Theme 1
Vision 2047

IMPACT OF CLIMATE CHANGE ON GROUNDWATER AND ADAPTATION MEASURES

IMPACT OF CLIMATE CHANGE ON GROUNDWATER RESOURCES OF HAROHAR BASIN, LOWER GANGA PLAIN, INDIA

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Groundwater is a crucial resource that fulfills essential needs such as drinking, industrial and agricultural purposes. In recent years, reliance on groundwater has surged, driven largely by the pollution of surface-water sources. Consequently, the quality and quantity of groundwater are deteriorating, primarily due to the population growth, which has propelled humanity into the Anthropocene era and exacerbated climate change. This transformation represents an undeniable reality, significantly affecting the availability of water resources worldwide. Climate change alters the physio-chemical characteristics of groundwater, making it imperative to understand these influences for effective management of global water markets. For India, home to over 1.37 billion people, the management of groundwater is vital for achieving the Sustainable Development Goals (SDGs), particularly in ensuring universal access to safe and clean water. Systematic evaluation and assessment of groundwater resources at the regional level are essential for sustainable management practices. These efforts are pivotal to achieving SDGs targets by 2030, fostering resilience in water systems and promoting equitable access. As the world faces increasing water challenges, prioritizing groundwater resource management will be crucial for sustaining communities and ecosystem. Therefore, In the present study, the impact of climate change on the Kiul-Harohar river basin in lower Ganga plain has been carried out to understand the effect of climate change on groundwater resources of the basin using satellite data, hydro-meteorological and hydro-geological data.

The basin is a tributary of Ganga River basin and covering a total area of around 17157 km^2 of Bihar and Jharkhand. The basin receives an average annual rainfall of 1,104 mm, which plays a critical role in shaping its hydrological dynamics. However, the Kiul-Harohar basin faces significant challenges related to groundwater availability and sustainability, exacerbated by over-exploitation of groundwater resources, increasing agricultural demands and irregular precipitation patterns. Kiul-Harohar river basin characterized by its unique geological formation comprises of Quaternary alluvium, underlain by Proterozoic Chotanagpur Gneissic Complex, the Bihar Mica Belt (Paleo-Mesoproterozoic), Neoproterozoic intrusive granites, Mesoproterozoic rocks of the Munger Group, Archean-Paleoproterozoic metamorphic rocks, and Lower Gondwana formations (Late Carboniferous to Permian). Geomorphologically the basin has diversified geomorphological features including alluvial plains, floodplains, denudational hills and plateaus, structural hills, along with many natural lakes and surface water bodies. The region is particularly vulnerable to drought and flooding, resulting in recurring water shortages that threaten both agricultural and domestic water supplies.

The study employs GIS tools and satellite data to analyze various factors affecting the groundwater resources of the basin including vegetation patterns, altered precipitation, changes in land surface temperatures and shifting evapotranspiration rates. The study results reveals that the rising surface temperature are intensifying evapotranspiration (ET) rates

while decreasing groundwater recharge. Simultaneously, unpredictable rainfall patterns are accelerating aquifer depletion and lowering groundwater levels. The increasing frequency and severity of droughts and other extreme weather events further exacerbate pressure on groundwater reserves, compelling unsustainable extraction practices to meet rising agricultural and domestic water demands. To assess the impact of climate change on groundwater resources of the basin, the important climatic variables such as precipitation (PT), land surface temperature (LST), ET and vegetation patterns along with groundwater level have been analyzed from 2004 to 2023. The spatial and temporal relation with various parameters such as LST, ET, PT, NDVI and groundwater have been carried out to understand the impact on water resources of the basin for the year 2004, 2013 and 2023. All the factors have been mapped using the data collected from various sources including groundwater levels, precipitation from the IMD and LST, ET, and Normalized Difference Vegetation Index (NDVI) data from NASA's MODIS products. The LST, ET, and NDVI data for the basin have been extracted through rescaling and reprojecting raster images using ArcGIS 10.8.2 software. In the first decade from 2004 to 2013, the average NDVI values have been found decline from 0.31 to 0.28. The mean annual LST also showed increasing trend. The change in temperature is closely associated with precipitation and groundwater levels changes over the years. The NDVI values, LST, ET, PT and groundwater level have positive relation. Based on the groundwater dynamic and interaction among temperature, vegetation health, and groundwater resources underscores positive relationships governing the groundwater availability in the Kiul-Harohar basin. Understanding these interactions is essential for developing effective strategies for sustainable groundwater management under changing climatic conditions. To ensure responsible groundwater use, implementing integrated groundwater resource management strategies is crucial. Policymakers and stakeholders must collaborate to create adaptive approaches that address climate variability, while advancing the Sustainable Development Goals.

Keywords: *Groundwater, climate change, Kiul-Harohar basin, NDVI, LST, remote sensing & GIS*

INSIGHT INTO GROUNDWATER VARIABILITY IN NORTH INDIA USING GRACE OBSERVATIONS: ROLE OF CLIMATIC AND SOCIO-ECONOMIC FACTORS

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Groundwater depletion is a global concern due to the large dependency of domestic and agricultural use of it. Between 1950 and 2000, annual groundwater extraction in North India increased dramatically from 25 to 200 km^3/year, making it one of the leading countries in terms of extraction rates. Recent studies indicate that human activities are contributing to groundwater depletion in northern India, especially in the states of Rajasthan, Punjab, Haryana, and Uttar Pradesh. The studies suggested that if current trends persist, 60% of aquifers could reach critical levels within the next two decades. Regular monitoring of changes in groundwater storage is essential for effective sustainable management of groundwater resources. In this study, we have investigated the spatiotemporal changes in groundwater storage in northern India from 2002 to 2023 by analyzing GRACE/FO RL06 mascon solutions for terrestrial water storage (TWS), GLDAS datasets, groundwater levels, rainfall, surface air temperature, population statistics, tubewell data and agricultural information. We reconstructed the TWS time series using singular spectrum analysis (SSA) to fill the gaps and apply the Mann-Kendall (MK) test with the Sen slope estimator, along with Standardized Precipitation Index (SPI) and change point analyses. The goals of this study are: i) to quantify the variability of groundwater storage over the past two decades at different scales, ii) to examine how these changes are related to climatic factors like rainfall and temperature, as well as human activities such as population growth, tubewell distribution, and the extent of irrigated areas, and iii) to evaluate the influence of aquifer heterogeneity on spatial trends. We have performed a spatiotemporal trend analysis of groundwater storage (GWS), groundwater levels (GWL), rainfall, surface air temperature, and tubewell distribution. To assess the variations in groundwater storage, we have employed several methods such as addressing gaps in the GRACE TWS data using singular spectrum analysis (SSA), calculating groundwater storage anomalies (GWSA) with the filled TWSA and GLDAS model, performed trend analysis of hydrological and climatic variables using the MK test and Sen's slope estimator, and utilized SPI and change point analyses to identify dry and wet periods and determine resilience phases. The estimated spatial variation of the GWS trends indicate a specific area centered in Haryana experiencing significant groundwater decline, with a maximum rate of around -6.6 cm/year. Our spatiotemporal analysis of CGWB GWL data from 1,798 monitoring wells across the study area reveals three distinct zones based on climate and aquifer characteristics: Z1 (northeast Rajasthan), Z2 (Punjab and Haryana), and Z3 (western and central Uttar Pradesh). In Z1, trends have shown severe groundwater depletion, with a maximum decline of about -300 cm/year. The north Indo-Gangetic plain, showing a moderate declining trend, is divided into zones Z2 and Z3. The average GWL time series for these zones indicates declining trends of approximately -61, -17, and -9 cm/year, respectively. Notably, Z3 exhibits clear seasonal variations. The GWL anomalies in Z1 are influenced by deeper aquifers (approximately 35 to 70 m), while Z2 and Z3 anomalies are primarily affected by shallower aquifers (less than 35 m). The average of annual rainfall and surface air temperature in the study area reveals that northern Punjab, northern Haryana and Uttar Pradesh receive moderate rainfall, while other regions have lower levels. The trend analysis of climatic factors shows a significant increase in rainfall in northern Rajasthan, while Haryana and western-central Uttar Pradesh experience declines. The surface air temperature increases toward the south, with the highest trend observed in central Haryana. Further, we have performed 12-month SPI analysis across different zones (Z1, Z2 and Z3) and we identified a pattern from 2002 to mid-2010, marked by alternating short-duration droughts and wet spells. This was followed by wet years from mid-2010 to mid-2014, a prolonged drought from mid-2014 to mid-2018, and a brief wet period from mid-2021 to 2022. We analyzed time series data for GWL, GWS, rainfall, SPI, and tubewells to assess temporal variations in GWS across different zones. Z3 exhibited the most pronounced seasonal variation in GWL anomalies, while GWS anomalies showed similar patterns across all zones. Change point analysis revealed five key episodes of GWS trends, including a prolonged decline from 2002 to 2011 and a steep decline from 2015 to 2017, followed by replenishment until mid-2020 and a mixed trend thereafter. The GWS stabilization during the wet period from 2011 to mid-2015 was significantly impacted by climatic conditions, especially in Z2 and Z3. Spatial analysis indicated that GWS trends are influenced by alternating dry and wet patterns. Additionally, the rise in tubewells, particularly deep and medium tubewells in Z1 and Z2, correlates with GWS changes, highlighting the combined effects of climatic and human factors. The GRACE-GWS anomaly exhibits noteworthy variability in north India, indicating a discernible decreasing trend with the highest value of approximately -6.7 cm/year. This trend is especially pronounced in the regions of NCT-Delhi, Haryana, north Rajasthan, and west central Uttar Pradesh and centered in Haryana. This well-established GWS depletion zone relates to the threatening declining rates of GWL in three zones of the study region. The current trajectory of groundwater storage shows a combined impact of temperature, rainfall, and groundwater pumping by tubewells for irrigation. These climatic and anthropogenic factors are influenced by climate change and rising crop water demand. Our SPI and change point analysis of rainfall and GWS demonstrates that successive dry spells in the periods from 2002 to mid-2010 and mid-2014 to mid-2018 govern the high declining rates of GWS. However, the wet periods from mid-2010 to mid-2014 and 2018 to mid-2020 relieve the subsurface groundwater stress. Over the past five years, the resurgence of groundwater in GWS likely corresponds to favorable government policies promoting recharge since the corresponding moderate wet period is short and not sufficient for changes alone. The rapid rise in the number of tubewells increases anthropogenic extraction of the groundwater and leads to the declining groundwater well-level trends in severely declining zones of Punjab, adjoining Haryana, and northeast Rajasthan. Our change point analysis reveals five main episodes of decline and replenishment of GWS due to the combined effects of the rainfall (climatic) and tubewell extraction (anthropogenic) effect. The spatial variation of GWS trend, SPI, and changes in tubewell numbers for different episodes exhibits that the Uttar Pradesh state shows high dependency on irrigation on shallow tubewells due to consistent dry spells and low rainfall.

Keywords: *Groundwater variability, GRACE, North India, socioeconomic factors, dry & wet periods*

GROUNDWATER MODELLING TO UNDERSTAND THE IMPACTS OF CLIMATE CHANGE IN THE CHENNAI BASIN, SOUTH INDIA

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Groundwater is a crucial resource for maintaining ecological balance and supporting the socio-economic needs of communities. The Chennai basin, a densely populated area in southern India, relies heavily on groundwater to meet its various demands. Over recent decades, rapid urbanization, industrial development, and climate variability have stressed the basin's groundwater resources. Climate change compounds these pressures by altering precipitation, temperatures, and extreme weather events. Given the basin's susceptibility to both natural and anthropogenic factors, it is essential to forecast future groundwater levels. Numerical modelling offers a powerful approach to simulate groundwater system responses under these variables, enabling water resource managers to make informed decisions about groundwater sustainability. This study aims to evaluate the impact of climate change on groundwater heads in the Chennai basin by integrating projected land use changes and population dynamics into a numerical model. This study integrates several datasets, including historical precipitation records, land use projections, and population growth data, into a numerical model developed using Visual MODFLOW. Precipitation data for the historical period (1995-2020) was obtained from the Tamil Nadu State Groundwater Department, and future precipitation projections from the NorESM2-MM climate model, downscaled and bias-corrected to suit the Chennai basin. The projected land use dataset, covering decadal changes from 1990 to 2040, reflects anticipated expansion in urban areas and corresponding reductions in agricultural land. Population growth data was sourced from the UN World Population Prospects, with estimates scaled to project urban and rural population changes within the basin. The groundwater model's conceptual framework comprises geological and hydrogeological units, recharge, extraction, and boundary conditions. The basin was spatially discretized into a 1 km size grid, with two distinct aquifer layers. Each aquifer's hydraulic properties were derived from the basin aquifer mapping dataset, which included lithological, stratigraphic, and transmissivity data from exploratory wells and Vertical Electrical Sounding (VES) surveys. Recharge calculations used the Curve Number method, correlating Thiessen polygons of rainfall distribution with land use and soil hydrology maps to estimate infiltration losses and adequate runoff per unit area. Land use classes were further divided by hydrological soil groups (C&D), representing low to moderate infiltration areas, which were especially important for simulating runoff in urbanized and agricultural areas. For future projections, precipitation estimates from climate models SSP126, SSP245, SSP370, and SSP585 were applied across various land use classes. Extraction rates were estimated by analyzing groundwater consumption across urban and rural areas, adjusted annually for population growth. Urban extraction rates were calculated based on domestic and industrial demands, with 40% of total urban water demand estimated as groundwater use. Conversely, rural extraction rates considered agricultural and domestic demands, with an estimated 80% reliance on groundwater. These projections were inputted as time-dependent parameters in the numerical model to simulate fluctuating extraction pressures across urban, suburban, and rural zones. Calibration and validation matched simulated groundwater levels with observed head data from 14 wells across the basin for both steady (1995) and transient states (1996-2020). Calibration focused on refining hydraulic conductivity values, while validation ensured the model could replicate observed conditions, resulting in a mean root square error of 3.87 m. With calibration complete, the model predicted groundwater head changes across the basin under each climate scenario from 2021 to 2050.

The model results indicate that climate change, urban expansion, and population growth are projected to impact groundwater levels across the Chennai basin significantly. Historical simulations show that groundwater levels fluctuate based on precipitation variability, particularly affecting rural regions dependent on agricultural recharge. Urban areas with limited recharge capacity experienced steady declines due to intensive extraction. Future projections suggest a gradual decrease in groundwater heads across the basin, with the most significant declines observed under the SSP585 scenario, where a predicted 1.25 to 2.0 m reduction in groundwater levels was noted at multiple wells by 2050. Urban expansion exacerbates the decline, as built-up areas reduce infiltration capacity, increasing runoff and limiting recharge potential. The impact of this expansion is especially pronounced along the basin's southern regions, where information technology and industrial zones are concentrated. Climate variability also plays a crucial role. Increased frequency of high-intensity rainfall events, as projected under SSP370 and SSP585, leads to higher surface runoff, reducing the amount of water available for recharge. Drought periods further compound water stress, especially in urban areas where groundwater remains a primary water source. Though benefiting from higher infiltration rates, increased irrigation demands, particularly during dry spells, impact rural areas, creating additional extraction pressures. Spatial disparities in groundwater head declines were evident across the basin. Wells in urban areas experienced consistently lower groundwater heads due to constant extraction pressures, while rural wells showed more variability, reflecting the influence of rainfall-driven recharge. However, the growing urban population will continue to increase water demand, potentially lowering the groundwater head further if extraction rates are not managed. The findings of this study highlight the vulnerability of the Chennai basin's groundwater resources to climate change, urbanization, and population growth. Numerical modelling under various climate scenarios demonstrates that urban expansion and increased extraction due to population growth will be critical drivers of groundwater decline in the basin. The most significant predicted declines occur under the SSP585 scenario, emphasizing the need for urgent policy interventions to mitigate potential water shortages. It is recommended that sustainable water management practices be prioritized to preserve groundwater resources. Effective strategies could include promoting rainwater harvesting in urban areas, enhancing irrigation efficiency in rural zones, and imposing restrictions on groundwater extraction. Additionally, irrigation optimization technologies could reduce the agricultural sector's groundwater reliance. Numerical modelling proves invaluable in predicting groundwater trends, enabling regional planners to anticipate resource challenges and adopt appropriate conservation measures. Future studies could enhance this model by integrating more localized socio-economic data. Ultimately, this study outcomes provides a framework for assessing groundwater sustainability in the Chennai basin, helping decision-makers balance development with the need for long-term water security.

Keywords: *Climate change, groundwater modelling, Chennai basin*

ASSESSING THE IMPACT OF THE 2023 FLOODS IN HIMACHAL PRADESH AND PUNJAB IN INDIA ON GROUNDWATER RECHARGE

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The summer monsoon brings South Asia much of its annual rainfall and is vital for the millions of farmers. However, the 2023 monsoon brought exceptional rainfall and multiple incidences of severe flooding. On the 9th of July 2023, the mountainous state of Himachal Pradesh (HP) experienced unprecedented and catastrophic flooding on a scale not seen for half a century. Flooding was triggered by persistent and intense monsoon rain, 400% more rain between 7th and 11th July than normal for that monsoonal period, leading to flash floods and widespread destruction. Rainfall intensity and damage far exceeded predictions, making this event an outlier in the region's hydro-climatic history. This event was followed by persistent heavy rain and subsequent flooding in HP on 12th and Punjab on 17th August. In this study, we have investigated the linked mechanisms and cumulative impact of these events. The flooding in Punjab has implications for regional water and food security. The aquifers of Punjab are heavily exploited for irrigation and as a result Punjab is the regional breadbasket. However, groundwater is overexploited. Furthermore, intensive agriculture severely impacts groundwater quality as fertilisers infiltrate into the groundwater. The scale of the successive floods during the 2023 summer monsoon provides a unique opportunity to investigate the role of flooding in counterbalancing groundwater depletion and in mobilising contaminants. It is critically important to understand the role of floods, like the increasing probable 2023 monsoon floods, play in longer-term regional water and food security.

The aim of this study is to constrain the scale of the extreme flood event that occurred in HP and Punjab in July 2023 and assess the cumulative impact of continued heavy rain and flooding, focusing on groundwater recharge and contamination during the 2023 monsoon. To achieve this, the study has three key objectives: (i) Characterise the hydro-meteorological nature of the floods and the cumulative impacts. (ii) Collect and interpret groundwater level and natural tracer data to quantify the impacts of floods on groundwater levels and recharge in the Punjab plains and relate this to upstream and downstream flood characteristics, and (iii) Quantify flood impacts on water quality by collating baseline data and conducting new groundwater quality sampling and analysis. The study area encompasses the Manali-Kullu-Mandi area in HP and the Bist-Doab and Malwa regions of Punjab, which experienced the most severe flooding. The emerging results are presented here related to groundwater recharge assessment. Drawing on the results of hydro-meteorological and remote sensing analysis, we have identified areas to investigate groundwater recharge. To investigate the floods impact on recharge, we collected groundwater level data, inorganic and organic water chemistry samples, data on stable water isotopes, and natural tracer samples (CFC and SF6). These data have been used to investigate the source and spatial/temporal extent of flood-related groundwater recharge. We collected groundwater data from the Central Groundwater Board (CGWB) and the Punjab Water Resources Department (WRD). The former consisted of 169 records of groundwater collected twice yearly with records beginning in 2013, the latter consisted of data collected at 15-minute intervals from early 2023 in the Bist-Doab and Malwa regions. We also collected 145 inorganic water chemistry and isotope samples, 36 environmental tracer samples for groundwater residence time assessments, 77 organic matter fluorescence and 77 pesticide samples from across the study area.

Initial results from groundwater level analysis in Punjab indicate that 69% of sites were affected by the floods. 74% of sites with groundwater levels less than 30 m showed an increase in groundwater level after the flood but only 37% of sites with groundwater levels below 30 m showed any response. Fewer (72%) sites in the Bist-Doab were affected by the two flooding events than in Malwa (90%), a higher number of sites in Bist-Doab have groundwater levels > 30 m. Furthermore, we observed distinct response typologies which appear to relate to the separate flood events in July and August. The effect of flooding on groundwater levels depends not only location of the sites, such as distance from surface water and drainage pathways, but also on site-specific characteristics such as depth to groundwater prior to the floods. Many of the samples collected from the Bist-doab and in the shallow to intermediate depth aquifers in the Malwa region (< 20 m depth) have electrical conductivity (EC) values < 1000 µS/cm, which are lower than the EC values observed during pre-flood conditions in 2019-21. Stable isotope values ($\delta^{18}O$) in these aquifers are <-7‰, which is indicative of recharge by surface water sourced from higher altitude regions in the Himalayas, and possibly related to the flooding that occurred in Himachal Pradesh in 2023. Furthermore, several sites in the Malwa region show stable isotope signatures in groundwater at shallow to intermediate depths which are indicative of surface water recharge sources, with slight shifts from -7.92‰ prior to the flooding to -8.67‰ after the floods, further indicating flood derived groundwater recharge. To further fingerprint the source of recharge water, we will use organic matter fluorescence, environmental tracers and pesticides to assess evidence for recent ingress of surface water, i.e., with higher dissolved organic matter (DOM) and more labile DOM, into the shallow groundwater system due to recharge of flood waters. Initial results from isotope, electrical conductivity, and groundwater level data indicate a clear influence of the flooding on groundwater recharge following the 2023 monsoon floods that occurred in Himachal Pradesh and Punjab. Further, work is required to more accurately fingerprint the source of the floodwater, particularly to distinguish between rainfall that occurred over Punjab during the two flood periods and precipitation that occurred in Himachal Pradesh and subsequently caused flooding in Punjab. The next steps will be to more quantitatively link the hydro-meteorological analysis to the hydro-geological and hydro-geochemical data, and to continue interpretation of the groundwater level and hydro-geochemical data.

Keywords: *Groundwater recharge, groundwater contamination, flooding, monsoon*

IDENTIFY THE OPTIMUM RAINFALL PATTERN AND DISTRIBUTION OF GROUND WATER SCENARIO AT DIFFERENT LEVELS AND FLUCTUATIONS OF WATER LEVELS OVER NORTH KARNATAKA, INDIA

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Rainfall is the natural phenomenon, which directly or indirectly affects all life on the Earth in one form or the other. It has large variations in time and space in terms of both amount and intensity. In India, rainfall is received mainly during the monsoon season. The orographic and rain shadow region dominate mainly rainfall distribution patterns over Karnataka during southwest monsoon season. The movement of depressions or cyclone over peninsular India during the northeast monsoon season and pre-monsoon season thunder storm activity is important in the summer season. In the present study, long term rainfall trends over thirteen districts of north Karnataka have been studied from 1901 to 2017 on monthly, seasonal and annual level. Daily rainfall data for 153 rain-gauge stations of North Karnataka have been collected for the period 1951 to 2013 from the database of AICRP on Agro-meteorology, RARS-Vijayapura, and subsequent years till 2017, from Directorate of Economics and Statistics, Bengaluru. Future climatic scenario dataset for 2021-2050 was downloaded from CMIP-5 and processed. Trend analysis has been carried out using Mann-Kendall (MK) test on annual and seasonal rainfall during 1951 to 2017. Results indicated a negative trend in Belgavi, Bidar and Dharwad districts at 1% level of significance and Koppal district showed positive trend at 5% level of significance. In case of south-west monsoon season rainfall, Bidar district showed negative trend with significance at 1% level and Koppal district showed positive trend with significance at 5% level. Study of inter-annual variations of seasonal and annual rainfall studied through moving average method indicated that the cyclic variations of different lengths in various taluks in all districts. In some taluks, the frequency of fluctuation was different from one period to another, for example, high frequency undulations in annual rainfall existed till 1990 but not later. Serial correlation and auto-regression (AR) models which were developed for long range forecast of annual rainfall, indicated high significance at 1% level of significance for Belagavi, Bidar, Dharwad, Raichur and Vijayapura districts. In Dharwad district, AR models for August, September, Kharif season, southwest monsoon and monsoon season showed high significance at 1% level. Comparison of projected rainfall for 2021 with 1988-2017 indicated lower annual rainfall for Ballari, Koppal and Vijayapura districts. Mapping of spatio-temporal variations in rainfall indicated that there was overall decrease over northern Karnataka during 1981-2017. Also, long-term behaviour of groundwater level according to groundwater recharge and draft conditions is presented in this paper based on different agro-climatic zones. The effect of seasonal rainfall on ground water levels was analysed. The highest south west monsoon rainfall of 1083.1 mm was received in the year 2019 in Belgaum and the of minimum 373.7 mm was received in Bijapur. The departure of seasonal rainfall ranged between -16% (Yadgiri district) to 89% (Belgaum district). Similar results have been obtained for individual districts for the projected rainfall patterns. In case of ground water levels, about 67 % and 93.5 % of the wells showed ground water levels within 10 mbgl, during pre- and post-monsoon season of 2019, respectively. It is observed that 78% of the wells in the North Karnataka State are showing fall and 22% of the wells are showing rise in annual water level during pre-monsoon 2019. While, during post-monsoon season of 2019, about 78% and 22 % of the wells are showing rise and fall in ground water levels, respectively. Analysis of the the pre-monsoon and post-monsoon season decadal (2009 to 2018) mean ground water level, indicated that 69% and 38% of wells show fall in ground water level, respectively. Comparison of projected and historical rainfall pattern for selected districts of north Karnataka indicated that in Ballari, Koppal and Vijayapura districts the projected rainfall pattern showed lower rainfall, whereas in Dharwad and Haveri districts it is projected to be higher rainfall. Changes in patterns of cyclicity and trend were also noticed. The spatio-temporal variations of rainfall indicated that there has been overall decrease in rainfall in the Northern Karnataka from Phase I to Phase II in annual, seasonal (*Kharif* and *Rabi*) and monthly rainfall, whereas increase in rainfall during Phase II has been identified in monthly rainfall for June and August. The coefficient of variation of annual rainfall, southwest monsoon season (SWM) rainfall and monthly rainfall of May, June and July increased from Phase I to Phase II, whereas it deceased in northeast monsoon season (NEM) and in August and October months. The study assessed the climatological variations in annual, seasonal and monthly rainfall at the district and taluk level, and also assessed its relation with depth to ground water levels in districts of North Karnataka. This paves way for more intense and focused studies in future.

Keywords: *Rainfall, groundwater, trend analysis, MK test, Karnataka*

ANALYZING THE IMPACTS OF RECENT CLIMATE CHANGES ON THE HYDROLOGY OF SURFACE WATER AND GROUNDWATER USING AN INTEGRATED HYDROLOGICAL MODEL

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Traditionally, assessments of climate change impacts on streamflow have focused primarily on water availability, often overlooking its effects on groundwater (GW) recharge and availability. There is a need for a comprehensive understanding of how changing climate patterns influence GW dynamics because GW plays a critical role in sustaining water resources, especially during dry periods. Therefore, this study aims to evaluate GW availability and its replenishment through recharge at the watershed scale, utilizing an integrated modeling approach. The impact of recent climate changes on streamflow, groundwater recharge (GWR) and groundwater head (GWH) in the Upper Godavari River Basin (UGRB), India, was analysed for the historical period from 1982 to 2020 using the integrated SWAT-MODFLOW hydrological model. The UGRB is a key sub-basin within the larger Godavari River Basin (GRB), located in Maharashtra State. This region spans approximately 21,774 km^2, supporting a population of around 8.6 million people across 1,883 villages and 45 towns. The land is predominantly agricultural, with the remainder classified as barren. Based on LULC data from 1985 and 1995, about 80% of the area is utilized for farming, with surface water from reservoirs serving as the primary irrigation source. The UGRB experiences a tropical climate, receiving nearly 85% of its annual rainfall during the southwest monsoon season, which occurs from July to September. The Bhandardara, Mula, and Jaikwadi reservoirs are the three main reservoirs situated within this basin, beginning operations in 1928, 1972, and 1976, respectively. Together, these reservoirs supply irrigation water to almost 75% of the region’s agricultural land.

The integrated SWAT-MODFLOW exchanges data between SWAT and MODFLOW to see the interaction between river and aquifer. The HRUs based recharge output from the SWAT is given to the MODFLOW grid to assess the change in the GWH. The SWAT model inputs included rainfall, maximum and minimum temperature data collected from the Indian Meteorological Department (IMD) at 0.25° × 0.25° resolution. LULC data was collected from the Environmental Systems Research Institute (ESRI) at 10 m resolution. Soil data was collected from Food and Agriculture Organisation (FAO) at 1:5 000 000 scale, which shows four main type of soil class present in UGRB. It consists of clay, clay-loam, sandy-clay-loam and loam. The SWAT model simulated the spatio-temporal distribution of streamflow, GWR rates, evapotranspiration. Then, the HRUs based output is given to MODLOW. Additionally, MODFLOW requires the initial GWH and aquifers properties such as storativity and permeability which are collected from Central Groundwater Board (CGWB).

We have chosen multisite inside the basin to calibrate and validate the model. Multisite calibration is done to see the spatial variation in the calibrated parameters. Calibration and validation of the model was done at two points namely Nagamthan and Jaikwadi gauge

stations, using 19 calibration parameters. The calibration at Nagamthan showed R^2 = 0.69, NSE = 0.69, and PBIAS = -21, while at Jaikwadi, R^2 = 0.69, NSE = 0.69, and PBIAS = 5.1 were observed. For the validation at Nagamthan and Jaikwadi, the statistical parameters the R^2, NSE, PBIAS value were 0.68, 0.69, -2.38 and 0.66, 0.62, -20.2 respectively. Then the setup model was run for time periods of 1982-2000 and 2001 -2020 taking LULC of year 2017 constant for entire simulation. To assess the climate change impact on surface water and GWR, the difference between simulation period 2001-2020 and 1982-2000 was taken. It is observed that in the UGRB, the changes in streamflow, GWR, and GWH resulting from climate change scenarios were significant. Streamflow in most of the sub-basin areas shows a substantial rise, ranging from 1 to 32 mm, in the period from 2001 to 2020 compared to the period from 1982 to 2000. While some sub-basins indicate a decrease in streamflow, the other sub-basins exhibit the greatest increases in streamflow. The GWR has declined in nearly half of the sub-basins, with reductions ranging from -2 to 0 mm. The most notable increase in GWR appears in sub-basin 1, attributed to climate change impacts. The remaining sub-basins display moderate increases in GWR, varying between 0 and 6 mm. It has been observed that among the meteorological factors, rainfall exerts the greatest influence on the streamflow, GWR and GWH. The rise in streamflow coupled with the decrease in groundwater recharge might result in flooding and a decline in the groundwater table within the basin. The findings of this study are expected to provide critical insights to the policymakers in formulating strategic water management plans.

Keywords: *Climate change, SWAT-MODFLOW, streamflow, recharge, groundwater*

NUMERICAL STUDY OF THE HILLSLOPE DRAINAGE PROBLEM FOR A HETEROGENOUS SOIL WITH A CHANGING TOPOGRAPHY

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The study examines the problem of hillslope drainage in heterogeneous soils with varied topographies by developing a robust numerical framework based on the Finite Difference Method. The study focuses on the challenge of accurately predicting the phreatic line, which marks saturated and unsaturated zones, under diverse hydrological and geological conditions. By using Darcy's law and mass conservation principles, the governing equations for groundwater flow in sloping aquifers were derived, which involved spatially varying parameters such as hydraulic conductivity $k(x)$, slope $\alpha(x)$, and recharge rate p. The nonlinear nature of these equations was discretized using the FDM and solved iteratively by the Newton-Raphson method to ensure computational efficiency and precision. The aquifer system considered in the present work involves a sloping soil layer, overlain with an impermeable base under steady recharge conditions from above and appropriate boundary conditions. The study makes three primary cases: uniform slope with constant p/k, a linearly varying slope and hydraulic conductivity, and exponentially varying hydraulic conductivity, as a means to explore their isolated and combined impact on the profile of hydraulic heads. Results show that uniform slopes with constant p/k produce symmetric hydraulic head profiles influenced by boundary conditions, and higher p/k ratios lead to steeper head reductions due to increased recharge rates. When slope and hydraulic conductivity are varied linearly or exponentially, the groundwater flow patterns shift significantly. Linear growth in $k(x)$ enhances subsurface flow with the development of hydraulic head peaks especially at steeper slopes, and exponential growth in $k(x)$ leads to a steep decrease in hydraulic head because of the increase in permeability. Conversely, exponential decreases in $k(x)$ slow down water movement and, consequently, lead to a gradual decline in hydraulic head. These show how heterogeneity in soil and slope dynamics significantly affects groundwater flow. Furthermore, increased slope angles shift the hydraulic head profile due to a lower gravitational head and moving the flow toward downstream boundaries, which points to the importance of including slope variability in models. The study highlights the role of spatially heterogeneous parameters like slope, conductivity, and recharge in defining the groundwater flow in sloping landscapes, and the integration of realistic field observations in the modeling process. Practical implications of these findings extend to sustainable groundwater management and hill drainage planning, offering insights into managing water resources in sloping regions characterized by complex geological and hydrological conditions. The study concludes by demonstrating the significance of integrating heterogeneity and topographical variations into groundwater models and establishes a foundation for future research on transient flow conditions and more intricate terrains. This study provides a holistic numerical approach to address the complexity of groundwater flow in hilly regions, which can improve water resource management and decision-making in regions prone to topographical and hydrological variability. This study has critical implications for advancing the understanding of groundwater dynamics in sloping aquifers and forms the basis for further exploration into the transient behaviour of hillslope drainage systems.

Keywords: *Hillslope drainage, heterogeneous soils, groundwater flow, numerical modeling*

ADDRESSING THE CLIMATE CHANGE IMPACTS IN NAGPUR DISTRICT OF MAHARASHTRA, INDIA: A SUCCESS STORY OF THE GREEN PROJECT

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In India's central region, Nagpur, called the Orange city, is the winter capital of Maharashtra State, characterized by extreme cold and heat waves. Certain sub-districts of Nagpur, despite receiving over 1000 mm of annual rainfall, are struggling with supply and demand management due to recent fluctuations in rainfall patterns and over-exploitation of groundwater. Water scarcity is increasingly affecting in essential government institutions like primary health care centers, schools and remote areas including tribal and non-tribal areas of the district. The challenges of managing supply and demand are further exacerbated by urbanization and intensive agriculture reliant on water, which compete with the needs of the community. Consequently, the unchecked exploitation of water resources and the potential depletion of these resources underscore the urgent necessity for water conservation measures. The region struggles with various challenges in fulfilling water needs for homes, institutions and healthcare due to various factors. These factors include inadequate access to remote areas, financial and management issues, depleting resources, unreliable electricity, high costs, rising electricity demands, inadequate WASH facilities, and uncomfortable conditions in schools due to high room temperature of buildings and availability of water in summer leading to high dropout rates. Therefore, this study presents the success story of 'The Green Project' initiative used to address climate change issues in the Nagpur district (Maharashtra State).

Over a period of time, bore wells can become obstructed by mud, sand and tree roots, rendering them unsuitable for drinking water. To restore these water sources, a cleaning process involving re-drilling or flushing is necessary. As of 2023, the Zilla Parishad in Nagpur has successfully completed the re-drilling or flushing of 2,141 bore wells. However, due to the deep-water levels, the flushed bore wells cannot be utilized for extraction. Instead, 106 of these bore wells have been repurposed as recharge shafts to improve groundwater levels. With a total roof area of 9,858 m^2, this initiative has facilitated the recharge of approximately 7.5 million liters of water annually. The existing bore wells present a cost-effective alternative, eliminating the need for new bore wells and associated expenses. It was found that most government and semi-government buildings especially in remote areas do not have parapet walls on the roof. Due to this, the falling rainwater usually runs off and wasted. The rainwater harvesting system utilizes a catch-and-collection approach by capturing rainwater from public building roofs with a parapet wall and directing it through pipes for storage and groundwater recharge via filters. The buildings' rooftops have been treated to prevent water damage. On the roof, a slight slope of approximately 1° is implemented on both sides. This is complemented by the application of two layers of white heat-resistant paint, which serves to fill in cracks and address minor leakages. Such measures contribute to the reinforcement of the building's structure, facilitate the efficient drainage of water, and enhance the albedo effect, thereby reducing the building's temperature by 3° to 5° C. Consequently, there is a decreased reliance on electrical appliances such as air coolers and air conditioning units during the summer months, leading to a potential conservation of over 30% of natural resources. Every rainwater harvesting system incorporates filtration as a fundamental element. The design of these filters includes a chamber filled with filtration materials, such as coarse sand and gravel layers, which effectively remove debris and contaminants from the water, preventing them from entering the storage tank or recharge structure. These materials require periodic cleaning and replacement, which can increase maintenance costs. To mitigate such maintenance issues, modern systems utilize online self-cleaning filters that operate based on the principles of cohesive and centrifugal forces. The storage tank can be positioned either at ground level or atop the premises to store water for use during dry periods, which is particularly beneficial in health emergencies where water is essential, as well as for fire emergencies, especially in primary health centers. Instead of traditional electric pumps, solar pumps are employed, which operate on sunlight and are more cost-effective. Additionally, solar net metering is a billing system that compensates owners of solar energy systems for the surplus electricity they contribute to the grid. A building equipped with a rooftop solar photovoltaic system can generate more electricity during daylight hours than it consumes, especially when combined with the increased efficiency provided by reflective white paint.

The execution of "The Green Project" presents an environmentally conscious and sustainable strategy for fostering a clean and green environment. According to initial qualitative findings, the initiative is expected to enhance groundwater levels, minimize runoff, and decrease building temperatures, which will lead to reduced energy consumption and improved water conservation and recharge. Additionally, an integrated system of rainwater harvesting and solar energy will contribute to a sustainable future by promoting energy conservation and enhancing energy efficiency. This approach will be cost-effective while also mitigating air pollution through the reduction of greenhouse gas emission. This approach has substantial potential for expansion and duplication to enhance the environmental sustainability of institutional systems, alleviate climate risks, and provide green technologies to underserved populations. The assessment of energy savings, carbon footprints, water availability, and similar factors, both qualitatively and quantitatively, proves valuable. A substantial investment in this strategy would significantly contribute to environmental sustainability and help alleviate the effects of climate change. The initiative referred to as 'The Green Project' has been found very effective to tackle a range of challenges arising from severe climate-related conditions, such as water shortages, rising temperatures, and the effects on service delivery and water accessibility, as well as providing an alternative to artificial energy sources. This project successfully aligns with the mitigation objectives of the Sustainable Development Goals (SDGs) agenda by promoting a resilient community among both service users and providers, while also safeguarding essential rights.

Keywords: *Reuse structure, rainwater harvesting, white paint, solar energy, SDGs*

RAINFALL-DRIVEN GROUNDWATER RESERVES IN THE KOYNA BASIN, INDIA: ASSESSING SEASONAL RECHARGE AND ENVIRONMENTAL INTERACTIONS

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The demand for groundwater resources in India is expected to rise significantly across multiple sectors, placing increasing pressure on water supplies. However, inadequate management has led to challenges such as rising pumping rates, declining well yields, shifting seasonal rainfall patterns, and diminished groundwater reserves, especially in Koyna basin of Maharashtra, Western India where mismanagement can even trigger seismic activity. Fluctuations in groundwater levels, driven by recharge and extraction, can be exacerbated by seismic activity. Numerous studies have demonstrated a link between excessive groundwater extraction and induced seismicity. Despite this, research on the replenishment of natural groundwater reserves by precipitation and its potential impact on seismic activity remains limited. Understanding these reserves is crucial for effective groundwater management and assessing hydrological loads related to seismic events. Remote sensing (RS), GIS techniques, and numerical simulations are increasingly used to assess groundwater reserves and their environmental interactions. Information theory, developed by Shannon, has emerged as a valuable tool in hydrology for estimating hydrogeological parameters, especially in data-scarce regions. This model provides a rapid approach for estimating groundwater reserves. Thus, the objectives of this study are to: (i) estimate rainfall-driven groundwater recharge using an information-based model, and (ii) explore the interplay between groundwater dynamics and environmental factors in the Koyna Basin.

Rainfall is a primary driver of groundwater recharge, influencing fluctuations in groundwater levels. This study calculated marginal entropies for rainfall, H(RF) and groundwater levels, H(GWL), along with their joint entropy, H (RF, GWL), using probability distributions. Trans-information, T (RF, GWL) was then used to assess how rainfall measurements reduce uncertainty in predicting groundwater levels. The natural groundwater reserve (NGR) was estimated based on the ratio of trans-information to the marginal entropy of rainfall, with the percentage of rainfall contributing to groundwater recharge (Re%) calculated accordingly. The NGR was determined using the equation: $NGR = R_e (\%) \times rainfall \times A \times 0.00001$. Where A: area influenced by each well, derived using Thiessen polygons. The IMD gridded daily rainfall data of 23 years was used for the Koyna basin analysis. Seasonal groundwater level data from the CGWB wells over the same period were utilized. The Landsat-8 OLI/TIRS images at 30 m resolution were processed in ArcGIS to create a LULC map. Groundwater prospect map was generated using RS and GIS and multi-criteria decision-making (MCDM) based on the Analytical Hierarchical Process (AHP). Finally, monthly total water and groundwater storage data from GLDAS-2.2 have been compared with the estimated natural groundwater reserves.

The gridded rainfall data have been analysed and the highest recorded rainfall occurred in 2005 in the northern part of the basin, an area characterized by dense forest cover. The rainfall data reveal significant spatial variability across the basin. Monthly rainfall patterns showed that July consistently received the highest rainfall, followed by August and June, reflecting the dominance of the monsoon season. Groundwater levels, monitored by the CGWB, showed seasonal fluctuations. Hydrographs indicated deeper groundwater levels in the south-eastern basin, with shallower levels generally within 16 m, bgl, closely linked to the rainfall patterns. Marginal entropy calculations for RF and GWLs, based on seasonal data, revealed a range of 0.8781 to 1.6889 bits for RF and 0.3902 to 2.5006 bits for GWLs, showing spatial variability in recharge potential. Natural groundwater recharge rates, based on annual rainfall, ranged from 1.4% to 41.0%, with the monsoon months (June to August) being most crucial for recharge. Groundwater reserves from monsoon rainfall was an average of 16.9%, revealing the limited recharge in certain wells, potentially due to human activity and lateral flows. The spatial distribution of recharge showed lower rates in the south-eastern part of the basin having more barren lands. Using the Thiessen polygon method, annual groundwater reserves (AGWR) were estimated for the selective years. As an example, it ranged from 1.50 to 192.95 MCM annually, depending on rainfall. Seasonal groundwater reserve (SGWR) was the maximum at 117.26 MCM, but it was highest in 2005 at one well with a value of 505.19 MCM, while lower reserves were observed at other wells. The LULC map indicated that forests, which dominate the northern and western parts of the basin, significantly contribute to groundwater recharge, with rates of 25.6% during the monsoon, compared to just 5.2% in built-up areas. Satellite and GLDAS-based analyses showed consistent Total Water Storage (TWS) anomalies, with positive anomalies during the monsoon and negative anomalies in the dry season. Seasonal trends in evapotranspiration (ET) and soil moisture (SM) were found to influence groundwater storage, with strong positive correlations between GWS, RF and SM, and negative correlations with ET, found the complex hydrological interactions in the basin.

The study estimates rainfall-driven groundwater reserves in the shallow aquifers of the Koyna Basin, Western India, by integrating groundwater level measurements with rainfall data through information theory. Natural groundwater recharge rates vary between 1.4% and 41.0% of annual rainfall, with an average of 19.3%. Monsoon rainfall, in particular, contributes around 16.9% to groundwater recharge, with forested areas in high groundwater potential zones showing a notable recharge rate of 25.6%. A strong positive correlation (R = 0.88) is observed between forest cover and recharge rates, revealing the role of land use in influencing groundwater dynamics. In contrast, wells downstream of the Koyna Reservoir discovered limited recharge response, likely due to human interventions and lateral groundwater flows. Seasonal groundwater reserves are found with strong correlations to the GLDAS data on the SM and GWS, though an inverse relationship with the ET is observed. These findings emphasize the importance of understanding seasonal recharge patterns and environmental interactions for effective groundwater management in the Koyna basin.

Keywords: *Rainfall, groundwater reserve, trans-information, Satellite and GLDAS data, Koyna basin, Western India*

CLIMATE CHANGE AND GROUNDWATER RESILIENCE IN TAMIL NADU: REGIONAL IMPACTS AND ADAPTIVE STRATEGIES

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Tamil Nadu relies heavily on groundwater for its agricultural, domestic, and industrial water demands. However, climate change is putting immense pressure on this critical resource, with shifts in rainfall patterns, rising temperatures, and increased frequency of droughts leading to notable declines in groundwater levels and quality. These changes have region-specific impacts, particularly affecting semi-arid and coastal areas, where salinization and over-extraction are growing concerns. This study examines the challenges posed by climate-induced pressures on groundwater in Tamil Nadu for two decades (2004-2023), using spatial analysis to map vulnerabilities, their relationship with the climatic factors such as precipitation, temperature etc., and assess adaptive measures. By identifying areas with critical water management needs, this study aims to inform sustainable strategies that enhance groundwater resilience and secure water resources for the future.

The study integrates district-level in situ groundwater data and satellite sourced data for Tamil Nadu to examine the spatial and temporal impacts of climate change on groundwater resources. The methodology encompasses four main stages: spatial and temporal analysis of ground water, computing relation between ground water and other climatic factors, generation of a strategic map for vulnerable regions and suggestion of adaptative strategies. The data collected for the study includes historical groundwater level data obtained from CGWB and Ground Water Storage data from NASA Global Land Data Assimilation System (GLDAS). This study also analyzed both annual and season wise data to provide insights on pre- and post-monsoon recharge rates and declination in ground water levels. Climatic datasets such as temperature, precipitation, extreme weather event frequency, evapotranspiration, storm surface runoff, etc. were sourced from the IMD records and from spatial datasets such as ERA-5 (ECMWF Reanalysis v5) and NASA GLDAS covering a period of 20 years to capture both short-term fluctuations and long-term trends. The Land Use/Land Cover (LULC) maps were sourced from Copernicus mission and significant locations are mapped manually and were sourced from Open Street Maps for the creation of strategy map. The mapping of gradient and district-level Groundwater Storage (GWS) was performed on Google Earth Engine platform. A Composite index of GWS for Tamil Nadu using the slope obtained by linear fitting of decadal, 5- and 3-year dataset was prepared to highlight areas with a significant need for groundwater management. Layers on slope obtained through linear fitting were overlaid by providing weightage to arrive at the index map. The correlation of thus developed GWS index with climatic datasets were also performed to identify the influence of such factors over the depletion or augmentation of groundwater.

From the study, it was identified that coastal districts of Tamil Nadu including metropolitan city of Chennai, Nagapattinam, Kadalur, etc., shows a declining trend in GWS rate. Therefore, a comprehensive note on groundwater management strategies focusing on the coastal regions is provided in the study. This involves Managed Aquifer Recharge (MAR), rainwater harvesting, water quality protection measures and water-efficient agriculture

practices, followed by suggestions on educational awareness and policy interventions under the frame of pre-existing government schemes and programmes. Based on the spatial location of already established freshwater structures such as ‘Aayiram Kanmaais’ (Thousand lake systems), Chain-tank system predominantly found in the coastal regions of Tamil Nadu, and fresh waterbodies, a strategic map with zones with classes of different interventions is proposed. This measure also takes into consideration the existing barren lands in agriculture sector, for suitable recharge zones. In urban regions, rainwater harvesting in residential buildings have proved to be an effective means of intervention. It is also noteworthy to mention that Tamil Nadu is a forerunner in residential rainwater harvesting structures thus allowing the urban regions to be a strategic point of suitable interventions. Altogether a taluk level strategy map with different intervention classes is compiled to facilitate the sensitization of different stakeholders in future. The classes of intervention include: residential rainwater harvesting, GW recharge zones, wetland conservation, identification and rejuvenation of coastal structures, management of water reservoirs, prevention of sea water intrusion, wastewater management, small check-dam constructions, repurposing bore-wells and controlling commercial water consumption. The study also highlights a set of sustainable and just ways for the implementation of the strategies for each of the intervention classes. The future scope of the study lies in initiation of inclusive stakeholder interactions at local level in selected taluks under diverse intervention classes provided in the strategic map. Overall, this study tried to add on to the efforts in bridging the gap between science and policy by embracing the scientific data and just strategic interventions for combating climate change induced ground water crisis.

Keywords: *Groundwater resilience, climate change adaptation, Tamil Nadu, managed aquifer recharge, spatial analysis*

FUTURE-PROOFING GROUNDWATER: MODELLING THE IMPACTS OF CLIMATE, LAND USE AND DROUGHT VULNERABILITY

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Groundwater is a critical resource that supplies fresh water for drinking, agriculture, and industry to large portions of the global population. As surface water sources become increasingly strained by growing demand, pollution, and climate variability, the role of groundwater as a stable water source has become more prominent. However, intensive groundwater extraction, contamination, and climate change impacts have placed severe pressure on groundwater systems, leading to significant depletion and quality degradation in many regions. This study seeks to address these challenges by developing a comprehensive groundwater model for a selected area to support sustainable groundwater management and ensure long-term water security. The groundwater model for this study integrates surface and subsurface water interactions using the SWAT in conjunction with Visual MODFLOW. This combination of tools allows for accurate simulation of the interactions between groundwater and surface water under various climatic and land use conditions. The model will be run for current climate and land use scenarios and then tested under future climate projections to assess potential changes in water demand and groundwater availability. Key parameters such as precipitation, evapotranspiration, soil moisture, and runoff are included to represent surface water components. Groundwater data including water table levels, recharge rates, and aquifer properties, are used to model subsurface conditions. The methodology also includes testing the impacts of current and future land use scenarios. Land use changes influence both groundwater recharge and demand, as urbanization and agricultural expansion alter the natural infiltration processes. Future scenarios considered potential shifts in land use patterns under climate change and population growth projections. A groundwater drought-prone index has been developed based on the model's outputs to identify areas most vulnerable to groundwater scarcity. This index will help prioritize regions requiring immediate attention to prevent long-term resource depletion. Data for this study utilized from various sources to ensure a comprehensive representation of both natural and anthropogenic factors influencing groundwater. Surface water data, including river flow and runoff measurements, have been collected from regional water management agencies and past hydrological studies. Climate data such as precipitation, temperature, and evapotranspiration, are obtained from global climate databases and local meteorological stations. LULC data are sourced from remote sensing imagery and government land-use databases to provide historical and projected land use patterns. Groundwater data include monitoring well records, groundwater extraction rates, aquifer properties, and recharge rates. This data is collected from national groundwater monitoring agencies. Data from the SWAT model outputs are calibrated with observed groundwater levels in Visual MODFLOW to ensure model accuracy. Additionally, high-resolution satellite data such as GRACE (Gravity Recovery and Climate Experiment) is used to incorporate large-scale groundwater storage changes. These datasets are essential for simulating both current conditions and future climate scenarios.

Preliminary results from the groundwater modeling indicates a significant depletion trend in regions with intensive agricultural and industrial activity. Under current climate and land use conditions, certain areas within the region are experiencing groundwater levels that are

unsustainable in the long term. The application of future climate scenarios suggests that groundwater availability may be further impacted by reduced recharge rates, particularly in regions projected to experience decreased rainfall and higher temperatures. Similarly, changes in land use, such as an increase in urbanized areas and agricultural expansion, show an added strain on groundwater systems by reducing infiltration and increasing water demand.

The groundwater drought-prone index has been developed in this study to identify several high-risk zones, primarily in areas with extensive irrigation and lower recharge rates. These zones are found to be most vulnerable to long-term groundwater scarcity and require focused management interventions. The index serves as a valuable tool for prioritizing regions where groundwater conservation and sustainable management practice are most urgently needed. This study presents a comprehensive approach to understanding groundwater dynamics in the face of climate change and land use modifications. By modeling groundwater under both current and future scenarios using SWAT and Visual MODFLOW, this study identified key areas of concern for groundwater sustainability. The results underscore the need for proactive management strategies that incorporate sustainable groundwater extraction rates, balanced with recharge potential under evolving climatic and land use conditions. The study's groundwater drought-prone index offers a targeted approach for prioritizing regions most vulnerable to groundwater scarcity. These findings have significant implications for policymakers, enabling more informed decisions on sustainable groundwater management and planning. The mitigation strategy developed in this study proposes guidelines for a suitable groundwater extraction draft that aligns with recharge potential and resource renewal rates. Recommendations for land use practices are also provided to reduce water demand and enhance natural infiltration. By prioritizing areas identified as high-risk through the drought-prone index, this study contributes to a more resilient and sustainable groundwater management framework that can adapt to future environmental and socioeconomic changes. This comprehensive approach has the potential to support water security in the region, ensuring that groundwater resources remain viable for future generations.

Keywords: *Groundwater modeling, climate change impact, sustainable management, land use scenarios, drought-prone index*

RAINFALL AND ITS VARIATION IN AND ARROUND BHANEGAO AND SINGORI OPEN CAST COAL MINING AREA, DISTRICT NAGPUR, INDIA

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Rainfall plays very vital role in availability of groundwater for various purposes viz. Agriculture, drinking, domestic and Industrial purposes. To understand the seasonal and temporal variation in rainfall large data set is required. The present study is carried out to establish the variation in actual rainfall with respect to normal for understanding its control over occurrence and movement of groundwater with respect to time. The key resource area covered under this study is part of 3 different talukas viz., Kampttee, Parsioni and Saoner from District Nagpur in Maharashtra State. The annual monsoon rainfall data of last 52 years (from year 1971 to 2022) for Parseoni, Saoner and Kamptee taluka is taken from the government web site *services.mahavedh.com* and also from office database of Groundwater Surveys and Development Agency, Nagpur and utilized for understanding the monsoon rainfall behaviour in the study area. The normal rainfall values from India Metrological Department (IMD) were taken and accordingly variation of rainfall was calculated. At the same time percentage variation with respect to normal rainfall is calculated and it is utilized for knowing the cyclicity of rainfall. The findings on the basis of 52 years' rainfall data for Parsioni indicate that there are 26 positive rainfall years and 26 negative rainfall years and same is the case with respect to Saoner where as in Kampttee the positive rainfall years decreased to 19. In the last 52 years, Parseoni received average 941.26 mm rainfall when compared with normal rainfall (919.8 mm) i.e., 21.46 mm or +2.33% more. Saoner has received average 945.12 mm rainfall as compared with normal rainfall 908.40 mm +4.04% more. When rainfall for Kampttee is analyzed, it has been found that it has received 983.97 mm rainfall when compared with the normal rainfall of 1064.80 mm. The rainfall percent deficit is -7.59%. The decadal percent deviation for each decade was analyzed for gaining rainfall behavior pattern on decade level. In Parseoni, the rainfall trend is showing increasing trend when compared with 1971-1980 rainfall decade. The Saoner taluka has received more rainfall during the last 2 decades. From 1981 to 2022, the rainfall shows an increasing trend. No pattern for Kamptee is identified. It can be concluded that the Kamptee has unpredictable behavior with respect to rainfall.

Keywords: *Trend, rainfall, Napur, coal mining*

IMPACT OF URBAN HEAT ISLAND ON GROUNDWATER RECHARGE: A BIBLIOMETRIC ANALYSIS

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Urbanization has grown significantly, with a projected 70% global population living in cities by 2050 compared to only 13% in 1900. This rapid urban growth makes managing urban water systems increasingly critical and complex. Groundwater is a key resource for freshwater. However, urbanization has altered the functioning of natural systems, particularly groundwater recharge processes. The increasing population density in cities, coupled with intensified industrial and economic activities, have exacerbated the strain on urban hydrological systems. The interplay between urban development and natural processes presents challenges that demand interdisciplinary solutions and innovative strategies for sustainable resource management. The present bibliometric review examines existing literature to explore the relationship between urban development, the Urban Heat Island (UHI) effect, and groundwater recharge, while identifying current research trends. The analysis reveals that urbanization typically reduces groundwater recharge due to the increase in impervious surfaces, which inhibits rainwater infiltration and increases the surface runoff. Studies indicate that rising surface and subsurface temperatures can decrease recharge rates by as much as 30% to 50%, particularly in regions experiencing high levels of urbanization. Thermal groundwater systems in cities are influenced by human activities, such as paving surfaces, constructing underground structures, and using groundwater for heating and cooling. The inputs, outputs, and storage of energy, water, materials, and waste in urban areas are key factors leading to adverse urban metabolism, contributing to UHI effects. Cities act as heat sinks due to high resource consumption and altered land surfaces, intensifying UHI. Waste heat from energy systems significantly contributes to UHI. Urban metabolism studies help link energy consumption patterns to UHI effects, enabling targeted reductions in emissions and waste heat outputs. Social, political, and economic factors also influence urban development and groundwater management. The methodology involves an extensive literature review of more than 200 articles from Scopus, Web of Science, and Google Scholar, covering the period from 2010 to 2024. Keywords such as "Urban Heat Island," "groundwater recharge," "urban hydrology," "urban metabolism," "water-energy nexus," "sustainable urban design," "green infrastructure," and "climate-resilient cities" were used for searches. Data cleaning and preparation processes ensured consistency in author names, institution names, and keywords. The R Bibliometrix tool was used for advanced statistical and graphical bibliometric analysis. Metadata (title, authors, keywords, abstract, citation counts) was formatted for compatibility with bibliometric tools (e.g., CSV, RIS). Duplicates were removed, author names were standardized, keywords were harmonized, and irrelevant studies were filtered out. The bibliometric analysis focused on emerging themes through keyword clustering and co-citation analysis. Co-authorship and citation patterns indicated strong collaboration among developed countries, while contributions from developing countries were limited. The thematic analysis identified gaps in understanding the long-term impacts of UHI on groundwater quality and recharge sustainability. Limited studies integrated field data, remote sensing, and hydrological modelling. The results highlight a steady increase in publications on this topic, with a marked rise after 2015, coinciding with a global emphasis on sustainable urban development. Leading contributions came from regions experiencing rapid urbanization, such as China, the United States, and India. Top journals in this field included *Hydrological Processes*, *Urban Climate*, and the *Journal of Hydrology*. Keyword clustering revealed three dominant themes: the influence of impervious surfaces on urban hydrology, UHI effects on evapotranspiration and recharge variability, and green infrastructure and artificial recharge as mitigation strategies. The review also revealed significant regional variations in the impacts of UHI and urbanization on groundwater recharge, driven by climatic, geological, and socioeconomic factors. For instance, arid and semi-arid regions experienced more pronounced reductions in recharge rates due to higher temperatures and limited precipitation. The findings further highlight the increasing use of advanced technologies such as GIS, remote sensing, and machine learning models in urban hydrology research. These tools are crucial for mapping impervious surfaces, identifying recharge zones, and predicting future scenarios under varying urbanization and climate conditions. Policymakers and urban planners must prioritize UHI mitigation strategies as part of sustainable urban water management to ensure resilience against climate change and urbanization pressures. The present review provides a comprehensive overview of the research landscape, presenting valuable insights for researchers and policymakers to analyze the complex interactions between urbanization, UHI, climate change, and groundwater systems. Sustainable urban designs, such as green infrastructure and water management practices like permeable pavements and rainwater harvesting systems, can mitigate adverse effects. Some studies suggest that urban environments can increase recharge under specific conditions, such as through managed storm water systems. Balancing urban growth with groundwater conservation efforts is essential. Comprehensive models that incorporate both hydrological and anthropogenic factors are urgently needed to analyze and mitigate the impacts of urbanization on groundwater resources effectively.

Keywords: *Urbanization, urban heat island, groundwater recharge, sustainability*

VARIABILITY OF THE SPRING ARCTIC SEA ICE AND ITS IMPACT ON INDIAN SUMMER MONSOON: A HYDROLOGICAL PERSPECTIVE

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Recent studies have identified the Arctic summer sea ice and Indian summer monsoon (ISM) as pivotal tipping elements within the climate system. Tipping elements are critical components of the Earth's climate system that can undergo abrupt and irreversible changes once they cross a critical threshold. Such elements of the climate system significantly influence the biosphere and population. The decline of Arctic Sea ice since the beginning of satellite monitoring underlines the reality that the Arctic is highly vulnerable to global warming. The seasonal dynamics of Arctic Sea ice play a crucial role in regulating the global climate, and it substantially affects the local and regional climate. The sea level changes and increase in extreme weather events in the form of heat waves and floods over Europe are a few examples of the impact of Arctic Sea ice reduction. On the other hand, the ISM, which occurs annually from June to September, is characterized by variability in rainfall, often leading to floods and droughts that impact groundwater storage. These hydrological extremes including floods and droughts, referred as an events having a relatively lower probability of occurrence, significantly impact socioeconomic activities and ecosystems across the World. Any changes in the ISM characteristic features would significantly affect the freshwater availability and the livelihoods of the population. Various ocean-atmospheric processes, including the El Niño-Southern Oscillation, Indian Ocean Dipole, and Eurasian snow cover, are considered to contribute to the ISM rainfall variability through the process known as teleconnections. In the past years, only a few studies acknowledged the existence of teleconnections between the ISM and Arctic Sea ice. Climate model studies predicted that the frequency of extreme weather events associated with the Indian monsoon may increase due to global warming, which would affect the Arctic Sea ice. Therefore, the current study seeks to investigate the existence of a teleconnection between the Spring Arctic Sea ice variability and the subsequent ISM during June-September.

Past studies have indicated that the decline of Arctic Sea ice began during the late 1970s, with a marked reduction occurring after 2000. Similarly, the time series of interannual variability of the ISM illustrates an increase in drought years after mid-1990s. This study is designed into parts focusing on the periods before and after 2000. The first part of the study examines fifty years of data from 1951-2000, where study investigates the period during which there was no sudden decrease in Arctic Sea ice or monsoon. The variability of sea ice concentration and atmospheric circulation changes over the Arctic region during spring (March-May) and the interannual variability of the ISM rainfall during (June-September) over the Indian monsoon region is analyzed. To establish a clear understanding of the teleconnection between Arctic Sea ice and the ISM, various methodologies including anomaly computations, the student-t test, standardization, and time series analysis, are carried out in this study. Observational, satellite and reanalysis datasets from multiple sources are analyzed. The atmospheric parameters are from the monthly National Center for Environmental Prediction/National Center for Atmospheric Research reanalysis dataset, sea ice and sea surface temperature data from the Hadley Centre Sea Ice and Sea Surface Temperature data set, and the daily gridded precipitation dataset (0.25 x 0.25^{o}) from the India Meteorological Department over the period of 1901-2023.

A close examination of the interannual variability of the ISM rainfall during 1951-2000 shows seven strong monsoon years and eight weak monsoon years. Composite analysis of flood and drought years, together with the analysis of various datasets during 1951-2000 illustrates that in addition to the North Atlantic Sea surface temperature and circulation changes, the Eastern Arctic Sea ice variability during spring significantly influences the onset and progress of the ISM. A comprehensive analysis of datasets spanning fifty years from 1951-2000, focusing on the Spring (March-May) Arctic Sea ice, Atlantic atmospheric circulation changes, and the interannual variability of the ISM rainfall (June-September) were carried out. The findings indicate that, together with the North Atlantic Sea surface temperature and atmospheric circulation, Eastern Arctic Sea ice variability during spring plays a crucial role in influencing the onset, progress, and hydrological cycle of the ISM. This evidence highlights a significant teleconnection between the Spring Arctic Sea-Ice and the ISM. Incorporation of climate model simulations and further analysis with satellite, reanalysis, observational datasets, are expected to enhance the understanding of the physical processes involved in this relationship.

Keywords: *Arctic sea ice, Indian summer monsoon, groundwater, sea surface temperature, teleconnection*

LAND USE CHANGES AND THEIR IMPACT ON GROUNDWATER SUSTAINABILITY IN NARKHED-PANDHURNA, CRITICAL ZONE OBSERVATORY, CENTRAL INDIA

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Groundwater is a vital resource for agriculture, horticulture and domestic use in arid and semi-arid regions, where there is limited surface water availability. The Narkhed-Pandhurna Critical zone observatory of CSIR-NEERI is located in agriculture intensive watershed of Central India. The region is heavily dependent on groundwater for agro-horticulture practices, predominantly orange orchards and other crops. However, over extraction of groundwater has resulted groundwater stage development of 100.16%. The changes in land use pattern, increasing population, and shift in agricultural practices significantly influences the hydrologic cycle, as these factors impact groundwater recharge as well as groundwater extraction. Substantial decline in groundwater has been observed in the watershed due to expansion of agriculture, especially the change of horticulture areas to agriculture land, forest degradation and minimal changes in built-up areas. The present study attempts to investigate the impact of change in land use patten on groundwater availability. The groundwater monitoring data and satellite imagery were analysed to understand both spatial as well as temporal variations in land use change and groundwater levels. The supervised classification using Landsat-8 data were used to analyse the changes in land use/cover (LULC) for the years 2005, 2010, 2015, 2020 and 2024. The land-use have been classified into five distinct class agriculture, horticulture (orange orchids), forest, barren land and built-up areas. The groundwater level data were collected from monitoring wells and hand pumps throughout the study area during the pre- and post-monsoon seasons. Groundwater data were correlated with land use patterns to understand the how shifts in land use especially changes horticulture, agriculture, forest and barren land, influenced groundwater levels. The investigation develops a hydrological framework to further comprehend groundwater replenishment trends, particularly in relation to agriculture practices and land cover. The analysis of land use data indicates significant changes including a shift from horticulture (orange orchids) to agriculture land. Loss of forest cover has also been observed while the built-up areas remained largely unchanged. This alteration from orange orchards, that require less water, to agricultural crops that require frequent irrigation, particularly during the dry season, is leading to increased groundwater extraction. Forest degradation has contributed to issue of decline in groundwater levels, as forests and vegetation play crucial role in groundwater recharge via natural infiltration. The coupled effect of loss of vegetation and forests leads to reduction in groundwater recharge during the monsoon periods.

The analysis reveals that the during pre-monsoon season, the area experiences significant decline in groundwater levels, while groundwater levels during the post monsoon season are observed to improve due to precipitation. However, the area has not exhibited recovery rates comparable to the pre monsoon depletion rates. This indicates that monsoon recharge is insufficient to compensate the high groundwater consumption driven by agriculture demands. Both horticulture and agriculture seem to be the primary contributors to this depletion. as irrigation requirements exceed the natural recharge ability. The study highlights the impact of land use changes on groundwater in the Narkhed-Pandhurna critical zone observatory region particularly the conversion of horticulture land to agriculture land, degradation of forests and elevated groundwater demand due to irrigation. A substantial reduction in the Groundwater levels have been observed during the pre-monsoon season, which is vital for irrigation. The forest degradation has further contributed to reduction in groundwater by impacting the natural processes for groundwater recharge. The declining groundwater levels indicate an imminent threat to the region's agro-horticultural productivity and water security. In order to restore the balance between the groundwater resources and land use, it is critical to implement effective irrigation systems, adopt rainwater harvesting methods, rejuvenate degraded lands, and, restore and conserve forests. These steps would contribute to restore the natural processes that support groundwater recharge and sustainability. Policymakers ought to prioritize combining land use management and water conservation techniques to make certain that future land use changes do not worsen the existing water crisis. This study provides insight into the air-plant-soil and water continuum in the context of land use changes, groundwater dynamics and ecosystem health. The findings highlight the urgent need for sustainable water management and conservation strategies to mitigate land degradation, protect ecosystems and ensure long term resilience of agricultural productivity, ecological systems and the water resource security in the region.

Keywords: *LULC, groundwater recharge, orange orchards, water conservation, central India*

HIGH-RESOLUTION CLIMATE PROJECTIONS FOR GROUNDWATER SUSTAINABILITY IN THE HIMALAYAS USING WRF-BASED DYNAMICAL DOWNSCALING

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The Himalayas and their surrounding regions are ecologically sensitive and climatically significant areas, often referred to as the "Third Pole" due to their crucial role in sustaining the global hydrological cycle. They serve as a vital water source for billions of people, supporting agriculture, drinking water supplies, and energy production across Asia. However, these regions are highly vulnerable to the impacts of climate change, evident in the increasing frequency and intensity of extreme weather events such as heavy precipitation, flash floods, and glacial retreat. These climatic changes directly affect the groundwater systems, which are intricately linked to precipitation and surface hydrology, posing challenges to water resource management and security. Accurately assessing the impacts of future climate change on groundwater recharge and availability in the Himalayas is critical for developing sustainable management strategies. Yet, the complexity of the region's topography and climatic variability presents significant challenges. Global Climate Models (GCMs), including those used in the Coupled Model Inter-comparison Project Phase 6 (CMIP6), are valuable for studying large-scale climate processes. However, their coarse spatial resolution on the order of hundreds of kilometers limits their capacity to capture localized climatic phenomena such as orographic precipitation, glacial melt, and localized storm systems, which are pivotal to groundwater dynamics in mountainous regions. This limitation introduces uncertainties in regional and local climate projections, rendering them less effective for guiding groundwater management strategies.

Dynamical downscaling, a technique that enhances the spatial resolution of climate projections, provides a robust solution to address these challenges. By employing high-resolution regional climate models (RCMs) such as the Weather Research and Forecasting (WRF) model, it becomes possible to bridge the gap between global climate outputs and the need for detailed regional insights. The WRF model is particularly well-suited for this purpose due to its flexibility, detailed physical parameterizations, and proven ability to simulate complex climatic processes over mountainous terrain. Numerous studies have demonstrated its effectiveness in improving the representation of regional climate variability and extremes, especially in regions like the Himalayas, where topography plays a dominant role. In this study, the WRF model is used to dynamically downscale CMIP6 climate projections over the Himalayas and surrounding regions. The focus is to produce high-resolution climate datasets capable of informing groundwater studies. By resolving topographically driven processes and localized climatic phenomena, this approach offers a more accurate representation of factors affecting groundwater recharge, such as seasonal precipitation patterns, temperature extremes, and glacial melt contributions. Historical climate data, including observations and reanalysis datasets, are used to validate the WRF model’s performance, ensuring reliability in its projections.

The results demonstrate the significant advantages of high-resolution downscaling in capturing localized precipitation and temperature patterns. For instance, the WRF model effectively resolves orographic precipitation processes, showing improvements over raw CMIP6 outputs in simulating monsoonal variability and extreme weather events. These improvements are critical for understanding changes in precipitation intensity, duration, and distribution, which directly influence groundwater recharge rates. The model also enhances the representation of temperature extremes, which are pivotal for understanding the dynamics of snowmelt and glacial retreat, key contributors to downstream aquifer recharge. The downscaled climate projections reveal significant shifts in precipitation seasonality and intensity under future scenarios. These changes have profound implications for groundwater systems. An increase in heavy precipitation events may lead to enhanced surface runoff, reducing infiltration and recharge potential in some areas. Conversely, warming-induced glacial melt may temporarily boost groundwater recharge in downstream regions, though this benefit is likely to diminish as glaciers retreat further. Such findings underscore the need for adaptive strategies that account for spatial and temporal variability in recharge processes, particularly in areas reliant on seasonal snowmelt and glacial contributions. Integrating these high-resolution climate projections with groundwater models provides valuable insights into the potential impacts of climate change on aquifer dynamics. Initial analyses suggest a decline in recharge rates in the western Himalayas, driven by reduced winter precipitation and increased evaporation due to rising temperatures. Meanwhile, the eastern Himalayas exhibit more complex patterns, influenced by intensified monsoonal activity and changes in land use. These spatial variations highlight the importance of localized studies to inform region-specific groundwater management strategies.

The importance of high-resolution climate projections for groundwater studies cannot be overstated. They provide critical insights into recharge dynamics by resolving fine-scale climatic processes that are essential for accurate hydrological modeling. This is particularly relevant in the Himalayas, where groundwater resources are vital for sustaining agricultural productivity and meeting the water demands of rapidly growing populations. Moreover, such projections enable more precise risk assessments for groundwater security, helping to identify areas vulnerable to depletion or contamination due to climate extremes. By informing the design of adaptive management strategies, including managed aquifer recharge and drought mitigation plans, high-resolution projections contribute significantly to regional water security. This study highlights the transformative potential of WRF-based dynamical downscaling in addressing the limitations of coarse resolution GCM outputs for groundwater applications. By capturing the intricate interplay of topography, precipitation, and temperature in the Himalayas, the approach provides a robust foundation for understanding the impacts of climate change on groundwater systems. Future efforts will aim to incorporate socio-economic factors, land-use changes, and policy scenarios into the modeling framework to develop a comprehensive understanding of groundwater sustainability in the context of coupled human-natural systems. Additionally, extending this methodology to other mountainous regions worldwide could significantly enhance global efforts to address water resource challenges under a changing climate.

Keywords: *WRF model, dynamical downscaling, CMIP6, groundwater recharge, climate change, high resolution projections*

CLIMATE CHANGE IMPACT ASSESSMENT ON GROUNDWATER RECHARGE IN NARSINGHPUR DISTRICT OF MADHYA PRADESH, INDIA

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Climate change, which has now become a reality, is one of the biggest challenges facing the world today and almost all sectors are ought to be impacted. Water is one of the key sectors that is likely to be impacted through which other water dependent sectors like forest, health, urban, and agriculture sectors may also be impacted. Groundwater is one of the major sources of freshwater particularly in major parts of India and largely caters to both domestic and irrigation demands in a big way. Climate change impacts on the groundwater system could affect the freshwater supplies leading to sustainability issues. Climate change can affect the groundwater recharge and storage due to changes in soil infiltration, deep percolation and higher evaporative demand owing to rising temperatures. The future changes in the groundwater storage could affect the base-flow contribution to streamflow and may also alter the groundwater availability for irrigation and domestic use. The impacts of the climate change on the groundwater recharge are generally based on hydrologic modelling studies. The groundwater models are calibrated and validated using the observed climate and groundwater datasets and thereafter driven using the General Circulation Models (GCMs) based climate data for multiple future climate scenarios. GIS-based Water and Energy Transfer between Soil, Plants and Atmosphere under quasi-Steady State (WetSpass) model has been used with ArcGIS to estimate the groundwater recharge using future climate datasets at 0.25^ox0.25^o resolution from 13 GCMs under two future climate scenarios viz., SSP245 and SSP585. The model uses both physical and hydro-meteorological inputs including soil texture, digital elevation model (DEM), land use/cover, temperature, precipitation, potential evapotranspiration, and groundwater depth. WetSpass was initially setup, calibrated and validated using IMD gridded precipitation at 0.25^ox0.25^o resolution and IMD gridded temperature at 1.0^ox1.0^o resolution. The frequency of very hot days (MaxT > 40^oC), hot days (MaxT > 35^oC), very hot nights (MinT > 25^oC) and tropical nights (MinT > 20^oC) are all projected to increase substantially in future whereas the number of cold nights (MinT < 10^oC) is projected to decrease significantly. This clearly indicates a warming in the study area in future as a direct consequence of climate change. The average annual rainfall is projected to increase considerably during all future time periods under SSP245 and SSP585 future climate scenarios. Higher groundwater recharge is projected in future in the Narsinghpur district as evaluated using WetSpass model mainly due to the increase in rainfall. The higher groundwater recharge may result in higher groundwater levels in future assuming that there may not be significant increase in the groundwater draft in future. Also, the groundwater recharge is projected to be marginally higher under SSP245 scenario as compared to SSP585 scenario.

Keywords: *Climate change, groundwater, groundwater recharge, modelling*

HYDROLOGICAL ANALYSIS OF SURFACE RUNOFF ESTIMATION IN BALLIA DISTRICT FOR SUSTAINABLE WATER RESOURCE MANAGEMENT

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Accurate estimation of surface runoff is a crucial component of hydrological studies and is essential for the sustainable management of water resources, flood mitigation, and groundwater recharge. Surface runoff is a key process that directly influences various hydrological events, including flood risks, water availability, and the overall water cycle. Among the numerous methods available for estimating surface runoff, the Soil Conservation Service Curve Number (SCS-CN) method, developed by the United States Department of Agriculture (USDA), has gained significant prominence due to its simplicity, adaptability, and reliability. This method is highly valued for its ability to integrate key factors such as land use, soil type, and antecedent moisture conditions (AMC) in estimating runoff, making it suitable for a wide range of environmental conditions and land-use scenarios.

This study applies the SCS-CN method to estimate surface runoff in Ballia District, located in the northeastern region of Uttar Pradesh, India. The district is characterized by diverse land-use patterns and heterogeneous soil types, offering an ideal setting for testing the applicability of the SCS-CN method in a complex environment. A detailed land-use and land-cover (LULC) analysis of the district was performed using high-resolution Landsat-8 satellite imagery from the year 2020. The LULC classification revealed that agricultural land is the dominant land-use type, occupying approximately 71% of the total area of the district. Built-up areas, including urbanized regions and infrastructure, account for around 16% of the total area. Other land-cover types, such as water bodies, barren land, scrublands, and vegetated areas, were also identified and played an important role in runoff estimation.

To estimate surface runoff, the study incorporated a five-day antecedent rainfall dataset to determine the antecedent moisture condition (AMC) for each land-use category. AMC is a critical factor in adjusting the curve numbers (CNs) assigned to different land-use types. Higher soil moisture conditions generally increase runoff potential, and this dynamic relationship was considered while assigning CN values to various land-use classes based on their respective Hydrologic Soil Group (HSG) classifications and AMC levels. The integration of these factors allowed for a comprehensive runoff estimation for Ballia District using daily rainfall data collected over a ten-year period (2001–2010). The analysis of rainfall patterns demonstrated significant temporal variability in runoff volumes, with the highest runoff occurring during the monsoon months, particularly from June to September.

The results of the runoff analysis revealed clear seasonal fluctuations, with the highest runoff occurring in July, when a total runoff volume of 358 million cubic meters (MCM) was recorded. This was followed by a decrease in runoff volume in August (233 MCM) and September (66 MCM), with seasonal variation aligning with the region’s monsoon rainfall patterns. The total annual average rainfall in Ballia District was approximately 1207 millimeters, of which around 20% (approximately 238 mm) contributed to surface runoff.

The remaining rainfall either infiltrated the soil or was lost through evapotranspiration, underscoring the critical role of vegetation and soil properties in regulating runoff and maintaining water retention within the landscape.

The study highlighted that agricultural land, predominantly composed of soils classified in Hydrologic Soil Groups C and D, contributed significantly to surface runoff due to its relatively low infiltration capacity. This effect was particularly pronounced during the monsoon season when intense rainfall events lead to substantial runoff. In contrast, built-up areas, characterized by impervious surfaces such as roads and buildings, contributed even more to surface runoff as these surfaces completely eliminate infiltration and increase the volume of surface flow. On the other hand, vegetated areas and water bodies were identified as natural buffers that promote infiltration and reduce runoff, demonstrating the positive impact of these land covers on groundwater recharge and water retention.

The findings of this study underscore the importance of managing land use and land-cover types to mitigate runoff and improve water retention. Sustainable land-use practices, such as implementing soil conservation measures, increasing vegetative cover, and incorporating rainwater harvesting systems, can significantly reduce surface runoff and enhance groundwater recharge. By managing the spatial distribution of land-use categories, it is possible to balance runoff generation and water retention, promoting both agricultural productivity and water resource sustainability. These findings also highlight the necessity of integrated water management strategies that consider both surface and subsurface water resources to ensure long-term water security.

This research demonstrates the applicability and effectiveness of the SCS-CN method in estimating surface runoff in Ballia District and provides valuable insights into the interplay between land use, soil characteristics, and hydrological processes. The study emphasizes the need for sustainable land-use planning, hydrological management, and water conservation strategies to mitigate runoff, reduce flood risks, and enhance groundwater recharge. The findings further suggest that integrating scientific analysis with practical interventions can lead to more effective solutions for addressing the challenges posed by water management, particularly in regions facing challenges related to water availability, climate variability, and changing land-use patterns. By incorporating both scientific methodologies and actionable water management strategies, the study proposes an integrated approach to address the ongoing challenges of water resource management, agricultural planning, and groundwater sustainability, especially in the context of rapidly changing climatic and land-use conditions.

This study not only demonstrates the robustness and adaptability of the SCS-CN method for surface runoff estimation in a complex region like Ballia District but also provides actionable insights for the sustainable management of water resources. The integration of remote sensing data, GIS-based land-use analysis, and the SCS-CN method offers a powerful framework for understanding runoff dynamics and informs the development of long-term strategies for sustainable land and water management in regions facing similar challenges.

Keywords: *Surface Runoff, SCS-CN, LULC, hydrologic soil groups, remote sensing*

CLIMATIC IMPACTS ON GROUNDWATER RECHARGE ESTIMATES FOR INDIAN GANGA BASIN (IGB)

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Groundwater (GW) recharge is the main forcing for aquifer-scale groundwater flows. It is a challenging task to quantify the spatial and temporal variability of GW recharge. It is an important component of aquifer water balance and extremely sensitive to climatic and anthropogenic stressors like groundwater extractions. Sustainable take of groundwater depends largely on the amount of water annually replenished through recharge. As the world's largest consumer of groundwater for irrigation, India is highly vulnerable to climate change impacts, making it crucial for water managers to understand groundwater recharge patterns. Despite the groundwater contributing to India's GDP, the estimations of recharge rates remain constrained, owing to the intricate nature of recharge mechanisms and the feasibility of practical measurement techniques. Traditional means of estimating groundwater recharge rely on the use of chemical tracers, isotropic analysis, and lysimeters all of which are limited by spatial and temporal resolutions. Several studies have also examined groundwater recharge variability by using a combination of GW level fluctuations, satellite-derived data, data-driven and physics-based numerical models.

Realistic representation of groundwater dynamics in Land Surface Models (LSMs) have received significant attention by the research community. LSMs are known to enhance our understanding of how climate impacts surface variables, by integrating sophisticated model physics of water, carbon and energy cycles. Many studies conducted over the Indian Ganga Basin (IGB) region, showed a consistent decrease in groundwater storage, driven largely by anthropogenic influences such as intensified agricultural activity. Existing studies over IGB have quantified GW recharge using empirical water balance, isotope analysis, in-situ water level, satellite data and hydrological models. However, there is a dearth of studies using LSMs that considered land-atmospheric interactions for the recharge estimation.

Every LSM differ in the representation of mass (water), energy, momentum and CO^2 exchange. The present study presents preliminary results of GW recharge estimates using the Noah-MP (Multi Parameterization) LSM that was developed based on the Noah land surface model. The latest Noah-MP model has options to choose the desired physical process (parameterization) for 10 modules (runoff, leaf dynamics, stomatal resistance, radiation transfer, etc.,), making possible for 4608 different simulations using a single Noah-MP model. This study focuses on understanding how differences in Noah-MP model structure and parameterization affect the GW recharge simulation. The main research problems addressed are: 1). Does Noah-MP provide reasonable estimates of GW recharge over IGB? 2. What are the fundamental reasons for GW recharge estimates to differ when using various runoff schemes? 3. Do the amount, seasonality, trend and spatial pattern of recharge vary based on the choice of runoff scheme? In Noah-MP, spin-up was executed using the ERA-5

Land data to bring the system to dynamic equilibrium or a stable state before starting the actual simulations. After initialization, the Noah-MP LSM was run at a 30-minute time step, thereby updating all the surface variables every half hour and the outputs were saved only every 12 hours. The model generating two outputs a day of all the surface variable have been run for a period of 15 years from 2009 to 2023, to capture long-term variations in recharge.

The LSM-derived recharge estimates were validated by comparing them with the recharge estimated using in-situ GW-level data from CGWB. The CGWB in-situ groundwater level data for the IGB has been filtered to retain only those wells with at least four consecutive observations, for validation purposes. The point GW recharge has been calculated by the difference in water level fluctuations assuming constant specific yield. The resulting in-situ GW recharge data were fitted to different variogram models, with the spherical variogram model providing the best fit (highest R-squared value). Consequently, kriging with a spherical variogram model was used as the interpolation technique, creating spatially varying annual and seasonal recharge datasets for the IGB.

Preliminary results shall be presented for the simulated GW recharges obtained from the multi-model Noah-MP towards selecting the best parameterization schemes for the IGB region. Results reveal a good correlation of LSM-derived recharge during monsoons. As the LSM models do not have provisions to include anthropogenic activities, the non-monsoonal abstractions were not reflected in the modelled recharge. The Noah-MP recharge estimates were found to effectively capture the spatial patterns observed in in-situ recharge and precipitation datasets, thereby supporting their reliability. These spatio-temporally continuous recharge estimates can serve as valuable inputs for high-resolution groundwater models, facilitating the simulation of surface and groundwater interactions. These model estimates could help communities better understand and adapt to climate-induced shifts in groundwater availability, offering a proactive approach to water scarcity. Even though the sub-surface physics of the LSM is optimized for IGB, its future scope can be further improved by governing limitations like irrigation modules and static land cover data. The recharge due to the flooded irrigation in non-monsoon seasons cannot be modelled, due to the lack of an established crop map for the study region. And also, the extant LSMs does not precisely depict surface roughness, surface albedo and leaf area index as the change in land cover is not considered.

Keywords: *Land Surface Model (LSM), groundwater recharge, Indian Ganga basin (IGB), climatic variations, sustainable water management, groundwater depletion*

INFLUENCE OF CLIMATE CHANGE ON MILAM GLACIER DYNAMICS (GORI GANGA RIVER BASIN, CENTRAL HIMALAYA, INDIA)

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The Himalayas are among the most ecologically sensitive and fragile regions on Earth. This region is warming at a rate exceeding the global average, making climate change a significant threat to both the local environment and interconnected ecosystems. Growing concerns about global warming have sparked widespread scientific interest in the behaviour of glaciers. Numerous studies have confirmed that glacier melting has accelerated over the past three decades across many mountain ranges worldwide, including the Arctic and Antarctica, and is now occurring at an unprecedented rate. The rising global temperature is having devastating effects, including accelerated glacier retreat, glacial lake outburst floods (GLOFs), global mean sea-level rise, altered precipitation patterns, an increase in extreme disaster events, and shifts in biodiversity. Despite these alarming trends, a critical knowledge gap remains regarding how the Himalayan cryosphere system will respond to these environmental changes. Therefore, understanding the mechanisms and behaviour of the Himalayan cryosphere is essential for quantifying the influence of climate change and assessing future water availability.

The present study focuses on assessing the evident effects of climate change on the Milam Glacier, which originates from Trishul Peak (7,001 m a.s.l.) in the Gori Ganga River Basin, Uttarakhand (Pithoragarh district). The Milam Glacier catchment spans an area of 235.28 km^2, with a total glacierized area of 66.45 km^2. As the second-largest glacier in the Kumaon division of Uttarakhand, Milam Glacier is the principal glacier of the river basin, extending 16.55 km in length with an approximate area of 52.7 km^2, and ranging in elevation from 6,656 m to 3,603 m a.s.l. It is located between latitudes 30°36' to 30°28'N and longitudes 80°00' to 80°07'30"E. The glacier is oriented northwest to southeast and is fed by five major tributary glaciers: Surajkund Glacier (~5.4 km), Mangron Glacier (~6 km), Pachhmi Bamchhu Glacier (~7.7 km), Syakaram Glacier (~6.2 km), Billanlari Glacier (~5.3 km), and an unnamed glacier. The accumulation zone of Milam Glacier is well-developed with steep slopes, and numerous transverse and longitudinal crevasses are observed near the lower accumulation zone, equilibrium-line altitude (ELA), and the upper ablation zone. However, the ablation zone is relatively narrow compared to the accumulation region and is characterized by gentler slopes. The ablation zone is covered by near-continuous rock debris and contains numerous supraglacial lakes, most of which are temporary. The Gori Ganga River catchment falls within the temperate-humid zone of India and is primarily influenced by western disturbances during winter (November to April) and the Indian Summer Monsoon during summer (June to September).

To analyse the impact of climate change on Milam Glacier dynamics and understand glacier-climate interactions, this study adopts a coupled approach that integrates in-situ/ground-based observations with space-based monitoring. The study estimated the retreat rate of Milam Glacier from 1968 to 2024 and examines the effects of climate change, particularly the formation of supraglacial lakes. Snout recession patterns were mapped using Landsat and Sentinel series satellite images supplemented by ground control points (GCPs) established during the ablation seasons of 2022–23 and 2023–24 hydrological years. The analysis revealed that between 1968 and 2024, the snout area decreased by 0.0194 km², with an average recession rate of 28.30 m per year. Additionally, the total glacier area declined by approximately 1.0 km² during this period. Furthermore, this study explores the dynamics of supraglacial lakes on the glacier surface. These lakes were mapped using the Normalized Difference Water Index (NDWI) applied to Landsat imagery for 2001 and LISS-4 imagery for 2017, 2023, and 2024. The lakes mapped in 2024 were further validated through a ground survey. The study identified a significant increase in the number of supraglacial lakes, rising from 28 in 2001 to 52 in 2017, 58 in 2023, and 72 in 2024. However, the total lake area varied over these years. In 2001, the total lake area was 0.79 km², which decreased to 0.028 km² in 2017, then increased to 0.034 km² in 2023, before slightly declining to 0.029 km² in 2024. The relatively larger lake area observed in 2001 may be attributed to the 30 m spatial resolution of Landsat imagery. The increase in the number and area of supraglacial lakes from 2017 to 2023 suggests intensified glacier melting in the ablation zone, while the slight decrease in total lake area in 2024 may be due to the fragmentation of larger lakes. Field investigations confirmed that many large lakes had disappeared and drained out by the end of the ablation season of 2023-24 hydrological year. These findings indicate a trend toward the formation of larger supraglacial lakes, which, in turn, accelerate glacier melting in the ablation zone.

The observed snout recession and supraglacial lake formation correlate with historic temperature and precipitation trends, derived from CORDEX and GLDAS datasets, respectively. Statistical analysis reveals that between 1968 and 2024, the average valley temperature increased from 5.69 °C to 7.63 °C, while annual precipitation rose by approximately 302 mm. Furthermore, an analysis of historical records suggests that between 1849 and 2017, the snout of Milam Glacier retreated by 2.90 km, with an average recession rate of 17.24 m per year. A comparison of these historical observations with present data indicates an accelerated glacier mass loss due to warmer climatic conditions, leading to an increase in supraglacial lake formation.

The findings of this study suggest that these contrasting meteorological changes have collectively influenced the dynamics of Milam Glacier and the formation of supraglacial lakes, highlighting the significant impact of climate change. This study is crucial for forecasting changes in the Himalayan ecosystem and assessing the cascading effects of cryosphere mass retreat on mountain ecosystem services and future water availability. Additionally, it helps bridge the knowledge gap in understanding contrasting climate forcings and their impact on high-altitude Himalayan watersheds. The study also provides insights into monsoonal and non-monsoonal climatic influences at a regional scale under changing climate conditions.

Keywords: *Himalayan glaciers, climate change, snout recession, supraglacial lakes, mountain meteorology*

INSIGHTS INTO THE AUGUST 2023 PUNJAB FLOODS: HYDROLOGICAL AND OPERATIONAL PERSPECTIVES

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Extreme precipitation events are intensifying globally due to climate change, often leading to unprecedented flood risks and challenges in water resource management. In August 2023, Punjab, India, experienced catastrophic flooding, impacting 11,927 villages and resulting in 65 reported fatalities. It highlighted the need to better understand the multifaceted drivers of such extreme events, especially in regions dependent on major dams. Public concerns emerged over the potential role of the Pong Dam, managed by the Bhakra Beas Management Board (BBMB), in exacerbating flood conditions downstream in Punjab. This study investigates the hydrological and operational factors contributing to the August 2023 flood events, with a focus on both meteorological conditions and operational dynamics of Pong Dam. The study area encompasses the Beas River basin and the state of Punjab, which was segmented into three zones for analysis: Beas River basin within Himachal Pradesh, Beas River basin within Punjab, and the remaining areas of Punjab. This segmentation enabled a focused analysis of rainfall patterns, soil moisture conditions, and their variations across different geographic contexts. In this study, precipitation and soil moisture data were analysed for each region to understand the hydrological setting leading up to the flood events. Additionally, hydrological simulations were conducted using the HEC-RAS model to assess flood scenarios under hypothetical “no-dam” conditions, providing insights into potential impacts without regulated outflows from Pong Dam. A detailed analysis of inflow and outflow dynamics at Pong Dam was carried out to assess how authorities managed the intense inflows during the peak periods of July and August 2023, as well as to evaluate the potential impact of these releases on downstream flooding.

Our analysis revealed that the baseline for the August floods was set by the intense rainfall experienced upstream of Pong Dam in July 2023. Specifically, the state of Himachal Pradesh experienced an intense period of precipitation between July 8th and July 12th. During these five days, the region recorded an extraordinary 224.1 mm of rainfall, a volume substantially surpassing the typical 42.2 mm expected for this period. This represents an anomaly of 431% above the average rainfall. The excessive precipitation during this time notably elevated soil moisture levels and contributed to increased inflows into Pong Dam, thereby creating critical preconditions that amplified flood risks. The SMAP soil moisture analysis indicated elevated moisture levels both at the surface (0-5 cm) and in the root zone (0-100 cm) across the study area. In August, the pattern of intense rainfall events continued, resulting in substantial and sustained inflows into Pong Dam over consecutive days. On August 13th and 14th, strong negative vertical wind velocities were recorded in upper Beas River Basin, with values of -1.6 Pa/sec and -1.92 Pa/sec, respectively. These negative velocities indicate significant upward wind movement, signaling the formation of strong upwelling zones. This atmospheric condition likely contributed to intense convective activity, further enhancing the heavy rainfall events over the region. Soil moisture values in the root zone over the Beas

Basin in Himachal Pradesh peaked on August 14th and 23rd, reaching 0.39 and 0.40 m^3/m^3, respectively, which aligned closely with the heavy rainfall recorded on those dates. Similar trends were observed in surface soil moisture levels. These conditions led to substantial inflows into Pong Dam, with the inflow reaching 4,058 m^3/s on August 13th, escalating to 5,907 m^3/s on August 14th, and peaking at an exceptional 12,469 m^3/s on August 15th. This surge in inflow raised the reservoir's water level to 426.54 m, approaching the maximum permissible level of 433.12 m. In response to these critical hydrological conditions, BBMB authorities maintained a controlled and phased water release strategy while balancing the dam's capacity and minimizing the downstream flood risks. The HEC-RAS analysis was conducted on the downstream sections of Pong Dam, which were divided into four key areas to capture a detailed picture of potential flood impacts. Flood conditions were specifically simulated starting from August 15, a peak period for inflows, and the observed scenarios were compared with a hypothetical "no-dam" condition. Results demonstrated that, without Pong Dam's regulation of the heavy inflows, the downstream regions would have faced a major disaster, with significantly increased flood extent, depth, and velocity. The controlled release strategy implemented by dam authorities effectively mitigated these risks, reducing the potential severity of flooding and underscoring the critical role of dam management in safeguarding downstream areas. The analysis revealed that the controlled release strategy not only mitigated the intensity of the flooding but also delayed the onset of flooding conditions, providing critical time for downstream communities and authorities to respond. This comparative approach highlights the importance of controlled inflow management in protecting vulnerable regions from extreme flood impacts.

Sentinel satellite imagery provided additional insights, illustrating extensive inundation following the August flood events. The imagery captured the expanded floodplain along the Beas River, demonstrating the widespread reach of floodwaters into previously unaffected areas. The combination of soil saturation from July rains, intense rainfall in August, and strategic dam management highlights the interplay between natural and operational factors that shaped the flood outcomes. This study emphasizes the critical role of Pong Dam operations in managing flood risks, particularly in the context of extreme precipitation events. By analysing both the hydrological setting and operational responses, this research offers a detailed understanding of how pre-existing conditions, such as elevated soil moisture, and active dam management contribute to flood severity. The insights gained from this analysis are essential for refining flood management strategies in Punjab and similar regions facing the dual challenges of intense rainfall and reliance on dam infrastructure.

***Keywords**: Punjab floods, flood modelling, dam operation, hydrological modelling, Beas basin*