Isolating the impacts of anthropogenic water use within the hydrological regime of north India

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ABSTRACT

The effects of anthropogenic water use play a significant role in determining the hydrological cycle of north India. This paper explores anthropogenic impacts within the regions hydrological regime by explicitly including observed human water use behaviour, irrigation infrastructure and the natural environment in the CHANSE (Coupled Human And Natural Systems Environment) socio-hydrological modelling framework. The model is constrained by observed qualitative and quantitative information collected in the study area, along with climate and socio-economic variables from additional sources. Four separate scenarios, including business as usual (representing observed irrigation practices), groundwater irrigation only (where the influence of the canal network is removed), canal irrigation only (where all irrigation water is supplied by diverted surface water) and rainfed only (where all human interventions are removed) are used. Under business as usual conditions the modelling framework closely matched observed groundwater levels. Following the removal of the canal network, forcing farmers to rely completely on groundwater for irrigation, water levels decrease throughout the model period, while under a canal only scenario flooding occurs. Under the rainfed only scenario, groundwater levels similar to current business as usual conditions are observed. This is despite much larger volumes of recharge and discharge entering and leaving the system under business as usual practices. The paper highlights the challenges and importance of balancing water management strategies. While groundwater abstraction alone may lead to aquifer depletion, the conjunctive use of surface and groundwater resources, which include unintended contributions of canal leakage, create conditions which are similar to those where no human interventions are present. In this paper the importance of suitable water management practices, in maintaining sustainable water resources, are shown. This may include augmenting groundwater resources through managed aquifer recharge and reducing the impacts on aquifer resources through occasional canal water use where possible. The importance of optimal water management practices that highlight trade-offs between environmental impact and human wellbeing are shown, providing useful information for policy makers, water managers and users.

1 | INTRODUCTION

The Indo-Gangetic Basin (IGB) is one of the largest and most important aquifer systems in the world, stretching from Pakistan across northern India, southern Nepal and Bangladesh. The IGB contains significant sedimentary deposits eroded from the Himalayas and redistributed by the region's major river systems including the Ganges, Indus and Brahmaputra (Macdonald et al. 2016). The region is bounded by the Himalayas to the north, and by the hard rock peninsular geology to the south – geomorphologically very different regions, creating a clear distinction in the water use behaviours of the inhabitants in each location.

The environmental characteristics of the region have provided India with significant benefits; allowing the country to produce sufficient food for its growing population, due in part to the introduction of diesel pumps and an increase in the number of tubewells, particularly during the green revolution (Scott and Sharma 2009; Shah et al., 2006) This allowed farmers to irrigate outside the command of the canal networks, intensively cultivating areas which were previously rain-fed (Moulds et al. 2010). Tubewells were easily drilled in the unconsolidated superficial deposits providing easy access to the water table.

The Indian monsoon supplies a significant proportion of water resources to the region, typically between the months of July and September and is critical to India's water resources (Moulds et al. 2010; Roxy et al. 2015). In addition, the IGB plains are home to some of south Asia's major rivers, including the Indus, Ganges, Yamuna and Brahmaputra. Major tributaries include the Ghaghara, the Gandak and the Kosi. The plains are well suited to canal construction; from the late 19th century an extensive network was built by British colonists, and further expanded by subsequent Indian governments following independence (Shah, 2008). While originally designed to transport water from rivers to more arid regions, canal construction inadvertently provides a significant contribution to groundwater recharge (Bonsor et al. 2017).

North India is one of the most densely populated regions in the world, placing an enormous demand on regional water resources. While in many locations within the IGB water is plentiful, resources are vulnerable to social and environmental change; for example from variations in climate or in the water use practices of stakeholders (Burney et al., 2014; Mukherji, 2016; Shah, 2016). A lack of adequate governance allows land owners to abstract as much water as individual finances allow (Kulkarni, Shah, and Vijay Shankar 2015; Shah et al. 2009). In some cases, energy is free for irrigators, placing even more pressure on water resources (Briscoe and Malik 2006; Shah et al. 2018). In addition, the rivers themselves are often controlled by major barrage systems, diverting significant amounts of water to canal networks, altering the natural flow of the river. Haddeland et al. (2013) highlighted that the impact of such human disturbances is equal to or greater than the impacts of expected climate change over the next 40-50 years.

Understanding the regions complex hydrological cycle, along with anthropogenic water use and infrastructure, is necessary to build resilience against change. The scarcity of data describing both water use and the environment poses an additional challenge (O’Keeffe et al. 2016). In order to fully represent the hydrological cycle in the context of water management, it is necessary to incorporate the practices and behaviours of humans and assess their influence on the region’s hydrology. Socio-hydrology is an interdisciplinary field which studies the dynamic interactions and feedbacks between water and society. Socio-hydrological models provide a useful framework for assessing and understanding the links between the natural and physical environments (Blair and Buytaert 2016; Sivapalan, Savenije, and Blöschl 2012). Such models encourage the user to extend their interest outside the narrow focus of water volume or quality, to instead consider all elements of the hydrological cycle, including human water use practices and demands, ecological flows and how change is likely to propagate throughout the entire system. They also provide a useful way to quantify the effects of human practices on the natural environment; for example, the abstraction of groundwater for irrigation, or the introduction of surface water through canal systems. This is possible by explicitly accounting for and representing the decisions and behaviours of humans who are often the dominant agents of change within a system.

In this paper, we quantify the influence of human behaviour on the water cycle in a study area in north India representative of the social and environmental conditions found across the region as a whole. Scenarios that represent different irrigation and non-irrigation practices, are explored. For the purpose of this analysis, our socio-hydrological modelling framework comprising groundwater and crop models, which explicitly accounts for water user behaviour in India (O'Keeffe et al. 2018), was expanded to include lateral groundwater flow leaving the model domain. By analysing the impacts of variations within the hydrological regime on the underlying aquifers we quantify the impact of human water use on the regions hydrological cycle. While often not clear, knowledge of the whole water system provides invaluable information which could be employed when making expensive societal decisions (Strum et al., 2017).

We hypothesise that by improving our understanding of human and environmental feedbacks, we will improve understanding of the hydrological cycle while highlighting potential trade-offs between sustainable development and economic growth.

1.1 | Study area

The Gandak river, located in north west Bihar, is representative of the majority of social and environmental conditions found across north India, including irrigation water sources, water use practices, crop production, land use, and population, as well as geology, geomorphology and climate. The region provides an ideal study area to explore the feedbacks and linkages between human water use and the natural environment. Known as the Kali-Gandaki in Nepal, the river flows from the Tibetan plateau, traversing Nepal before reaching India at Valmikinagar in north west Bihar. It then flows 335 km south, entering the Ganges at Patna (Choudhary 2010). It is a sinuous river and frequently transitions between braided and meandering channels (Sinha 1998). It has one of the highest discharges of antecedent rivers in the northern plains, while also being one of the most flood prone in north Bihar (Jain and Sinha 2004). It is regionally important, supporting fishing communities, agriculture and a globally significant eco-system; it is one of only two breeding sites for gharial crocodiles, in addition to providing an important habitat for the Ganges river dolphin (Choudhary 2010).

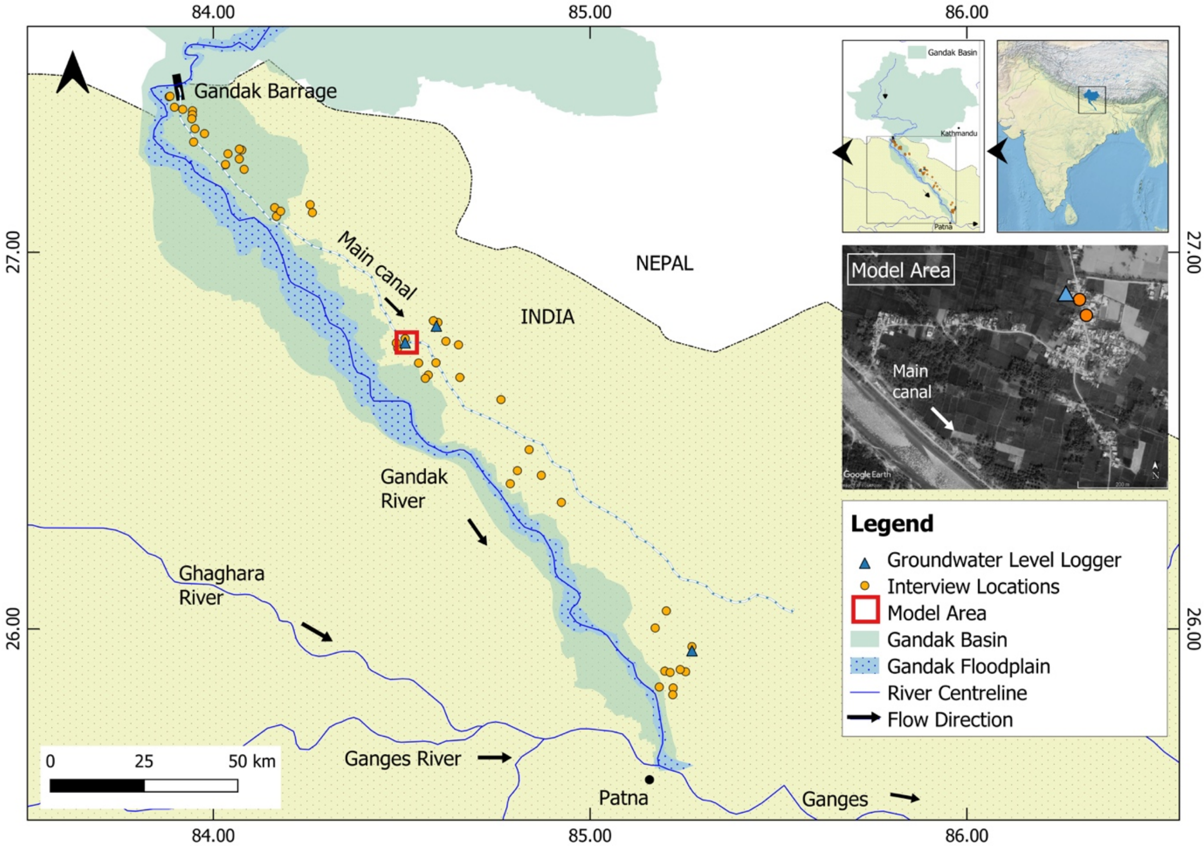


Figure 1: Study area map showing interview and groundwater level logger installation locations. The area explored in the modelling framework is also highlighted.

The river is regulated by the Gandak Barrage located at the Indian-Nepali border. Barrage construction began during the 1960s with irrigation beginning in the early 1970s supplying surface water to a command area of over 870,000 ha (WRIS, 2015). In addition to irrigation, the barrage is also designed to manage river discharge in a region prone to large flood events, particularly during the monsoon period. The canals are predominantly clay-lined and while published leakage rates for the Gandak canal network are difficult to find, India wide studies suggest losses of up to 50% are likely, leading to increased groundwater recharge (Bonsor et al. 2017). This is often associated with rising groundwater levels and increased soil waterlogging; a known issue in the study area (see Chowdary et al. 2008). Gandak river flow is controlled by the barrage operators at Valmikinagar. Water is channelled into three main canal branches: the Nepalese branch, the Western branch supplying water predominantly to Uttar Pradesh, and the Eastern branch serving Bihar. Canal water releases are timed to coincide with the most important crop irrigation events (Gandak Irrigation and Power project, 1959).

The region is intensely irrigated and while numerous crops are grown, rice, wheat and maize are the most dominant (Chowdary et al. 2008; ICRISAT, 2012). Sugarcane, typically grown in the north of the Gandak basin, and tobacco grown in the south, are cultivated as cash crops. The source of irrigation water depends on location and availability. Within the Tirhut Division, comprising the main districts within the Gandak basin, groundwater is the most common irrigation water source, accounting for 70% of net irrigated area, while canal irrigation contributes 27% of net irrigated area (Government of Bihar, 2014).

Irrigation water supplied through the canal network is typically less expensive than groundwater abstraction (O’Keeffe et al. 2016), making it a desirable irrigation water source for farmers when available. However, farmers reported reliability issues, which increased closer to the tail of the canal. The canal system comprises lined and unlined sections and like many other canal systems, leakage occurs throughout the network. While canal leakage can benefit those closer to the head of the canal through increased groundwater recharge, it reduces the amount of water available to down-stream users. However, canal leakage also increases the vulnerability to groundwater flooding, a problem for some farmers in the study region (Chowdary et al. 2008). This information was used to inform and improve an existing socio-hydrological model developed for eastern Uttar Pradesh (O’Keeffe et al. 2018) in order to better represent local conditions.

2 | METHODOLOGY AND DATA

Field work and interactions with water users provided valuable insights on hydrological processes and human water use within the Gandak Basin. This information was crucial for the developing whole water system understanding, leading to increased model realism. From this information, the CHANSE (Coupled Human And Natural Systems Environment) socio-hydrological model, adapted from the model developed by O’Keeffe et al. (2018) was informed and improved to better represent local conditions. Quantitative data on climate, groundwater levels and relevant socio-economic variables were also used to drive the modelling framework. This section describes the collection of data and insights from the field, and the modelling framework which was used to test a number of scenarios to explore the impact of humans on the regions hydrological cycle.

2.1 | Developing water system understanding through stakeholder interaction

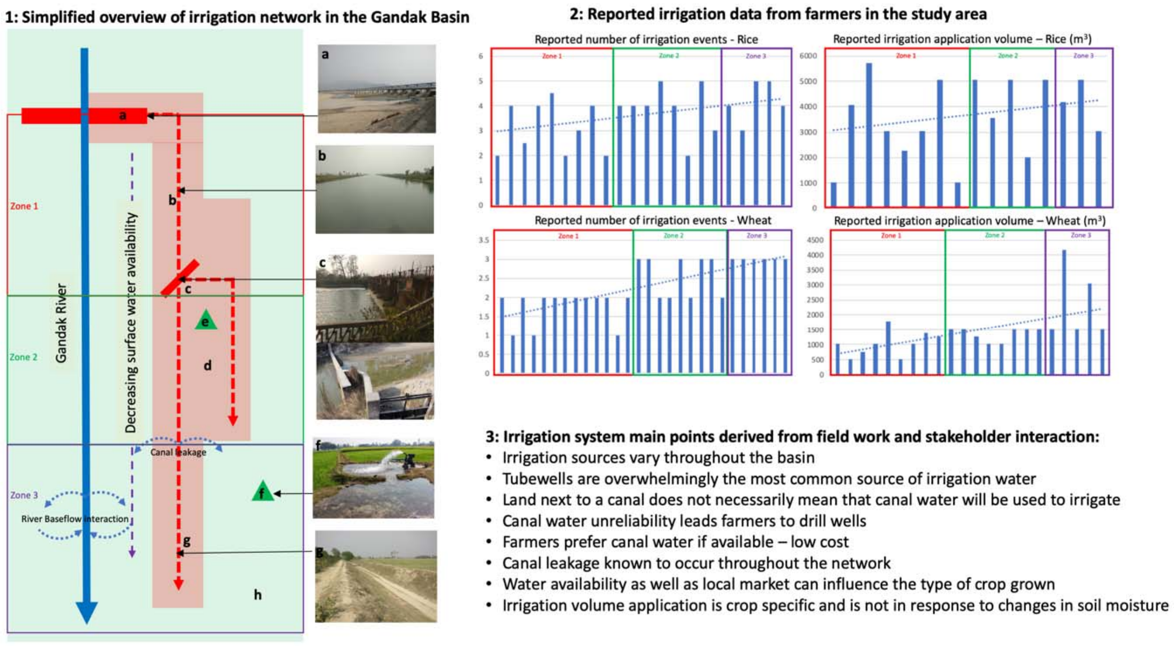
Data collection.

Forty-seven semi-structured interviews were undertaken with water users during February and March 2017 (Figure 1) using the approach outlined in O’Keeffe et al. (2016). Focus group sessions were also held with farmers and water managers, including barrage operation managers. The information collected provides a valuable overview on the decisions and practices of farmers, along with how and why they vary spatially and temporally across the study area. Building understanding from the bottom up is crucial to developing a complete picture of the whole water system, as taking a top down only approach can miss some of the most important drivers.

All interviews were conducted through a translator using specially designed topic guides centred around the challenges faced by stakeholders and the feedbacks between water use, water governance and the surrounding natural environment. All interviews were recorded and transcribed verbatim and analysed thematically using the open source qualitative analysis software package RQDA (Huang 2014). Socio-economic data collection requires a strict adherence to ethics and preservation of anonymity, however a selection of the data collected is presented in Appendix 1, along with the topic guide used during the interviews in Appendix 2.

Insights from field work

Access to irrigation water sources vary throughout the Gandak basin, however groundwater, was available to all interviewees, information which is also reflected in the Government of Bihar’s Statistical Abstract (Government of Bihar 2016). Groundwater is typically accessed through tubewells rather than larger diameter hand dug wells, the vast majority of which are privately owned. Two operational Government tubewells were encountered during field work. Where possible, farmers prefer to own their own tubewells and pump sets. However, where land is fragmented, as is often the case, farmers typically use tubewells, or tubewells and pumps owned by neighbouring farmers. A typical cost for running a diesel pump is 120 rupees/hr. It was also observed that owning a farm close to a canal is not an indication of canal use; for example, if the land to be irrigated is higher than the water level in the canal it is quite likely that pumps will be required, leading farmers to incur additional irrigation costs. In such cases, given the unreliability of the canal systems, farmers prefer to drill their own tubewells to have constant access to a more dependable water supply. However, groundwater is more expensive to use than canal water and the reliability of the canal network can influence the practices of farmers in the commands, including the types of crops grown. For example, in the north of the Gandak basin, sugarcane is the cash crop of choice, whereas towards the south tobacco is preferred as it requires less irrigation water (Brouwer and Heibloem 1986; Islam et al. 2017). Crop growth patterns are also influenced by markets; farmers reported that the presence of a number of sugar cane processing plants in the north of the Gandak basin encouraged its growth in the surrounding area.



3: Irrigation system main points derived from field work and stakeholder interaction:

- Irrigation sources vary throughout the basin
- Tubewells are overwhelmingly the most common source of irrigation water
- Land next to a canal does not necessarily mean that canal water will be used to irrigate
- Canal water unreliability leads farmers to drill wells
- Farmers prefer canal water if available – low cost
- Canal leakage known to occur throughout the network
- Water availability as well as local market can influence the type of crop grown
- Irrigation volume application is crop specific and is not in response to changes in soil moisture

Figure 2: Simplified overview of the surface water and groundwater irrigation network as observed within the Gandak Basin (1), along with selected reported irrigation practices as

reported by farmers (2) and an overview of some of the main insights derived during field work (3).

Key for part 1: a. Gandak barrage – controlled by barrage operators, b. Main Gandak canal close to head of system, c. Main canal and distributary canals – water diversions controlled by irrigation officials, d. Canal command area (Canal accessible to most farmers within this zone), e. Farm within canal command area (Surface and Groundwater access), f. Farm outside of canal command area (Groundwater access only), g. Gandak canal close to tail, h. Groundwater accessible to all farmers within this zone

Some of the most important data collected during interviews related to the irrigation practices of farmers, and how they varied under changing environmental and social conditions. Crop irrigation followed a schedule in which each crop received a number of irrigation applications depending on seed type, environmental conditions and water availability. Farmers do not irrigate in response to daily changes in soil moisture, as assumed in many regional water use models (e.g. Wada at al., 2012); instead relying on experience, constrained by access and cost, to ensure crops receive sufficient water on time. However, areas with lower soil moisture will require more irrigation water. This is reflected in the reported increasing number of irrigation events and volume of water applied towards the tail of the canal network (Figure 2, part 2).

Information describing canal operation was obtained through discussions with barrage operators and farmers within the canal command area. The operation of the barrage is governed by a transboundary agreement between the Indian and Nepalese government, which specifies monthly discharge to each canal. On a daily basis, releases to the canal network are controlled by the barrage operators and canal officials who direct water through the main, branch, sub branch and sub-distributary canals. Canal reliability was reported as an issue by many farmers throughout the basin, though as expected, this decreases towards the tail of the system. Nevertheless, due to the lower application costs, farmers used canal water in preference to groundwater where possible. In addition, leakage is a known issue across Indian canal networks as described by Bonsor et al. (2017) and Singh (2002).

The information collected from stakeholders, particularly when coupled with secondary socio-economic data sources such as the District Level Database Documentation (ICRISAT, 2012) and the Statistical Abstracts produced by the Government of Bihar (Government of Bihar, 2016), provide a detailed overview of regional irrigation practices. This leads to improved conceptual model development by highlighting the most important feedbacks and linkages between human water use and the natural environment. Field collected irrigation water use information used in the parameterisation and driving of the CHANSE modelling framework can be seen in Table 1. A conceptual model derived from collected information can be seen in Figure 3.

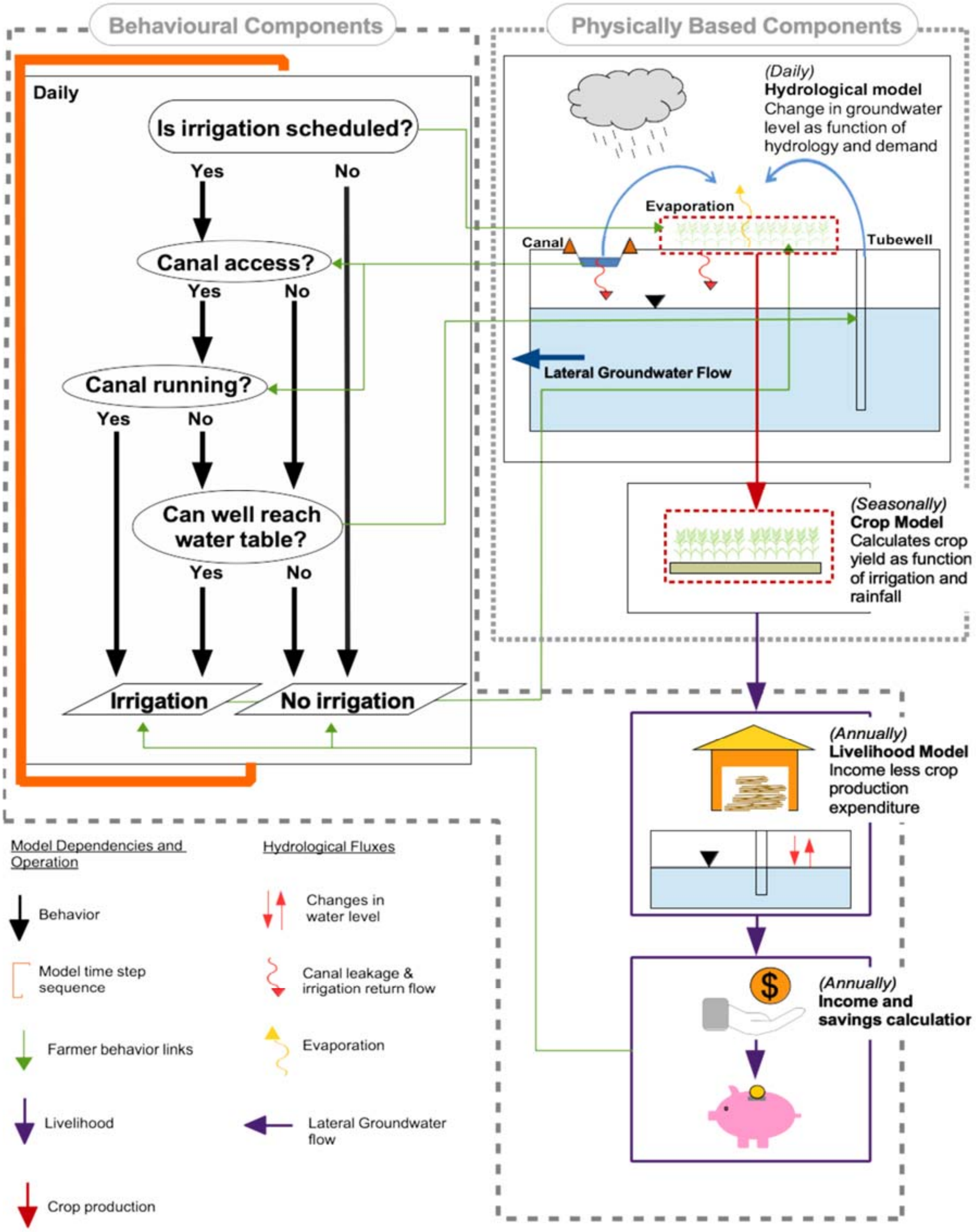


Figure 3: Schematic overview of the conceptual model highlighting both behavioural and physically based elements and how they are connected within the modelling framework. Adapted from O'Keeffe et al., (2018) to represent the most important aspects of model operation for the Gandak study area.

2.2 | Sociohydrological model setup

We use a socio-hydrological modelling framework developed by O’Keeffe et al. (2018), henceforth referred to as the CHANSE (Coupled Human and Natural Systems Environment) modelling framework. The model represents observed farmer irrigation practices with the overall aim of highlighting the feedbacks and interactions between the environment and the behaviour of water users. A simplified description of the modelling framework is outlined here. For a detailed description of the modelling framework please refer to O’Keeffe et al. (2018).

The hydrology module utilises a single cell approach which partitions incoming rainfall into runoff, evaporation and infiltration. Irrigation is added to rainfall according to a predetermined schedule. The root zone is represented as a leaky bucket. Incoming water from rainfall and irrigation replenishes the water store until field capacity is reached, with additional water becoming groundwater recharge. Irrigation water sources include groundwater and canals which operate on a set of rules based on field observations, including the water use practices of farmers, taking into account their financial ability to irrigate as well as the operational procedures of the canal network. A proportion of applied irrigation water is channelled to the aquifer as return flow. In addition, water in operational canals enters the aquifer as leakage.

Crop production is also taken into account and represents the primary link between farmer livelihood and agricultural water use. It is calculated according to the relationship between yield and evapotranspiration outlined in FAO Irrigation and

Drainage Paper 33 (Doorenbos and Kassam 1979) is used to calculate crop production. Farmer income is based on the market price of crops less the expense of fertiliser and irrigation, which varies with irrigation source and depth to groundwater. A lack of income reduces farmers' capacity to irrigate, in turn affecting irrigation practices and water resources. Crop production and corresponding income, less expenses from irrigation and fertilizer application are annual values computed from daily calculations.

The model is set up to represent a farm located in the centre of the study area, incorporating environmental and anthropogenic conditions found across the region as highlighted by qualitative and quantitative data collected in the study area. This includes typical crop production and irrigation practices, as well as canal and groundwater access. The farm size is set to 1 ha.

We expanded the functionality of the CHANSE model by including outgoing lateral groundwater flow. The lateral flow component is based on an approach described by Mackay et al. (2014) in their lumped conceptual model, AquiMod. Lateral groundwater flow is considered in the following way:

$$Q = C.(h_i - z) \tag{1}$$

where Q is lateral groundwater flow leaving the model ($m^3 day^{-1}$), h_i is the groundwater head from the previous time-step (m), z is the elevation of the drainage point (m), and C is a conductance parameter ($m^2 day^{-1}$):

$$C = \frac{K\,B\,W}{L} \tag{2}$$

where K is the aquifer hydraulic conductivity ($m\ d^{-1}$), B is the saturated aquifer thickness (m), W is the width of the aquifer (model cell), and L the distance to the drainage point (m). For a full description of how the model operates please see O'Keeffe et al. (2018).

2.3 | Quantitative Data

While information describing water use and management was used to inform model set up, additional quantitative information collected in the field, such as irrigation water application volume, was used during model initialisation and operation. These data are outlined in the sections below, and in Table 1.

Groundwater level data.

High resolution data describing groundwater variations in the study area formed important information for this study, crucial for model calibration and output comparison. As this information was not available, groundwater level loggers were installed in three boreholes within the Gandak basin in March 2017. Observed information used in this paper extends from logger installation to August 2018 capturing a Kharif (dry) and Rabi (monsoon) season. Groundwater level information was recorded at 15-minute intervals. The locations of the loggers is shown in Figure 1, and the groundwater levels time-series data presented in Figure 3. Results show similar groundwater signals across all locations, highlighting the homogeneity in environmental conditions within the study region. Data from logger B, located within the modelled area was used as a comparison with model outputs.

Climate data.

Gridded daily rainfall and temperature data compiled by the Indian Meteorological Department (IMD) were used in model operation. Data ranged from 2000 to 2018, coinciding with collected groundwater level information between 2017 and 2018.

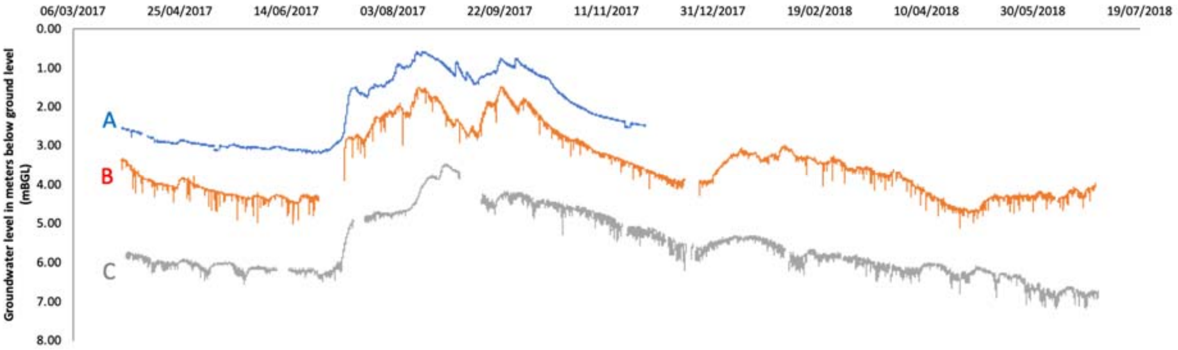


Figure 4: Observed groundwater levels in selected areas of the Gandak Basin. Letters on time series correspond to locations in Figure 1.

Irrigation data.

Irrigation water application and canal operational information used in the model were obtained from farmers who use the network and barrage operators. The range of irrigation events and water application depths are outlined in Table 1, along with the distribution of irrigation source for farmers in the study area. Leakage is a known issue in canals, as highlighted by a number of studies conducted across India; a value of 40% has been used in this study after Bonsor et al. (2017) and Singh (2002) who highlight similar values in their studies.

Socio-economic data.

Data describing crop production and the market prices of crops were obtained from the ICRISAT All India Village Level Data Set (ICRISAT, 2012), and the India Village-Level Geospatial Socio-Economic Data Set (Meiyappan et al. 2017) along with Statistical Abstracts of Bihar (Government of Bihar 2014). Fuel prices, used to compute the cost of irrigation with respect to volume of water abstracted and depth to groundwater were obtained from Indian Oil (2018).

Table 1: Overview of initialisation values and parameters used in model operation

Model parameter	Value	Source
Rainfall Runoff (% of precipitation)	5%	User defined
Evaporation Loss (% of water applied)	20%	User defined
Hydraulic Conductivity (m/day)	30	Bonsor et al., 2017
Specific yield (%)	13%	Bonsor et al., 2017
Canal Leakage (% of canal volume)	40%	Bonsor et al., 2017
Irrigation return flow (% of water applied)	40%	Field work
Irrigation application Depth range - Wheat (m)	0.02 - 0.14	Field work
Irrigation application Depth range - Rice (m)	0.05 - 0.20	Field work
No. of irrigation events - Wheat	2	Field work

No. of irrigation events - Rice	4	Field work
Surface elevation (mASL)	79	Field work
Distance to drainage point (m)	11500	Field work
Farm Size (ha)	1	Field work
N application (kg/ha)	120	Yadav, 2003
P application (kg/ha)	26	Yadav, 2003
K application (kg/ha)	48	Yadav, 2003
Irrigation efficiency	0.4	Perry, 2017
Field Capacity	0.3	FAO
Wilting point	0.12	FAO
Rooting depth - Wheat	1.25	Mishra, 1997
Rooting depth - Rice	0.65	Mishra, 1999
Water stress coefficient: Min	0	User defined
Water stress coefficient: Max	1	User defined
Yield response factor: Wheat	0.8	FAO
Yield response factor: Rice	1.3	FAO
Crop coefficient: Wheat	0.8, 1.12, 1.25, 0.46	Choudhury, 2013
Crop coefficient: Rice	0.61, 0.80, 1.23, 0.74	Choudhury, 2013

3 | WATER MANAGEMENT SCENARIOS AND IMPLICATIONS

In order to delineate the influence of anthropogenic water use four separate scenarios were applied to the model:

1. Business as usual (BAU) – current irrigation practices using both canal and groundwater irrigation

2. Groundwater irrigation only – removing the influence of canal water from agricultural practices and the hydrological regime; this forces farmers to use more expensive groundwater
3. Canal irrigation only – removing the influence of groundwater abstraction from agricultural practices and the hydrological regime; this allows us to explore the implications of providing free surface water to farmers
4. No irrigation – where crop production depends completely on rainfall to satisfy water requirements. This scenario provides insights on how the system operates under natural conditions, allowing comparison with human induced change

These scenarios allow us to isolate the effects of the most common irrigation practices used across the region within the socio-hydrological model, while also exploring what is likely to happen if no irrigation takes place. Through this approach, we describe the contribution manmade irrigation infrastructure and practices have on influencing the hydrological regime, while also quantifying their contribution to aquifers through artificial recharge, and to society through crop yield.

Wheat and rice are grown in all scenarios and their water requirements are included in the modelling framework accordingly, with plants taking water from soil moisture provided through rainfall, topped up by irrigation when it occurs during scenarios 1, 2 and 3. The initialisation parameters and values used during model operation are listed in Table 1.

In Figure 5, modelled groundwater level outputs under each scenario are compared to observed groundwater level data collected in the study area between March 2017 and June 2018. Figure 6 directly compares the groundwater balance under each scenario. This is achieved by subtracting all groundwater recharge components from discharge, including groundwater abstraction and lateral groundwater flow, providing a useful measure of system sustainability, both annually and over the entire model run.

Outputs of modelled crop yield in tonnes/ha are shown in Figure 7 for wheat and rice. Observed crop yield values, as reported by the Government of Bihar (2017), are represented by the trend line showing the linear change in average annual crop yield from the study area between 2000 and 2018. Final rice yield was not calculated in 2018 as its harvesting date is outside the modelled period. However, its crop water requirements, supplied through irrigation practices if applicable, are still taken into consideration throughout the entire model run. Variations in farmer income in relation to crop production are shown in Figure 8.

Modelled outcomes are not intended to provide a definitive representation of farmer income, as the modelling framework does not take into account all sources of income and expenditure, but to show how basic farmer income is likely to change under variations in human practices and environmental conditions.

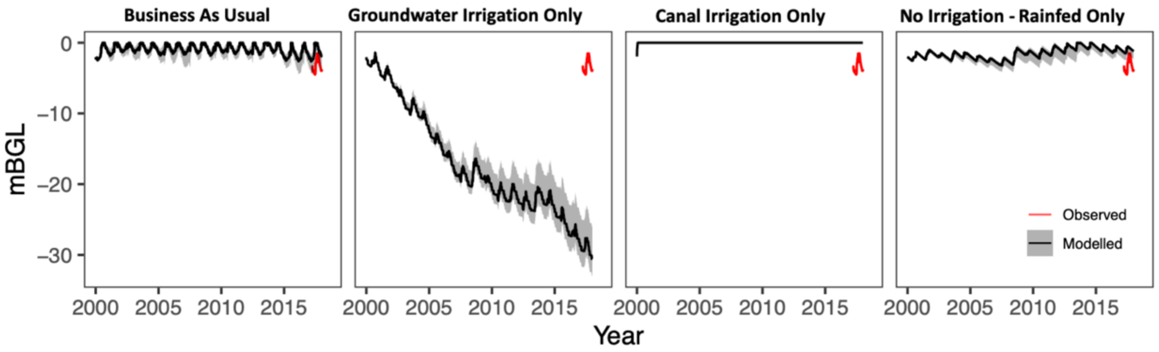


Figure 5: The range and median modelled groundwater level under business as usual, groundwater irrigation only, canal irrigation only and no irrigation scenarios between 2000 and 2018. The shaded area represents the range of values obtained from 20 model iterations with variations depending on stochasticity of rainfall and irrigation application volumes. The black line represents the median groundwater level. Observed groundwater levels from March 2017 to June 2018 are shown as a red line.

2.1 | Business as usual

Under a business as usual scenario, modelled groundwater level outputs closely match observed groundwater levels. Groundwater fluctuates with rainfall and groundwater abstraction, canal leakage and irrigation return flow as well as lateral groundwater movement out of the model domain. Water levels fluctuate between 0 and 4.5 metres below ground level (mbgl) during the simulation. The annual recharge-discharge difference (RDD) (Van Camp et al., 2010), shown in Figure 5, suggests that under the business as usual scenario the system is currently sustainable, with a surplus of approximately 12,700 m^3 over the model period. However, the RDD shows considerable inter-annual variability and there are a number of years when discharge exceeds recharge. This may have important implications for individual smallholders, particularly when there is a shortfall in consecutive years (e.g. 2004-2006, 2014-2017). Modelled crop yields for both wheat and rice increase in line with the linear trends of reported district crop production (Government of Bihar 2016). Median wheat yields increase from 1.9 tonnes/ha in 2000 to 2.4 tonnes/ha in 2018, peaking at 2.7 tonnes/ha in 2014. Modelled rice yields average approximately 1.6 tonnes/ha during the simulation period. Farmer income increases by approximately 2300 INR/year between 2000 and 2018, reaching a maximum of approximately 61,000 INR in 2018.

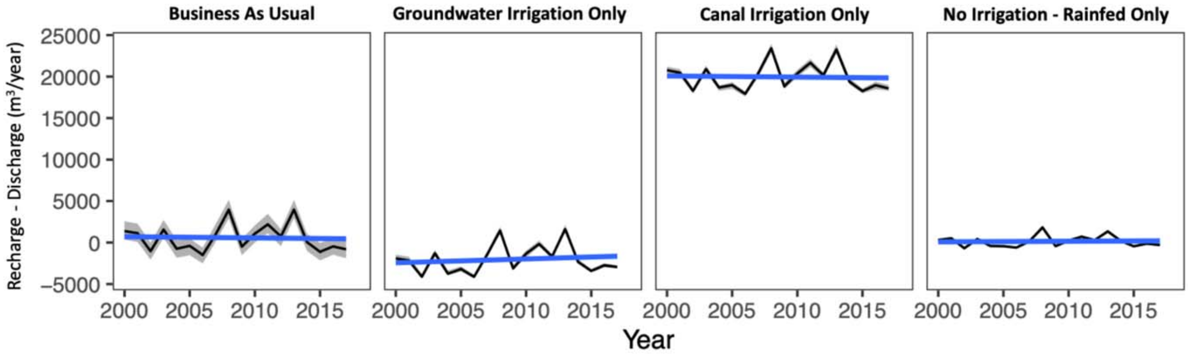


Figure 6: Calculated annual recharge less discharge values for each of the three scenarios. Units are in m^3/year

2.2 | Groundwater irrigation only

To explore the contribution that canal system leakage makes to the groundwater regime of the study area, canals are removed from the simulation in scenario 2 (Figure 5, Groundwater irrigation only). Without access to canals, stakeholders must rely solely on more expensive groundwater to irrigate their crops. As expected, groundwater levels fall under additional demand conditions with inflow coming from precipitation, and outflows comprising groundwater abstractions and lateral flows in the aquifer system. Overall, water levels show a downward trend, from 2 mbgl in 2000 to 31 mbgl in 2018, falling at approximately 1.6 m/year. By the end of the simulation in 2018, median modelled groundwater levels were found to be approximately 27 m below observed groundwater levels. Figure 6 shows recharge is less than discharge for the majority of the model run, leading to an overall deficit of -36,120 m^3. This indicates that groundwater resources are not sustainable under current water demands without the additional contribution of canal water. There is little change in modelled crop yields for either wheat or rice between a BAU scenario and one where canals are not operational (Figure 7). Field data suggest farmers in the study region strive to maximise their yields rather than profits, where possible, and do this despite rising irrigation costs; for example, when the only water source available is more expensive groundwater. This is reflected in Figure 8, where results indicate farmer incomes of approximately 3,000 INR less than farmers who have canal water access.

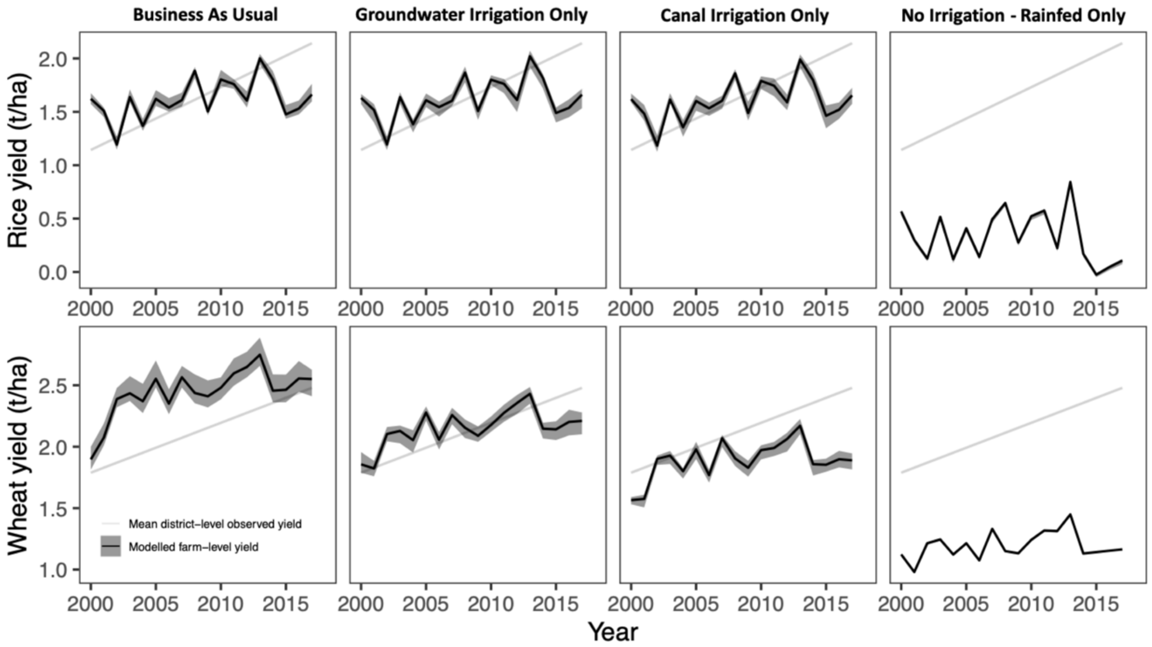


Figure 7: The modelled v observed yields of rice and wheat grown in the study area between 2000 and 2018 under BAU, no canal and no irrigation scenarios. Reported mean district level crop yield is also shown. Units are in tonnes/hectare (t/ha)

2.3 | Canal irrigation only

Canals supply approximately 30% of Bihar's irrigation water (Government of Bihar 2016); therefore understanding the feedbacks between canal management, the hydrological regime and human welfare is important. Canal water is limited to farmers within the canal command area who have access to the surface water distribution network; farm elevation or poor network access may result in many farmers missing out on surface water supply benefits, despite being within the command area. Canal network reliability is a common issue reported by farmers, and most who have canal access also use groundwater. In reality, a scenario where farmers rely on canal water only without abstracting groundwater is unlikely. However, exploring this scenario establishes water management boundary conditions and allows us to investigate an important "what if" scenario. Here, the implications of a fully operational canal network are explored.

Figure 5 shows that the use of canal water for irrigation coupled with a cessation of groundwater abstraction results in rising groundwater levels. This elevated groundwater table, represented by a flat line at surface level, is maintained throughout the simulation, approximately 5 m above observed values. Under a fully operational canal network which farmers use exclusively, recharge is considerably more than discharge; a surplus of almost 376,000 m^3 is generated by a switch to surface water irrigation only. This highlights that the introduction of canal water into a hydrological system with low groundwater storage increases the risk of flooding.

There is little change in modelled crop yields for either wheat or rice between any of the scenarios where irrigation takes place (Figure 7), however, the model does not take into consideration the impacts of water logging on crop production. The cost for using the canal network is minimal and users are often not charged for its use (O'Keeffe, 2016). This removes one of the larger annual expenses incurred by farmers, which can be seen in the slightly higher income values generated during this scenario Figure 8; approximately 8,000 INR more than under a conjunctive groundwater-surface water system and 15,000 INR more than under a groundwater only regime.

2.4 | No irrigation

Under no irrigation conditions, groundwater levels vary with precipitation and lateral groundwater flow exiting the model domain (Figure 5, No irrigation, rainfed only). Median groundwater levels range from between 0 and 2.1 mbgl. Groundwater recharge is greater than discharge over the simulation period (2,400 m^3) (Figure 6). As expected, under a scenario of no irrigation, yield significantly falls for both rice and wheat. Wheat yields fall by 0.7 to 2.4 tonnes/ha below the average state-wide reported yields. Modelled rice yield reaches a peak of 0.7 tonnes/ha in 2014, however the model predicts that most annual rice yields will fall below 0.5 tonnes/ha. This is also reflected in Figure 8, where modelled values indicate a significant reduction in the income levels of farmers under rain-fed conditions. Results indicate irrigation allows farmers to generate incomes of up to 45,000 INR more by 2018 than those who rely solely of rainfall to grow crops.

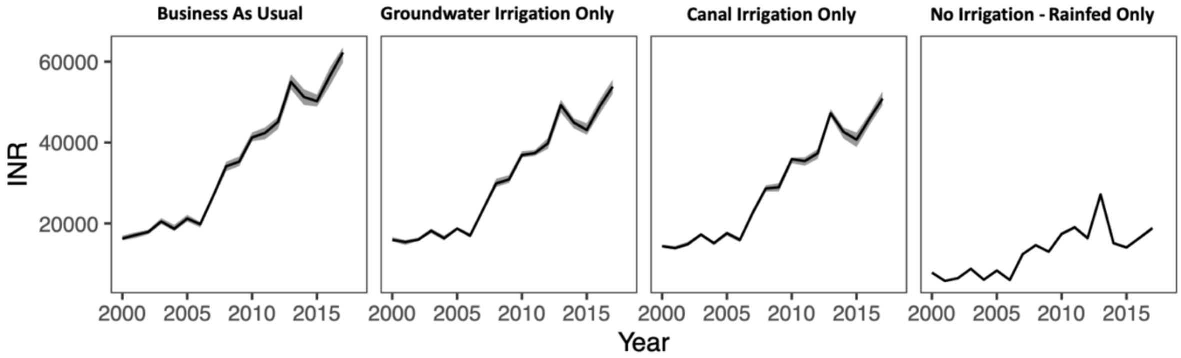


Figure 8: Modelled income levels providing an indication of how farmer income is likely to change in the study area between 2000 and 2018 as a result of variations in human water use

practices and environmental conditions during business as usual, no canal and no irrigation scenarios. Units are in Indian Rupees (INR)

3 | DISCUSSION

By directly including detailed hydrological and socio-economic information in addition to the observed water use behaviours of farmers, the primary resource users in the study area, the model closely replicates variations in observed groundwater levels under anthropogenic and natural regimes (Figure 5), highlighting the significance of humans as drivers of environmental change. Modelled results and observed groundwater levels also suggest the hydrological system, employing conjunctive use of water sources, provides enough water for all demands in its current form and management structure (Figures 5 and 6). Deviation from observed human irrigation practices, however, results in a significant change in system behaviour as can be seen in model outputs. Operational canals affect the system in two ways; hydrologically, by introducing an additional inflow of water, supplementing irrigation water provided by aquifers while also inadvertently increasing groundwater recharge through canal leakage. Removal of the canal network and its influence from the system results in a significant reduction in groundwater levels as farmers are forced to rely on the aquifer for all irrigation in order to maintain crop yields. However, this also has an impact on income levels as groundwater is typically a more expensive irrigation source due to the additional energy costs associated with its abstraction (O’Keeffe et al. 2016); farmers prefer using canal water when possible, as this reduces their overall irrigation cost. In the study area, groundwater abstraction is most commonly undertaken using diesel powered suction pumps, linking irrigation costs to fuel prices. This can place an additional constraint on crop production, as at a certain point it may no longer be financially viable for farmers to irrigate. Deepening groundwater levels may also force farmers to change groundwater abstraction techniques; switching from diesel suction pumps to more powerful submersible pumps in order to maintain aquifer access (Misstear et al., 2006), leading to additional costs to farmers and placing increased strain on aquifer resources. Results also highlight the contribution of canal leakage to groundwater levels; a phenomena seen across India (see Bonsor et al. 2017). This demonstrates the role canals could play in maintaining irrigation water supply through managed aquifer recharge (Shah 2009), an idea central to the Ganges Water Machine concept (Amarasinghe et al. 2016; Khan et al. 2014; Revelle and Lakshminarayana 1975). However, it is important that any increase in canal operation is done responsibly. This is demonstrated in scenario 3 where farmers utilise free surface water exclusively rather than the more expensive diesel abstracted groundwater. The model results show that under current demand scenarios this could result in significant groundwater flooding. It should be noted that the model does not account for the impacts of water logging on crop production.

The risk of groundwater flooding is also highlighted during a business as usual scenario (seen in Figure 5 when groundwater levels reach surface levels). Under conditions where all ground and surface water irrigation is removed, groundwater levels rise and fall with precipitation and lateral groundwater flow. Under this more natural hydrological regime, the likelihood of groundwater flooding is reduced; median groundwater levels are maintained at approximately 3 m below surface levels. This further demonstrates the influence human water use behaviour has on the hydrological regime, while providing an indication of how common irrigation scenarios (groundwater + canal, or groundwater only) and crop rotation practices (wheat and rice) are likely to impact groundwater levels. While the influence of urbanisation is increasing (Misra 2011), human activities which impact the hydrological regime are largely driven by crop production. This is made clear in the modelled outputs of rice and wheat, which show a significant reduction under conditions of no irrigation.

4 | CONCLUSIONS

This study has focused on understanding and quantifying the role humans play in north India's hydrological cycle. The IGB is one of the most intensely irrigated regions of the world. Quantifying the influence of human practices on the hydrological cycle is challenging. We examine an area of north India representative of social and environmental conditions found across the region as a whole. Field studies involving semi-structured interviews with irrigators and water managers, as well as the installation of groundwater level monitoring equipment, were undertaken to advance the understanding of the hydrological regime and water use practices.

This results show the importance of appropriately managing surface and groundwater sources in order to mitigate flooding or unsustainable groundwater depletion. The results highlight the role the canal network plays in keeping groundwater levels artificially high in some regions, while also providing direct irrigation water to certain farmers, reducing demand on groundwater resources. As can be seen under groundwater only irrigation scenarios, without the contribution of canal water, current irrigation demands appear unsustainable (Figure 5). Such water use practices will likely result in falling groundwater levels due to the increased demand placed on aquifers to maintain crop production. Additional challenges may arise from water levels falling below the range of typical groundwater abstraction infrastructure. Results indicate the potential economic benefits provided to farmers by canals, relieving some of the irrigation costs. The modelling also highlights the potentially negative impacts of a canal irrigation only scenario, which increases the likelihood of surface and groundwater flooding.

Human water use practices play a major role in north Indian hydrology, significantly altering groundwater levels through abstraction, while artificially recharging aquifers though leakage from canals supplied by diverted surface water. Anthropogenic impacts to the hydrological regime are likely to increase in line with a growing population and the subsequent increased demand for water intensive crops. Additionally, while outside the scope of this paper, the transfer of water from the nearby river system, in this case the Gandak, has the potential to impact environmental flows, sediment transport and the welfare of communities who depend on the river for their livelihood. The capacity to understand and represent human behaviour and quantify the level of environmental change is central to developing and maintaining future environmental sustainability. System sustainability is significantly affected by anthropogenic water use. However, the results highlight the opportunities provided through suitable water management options, including augmenting groundwater resources through managed aquifer recharge and reducing the impacts on aquifer resources through occasional canal water use. How such practices will affect environmental flows will require further examination. We have shown that by including the feedbacks between the human and natural environment, optimal water management practices can be identified while highlighting trade-offs between impact and benefit, providing actionable knowledge to policy makers, water managers and water users.

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