Authors' Response to Reviews of

Changes in groundwater-surface water interactions following two centuries of irrigation practices and groundwater use in the Upper Ganges-Yamuna interfluve, North India.

Original comment

AR: Authors' response (blue italic)

Referee #1

General comments

This is a well written paper that presents an interesting historical study on the recharge and water level dynamics of an area of the Indo-Gangetic Basin. The quantification of different sources of recharge over an almost two-hundred-year period using numerical modelling is novel and an important contribution. After moderate revisions I suspect the paper will be suitable for publication.

I have some overarching comments.

AR: Thank you for your kind words, in the following sections we will respond to your comments.

RC1-GC1

The apparent lack of model calibration and validation using in-situ groundwater level data is an important element of the analysis that is missing. Do you have any longer-term groundwater level records at all from this region? I think these would be useful as a sense check to your results. The time series length does not need to be as long as the modelled period, but some slightly longer timeseries data would really help. I think it would be worth trying to find some longer-term data. It is often available offline in local government offices. I would suspect at the very least it should be possible to get some water level data with timeseries staring sometime in the period from the 1950 - 1970s. Even if you can't get continuous time series data, you could look at regional water level behaviour over a longer period, by collating a slightly more extensive water level dataset. At the very least it would be beneficial to present the groundwater level data you already have, but I do think it should be possible to find a little more longer-term data which would considerably improve the novelty and impact of the paper.

AR: We agree that longer groundwater-level time series would strengthen the model validation. However, despite extensive efforts, no longer-term groundwater-level records could be obtained for the study area. The Indian project partners contacted the relevant authorities and conducted repeated searches for archival and offline datasets, but no additional records were made available. Surface-water level data were also inaccessible because these datasets are subject to national security restrictions.

The groundwater-level observations currently included in the study therefore represent the only available in-situ data for this region to the best of our knowledge. We will acknowledge this limitation more explicitly in the revised manuscript and discuss its implications for model validation and interpretation of the results.

RC1-GC2

Can you use the groundwater level data you already have to illustrate how your model results compare to observed groundwater level trends during the period data is available?

AR: We will present some plots that compare observed and modelled groundwater levels and trends at observation well locations.

RC1-GC3

Does your model account for the distribution canals that provide water to farmers fields? Is this accounted for implicitly in your irrigation return flows? Distribution canals are likely to play a significant role in the spatial variation of canal derived recharge in the region.

AR: Yes, the model accounts for both the main canal network and the distribution canals. Canal-derived recharge is represented through two pathways: 1) Direct canal leakage recharge, which is applied at the mapped canal locations, including distribution canals. The canal dataset contains a relatively detailed representation of the canal network. Canal type is used as a proxy for canal width and therefore influences the estimated leakage recharge. 2) Indirect recharge through irrigation return flow, which originates from both canal water and groundwater used for irrigation. The relative contribution of canal irrigation is estimated using census data at the panchayat (village) level, allowing spatial variation in irrigation water sources to be incorporated into the return-flow calculations. In the manuscript this is explained in sections A.5 and A.6 and we will clarify this in the main text.

RC1-GC4

As the other reviewer has highlighted the lack of seasonality in your model has implications. For example, whether rivers are receiving or losing depends on the time of year and the range of water level fluctuation experienced in a year. The range of water level fluctuation in this region can be considerable. How might this impact your findings? How does lack of representation of seasonality more generally impact your findings?

AR: (This response addresses comments RC1-GC4, RC2-SC4 and CC2, which concern the same issue). We agree that the use of yearly time steps limits the representation of seasonal groundwater dynamics in this monsoon-dominated system. With a finer temporal resolution (e.g. monthly timesteps), the model could capture seasonal reversals in SW–GW exchange and distinguish, for example, between dry-season infiltration and monsoon-driven exfiltration. However, the objective of this study was to assess long-term regional trends over a two-century period, for which yearly net SW–GW exchange was considered the most relevant metric. In particular, for evaluating the long-term spreading of polluted surface water into the groundwater system, the annual net exchange is more important than seasonal fluctuations. For example, if polluted river water infiltrates into the aquifer during the dry season but is subsequently discharged back to the river during the monsoon, the net annual exchange remains exfiltrating and the long-term transfer of pollutants to groundwater would be limited.

We acknowledge that a higher temporal resolution could provide additional insight into seasonal dynamics and the timing of exchange reversals, but such simulations were beyond the scope of the present long-term regional analysis and would substantially increase computational demands. We will clarify this limitation in the revised manuscript.

RC1-GC5

You have made quite a lot in the summary and abstract of the threat to drinking water quality from losing rivers, but water quality isn't something you explicitly model. So it might be worth being a little more cautious in your discussion about this.

AR: We agree with this comment, and we will be more cautious about the statements and more clear about it. We have therefore revised the summary and abstract to better distinguish *between modelled results and their possible implications. Please see our responses to comments RC1-SC1 and RC1-SC2 for the specific changes made.*

RC1-GC6
Is it possible to present the data you compiled on groundwater abstractions and recharge in the manuscript or an appendix? It would be helpful to see the vector or raster datasets you compiled.
AR: Spatially explicit input data are available for all recharge and abstraction components for each year. Aggregated maps of these components are already presented in figure 6 for the different time periods considered in the study. However, due to space constraints, the maps in the main manuscript are relatively small and do not clearly show the spatial details. We will add larger versions of these maps in the appendix.

Specific comments

RC1-SC1
Short summary: the implication that losing waters from rivers to groundwater threatens drinking water supply isn't inevitable. Without more context in the summary, I would reconsider the weight you attach to this conclusion.
AR: We will be more cautions and we will change it into this:
"Model simulations show how North India's water system changed over the past two centuries. From 1830, irrigation canals increased recharge and groundwater flows to rivers and streams. After 1970, groundwater pumping, mainly for irrigation, surged, lowering groundwater tables and reducing flows to surface waters. Since 2000, some local rivers likely switch to lose water to the groundwater. This may have implications for river ecosystems and groundwater quality, especially where rivers are polluted."

RC1-SC2
Abstract: You say that 'local rivers likely shifted from draining to infiltrating conditions' and that 'groundwater–surface water interactions in local rivers may have fundamentally changed'. It's not clear in the abstract whether your model shows this effect explicitly or whether you infer this? It's clear when reading the rest of the manuscript, but it needs to be made clearer here. Likewise, the continued role of canals after 1970 is not clear in the abstract. You mention that they boosted recharge prior to 1970 but do they continue to recharge groundwater levels after this period?
Reading on the answers to these questions are clear, but they need to be made clearer in the abstract.
AR: We have rewritten the abstract to be more clear what the model showed and what is inferred. We also clarified that the canals continue to recharge the groundwater. The new abstract will read like this:
"The Indo-Gangetic Basin (IGB) is a global hotspot for groundwater overexploitation. Previous studies have shown that groundwater levels initially rose due to enhanced recharge following the construction of irrigation canals, but subsequently declined as agricultural, municipal, and industrial abstractions intensified. However, the relative impacts of separate recharge and abstraction components (precipitation, canal leakage infiltration, irrigation return flow, and irrigation, municipal and industrial abstraction), remain unclear, as do the effects on groundwater-surface water interactions and environmental flows. This study therefore aims to quantify spatio-temporal changes in groundwater recharge and abstraction components over

the past two centuries and assesses how these changes have impacted groundwater–surface water interactions in the Upper Ganges–Yamuna interfluve in northern India. Groundwater model simulations indicate that canal water infiltration following canal construction after 1830 increased groundwater recharge and groundwater discharge to local rivers. Although canals continue to provide significant recharge, rapid rise in groundwater abstraction since the 1970s has lowered groundwater tables and reduced groundwater discharge to surface waters. Currently irrigation accounts for roughly 85% of the abstractions, with municipal (15%) and industrial (< 1%) uses accounting for much smaller shares. The model simulations indicate that around 2000 local rivers likely shifted from draining to infiltrating conditions. This change in groundwater–surface water exchange may affect environmental flows and increase the vulnerability of groundwater to contamination where surface waters are polluted. Although both the Yamuna and the Ganges show reduced groundwater exfiltration, they are not (yet) infiltrating."

RC1-SC3

Introduction: arguably water resource development has been going on in the region for much longer than this. The Mughals actively managed water resources and there is evidence as far back as the Indus Valley civilisation of large-scale water resource development. To be more accurate you could say something like, 'development of modern irrigation canal systems began in 1830 with the Eastern Yamuna irrigation canal'.

AR: Good suggestion we implemented this in the introduction.

"…. that small-scale canal systems in the Indo-Gangetic Basin (IGB) date back to 16th century under Mughal rule (Jain et al., 2022) and the development of modern irrigation canal systems began in 19th century with the Eastern Yamuna irrigation canal in 1830 (Irrigation and Water Resources Department, n.d.)."

RC1-SC4

Figure 1: The model schematisation does not seem to include the canals. Is that correct?

AR: Yes, the canals are deliberately not shown in this schematisation as they are treated as a recharge component and are therefore included in figure 6 as "canal leakage recharge". In the next comment (RC1-SC5) we explain why we implemented canals as recharge and not as surface water (RIV-package) in the MODFLFOW 6 model.

RC1-SC5

2.2 MODFLOW 6 – model schematisation: it would be helpful to know why rivers and canals were simulated differently in your model.

AR: (This response addresses both comments RC1-SC5 and RC2-SC8, which concern the same issue). Irrigation canals were represented as recharge sources rather than as explicit surface-water boundary conditions (e.g. using the RIV package). This conceptualization assumes that canals are generally located at relatively elevated positions in the landscape while groundwater tables are comparatively deeper, resulting in predominantly downward leakage from canals to the aquifer. This is a realistic assumption backed by field observations. Under this assumption, canal leakage is treated as disconnected surface water recharge and is therefore not directly influenced by simulated groundwater levels.

This approach was also adopted because detailed data on canal bathymetry, canal-bottom elevations, and surface water levels were unavailable. We will clarify this modelling choice and its implications in the revised manuscript.

RC1-SC6

2.3 Monte Carlo analysis and validation: How were the groundwater level data used to validate your model? Can you present some plots to show observed versus modelled water level changes?

AR: The groundwater level observations from 94 monitoring wells were used to evaluate model performance by comparing observed and simulated groundwater levels and calculating the Mean Absolute Error (MAE) and Mean Error (bias) for each model realization. This evaluation procedure is described in lines 174–180 of the manuscript.

We will include several figures in the appendix showing comparisons between observed and simulated groundwater levels.

RC1-SC7

3.2 Effects on groundwater table: You state that, 'after 2000, groundwater tables declined further.' Which appears to be based on Figure 8. However, it appears from Figure 7 that after this period groundwater decline slows and groundwater levels are arguably more stable. It would be helpful to clarify this apparent discrepancy.

AR: Yes, we will make this more clear in the revised manuscript, and we will adopt more cautious wording where appropriate.

RC1-SC8

Figure 8 and 10: The layout of these figures is quite confusing, I would suggest reconsidering the placement of the 'natural situation' and 'current situation' plots and their associated legends. At present it appears as if the legend on the left is for the plots it underlies and likewise on the right. However, I think the legend on the left is only for the 'natural situation' and 'current situation' plots.

AR: We will make new clearer versions for figure 8 and 10 with special attention to the layout and placement of the legends.

RC1-SC9

4.1 Groundwater balance evolution over the past two centuries in the Upper Ganges-Yamuna interfluve: At the start of this section, you mention that changes in recharge and abstraction influence groundwater levels with a temporal delay, but this is the first time this temporal delay is mentioned. What is the temporal delay for the different recharge sources?

AR: In our model, temporal delays are not prescribed separately for different recharge sources. Instead, they emerge from the groundwater system response, which is governed by groundwater storage, aquifer properties, and groundwater flow dynamics. As a result, changes in recharge or abstraction do not translate immediately into changes in groundwater levels or groundwater–surface water exchange. For example, canal construction causes an immediate increase in recharge, but groundwater tables rise more gradually as water is stored and spatially redistributed within the aquifer. Similarly, changes in groundwater–surface water exchange occur with an additional delay because these fluxes depend on the evolution of groundwater heads and hydraulic gradients. We will revise the text to explain this more clearly.

RC1-SC10

The discrepancy of your results with those observed by MacAllister et al. (2022) could also be related to a much less dense canal network in your study area and less continuous canal development through the 19th and 20th century.

AR: Thank you for this suggestion. We will include differences in canal density as a potential explanation in the discussion alongside the other factors that could explain this discrepancy.

RC1-SC11
4.2 Model uncertainties and limitations: Is the assumption of stable land use patterns over a nearly two-hundred-year period in this area really justified? This ties into the other reviewer's comments.
AR: (This response addresses both comments RC1-SC11 and CC1, which concern the same issue). We agree that the assumption of stable land-use patterns over a two-century period is a simplification and an important source of uncertainty. Unfortunately, no spatially explicit historical land-use datasets were available for the study area covering this period. Nevertheless, the study area has long been characterized by intensive agriculture and a relatively dense rural population. While the extent of urban areas has undoubtedly increased, particularly around major cities, and agricultural practices have intensified over time, we expect the dominant land-use classes (agricultural land and settlements) to have remained broadly similar in their spatial distribution.

RC1-SC12
4.3 Implications: It would be helpful to show evidence of the current extent of wastewater inputs to rivers. Do you have any data for this?
AR: We thank the reviewer for this suggestion. However, we believe that quantifying the extent and sources of wastewater inputs to rivers was beyond the scope of the present study, as this study focuses on the effects of changing recharge and abstraction patterns on groundwater–surface water interactions and thus on the baseflow of the river. Evidence for substantial wastewater impacts on surface-water quality is available from previous work in the region. For example, Van Broekhoven et al. (2024) showed that surface waters in the Hindon subbasin are heavily influenced by wastewater inputs outside the monsoon season. The purpose of the implications section is therefore not to quantify wastewater loads, but to highlight how the modelled changes in groundwater–surface water interactions may increase the vulnerability of surface and groundwater quality.

van Broekhoven, F. J. G., Griffioen, J., Dekker, S. C., Sharma, M. K., Bhagwat, A., and Schot, P. P.: Linking recharge water sources to groundwater composition in the Hindon subbasin of the Ganges River, India, Sci. Total Environ., 954, 176399, https://doi.org/10.1016/j.scitotenv.2024.176399, 2024.

RC1-SC13
5 Conclusions: You conclude by saying unless substantial recharge enhancement occurs groundwater level decline is inevitable. However, India is investing in Managed Aquifer Recharge on a very large scale. It would be worth recognising this in your conclusions and/or discussions.
AR: We thank the reviewer for this valuable comment. We will recognize the efforts in MAR in the discussion.

RC1-SC14

A.1 Irrigation groundwater demand: Is the 2011 census data the most recent data available? Could you not use consecutive census to better quantify changes with time?

AR: The 2011 Census is currently the most recent census dataset available. Although the next census was scheduled for 2021, it was postponed due to the COVID-19 pandemic and its results have not yet been released. Consequently, the 2011 Census represents the latest available dataset for this analysis.