscores the need for a nuanced understanding of groundwater dynamics, particularly in regions like central India, which are highly dependent on groundwater resources for agricultural, domestic, and industrial needs. The region is also characterized by semi-arid conditions and recurrent droughts, exacerbated by climate change, over-extraction, and unsustainable land-use practices. Central India's vulnerability to groundwater depletion and drought-related stress necessitates a robust assessment framework. Traditional methods of groundwater monitoring, such as well observations, often lack the spatial and temporal resolution needed for comprehensive analysis. The advent of satellite-based remote sensing techniques, such as those provided by the Gravity Recovery and Climate Experiment (GRACE) mission, offers unprecedented opportunities to monitor groundwater storage changes over large areas with high temporal resolution. GRACE measures changes in Earth's gravity field, enabling the estimation of TWS anomalies, which include groundwater, soil moisture, and surface water storage. However, isolating groundwater storage from TWS requires careful subtraction of other hydrological components, such as soil moisture and surface water.

This study employs GRACE-derived TWS data alongside ERA5 soil moisture datasets to develop a novel GRACE-based Groundwater Drought Index (GGDI) for central India. Covering the period from 2002 to 2022, the GGDI captures the temporal and spatial dynamics of groundwater drought, offering insights into the severity, duration, and recurrence of groundwater deficits. By incorporating ERA5 soil moisture data, which provides a high-resolution reanalysis of land surface hydrology, the study ensures a more accurate estimation of groundwater variability. The GGDI thus serves as a reliable indicator of groundwater drought, bridging gaps in traditional monitoring methods. Furthermore, the study examines the interrelationships between groundwater variability and climate-induced drought indices, such as the Standardized Precipitation-Evapotranspiration Index (SPEI). SPEI, calculated at multiple timescales, reflects the balance between precipitation and atmospheric demand for water (evapotranspiration), making it a valuable metric for assessing meteorological and agricultural droughts. By comparing SPEI with GGDI, the study aims to unravel the temporal lag between meteorological drought and its impact on groundwater. This lagged response is critical for understanding how prolonged dry periods and extreme weather events contribute to groundwater depletion over time.

In addition to climate-based indices, the study integrates vegetation indices—specifically the Normalized Difference Vegetation Index (NDVI) and Enhanced Vegetation Index (EVI)—to

assess the ecological implications of groundwater drought. Vegetation indices derived from remote sensing reflect the health and productivity of plant cover, which is closely tied to water availability. The relationships between GGDI and vegetation indices provide valuable insights into how groundwater drought impacts ecosystem health, agricultural productivity, and land surface processes. This multi-faceted approach ensures a holistic view of hydrological drought attributes, encompassing groundwater, climate, and ecological dimensions. The GGDI reveals significant interannual variability in groundwater storage, with pronounced drought events in 2009, 2015, and 2018 coinciding with major meteorological droughts. A lagged response of 4–8 months between SPEI and GGDI underscores the delayed impact of climate variability on groundwater resources. The comparative analysis indicates moderate to strong correlations between GGDI and SPEI at longer timescales (9–12 months), highlighting the cumulative effect of prolonged dry spells on groundwater storage. NDVI and EVI exhibit seasonal fluctuations but show significant declines during severe groundwater drought periods. This relationship emphasizes the role of groundwater as a crucial determinant of vegetation health in semi-arid regions. The spatial analysis reveals hotspots of groundwater depletion in regions with intensive agriculture and over-reliance on irrigation, aligning with known areas of groundwater stress.

The results of this study have significant implications for water resource management and drought mitigation strategies in central India. By revealing spatial hotspots of groundwater drought and their temporal evolution, the GGDI offers a powerful tool for identifying areas at greatest risk. The comparative analysis with SPEI provides actionable insights into the interplay between climate and groundwater systems, highlighting the need for integrated management approaches that address both immediate and lagged impacts of drought. Additionally, the linkages with vegetation indices emphasize the broader ecological consequences of groundwater depletion, underscoring the need for sustainable groundwater use to support ecosystems and livelihoods. This research advances the understanding of groundwater drought dynamics in central India, contributing to the global discourse on sustainable water management. By leveraging satellite data, climate indices, and vegetation metrics, it bridges the gap between scientific analysis and practical applications, paving the way for more resilient and adaptive water resource policies. The comprehensive insights offered by the GGDI can inform decision-makers, researchers, and stakeholders in devising strategies to mitigate the impacts of drought and ensure the long-term sustainability of groundwater resources.

Keywords: *Groundwater drought, GRACE, Vegetation indices, SPEI, Central India*

APPROACHES TO EVAPOTRANSPIRATION PARTITIONING: INSIGHTS ON ISOTOPE BASED EVALUATION METHOD

Anushka[1]*, Gopal Krishan[2], Arif Ahamad[1] and M.S. Rao[2]

[1]Jamia Millia Islamia University, New Delhi
[2]National Institute of Hydrology, Roorkee, Uttarakhand, India
**Corresponding author e-mail: chandanushka83@gmail.com*

Evapotranspiration (ET) is a fundamental component of the hydrological cycle, representing the total water loss from a surface through both transpiration (T) by plants and evaporation (E) from the soil. Understanding how ET partitions into these components is crucial for efficient water resource management, particularly in agriculture, where it directly impacts crop water requirements and productivity. The T/ET ratio, indicating the proportion of water lost through transpiration relative to total ET, is an essential measure of water use efficiency (WUE) in plants. Transpiration supports photosynthesis and crop yield, while evaporation, which does not contribute to productivity, should be minimized for effective water conservation. Several methods have been developed to partition ET into its components. This paper reviews methodologies for partitioning evapotranspiration (ET) into crop transpiration (T) and soil evaporation (E), focusing on their role in eco-hydrology, crop water requirements, and sustainable agricultural practices. Various techniques have been developed to partition evapotranspiration (ET) into its components, with isotopic methods being one of the key approaches. These methods leverage stable water isotopes, particularly ^{18}O and ^{2}H, which exhibit different rates of fractionation during evaporation and transpiration, allowing differentiation between the two processes. Early studies laid the foundation for using isotopic signatures to partition ET, with significant advancements through the Keeling plot method, which enhanced measurement precision. Over time, tools like the Craig-Gordon model and laser-based analysers have further improved accuracy, achieving 10-20% precision in controlled conditions despite their high cost and complexity.

Isotopic methods exploit the distinct fractionation effects of evaporation and transpiration. Evaporation enriches the remaining water in heavier isotopes, while transpiration shows minimal fractionation as the water taken up by plants undergoes little isotopic change. This difference is quantified through mass balance equations, which estimate the contributions of each process to total ET. The method has evolved since its inception in the 1950s, with innovations like the Craig-Gordon model and Keeling plots providing frameworks for ET partitioning across ecosystems. Measurements of $\delta^{18}O$ and $\delta^{2}H$, along with d-excess and lc-excess, offer a more accurate partitioning by accounting for both kinetic and equilibrium fractionation effects. Distinct isotopic signatures of water vapor to partition ET, addressing isotopic fractionation, where lighter isotopes evaporate more readily, while transpiration exhibits minimal fractionation. The partitioning follows a mass balance equation: ET=E+T and $\delta ET = f_E \cdot \delta_E + f_T \cdot \delta_T$, where δET is the isotopic composition of total ET, f_E and f_T are the fractions of E and T, and δE and δT are their respective isotopic compositions. Global studies have enhanced our understanding of ET partitioning. For example, in China's Shiyang River Basin, T/ET ratios ranged from 71% to 96%, with an average of 87%, varying significantly with irrigation events. In India, isotopic analysis has revealed post-monsoon enrichment and moisture depletion during the monsoon, with delayed responses in deep-rooted plants. Similar insights from regions like Austria, Morocco, and the USA have highlighted the impact of irrigation and drought on soil and plant water uptake. Despite the use of advanced tools for ET assessments, research on ET partitioning in India remains limited. There is a significant gap in applying these advanced methods, necessitating multidisciplinary approaches tailored to local agricultural contexts. Translating research into actionable water management policies is crucial for enhancing India's contribution to global water resource management.

Global synthesis studies estimate that transpiration accounts for 61 ± 15% of total ET, challenging earlier assumptions about the dominance of evaporation. This ratio varies with vegetation type and climate, increasing from dry-land habitats (51%) to tropical rainforests (70%), emphasizing the role of vegetation in water dynamics. Technological advancements have improved isotopic analysis. Early methods like cold-trapping were labour-intensive and lacked temporal resolution. The development of laser spectroscopy in the 2000s enabled high-resolution, real-time measurements, allowing for continuous monitoring of ET components. CRDS has facilitated in situ, high-frequency measurements, enhancing isotopic data collection in field studies. Sampling for isotopic analysis involves the extraction of water from soil, plants, and atmospheric vapor. Soil water extraction uses vacuum distillation or cryogenic methods, while plant water is obtained through cryogenic vacuum distillation or by sealing leaves in bags. Atmospheric water vapor is captured using cold traps or ice cones. CRDS enables continuous monitoring of vapor isotopes, crucial for tracking diurnal and event-driven changes. Multiple sampling heights are required for Keeling plots.

This research aims to optimize irrigation practices using stable isotopes, with techniques like the Craig-Gordon model and Keeling plots being employed for detailed analysis. Studies are also underway to analyse groundwater, precipitation, and soil water, with a focus on understanding ET components and how drought conditions impact evaporation-transpiration (E/T) ratios. The approach combines field experiments with isotopic analysis to assess water balance in river basins and agricultural areas. Experiments are also being conducted to explore how different crop species and soil types affect the isotopic composition of water, influencing ET partitioning. These studies also consider the impact of land use changes on ET components, and isotopic composition of rainfall, groundwater, and plant water to understand ET dynamics in various climatic regions. Future directions include expanding the use of portable isotopic analysers for field studies across different Indian ecosystems, enhancing collaboration between institutions to pool resources and data for larger-scale studies, and applying isotopic data to water resource management, particularly in the context of climate change and agriculture. These research efforts contribute significantly to both local and global understandings of water cycle dynamics, showcasing South Asia's unique hydrological characteristics while reinforcing universal hydrological principles.

Keywords: *Evapotranspiration, water use efficiency, isotopic techniques, energy balance models, soil evaporation, plant transpiration*

CONJUNCTIVE USE PLANNING OF GROUNDWATER AND SURFACE WATER TO DETERMINE OPTIMAL CROPPING PATTERN

Vipul Kumar Rai[1*], Brijesh Kumar Yadav[1] and Swati Sirsant[3]

[1]*Department of Hydrology, Indian Institute of Technology, Roorkee, India*
[3]*Department of Civil Engineering, Nirma University, Gujarat, India*
[*]*Corresponding author e-mail vipul_kr@hy.iitr.ac.in*

Increasing population and its consequent demand for water is also increasing which poses a major issue in the context of adequacy of supply as per water demand. One of the major sectors facing the lack of supplies is the agricultural sector. Moreover, the changes observed in the climatic conditions in the recent years gave rise to a major decline in the availability of surface water and groundwater resources. In India, the availability of subsurface and surface water sources is 432 BCM and 690 BCM, respectively. While the annual water demand for the nation is predicted to be double by 2050 than the demand in 2000. According to the 2011 census, the availability of water per capita per year was 1614 m^3, while this number is predicted to reduce to a value of 1137 cubic meters by 2065. Different solutions to this problem are being investigated from decades and the most efficient way to deal with it has emerged as the conjunctive use of surface water and ground water. The coordinated and planned use of surface water and groundwater resources together is said to be conjunctive use. Several SWOT analyses (strength, weakness, opportunities, and Threats) have been conducted on the conjunctive use strategies and it has been found out that it is a very useful first predictive cum approximation tool which can further be used for analysing the problem more specifically and carrying out cost benefit analysis which help in making the decision-making ability more comprehensive. The study explores the use of genetic programming within a conjunctive water use framework in order to determine an optimal cropping pattern for culturable command area of 58750 ha located in the Tapi district of Gujarat, India. The majority of the area comes under the command of the Kakrapar Right bank main canal situated 30 km downstream of the Ukai dam constructed over the Tapi river. The primary objective of the model is to maximize the net benefits obtained from different crops while keeping constraints on land availability, water demands, and minimum cropping area allocated to each crop. This will further help to make a decision-support framework that will eventually enhance the water use efficiency for the agricultural system while minimizing the environmental impacts as well as inequalities due to socio-economic factors. The study in the initial stage involves assessment of the resources present in the region. This involves quantitative estimation of groundwater and surface water resources, existing agricultural patterns of the study area, suitability of the soil, current water demands etc. The data collection involves field measurements, satellite imageries and consultations by the stakeholders in order to get a holistic understanding of the area under consideration. The inputs to the model include water availabilities from different resources, meteorological data, crop data and economic data which includes market prices, pumping costs, cultivation costs etc. The methodological framework consists of generating an initial solution and evaluating its fitness, followed by selection of best solution, crossover, mutation and finding out the optimal solution. A 20% variation from previously allocated crop area is permitted in order to fulfil the minimum crop water requirements and a cost-benefit function is also formed for finding out the optimal results. While the use of CROPWAT 8.0 enables to account for the evapotranspiration needs considering threshold temperatures, humidity, rainfall, soil characteristics and crop coefficients for different crops for finding out the crop-water requirements which after defining the cropping pattern provides the net irrigation water requirements. The results obtained showed that opting the conjunctive use plan is both feasible and equitable for finding out an optimal cropping pattern. The net benefits thus obtained from the optimal allocation of land using the genetic algorithm increased by 35% at 100% water availability with no water stressed conditions compared to the initial allocation strategy. While, in the water stressed conditions the net benefits after optimal allocation of cultivable land increased by 28% and 24% at 90% and 75% water availability respectively. The majority of the land was allocated to sugarcane crop due to its high net returns followed by paddy and wheat. The cropping pattern was fractioned into five parts namely Kharif, Rabi, two-seasonal, hot-weather and perennial crops. The results also showed that in the months of June to September the acquisition of land from different crops was at peak covering almost all of the available cultivable area. The constraints were satisfied and the water demand for crops was always less than the available water for irrigation. The study's outcomes underlined the potential of conjunctive optimization models in addressing the challenges faced by the agricultural sector due to limited resource availability and sustainable management of water resources. The developed framework is a powerful tool for the policy making authorities and regulating bodies offering them the insights for designing sustainable water allocation strategies which focuses on environmental conservation objectives as well as fulfilling the economic development goals. The study also provides a notable contribution addressing the trade-offs between economic gains, environmental sustainability while ensuring the livelihoods of the farming communities.

Keywords: *Conjunctive use, genetic algorithm, optimal cropping pattern, irrigation water requirements*

ESTIMATION OF GROUNDWATER RECHARGE FOR SHALLOW AQUIFERS IN GANGA-YAMUNA DOAB REGION USING HYDRUS-1D AND IWTF METHOD

Mayank Raturi[1], Nitesh Patidar[2]* and Deepak Khare[1]

[1]*Department of Water Resources Development and Management, Indian Institute of Technology Roorkee, India*
[2]*National Institute of Hydrology Roorkee, India*
**Corresponding author e-mail: npatidar.nihr@gov.in*

Groundwater plays a key role in irrigation and domestic needs across the globe, specifically in areas with high agricultural activity and population density. Due to rapid urbanization and over-drafting for intensive agricultural activities and industrial use, groundwater is becoming increasingly limited in many regions worldwide, particularly in countries with arid and semi-arid climates. The excessive extraction of groundwater, primarily for irrigation, has resulted in significant depletion in groundwater levels. Therefore, sustainable groundwater practices, reclamation, and artificial groundwater recharge are very important to solve such problems. Knowledge of groundwater recharge is essential for the sustainable management of groundwater. However, the complexity of groundwater systems, along with the scarcity of observed data and challenges of selecting appropriate estimation methods, makes with task difficult. Traditional methods, like the Water Table Fluctuation (WTF) method, are often inadequate in regions with high variability in recharge due to irrigation, land use, and uneven monsoon patterns. To overcome these limitations, this study employs a combination of HYDRUS-1D simulation (HS) and an improved water table fluctuation method to estimate groundwater recharge in the Ganga-Yamuna Doab region. The Ganga-Yamuna Doab region has a total surface area of 57,467 km^2. It covers a total of 42 districts of Delhi, Uttar Pradesh, Haryana and Uttarakhand. The average annual rainfall of the study area is 654 mm. Silt and loam with low organic content are the dominating soil types in the region. Major aquifers in the region are older alluvium and younger alluvium. Firstly, HYDRUS-1D software is used to simulate the vertical movement of water in the soil column. Hydrus-1D is a free and open-source Windows-based modeling environment for analysis of water flow and solute transport in variably saturated porous media. It was developed by Jirka Šimůnek in 1990. This model applies Richard's equation, van Genuchten formula, and Feddes formula to simulate the vertical movement of water under varying boundary conditions. Soil and rainfall data were imported into the HYDRUS-1D model to construct a conceptual model that is a close representation of the field conditions. The model uses flexible time steps to simulate the movement of water through the soil column and generate bottom flux, which is the potential recharge infiltrating through the soil column. The bottom flux obtained from HS is used with the corresponding groundwater level to calculate specific yield. The improved WTF method was then applied to calculate groundwater recharge, which addresses the limitations of the traditional WTF methods. Particularly, the traditional WTF method is not efficient in estimating the groundwater recharge accurately when the groundwater table is stable or declining, as it hypothesizes no recharge under these conditions. The improved WTF method overcomes this limitation by taking into account the impact of factors like groundwater table fluctuations, lateral flow, and pumping. The application of HYDRUS-1D and the improved WTF method offers a comparative analysis of two different approaches. The output of this study highlights the major differences between the groundwater recharge estimate obtained using HS and the improved WTF method, highlighting the importance of incorporating advanced tools and correction for anthropogenic variability. The outcomes of this study emphasize the improved WTF method and its suitability for regions like Ganga-Yamuna Doab, where traditional approaches may fall short in capturing the dynamics of recharge processes. This study provides valuable insights into sustainable groundwater management. The methods and results can be extended to similar regions facing challenges in recharge assessment, enabling better planning and conservation of groundwater resources.

Keywords: *Groundwater, groundwater recharge, HYDRUS, water table, simulations*