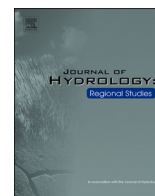




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Journal of Hydrology: Regional Studies

journal homepage: www.elsevier.com/locate/ejrh

Modelling groundwater futures under climatic uncertainty for local policy and planning: A case of quantification of groundwater resources at sub-regional level in the Ganges basin

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ARTICLE INFO

Keywords:

Groundwater modelling

MODFLOW

Climate scenario

Rainfall intensity

Gangetic basin

India

ABSTRACT

Study region: Nalanda district, Bihar, India, a sub-tropical region, and part of middle Ganga River basin.

Study focus: Assessing the impacts of climate change on aquifers' seasonal replenishment is thus crucial for planning for future local food and water security. This study looks at how future groundwater levels will be affected by climate change in relation to important functioning thresholds that are typical for aquifers that replenish periodically.

New hydrological insights for the region: The result shows the projected groundwater levels from 2018 to 2060 using the CMIP6 global climate model, using rainfall data from three GCMs selected based on their different projected scenarios of levels of high intensity rainfall. Given the key role of low intensity rainfall in groundwater recharge, we find that incorporating rainfall intensity in groundwater models can be crucial for more robust projections. Our findings also show that higher total rainfall does not necessarily equate to higher groundwater recharge or lesser groundwater declines. Instead, the least groundwater declines were found in projections, where relatively higher total rainfall was also associated with lower high intensity rainfall periods, highlighting the need for combining and comparing varied SSPs and climate models for accurate future trends. At the sub-regional level, we find that climate change could lead to maximum groundwater loss of ~ 0.8 km³ in 42 years in Nalanda district. Current trend analysis (2000–2018) already shows a negative annual groundwater balance. Even assuming no changes to current groundwater extraction rates, climate change will result in decreased groundwater levels and storage. The projection trends also reveal distinct short-term, medium-term, and long-term shifts which offer different policy windows for managing and governing the groundwater resources.

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<https://doi.org/10.1016/j.ejrh.2025.102315>

Received 9 August 2024; Received in revised form 15 February 2025; Accepted 8 March 2025

Available online 17 March 2025

2214-5818/© 2025 The Author(s).

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1. Introduction

Stress on global water resources has increased sixfold over the 20th century given increasing impacts of climate change, rising population density, and changes in food consumption habits that entail increasing energy and water consumption to support altered diets (Milly et al., 2005; Vorosmarty et al., 2000; Davamani et al., 2024). Water demand is anticipated to further increase by 1.8 % per year over the next two decades. This is likely to place increasing stress on groundwater resources, which is already in short supply in many parts of the world (WWAP, 2018). Groundwater depletion has been significant globally and given its importance as an essential freshwater source for agriculture and domestic water demand for half of the global population (Zektser and Everett, 2004), the impact of this depletion on water and food security is anticipated to be critical (Aeschbach-Hertig and Gleeson, 2012; Gleeson et al., 2012; Dalin et al., 2017). The increase in the global mean surface temperature by 0.6°C ($\pm 0.2^{\circ}\text{C}$) since 1861 and projected trajectories of continued increase of up to 4°C by 2100 (IPCC, 2014) will alter rainfall patterns, and consequently the global distribution of water, which will further contribute to current demands on groundwater resources.

India has emerged as one of the country's most significantly impacted by these trends (Tiware et al., 2009) given its high dependence on groundwater extraction to meet increasing irrigation as well as domestic water demands. The Ganges River Basin, covering much of the Indo-Gangetic Plain (IGP), is the major repository for groundwater resources in India, as well as being home to 8 % of the world's population that produce food crops on 10 % of the world's irrigated land (Siebert et al., 2015, 2010). Across the IGP, groundwater tables have significantly declined at a rate of approximately 2 cm per year (Asoka et al., 2017; MacDonald et al., 2015; Nair et al., 2021). The rapid decline of groundwater in the Ganges River Basin – and particularly in its eastern region has been a result of intensive irrigation practices, competition for groundwater resources from increasing urbanization, changes in the rainfall distribution, timing, and intensity, and increasing incidences of drought (Dangar and Mishra, 2021). Groundwater resources in the Ganga basin reduced by almost 200 km^3 between 2002 and 2016 (Dangar and Mishra, 2021). A key challenge in this region, therefore, is to enable farmers to increase their farm productivity and income while reducing risk. Since access to groundwater for irrigation offers a key strategy for building climate resilience for food production in the region, ensuring its sustainability in a changing climate assumes critical importance.

Projections of groundwater levels and recharge are found to be significantly controlled by trends in rainfall, however, the transformation of rainfall to groundwater recharge is often underestimated (Mileham et al., 2009; Kotchoni et al., 2018; Al Atawneh et al., 2021). While most groundwater modelling analyses consider total annual or seasonal rainfall as a key parameter, there is established evidence on the importance of considering rainfall intensity for more robust modelling of groundwater flow and levels since low intensity rainfall is found to contribute most to groundwater recharge (Asoka et al., 2018; Wang et al., 2015). Long-term rainfall data suggests a significant reduction in low intensity rainfall ($< 35.5 \text{ mm}$ rainfall per day) in the IGP, which is also the main source of groundwater recharge in this area (Asoka et al., 2018). Here, we thus model and analyse future groundwater projections for the region

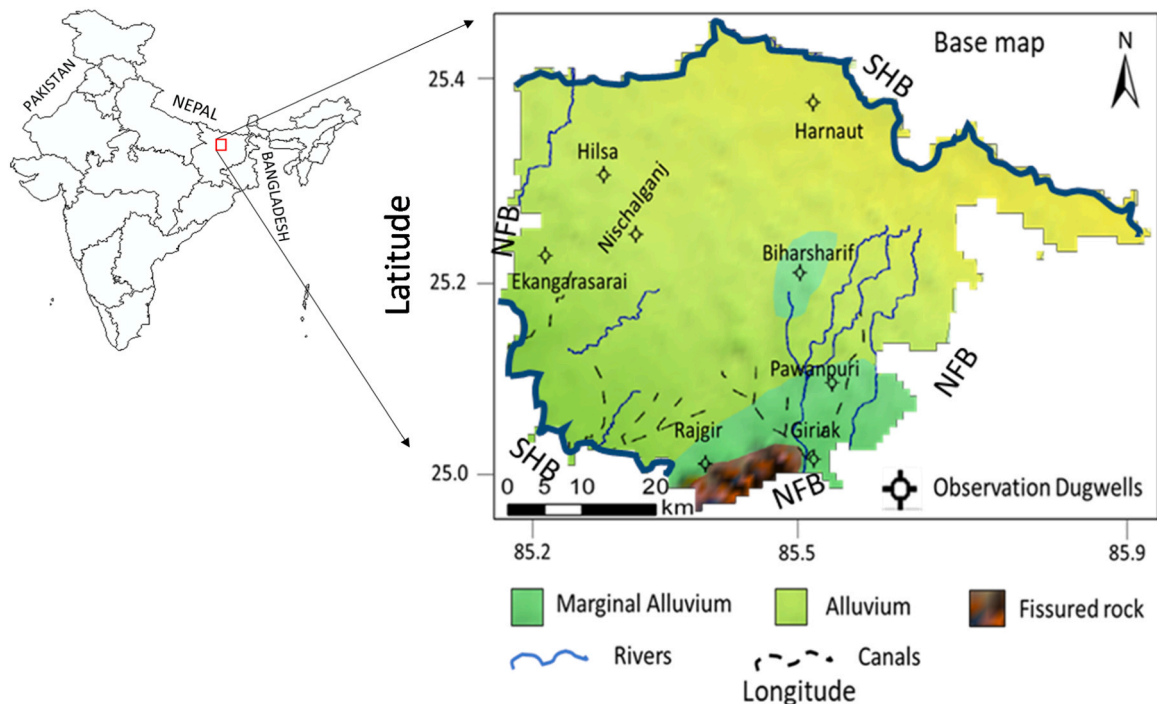


Fig. 1. Conceptualized geological and hydrological map of Nalanda district, Bihar, India. The aquifer boundary SHB and NFB are specified head and no flow boundaries.

based on trends in low intensity rainfall integrated into different climate models and emission scenarios.

Further, while most studies conducted in the Ganges River Basin focus analysis on a larger scale i.e. the basin level, the present study focuses its analysis on smaller sub-regional scale choosing the “district” as the local administrative level of assessment. In India, where water resources planning and management is a mandate of the sub-national administrative levels, most policies and planning decisions regarding groundwater issues are often relevant for implementation at the district levels. Therefore, in order to provide useful information to policy and other decision makers, it is relevant to estimate groundwater resources not only at larger scales of the watershed and basin, but also at administrative scales of policy and planning.

The primary objective of this paper is, thus, to assess the current state of the groundwater system and to anticipate the potential impact of climate change on groundwater resources by 2060 at the local administrative level. Given that water related policies are formulated and implemented at this scale, understanding these dynamics is crucial. Consequently, agricultural water resource planners can devise sustainable management strategies to navigate forthcoming climate scenarios effectively.

2. Material and Method

Groundwater in the Ganges River Basin is part of a complex system arising from the inhomogeneous anisotropic nature of water flows and the irregular shape of their boundaries (Rai, 2005). Complexity in groundwater movement can be addressed through mathematical modelling (Zienkiewicz, 1971; Rushton and Redshaw, 1979 and Rushton, 2004). Such modelling is crucial for the comprehensive understanding and efficient management of groundwater resources, as it aids in the detection of small or subtle changes in the spatial dynamics of groundwater levels resulting from both seasonal changes and system shocks. Models can assist policymakers and planners to account for the factors affecting groundwater flow, to identify areas of water deficit and abundance, and to examine interactions between these components when considering potential changes in land use management under current and future climates. The ModelMuse (Winston, 2009, 2014) interface is frequently employed alongside MODFLOW-NWT due to its open accessibility. The selection of Nalanda district in Bihar, located in eastern India, as a learning site is predicated upon examination of pertinent data regarding deficiencies in food and nutrition security, prevailing environmental pressure, and the intricate dynamics of climate-related adversities (Transforming agrifood system in south Asia (TAFFA), 2022).

2.1. Site description

Nalanda covers an area of approximately 2300 km² (Fig. 1). The administrative and hydrological boundaries of the district were determined using Government of India survey maps (SI, n.d.). The climate is sub-tropical to sub-humid, with an annual average rainfall of 975 mm, about 90 % of which occurs in the June to October monsoon season. Topography in Nalanda varies from 35 to 450 m above sea level. Approximately 90 % of the land in the district is used for agriculture, primarily for water-intensive cereal-based crop production.

Nalanda’s soils are primarily composed of flat alluvium terrain, with the exception of the Rajgir Hills (343 m above sea level) in the south, which is hard rock (CGWB, 2022). Geologically, Nalanda is divided into three zones, alluvium, marginalized alluvium & hard fractured rock. The alluvial terrain has been explored to a depth of 120–150 m and contains layered aquifers. The district is characterized by clay beds interspersed with sand of different grades. In the north of the district there are four alluvial fills with coarse sand and gravel with a depth of 100–120 m overlaid with clay at the top (Saha, 2007). Across Nalanda there is a general downwards slope towards the northeast, with the Mohana, Panchane, Falgu and Sakri Rivers flowing northeast into the river Ganges. Groundwater flow is also generally to the northeast following topology (CGWB, 2022), however there are local flows in different directions based on hydraulic gradients.

Water levels in Nalanda are monitored across 39 hydrograph stations integrated into the National Hydrograph Monitoring

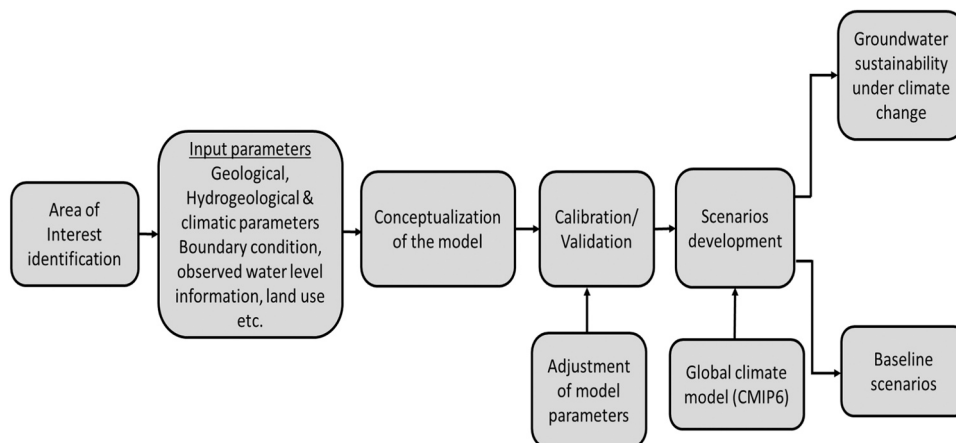


Fig. 2. The methodologic framework of the study.

Network. To calibrate and validate the groundwater model, data from uniformly distributed eight dug well stations with water-level records dating back to 2000 were utilized. The remaining 31 stations have provided data only from 2013. Analysis reveals an average decline of 1.5 m in water levels over approximately two decades. The mean water level in Nalanda stands at 3.5 m below ground level (m bgl), with a standard deviation of 1.2. Notably, the Biharsharif block, an urban area within the district, and the Rajgir area, characterized by a hard rock aquifer, exhibit deeper (~ 7–9 m bgl) water levels. (Supplementary figure; SM1).

2.2. Method

Groundwater flow modelling for Nalanda district was conceptualized using a combination of geological, hydrogeological, and climatic parameters (Fig. 2). The specific model was developed using MODFLOW-NWT with MODEL Muse 5.1.1 as a graphical interface (Winston, 2009). MODFLOW is used globally to simulate groundwater aquifer system dynamics (Winston, 2009, 2014). It uses the finite difference method to quantify the movement and distribution of groundwater components through porous media. MODFLOW is also used to forecast groundwater movement over time and as influenced by both anthropogenic and natural processes. The model is capable of simulating both steady and transient groundwater states and flows across multiple aquifer layers (Tamma Rao et al., 2012; Surinaidu et al., 2016).

2.2.1. Conceptual model

The conceptual model for this study was developed assuming the presence of different hydrological boundaries following the method of Bredehoeft (2005). Based on the groundwater head elevation map, the north boundary is considered as specified head and southwest boundary of the model as specified flux which is also known as time dependent constant head boundary. Similarly, the west and east boundaries including the hard rock area assumed no flow. The active rivers along with the canals are defined as aquifer boundaries. River network and time variant water elevation of rivers were mapped from the google earth pro. Riverbed conductance is 1000 m²/day as initial condition (Lu et al., 2022). It has been calibrated to 800–1500 m²/day.

Based on the lithological data (~13 wells) from CGWB (2022), the 2-layer aquifer model was conceptualized separated by clay layers. The first sandy clay and sand layers are considered as unconfined aquifer, while the deeper sand layer under- and over-lain by clay layers are confined aquifer (Table 1).

Nalanda district was partitioned into 500 m × 500 m cells (Fig. 3), with a total number of 9200 active cells inside the administrative boundary. June-2000 is assumed to be the initial condition and observed water level data from August 2000 to June 2013 are used for the calibration and the August 2013 to June 2018 period are considered for model validation. Seasonal stress periods are used for the period of June-2000 to June-2018 based on the observation of water level for the calibration and validation of the model. The conceptual model has been transformed into the numerical model and simulated for both steady and transient states. The steady state means pre-development stage of groundwater i.e. there is no change with time whereas the transient system observes the variation in the resources with time.

2.2.2. Model inputs

The input groundwater components of the model include groundwater recharge from rainfall & Irrigation return flow, groundwater draft, evaporation from water table, and hydraulic boundary conditions etc.

The groundwater recharge from rainfall is distributed into the model based on the geological zones. The mean reference value is taken from 0.0014 m/day (CGWB, 2022). Based on the Groundwater estimation committee 2015 (Groundwater Estimation committee report, 2015), a percentage of annual rainfall is assumed as groundwater recharge according to geological zone - 20 % in alluvium; 0.0014 m/day, 16 % in marginalised alluvium; 0.001 m/day and 8 % in hard rock; 0.005 m/day. The groundwater recharge from

Table 1

Layer specifications in the conceptual model based on lithologs (Data source: CGWB, 2022).

Parameter	Layers
	The alluvium & marginal alluvium geological zones captured two-layer aquifers (unconfined & confined aquifers) while small, fractured zone (in south of Nalanda) has only one aquifer system (Unconfined).
	Ground level: 40–282 m ASL
	Sandy Clay/saprolite layer for hard rock – Top layer including soils
	30–272 m
	ASL
Formation	First sand layer/fissured layer for hard rock area
	–10–265 m
	ASL
	Impermeable clay layer/No more fractured aquifer at this elevation
	–10–265 m
	ASL
	Second sand layer/no more fractured aquifer at this elevation
	–50–265 m
	ASL
Thickness	Aquifer I - 30–45 m
	Aquifer II - 20 –25 m

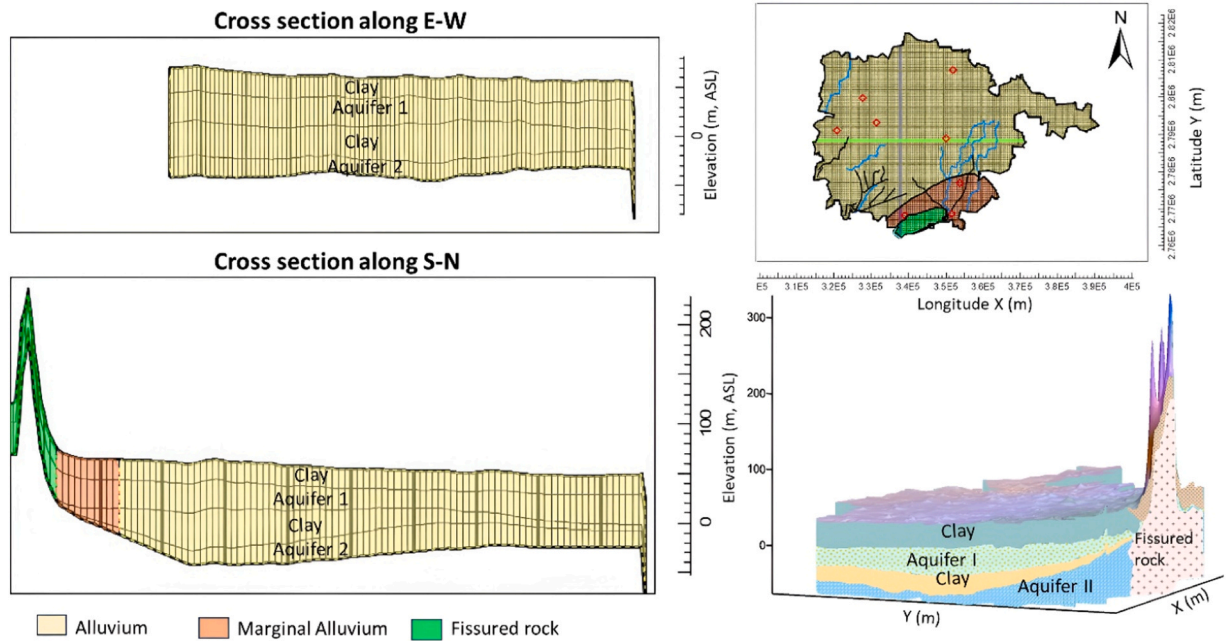


Fig. 3. Three-dimensional conceptualization of the geometry of Nalanda groundwater.

irrigation return flow is also considered based on (Groundwater Estimation committee report, 2015) recommendation (~30 % of total groundwater draft). The groundwater recharge is then calibrated manually to 0.0009 m/day (average) for alluvium, 0.0007 m/day for marginalized alluvium, and 0.0002 m/day for fractured hard rocks.

Groundwater abstraction in the district is primarily for irrigation purpose. However, domestic consumption is also considered (55 liters/person/day: $\sim 9 \times 10^{-5}$ m/day at district level) in rural and suburban areas (TERI, 2022). The groundwater draft is assigned based on the agricultural and suburban areas, considering each cell (500 m \times 500 m) as a single pumping unit (i.e. total groundwater pumping from a cell). The present rate of total groundwater draft in the study area is 0.0004 m/day (CGWB, 2022). The draft is 0.00035 m/day after the manual calibration process.

Evapotranspiration (E) from the water levels was estimated using empirical relationship ($E = 71.9z^{-1.49}$; where Z represent the depth of water level (Coudrain-Ribstein et al., 1998). The proposed method is not ideal, but the contribution of E (20 MCM/year; 3 % of total outflow) is very small in the budget and therefore will not affect the overall groundwater budget significantly (Dewandel et al., 2010). Thus, we have adopted a simple formula.

CGWB (2022) suggest wide range of aquifer transmissivity T (~ 0.7–6000 m²/day), Specific yield (0.1) and storativity (2.2×10^{-4} to 4.3×10^{-7}). The Harnaut and Noor Sarai blocks of Nalanda have maximum transmissivity. For the present study, the aquifer parameters are used as initial parameters and further these parameters have been automatically calibrated using PEST (Doherty and Hunt, 2010) under acceptable range (Table 2).

2.2.3. Model calibration and validation

Initially, the groundwater model was calibrated manually by adjusting two key components, ‘groundwater recharge’ and ‘groundwater draft’. We sequentially changed parameters within the model until an acceptable match between the calculated and observed hydraulic heads was achieved (Anderson and Woessner, 1992; Senthikumar and Elango, 2001; Singh and Woolhiser, 2022; Abdulla and Al-Assa’, 2006).

Table 2
Initial (CGWB, 2022) and calibrated aquifer characteristics.

Aquifer Parameter	Initial	Calibrated
Hydraulic conductivity (k in m/day))	Sand 25–70	35–240
Specific yield (S_y)	Fractured part - 0.2	0.1
	Sand - 0.15	0.03–0.25
Specific storage (S_s)	Fractured part - 0.01	
	Sand - $1.5E-4$	$7.8E-6-1.2E-4$
	Fractured part - $1E-7$	

2.2.3.1. Steady state. The steady state condition, with equivalent inflows and outflows and no alterations in aquifer storage, serves to benchmark the status of the aquifer before the simulation of water resources development in the district (Surinaidu et al., 2016). Under the steady state condition, groundwater recharge and draft were calibrated manually and hydraulic conductivity calibrated using PEST (Doherty and Hunt, 2010) within the acceptable limit (Table 2). The accuracy of simulated groundwater levels was verified by comparing the root mean square (RMS) error (Anderson and Woessner, 1992), with an RMSE during the quasi-steady state was 0.9 m (Fig. 4).

2.2.3.2. Transient state. In aquifer systems, reaching a steady state is often impossible due to aquifer use. We simulated our groundwater flow model under transient conditions spanning from 2000 to 2060 for current and future analysis. All layer parameters were retained as initially set and calibrated hydraulic conductivity values under steady state were subsequently used as input here. The value of S_y and S_s were kept as calibrating parameters using PEST (Doherty and Hunt, 2010) under acceptable range. The model was re-run to achieve satisfactory S_y and S_s values that adequately matched the observed and computed hydraulic heads. The computed RMSE was 2 m between simulated and observed head (Fig. 5a). The range of S_y and S_s after calibration, between 0.03 and 0.25 and $7.8E-6$ – $1.2E-4$. The fissured hard rocks represent very low S_s and S_y values.

Further the model is simulated over the period of August 2013 to June 2018 for the validation purpose. The RMSE computed was 2.5 m (Fig. 5b) and shows an adequate match between observed and simulated water level elevation (Surinaidu et al., 2016) because both calibrated and validated RMSE is below 5 %. Assessing the adequacy of model calibration and validation involves a degree of subjectivity; however, the following general criteria have been utilized to evaluate the sufficiency of calibration for this model. Calibration efforts persist until specific objectives are met: the residual mean constitutes 5 % or less of the range in observed water levels, the residual standard deviation amounts to 10 % or less of the same range and the absolute residual mean remains below 10 % of the same range. The calibration approach outlined above is based upon the concept that the model should be calibrated to discrete points where values are known rather than water level contour maps where known values are extrapolated (Konikow, 1978; Anderson and Woessner, 1992). We carried out a sensitivity analysis on the input base parameters k , S_s and S_y which determined that k is more sensitive to the model followed by S_y and S_s . With changing 10 % hydraulic conductivity, the resultant root mean square error percentage reduced 3 %. There are no significant changes in RMSE with S_y & S_s .

2.3. Projected groundwater scenarios under climate models

A state-of-the-art endeavour in climate science, the Coupled Model Intercomparison Project Phase 6 (CMIP6) encourages international cooperation among researchers to improve our comprehension of Earth's climate system. By incorporating more complex and all-encompassing climate models, CMIP6 improves on its predecessors and allows scientists to simulate a wider spectrum of climatic phenomena with increased accuracy and resolution. Comprehensive evaluations of the past, present, and future climate conditions are made possible by these models, which represent different elements of the Earth system, such as the atmosphere, seas, land surface, and cryosphere. Policymakers, stakeholders, and the general public can make evidence-based decisions to reduce risks and adjust to changing environmental circumstances by using the CMIP6 models, which are essential in this regard.

The groundwater flow model simulated the impact of climate change over the period of 2018–2060 under the business-as-usual groundwater withdrawal pattern. The recent global climate model 6 (CMIP6) has been used for future groundwater trend analysis. The bias corrected daily rainfall data (13 GCM model: NOR-ESM2, NorESM2-MM, MRI-ESM2-0, MPI-ESM1-2-LR, MPI-ESM1-2-HR, INM-CM5-0, INM-CM4-8, EC-Earth3-Veg, EC-Earth3, CanESM5, BCC-CSM2-MR, ACCESS-ESM1-5 & ACCESS-CM2) were taken from

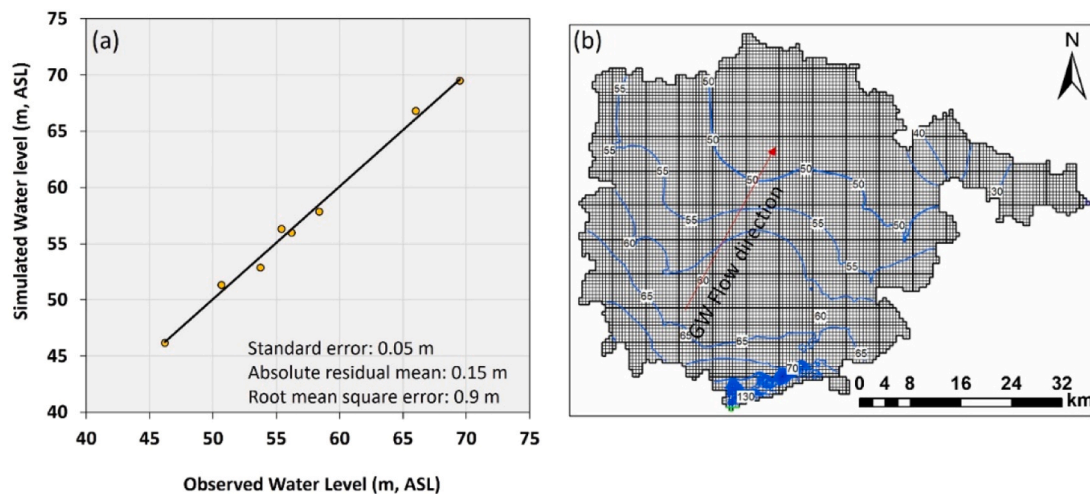


Fig. 4. (a) Comparison of observed and simulated water levels (WL) at the eight reference hydraulic heads under steady state conditions; (b) Simulated water levels (WL) contour within Nalanda district under steady state conditions.

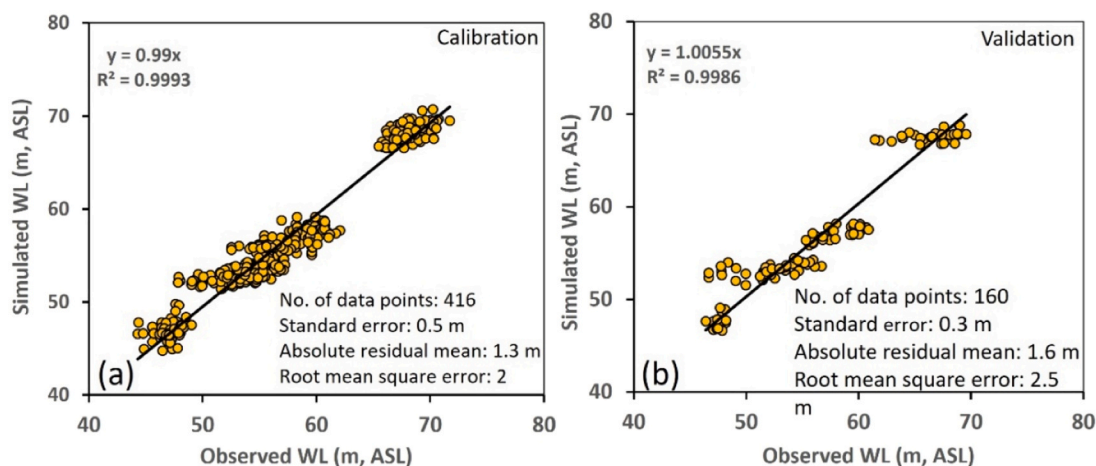


Fig. 5. Groundwater flow model calibration (2000–2013) and validation (2013–2018) by comparing observed and simulated hydraulic heads (groundwater depth above sea level) under transient state.

Mishra et al. (2020). Each model of CMIP6 has projected scenarios (shared socioeconomic pathways: SSPs) which have been classified based on the radiative forces. The SSPs consider qualitative and quantitative trends in the population growth, economic development, urbanization, and education leading to future development of nations (O'Neill et al., 2014, 2016, 2017). SSP126, SSP370 and SSP585 were used in this study. The SSP126 focus on sustainability with aggressive emission reduction, resulting in low global warming, SSP370 characterized by regional conflicts and moderate emission increases, leading to medium warming and SSP585 driven by economic growth with high reliance on fossil fuels, resulting in the highest level of global warming.

Out of 13 GCM models, three models were used for the projection of futuristic water level. These were selected based on the objective to compare scenarios of three different levels of high intensity rainfall projected by the models (highest, median, lowest levels of projected high intensity rainfall periods) - ACCESS-CM2 (suggests ~ 40 % high intensity rainfall), MPI-ESR1-2-LR (suggests ~28 % high intensity rainfall) and INM-CM4-8 (~ 16 % high intensity rainfall events). Asoka et al. (2018) suggests a strong linkage between low intensity rainfall and groundwater recharge in India. Based on the classification for rainfall intensity set by Indian meteorological department (Indian Meteorological Department (IMD), n.d.), the projected low (< 35 mm per day) and high (>= 35 mm per day) intensity rainfall events (from 2018 to 2100) were identified (see supplementary material S2) and low intensity rainfall was converted into groundwater recharge based on linear regression models (Asoka et al., 2018). The average of all 13 GCM is not considered because it averages across rainfall events of varied intensity, thus obscuring rainfall events of high or low intensity that have direct implications for groundwater recharge.

The current rainfall trend indicates a rise in the frequency of intense rainfall over short durations, attributed to the effects of climate change (Asoka et al., 2017; Dangar et al., 2021). This shift would also have an impact on groundwater recharge and trend of groundwater levels as well. Based on the average of all 13 GCM, the rainfall shows an increasing trend during 2018–2100 (see supplementary material S3). While it may be implied that such increasing rainfall would lead to increasing groundwater recharge rate, given the crucial role of rainfall intensity in groundwater recharge, this assumption may not hold true and would accordingly affect the model parameters and conditions for this analysis.

3. Results

3.1. Groundwater balance from 2000 to 2018

Between year 2000 and 2018 observed groundwater in Nalanda District declined at about 6 cm/year. Our model suggests that the depletion was a result of natural discharge through rivers, aquifer boundaries and extraction of groundwater by pumping wells

Table 3

Changes in annual average groundwater (in MCM: million cubic meter) from 2000 to 2018 in Nalanda district.

Water flow category	Groundwater in (MCM)	Groundwater out (MCM)	Groundwater balance (in - out, MCM)
Specified Head	32.50	72.714	-40.24
River Leakage	38.95	113.52	-74.62
Recharge	402.95	—	402.92
Well	—	278.33	-278.33
ET	—	20.91	-20.91
Net groundwater balance/Change in storage	—	—	-11.19

(Table 3). While groundwater levels are currently within a range of 1.5–6 m below the ground level, groundwater recharge from rainfall is inadequate to fully recharge the aquifer. This excess loss beyond rechargeable levels is primarily owed to high water extraction (~70 % of total outflow) through pumping wells. Across Nalanda, average net storage loss was 11.19 MCM year⁻¹ between 2000 and 2018 (Table 3).

3.2. Impact of climate variability on groundwater levels

The projected groundwater levels in all three climate models are based on the low intensity rainfall trends of the projected climate models (see supplementary Figure S4). The three climate models (predicting varied levels of low intensity rainfall component) and three selected SSPs (predicting different trends for quantum of rainfall as reflected in the total rainfall amount), offer us scenarios with different combinations of rainfall amount and intensity, together affecting groundwater recharge and therefore projected groundwater levels.

3.2.1. Scenario 1 (ACCESS-CM2 climate model)

Scenario 1 shows the impact of climate change based on the ACCESS-CM2 climate model (maximum levels of high intensity rainfall) on groundwater level under SSP126, SSP370 & SSP585 from 2018 to 2060 (Fig. 6). Here, the model suggests a water level decline ranging from 2 to 4 m, with the highest decline in SSP585 and least in SSP126. The trend overview for SSP126 shows a gradual decline in water level over the years, with a steep fall in the short-term, followed by a mid-term period of steep recovery of water levels, gradually tapering off in the long term. The water levels under SSP126 remain higher than those under SSP370 & SSP585 in the short- and long-term projection periods. On the other hand, SSP370 and SSP 585 exhibit more pronounced decline in water levels as compared to SSP126, despite projecting overall higher and more steeply increasing average trends in total annual rainfall across all climate models (Figure S3, supplementary). This highlights the significance of capturing rainfall intensity in the groundwater model as projections deviate from the hypotheses based on total annual rainfall amount and its linear relationship with groundwater recharge. Under this climate model with higher intensity rainfall projections, despite the increase in total rainfall volume in high emission scenarios such as SSP585, with greater fluctuation and extremes in rainfall a significant volume of the total rainfall would be lost to high intensity rainfall events reducing the rainfall available for groundwater recharge.

In both SSP370 and SSP585, baseline water levels are similar but face a steep decline over time. The SSP585 shows the steepest decline among the two other SSPs. By year 2060, the water level stabilizes but remains lower than SSP126. The steep decline and heavy fluctuations in water level is primarily seen in the early short-term period, gradually stabilizing at these low water levels with minor recovery in the mid- and long-term periods of the projection. The water level trends among three SSPs are found to replicate the low intensity rainfall trend (see Supplementary Fig. 4a).

3.2.2. Scenario 2 (MPI-ESM1-2LR climate model)

Scenario 2 shows the impact of climate change based on MPI-ESM1-2LR model (medium levels of high intensity rainfall) on groundwater level under SSP126, SSP370 & SSP585 from 2018 to 2060 (Fig. 7). In scenario 2 we find that while all three SSPs show declining trends in groundwater levels, the decline is steeper for lower emission SSP126 and SSP370 associated with lower projections for increasing trends in annual rainfall, than SSP585, contrary to scenario 1. In this climate model, with lower levels of high intensity rainfall component than in scenario 1, there is lesser proportion of the rainfall lost to high intensity events and more of the total rainfall volume is available in low intensity events for groundwater recharge. This thus gives an advantage to the high emission SSP585 associated with higher and increasing total annual rainfall trends since more volume of rainfall (see Supplementary Fig. 4b) is available

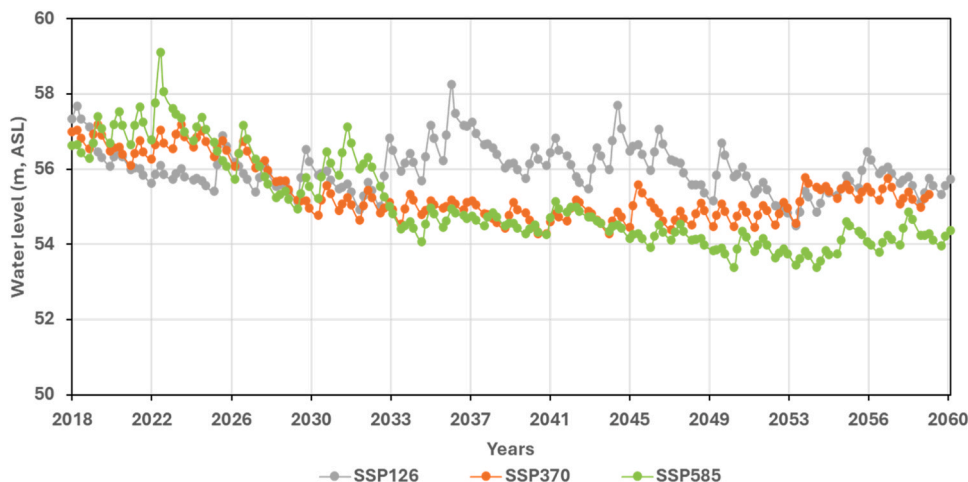


Fig. 6. Simulated average groundwater levels in Nalanda between 2018 and 2060 using the ACCESS-CM2 climate model under three SSPs.

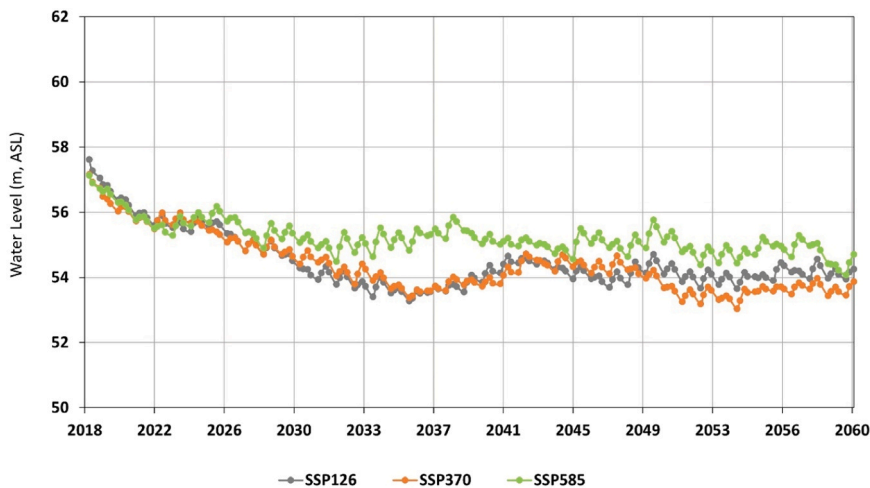


Fig. 7. Simulated average groundwater levels in Nalanda between 2018 and 2060 using the MPI-ESM1-2-LR climate model under three SSPs.

for groundwater recharge compared to other SSPs with lower total annual rainfall projection.

All three SSPs show a significant decline in the near short-term period up to 2035, followed by a mid-term period of stabilization for SSP585 and recovery for SSP126 and SSP370, and finally a decline to low groundwater levels in the long-term period of the projection. The average water level decline is around 2–3 m based on MPI-ESM1-2-LR climate model.

3.2.3. Scenario 3 (INM-CM4-8 climate model)

The INM-CM4-8 suggests minimum high intensity rainfall (or highest levels of low intensity rainfall) that contributes to climate change impact evaluation on groundwater levels (Fig. 8). The overall comparative pattern between the SSPs remains similar to scenario 2 with high emission SSP585 showing higher groundwater levels overall. In this climate model, with further lower levels of high intensity rainfall, a higher proportion of the total rainfall is available (see Supplementary Fig. 4c) in low intensity rainfall and therefore conducive for groundwater recharge thus offering an advantage to projections with higher and increasing total annual rainfall trends since more quantum of rainfall goes towards groundwater recharge than scenarios with lower amount of total rainfall.

The trends of the three SSPs are less secular and show variations between the SSPs. SSP126 and SSP585 show steep initial decline followed by a recovery within the short-term period of the projection. Whereas SSP370 shows initial stable groundwater levels followed by a steep decline within the short-term period. In the mid-term of the projection period SSP585 shows a decline, whereas SSP126 and SSP370 shows a rise in groundwater levels. The long-term period of the projection shows an increase in groundwater levels in all three SSPs recovering resource and water levels back to the baseline levels of 2018.

3.2.4. Combined comparative scenarios

The three scenarios discussed above, combining three different climate models and three SSPs, offer nine different alternative

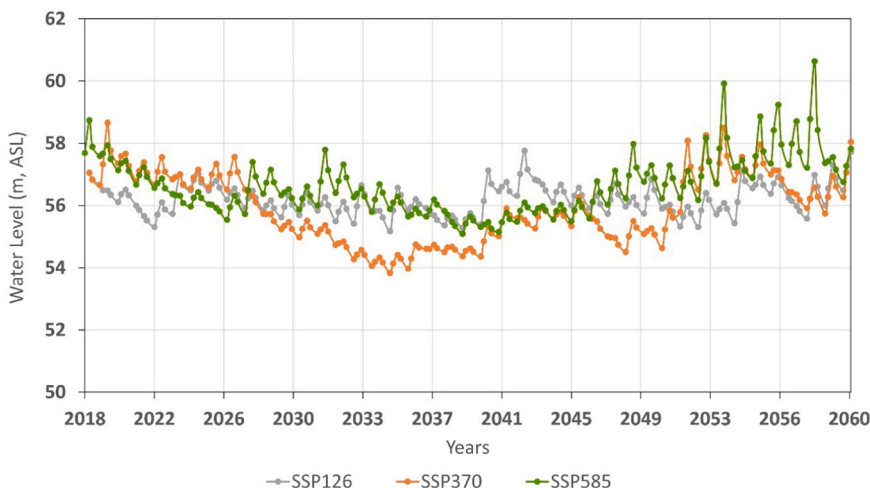


Fig. 8. Simulated average groundwater levels in Nalanda between 2018 and 2060 using the INM-CM4-8 climate model under three SSPs.

groundwater level trends and projections (Fig. 9). While looking at the three scenarios separately allow us to appreciate the combined effects of total rainfall amount and rainfall intensity on the groundwater modelling, viewing these nine alternatives comparatively helps identify the range of projected groundwater levels and trends faced by the region. Groundwater levels show the highest decline up to 3–4 m on average for the district. The maximum fall in groundwater levels is found in medium rainfall intensity-low/medium emission scenarios of MPI-ESM1–2LR model (SSP126 and SSP370) and high rainfall intensity-high emission scenario of ACCESS-CM2 model (SSP585). Whereas the minimum long-term decline is seen in all three emission scenarios under low rainfall intensity model (INM-CM4–8 model). This suggests that assumptions of linear relationships between only total rainfall (as implied by SSPs) or rainfall intensity and groundwater recharge can be overly simplistic, and the combined effects of intensity and quantum of rainfall can offer projections that deviate from these simplistic one-to-one relationships and assumptions. However, scenarios which show maximum decline show less annual fluctuations in groundwater levels and the declines are relatively secular throughout the projection period. Whereas, in the scenarios with the least long-term decline in groundwater levels, we also find very high annual fluctuations in groundwater levels leading to greater extremes and uncertainties. Finally, from viewing all the projections comparatively, we find some time periods which show distinct shifts in the trends within the larger projection timeline. We consider these to delineate short-term, medium-term, and long-term trends which may offer different policy opportunities for intervention. While in the short-term we find most projections showing similar trends with minimal deviation between them, in the long-term we find increasing deviation between the groundwater levels and trends projected by these difference scenarios.

4. Discussion

The results reveal several important insights for local scale groundwater modelling assessments.

4.1. Combined effects of rainfall amount and intensity

Firstly, we find that there is significant value in incorporating rainfall intensity considerations in the groundwater model, especially without integrated surface water model (like SWAT) in with groundwater model for the assessments under climate projections. The combined effects of rainfall amount and its distribution across different intensity of rainfall on groundwater recharge show deviations from the assumptions relating higher total rainfall with higher groundwater recharge and lower groundwater declines. As we noted, results presented in Table 4, the least declines in groundwater levels were not necessarily found in SSPs high annual rainfall projections (associated with higher emission levels), but also in SSPs with low or medium annual rainfall projections associated with lower emissions. It was the climate model with the lowest levels of projected high intensity rainfall periods that captured the least groundwater declines in the long-term. This indicates that a matrix of SSPs (with varied implications for total annual rainfall projections) and climate models (with implications for varied levels of high intensity rainfall) provide us a better understanding of future trends in groundwater levels.

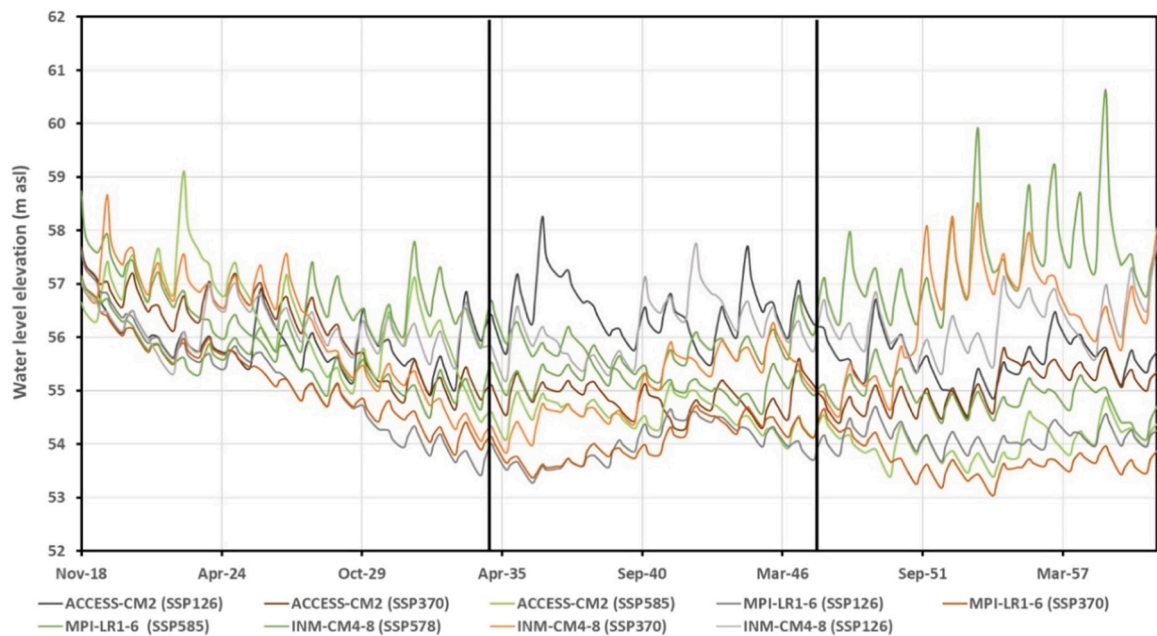


Fig. 9. Simulated average groundwater levels in Nalanda between 2018 and 2060 comparing projections using the INM-CM4–8, MPI-ESM1–2LR, and ACCESS-CM2 climate models under three SSPs.

Table 4
Matrix of climate models scenarios and groundwater trend.

Climate model Scenarios	CIMIP6 Climate Model		
	ACCESS-CM2 Model suggest 40 % High Intensity Rainfall	MPI-ESM1-2-LR Model suggest 28 % High Intensity Rainfall	INM-CM4-8 Model Suggest 16 % High Intensity Rainfall
SSP126 (Sustainability)	Medium GW decline	High GW decline	Low GW decline
SSP370 (Regional Rivalry)	Medium GW decline	High GW decline	Low GW decline
SSP578 (Fossil Fuel Development)	High GW decline	Medium GW decline	Low GW decline

4.2. Spatial groundwater drawdown

Secondly, we find that while the comparative analysis of all nine groundwater projections shows a highest decline of up to 3–4 m average for the district, a spatial analysis under a high decline projection scenario ACCESS-CM2 (SSP585) (Fig. 10), provides us a further nuanced and intensified range of groundwater decline. The spatial groundwater drawdown variation analysis within the district suggests that the northern part of the district is more exposed to depletion as compared to southern Nalanda (except the hard rock area). During year 2018, the northern area presented a maximum drawdown of around 4 m (Fig. 10a) compared to initial water level in 2000, whereas it the drawdown is further intensified, increasing to 10 m in 2060 (Fig. 10b). Also, a larger area of the district faces more intensive drawdown in the future than faced in the past observed period.

Model simulations project that the average net annual groundwater loss in Nalanda would be around –19.47 MCM per year and groundwater level is likely to decline by 2 m in the next 42 years from climate change impacts alone without considering any increase in groundwater extraction for irrigation.

The groundwater depletion of 2–3 m between 2018 and 2060 is not overly large. However, most irrigation wells in Nalanda are of shallow depth (30–40 m) and under current conditions during some dry seasons irrigation flow rates reduce due to lowered groundwater tables. Therefore, even a small decline in groundwater levels will impose additional financial costs on farmers as they seek to retain irrigation access for crop production, thus reducing profitability. Additionally, while 2–3 m decline represents the long-term decline between the two ends of the projection period, the trends show that in the interim period there are heavy annual and inter-annual fluctuations in water levels with intermittent periods of steep decline beyond 3–4 m, which can create water stress during these seasons and years.

While in this analysis, the groundwater withdrawal is sustained as business-as-usual, in ground conditions it is likely that there will be an increase in groundwater withdrawal during the winter season due to increasing trend in temperature due to climate change (Bhattarai et al., 2023). They showed that warming temperature may triple groundwater depletion rate at national scale (India) under future climate scenarios (CMIP5). Previous research has demonstrated connections between temperature & rainfall variation and groundwater levels (e.g. Asoka et al., 2017; de Graaf et al., 2017; Russo and Lall, 2017; Sivarajan et al., 2019; van der Knaap et al., 2015; van Engelenburg et al., 2018). Changes in climatic variables as a consequence of climate change also directly affect the components of groundwater systems such as groundwater-surface water interactions, groundwater flows, groundwater recharge and storage, groundwater discharge and groundwater quality (da Costa et al., 2019; Asoka et al., 2017).

4.3. Phase-wise policy implications

Finally, the trends show distinct short-term, medium-term, and long-term shifts which offer policy opportunities for managing and governing the groundwater resources in the districts so as to enable access to water resources in a sustainable manner. Broadly, the initial 15years of the projection period represents a short-term trend showing a period of steep decline in groundwater levels. This is followed by a medium-term period of some recovery in water levels (varying levels of recovery between scenarios). The long-term period covering roughly the latter 15years of the projection period reflects a return to declining trends for some scenarios and, for others, a stabilization of early groundwater levels with marginally increasing trends. It is important to note that the projected trends estimated in this analysis assume no changes in groundwater extraction and therefore increases in groundwater demand and extraction in the future will exacerbate these trends.

From a policy perspective, the initial period of steep declining trends will require stronger regulation and monitoring of groundwater extraction supplemented by strong initiatives for groundwater recharge. This steep groundwater decline will also critically affect groundwater access for irrigations for farmers depending on shallow tubewells with implications for crop production. The period will benefit from complementary policy initiatives that promote community-based water allocation for demand management and equitable distribution at local levels. Cropping patterns may be affected by the lower irrigation access (under status quo of irrigation practices and technology) which will require more support for wider market linkages for alternate crops and improved access to social safety net policies for food access through public distribution systems. The medium-term trend of recovery in groundwater levels may be faced with improved access to groundwater irrigation which will facilitate extraction and may negate the resource gains from the recovery in groundwater levels. On the other hand, this phase also shows improved conditions for groundwater recharge.

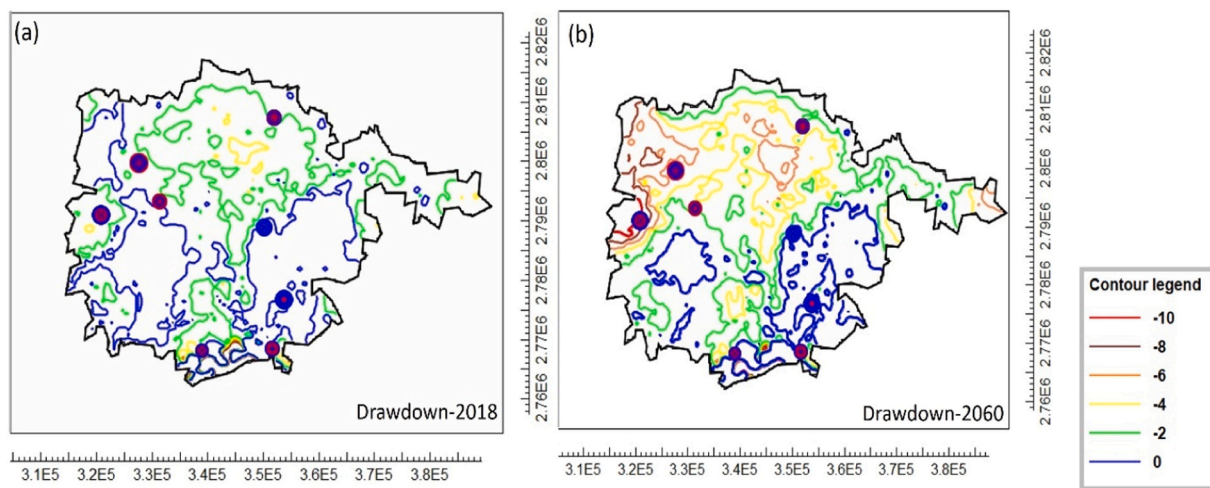


Fig. 10. Spatial groundwater drawdown distribution (in meters) for 2018 (a) & (b) 2060 within the Nalanda district under ACCESS-CM2 (SSP585).

Therefore, this phase will benefit from policies that lift harsh regulations that limit access to groundwater but strengthen initiatives for groundwater recharge. This will ensure that farmers can capitalize on both the improved irrigation availability and consequent production benefits, as well as the increased groundwater recharge potential during this period to sustain the recovery in groundwater levels.

Finally, in the long-term period we find two different conditions – one of secular declining trends for some scenarios, while another where we see a marginally increasing/recovery trend but with heavy fluctuations in water levels. In both of these cases, the access to irrigation will be compromised through either continued decline or high levels of uncertainties in groundwater availability. This phase will need increased focus of policy on supporting artificial groundwater recharge structures to capture runoff emanating from high fluctuations in rainfall, sustained shifts in cropping patterns with market incentives and support, support to sustain groundwater irrigation access through conducive energy policies for pricing so that water access is sustained for farm livelihoods. Instruments for risk sharing and management such as access to insurance, forecast and advisories for climatic/water resource conditions and response, buffering water access from surface water sources, and collective and cooperative mechanism for agricultural inputs, water management, and marketing of production, can support stability under high uncertainty or resource-scarce conditions.

These policy initiatives would be required more strongly for the regions and communities of north and central regions in Nalanda district which project higher levels of decline in water levels. With significant areas under 4–10 m decline, these regions will be faced with more critical situations of groundwater access and uncertainties. An Integrated Water Resource Management (IWRM) framework would be crucial for management of groundwater in the district but with different windows of opportunity for different policy priorities in the future.

4.4. Limitation

This groundwater model's main limitation is the absence of a parameter uncertainty analysis, which was restricted by the Mod-elmMuse interface. Including such a study would improve confidence in the model's predictions by evaluating the possible effects of changes in important factors such as hydraulic conductivity, porosity, and groundwater recharge rates. Additionally, the climate change is only considered in the groundwater recharge and specified head boundary conditions is assumed unchanged. Moreover, climate change is predicted to raise crop water demands throughout India, but this is not taken into consideration in the model. The region's groundwater depletion may worsen if farmers increase irrigation in response (Bhattarai et al., 2023).

5. Conclusion

The MODFLOW-NWT model was used to simulate the groundwater dynamics under current agronomic management practices in Nalanda district, Bihar during 2000–2018. A projection of future groundwater level between 2018 and 2060 was also generated from the CMIP6 global climate model, with rainfall intensity and thus groundwater recharge informed by inputs from the ACCESS-CM2, MPI-ESM1-2LR and the INM-CM4-8 climate models. The three climate models (INM-CM4-8, MPI-ESM1-2LR, and ACCESS-CM2) under three SSPs provide nine different groundwater level projections for Nalanda (2018–2060). The highest groundwater decline (3–4 m) occurs in medium rainfall-low/medium emission scenarios (MPI-ESM1-2LR, SSP126 & SSP370) and high rainfall-high emission scenario (ACCESS-CM2, SSP585). Minimum decline is observed under low rainfall scenarios in INM-CM4-8. Maximum decline scenarios show steady decreases, while minimal decline scenarios exhibit high annual fluctuations, increasing uncertainty. Comparing these projections helps identify short-, medium-, and long-term trends, informing policy interventions. We observed stored groundwater reduced by 11.9 MCM y^{-1} between 2000 and 2018 and simulated a future reduction in groundwater of up to 2 m, or 19.47 MCM

per year (0.8 km³), by 2060. This will deplete the aquifer and deleteriously affect farmers' already precarious ability to access irrigation water, particularly during the dry season. The model lacks parameter uncertainty analysis due to ModelMuse limitations, affecting assessment of key variables like hydraulic conductivity and recharge rates.

Climate change will likely increase crop water demand across India and farmers may adapt to the demand by applying more irrigation (Bhattarai et al., 2023). In such a case, it will further accelerate the rate of groundwater depletion within the district. Different phases of the future projection offer different groundwater trends that will require varied policy priorities for the short-term, medium-term, and the long-term periods. Policies to manage different groundwater conditions and trends will need to integrate supply and demand management for water, agricultural policies, market incentives and energy policies. Future research will focus on groundwater projection by integrating participatory stakeholder-driven cropping scenarios (Chakraborty et al., 2023) through APSIM (Agricultural Production Systems sIMulator) model. This research contributes to climate adaptation planning, safeguarding water security and agricultural productivity in India's vulnerable regions. Furthermore, this approach is scalable and can be applied to other groundwater-stressed regions. By adapting the methodology to different hydrogeological and climatic conditions, similar projections can guide local to regional policies, helping communities proactively manage their groundwater resources in the face of climate change and increasing agricultural demands.

CRedit authorship contribution statement

Urfel Anton: Writing – review & editing, Supervision, Project administration, Conceptualization. **Krupnik Timothy J:** Writing – review & editing, Supervision, Project administration, Funding acquisition, Conceptualization. **Laing Alison M:** Writing – review & editing, Supervision, Project administration. **Sikka Alok:** Writing – review & editing, Supervision, Conceptualization. **Chakraborty Shreya:** Writing – review & editing, Supervision, Project administration. **Mizan Syed Adil:** Writing – original draft, Formal analysis, Conceptualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This work was carried out under the CGIAR initiative on Transforming Agrifood Systems in South Asia (TAFSSA) and the CGIAR Policy Innovations Science Program, which is grateful for the support of CGIAR Trust Fund contributors (www.cgiar.org/funders). The authors acknowledge the two anonymous reviewers for their insightful suggestions and comments, which have significantly improved the quality of the manuscript.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at [doi:10.1016/j.ejrh.2025.102315](https://doi.org/10.1016/j.ejrh.2025.102315).

Data availability

Data will be made available on request.

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