Interactive Discussion: Author Response to Referee #2

Groundwater recharge in Brandenburg is declining – but why?

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RC: ***Reviewer Comment***, AR: *Author Response*, ☐ Manuscript text

Dear madam or sir,

thank you very much for your referee report, and for the time and effort you spent to examine the manuscript. In particular, we appreciate the detailed suggestions along the entire manuscript text.

Similar to referee 2, you specifically mention the overall impression that parts of the manuscript were difficult to follow. We will hence attempt, in a revised version, to particularly improve the comprehensibility.

Please find both your comments and our responses below in a point-by-point reply.

Thanks again for your feedback, and your support in improving the manuscript.

Kind regards,
Till Francke and Maik Heistermann

Point-by-point replies

RC: ***The manuscript by Francke and Heistermann is giving an approach to explain dropping groundwater recharge in Brandenburg. Overall, the study is impressive and very interesting and will doubtless find its place in the journal, where it fits well into. The manuscript is appropriately designed and consistent, figures are of high quality and in principle well prepared. Few minor things should be modified, which I marked below.***

AR: Thank you for the overall positive assessment.

RC: ***More specifically I was wondering, why the authors mainly base their arguments on discharge measurements only rather than including direct groundwater observations to justify dropping groundwater recharge.***

AR: This issue is raised again by the referee below in the comment reg. ll. 69-73 of the preprint. We will address this issue in response to the below comment.

RC: ***During reading, I also had the problem, that I often had to jump back in the text to be sure I understand what is meant and don't miss things. Sometimes expressions are difficult to read and to follow, but when authors carefully inspect the manuscript again, I'm confident it will be improved and become published in NHESS.***

AR: This impression is consistent with the report by referee #1. In the revised manuscript, we will address the referees' numerous suggestions to improve the comprehensibility of the manuscript. Please see our below responses with respect to specific comments.

RC: ***L30 f. I would rather use deep and shallow instead of distant and close water tables.***

AR: We will revise the wording accordingly.

RC: ***L38. In an intensely cultivated and urbanized region as Brandenburg, there might be increased abstraction by man different actors (farmers, water suppliers, private wells, etc.). How comes you generally state: "there is no basis to assume such a widespread abstraction of groundwater"? That statement is a fundamental prerequisite of the coming explanation for dropping gwr, but there is no evidence presented.***

AR: We agree that this statement should be better justified. It is also imprecise in its original form and hence needs improvement.

We agree with the referee that there are abstractions from the groundwater across the state of Brandenburg (although we would not qualify Brandenburg as "intensely cultivated and urbanized" in comparison to other federal states in Germany). However, these abstractions are unlikely to explain the widespread decline of groundwater levels in the recharge areas because there is no evidence that these abstractions were *increasing*. Quite the contrary, water abstractions have been *decreasing* considerably for the past decades - at least since 1991 (see Landesamt für Umwelt Brandenburg, 2022).

We will revise the sentence around ll. 37-38 of the preprint to make clear that there is no basis to assume that a *change* in water abstraction led to the observed decline in groundwater levels.

> [...] ground water levels decreased significantly between 1976 and 2020 in the recharge areas (i.e. in the elevated areas with large distances to the ground water table, see Fig. 1). The most plausible hypothesis to explain such a state-wide prevalence of negative trends is a declining GWR, while there is no evidence for increasing water abstractions in the past decades. Quite the contrary, water abstractions considerably decreased at least since 1991 (Landesamt für Umwelt Brandenburg, 2022) [...]

Furthermore, we would like to point out that we show, in section 5.4, that there is no evidence of significantly increasing irrigation water withdrawals over the past four decades. In section 5.4, we focused on irrigation because it is the only type of water use during which a large portion of the water is actually lost to evapotranspiration, while water from most other water uses actually returns to the local catchments so that these water uses will typically not affect the catchment's long-term water balance.

RC: ***L39. How is it possible, an aquifer gets confined by a river? Please think about wording.***

AR: We agree that the word "confined" already has a different meaning in hydrogeology. In the revised version, we will rephrase as follows:

> Please note that the lowlands do not show strong trends in either direction because the groundwater level is stabilised by the water level of the heavily-regulated streams and rivers to which the aquifers are connected.

RC: ***L50: is it indeed possible to generalize it as you do: "Given the highly permeable soils in Brandenburg and the resulting insignificance of surface runoff..."? I think the evidence coming from that statement is very***

serious and actually builds the foundation of the subsequent argumentation: dropping river discharge as mirror of dropping gwr, because baseflow is (in your argumentation) the only source of surface runoff. I think that point, in combination with my concerns from line 38 (missing abstraction), should be treated with more caution and seriously justified.

AR: In the preprint, we introduced, in line 66, the corresponding reference which establishes that surface runoff is negligible in Brandenburg (LUA Brandenburg, 2001). In order to improve the readability of the manuscript, and avoid the need to jump back and forth while reading, we will also add the corresponding reference after the statement in ll. 50-52 of the preprint.

RC: ***Fig. 1: a) the names given therein are unclear in their meaning: are these cities, counties, catchments?***

AR: Thank you for pointing this out. In fact, these are names of counties. We will point out this fact in the figure caption.

RC: ***b) in each of the figures, 2 numbers are given, but it is not clear what they represent. Also the unit is not clear to me: mm/a/dec, millimeter per year is okay, but what is "Dec"?***

AR: We will clarify this information in the figure caption of the revised manuscript , but also use the opportunity to provide some explanation here: as the referee states, the annual average discharge or the average GWR in a catchment can be expressed in the unit $\mathrm{mm\,a^{-1}}$. The temporal trend of such a quantity, i.e. the change of that quantity over a given time period, would then be expressed by the unit of our quantity ($\mathrm{mm\,a^{-1}}$) in relation to (i.e. divided by) the length of that period. For our study, we chose to represent the trend as the change of the quantity over the period of a decade (10 years). We explained this in the original preprint in section 3.6 (l. 291), but we agree that it is necessary to explain this unit before.

In the revised version of the manuscript, the unit will also be explained after its first occurrence in the introduction, according to l. 50 of the preprint.

RC: ***L69-73: I partly disagree with that statement. The analyses of gw-timeseries gives worthwhile information as for gwr and though the given issues are valid in a certain way, it is mentioned before, the catchments that are investigated are not influenced by abstraction. Of course, storativity is always an uncertain parameter, but I guess there should be few pumping tests available to at least estimate gwr in few areas, based on gw timeseries.***

AR: The estimation of GWR from GW level records is not only limited by the high uncertainty of storativity. A local change in GW level results from the water balance in a control volume which is not only affected by GWR, but also by the aquifer flow, and it is difficult to distinguish these quantities without further assumptions. But while Collenteur et al. (2020) in fact demonstrated how to reconstruct GWR from GW level series under certain conditions, they also outlined serious limitations in case of deep and shallow groundwater tables. This makes it very difficult to derive *robust* quantitative long-term trends in Brandenburg where we have both, very shallow and very deep groundwater, in each study catchment.

RC: ***L75 ff. Please use consistent wording: shallow and deep gw tables and don't switch between deep and distant.***

AR: We agree. The manuscript will be revised accordingly.

RC: ***L107: where is the dataset from? Reference?***

AR: The reference to the dataset, including some background, was provided in section 2.5 in the overall "Data" section. To improve readability, we will already introduce the reference after "we use a recently published

LAI dataset", corresponding to l. 107 of the preprint.

RC: ***L136: I do not understand the integration of neighbouring catchments: they do not contribute to the discharge of the gauge. And what does it mean to include them "partly"?***

AR: Thanks for the comment. We agree that our explanation was prone to misunderstanding. In order to be more explicit, we will change the sentence as follows:

> In three cases, adjacent catchments were aggregated in order to further reduce the effect of uncertain belowground watersheds, and to increase the area over which the water balance is computed. "Aggregating" two (or three) catchments means that their areas were merged to one coherent area, and that the observed runoff at the gauges of each catchment was summed up in order to obtain the total runoff from the merged area. Tab. 1 gives a comprehensive overview of the used discharge gauges and the aggregation of catchment areas and runoff gauge observations for our analysis.

RC: ***L162. There is a spare parenthesis at the end of the sentence.***

AR: Will be removed.

RC: ***L179. Where are the field LAI measurements were taken from? Just out of curiosity: during 2019-2024, forest dieback (as observed in other areas in Germany) did not apply to Brandenburg at all?***

AR: The sources of field measurements are comprehensively documented in section 2.8 of the underlying reference by Cao et al. (2023). As to the question of forest degradation as a consequence of the subsequent drought years between 2019 and 2024 (or, rather, between 2018 and 2022), it should be noted that the number provided in ll. 179 is a long-term trend over four decades which is also an average over all of Brandenburg. The increase of 0.1 m^2 m^2 per decade over almost 40 years does not imply that Brandenburg's forests were unaffected by the impacts of the recent drought years, although the most dramatic consequences, Germany-wide, were observed for spruce forests which are rather uncommon in Brandenburg. It should also be noted that the dataset by Cao et al. (2023) only reaches until 2020. Still, we can observe some decline in the most prominent drought years in 2018 and 2019 (see Fig. 3f of the preprint). However, we would prefer not to go into further depth here since this issue is, although relevant as such, beyond the immediate scope of the present study.

RC: ***L196 ff. The steady state type of gw-depth information may not fit to the proposed changes in gw depth due to dropping gwr, am I wrong?***

AR: You are right: our model approach does not account for transient changes in ground water depth. The data that would be required to force the model with a dynamic lower boundary condition is, however, not available in sufficient spatial and temporal detail. A transient lower boundary would also make it difficult to apply our hydrotope concept, since the temporal variation would be another dimension that would need to be accounted for when defining the hydrotopes. However, in section 5.6 of the preprint, we discuss possible uncertainties with regard to the simulation of GWR that may arise from the assumption of stationarity. These are expected to be rather low: In areas with deep groundwater, groundwater depth does not affect GWR (only the transit time in the unsatured zone). In areas with shallow groundwater tables, groundwater depth *does* exert a fundamental control on evapotranspiration and hence GWR. Yet, groundwater tables in areas of shallow groundwater appeared to be quite stable in the past decades (as pointed out before, in section 1) as they are mostly coupled to surface water bodies and stabilised by their hydraulic regulation. So here, the assumption of stationarity is in fact more justified.

RC: ***L246: where is soil moisture data taken from?***

AR: The soil moisture simulated by the model itself is used to compute actual evapotranspiration from reference evapotranspiration, essentially based on the Penman-Monteith equation and the Feddes model, as outlined in Kroes et al. (2017). In the revised manuscript, we will try to clarify this by changing the sentence in ll. 246 ff. as follows:

> Evapotranspiration depends on atmospheric conditions as well as on vegetation and soil properties and is estimated using the Penman-Monteith equation in combination with the Feddes model which accounts for the limitation of transpiration by the availability of soil water (Kroes et al., 2017).

RC: ***L251: is a constant head not contradicting the question, whether gwr is dropping and hence gw tables?***

AR: Please see our above response with regard to the comment in ref. to ll. 196 ff.

RC: ***L265 ff.: is the concept of hydrotopes following the idea of HRUs in hydrology? How did you include the depth to groundwater, 13 classes of gw depth each mulitplied by land use, soil type etc.? How did you integrate the hydrotopes spatially: as grid or as a mesh of irregular/regular triangles?***

AR: We will add a brief sub-section at the very beginning of the methods section (section 3.1) in which we will provide an overview of the methodological approach, including the hydrotope concept and area-weighted averaging.

> The main methodological approach of our study is to simulate series of GWR in each study catchment for the period from 1980 to 2023. From these series, we computed the trends (section 3.6) in GWR and compared them to the corresponding trends of observed discharge. A good agreement between both would indicate that the simulation model is able to explain the discharge trends as outlined in Fig. 1 and Tab. 1 (see also section 1 for additional background).
>
> To obtain GWR, the one-dimensional Soil-Water-Atmosphere-Plant (SWAP, van Dam et al., 2008, section 3.4) was used to simulate the surface water balance and the resulting percolation of water through the unsaturated zone down to the groundwater table. This daily ”bottom flux” was aggregated to obtain the annual sum of groundwater recharge.
>
> In order to obtain the spatial average of GWR per catchment, we followed the concept of ”hydrotopes”, i.e. spatial sub-units that are considered as homogeneous with regard to (i) climate forcing, (ii) soil texture, (iii) land use, and (iv) groundwater depth. For each catchment, climate and soil were assumed to be uniform across the entire catchment (i.e. *one* class each per catchment): the climate forcing was based on the nearest of the four selected climate stations (section 2.3), and soil texture was represented by the dominant soil texture class in the catchment (section 2.6). Land use and groundwater depth, however, were assumed to be heterogeneous across the catchment: land use was represented by *two* classes (forest and grass-/cropland) and groundwater depth by *13* classes of groundwater depth (see section 2.6). This resulted into a total of 26 hydrotope classes (1 climate x 1 soil x 2 land uses x 13 groundwater depths). By spatially intersecting all four layers, we quantified the areal fraction of each hydrotope class per catchment. Running the SWAP model for each of the 26 hydrotope classes, the daily GWR per catchment was then obtained as the area-weighted average of the simulated daily bottom flux per hydrotope.

In the following subsections, we further explain the treatment of missing hydro-climatological data (section 3.2), the precipitation correction (section 3.3), the SWAP model and its parameterisation (section 3.4), the specific design of the simulation experiments (section 3.5) and the calculation of trends (section 3.6).

RC: ***L281: what is the unit "dec" standing for?***

AR: Please see our response to the comment of the referee concerning Fig. 1 b).

RC: ***L291: now the explanation comes, much too late...***

AR: Please see our response to comment of the referee concerning Fig. 1 b).

RC: ***In general, it is hard to understand the concept of mm/a/dec. To become able to translate it into a logical unit, it needs a brief explanation at the very beginning.***

AR: Please see our response to the comment of the referee concerning Fig. 1 b).

RC: ***L296: why was just LAI selected to be the controlling parameter of dropping gwr? Increasing ET is obviously a key-parameter as well controlling the soil moisture (fig. 3d).***

AR: We are not sure how the comment refers to l. 296 of the preprint. However, we will try to respond to the comment itself.

We do not quite agree with the notion that we "selected just LAI to be the controlling parameter of dropping GWR". What we did was to compare GWR trends with and without an external LAI trend, given the observed climate forcing.

GWR and its change are governed by the long-term balance between precipitation and (actual) evapotranspiration. But while precipitation is an external forcing, *actual* ET is inferred internally. Although it is driven externally by irradiation, temperature, vapour pressure, and wind speed (which all affect *potential* ET), actual ET is the result of various interlinked internal processes (e.g., root water uptake, bare soil evaporation, percolation below the root zone) and internal state variables, the most important of which is soil water content, representing the actual availability of water for transpiration and evaporation (in combination with the soil hydraulic properties which, in essence, control the matric potential for a given water content). We have clarified in our response to the referee's above comment how the Feddes model is used to account for the effect of soil water content on transpiration.

As a consequence, soil water content cannot be used as a "control" parameter in the sense of an external forcing. In turn, potential evapotranspiration (referee's reference to Fig. 3d) and its trend is the result of a variety of forcing variables (as outlined above), so it is not helpful to consider it as a control variable, either, in the sense that it could be varied (controlled) independently.

Surely, LAI could also be considered as an internal state variable, in the case that vegetation dynamics were computed internally as a function of atmospheric forcing and internal limitations by water and nutrients. However, this is deliberately not how we set up the model, since this introduces a series of other uncertainties.

RC: ***L297: please explain CI***

AR: We apologize, but we cannot relate this comment to the content of l. 297 in which the term "CI" does not occur in the preprint. The first occurrence of the abbreviation "CI" is in l. 323 where the meaning (confidence interval) is also explained.

RC: ***L344: where do I see it in Fig. 5? The figure is very complex but nice. However, I have difficulties to differentiate between various shades of grey in some of the graphs.***

AR: We understand this difficulty. We had tried various ways to differentiate levels of significance for the simulated GWR without introducing too many different colours (which again causes problems in interpretability). Still, we think that three different levels of grey (one actually black, one intermediate, one very light) are an acceptable compromise. One might have to look twice to be sure, but this is still our preferred solution. So regarding the question with regard to l. 344: "where do I see [significance levels of $p \leq 0.1$] in Fig. 5?', the answer is: everywhere where the dots do *not* have the lightest shade of grey. We will add an explanation after the corresponding sentence in the revised manuscript to support the interpretation of the figure.

RC: ***L362: in fig. 3 there is no real trend in precipitation observable, how comes it though brings the gwr to drop?***

AR: Fig. 3e is maybe not ideal to appreciate the long term precipitation trend because the strong interannual variability of precipitation requires the y-axis scaling to cover quite a wide range, making it difficult to read the precipitation trends of the four selected climate stations directly from the trend lines. This is why we highlight the trends at the four selected climate stations also in Figs. 4 (large dots) and 5 (large triangles), showing that the downward trend in precipitation is substantial (though not statistically significant) at the stations in Lindenberg and Marnitz, and, to a lesser extent, in Potsdam, too.

RC: ***Fig. 6: how is it explainable, gwr is almost negligible in 4 out of 5 catchments fro shallow water tables? Contrastingly, the deeper groundwater receives reasonable gwr of 100-150 mm/a.***

AR: The reason behind this is explained in ll. 380-386 of the preprint. In that paragraph, we will again explicitly refer to Fig. 6a in order to improve the comprehensibility. At the beginning of the paragraph, we will add another reference to section 1 (where the effect of shallow groundwater tables on net GWR is explained).

RC: ***What does "area weighted" mean here? How is areal fraction calculated?***

AR: We assume that this comment specifically refers to the caption of Fig. 6. Let use explain this more explicitly: for each study catchment of area A (see Tab. 1), we define $A_{\leq 3}$ as the total area of hydrotopes with a groundwater depth ≤ 3 m, and $A_{>3}$ as the total area of hydrotopes with a groundwater depth >3 m. The term "areal fraction" (Fig. 6c) hence refers to the fractions $\frac{A_{\leq 3}}{A}$ and $\frac{A_{>3}}{A}$, respectively, summing up to a total value of 1. These fractions also constitute the weights for an area-weighted average of the GWR itself (Fig. 6a) and the area-weighted average of the *trend* of GWR within each of the two groundwater depth classes.

RC: ***L383 ff. I have difficulties to understand why the contribution of the shallow gw is that high, if their (however calculated) areal contribution in the total catchment is low. And why show shallow gw at all different gwr compared to deeper gw bodies? Is it a function of delay? But how was it modelled in 1D?***

AR: Areas with shallow groundwater tables are characterised by very high evapotranspiration rates because of the connectivity of the vegetation's root system to the groundwater table. The vegetation is able to draw water from the groundwater even if the groundwater table is somewhat below the maximum rooting depth. One reason behind this is capillary rise. The second reason is the inversion of the hydraulic gradient under dry summer conditions, leading to an upward water flux that can, within limits, be sustained in case the groundwater table is sufficiently shallow. Both processes are represented by the model. The resulting high values of summerly evapotranspiration lead to very low net fluxes towards the groundwater table, if integrated over the entire year. In total, this phenomenon has nothing to do with transit times, but with the connectivity between plants and groundwater and its effect on net water fluxes.

In the revised manuscript, we will provide more explanation in the introductory part (ll. 74-76 of the preprint) where this issue is addressed first, and refer to the introduction in the line that corresponds to l. 380 of the preprint.

RC: ***L403: there is a "by" too much.***

AR: Will be removed.

RC: ***L453f. Where stems the data from? A study from 2009 might not be representative to activities during the last decade.***

AR: There is no evidence of a substantial extension of irrigated areas since 2009. The most recent figure, as provided by the statistical agency, is 309 km² in the year 2022 (Amt für Statistik Berlin-Brandenburg, 2024). This is close to what we referred to as "roughly between 200 and 300 km²" (l. 453 of the preprint) and cannot help to explain any substantial portion of the overall trend. We will revise the manuscript accordingly in order to include the information and the additional reference.

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