Response to Anonymous Referee #2’s comments on manuscript hess-2017-679 (Predicting groundwater recharge for varying landcover and climate conditions: – a global meta-study)

We sincerely thank Anonymous Referee #2 for their constructive comments, which have helped to improve the article. We address each comment in turn below.

Comment: a) I believe this work validates modelling results against the estimations found in the literature and those of the FAO simultaneously. It could be a good exercise to validate the model using each dataset independently, to see how the use of the newly compiled information improves (hopefully) model estimations.

We tested model predictions in three ways using two data sets: estimates from the recharge studies we collated; and estimates from FAO. First, we undertook a cross-validation of the model structure and predictor selection by setting aside 20 percent of the recharge studies and repeating that exercise. Second, we undertook a leave-one-out cross validation of the individual predictions, also using the collated recharge studies. Both these are independent because the validation points were not used in model fitting, as is standard practice for cross-validation studies. This is explained in the methodology. Third, we compared our model predictions against FAO country level statistics. The country level statistics were not used at any other point in the study. Finally, in response to Referee #1, we also plan to add a comparison against a global model. All of this represents a significant effort in independent validation, most of which is documented in the original paper. The validations described above were actually implemented on each data set independently in the original paper. We will review the wording of the methodology to ensure that the independent nature of this validation is conveyed more clearly.

Comment: b) Line 425: Figure 11 compares modelled recharge estimates to those of the FAO, why is this done, if in line 412 it states the comparison is unreliable? Would it not be better to compare modelled results to those of the 715 recharge sites? I think this is particularly important, as the compilation of this information to validate model results is one of the key things which separates this work out from others. Hence, I would like to see how they compare to each other.

We agree that comparing the model results against FAO is not an ideal validation of the results, although it is a useful comparison to understand the differences between the data sets. The FAO data were used for a country level validation because there are no other non-modelled large scale estimates, as far as we are aware. In section 3.2.3, the model results were compared against the literature compiled groundwater recharge. We did actually compare results against the 715 recharge sites via a leave-one-out cross validation in Figure 7.

In response to Referee 1’s comments, we also undertook a comparison against global model estimates of recharge and will add a figure comparing the modelled recharge against the recharge estimates from a global hydrological model (WaterGAP), together with the following text

Line 428-431:

Recharge estimates from the best models in the present study were compared to recharge estimates from the complex hydrological model (WaterGAP). Even though the model in this study overestimates recharge for countries with fewer data points, the scatter shows a smaller spread compared to the FAO estimates.

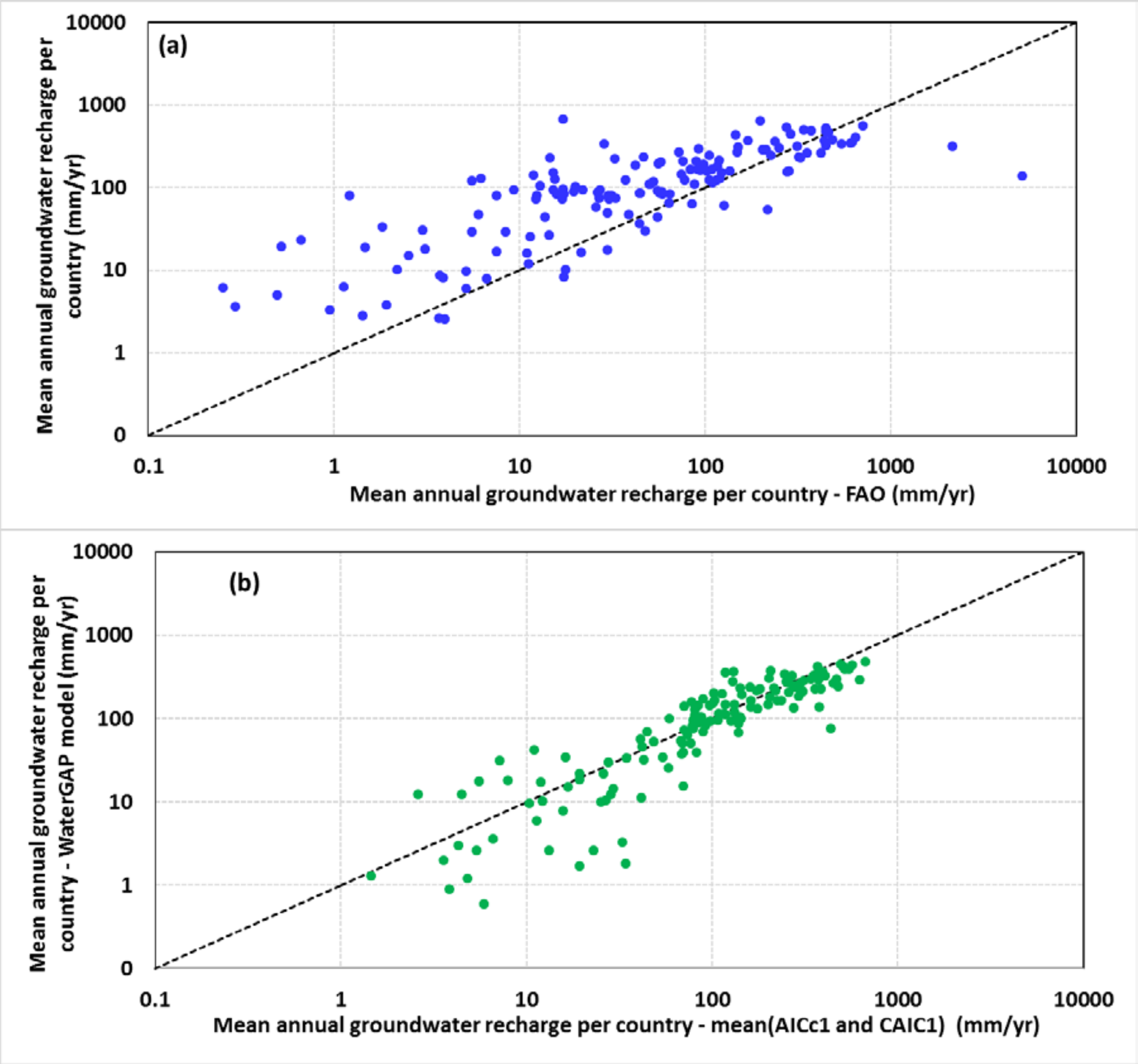

Figure 11. Comparison of predicted recharge against country level estimates from (a) FAO and (b) WaterGAP model.

2. Selection of model predictors

a) Lines 123-130: Would benefit from explaining the rationale used in selecting the potential predictors further (especially as it is deemed a "key step"), i.e. why is the number of rainy days important? Why were mean precipitation and potential evapotranspiration selected as well as aridity index?

We have amended the relevant paragraph to explain this more clearly. The relevant section of the paragraph now reads (Line 134-140):

Recharge depends on drainage from the soil profile and the partitioning of that drainage between shallow lateral flow to streams and deep drainage to the water table. A variety of factors influence this including the meteorological forcing, the properties of the soil profile, the properties of the vegetation, and the topography (Scanlon et al., 2002; Kim and Jackson, 2012;Scanlon et al., 2005). Vegetation is important particularly in its influence on partitioning of available water to evapotranspiration (Zhang et al., 2001) and we selected land use to represent this. The most important soil properties are likely to relate to the soil water storage capacity and drainage properties of the soil profile as they represent the capacity of the soil to buffer meteorological forcing variation and the capacity of the soil to transmit water to depth(Scanlon et al., 2005). We chose hydraulic conductivity, soil water storage capacity, clay content and bulk density as surrogates for these soil hydraulic properties. Partitioning of drainage between vertical and lateral is likely to depend on both the existence or otherwise of impeding layers in the vadose zone profile and on the topographic slope (Saffarpour et al., 2016). We included slope as a predictor but could find no specific information beyond the above soil properties on drainage impediments.

Focussing on the meteorological aspects, drainage depends on there being an excess of water availability in the soil profile and hence on variations in precipitation and evapotranspiration at both short-term (hours and days), seasonal timescales and longer. This suggests that precipitation, evaporative forcing and aridity index are obvious candidate predictors, although we should only expect a subset to prove valuable in the final model as there is shared information between them. In addition, the concentration of the precipitation in time and the relationship between precipitation of evapotranspiration seasonally also influence the occurrence of drainage. The number of rain days was considered as it potentially provides useful information on how concentrated the rainfall is in time. The seasonality of soil water content and drainage is also strong (Grayson et al., 1997;Western et al., 2004) and is typically driven by a seasonal excess of precipitation over potential evapotranspiration, which we aim to capture using the Excess Water predictor.

A set of 12 predictors comprising meteorological factors, soil/vadose zone factors, vegetation factors and topographic factors was finally selected (Table 1). Data for these corresponding to 715 recharge study sites were extracted from…..

Minor Suggestions

1. Lines 76-79: Questions the reliability of the FAO estimates. Please make it clear why these estimates are unreliable. How are they derived?

We have added the following to Lines 78-84 to clarify this.

FAO statistics are based on estimates compiled from national institutions. The data acquisition and reporting capacities of national agencies varies significantly and this raises concerns about the accuracy of the data (Kohli and Frenken, 2015). In addition, according to the FAO AQUASTAT reports, most national institutions in developing countries prioritise subnational level statistics over national level statistics, and in most cases data is not available for all sub national entities. This decreases the accuracy of country wide averages and raises concerns about the reliability of using them as standard comparison measures.

2. Line 79: States no study has previously validated modelled estimates against small scale recharge estimates. However, Doll and Fiedler (2008) used local recharge estimates to test the performance and modify the algorithm used to determine recharge for arid and semi-arid cells.

We agree that Doll and Fiedler (2008) used 51 observed recharge estimates for tuning the model results and the comparison is restricted to arid and semi-arid zones only. We have modified our text at line 79 as follows:

Line 84-88: Very few large-scale studies had validated modelled estimates against small scale recharge measurements. Döll and Fiedler (2007) used 51 recharge observations from arid/semi-arid regions for adjusting the model outputs. In comparison to it, this study does a more extensive validation of the model against 715 local recharge measurements.

3. Line 109: Would be interesting to know how the use of different recharge estimation methods found in the literature varied spatially and why. Could be shown graphically.

We modified Figure 1 to represent recharge estimation methods spatially and added the following text (Line 112-115):

The final recharge data set consisted of 715 data points spread across the globe (Figure 1). Of these studies, 345 were estimated using the tracer method, 123 using the water balance method, and the remaining studies used base flow, lysimeter, or water table fluctuation methods

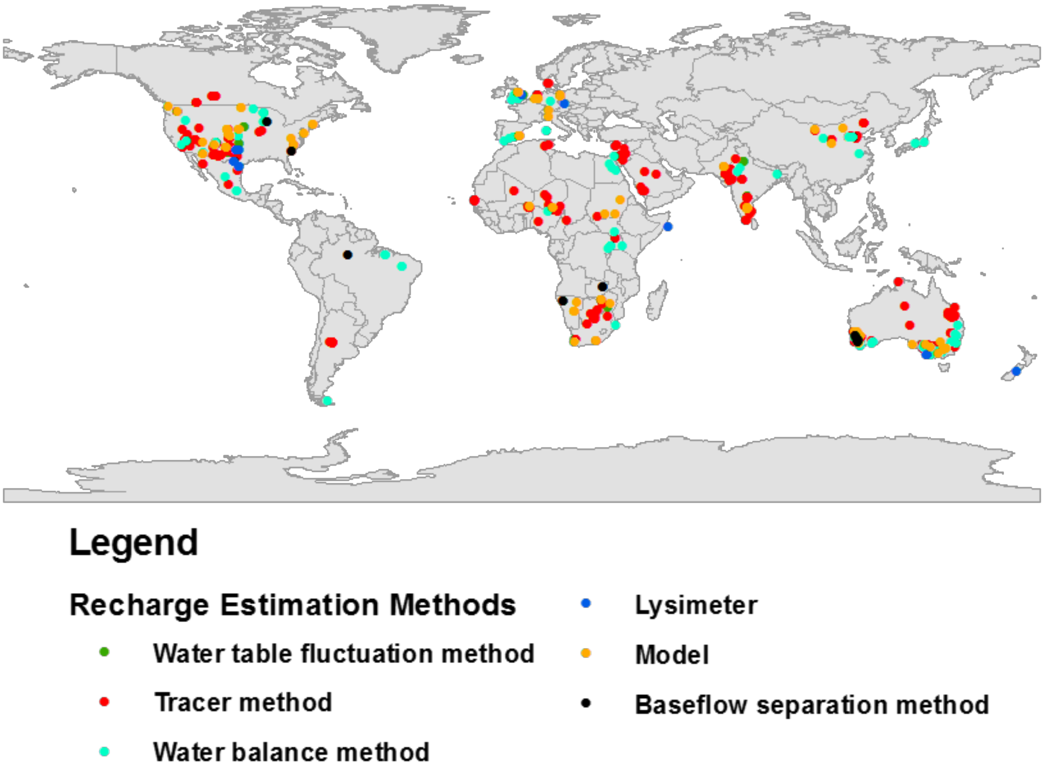

Figure 1. Locations of the 715 selected recharge estimation sites used for model building, together with the corresponding recharge estimation method.

4. Line 118: Were certain climates or land uses over or under represented by the 715 recharge estimation sites? Is there an inherent bias in the dataset collected? A histogram could be useful.

We have modified Figure 2 and expanded the discussion accordingly.

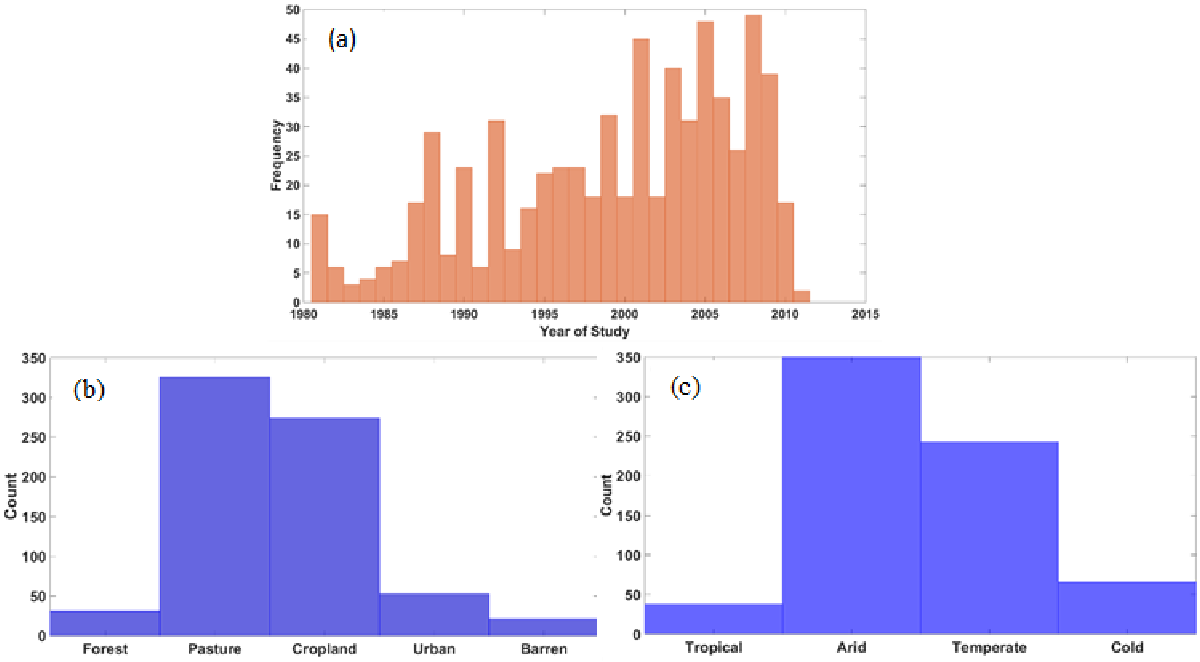

Figure 2. Histogram showing (a) frequency and spread of year of study and distribution of recharge estimates across different (b) Land Use and different (c) Climate zones based on Koppen Geiger climate classification.

Line 122-126: Moreover, the compiled dataset does not represent all climate zones well (Figure 2 (c)), with most studies being in either arid, semi-arid or temperate zones. Pasture and cropland were the dominating land uses in the dataset (Figure 2(b)).

5. Line 114: Recharge estimates in the literature may be representative of different time periods, especially if they were determined via water balance are water table fluctuation methods. However, the model predictors and the modelled recharge estimates are given as a mean for the period of 1981 and 2014. How was the inconsistency in the timeframe of the data managed? How did it effect model validation using the new dataset?

One of the major limitation of this study is the inconsistency in time frame of the estimates (line 111 -114). Overall the recharge measurements spaned 34 years from 1981 to 2014 and study lengths varied from 1981 to 2014 years. When it comes to globally scattered measurements, it was practically impossible to get consistent data spatially and temporally. Therefore, in this study, both for model building and validation, variables were averaged over the period of 34 years to minimize the inconsistency. The averaging of the variables can introduce bias in the prediction, especially in extreme recharge areas. The higher recharge may be slightly under predicted and the lower recharge may be slightly over predicted.

6. Lines 127-128: Were there any predictors which you would have liked to use, but were not available from the global datasets?

It is true that insufficient and poor quality data often limit studies such as ours, and we have amended the relevant paragraph to acknowledge this more clearly. The relevant section of the paragraph now reads:

Line 134 -142: The choice of predictors was made based on the availability of global gridded datasets and their relative importance in a physical sense, as informed by the literature. We employed 12 predictors comprising meteorological factors, soil/vadose zone factors, vegetation factors and topographic factors. However, other factors which could have a sizable influence on recharge were not included in this study because there was insufficient data. These included: the effects of irrigation on recharge, limiting the scope of the study to rainfall induced recharge; and subsurface lithology, which may be another important factor determining recharge.

7. Line 201: I'm uncertain whether there were predictors which were rejected prior to the main bulk of the work. i.e. were there initially more predictors than shown in Table 1, with those in Table 1 just being those accepted for use?

As mentioned in the above response, some of the predictors were eliminated from the study due to data unavailability. Particularly all irrigation factors and geology factors were excluded because of lack of proper datasets. Other than that, we did not eliminate any predictors prior to the main bulk of work.

8. Line 284: States that maps illustrating the percentage of rainfall becoming recharge were generated. However, these are not shown in this work.

The maps were not included in the final manuscript to reduce the length of the final draft. In response to this comment, we decided to include the following figure in the supplementary material.

9. Line 287: Refers to the koopan classification which I believe is meant to be Koppen Geiger.

Yes we meant Köppen-Geiger classification. The following changes were made to reflect this:

Line 314-315: As recharge data from regions with frozen soil were scarce in the model building dataset, the model predictions in those regions particularly for regions with Köppen-Geiger classification Dfc, Dfd, ET and EF are not highly reliable, so the EF regions of Greenland and Antarctica were excluded due to lack of data.

10. Line 415: Section 2.3 states that Figure 8 (global recharge estimation map) was derived from the best model found. It would be good to repeat this in the Figure heading "Best model estimation".

Figure 8 is changed as given below

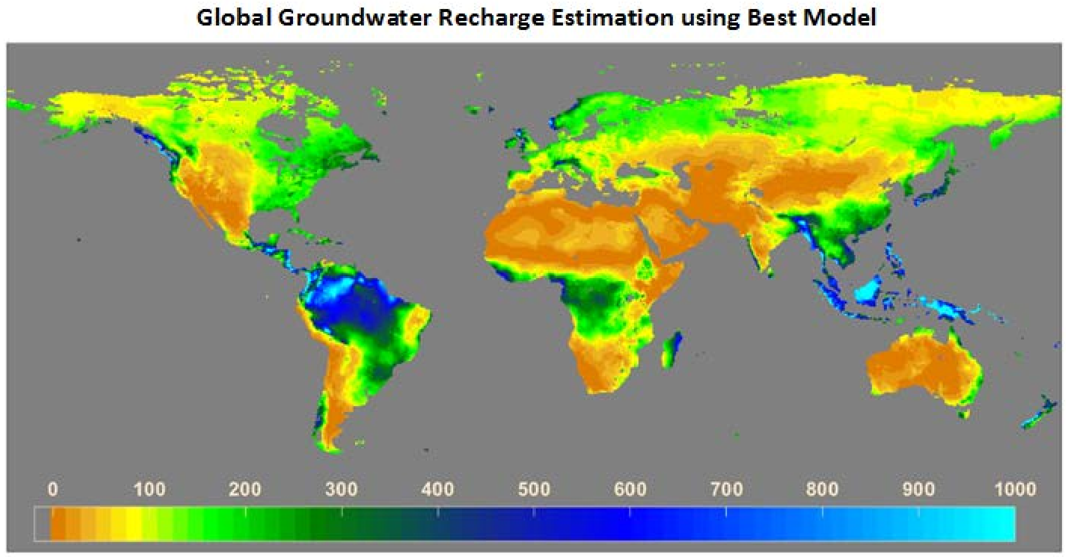
Global Groundwater Recharge Estimation using Best Model

Figure 8. Long-term (1981 -2014) average annual groundwater recharge estimated using the best model.

11. Line 415: Interesting to see some of the regions where greater recharge estimates are determined (South America, Indonesia) also coincide with areas which are less represented by the 715 studies. How uncertain are results in these areas? Could the uncertainty of these estimates be assessed?

We acknowledge this is an issue and have addressed it by adding the following:

Line 531-535: Uncertainty in recharge estimates is likely to increase in areas with poor data coverage, which tend to be those that are wetter, both in the tropics and cold regions. While we would expect this to be the case, it is surprising that the residual analysis from the cross validation (Figure 7b) suggests uncertainty does not grow particularly rapidly with precipitation, at least up to 1500mm/year.

12. Line 417: Figure 9 clearly indicates the importance of mean annual precipitation for mean annual diffuse recharge at the global scale. It would be interesting to contrast this to the relationship between mean annual precipitation and the annual recharge rates reported in the studies, in order to illustrate whether the influence of meteorology on groundwater recharge is site specific.

Please refer to the following lines in the manuscript which answers the above comment.

line 498 - 506: In most cases, especially dry regions, groundwater recharge is controlled by the availability of water at the surface, which is mainly controlled by precipitation, evapotranspiration and geomorphic features (Scanlon et al., 2002). Numerous studies agree with this finding. For example, in south western USA, 80% of observed recharge variation is explained by mean annual precipitation (Keese et al., 2005). However, the influence of meteorological factors on groundwater recharge is highly site-specific (Döll and Flörke, 2005). The effect of meteorological factors can also depend on whether the season or year is wet or dry, type of aquifer and irrigation intensity (Adegoke et al., 2003;Moore and Rojstaczer, 2002;Niu et al., 2007).

13. Line 486: Is this work able to say whether there are regions in the world which have declining or augmenting rates of recharge in the 1981-2014 time period?

To address this comment, the following figures showing inter decadal percentage change in groundwater recharge have been added in the supplementary material.

It is possible to say using the model whether the regions have declining or augmenting recharge rates. Hence the model is highly influenced by the changes in precipitation, the inter annual changes in the recharge will be highly correlated to that in precipitation. The following figures are added in the supplementary material and the following paragraph is added to explain this idea further.

Line 434 – 445: It is also interesting to consider trends in recharge over time. Our model includes both meteorology and landuse as predictors that can change in time and so can produce estimates of change in response to these variables only. We estimated recharge on a decade-by-decade basis based on meteorological fluctuations only and then calculated percentage change between the decades (Figure S2 Supplementary). These maps show some distinct regional patterns that appear to reflect a) linear features where there are strong and shifting regional gradients such as the African Sahel (Giannini et al., 2008) that show as distinct linear features and b) more general regional to continental scale changes, such as in Australia, which was strongly affected by the Millennium Drought (van Dijk et al., 2013) and associated climate fluctuations. These results suggest that inter-decadal variability in groundwater recharge may be quite large in many regions.

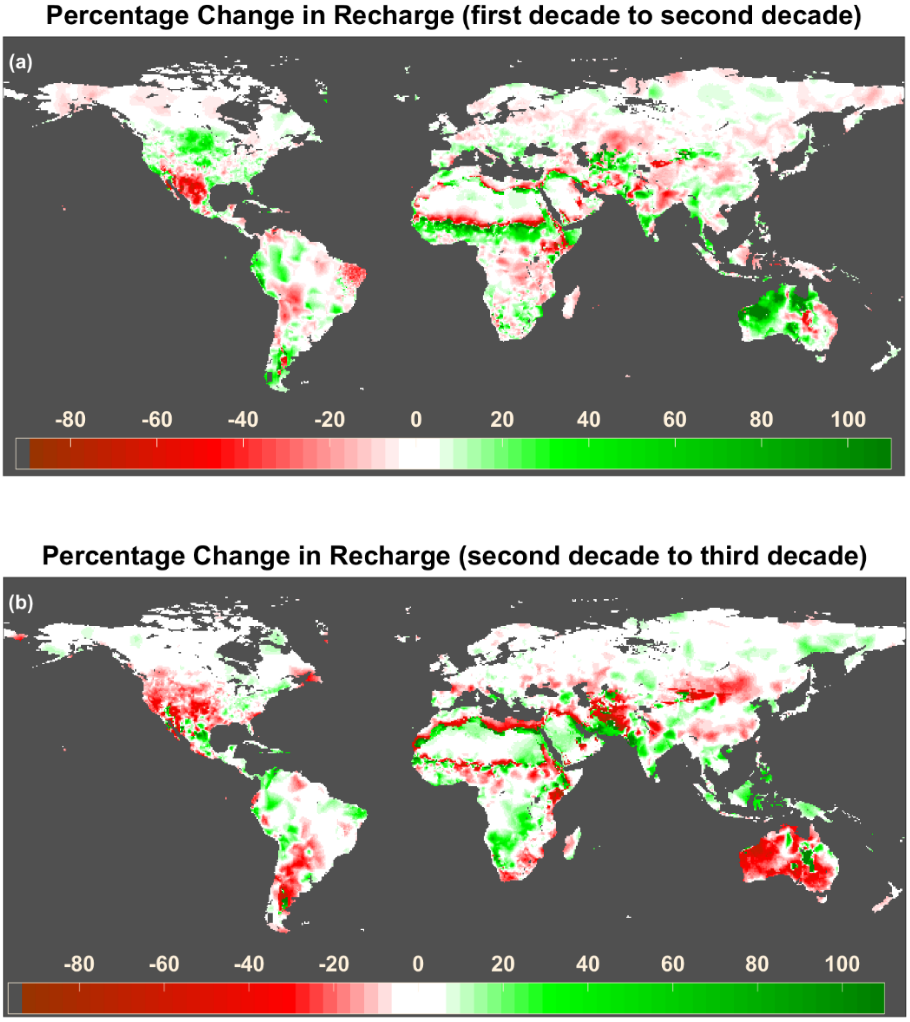

Figure S2. Map showing change in mean percent decadal recharge (a) from 1981-1990 to 1991-2000 and (b) from 1991-2000 to 2001-2010. (Decadal change = mean decadal recharge of later decade – mean decadal recharge of former decade).

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