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## Reply on RC1

Alemu Yenehun et al.

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Author comment on "Spatial and temporal simulation of groundwater recharge and cross-validation with point measurements in volcanic aquifers with variable topography" by Alemu Yenehun et al., Hydrol. Earth Syst. Sci. Discuss., <https://doi.org/10.5194/hess-2021-527-AC2>, 2022

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### ▪ **Response to reviewer 1 review comments**

#### **Response to the general comments:**

English language improvements and corrections have been made including suggestions made by you in the revised version.

In the general comment as well as in the specific comments (in the attached manuscript of the referee), clarity about the objectives has been raised as the main limitation of the manuscript. This could be due to problems of us in explaining the main objectives as explicitly as possible which we thought we have done in the revised version that we will attach.

The main aims of this paper are:

- Each recharge estimation technique has its own limitations, depending on the recharge mechanisms, the aquifer topographical setting, aquifer type (for example fracture vs porous soil aquifers, confined vs unconfined), aquifer geometry, etc. Hence, the effectiveness of recharge estimation techniques is varying, and thus in this study evaluation of the hydrological model (WetSpass) has been made (i.e. validation with measured point values though some variables are estimated in these methods too) for the Lake Tana basin having high topographic, variable slope, and comprising different volcanic aquifers. Such aquifer types are found in many parts of Ethiopia and is the major groundwater resources for the global water need. The WetSpass model applied in this study is a physically-based distributed hydrological model which gives spatially distributed water balance terms including groundwater recharge. Yes, there are statistical interpolations for some of its input variables but the final spatial recharge and other water balance output maps are different from simply estimated point value interpolations, rather they have resulted after optimal global model parameters are set through the calibration process (detail explanation about this issue can be found in the response to the line by line comments). Hence, one of the objectives of the paper is to evaluate the hydrological model, and thus give suggestions for recharge methods to be better applied for different aquifers lying at different topographical settings: this has been clearly put in the discussion and conclusion section of this manuscript. The paper put concluding remarks, where physical hydrological models, would be effectively applied. Why they are less effective for some aquifers and more for others. This helps to take into account the accuracy of recharge values in the area-specific water management plans and decisions being made at different levels.

- The next aim of this manuscript is to produce a spatially distributed groundwater recharge rate map for the Lake Tana basin, which is the source of the transboundary Blue Nile River basin where a high tension of hydropolitics is currently affecting the entire region. The spatially distributed recharge rate map produced in this study for the Lake Tana basin is an important output for further groundwater modeling, and water management issues of the basin.
- The other one is identifying the most important hydrometeorological and physical factors and prioritizing them for groundwater recharge distribution (qualitatively) for the study basin, and so for similar study areas, including the effect of land use change on the recharge and other hydrological terms. These have been discussed in the result and discussion section and concluded in the conclusion part.

With due respect, these objectives, especially the first one are important for international readers. Many hydrological models for different areas (small catchment-scale to large basins) are developed for estimating groundwater recharge. However, evaluation of the method with point estimations based on direct water level measurement (WTF) and chemical tracer (CMB) gives a good insight for future recharge estimation techniques for similar aquifer types wherever they are located in the world. In this study, identifying topographical and geological characteristics, and thus the recharge mechanisms have found an important factor and starting point in selecting recharge estimation methods. The study also pointed out that the common approach that is being implemented i.e. calculating recharge by a multitude of methods and averaging out the results of the different methods is found unreliable. Rather selecting an appropriate one or few technique/(s) and considering that as the optimal result is recommended. Evaluating the groundwater recharge estimation mechanism for the volcanic aquifers lying at different topographical settings, that represents a vast major part of the world groundwater aquifers, and able to suggest more appropriate method/(s) will benefit different further similar studies and researchers. Hence, this study can be seen as a dual purpose paper: evaluating the physical-based hydrological model (and so other similar models), and giving a spatial recharge rate map for the important Lake Tana basin. Thank you (the reviewer) for your valuable comments, in the new version, shortcomings in the introduction section have been improved as per the suggestions. The research questions are outlined and the contribution of the research output is mentioned in the new version.

The reason why we talk about “choosing appropriate methods” is to direct our reader that evaluation of a method will be one of the objectives of this manuscript. The reason why different methods were developed for recharge estimation rather than using the simplest and cost-effective method is due to the fact that different aquifers have different recharge mechanisms for which some methods are more effective than others. It is why we did an evaluation and validation of the existing method. Furthermore, when we say point recharge estimation, we are referring to recharge estimation techniques that estimate at a given point (e.g. on groundwater well, spring, etc.) such as WTF and CMB methods. Otherwise, yes indeed, we agree with the advance of Remote sensing and GIS, and with the developing capability of the grid-based spatially simulating hydrological models, producing spatially distributed water balance maps is so possible and being widely applied. The applied WetSpas model for this study is one of such kind, and we only applied an existing model (nothing new is done in this study as far as new methodology is concerned). As we have aforementioned, we pursued this study, for evaluating the physically-based hydrological models for our study basin so that areas having similar hydrogeological characteristics will take into account the suggestions of our evaluation result for future application. Besides, the recharge rate map for the basin, which is an important research product for groundwater exploitation practices and plans, will help groundwater managers and policymakers in this important area which is regarded as one of the growth corridors of the country. Besides, the recharge map is also an important input for further groundwater modeling work.

With due respect, the studies by (Alemayehu and Kebede, 2011; Ayenew et al., 2008; Demlie et al., 2008, 2007b; Kebede et al., 2005) are not all about recharge estimations studies. It is only Demlie et al., 2008, who did a recharge estimation only using the CMB method on a volcanic aquifer for the Akaki catchment located at about 550 km from the Lake Tana basin. The others had made different hydrogeological studies but had put general statements about the recharge variability across the volcanic aquifers. Thus, we can make clear that the presented study in this paper is different from the studies made by these authors.

Some maps in the methodology are shifted to the result section as suggested. The shortened explanation of the methodology section is for the reason of shorting the paper. We thought citing the papers that develop the original methodologies and later modifications will be enough and give detailed background knowledge including the different mathematical equations. However, parameter value modifications that have been done in this paper are discussed and justified in the new version of this paper (some of the details can be found in the following response to your line-by-line comments).

#### **Response to detail line by line comments**

**Comment1:** Language editing such as deletion, addition, and rewriting are suggested.

Reply: kindly accepted, and language edition has been done throughout the body of the manuscript, according to the suggestions.

Comment 2: The different correction suggestions for the location map (Fig. 1)

Reply: accepted, and appropriate corrections have been done in the new revised manuscript.

Lines 128-126: "That means years of seasonal or monthly time series data are averaged into single seasons or months." How this limitation is considered in this study?

Reply: The objective of this study (as far as WetSpss is concerned) is to produce long-term average spatial recharge and other water balance component maps showing the spatial variation of the components. Furthermore, it is to see the seasonal variations of these water balance terms. It is not to see the fine-time scale temporal variability of them. It would indeed be nice if we, for example, were able to see the change of recharge over the years, but the WetSpss model cannot do that.

Line 139: how this parameter is calculated

Reply: thank you for the comment. The parameter is the amount of rainfall that reaches the surface (total RF minus the one intercepted by the plant canopy). The interception is calculated by the model using the land use at each modeling pixel.

In the WetSpss model, depending on the type of vegetation, the interception fraction represents a constant percentage of the annual precipitation value. Thus, the fraction decreases with an increase in the annual total rainfall amount (since the vegetation cover is assumed to be constant throughout the simulation period). The detail about it is found in Batelaan and De Smedt (2007, 2001).

Line 142: how EP is calculated? What do you mean by open water?

Reply: Open water used here to mean a water body (could be lake water, dam reservoir, etc.).

The description how evapotranspiration is calculated in WetSpss is mentioned as follows. For the calculation of seasonal evapotranspiration, a reference value of transpiration is obtained from open-water evaporation and a vegetation coefficient:

$$Trv = c Eo$$

Trv = the reference transpiration of a vegetated surface [LT-1];

Eo = potential evaporation of open water [LT-1] and

c = vegetation coefficient [-].

This vegetation coefficient can be calculated as the ratio of reference vegetation transpiration as given by the Penman-Monteith equation to the potential open-water

evaporation, as given by the Penman equation

For vegetated groundwater discharge areas, the actual transpiration ( $T_v$ ) is equal to the reference transpiration as there is no soil or water availability limitation:

$$T_v = T_{rv} \text{ if } (G_d - h_t) \leq R_d$$

$G_d$ , is groundwater depth [L];

$h_t$  is the tension saturated height [L] and

$R_d$  is the rooting depth [L].

For vegetated areas where the groundwater level is below the root zone the actual transpiration is given by:

$$T_v = f(\theta) T_{rv} \text{ if } (G_d - h_t) < R_d$$

$f(\theta)$  is a function of the water content

the detail about it is found in the original model developing literature by Batelaan and De Smedt (2007, 2001).

Line 147: give detail explanation about the parameter modifications

Reply: Detailed explanation is added in the revised one. We mean some adjustment for the parameters' values on the default land use parameter table has been made, for example, the root depth of forest land is changed. In the model parameter table, each land use type has given impervious, bare land, vegetation, and open water percentages. In the default parameter of the WetSpa model, the vegetation area coverage for the Bush and Shrubland is 100%. This is based on the observation of the land use class type in the temperate zone (the Netherlands and Belgium). However, the Bush and Shrubland land use type in the Ethiopian (tropics) context is different: the vegetation is sometimes sparsely distributed, and is with some bare land component, during our field verification on the land use type, we tried to guess (using parcels land on which we do some measurement), and came up with about 10% is bare land and the rest 90% is consisting of vegetation. Similarly, adjustments have been made by Gebreyohannes et al. (2013) during their application of the model for Geba catchment, in northern Ethiopia. Similarly, the sub-afro-alpine vegetation land use type found in our area (consisting of about 0.3% of the total area coverage) is not present in the default land use classes of the WetSpa model. However, we made an equivalent with wet meadow land use type, and following a similar procedure, we modified the land use percentage to 80% vegetation and 20% bare land (it was 100% vegetation for wet meadow land cover type in the model parameter table).

Line 165: Paragraph above does not include land use as a parameter for calibration??

Reply: Yes, indeed land use is not used for calibration. It is to mean the land use which is used for model calibration is the one made using 2014 satellite images. The model parameters were optimized using this land use and then after the developed model was rerun using other land uses (1986 and 2000), just to see the change of the water balance components as a result of the change in land use over these years. Some paraphrasing has been done to make clear the issue.

Line 166: why these years (186, 2000, 2014) are chosen?

Reply: Because we have existing land use maps made using the satellite images taken in those years.

Line 170: It is unclear how the different model parameters serve the model?

Reply: as it is mentioned earlier in our response to your general comments, putting every detail of the model here would make the paper too long as the objective of this manuscript is neither modifying the model nor testing it. It is rather for applying the

model and comparing (validating) with other methods, see how effective are such models (physically-based hydrological models) in estimating groundwater recharge (given the different assumptions these models have though they give fine spatially distributed maps), and identifying the controlling physical and meteo(hydro)logical factors, etc. Hence, detailed equations are better to be cited and be read from the published papers (containing model development and latter modifications). However, thank you to you, we found it is short and we added some more elaborations in the revised version.

Line 179: why??

Reply: Because the source for all water balance components including recharge is rainfall. For the months with no rainfall at all (most of the winter months) is less important. However, it does not mean that knowing at what month of summer (June, July, August, September ) is the most important recharge is happening, and at which month is the less, and why that is happening is insignificant for the hydrological knowledge of the area. It is so important and other works dedicated to it should focus on and study it.

Line 183: Unclear

Reply: it is to the rainfall amount, corrected accordingly.

Line 184: provide the number 8??

Reply: 8 of the stations are established by the project that funds this study. It is BDU-IUC project (funded by VLIR-UOS, by the Flemish Government of Belgium).

Line 187: In the introduction section you criticize the interpolation techniques.

Reply: Yes, in general, interpolation has drawbacks as it is estimations at several places given real measurement at some spatial points of an area. However, it depends on the property of the parameter (the matter) for which that interpolation is being executed for. For example for our specific case, interpolation for RF and other meteorological parameters has been done as the WetSpass model needs spatial maps as an input. However, interpolation of some parameters e.g. groundwater recharge (which is mentioned in the introduction section) is highly dependent on the ground hydrogeological condition of the area and is highly variable irrespective of spatial proximity for which interpolation mostly depends. Hence, instead of interpolating estimated results at measuring points of an area (e.g. by the WTF method), it is highly better to produce it using some method which can take into account all those hydrogeological factors (which use them as input). Hence, playing with spatially distributed input factors in the mathematical calculations (though some are prepared by interpolation) is not the same as final point value interpolation. It is true that we need spatially distributed groundwater values (maps) for example for groundwater modeling, and further management works, and hence, preparing it by interpolation of point values is unwise and will have significant errors and uncertainties.

Line 192: some detail on this method is required, at least the equation

Reply: Penman-Monteith method is a well-known method in hydrology. We think citing it would be enough for the reader.

Line 199: How these data on the groundwater level are collected??

Reply: the detail about it is discussed in WTF section, but it is true that we have to put some information on how we collect them. We have given some details in the revised one.

Line 201: is it possible to show them in your map?

Reply: Yes, they are shown on Fig. 6.

Line 204: separate section for calibration

Reply: thank you, yes, we agree, and hence, we put the calibration details under the heading model calibration in the revised manuscript.

Line 206: is there no climate change over the years 1986-2014, and 2012 to 2013?

Selection should be justified here.

Reply: yes, there might be climate change over 1986 to 2014. However, the objective here is to see how the land use change affects the major water balance components using an already optimized WetSpass model. yes, in reality, the values of the actual water balance terms for 186, 2000, and 2014 might be more or less than what is simulated in this paper due to climate change or due to variabilities in meteorological parameters, however, it is common to keep other factors constant to evaluate the effect one

influencing factor. Thus, the effect of land use on the hydrological variables was evaluated keeping other variables constant. The reason why these specific years were used for the evaluation is already mentioned above (it is because of the availability of land uses, mapped based on the satellite images taken in those years).

Line 222: the limitation factor of what?

Reply: corrected, it is to mean one of the limitation of this study.

Line 231-232: should be explained

Reply: It is to mean the same codes that the WetSpass model uses for each land use class has been given for each class of land use map used in the model as an input variable. Otherwise, the model would not read it. Corrected accordingly in the revised version.

Line 247: is there fieldwork that has been done? should be detail in this case

Reply: There was no fieldwork for this part, however, the authors use their general area knowledge.

Line 278: what about Johnson (1967)? Provide some detail.

Reply: It is a literature compilation of different possible specific yield values for different geological materials (aquifers in this case). We added some explanation about it in the revised one.

Line 279: where is the formula?

Reply: the formula, how it is developed, and detail about it is found in the paper cited. It is an empirical formula. The equation is included in the revised version.

Line 281: is it possible to provide it a supplementary material?

Reply: Unfortunately, the pumping test analysis paper is written and being submitted to a journal as a continuous part of this study. Hence, providing here as a supplementary material may not be possible. Sorry, for the inconvenience in the follow-up of the studies. the pumping test paper has to be published before this manuscript submission.

Line 293: period of what?

Reply: the period that the total RF is collected. Corrected accordingly.

Line 296: how many groundwater samples are considered, sampling map is required.

Reply: 138 groundwater samples distributed all over the basin have been used. Ok, the groundwater sample map is included in the revised version.

Line 297: there is some confusion related to runoff characteristics and coefficients. Could you provide us more details.

Reply: As it is shown in equation 5, the CMB method takes into account the runoff amount because what is needed in the equation is the amount of the infiltrated water i.e. the rainfall minus the surface runoff amount. As it is difficult to get runoff amount at each groundwater sampling point, we subdivided the area based on studied runoff characteristics. Dessie et al. (2015), studied the runoff characteristics of the Lake Tana basin using a conceptual based hydrological model and calculated average runoff coefficients ( $=$  surface runoff amount divided by rainfall amount) for each area. In their study, they classified the basin into southern, northern, eastern, and western catchments, based on the runoff coefficient values and characteristics. We used those coefficients and calculated the runoff amount needed in the CMB equation. Accordingly, the recharge amount for each sub-area is shown in table 4.

It was possible to get runoff values at each groundwater sampling point using our distributing runoff map (from the WetSpass model output) and perhaps calculation of recharge at each sampling point would seem possible. The reason that we did not do it is because our objective i.e. we need to compare the different methods' results independently. Besides, as we have taken average chloride values of rainfall samples for each sub-area, the chloride values at each groundwater sampling point would be less certain (our rainfall samples were not sampled at each groundwater sampling point).

Line 298: I do not have any idea about these four catchments. Should be detail.

Reply: Thank you, some descriptions about these catchments grouped based on runoff characteristics are added in the revised version of the manuscript. Also few descriptions about how runoff is calculated have been also added.

Line 330: maybe in different periods as you have only 60 wells.

Reply: About 138 groundwater samples for chemical analysis (chloride concentration)

were considered in this study (not 60). Equation 5, shows chloride concentration in the rainfall is needed in the CMB method. However, the problem here is the chemistry of the rainfall is not constant temporally and spatially. The rainfall may have different sources: seawater or maybe also fresh water for which chloride concentration reaching at a specific area in different seasons or months or periods would be variable. In this study, we tried to consider such possible causes of uncertainty to a certain extent, for the spatial variation (as stated earlier, we grouped the catchments), and for the possible temporal variation, we tried to sample both the groundwater and the rainfall in the similar period so the chloride concentration in the groundwater is mostly from the sampled rainfall that infiltrated recently. At least being able to sample the groundwater which percolates from the rainfall that we sampled too will give a reasonable recharge rate. But if we, for example, sample the groundwater in June and the rainfall in August, perhaps there will be a high error in the recharge value estimated.

Line 341: it is better to start by Evap, runoff and after R. Including the precipitation is valuable.

Reply: the suggestion is accepted, and corrected accordingly

Line 346: why so include in the result and discussion part.

Reply: thank you for the comment, moved to the methodology section.

Line 352: is there analysis (e.g. statistical analysis) to prove this.

Reply: Unfortunately, there is no such a solid analysis for all the factors rather we used our physical observation of the maps. But we extract the recharge map by the different class combinations of soil, land use, slope, and rainfall amounts, and tried to see the attribute table of extracted raster maps of class combinations vs recharge rate. In doing so, we tried to judge which factor is the most important and gave rank in controlling the recharge amount. It is impossible to explain it in quantification.

Line 355: some confusing with this value of 0 mm.

Reply: at the water body recharge is assumed 0 (there is no infiltration beneath the floor of the water body).

Line 360: it looks no appropriate to consider the 0 mm at water bodies for determining an average.

Reply: I think we have to consider rather. Because we are reporting the average value of the basin including the lake body. It is one of the land use classes where the other water balance components are influenced on. Since we are comparing it with RF that rains over all parts of the basin, the one (even 0 value) should be also included in the average.

Line 386: As winter is the dry season, we expect to have evp more important than summer, but this is not the case of the present study. Why?

Reply: yes, winter is the dry season, and hence there is no enough rainfall as the water source for evapotranspiration, the less value in winter is reasonable. The source water for evapotranspiration is basically coming from rainfall plus the evaporation on the lake. The lake evaporation is happening throughout the year irrespective of being summer or winter (it only depends on the amount of potential evaporation). Even compared to the low amount of rainfall, the 44% of winter evapotranspiration is high. This is due to the evaporation taking place from the lake water surface during the long dry winter.

Line 395: validation section

Reply: Ok, we will shift it to the validation section.

Line 397: It is better to compare with other methods.

Reply: Yes, it is also compared with other literature values made by other methods (shown in table 2, and has been discussed in the text preceding the table).

Line 402: coarser time scale??

Reply: It means not for fine time scale like for daily or hourly but it is per seasonal. The term is common in GIS, RS, and other spatio-temporal modeling works.

Line 428: where is R2 in the figure?

Reply: It will be added in the revised one.

Line 443: 1:1 line??

Reply: It is called an 'identity line' or 'line of equality'. It is standardizing the axis to compare measured data with predicted data, or two different models. The starting and

ending point of both axes should be the same (through the axis origin in our case).

Line 465: about name the caption preceding or following the description?

Reply: thank you, we corrected it according to the suggestions.

Line 473: rephrasing suggestion on the subtopic??

Reply: accepted, and corrected as per suggested.

Line 500: you used WTF for validation in the previous section. So, it is better to introduce this result before validation.

Reply: accepted, rearrangement is made.

Line 511: what do you mean by degree of weathering?

Reply: It means the rate of weathering. A term used to mention the different grades of rock weathering which in turn refers to the different physical strengths of lithological materials from rock to soil. Hydraulic properties like porosity, hydraulic property, transmissivity, specific yield, etc. depend on weathering effect.

Line 542: It is better to include the chemical analyses of Cl both for rainfall and the selected groundwater samples. The effective precipitation values used for calculation are also required.

Reply: kindly accepted, a map consisting of the groundwater sampling location (for 138 GW samples), with a label of its chloride values is presented in the revised version. Also, the Cl amount of the RF is presented in table 4.

Line 552: I do not understand what represents this value as you have several periods and catchments.

Reply: accepted, and corrected accordingly. These values are the mean annual values for the whole Lake Tana basin. They are the average values for the whole basin estimated by the three methods.

Line 616: This R2 is good but as can be seen in figure, there is some lag between simulated and observed values.

Reply: yes, there are overestimations of river discharge by the WetSpas model (except for three of the major rivers: Gumara, Gilgel Abay, and to a certain extent, Gelda rivers). The possible reasons have been discussed in Lines 426-441 of the old version. The possible reason would be the assumption of the method that we followed to calculate the total river discharge: as it is already stated, we assumed the total discharge is a summation of surface runoff (SR) plus groundwater recharge (GWR) that the model gives both spatial maps and as a single total average value for the whole basin. However, theoretically, river discharge can be lower than this summation when there is significant deep groundwater flow that flows through the subsurface (without emerging to the surface) i.e. part of the water goes without being measured by the river gauging station. Hence, there is a possibility that the measured river discharge value is less than the sum of SR and GWR. In other words, it is with a special assumption that baseflow is equal to groundwater recharge (when all the recharge water emerges to the surface and flows through the river flow measuring station). The real geological conditions for the different catchments are already mentioned with reference to previous studies in the discussion section.

Hence, it does not mean that the WetSpas model overestimates the river discharge but it maybe because of the assumption of the baseflow amount to be equal to groundwater recharge in the total river discharge calculation of this paper. As the WetSpas model does not give total river flow amount as an output, we have followed this procedure to equate it so that we can compare it with the measured river discharge amount measured at the river outlets.

■