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INITIATIVE ON
Transforming Agrifood Systems in South Asia

# Sustainable development and management of a crucial natural resource

## A research protocol to model groundwater flow in Nalanda District, Bihar, India

Research Protocol 8 August 2023

## BACKGROUND/CONTEXT

Across South Asia, millions of small-scale farmers are confronted with a range of urgent challenges. These include poverty, malnutrition, environmental deterioration, and the growing impacts of climate change and unpredictability (Ericksen et al., 2011). Despite these pressing concerns, the region's farming systems still have potential to sustainably its productivity and profitability (Islam et al., 2019; Gathala et al., 2021). The Transforming Agrifood Systems in South Asia (TAFSSA) research integrates interdisciplinary studies at both the farm and landscape levels to discover approaches that enable farmers to enhance their income and nutritional output while also preserving natural resources.

One of the key high-priority learning locations in which TAFSSA conducts research is Nalanda District in Bihar, India. Here, as in much of the region in which TAFSSA's studies are ongoing, a key component of agricultural production is the use of groundwater to irrigate crops. The use of groundwater – like other natural resources – should be managed carefully, with an eye towards assuring long-term sustainability and avoiding trade-offs that can compromise continued use of the natural resource.

Groundwater flow modeling plays a crucial role in comprehending and efficiently managing groundwater resources. Modeling can help in the the identification of :

- Understanding variations in groundwater levels over time, including seasonal patterns and system shocks.
- Analyzing the influence of subsurface characteristics on groundwater flow behavior.
- Identifying areas with water deficits or abundance within aquifers.
- Tracking the movement of contaminants within aquifers.
- Developing effective strategies for sustainable groundwater management and conservation.

As a response to these issues, groundwater modeling was conducted across Nalanda District as an example research learning location to assess the influence of climate change on groundwater resources and explore viable cropping system diversification choices for smallholder farmers.

## OBJECTIVES

- Gather input data for model calibration and validation.
- Parameterize, calibrate, and validate a groundwater flow model for Nalanda District in Bihar, India.
- Determine locally-relevant scenarios for sustainable and intensified agronomic production that appeal to smallholder farmers and policymakers.
- Assess the impact of crop diversification on sustainable groundwater management through scenario analysis.
- If groundwater levels are predicted to significantly decline under different cropping systems options, then identify feasible sites to manage aquifer recharge to meet demand and supply, considering irrigation and other uses of groundwater.

## RESEARCH QUESTIONS

1. What is the spatial and temporal variability of groundwater in Nalanda District?
2. What strategies can be employed to ensure the sustainable utilization of groundwater resources in the face of future climate scenarios, thereby facilitating enhanced production of nutritious crops while preventing further groundwater depletion?
3. Provide a preliminary approach to identify if it feasible to achieve sustainable intensification of food production systems while simultaneously implementing groundwater recharge measures in Nalanda District?

**Above:** A farmer in Nalanda can be seen diligently irrigating his farmland. Photo credit: Shawn Sebastian

## LOCATION

Nalanda District spans approximately 2,300 km$^2$ (Figure 1). The administrative and hydrological boundaries of the district were determined using Government of India survey maps (available online and accessible at [https://onlinemaps.surveyofindia.gov.in/FreeMapSpecification.aspx](https://onlinemaps.surveyofindia.gov.in/FreeMapSpecification.aspx)).

The climate in Nalanda falls within the sub-tropical to sub-humid category, characterized by an annual average rainfall of approximately 975 mm. The majority of this rainfall, around 90%, is received during the monsoon season from June to September. Nalanda's topography varies from 35 to 450 meters above mean sea level. Agriculture is the dominant land use in the district, occupying approximately 90% of the total land area, with a primary focus on cereal-based crop production.

Nalanda is primarily composed of flat alluvial terrain, with the exception of Rajgir Hill (343 m above mean sea level) in the south, which is crystalline rock. (CGWB, 2022). The alluvial area has been explored to a depth of 150 m and contains layered aquifers. The region is characterized by clay beds interspersed with sand. In the north of the district there are four alluvial fills with coarse sand and gravel a depth of 100-120 m overlaid with clay (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 which borders the district. Groundwater flow is also largely northeast following topology, however there are local flows in different directions based on local hydraulic gradients.

Groundwater is monitored at 39 hydrograph stations which contribute to the National Hydrograph Monitoring Network. Water level data from eight dug well stations are available from 2000 onwards; these were used in calibrating and validating the groundwater model. Data from another 31 stations are available from 2013 onwards.

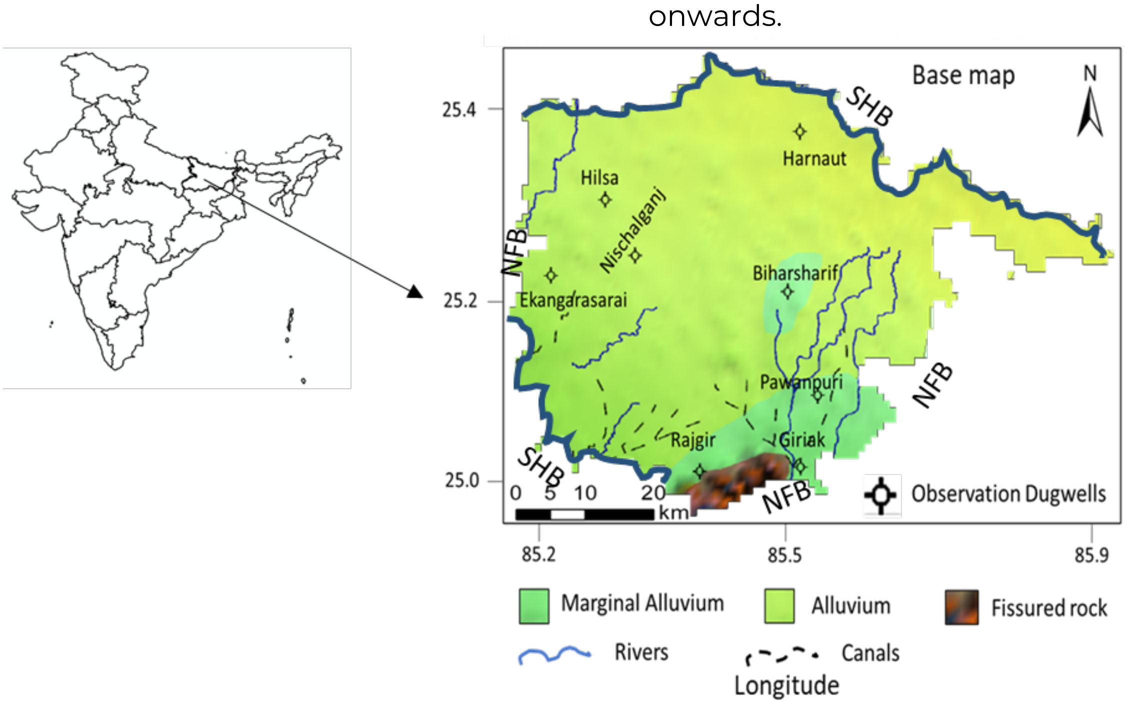



**Figure 1:** Nalanda District in Bihar, India

## METHODOLOGY

MODFLOW is a modular finite-difference groundwater flow model (Winston, 2014). It is extensively used to simulate groundwater aquifer systems. It employs the finite difference method and is used to quantify the movement and distribution of groundwater components through porous below-ground media. MODFLOW can also be used to predict changes to groundwater levels and behavior over time based on the anthropogenic and natural processes.

MODFLOW is underpinned by a three-dimensional groundwater flow equation (Rushton and Redshaw, 1979), as well as a second order partial differential equation which is transformed into a finite difference equation using a Taylor series and then into a more readily solvable linear equation (Figure 2). This enables researchers to estimate 'hydraulic head,' i.e. the level of elevation and depict direction of flow of groundwater.

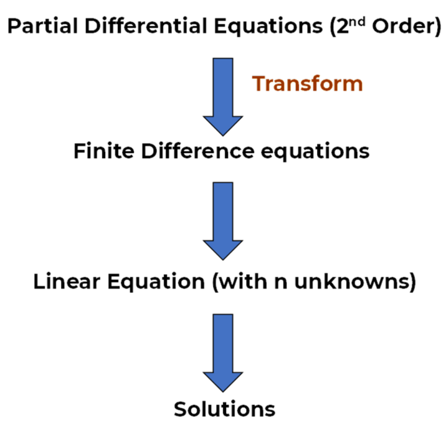



**Figure 2:** The MODFLOW process for generating each hydraulic head

Here we develop a groundwater flow model for Nalanda District in Bihar, India, using MODFLOW-NWT and the graphical interface Model Muse v5.1.1 (Winston, 2009 & 2014).

We use MODFLOW to estimate groundwater flows and analyze the potential effects of different agricultural management scenarios in a three-step process:

1. Conceptualizing the aquifer and defining its boundaries to devise a good-fit locally-specific model;
2. Calibrating and validating the locally-specific model using field data;
3. Identifying and developing different scenarios to examine groundwater extraction and recharge under different agronomic management practices and climates.

Field data are used to define a conceptual model of an underground aquifer, including its area and subsurface characteristics. The conceptual model is then converted into a numerical model using Darcy's Law (equation 1) to compute flows into and out of the aquifer (Mercer, & Faust 1980) as follows in Equation 1:

$$Q = -KA\frac{\partial h}{\partial z} \qquad (1)$$

where $Q$ is the flow rate, $K$ is hydraulic conductivity within the aquifer, $A$ is the cross-sectional area of the aquifer, and $\frac{\partial h}{\partial z}$ describes the gradient and direction of water flow.

To develop a local groundwater model for Nalanda District, we incorporate Darcy's Law into MODFLOW. This includes defining boundary and initial conditions and accounting for observed water extraction, like irrigation pumping, to simulate aquifer water flow. The model is then calibrated and validated against real water level data from the aquifer, ensuring its accuracy for Nalanda's specific conditions.

### *Conceptualizing the groundwater model*

The Nalanda District groundwater aquifer is conceptualized with 500 m × 500 m cells (Figure 3) in three dimensions using lithology data from the Indian Central Groundwater Board (CGWB, 2022). Intermittent sand layers at the surface are unconfined aquifers, while the deeper sand layers under- and over-lain by clay layers are confined aquifers.

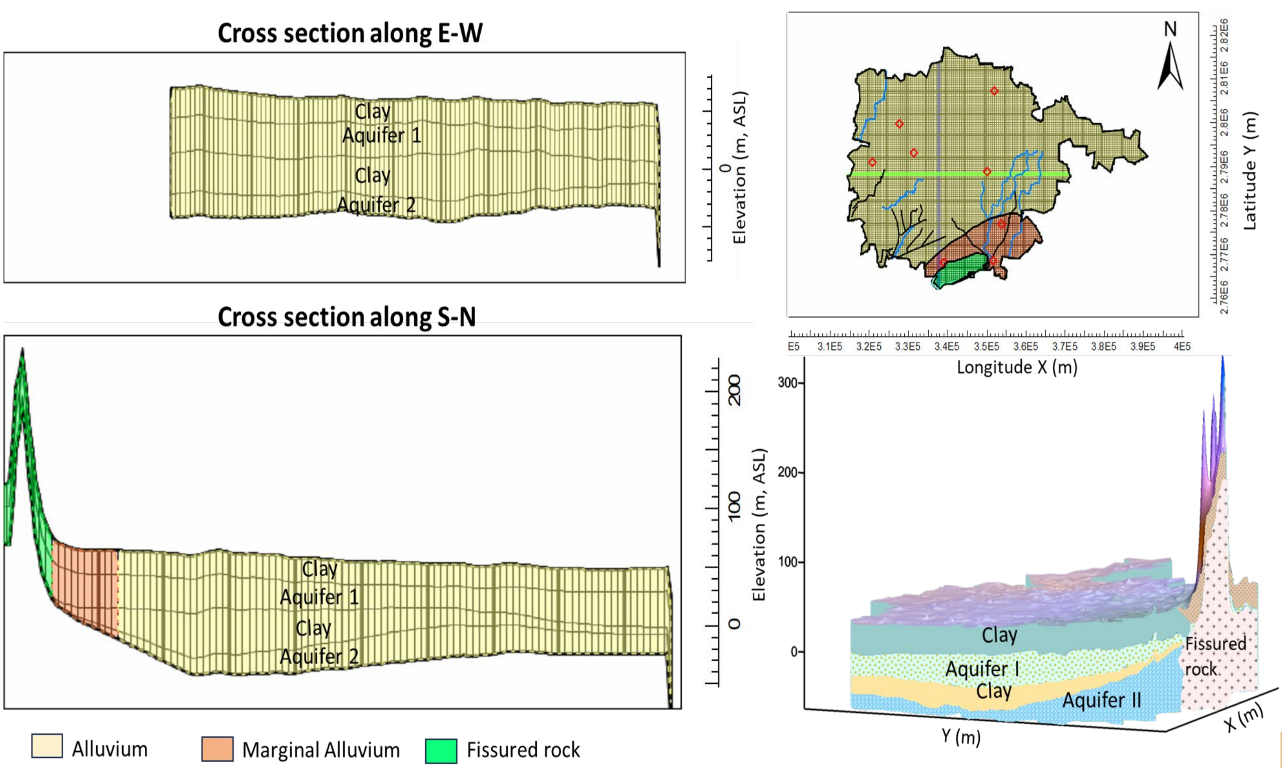
Hydraulic conductivity differs in the horizontal and vertical plains. The general flow direction of groundwater is from the southwest to the northeast; administrative district boundaries mean that the southwest and northeast outer boundaries in the model have no flow conditions. On the south boundary an outcrop of crystalline rock associated with Rajgir Hill also has no flow condition.

Multiple rivers and canals across the district act as river boundaries; rivers also act as water sources and sinks, depending on flow. Information on river flow patterns was derived using Google Earth images. Riverbed conductivity is initially assigned a generic value which is subsequently calibrated using observed data from across Nalanda District.

Groundwater recharge, abstraction and initial aquifer parameters (such as hydraulic conductivity, specific yield & storage capacity) are sourced from the Indian Central Groundwater Board (CGWB, 2022). The spatial variability of recharge and pumping are defined based on geology and land use across different seasons.

Lateral inflows and outflows from southwest to northeast across the District boundaries are simulated using time-variable specified head boundaries. These boundaries are then calibrated using the nearest observed hydraulic head data.

**Figure 3:** Three-dimensional conceptualization of aquifer geometry in Nalanda District.



### *Calibrating and validating the groundwater model*

Initially, we conducted a steady-state run of the MODFLOW model to assess topographic variability. During this phase, hydraulic conductivity was calibrated and subsequently utilized as an input parameter in the transient model.

Subsequently, a transient version of the model was calibrated by incorporating groundwater level data observed during the period from 2000 to 2014. In this calibration process, we utilized a total of 480 distinct data points to optimize parameters such as 'river conductance,' 'specific yield,' and 'specific storage' specific to Nalanda District. Finally, for model validation, an additional set of 111 data points from the years 2014 to 2018 were employed.

The root mean square error (RMSE) for model calibration and validation were both less than 5 % (1.6 and 2.0 m, respectively), indicating the model reasonably closely replicates the aquifer system to a level acceptable for subsequent additional simulation (Figure 4). There is also a high degree of confidence in simulated groundwater flows generated for Nalanda District using MODFLOW.

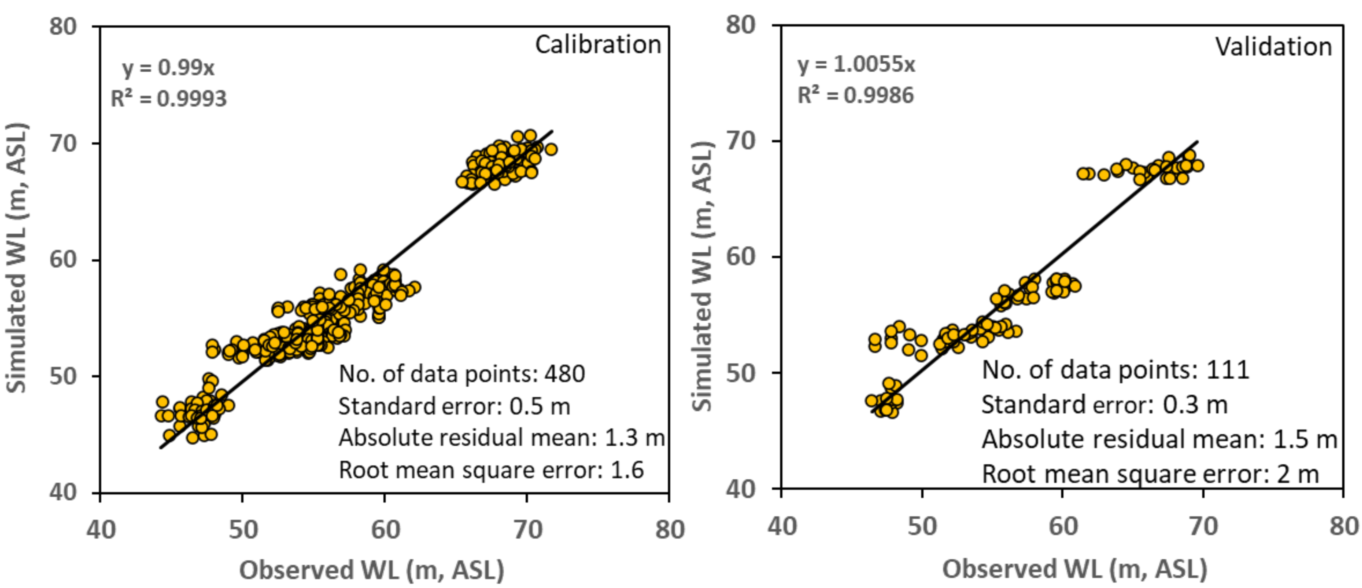



**Figure 4:** Calibration and validation of modelled water levels within Nalanda District

**Above:** Farmer in Nalanda managing irrigation in his field. Photo credit: Shawn Sebastian

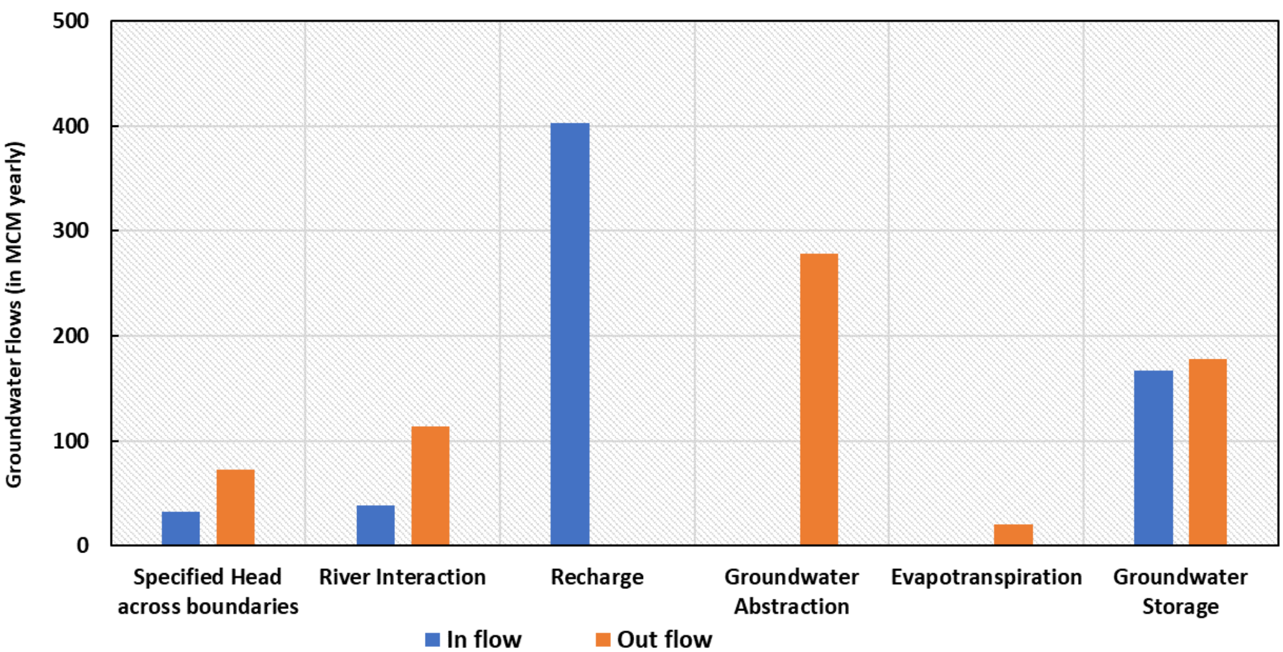



**Figure 5:** Annual average groundwater in- and out-flows

### *Historical groundwater trends inform scenario development*

Between 2000 and 2018 groundwater in Nalanda District declined at about 6 cm year$^{-1}$. This depletion appears to be at least partly a result of both natural discharge from rivers and aquifer boundaries, and from anthropogenic extraction through groundwater pumping for agronomic irrigation.

While groundwater levels are currently within a range of 1.5 to 6 m below from the surface, recharge from rainfall and river inflows appears to be inadequate to fully recharge the aquifer. This therefore signifies some concerns for long-term sustainability of this important natural resource.

Across the District average annual net storage loss was 11.19 MCM year$^{-1}$ between 2000 and 2018 (Figure 5).

### *Scenario modelling*

MODFLOW was used to estimate groundwater flow, extraction and recharge for current and alternative agronomic management practices for climate scenarios in Nalanda District Plausible future climate information for 2018 to 2060 has been generated from the CMIP6 global climate model (Mishra et al., 2020).

In a business-as-usual scenario, considering current agronomic management practices and recharge variability based on the ACCESS-CM2 climate model (SSP585), there is a projected reduction in groundwater levels of approximately 3 meters from 2018 to 2060, as illustrated in Figure 6. This decline poses a significant threat to the aquifer's sustainability and will negatively impact farmers' capacity to access irrigation water, particularly during the dry season.

In response, TAFSSA researchers are collaboratively developing a range of agronomic management scenarios for additional modeling in partnership with key stakeholders in agriculture and water management. These scenarios are being carefully designed to be both practical and appealing to decision-makers in both the public and private sectors.

These scenarios will facilitate the comparison of future alternative crop management practices, aiming to reduce irrigation water usage, enhance water-use efficiency, recharge the aquifer, and/or diversify crops within cropping systems. These innovative cropping systems will also seek to increase the nutritional and economic value of smallholder production systems without imposing significant labor requirements or production costs.

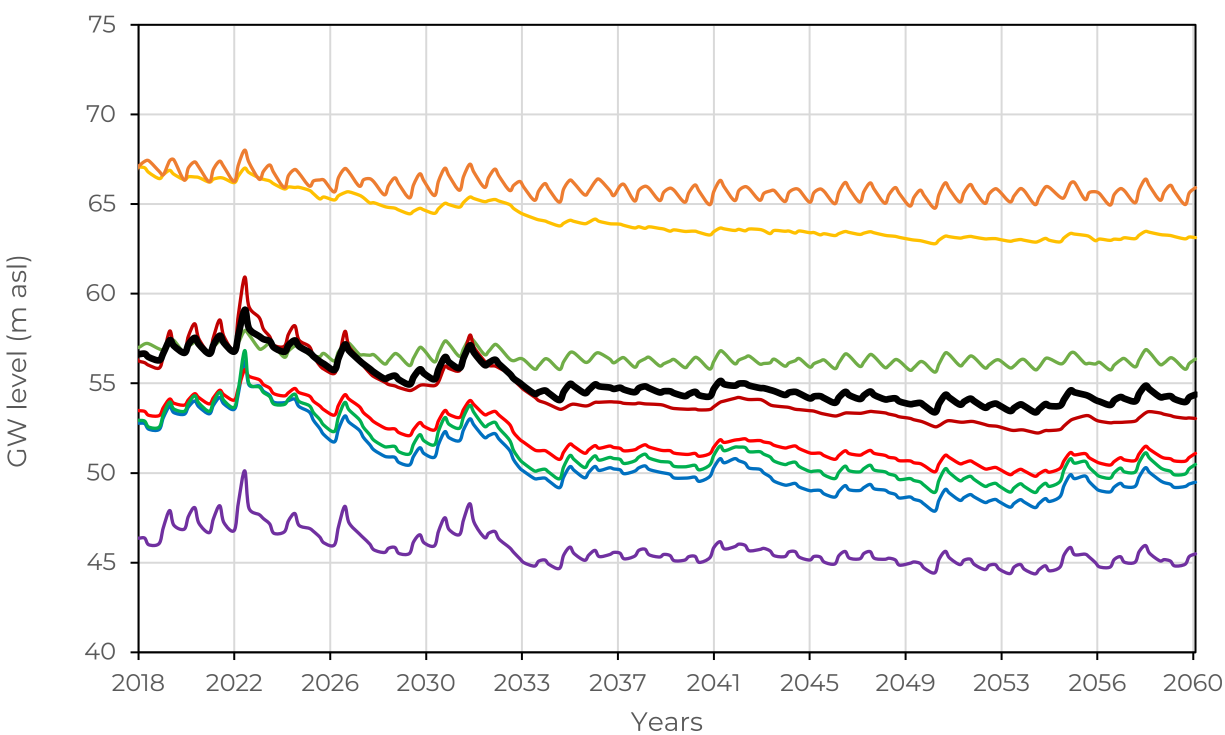



**Figure 6:** Simulated groundwater levels from 2018-2060. Colored lines show simulated groundwater levels for dug well sites across Nalanda, the bold black line is the average groundwater level

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## ABOUT TAFSSA

TAFSSA (Transforming Agrifood Systems in South Asia) is a CGIAR Regional Integrated Initiative that supports actions improving equitable access to sustainable healthy diets, that boosts farmers' livelihoods and resilience, and that conserves land, air, and water resources in a climate crisis.

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## SUGGESTED CITATION

Mizan, S., Sikka, A., Urfels, A., Laing, A.M., Krupnik, T.J. 2023. *Sustainable development and management of a crucial natural resource - A research protocol to model groundwater flow in Nalanda District, Bihar, India*. TAFSSA Research Protocol 8. Transforming Agrifood Systems in South Asia *(TAFSSA*). International Water Management Institute, New Delhi, India

## FUNDING ACKNOWLEDGEMENT

We would like to thank all funders who supported this research through their contributions to the CGIAR Trust Fund: https://www.cgiar.org/funders/



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