Dear Editor, dear Erwin Zehe,

We thank you for your great interest in the manuscript and your positive words on the interesting interdisciplinary discussions we had with the referees.

We have thoroughly revised the manuscript to incorporate the interesting and constructive comments made by the referees. Main changes include:

- *Revision of the discussion to include a more thorough and structured discussion on the implications, limitations and outlook. We discussed other potential strategies of vegetation to cope with increasing water stress. We also discussed that climate and land-use changes likely affect other aspects of catchment functioning besides the root-zone storage capacity. We discussed that we did not explicitly consider this as it remains problematic to meaningfully quantify. Neither did we account for a different interception storage capacity in the scenarios $2K_C$ and $2K_D$, as the sensitivity of the root-zone storage capacity to this maximum interception storage capacity was shown to be limited in Bouaziz et al. (2020). We also addressed in the discussion that we did not adapt the model structure under the changing conditions as we do not have the detailed level of data required for this.*
- *We have more strongly emphasized the main objective of our study as a sensitivity analysis in the title, abstract, introduction and conclusion.*
- *The method section has been revised and a schematic overview of the methodology has been added in Fig.2*
- *Technical details in the Method section on the calculation of the root-zone storage capacities has been moved to the supplement to improve readability of the methodology.*
- *We have moved the model schematization and explanation to the Supplement to have it next to the model equations. In the main manuscript, we included a more detailed explanation on the model forcing and on the calculation of actual evaporation from the root-zone by the model.*
- *We have incorporated the other minor comments made by the referees.*

We fully agree with your suggestion, that it would be very interesting to compare transpiration and evaporation simulated by the land surface model and the hydrological model for the historical and 2K runs. However, considering the already complex methodology and analyses, we think these extended analyses would better fit in a separate dedicated study on a comparison between land surface and hydrological models. Note, that within our group, we are currently working on the implementation of the climate-based root-zone storage capacity estimates in land surface models (van Oorschot et al., 2021).

Best wishes,
Laurène Bouaziz and co-authors

References:

Bouaziz, L. J., Steele-Dunne, S. C., Schellekens, J., Weerts, A. H., Stam, J., Sprokkereef, E., Winsemius, H. H., Savenije, H. H., and Hrachowitz, M.: Improved understanding of the link between catchment-scale vegetation accessible storage and satellite-derived SoilWater Index, Water Resources Research, https://doi.org/10.1029/2019WR026365, 2020

van Oorschot, F., van der Ent, R. J., Hrachowitz, M., and Alessandri, A.: Climate-controlled root zone parameters show potential to improve water flux simulations by land surface models, Earth System Dynamics, 12, 725–743, 2021.

Reply to Anonymous Referee #1

We thank the anonymous referee for his/her positive, thorough and constructive review. We provide an answer to each comment below.

Comment 1:

Study objectives are not clearly and consistently stated

According to the abstract, introduction and conclusion, the study has two main objectives. The first isto propose a top-down approach to include vegetation change into hydrological models via the root-zone storage capacity (l. 4-5, 575, 581-583). The second is the quantification of the sensitivity of modelled hydrology to changes in root-zone storage capacity under climate change and related to that, the testing of the hypothesis that changes will be more pronounced when considering an adapted root-zone storage (l. 93 ff).

Although these two objectives are clearly connected, they are never stated together. The first objective (proof-of-concept and methodological aspect) of the study is stressed in the discussion and conclusion, whereas the introduction highlights only the second objective (application and sensitivity analysis). The objectives of the study should be more clearly stated in the introduction and the discussion and conclusion should build on these objectives.

Reply 1:

We agree that these are two main aspects of the manuscript. However, in the revised version of the manuscript, we will more clearly state that our objective is to evaluate the sensitivity of hydrological model predictions to ecosystem adaptation in response to climate and potential land use change. To reach this objective, we introduce an approach, subject to assumptions, to estimate future evaporation and associated changes in the root-zone storage capacity. As the future is unknown, we cannot evaluate our results against observations. Therefore, we would rather not qualify the introduced methodology as an objective as the underlying hypothesis cannot be tested. In the revised version of the manuscript, we will not use the terminology "proof-of-concept". However, we fully agree with the suggestions of the reviewer to more thoroughly discuss the limitations and opportunities of the proposed methodology in the discussion (see our reply to the next comment).

Comment 2:

Discussion and conclusions leave open questions

The discussion could be more thorough and consistent regarding both, the modelling results and the methodological approach.

The discussion is structured into two separate parts: *Implications* (l. 500- 539) and *Limitations and knowledge gaps* (541-577).

However, two paragraphs from the first section (Implications) are better suited for the second section (limitations): l. 512-519 on possible further exploration of the space-for-time concept and l. 535-539 on the limitations of the simulated climate time series used in the study.

Also, given that one major objective of the study is to propose an approach to include vegetation change into hydrological models, I feel that the model results are not thoroughly discussed as to whether the proof-of concept of the method was successful.

The following questions/issues remain unaddressed:

a) The approach showed that the root-zone storage capacity parameter has a potentially large effect on future water flows. How realistic are the values for root-zone storage capacity that were calculated for the different scenarios? Is there any evidence from literature regarding the extent to which plants adapt their root system to changing climate? Does this adaptationdepend on vegetation type (e.g. crop/grass vs. tree) or species?

b) Are the results regarding the water flow under future conditions realistic? Is this what couldbe expected under climate change?
c) In which situations can this method be applied? Which hydrological models? Which ecosystems?
d) What are the limitations and chances of this approach?

Reply 2:

In the revised version of the manuscript, we will more thoroughly and consistently discuss the limitations and opportunities of the methodological approach and the modelling results.

We agree that the two paragraphs in the Implication section mentioned by the reviewer are more related to "Outlooks" of possible future work. Initially we had treated this as implications of our work for future work, but we agree that it may better fit in a section called: "Limitations and outlook". We will adapt this in the revised version of the manuscript.

As the future is unknown, we cannot evaluate our results against observations. Therefore, "proof-of-concept" may not be the right terminology, we will adapt this in the revised version of the manuscript. Our study should really be considered as a sensitivity analysis to test the sensitivity of hydrological model predictions to non-stationary systems through plausible assumptions of ecosystem adaptation. To emphasize this more strongly, we propose to adapt the title of the manuscript to: "The sensitivity of hydrological model predictions to ecosystem adaptation in response to climate change."

In the discussion of the revised manuscript, we will address the following discussion points:

a) *The estimated values of the root-zone storage capacity for the different scenarios have median values below 250 mm for a return period of 20 years, which is within the range of global root-zone storage capacity values estimated by Wang-Erlandsson et al. (2016). We will mention this in the discussion of the revised manuscript.*

   There is increasing evidence that vegetation efficiently adapts to its (changing) environment (Gentine et al., 2012, Troch et al., 2013, Hrachowitz et al., 2020). Guswa (2008) shows that the active root zone tends to be larger in water-limited ecosystems in comparison to wet environments. A distinction should be made between individual plant adaptions of roots and the adaptation of the root system of the collective of plants at the ecosystem scale. The study of Brunner et al. (2015) describes several strategies of tree root to cope with drought, which include root biomass adjustments, anatomical alterations and physiological acclimations. Individual plants that have not adapted to meet their water and light requirements will disappear and be replaced by better adapted plants. Therefore, the root system at the ecosystem scale and associated root-zone storage capacity continuously adapt to changing environmental conditions in a state of dynamic equilibrium (Hrachowitz et al., 2020). While the adaptation of individual plants depends on vegetation type and species, here, we determine effective values of the root-zone storage capacity at the catchment scale to reflect the adaptation of the whole ecosystem.

b) *Given the changes in temperature and precipitation, the future predicted hydrological response does not seem unrealistic, although, of course, this cannot be tested against observations. Common practice in hydrological studies on the impact of climate change is to assume a stationary system (Benchmark Scenario $2K_A$ in our analysis). In addition to this* *scenario, we suggest a possible approach to consider ecosystem adaptation in response to climate change and test the sensitivity in the resulting hydrological response. Our approach is subject to considerable uncertainties in the estimation of the future transpiration (required to estimate the root-zone storage capacity) as we are using the Budyko framework for future conditions (Berghuijs et al., 2020; Reaver et al. 2021). Besides, we do not explicitly consider that vegetation can adapt to drier conditions by regulating their stomata and hence reducing transpiration (which is the topic of your comment 3). Moreover, the increased CO_2 concentration may, on the one hand, increase water use efficiency, while on the other hand increase green foliage due to fertilization effects (Donohue et al., 2013; Frank et al., 2015; Yang et al., 2019). Hence, we cannot predict what will exactly happen, but we can at least test the sensitivity of the hydrological response to changes in the system representation.*

c) *Root-zone storage capacity estimates derived from the water-balance approach are applicable in various hydrological and land surface models, provided that they include a root-zone parameterization, which is the case for most models (Nijzink et al. 2016, van Oorschot et al., 2021). The water-balance approach to estimate the root-zone storage capacity has successfully been applied in a variety of climate zones and across various ecosystems (New-Zealand in de Boer et al. 2016; Australia in Donohue et al., 2012, United States in Gentine et al. 2012 and Gao et al., 2014; and at the global scale in Wang-Erlandsson et al., 2016). The method was also applied along rainforest-savanna transitions to reveal drought-coping strategies (Singh et al., 2020). However, the method is not suitable in areas where the water table is very close to the surface and where vegetation directly can tap from the available groundwater instead of creating a buffer capacity (e.g. Fan et al. 2017). Another limitation of the water-balance approach relates to equation 6, in which we scale the daily transpiration estimates with a constant factor to the patterns of potential evaporation minus interception evaporation, implying that vegetation can extract water for transpiration from dry soils as easily as from wet soils.*

d) *The proposed methodology to estimate future root-zone storage capacities relies on the underlying assumption that past empirical relations between aridity index and evaporative index (i.e. the Budyko framework) still apply in the future. The Budyko framework reflects the long-term hydrological partitioning under dynamic equilibrium conditions. Therefore, when using the Budyko framework to estimate the future rate of transpiration, we assume that the future vegetation has adapted to the future climatic conditions and that it is in a state of dynamic equilibrium. This is a considerable uncertainty of our methodology because it implies that vegetation has had the time to adapt to the rapidly changing environmental conditions. There is no doubt that vegetation eventually will adapt, otherwise we would not see the hydrological partitioning of catchments around the world broadly plotting along the Budyko curve. However, unanswered questions are how long it will take for vegetation to adapt and how it will adapt. While the Budyko framework is a well-established concept, the recent study by Reaver et al. (2021) shows that it should be cautiously applied in changing systems which are not in equilibrium. We will include this discussion in the revised version of the manuscript.*

Despite these uncertainties, there are also strong aspects of our methodology. Current practice in most climate change assessment studies assumes constant system properties in the future, thereby neglecting adaption of vegetation to local climate conditions. Our analysis is a first step in evaluating what may happen if we consider ecosystem adaptation in response to climate change in hydrological model predictions. Our method is based on readily available data and is therefore easily applicable. Furthermore, if we assume space and time symmetry, i.e. the exchange of spatial knowledge with temporal knowledge, we may be able to transfer root-zone storage capacity estimates from a location X with a current climate similar to the future climate of a location Y.

Comment 3:

Methods: no limitation of the root-zone storage capacity

The methodological approach assumes a limitless adaptation of the root-zone storage capacity to changing aridity index (compare l. 243). I was wondering whether this is realistic. The adaptability of the root-zone depends on the vegetation's capability to change the root system following a change inclimate/water demand. This capability probably depends on the vegetation type (crop, grass, or tree)but also on the species. Also, adapting the root-zone storage capacity is not the only way that plants/vegetation might adapt to a change in aridity index. Plants can adapt to drier conditions by closing their stomata and reducing gas exchange with the atmosphere and hence transpiration. Also,overall vegetation cover could decrease if the water supply is not sufficient to support the same cover.Although I think it is not necessary to consider this limitation in this proof-of concept study, it is nevertheless an important point to discuss in the discussion section.

Reply 3:

This is a very good point, we briefly mention it in the discussion when we refer to the study of Zhang et al. (2020). However, we fully agree that the different strategies of vegetation to cope with changing environmental conditions need to be discussed in more detail in the revised version of the manuscript.

Comment 4:

Links to ecohydrological modelling or dynamic global vegetation models (DGVMs) missing Although this study is about hydrological modelling, I think that the advances and contributions ofecohydrological models and DGVMs to studying the feedbacks between vegetation and the watercycle should be mentioned and discussed in the introduction and, if applicable, also in the discussionsection of the manuscript. Please find some hints on where to start in the following:

One prominent model is e.g. the DGVM LPJmL which dynamically models carbon, nitrogen and waterflows. The model has been applied to various question among them also questions related to water flows under climate and land-use change.

You can e.g. have a look at the following publication:
Rost et al. (2008), *Water Resources Research*.

https://doi.org/10.1029/2007WR006331Here you can find a list of some key

publications of the model:

https://www.pik-potsdam.de/en/institute/departments/activities/biosphere-water- modelling/lpjml/key-publications
In the field of ecohydrological modelling, you could have a look at the works of Ignacio Rodriguez-Iturbe and Amilcare Porporato. An ecohydrological study to look at might be Tietjen et al. (2017), *Global Change Biology* https://doi.org/10.1111/gcb.13598. The study looks at feedbacks betweensoil water availability, vegetation change and climate change and they disentangle the effects of climate change alone and climate change in combination with vegetation change.

Reply 4:

We thank the reviewer for providing the references of these relevant studies on ecohydrological modelling. It is interesting to read that in the study of Tietjen et al. (2017), the future vegetation cover is determined based on empirical relations relating the fraction of each plant functional type to mean *annual temperature and precipitation. The rooting depth for each plant functional type is a fixed estimate derived from a re-analysis of a global root dataset. Instead in our approach, we do not impose a fixed rooting depth, but it is estimated from the future climate data and our estimate of future transpiration. In the LPJmL4 model (Schaphoff et al., 2018), transpiration depends on the water accessible for plants, which is computed from the relative water content at field capacity and the root distribution within each soil layer. These root distribution estimates are also fixed parameters for each plant functional type considered in the model. Accounting for this climate control on root development and root-zone parameterization in ecohydrological model could potentially also be very interesting (van Oorschot et al., 2021). We will discuss the links with ecohydrological and vegetation models in the revised version of the manuscript.*

Comment 5:

l. 58: optimality principles: is this an established term? If not specify what is optimized in this approach(probably it's vegetation growth or something similar)

Reply 5:

We will clarify in the revised version of the manuscript that the optimality principles indeed refer to vegetation growth through optimal allocation of aboveground and belowground resources. This implies that ecosystems have developed root systems to ensure access to sufficient (but not more) water to overcome dry periods (Guswa 2008; Schymanski et al., 2008).

Comment 6:

l. 95: "land-use change under future conditions": The manuscript does not tackle land-use under future conditions. The authors test what happens if land-use is the same in the whole catchment basedon what is already there. But it is never discussed which land-use types are realistic for the future or whether there is a trend in land-use towards any of the present land-use types. Rephrase to make clear that this is just a theoretical assessment of the sensitivity towards different types of land-use instead of a projection into the future. Also, the statement "we exchange space-for-time" (l. 96) suggests, that there is a known land-use trend for the future.

Reply 6:

We agree that we perform a sensitivity assessment of potential/theoretical land-use change and not necessarily projected land-use change and we will rephrase this to "land-use change under potential future conditions". However, the potential changes applied are based on a space-for-time exchange, using characteristics from the Budyko framework of a set of existing catchments to simulate potential changes in a set of different catchments. We believe that the statement "exchange space-for-time" can also be used in case the land-use change for the future is only theoretical.

Comment 7:

The method description is generally a bit confusing. I feel that generally it could be a bit shorter (e.g. the scenario description and the description of the 4 different root-zone storage capacities) are repetitive at some points. It might also help to provide a supportive figure of the study's workflow that clearly separates between different sources of input data, generation of scenarios and model application (instead of Fig. 3 which would fit better in the Supplemental material). Please revise the method section for more clarity and structure. The specific comments below hopefully help to do that.

Reply 7:

We thank the reviewer for his detailed comments to improve the clarity of the method section. In the revised version of the manuscript, we will try to improve Figure 4 to clarify the workflow, the scenarios and the data used for each scenario. We agree that the current structure is sometimes repetitive, but we think it has the advantage of clearly distinguishing the four different scenarios. Nevertheless, in the revised version of the manuscript, we will try to restructure the Method section in such a way that repetitions are reduced while keeping the distinction in modeling results for each of the scenarios. We agree with the suggestion of the reviewer to move Figure 3 to the Supplement.

Comment 8:

l. 109: "divided into three main zones": It would be nice to see these three main zones in the Figureas well. In the figure, it is unclear which part of the catchment represents which of these three zones.

Reply 8:

Yes, you are right, we will indicate the three zones on the map.

Comment 9:

l. 120: reference is missing for the meteorological variables

Reply 9:

Indeed. The numbers are based on the E-OBS data (Section 3.1) and the historical streamflow data (Section 3.3), we will add these references in the text.

Comment 10:

l. 122: always refer to the specific label of the figure if possible (here it's Fig. 1c and not Fig. 1)

Reply 10:

Agree, we will be more specific.

Comment 11:

l. 147-161: A figure or some numbers comparing the simulated historical and 2K climate scenarios could be a nice addition. From the description, it remains unclear what a "globally 2K warmer world" (l. 158) will translate to in this regional data set. Does this 2K warmer world lead to a mean 2K warmer regional climate? What's the difference in mean annual temperature and mean annual precipitation in 2K vs. historical climate?

Reply 11:

We agree that a Table summarizing mean annual temperature, potential evaporation and precipitation for the different data sources is a useful addition. Differences in mean annual potential evaporation and precipitation between the simulated 2K and historical climate are now shortly described in the result section 5.1.3 (L396). We will elaborate this further in the revised version of the manuscript.

Comment 12:

l. 164: It would be helpful to add Borgharen to the catchment map in Fig. 1

Reply 12:

Good point, we will add Borgharen on the map of Figure 1.

Comment 13:

Methods: The decision to divide the land-use types into broadleaved forest on the one hand, and coniferous forest/agriculture on the other hand needs better explaining. Why is a tree-dominated (coniferous) vegetation grouped with crops? I would expect that crops and trees are very different with regard to their effect on the water cycle and concerning their root-storage capacity.

Reply 13:

We understand that it may sound confusing. However, the division of both groups was made according to the percentage of broadleaved forest, as we found that omega values tended to be lower for areas with relatively more broadleaved forests (25-38%) in comparison to catchments with relatively low fractions of broadleaved forests (1-12%), as also shown in 5b. We then related this finding to the fact that in the Walloon part of the catchment, most of the old broadleaved forest has been converted to coniferous plantations and agricultural areas, whereas the broadleaved forest mostly remained in the French part of the catchment. In the manuscript, when we refer to "broadleaved forest" versus "coniferous and agriculture", we implicitly mean catchments with relatively high or relatively low percentages of broadleaved forest. However, it is easy to overlook the words "high" and "low" when reading these descriptions, which is why we refer to "broadleaved" and "coniferous and agriculture". We will add a note on this in the revised version of the manuscript.

Comment 14:

l. 233: Why is Imax taken as 2mm?

Reply 14:

We estimate the interception storage capacity (Imax) at 2 mm based on analyses performed in previous studies which report a low sensitivity of the root-zone storage capacity to the value of Imax *(de Boer-Euser et al., 2016, Bouaziz et al. 2020). In Bouaziz et al. (2020), we tested the sensitivity of applying interception storage capacities of 0.5, 1.0, 2.0 and 3.0 mm and found a relatively limited impact on the root-zone storage capacity. To reduce the complexity of our analyses, and because of this low sensitivity and our interest in the effect of stationarity versus non stationarity of the root-zone storage capacity in the four scenarios, we decided to use a single value for the interception storage capacity. A single value was also used in van Oorschot et al. (2021). We will include these references in the revised version of the manuscript to explain our choice.*

Comment 15:

l. 262: Why are E-OBS data taken from 1980-2018 while streamflow data is only from 2005-2017? Would the results have been different if E-OBS data from 2005-2017 were used instead?

Reply 15:

Thank you for pointing this out. When calculating the root-zone storage capacities, we actually used the period 2005-2017 for both the streamflow data and the meteorological data. This was then not correctly reported in the text, we will make sure to correct this in the revised version of the manuscript. Using the period 2005-2017 or 1980-2017 for the meteorological data in the estimation of $S_{R,max}$ leads to relatively similar ranges of root-zone storage capacities across the scenarios, as shown in Figure 1.

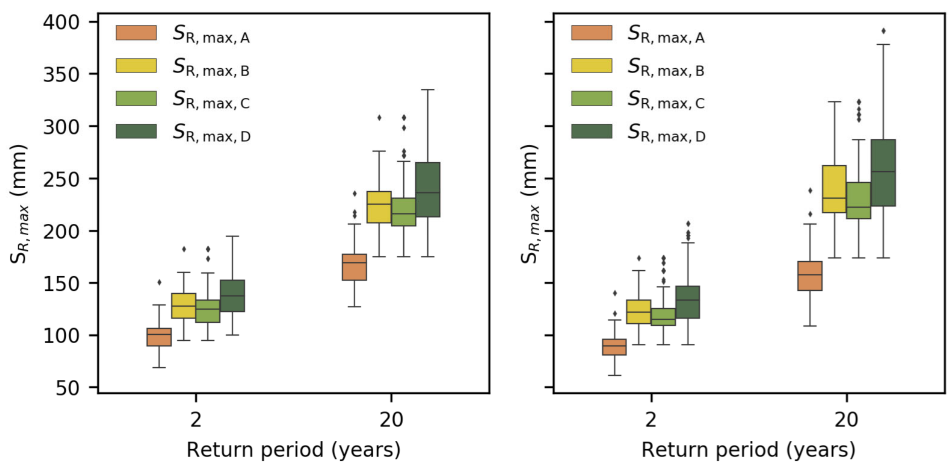

Figure 1 Left: Root-zone storage capacities for the 35 catchments of the Meuse basin for the four scenarios derived using meteorological data between 2005-2017 (sane as Figure 5c of the manuscript). Right: Root-zone storage capacities derived using meteorological data between 1980-2017.

Comment 16:

l. 289 ff: How were the ω values sampled?

Reply 16:

When we estimated the root-zone storage capacities for the land-use change scenarios C and D, we estimated the long-term actual evaporation from the Budyko curve through a horizontal shift along the parametric Budyko curve to account for a change in aridity index, and a vertical shift towards a *different parametric Budyko curve to account for a change in land-use. For each catchment under change, we assigned an omega value randomly sampled from the set of catchments with current characteristics representing the future characteristics of the catchments under change. We repeated this random sampling seven times, which resulted in seven parameter combinations of $S_{R,max}$ for scenario C and seven parameter combinations for scenario D. We will clarify this in the revised manuscript.*

Comment 17:

l. 306: hillslopes are associated with forest and plateau with agriculture. But which type of forest do you mean here? Broadleaved or coniferous?

Reply 17:

The three hydrological response units defined in the hydrological model are determined from topographical data (based on thresholds for Height Above the Nearest Drain and slope) and land-use data (where broadleaved and coniferous forests were both included in the hillslope class, while agricultural land was included in the plateau class). The three classes have slightly different parameterization to reflect different dominant hydrological processes. In the land-use scenarios, we did not change the percentages of each HRU in our model representation. We agree that this is a limitation of our approach, which we will add in the Discussion. However, the data to determine how the link between land-use and HRU may change in the future is not known at this detailed level. Additionally, we expect a limited impact of adapting the fractions of HRU on the hydrological response and we therefore consider this to be an acceptable limitation of our study.

Comment 18:

l. 331ff: "the performance … for the ensemble of retained parameter sets": From the 10000 calibration runs: how many parameter sets were obtained for the model runs? From the supplemental material it looks like the prior is almost the same as the posterior parameter distribution.

Reply 18:

We retained 124 parameter sets based on the defined criteria for model performance. To deal with the relatively long computational costs of running the model, we applied a preliminary first calibration to pre-scan the range of prior distributions. The real calibration was performed with these reduced parameter ranges as prior, which explains the limited difference between prior and posterior distributions.

Comment 19:

l. 334-337: This section can be removed as it is a repetition of what was already mentioned above in lines 272-274.

Reply 19:

We agree and will remove the repetition.

Comment 20:

Scenario description in 4.4:

- It is unclear which values of S_R with regard to the return period are used (2 years or 20 years?)
- How did you decide for the return period in the mixed agricultural/coniferous land-use? Agriculture should be 2 years and forest 20 years (l. 251-253)

Reply 20:

In the distributed model, each cell has a percentage wetland, hillslope and plateau. The root-zone storage capacity parameter for the wetland and plateau hydrological response units were assigned a return period of 2 years, while a return period of 20 years was assigned to hillslope. We refer to the studies of Nijzink et al. (2016) and Gao et al. (2014) where return periods of 20 years are associated with forested areas. Lower return periods of 2 years are better suited for agricultural areas (Wang-Erlandsson et al. 2016). We will clarify this in the revised version of the manuscript.

Comment 21:

l. 357, 362, 369: no need to repeat that $S_{Rmax,a}$ is used as a parameter in the historical run for every scenario. Better to mention it once, when the historical run is explained.

Reply 21:

Agree, we will adapt this in the revised version of the manuscript.

Comment 22:

Results: It is not always clear what the reported numbers represent. Median and standard deviation? Mean and standard error of the mean? E.g. l. 374 & 377, l. 382, l. 390 & 391, l. 402, l. 408.If the reported values are always the same, you could also mention it once and state that all subsequent values represent the same measures.

Reply 22:

Good point, the reported numbers represent the median and standard deviation, we will make sure to mention this once clearly.

Comment 23:

l. 376: should this be ω_{obs} instead of ω?

Reply 23:

Correct, we will adapt this.

Comment 24:

l. 377: should this be transpiration instead of evaporation? This is a general issue: there is no clear distinction between evaporation, transpiration and evapotranspiration in the text.

Reply 24:

Throughout the manuscript, we use the term evaporation to represent all the different evaporation components (interception, transpiration and soil evaporation). It is perhaps a matter of taste, but we like to follow the terminology proposed by Savenije (2004) and Miralles et al. (2020), where evaporation instead of evapotranspiration is used to refer to all evaporative fluxes.

Comment 25:

l. 377-379: The differences of ω between the catchments is mainly attributed to the differences in the main vegetation type (broadleaved vs. coniferous/agriculture, l. 377-379). However, the catchments also differ substantially in other characteristics (French part: thick soils and gentle slopes, thin soils and steep terrain in the Ardennes, porous chalk in Wallonia (l. 109-113)). It should be discussed to what extent the differences in ω might not be dependent on the vegetation cover alone but also on the topography and soil type/thickness. Also, what are the implications of this regarding the method?How sure are you that the differences in hydrology between land-use types are really caused by the vegetation cover and not by the underlying topographical and soil characteristics?

Reply 25:

This is an interesting question which we will include in the discussion of the revised version of the manuscript. The differences in omega-values are most probably related to a combination of biophysical features. However, considering that transpiration is the largest continental water flux (Jasechko, 2018) and that omega values determine the hydrological partitioning, we assume that the variability in omega values is largely controlled by the root-accessible water volume $S_{R,max}$. This root-accessible water volume is independent from the soil type, as root systems will develop in a way to ensure sufficient access to water. In clayey soils, the rooting depth might be shallower than in sandy soils for an identical root-zone storage capacity. In our opinion, geology, soils characteristics and topography are implicitly integrated in other model parameters, e.g. the time scales of the linear reservoirs which represent the subsurface flow resistance in different parts of the system.

Comment 26:

l. 394: Fig. 2b should either be referenced earlier in the text, e.g. when talking about the difference between the historical and the 2K climate time series in the method section or it should be a separateresult figure that comes later in the text.

Reply 26:

Is it perhaps possible that you overlooked the reference to Fig 2b earlier in the text in Section 4.1.2 (L243) to illustrate the water-balance approach to estimate the root-zone storage capacity?

Comment 27:

l. 424: “median values of approximately 0.93”: why approximately?

Reply 27:

You are right, we will remove ‘approximately’

Comment 28:

l. 431: “streamflow during the wettest months”: include which months you mean by “wettest months”

Reply 28:

Good point, we will clarify that here we refer to the months December and January as wettest months.

Comment 29:

l. 500: “shows distinct patterns of change”: more precise language could be used: Which response variables differ and are they larger or smaller compared to the stationary scenario?

Reply 29:

This is a good suggestion, we had not included more details to avoid repetition from the result section. However, we think changes in streamflow and evaporation can briefly be repeated here to be more precise. We will clarify this in the revised manuscript.

Comment 30:

l. 512-519: This section does not fit in the “Implications” section of the discussion. It is more of a limitation of the current study or an outlook of what could be done next. It could e.g. be moved to the“Limitations and Knowledge gaps” section of the discussion.

Reply 30:

We agree that this paragraph contains an outlook of what could be done next. Initially, we had seen this as an implication of our work for future work, but we agree that it would better fit in a "Limitations and outlook" section of the discussion. We will adapt this in the revised version.

Comment 31:

l. 524-256: It is not clear to me, why the results on actual evaporation differences between the scenarios indicate disagreements among model process representations. Please elaborate more on this point. Also, what are the specific "processes that become relevant in the future"?

Reply 31:

What we mean here is that in the future scenario, evaporation demand increases. In scenario $2K_A$, where the root-zone storage capacity has not adapted to the future climate, we see water stress conditions that do not occur in the other scenarios. The different model representations amongst scenarios lead to different hydrological responses. However, we might consider removing this point in the revised version of the manuscript and add the other relevant points of discussion mentioned earlier in our reply to Comment 2.

Comment 32:

l. 333-334: The conclusion, that vegetation is important for regulating the water cycle is correct but itis also quite established and not really a specific discussion of your results.

Reply 32:

We agree that this conclusion is already quite established. We will rephrase this statement to emphasize how our study contributes to the quantification of the potential impact of vegetation adaptation in regulating the water cycle.

Comment 33:

l. 535-539: This discussion is also a limitation of your study or an outlook to further work. It should notbe under the "Implications" subheading of your discussion.

Reply 33:

We agree that this part of the discussion is also more an outlook for future research and will move this to the Limitation and outlook section.

Comment 34:

l. 542: “it is unclear how ecosystems will cope with climate change”: A discussion of how useful your approach to include vegetation into hydrological models under climate change in the light of this uncertainty would be interesting. To what extent can we be sure that the root-zone storage capacity can adapt to changing climate? What evidence is there from other studies regarding this issue? How would you proceed with your approach if vegetation changes to a vegetation type for which there is no data from the same region?

Reply 34:

This is a very interesting point. There is increasing evidence that vegetation efficiently adapts its root-zone storage capacity to ensure sufficient access to water (Guswa 2008, Schymanski et al. 2008). However, while we know that the ecosystem will eventually adapt to changing environmental conditions, partly by changing the mix of vegetation species and partly by vegetation adjusting its rooting depth or density, the question is how long it will take for an ecosystem to adapt in relation to the rate of climate change. Also, there are limits to the capacity of an ecosystem to adapt, for instance when is the threshold passed for the adaptability of rainforest to become savannah, or where lies the threshold for savannah to become desert? In this study we assume that adaptation thresholds are not reached. We refer to our reply to comment 2 for further details on this matter.

An interesting next step for our methodology will be to apply it in a climate-matching approach (Fitzpatrick and Dunne, 2019), where the current climate and landscape characteristics of a location X match the future climate or landscape characteristics of a location Y. This climate matching could be applied over distant regions, using datasets which combine landscape and climatological data over large samples of catchments (e.g. the various CAMELS datasets). Despite considerable uncertainties, this may allow us to infer vegetation adaptation and the associated changes in root-zone storage capacity from identifying regions in the world where the current climate resembles the projected future climate in a different region.

Comment 35:

At the end of the discussion, you mention several times that this study should be read as a sensitivityanalysis (l. 571) and a proof-of-concept (l. 575). This should also be made clear in the abstract. Also, athorough discussion of the advantages and disadvantages of the presented method is missing. What are possible applications of it, to what types of regions/questions can it be applied? What are the limitation and what could be improved?

Reply 35:

This is a very good suggestion, in the revised abstract, we will more strongly emphasize that our study should be understood as a sensitivity analysis. As also mentioned in our replies to the main comments (1 and 2), we will not use the terminology “proof-of-concept” anymore as we cannot test our results against future observations. We agree with your suggestion to more thoroughly discuss the advantages and disadvantages of the presented method in the discussion. We refer to our detailed reply to Comment 2 for the specific points that we will address.

Comment 36:

Figure labels should be in the same position for all figures (e.g. top left)

Reply 36:

Agree, we will adapt this in the revised version.

Comment 37:

Figure labels could be bold for better visibility?

Reply 37:

Good suggestion, we will adapt this in the revised version.

Comment 38:

Why are the scenario names (2Ka-d) that are defined in Fig. 4 never used? Instead $S_{rmaxa\text{-}d}$ isused in Figs. 5,8,9? If scenario names are given, they should be used consistently.

Reply 38:

Very good point. In Figure 9, we are actually showing values of $S_{R,max}$. However, in Figure 8 and 9, it indeed makes more sense to refer to Scenario 2KA etc in the labels.

Comment 39:

Fig. 1:

- colours of figure b): better use some continuous colour scheme
- Figure labels are inconsistent, b and c not on the same height
- Fig. 1b: what are the black points? Are they the streamflow measurement locations? Mention in the caption
- Fig. 1 does not reflect well many aspects mentioned in the text (2.1 landscape and 2.2 landuse)
    - Which are the three zones mentioned in l. 109? Are they represented in Fig. 1b? If yes you could add this to the caption. It is not clear what is the French, the Ardennesand the Wallonia part mentioned several times in the text
    - Fig. 1b: The numbers don't really match with the text. In Walloon 44% of the broadleaved forest should be there (l. 126), but in the figure the max. percentage is38%.

Reply 39:

- *We will test if an alternative color scheme improves readability.*
- *We will move the labels*
- *The black points are indeed the streamflow measurement locations, we will add this in the*

caption.

- *We will add the location of the three zones*
- *When we refer to 44% in the text, we mean 44% of the 18th century Walloon forests of Belgium that have remained from the original broadleaved forests. The 38% in the figure refer to the fraction of broadleaved forest within a catchment.*

Comment 40:

Fig. 3:

- Maybe this figure fits better in Supplement S3 because it is part of the model description? Idon't find it very helpful in the manuscript without the context of the model formulas

Reply 40:

We agree that Figure 3 can be moved to the Supplement to be connected to the model description. We will modify this in the adapted version.

Comment 41:

Fig. 5:

- Labels are missing
- Figures are a bit small: Could be a made bigger if empty space between panels is reduced
- 5b:
    - ω_{obs} should be on the y-axis not just ω
    - Axis text: No % because it's already in x-axis title
- 5c:
    - Caption last sentence: “A similar but reversed approach is applied …” It is the *same* and not a *similar* approach that was used.

Reply 41:

- *Indeed, we will add the labels in the revised version.*
- *We will try to decrease the empty space between the panels to increase the panels themselves.*
- *We will replace ω by ω_{obs}*
- *We will remove % from the x-axis title*
- *Indeed, we will replace similar by same.*

Comment 42:

Fig. 6:

- What is the ribbon for the modelled values: range from all realistic parameter sets of thecalibration?

Reply 42:

Indeed, the ribbon represents the ensemble of feasible parameter sets, we will clarify this in the caption.

Comment 43:

Fig. 7:

- Could be larger: box is not visible
- Don't use transparent colours to distinguish the panels. In my opinion they are alreadydistinguished enough by the panel titles and labels in the caption (same for figures in Supplement S3)
- Labelling is not consistent (compare to labelling of Fig. 6)
- Why is there such a big difference between Borgharen and the 34 catchments? Isn'tBorgharen just a summary of all the catchments?

Reply 43:

- *It is more the shape of the violin plots (left and right) which are important here.*
- *We consistently applied a color code throughout the Figures and would like to keep it as we believe it increases the clarity.*
- *We will change the labeling order.*
- *Borgharen is the most downstream outlet point considered. Often, model performance tends to decrease for smaller catchments. Additionally, the calibration was performed at Borgharen.*

Comment 44:

Fig. 8:

- Caption 8e) maybe mention that y-axis is different scale (compare to caption of Fig. 7)

Reply 44:

Yes, we will add this in the revised version.

Comment 45:

Fig. 9:

- What are the ribbons and lines? Median + conf. interval?

Reply 45:

Good point, they indeed show median and range of ensemble retained sets, we will clarify this in the caption.

Comment 46:

S1: Monthly correction factors for E-OBS precipitation data

- First sentence: Citation missing

Reply 46:

Indeed, we will add the missing reference.

Comment 47:

S4: Prior and posterior parameter distributions

- State in table heading, that the last 3 columns are the posterior parameter distributions

Reply 47:

Yes, we will add this in the revised version.

Comment 48:

l. 54: rephrase to: sensitivity of the hydrological response to change in …

Reply 48:

Yes, we will rephrase.

Comment 49:

l. 62: remove "as often referred to"

Reply 49:

Agree.

Comment 50:

l. 79: remove the full stop before the list of references

Reply 50:

Yes.

Comment 51:

l. 191 & 1197: same style for (p1), (p2) and p3 (either with or without brackets)

Reply 51:

Yes, we will make this consistent in the revised version.

Comment 52:

l. 392: replace "return periods of 2 year" with either "2 year return period" or "return period of

2years”. Also check the subsequent text as this mistake happens several times.

Reply 52:

Good point, we will replace.

Comment 53:

l. 410: Vertical space is missing as a new paragraph begins in line 411

Reply 53:

Not sure what is meant here, the spacing looks the same as in the other paragraphs.

Comment 54:

l. 500: “compared to” instead of “with respect to”?

Reply 54:

Ok, we will adapt.

Comment 55:

l. 592: “distinct change of sign”: remove distinct

Reply 55:

Agreed.

Comment 56:

Avoid unspecific adverbs. Either remove them, or state specifically what you mean by them. E.g.

- l.114: “relatively short response time” (how short is relatively short?)
- l. 422: “relatively well reproduced”
- l.423: “slight underestimation” and “relatively similar performance”

Reply 56:

L114, we will be more specific about the response time in the revised version.
L422 and 423, numbers are given later in the sentence, we will clarify this in the revised version.

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Reply to Anonymous Referee #2

Comment:

This manuscript evaluates how predicted changes in climate, e.g. aridity and seasonality, reflect on catchment hydrology in an exemplary basin using a hydrological model. The novelty lies in the accounting for the necessary adaptation in the vegetation root zone storage (essentially rooting depth) to actually satisfy predicted changes in actual evapotranspiration. For this, the authors first establish the expected rooting depth required to satisfy evapotranspiration due to climatic shifts of precipitation, evapotranspiration and their timing. Next they use those in a hydrological model to show that vegetation root adaptation and to a lesser extent als land use changes have a discernible effect on predicted catchment water balance. The authors conclude that this study serves as a proof of concept that adaptive vegetation has to be considered when evaluating climate change effects on hydrology. I agree with this conclusion and believe (although I have some questions) that the methodology is suitable to make this statement. I think this is a valuable contribution and of interest to the readership of HESS.The manuscript is formulated grammatically well. Having said this, it does not read well, for reasons stated below and requires revision. I fact, I really had to fight my way throughthe methods section. I alos have some serious concerns on lack of information and general organization of the manuscript. I recommend major revisions.

Reply:

We appreciate the reviewer's overall positive assessment of the manuscript and we are thankful for his/her thoughtful comments. We provide detailed clarifications below on how we will revise the manuscript.

Comment:

I have some concerns about missing information or implications of some assumptions that prevents me from fully evaluating the results.

I find it difficult to understand how the evapotranspiration was estimated for the model,and this needs to be laid out more clearly. For the rooting depth estimation ET from theroot zone was derived from applying the observed \omega to the predicted potential ET. But what was used for forcing the hydrological model? Potential ET from the climateprediction? What happens in the hydrological model, when the root zone storage runs dry? I read in the discussion that water limitation reflects on ET, but there is no mention how?

Reply

The three inputs used to force the hydrological model are indeed potential evaporation, temperature and precipitation from the observed and simulated historical and future climate data. We will make sure to clearly state this in the model description of the revised version of the manuscript. For the actual evaporation from the root-zone storage in the hydrological model, we apply a simple formulation to express water stress. The equation is provided in Table S4 of the Supplementary *material and describes how actual evaporation is linearly reduced when the root-zone storage is below a certain threshold (parameter). This standard formulation is used in many conceptual models, including HBV, NAM and VHM (Bouaziz et al., 2021). We will clarify this in the revised version of the manuscript.*

Comment:

Fig 3 is very repetitive, while the essential difference between the hillslope, plateau andwetlands is difficult to spot: It is whether or not the model allows for ground water exchange. Now, since the vegetation types are attributed to either hillslope (broadleaved forest) and plateau (conifers, agriculture) this small detail becomes important (and should be spelled out). How is this accounted for when the vegetation isswapped? Are also the HRUs swapped, e.g. does the area capable of ground water recharge increase / decrease as a result of the swap? In other words, does the model structure change as a result of the swap?

Reply

This is an interesting suggestion. However, in the land-use change scenarios, we did not change the percentages of each HRU in our model structure. The approach we propose to estimate the effect of land-use change really is a top-down approach based on assumed trajectories within the Budyko framework, but without the level of detailed required to specifically change land-use type at the pixel level. Therefore, we did not have the data available to change the percentage of each Hydrological Response Unit in our theoretical land-use change experiments. However, we think it is a good suggestion to discuss this limitation in the discussion section of the revised manuscript. We will also make sure to add a more detailed model description in the Supplement of the revised version of the manuscript, and to clarify the main differences in the caption of the Figure. In relation with the comments from Referee #1, we propose to move Figure 3 to the Supplement.

Comment:

As a follow up on that, I was left unclear as to whether all 2K scenarios see the same climate forcing? Does the change in \omega only apply to the rooting depth parameteror also to the evapotranspiration forcing? Please spell this out.

Reply

In the revised version of the manuscript, we will clarify that the same climate forcing is used for each of the 2K scenarios. The change in omega in combination with the change in climate data are indeed translated to a change in root-zone storage capacity parameter. However, we did not change the potential evaporation. We will clarify this in the revised version of the manuscript.

Comment:

I would appreciate an extension of the discussion to critically review the results.

a) The discussion already has a section called „limitations“, which is good. But it should include some more discussion on the assumptions above.

b) Correlations between parameters / vegetation and the environment are neglected in this study. For example, could the differences in \omega between catchments in Franceand the Belgium partly be related to differences in geology, topography etc. besides forest cover? Can you safely assume that the calibrated catchment parameters obtained for a specific vegetation distribution are still valid when changing the vegetation? I agree with the general statement that this a modeling study to provide a proof of concept, but would be good to include this in the discussion.

c) The manuscript starts with hypotheses which is nice and suitable for this study. It would be good to come back to them specifically in an interpretation section of the discussion.

Reply

a) We agree with the suggestions of the Referee #1 and Referee #2 to revise the Discussion Section in the revised version of the manuscript.

b) This is in an interesting question, which we will discuss in the revised version of the manuscript. We agree that the differences in omega-values are most likely related to a combination of biophysical characteristics. However, the omega parameter describes the hydrological partitioning and because transpiration is the largest continental flux, we think it is reasonable to assume that land use plays a major role to explain the differences in omega values (Teuling et al., 2019). Therefore, the variability in omega values is largely controlled by the water volume accessible to the roots of vegetation for transpiration (i.e. $S_{R,max}$). Topography, geology and soil type are likely implicitly integrated in other model parameters, e.g. the various recession time-scales of the linear reservoirs, which represent subsurface flow resistance throughout the system. We will include this in the revised discussion.

c) Thank you, this is a good point and we will make sure to clearly come back to the hypothesis in the Discussion of the revised manuscript.

Comment:

The manuscript reads technical at many levels, and this seriously prevents communicationto the point where important information seems to be missing. For example,

a) The introduction of the simulated climate in section 3.2. gives information about the origin of the time series, but leaves out which variables were actually used in the study. Specifically, the reader is left to guess whether it is potential ET or actual ET ?

b) Similarly, the structure of the hydrological model is shown in Fig 3, and given in a very short section 4.2. The model description does not include a reference to how root zone storage affects actual evapotranspiration. In this study on rooting depth and effects onthe water cycle this is a central point and should not be left out. It is only mentioned (Ibelieve once) in the discussion.

c) I am assuming that two parameters for the root zone storage capacity are used in each model run, one for shallow (agriculture and coniferous forest) and one for deeper rooted (broadleaf forests) vegetation. I am not sure whether I overlooked this, but it would be good to spell this out in the section where the model or the calibration are introduced.

Reply

a) *In the revised manuscript, we will clarify that potential evaporation is used to force the model and that actual evaporation is estimated in the model, following the equations provided in the Supplement.*

b) *The equations that describe how root-zone storage affects transpiration are included in the supplement. Following the suggestion of Referee #1, we will move Fig 3 to the Supplement of the revised version and include a more detailed description of the modelled processes.*

c) *For the root-zone storage capacity parameter, we use a return period of 2 years for the wetland and plateau classes and a return period of 20 years for the hillslope HRU. This is indeed already mentioned in the Model calibration section (4.3.1).*

Comment:

There are plenty of abbreviations that are barely introduced, sometimes the introduction appears even in a subheading.

Reply

Thank you for pointing this out, we will make sure to clarify the abbreviations in the revised version of the manuscript.

Comment:

The order within the methods section prevents understanding the methods. For example, there are many references to the model runs, before the model structure iseven introduced. Therefore it is really difficult to digest the information or interpret what the assumptions mean for the model. etc.

Reply

In the revised version of the manuscript, we will try to restructure the Method section to clarify our approach and experiments. We think that improving Figure 4 and introducing it earlier in the manuscript (perhaps already at the start of the Method section) can potentially also improve the clarity of the reading.

Comment:

Currently the headings and subheadings are not suitable for a reader navigating the text. Consider that they should help finding information when the reader does not diveinto the main text completely. For example take section „4.1.2 Seasonal water balancefor estimating the change in root zone storage capacity S_R,max“, would be more easily called „4.1.2 Estimation of root zone storage capacity“. I could make such propositions for almost every heading. Please revise.

Reply

We thank the reviewer for this good suggestion, we will go through the section titles and simplify them in the revised version of the manuscript.

Comment:

It is difficult to interpret the results without a table showing an overview of the climateof the different scenarios, e.g. precipitation, E_pot, aridity, seasonality, if applicable actual evapotranspiration used as forcing, actual evapotranspiration as model output.

Reply

We agree with this suggestion of the referee and will include such a table in the revised version of the manuscript.

Comment:

I believe the manuscript can be shortened and the important information be fleshed outto improve it being understood.

Reply

This is a good point and we will critically go through our manuscript to see which part of the analyses can possibly be moved to the Supplement to cut down on some technical details. We will also revise the Discussion to include additional implications and limitations as suggested by the referees.

Comment:

L 8-10: Needs to become obvious that these are modeling hypotheses. Please reformulate

Reply

We will clarify that our hypothesis relates to a modeling study.

Comment:

L 14-15: At this point in the manuscript it is difficult to understand why those particular changes are considered. Maybe formulate more general

Reply

We agree and will remove "from coniferous plantations/agriculture towards broadleaved forest and vice versa" and only keep the "two hypothetical changes in land use.".

Comment:

L 17-18 Are these numbers consistent with the water balance? They do not look like theydo ..

Reply

The numbers mentioned here reflect the mean differences between, on the one hand, the change in mean annual streamflow and evaporation between the scenarios $2K_B$, $2K_C$, $2K_D$ with adaptive ecosystems and, on the other hand, the stationary scenario $2K_A$ (see section 5.3.5). Therefore, these fractions do not relate to the total water balance. We will rephrase these sentences: "We found that the larger root-zone storage capacities (+34%) in response to a more pronounced seasonality with drier summers under 2K global warming strongly alter seasonal patterns of the hydrological response. The differences in the change of mean annual evaporation, recharge and streamflow between, on the one hand, the three scenarios with adaptive root-zone storage capacity and, on the other hand, the stationary system are +4%, -6% and -7%, respectively."

Comment:

L 25-27: There should be more appropriate references for this very general comment.

Reply

We will add additional references on the increasing evidence that ecosystems have the capacity to adapt to local (and changing) climate conditions, including Guswa, 2008; Schymanski et al., 2008; Gentine et al., 2012; Harman and Troch, 2014; Hrachowitz et al., 2020.

Comment:

L 42: „stationarity is dead" - use citation marks, otherwise it seems a bit awkward language, as strictly speaking stationarity never lived.

Reply

We agree and will add the citation marks.

Comment:

L 55: „require …" I do not agree. In a distributed model it could also s just be representedby distribution of land cover. This does not require a priori knowledge of the relation to catchment outflow.

Reply

We are not sure to understand the comment made by the reviewer, but what we mean is that in a *distributed model, the land cover map somehow needs to be translated to parameter values. Often, look-up tables retrieved from literature are used to relate a specific land use to a model parameter value. An alternative approach is to transfer parameters values from one location to another location through regionalization approaches. However, there is considerable uncertainty in both of these a priori parameter estimations.*

<u>Comment:</u>

L 56 „uncertainty in ..“ this statement is very vague. Can you be more explicit?

<u>Reply</u>

See our reply to the previous comment. We will try to be more explicit in the revised version of the manuscript.

<u>Comment:</u>

L 72-25: As it stands, this appears quite unrelated. Either erase or put into context.

<u>Reply</u>

We agree and we will rephrase to clarify the context in the revised manuscript to better introduce this paragraph. Here, we want to emphasize that there are multiple factors, besides the aridity index, affecting the position of a catchment in the Budyko space. One of these factors relates to the responses of ecosystems to elevated CO_2 levels, which are complex and can counteract one another (Jasechko 2018). On the one hand, vegetation density may increase from CO_2 fertilization, leading to increased transpiration. On the other hand, higher water use efficiencies may lead to declining transpiration rates as plants may transpire less water per unit of CO_2 taken up.

<u>Comment:</u>

L 76: „match expectations of the Budyko curve“ - Unclear, please be more specific: Which expectations?

<u>Reply</u>

We agree and we will rephrase. What we mean here is that the fact that most catchments worldwide scatter closely around the analytical Budyko curve is evidence for the co-evolution of catchment vegetation and soils with climate.

Comment:

L 77-78: „Vegetation tends to efficiently adapt its root-zone storage capacity to satisfycanopy water demand.“ - reference needed, ideally with an observation component.

Reply

Good point, actually the references are mentioned after the next sentence, but we will move them earlier in the revised version of the manuscript.

Comment:

L 78-79: I believe Yang et al., 2016 wold be good to cite here

Reply

We thank the referee for this very interesting reference, which we will include.

Comment:

L 95-98: Very difficult to grasp. I am not sure whether this paragraph really helps to understand what is coming.

Reply

We will rephrase the last two paragraphs of the introduction to emphasize that current studies assume that model parameter remain constant in a changing system. The objective of our study is to test how sensitive hydrological predictions are when changing vegetation related parameters, thereby accounting for the adaption of vegetation to future climate conditions.

Comment:

L 99-100: Any reasons for this hypothesis? Also, would be good to come back to it specifically in the discussion.

Reply

This is a good suggestion, we will clarify in the discussion that we expect the changes in the predicted hydrological response as a result of 2K global warming to be more pronounced in comparison to current-day conditions due to the potentially drier and warmer summers.

Comment:

102-105: Again, not sure this really helps. It is too detailed to soon.

Reply

Agree, we will remove these lines in the revised version of the manuscript.

Comment:

L 119-120: Reference missing

Reply

You are right, in the revised version, we will clarify that these numbers are calculated from the observed historical E-OBS data (section 3.1) and the streamflow data at Borgharen (section 3.3).

Comment:

L 131: Reference on the biodiversity statement required.

Reply

Agreed, we will add the reference of Kervyn et al. (2018) here.

Comment:

L 138: „E-Obs“ Add definition also in the text, not only in subtitle

Reply

Thanks, we will clarify this.

Comment:

L 147: Same as above, please introduce abbreviations in the text before using them. Also,with 2 K you probably refer to 2 Kelvin. Please spell this out as well.

Reply

Agreed.

Comment:

L 150: Spell out RACMO2 and HTESSEL ?

Reply

Agreed.

Comment:

L 168-180: Generally, it is a good idea to explain what is coming, but I really did not getit. Maybe try rewording in plainer language and less specific?

Reply

We will try to rephrase this paragraph to increase readability. In the first sentence, we will explicitly refer to the change in vegetation related parameters in hydrological models (more specifically the root-zone storage capacity) in response to climate change. We will try to be less specific to clarify the broader picture.

Comment:

L 193-195: Here I was entirely confused. Is \omega_{change} derived from the climate data using E_A from there? This part is very opaque, but really critical to understanding the methods.

Reply

We will rephrase to clarify that the long-term E_A is derived from trajectories in the Budyko space considering a change in aridity index (from the climate data) and a potential change in omega-values. The change in omega-values are derived from historical omega-values in catchments with relatively high and relatively low percentages of broadleaved forests.

Comment:

L203-206: Can you be sure that the runoff coefficients only depend on the forest cover and not on the geology? It seems that the regions with high / low cover are geographicallydistinct. How to avoid misinterpretation?

Reply

In the revised version of the manuscript, we will acknowledge that runoff coefficients are of course also related to other physical catchment characteristics besides land cover. However, as transpiration is the largest continental flux, we assume that vegetation plays a major role in the hydrological partitioning. There is increasing evidence that vegetation develops root systems in an optimal way to fulfill their needs. It is important to make the distinction between rooting depth and root-zone storage capacity. The root-zone storage capacity is independent from the soil type, as in clayey soils the rooting depth may be shallower than in sandy soils for an identical root-zone storage capacity (= root-accessible water volume). Geology also plays an important role in the hydrological response but *is likely implicit in other model parameters (e.g. the recession time scales of the different reservoirs, which represent subsurface flow resistances through the system). We will include this in the discussion of the revised manuscript.*

Comment:

L 208 „we expect …" First off, I appreciate the formulation of hypotheses. I wold only statethem at the end of the introduction however. Also, where hypotheses are formulated, it can be highly confusing to leave ambiguity between transpiration, bare soil evaporation, or evapotranspiration for the two combined. Please specify. Finally, where does the hypothesis come from? Please add references.

Reply

We will clarify in the revised version of the manuscript that we use the term evaporation to represent all different evaporative fluxes (interception, soil evaporation, transpiration). We follow the terminology proposed by Savenije (2004) and Miralles et al. (2020), where evaporation instead of evapotranspiration is used to refer to all evaporative fluxes.

In the revised version of the manuscript, we will also include the references of Fenicia et al. (2009), Teuling et al. (2019) and Stephens et al. (2021).

Comment:

L 222 „match expectations .. ": Unclear formulation, please be more specific on what typeof expectation.

Reply

Also here, we will rephrase that it is about the expectation that catchments scatter closely around the analytical Budyko curve, suggesting a co-evolution of vegetation and soils with climate.

Comment:

L 279 What is meant with „imposing"? I do not understand what is done here.

Reply

Agree, we will rephrase to explain that we added the difference between the simulated 2K and historical water deficits to the observed historical climate deficits (E-OBS data). This was done to account for the bias between the simulated and observed historical climate data. Perhaps this technical detail can be moved to the supplement of the revised version of the manuscript not to confuse the reader.

Comment:

Table 1

I am confused about the last Last column: Over what sample is the max and min taken?Why do those max and min not appear on the first two lines?

Reply

See also our reply to the previous comment, for the 2K scenario, we add the difference between the simulated 2K and historical water deficits to the observed historical climate deficits to account for the bias between the simulated and observed historical climate data. In the revised version of the manuscript, we will move these technical details on this "bias-correction" to the supplement in order not to confuse the reader in the main storyline.

Comment:

L 298: See my previous notes on abbreviations. Better would be „Hydrological model:xxxx"

Reply

Agreed, we will change this.

Comment:

L 303-304: The values appear arbitrary, and maybe are explained in the references. Isuggest adding an explanation of their origin, so that the reader can understand the general idea without need to refer elsewhere.

Reply

Agreed, these values were retrieved from the study of Gharari et al. (2011), we will clarify this in the revised version of the manuscript.

Comment:

L 306: Am I understanding correctly that hillslope vs plateau was derived from a vegetation map? If yes, please spell this out more clearly, it is very opaque from the current description. Also, in other words, the main difference between hillslope and plateau, which is the consideration of deep drainage, depends on the vegetation as well, with agricultural areas allowing for deep drainage and forested areas (per definition of thelocations) does not? How does this affect the model results? This needs to enter the discussion.

Reply

In the revised version of the manuscript, we will make sure to clarify that the Hydrological Response

Units hillslope, plateau and wetland are first derived from topographical information based on thresholds for the Height Above the Nearest Drain and slope. As additional step, we associate forest with hillslope and agricultural area with plateau using the land use map. Groundwater recharge occurs both in the plateau and the hillslope HRU through preferential recharge from the root-zone storage. In the plateau class, there is also recharge through percolation from the root-zone to the groundwater. In the land-use scenarios, we did not change the percentages HRU as we are using a top-down approach to estimate the changes in runoff coefficient through trajectories in the Budyko space, which does not include detailed information on the exact spatial extent of change. We do not expect a large effect of this limitation on our results, but we will mention it in the discussion.

Comment:

L 307 - 311: Important information is missing. Important information would be, what happens, when the root zone storage runs dry? Does this affect ET at all? What happenswhen ET cannot be satisfied?

Given the general topic of the paper, it needs to be clearly explained how vegetation affects hydrology in this model, especially E_A. At this point I am assuming that E_A is imposed either from observations or regional climate model and further modified to accommodate the different runoff coefficients that are taken to represent the vegetationcover? Later (in the discussion) I am learning that water availability actually affects E_Aand I am back at point zero. This section really needs attention.

Reply

In the revised version of the manuscript, we will clearly explain that we use a standard formulation to express water stress. Evaporation from the root-zone (E_R) is reduced when the storage is below a certain threshold. The detailed equations are provided in the Supplement (Table S4).
The model is forced with potential evaporation and actual evaporation is an output of the model.

Comment:

L 324-326: We learn elsewhere that this corresponds to plateau corresponds to agricultureand hill slope to forest. Please repeat this here. This is an important part of the study.

Reply

This is a good point, the HRU are actually derived both from topographical and land use data, we will repeat it here.

Comment:

L 339-340: In other words, potential interactions between the model parameters are neglected? Was this tested?

Reply

We agree that it is not unlikely that future changes may also influence other system characteristics. However, the mutual interactions between parameters are so far unknown and were therefore not explicitly considered. We did use an ensemble of parameter sets to somehow account for the uncertainty in model parameters and the possibility that parameters compensate for each other due to simplistic process representation. In many studies, the hydrological model used for future simulations remains completely identical to the model structure derived for historical conditions. In our study, we perform a controlled experiment to test the sensitivity of changing the root-zone storage capacity, which we can estimate from the future climate data. We will discuss this in the limitation section of the discussion of the revised manuscript.

Comment:

L 358: Here and in D: Does the forcing for ET change as a result of the land use change?

Reply

The potential evaporation used as forcing was calculated with the Makkink formula and we did not change it as a result of the land-use change. We will mention this in the limitation section of the discussion.

Comment:

L 378-379: Sounds like interpretation and this should go to discussion.

Reply

We agree that this sentence could be perceived as discussion. However, it is always difficult to clearly separate results from discussion. Here, we think it provides guidance to the reader to place the results in a broader context

Comment:

L 389-399: Maybe merge the sections on root zone storage across scenarios A-D?

Reply

We agree that splitting the results with separate sections for each scenario leads to some repetitions. However, we also think it increases the clarity to treat each scenario separately. In the revised version of the manuscript, we will critically reflect on how we can further clarify the structure to present the different scenarios.

Comment:

L 395-396: Would be good to have an overview table with the climate conditions (aridity, seasonality, P, E_pot) for all scenarios, including separate listing of E_pot and E_A for the scenarios.

Reply

We thank the reviewer for this suggestion, and we will include such a table in the revised version of the manuscript.

Comment:

L 445-455: Was very confused about how the E_A was obtained. It is a model output or forcing?

Reply

In the revised version of the manuscript, we will clarify that actual evaporation is model output. The forcing variables of the model are potential evaporation, precipitation and temperature.

Comment:

L 467-468: „result of soil moisture stress in the root-zone“ This is not mentioned in themodel description and is absolutely a must. Also, please report on times of soil water stress in the model scenarios.

Reply

As also mentioned in earlier replies, we will explain that we use a standard formulation to represent water stress, as described in the model equations of Table S4.

Comment:

Discussion: I find it more logical that the limitations are stated first, followed by interoperation and implications last.

Reply

This is perhaps a matter of taste, but we think limitations can also be read as an outlook for future work and we therefore think it might better fit after the implication section.

Comment:

L 501-503: This sentence can be erased without loosing information.

Reply

Agree, we will remove this sentence.

Comment:

L 547-548: Also rooting depth is species specific, and mono-cultures would have limited capacity to adapt.

Reply

We agree. As also mentioned in one of the earlier replies, there is a distinction between rooting depth and root-zone storage capacity (i.e. the water volume accessible to the roots of vegetation for transpiration).

Comment:

Figure 2: The arrow with script \Delta \omega is misleading. What is shown is \Delta (E_A / P),which is really not the same.

Reply

Thank you for this good point. We will remove the arrow from the schematization and revise the caption.

Comment:

Figure 3: See above major comments. The important difference is in how the interaction with groundwater is accounted for in the different slope positions, which are at the same timedirectly linked to vegetation cover. This is an important detail and should be made obvious. In contrast, the remainder of the Figure is not very important and could in my opinion go to the appendix.

Reply

Thank you for this suggestion. We will emphasize the differences in the caption and we agree to move the Figure to the Supplement. This way, it will be clearly connected to the model equations.

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Reply to Anonymous Referee # 3

Overall assessment by Referee #3:

This is a very interesting study on the possible implications of ecosystem root-zone storage capacity changes induced by vegetation adaptation to climate change. The authors use a top-down approach based on the Budyko model. I believe that the study is novel and the insight provided by the study is valuable. The methods are innovative and useful for the Hydrology and earth system science community. However, there are several aspects in the methodology that need to be further explained/clarified to improve the quality of this contribution.

Reply:

We thank Referee #3 for his/her positive assessment of our manuscript. We provide a reply to each of the valuable comments below.

Comment 1:

Lines 144-145 refers to a monthly bias-correction factor applied to improve the consistency between the "E-OBS dataset in the center of the basin when compared to an operational dataset" which is "based on local precipitation data provided by the Service Public de Wallonie for the period 2005-2017". Though there are some additional details in the supplement this comment is very vague here, so it would be good to add some further clarification on the rationale for the use of the bias- correction factor, and why it "improves consistency".

Reply 1:

We agree with this suggestion and will clarify in the main text that we correct the E-OBS dataset to better represent the local precipitation data provided by the Service Public de Wallonie. As also detailed in the Supplement, we use a monthly correction factor in the center part of the basin because the E-OBS data underestimates the interpolated station data with more than 20%.

Comment 2:

Lines 227-228 state: "The water-balance method requires daily time series of precipitation, potential evaporation and a long-term runoff coefficient to estimate transpiration, as it depletes the root-zone storage during dry spells." Dry spells can be interpreted as interannual periods (a dry spell could potentially last more than one year in certain regions), but here you are only considering seasonal dry periods… so please clarify.

Reply 2:

The reviewer is completely correct. We will clarify that, in our study area, the dry spells are seasonal as storage deficits become zero again in the fall and winter when excess precipitation drains away as direct runoff or recharge.

Comment 3:

Lines 231-235: The explanation on the use of equation (4) and the estimation of the associated variables is not clear. The problem might be that at this stage in the manuscript, the model used for the estimation of the hydrologic variables has not been presented yet (it is later presented in section 4.2 and schematized in Figure 3). It is then difficult for the reader to understand how is PE estimated based on the other variables in this equation (as EI and SI are not available from observations). It is therefore important to explain how EI and SI are estimated (here and not later, perhaps linking to the use of the model here, mentioning that the details will be described later). Please also explain if there is an implied iterative process. That is, in order to estimate EI and SI from the model (shown also in Figure 3), the value of Sr, max needs to be set, right? But it is obtained after using equation 4 (which uses the results of the model). I find the explanation of the methodology in this aspect unclear, so this needs to be further clarified.

Reply 3:

The estimation of the root-zone storage capacity with the water-balance approach is an independent step, which is not necessarily linked to the use of a specific model structure. However, it is correct that we use the same interception module as in the model to estimate the interception evaporation in the water-balance approach. The module consists of a reservoir with a maximum interception storage I_{max} to determine effective precipitation ($P_E = max(0, S_I – I_{max})/dt)$) and interception evaporation ($E_I = min(E_P, (S_I - I_{max})/dt)$). We will include these formulas in the revised version of the manuscript. The value of $S_{R,max}$ does not need to be set to run the interception module to estimate E_I and S_I, as interception processes occur before precipitation reaches the root-zone. Therefore, after estimating the effective precipitation, the value of $S_{R,max}$ in the water-balance approach is estimated, which does not require an iterative process. We will clarify this part in the revised version of the manuscript.

Comment 4:

Line 249: I think it should be “By fitting the extreme value distribution of Gumbel to the series of annual maximum storage deficits”

Reply 4:

Yes, thank you, we will change this!

Comment 5:

Lines 249: Why Gumbel?

Reply 5:

We used the Gumbel distribution as it is frequently used for estimating hydrological extremes. In particular, it was previously shown to be a suitable choice for the estimation of the root-zone storage capacity through the water-balance approach by several other studies (Gao et al., 2014; Nijzink et al., 2016; de Boer-Euser et al.; 2016, Wang-Erlandsson et al., 2016; Bouaziz et al., 2020; Hrachowitz et al., 2020). We will clarify this in the revised version of the manuscript.

Comment 6:

Line 271. What do you mean by “native” simulated … ?

Reply 6:

With “native”, we mean that we did not apply a bias-correction to the simulated historical climate data. We will clarify this in the revised version of the manuscript.

Comment 7:

Figure 5 a is not clear (difficult to visualize). Perhaps a change on the colour scheme used for the lines (more contrasting colours) could help.

Reply 7:

We agree with the reviewer that all the curves in Fig 5a are difficult to visualize. The color scheme used in Figure 5 is consistent with the color scheme used in the other Figures. However, we think it might be sufficient to only show the dashed curves representing the median ω_{obs}-values and remove the 35 curves of the other catchments that are indeed not clearly visible in the Figure. We will adapt this in the revised version of the manuscript.

Comment 8:

Line 421 states: “The ensemble of parameter sets retained as feasible after calibration mimics the observed hydrograph…”. I think that you are trying to say: The simulated values of Q obtained using “the ensemble of parameter sets retained as feasible after calibration mimics the observed hydrograph…”.

Reply 8:

Yes, this is correct, thank you, we will adapt this.

References

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Ecosystem adaptation to climate change: the sensitivity of hydrological predictions to time-dynamic model parameters

Laurène J. E. Bouaziz[1,2], Emma E. Aalbers[3,4], Albrecht H. Weerts[2,5], Mark Hegnauer[2], Hendrik Buiteveld[6], Rita Lammersen[6], Jasper Stam[6], Eric Sprokkereef[6], Hubert H. G. Savenije[1], and Markus Hrachowitz[1]

[1]Department of Water Management, Faculty of Civil Engineering and Geosciences, Delft University of Technology, P.O. Box 5048, NL-2600 GA Delft, The Netherlands
[2]Department Catchment and Urban Hydrology, Deltares, Boussinesqweg 1, 2629 HV Delft, The Netherlands
[3]Royal Netherlands Meteorological Institute (KNMI), P.O. Box 201, 3730 AE De Bilt, the Netherlands
[4]Institute for Environmental Studies (IVM), Vrije Universiteit, Amsterdam, 1081 HV, the Netherlands
[5]Hydrology and Quantitative Water Management Group, Wageningen University and Research, P.O. Box 47, 6700 AA Wageningen, The Netherlands
[6]Ministry of Infrastructure and Water Management, Zuiderwagenplein 2, 8224 AD Lelystad, The Netherlands

Correspondence: Laurène Bouaziz (laurene.bouaziz@deltares.nl)

Abstract. ~~To predict future~~ Future hydrological behavior in a changing world ~~, often use is made of models~~ is typically predicted based on models that are calibrated on past observations, disregarding that hydrological systems, ~~hence~~ and therefore model parameters, ~~will~~ may change as well. ~~Yet, ecosystems likely adjust their~~ In reality, hydrological systems experience almost continuous change over a wide spectrum of temporal and spatial scales. In particular, there is growing evidence that vegetation adapts to changing climatic conditions by adjusting its root-zone storage capacity, which is the key parameter of any ~~hydrological system, in response to climate change~~terrestrial hydrological system. In addition, other species ~~might~~ may become dominant, both under natural and anthropogenic influence. In this study, we test the sensitivity of hydrological model predictions to changes in vegetation parameters that reflect ecosystem adaptation to climate and potential land-use changes. We propose a top-down approach, which directly uses projected climate data to estimate how vegetation adapts its root-zone storage capacity at the catchment scale in response to changes in magnitude and seasonality of hydro-climatic variables. Additionally, ~~the Budyko~~ long-term water balance characteristics of different dominant ecosystems ~~in sub-catchments~~ are used to ~~simulate~~ predict the hydrological behavior of potential future land-use change, in a space-for-time exchange. We hypothesize that changes in the predicted hydrological response as a result of 2K global warming are more pronounced when explicitly considering changes in the sub-surface system properties induced by vegetation adaptation to changing environmental conditions. We test our hypothesis in the Meuse basin in four scenarios designed to predict the hydrological response to 2K global warming in comparison to current-day conditions using a process-based hydrological model with (a) a stationary system, i.e. no assumed changes in the root-zone storage capacity of vegetation and historical land use, (b) an adapted root-zone storage capacity in response to a changing climate but with historical land use, and (c,d) an adapted root-zone storage capacity considering two hypothetical changes in land use~~from coniferous plantations/agriculture towards broadleaved forest and vice-versa~~. We found that the larger root-zone storage capacities (+34 %) in response to a more pronounced ~~seasonality with drier~~ climatic

seasonality with warmer summers under 2K global warming ~~strongly alter seasonal patterns~~ result in strong seasonal changes of the hydrological response, with ~~an overall increase in mean annual evaporation (+4~~in the non-stationary scenarios up to -15 % ~~), a decrease in recharge (-6~~and -10 % ~~) and a decrease in streamflow (-7~~lower streamflow and groundwater storage respectively in autumn and an increase of summer evaporation of up to +14 % ~~), compared to predictions with a stationary system~~compared to the stationary benchmark scenario. By integrating a time-dynamic representation of changing vegetation properties in hydrological models, we make a potential step towards more reliable hydrological predictions under change.

1 Introduction

Hydrological models are required to provide robust short-term hydrological forecasts and long-term predictions of the impact of natural and human-induced change on the hydrological response. Common practice is to predict the future using a hydrological model calibrated to the past (Vaze et al., 2010; Blöschl and Montanari, 2010; Peel and Blöschl, 2011; Coron, 2013; Seibert and van Meerveld, 2016). For the near future, it seems acceptable to assume no fundamental change in the hydrological system, although we know that ~~ecosystems, the manager of the hydrological system, have the~~ vegetation has the capacity to adapt to ~~climatic change (Savenije and Hrachowitz, 2017)~~changing climate conditions at scales reaching from individual plants to the composition of entire plant communities at larger ecosystem scales (Guswa, 2008; Schymanski et al., 2008; Gentine et al., 2012; Harman a . For longer term predictions, it is therefore ~~not correct~~ problematic to assume an unchanged system within a changing world. This raises the question on the robustness of hydrological predictions, especially in the context of climate change (Coron et al., 2012; Stephens et al., 2019).

For example, Merz et al. (2011) clearly shows the non-stationarity of hydrological model parameters when calibrating 273 Austrian catchments in subsequent 5-years periods between 1976 and 2006. Being the core parameter of any hydrological system, Merz et al. (2011) report almost a doubling of the root-zone storage capacity and this gradual increase is assumed to be related to changing climatic conditions, such as increased evaporation and drier conditions in the more recent years. The temporal variability of model parameters could also be attributed to uncertainties in input and model structure or inadequate calibration strategies. However, the observed trends in model parameters are also likely to reflect transient catchment conditions over the historical period.

Under continued global warming, precipitation and temperature extremes are expected to further increase and the hydrological cycle is likely to further accelerate (Allen et al., 2010; Kovats et al., 2014; Stephens et al., 2021). In addition, natural land cover change and anthropogenic activities of land-cover change and land-use management can substantially alter a catchment's water balance ~~(Brown et al., 2005; Wagener, 2007; Fenicia et al., 2009; Jaramillo and Destouni, 2014; Nijzink et al., 2016a; ?; Levia et al.~~ (Brown et al., 2005; Wagener, 2007; Fenicia et al., 2009; Jaramillo and Destouni, 2014; Nijzink et al., 2016a; Hrachowitz et al., 2021; Lev . Considering the unprecedented speed of change, Milly et al. (2008) ~~declared that~~ postulated that "stationarity is dead" and no longer should serve as a default assumption in water management. ~~He advocates~~ They advocate the development of methods that quantify the non-stationarity of relevant hydrological variables.

However, ~~understanding and representing~~ describing and quantifying non-stationarity is challenging due to the complex interactions and associated feedback between climate, vegetation, soils, ecosystems and humans at multiple spatial and temporal scales (Seibert and van Meerveld, 2016; Stephens et al., 2020). The main ~~methods~~ approaches to understand how changes in hydrological functioning relate to changes in catchment characteristics rely on paired watershed studies and hydrological modeling (Andréassian et al., 2003). In many modeling studies, a selection of one or more parameters are changed using values from literature in combination with adapted land-cover maps to (partly) reflect the characteristics of the altered system (Mao and Cherkauer, 2009; Buytaert and Beven, 2009; Pomeroy et al., 2012; Gao et al., 2015). Alternatively, Duethmann et al. (2020) uses satellite observations of vegetation indices to improve the representation of the surface resistance dynamics to calculate reference evaporation used in conceptual hydrological models over a historical record. A similar approach is applied by Fenicia et al. (2009) to account for changes in evaporation as a result of land-use management changes in the Meuse basin.

While these approaches are valuable to test the sensitivity of ~~change on~~ the hydrological response to changes in catchments characteristics (Seibert and van Meerveld, 2016), they require an understanding of how catchment characteristics (e.g. land use, soil properties) relate to model parameters. Yet, there is considerable uncertainty in ~~a priori parameter estimation~~ the a priori estimation of parameter values through the use of look-up tables relating physical catchments properties to parameter values and the use of regionalization approaches to transfer parameter values from one location to another (Wagener, 2007). Besides, the required data (e.g. future land-use maps or vegetation indices) may not be available in the context of climate change impact assessment (Duethmann et al., 2020). Instead, a way forward may be to develop robust top-down modeling approaches based on optimality principles of vegetation growth by considering the co-evolution of soils, vegetation and climate in a holistic way ~~(Blöschl and Montanari, 2010)~~(Schymanski et al., 2009; Blöschl and Montanari, 2010).

As complex and heterogeneous as landscapes may be across a diversity of climates, the long-term hydrological partitioning of a catchment is governed by a surprisingly simple and predictable relation, which relies on the available water and energy for evaporation (Turc, 1954; Mezentsev, 1955; Budyko, 1961; Fu, 1981; Zhang et al., 2004). ~~The~~ This is described in the Budyko hypothesis, ~~as often referred to, describes that~~ which suggests that the ratio of mean annual evaporation over precipitation (E_A/P) is mainly controlled by the aridity index, defined as the ratio of mean annual potential evaporation over precipitation (E_P/P). However, Troch et al. (2013) found catchments to deviate from the Budyko hypothesis when exchanging climates across different catchments in a modeling experiment. Their results suggest that long-term hydrological partitioning results from the co-evolution of catchment properties and climate characteristics, including not only the aridity index but also climate seasonality, topography, vegetation and soils.

The combination of these other factors influencing the water balance partitioning besides the aridity index are explicitly considered in the ω parameter of the parametric description of the Budyko hypothesis (Fu, 1981; Zhang et al., 2004). Deviations from the Budyko curve suggest that different vegetation develops in different climates, along a different ω curve. If climate changes, catchments are likely not only to shift ~~horizontally~~ in the Budyko space as a result of a changing aridity index, but also ~~vertically~~ as a result of a changing vegetation cover (Jaramillo and Destouni, 2014). ~~Vertical shifts within the Budyko space can also be related to vegetation-CO~~Other factors affect the positions and trajectories of catchments in the Budyko space, including the complex and counteracting responses of ecosystems to elevated CO_2 ~~interactions, e. g.~~ levels (Jasechko, 2018). More specifically, vegetation density may increase from CO_2 fertilization~~and improved~~ , leading to increased transpiration, implying an upward shift in the Budyko space. While higher water-use ~~efficiency as a result of increasing CO_2 levels~~ efficiencies may lead to declining transpiration rates, leading to a downward shift in the Budyko space (Keenan et al., 2013; van der Velde et al., 2014; van Der Sleen et al., 2015; Ukkola et al., 2016; Jaramillo et al., 2018; Stephens et al., 2020).

The ~~interdependence of climate seasonality, aridity index and vegetation to match the expectation from the Budyko curve was also demonstrated by Gentine et al. (2012); Donohue et al. (2012)~~fact that most catchments worldwide scatter closely around the analytical Budyko curve is evidence for the co-evolution of vegetation and soils with climate at the catchment scale (Gentine et al., 2012; Donohue et al., 2012). Vegetation tends to efficiently adapt its root-zone storage capacity to satisfy canopy water demand (Milly, 1994; Schymanski et al., 2008; Gerrits et al., 2009; Gentine et al., 2012; Gao et al., 2014; Yang et al., 2016) . This implies that vegetation creates a larger buffer to survive dry spells when seasonal water supply and demand are out of phase, than in a climate where demand and supply are in phase. ~~(Milly, 1994; Schymanski et al., 2008; Gerrits et al., 2009; Gentine et al., 2~~ ~~.~~ The root-zone storage capacity is, therefore, the key element regulating the partitioning of water fluxes in many terrestrial hydrological systems. In addition, not only natural changes to the environment, but also human interference with vegetation affect transpiration water demand and hence the root-zone storage capacity ~~(Nijzink et al., 2016a; ?)~~(Nijzink et al., 2016a; Hrachowitz et al., 202 .

Detailed observations of rooting-systems are very scarce in time and space and difficult to integrate to the catchment scale due to heterogeneity of landscapes ~~(de Boer-Euser et al., 2016; ?)~~(de Boer-Euser et al., 2016; Hrachowitz et al., 2021). Instead, the catchment-scale root-zone storage capacity is often estimated through calibration of a hydrological model. Other methods rely on optimality principles that maximize net primary production, carbon gain or transpiration ~~(?Kleidon, 2004; Collins and Bras, 2007; Gusw~~ (van Wijk and Bouten, 2001; Kleidon, 2004; Collins and Bras, 2007; Guswa, 2008; Speich et al., 2018). Alternatively, there is increasing evidence that the catchment-scale root-zone storage capacity can be robustly and directly estimated from annual water deficits using water-balance data ~~(Gao et al., 2014; de Boer-Euser et al., 2016; Wang-Erlandsson et al., 2016; Nijzink et al., 2016a; Bou~~ ~~.~~

(Gao et al., 2014; de Boer-Euser et al., 2016; Wang-Erlandsson et al., 2016; Nijzink et al., 2016a; Bouaziz et al., 2020; Hrachowitz et a . However, it remains unclear how vegetation may adapt its root-zone storage capacity to climate change and how these changes affect future hydrological behavior.

~~The~~

In contrast to current studies assuming stationary model parameters in a changing system, the objective of this study in the Meuse basin (Western Europe) is to ~~quantify the sensitivity of the~~ test how sensitive hydrological predictions are when changing vegetation related parameters, thereby accounting for the adaption of vegetation to future climate conditions. We test the hypothesis that changes in the predicted hydrological response to ~~potential changes in~~ a 2K global warming are more pronounced when explicitly considering time-dynamic values for the root-zone storage capacity ~~of vegetation in combination with~~ parameter, which reflect vegetation adaptation to changes in hydro-climatic variables and potential land-use changes~~as a result of 2K global warming.~~ .

Using the Budyko framework, we first estimate changes in the long-term hydrological partitioning. To evaluate the effect of land-use change under potential future conditions, we exchange space-for-time by connecting the spatially variable ω parameter of the Budyko curve to different dominant land uses. We then use water-balance data to estimate how the root-zone storage capacity may adapt to increasing seasonal water deficits under climate change.

~~We hypothesize that changes in the predicted hydrological response as a result of 2K global warming in comparison to current-day conditions are more pronounced when explicitly considering an adapted root-zone storage capacity to reflect changes in the magnitude and seasonality of hydro-climatic variables as well as potential land-use changes. We test our hypothesis using a process-based hydrological model and compare the difference in hydrological response when assuming (a) a stationary system without changes in the root-zone storage capacity and historical land use, with three non-stationary systems involving (b) an adapted root-zone storage capacity in response to climate change but no changes in land use, and (c,d) an adapted root-zone storage capacity and two hypothetical land-use change scenarios.~~

2 Study area

2.1 Climate and landscape

The Meuse basin upstream of Borgharen, at the border between Belgium and the Netherlands, covers an area of approximately 21300 km^2 with an elevation ranging between 50 and 700 m and can be divided into three main zones (Fig. 1). The French Southern part of the basin in the Grand Est region is characterized by relatively thick soils, broad valleys bottoms and gentle slopes underlain by sedimentary consolidated rocks. Metamorphic rocks and relatively thin impermeable soils dominate the steeper Ardennes Massif in Belgium. On the West bank of the Meuse in Wallonia, the lithology is characterized by porous chalk layers with deep groundwater systems.

The Meuse is a rain-fed river with relatively short response times of several hours up to few days. Streamflow has a strong seasonality with low summer and high winter streamflow reflecting the seasonality of potential evaporation, while precipitation is relatively uniformly distributed throughout the year. The large storage capacity due to relatively thick soils in the French part of the basin increases the hydrological memory of the system, implying a strong influence of winter precipitation on streamflow deficits in the subsequent summer (de Wit et al., 2007). Snow is not a major component of the water balance, but snow melt can have a significant influence during some events (de Boer-Euser, 2017; Bouaziz et al., 2021). Mean annual precipitation, potential evaporation and streamflow is approximately 950 mm yr^{-1}, ~~580~~590 mm yr^{-1} and 407 mm yr^{-1}~~.~~, as derived from the historical observed climate and streamflow data (Sect. 3.1 and 3.3).

2.2 Land use

Land use in the basin consists of 35 % forest, 32 % agriculture, 21 % pasture and 9 % urban areas ~~(Fig. 1, European Environment Agency, 20~~ (Fig. 1c, European Environment Agency, 2018). The large majority of forests in the French part of the basin is characterized as "old growth", here defined as forested area which has been continuously wooded since at least the middle of the 19$^{\text{th}}$ century

(Cateau et al., 2015). These broadleaved forests consist primarily of European ~~oaks, sessile oak and beech~~ Oaks, Sessile Oak and Beech (Institut National de l'Information Géographique et Forestière, 2019). In contrast, only 44 % of the 18$^{\text{th}}$ century Walloon forests of Belgium has remained from the original broadleaved forest, the rest being cleared for agriculture on high fertility soils in the North West (30 %) or converted to coniferous plantations (Scots pine, Norway spruce and Douglas-fir) on the poor soils of the Ardennes (26 %, Kervyn et al., 2018). The status of "old growth" forest does not exclude human disturbances, but assumes a relatively limited impact. Soils are less disturbed and their structure and biochemical composition have been preserved for several centuries. This favors a high degree of biodiversity, which is a key element for the resilience of forest ecosystems to perturbations (Kervyn et al., 2018). In contrast, recent short-rotation plantations lack many of these characteristics. Particularly thick canopy plantations, such as the spruce and Douglas-fir, significantly alter the typical biodiversity of forests. Additionally, relatively higher evaporation water use is expected in these recent, short-rotation exotic plantations in comparison to older, more natural forests (Fenicia et al., 2009; Stephens et al., 2021).

3 Data

3.1 Observed historical ~~E-OBS~~ climate data

~~The E-OBS dataset~~ We use the European daily high-resolution gridded dataset, termed E-OBS (v20.0e), as observed historical climate data, which includes daily precipitation, temperature and radiation fields for the period 1980-2018 at a 25 km^2 resolution ~~(Cornes et al., 2018)~~(Table 1, Cornes et al., 2018). The data are based on station data collated by the European Climate Assessment & Dataset (ECA&D) initiative. Temperature is downscaled using the digital elevation model and a fixed lapse rate of 0.0065°C m^{-1}. Potential evaporation is estimated using the Makkink formula (Hooghart and Lablans, 1988). There is a relatively large underestimation of precipitation (> 20 %) in the E-OBS dataset in the center of the basin when compared to an operational dataset, which is based on local precipitation data provided by the Service Public de Wallonie for the period 2005-2017 ~~(Bouaziz et al., 2020)~~and used in Bouaziz et al. (2020). A monthly bias-correction factor is applied to ~~improve the consistency between both datasets~~ correct the E-OBS precipitation in the center of the basin to better represent the local precipitation data provided by the Service Public de Wallonie (Sect. S1 of the Supplement).

3.2 Simulated historical and 2K climate data

To study the impact of 2 Kelvin (2K) global warming on the hydrological response of the Meuse basin, we use climate simulations of precipitation, temperature and potential evaporation for the historical period ~~1979-2018~~ 1980-2018 and a 2K global warming simulation (Table 1), provided by the Royal Netherlands Meteorological Institute (KNMI). The simulations are generated with the ~~regional climate model~~ KNMI Regional Atmospheric Climate Model (KNMI-RACMO2) (van Meijgaard et al., 2008) at 12 km x 12 km resolution. RACMO2 uses ~~the~~ as land surface scheme ~~HTESSEL~~ the Hydrology Tiled European Centre for Medium-Range Weather Forecasts (ECMWF) Scheme for Surface Exchanges over Land (HTESSEL) (Balsamo et al., 2009), which employs four soil layers with a total depth of 2.9 m. Each land-grid cell includes separate tiles for high and low vegetation (16 vegetation types), bare soil, snow and intercepted water, for which the energy and water balances are solved individually.

The historical simulation uses ECMWF Re-Analysis 5th Generation (ERA5~~reanalysis~~) data (Hersbach et al., 2020) as initial- and lateral boundary conditions. The 2K simulation is a so-called pseudo-global warming ~~(PGW)~~ simulation (e.g. Schär et al., 1996; Attema et al., 2014; Prein et al., 2017; Brogli et al., 2019), which is an alternative method to generate high-resolution climate change information. Instead of downscaling global climate model (GCM) projections, the historical period is re-simulated, but set against a warmer climate background by adding perturbations to the ERA5 initial- and boundary conditions. The perturbations represent the change in the mean climate state in a globally 2K warmer world, derived from a large initial condition GCM ensemble (Aalbers et al., 2018). The method minimizes biases in the mean climate state of the historical simulation, guaranties a realistic atmospheric circulation under both historical and 'future' conditions and increases the signal-to-noise ratio of the climate change response. A full description of the dataset is provided in Aalbers et al. (2021).

3.3 Streamflow

Streamflow data is available for 35 catchments nested within the Meuse basin upstream of Borgharen for the period 2005-2017 (Fig. 1, Service Public de Wallonie, 2018; Banque Hydro, 2018). The streamflow at Borgharen is a constructed time series which sums the observed streamflow of the Meuse at St Pieter and of the Albert Canal at Kanne to represent the total flow from the tributaries before part of it is extracted in the Albert Canal (de Wit et al., 2007).

4 Methods

~~To quantify the importance of reflecting~~ In four scenarios, we evaluate the sensitivity of hydrological model predictions to ecosystem adaptation in ~~hydrological models in~~ response to climate ~~change, the~~ and potential land use change by changing a key vegetation parameter, i.e. the root-zone storage capacity, in a process-based model. Our methodology to estimate how vegetation adapts its root-zone storage capacity to changing climate and land-use conditions requires to estimate future transpiration. The following stepwise approach is designed: (1) we first estimate the long-term runoff coefficient (Q/P) in a 2K warmer world from movements in the Budyko space as a result of a shift in aridity index and a potential shift in dominant land-use~~from broadleaved forests to coniferous plantation and agriculture and vice-versa by trading space-for-time in the Meuse basin; (2)~~; (2) we then use these estimates of projected future runoff coefficients to estimate future evaporative demand E_A by closing the water balance ($E_\mathrm{A}/P = 1 - Q/P$). Based on these values of E_A and future projections of P we then apply a water balance approach to estimate how the root-zone storage capacity adapts ~~in response to a more pronounced seasonality with drier summers and changing dominant land use using the observed historical and estimated long-term runoff coefficient in a 2K warmer world with potential changes in land use;~~ to a changing climate. (3) Next, we calibrate a hydrological model ~~with~~ using the observed historical E-OBS climate data to represent current-day hydrological conditions ~~;~~ and (4) test if the use of the historical climate data simulated by the regional climate model leads to a plausible representation of current-day hydrological conditions~~;~~ . (5) In a next step, we run the hydrological model with the 2K climate data in four scenarios describing (a) a stationary system with historical root-zone storage capacity and historical land-use, (b) an adapted root-zone storage capacity in response to a changing climate but a historical land-use, (c,d) an adapted root-zone storage capacity and a shift in dominant land-use~~; and finally~~ . (6) Finally, we compare the change in hydrological response between the 2K and historical conditions for these four scenarios. An overview of the procedure is summarized in Fig. 2.

4.1 Changing climate, vegetation and land use

4.1.1 ~~Long-term water balance framework for estimating the change in~~ Estimating future runoff ~~coefficient~~coefficients

The long-term partitioning of precipitation (P) into evaporation (E_A) and streamflow (Q) is mainly controlled by the long-term aridity index (ratio of potential evaporation over precipitation, E_P/P), according to the Budyko hypothesis. To account for additional factors that influence the ~~long-term hydrological partitioning~~relation between aridity and the evaporative index E_A/P (and runoff coefficient $Q/P = 1 - E_\mathrm{A}/P$), Fu (1981) introduces a parameter ω to encapsulate the combined influences of climate, soils, vegetation and topography (~~Equation~~ Eq. 1). It should be noted that throughout this manuscript, we use the term evaporation to represent all different evaporative fluxes (interception, soil evaporation and transpiration), following the terminology proposed by Savenije (2004) and Miralles et al. (2020).

$$\frac{E_\mathrm{A}}{P} = 1 - \frac{Q}{P} = 1 + \frac{E_\mathrm{P}}{P} - \left(1 + \left(\frac{E_\mathrm{P}}{P}\right)^{\omega}\right)^{1/\omega} \tag{1}$$

We solve ~~Equation~~ Eq. 1 to determine the value of ω for each of the 35 catchments of the Meuse basin for observed historical conditions for the period 2005 to 2017 (ω_obs), using the meteorological E-OBS data (P_obs and $E_\mathrm{P,obs}$) and observed streamflow (Q_obs). Assuming only a change in long-term mean climate conditions, i.e. aridity index, a catchment will move along its ω_obs-parameterized curve from its original position ~~(~~p_1 ~~)~~ to a new position ~~(~~p_2 ~~)~~ due to the horizontal shift in aridity index ~~$(\Delta E_\mathrm{P}/\Delta P,$~~ $(E_\mathrm{P}/P)_\Delta$ (Fig. 3a). Here, we use the simulated historical and 2K precipitation and potential evaporation climate data to determine how the change in potential evaporation ($\Delta E_\mathrm{P} = E_\mathrm{P,2K} - E_\mathrm{P,hist}$) and precipitation ($\Delta P = P_\mathrm{2K} - P_\mathrm{hist}$) lead to a change in aridity index (~~Equation~~ Eq. 2) and therefore in actual evaporation ($\Delta E_\mathrm{A} = E_\mathrm{A,2K} - E_\mathrm{A,hist}$) and streamflow ($\Delta Q = Q_\mathrm{2K} - Q_\mathrm{obs}$), using ~~Equation~~ the Budyko hypothesis in Eq. 1.

$$\left(\frac{E_\mathrm{P}}{P}\right)_\mathrm{2K} = \frac{E_\mathrm{P,obs} + \Delta E_\mathrm{P}}{P_\mathrm{obs} + \Delta P} \tag{2}$$

However, land cover and vegetation are likely to also change in response to a changing climate, introducing an additional ~~vertical shift ($\Delta\omega$)~~ shift toward a position p_3 on a different ~~ω_change curve~~ curve with ω_change (Fig. 3a). A downward ~~vertical~~ shift from ω_obs to ω_change indicates less water use for evaporation, as opposed to an upward shift for higher evaporative water use. These ~~vertical~~ shifts in ω values represent changes in drivers other than aridity index, including e.g. land cover, tree species, forest age, biomass growth and water use efficiency (Jaramillo et al., 2018).

To test the sensitivity of the hydrological response to a change in ω in addition to a change in aridity index, we consider two scenarios. The catchments with relatively high percentages of broadleaved forests (25-38% as in the French part of the basin) receive the ω values of catchments with relatively low percentages of broadleaved forests (1-12% as mainly in the Belgian Ardennes) and vice-versa (Fig. 1b). We denote $\omega_{\mathrm{broadleaved}}$ for the catchments with relatively high percentages of broadleaved forests and $\omega_{\mathrm{coniferous}}$ for the catchments with relatively low percentages of broadleaved forest, i.e. where broadleaved forests were largely converted to coniferous plantations or agriculture. These scenarios are meant as a sensitivity analysis in the spirit of trading space-for-time (Singh et al., 2011) to evaluate the effect of potential future land-use management on the overall water balance.

When converting broadleaved forest to coniferous plantations, we expect an increase in water use for evaporation and therefore ~~a vertical~~ an upward shift in ω values, as opposed to a downward shift when converting coniferous plantations to more natural broadleaved forests (Fenicia et al., 2009; Teuling et al., 2019; Stephens et al., 2021). The described ~~vertical and horizontal~~ movements in the Budyko space are used to estimate the projected long-term runoff coefficients ($(Q/P)_{\mathrm{2K}}$, ~~Equation~~ Eq. 3) as a result of, both, climate change but no changes in vegetation cover (ω_{obs}), and climate change in combination with changes in vegetation cover (by swapping $\omega_{\mathrm{broadleaved}}$ values to $\omega_{\mathrm{coniferous}}$ for a selection of catchments and vice-versa). The projected runoff coefficients are subsequently used to estimate the long-term projected 2K evaporation E_{A} by closing the water balance, which in turn allows us to estimate projected transpiration E_{R} and changes in the root-zone storage capacity parameter~~(~~, as described in detail in Sect. 4.1.2~~)~~.

$$\left(\frac{Q}{P}\right)_{\mathrm{2K},\omega} = \frac{Q_{\mathrm{obs}}+\Delta Q}{P_{\mathrm{obs}}+\Delta P} = -\left(\left(\frac{E_{\mathrm{P}}}{P}\right)_{\mathrm{2K}} - \left(1+\left(\frac{E_{\mathrm{P}}}{P}\right)^{\omega}_{\mathrm{2K}}\right)^{1/\omega}\right) = 1-\left(\frac{E_{\mathrm{A}}}{P}\right)_{\mathrm{2K},\omega} \tag{3}$$

4.1.2 ~~Seasonal water balance for estimating~~ Estimating the ~~change in~~ root-zone storage capacity $S_{\mathbf{R,max}}$

The root-zone storage capacity represents the maximum volume of water which can be held against gravity in pores of unsaturated soil and which is accessible to roots of vegetation for transpiration. It is a key element controlling the hydrological response of hydrological systems. The long-term partitioning of precipitation into streamflow and evaporation ~~in a changed climate can only match expectations as estimated from movements in the Budyko space (Sect. 4.1.1) if we consider~~ of catchments worldwide plots closely around the Budyko curve suggesting that vegetation has adapted its root-zone storage capacity to offset hydro-climatic seasonality, by creating a buffer large enough to overcome dry spells (Gentine et al., 2012; Donohue et al., 2012; Gao et al., 2014). This is the main assumption underlying the water-balance method to estimate the root-zone storage capacity at the catchment scale ~~(Gao et al., 2014; Nijzink et al., 2016a; de Boer-Euser et al., 2016; Wang-Erlandsson et al., 2016; B~~ (Gao et al., 2014; Nijzink et al., 2016a; de Boer-Euser et al., 2016; Wang-Erlandsson et al., 2016; Bouaziz et al., 2020; Hrachowitz et al.,
.

The water-balance method requires daily time series of precipitation, potential evaporation and a long-term runoff coefficient to estimate transpiration, ~~as it~~ which depletes the root-zone storage during ~~dry spells~~seasonal dry periods. Annual water deficits ($S_{\mathrm{R,def}}$) stored in the root-zone of vegetation to fulfill canopy water demand for transpiration are estimated on a daily time step as the cumulative sum of daily effective precipitation (P_{E}) minus transpiration (E_{R}).

First, effective precipitation, i.e. the amount of precipitation that reaches the soil after interception evaporation (E_{I}), is estimated by solving the water balance of a canopy storage (S_{I}) with maximum interception storage capacity (I_{max}, here taken as 2.0 mm), according to ~~Equation 4.~~ Eq. 4. A value of 2.0 mm for I_{max} was previously also used by de Boer-Euser et al. (2016) and Bouaziz et al. (2020), who also show a low sensitivity of the root-zone storage capacity to the value of I_{max}.

$$P_{\mathrm{E}}(t) = P(t) - E_{\mathrm{I}}(t) - \frac{\mathrm{d}S_{\mathrm{I}}(t)}{\mathrm{d}t} \tag{4}$$

With daily interception evaporation $E_{\mathrm{I}}(t) = \min(E_{\mathrm{P}}(t), S_{\mathrm{I}}(t)/\mathrm{d}t)$ and daily effective precipitation $P_{\mathrm{E}}(t) = \max(0, (S_{\mathrm{I}}(t) - I_{\mathrm{max}})/\mathrm{d}t)$, both in mm d^{-1}.

Next, the long-term historical and projected “future” transpiration $\overline{E}_{\mathrm{R}}$ is estimated from the long-term water balance, using mean annual ~~streamflow~~ historical and projected "future" streamflow, estimated by movements in the Budyko space, and effective precipitation ($\overline{Q}$ and $\overline{P}_{\mathrm{E}}$, all in mm yr^{-1}, ~~Equation~~ Eq. 5), assuming negligible changes in storage and intercatchment groundwater flows (catchments where ~~$\overline{E}_{\mathrm{A}} = \overline{P} - \overline{Q} < \overline{E}_{\mathrm{P}}$~~ $\overline{E}_{\mathrm{A}} = \overline{E}_{\mathrm{I}} + \overline{E}_{\mathrm{R}} = \overline{P} - \overline{Q} < \overline{E}_{\mathrm{P}}$).

$$\overline{E}_{\mathrm{R}} \approx \overline{P}_{\mathrm{E}} - \overline{Q} \tag{5}$$

The long-term transpiration $\overline{E}_{\mathrm{R}}$ is subsequently scaled to daily transpiration estimates E_{R}, using the daily signal of potential evaporation minus interception evaporation, according to ~~Equation~~ Eq. 6 (Nijzink et al., 2016a; Bouaziz et al., 2020).

$$E_{\mathrm{R}}(t) = (E_{\mathrm{P}}(t) - E_{\mathrm{I}}(t)) \cdot \frac{\overline{E}_{\mathrm{R}}}{(\overline{E}_{\mathrm{P}} - \overline{E}_{\mathrm{I}})} \tag{6}$$

The maximum annual storage deficits can then be derived from the cumulative difference of effective precipitation (P_{E}) and transpiration (E_{R}), assuming an "infinite" storage, according to ~~Equation~~ Eq. 7 and illustrated in Fig. 3b. For each year, $S_{\mathrm{R,def}}$ represents the amount of water accessible to the roots of vegetation for transpiration during a dry period. Storage deficits are assumed to be zero at the end of the wet period (T_0, here April) and increase when transpiration exceeds effective precipitation during dry periods, until they become zero again (T_1) in the fall and winter, when excess precipitation is assumed to drain away as direct runoff or recharge.

$$S_{\mathrm{R,def}}(t) = \min \int_{T_0}^{T_1} (P_{\mathrm{E}}(t) - E_{\mathrm{R}}(t))\mathrm{d}t \tag{7}$$

By fitting the ~~annual maximum storage deficits to the~~ extreme value distribution of Gumbel to the series of annual maximum storage deficits, the root-zone storage capacity at the catchment scale $S_{\mathrm{R,max}}$ can be derived for various return periods. ~~Previous studies~~ The Gumbel distribution was previously shown to be a suitable choice for the estimation of the root-zone storage capacity through the water-balance approach by several other studies (Gao et al., 2014; Nijzink et al., 2016a; de Boer-Euser et al., 2016; Bo . These studies used a return period of 20 years for forested areas, ~~meaning~~ suggesting that forests develop root systems to survive droughts with a return period of ∼20 years~~(Nijzink et al., 2016a; de Boer-Euser et al., 2016; ?)~~. The root-zone storage capacity of cropland and grasslands is assumed to correspond to deficits with lower return periods of ∼2 years (Wang-Erlandsson et al., 2016). It should be noted that the methodology assumes that vegetation taps its water from the unsaturated zone and not from the groundwater.

Using the above described methodology, we determine several sets of $S_{\mathrm{R,max}}$ values for each of the 35 catchments of the Meuse basin to represent the historical and adapted root-zone storage capacity in response to a changing climate and changing/historical land-use, using historical climate observations (E-OBS) and the historical and 2K climate simulations~~(Table ??).~~ . Technical details for the calculation of the various $S_{\mathrm{R,max}}$ are given in Sect. 2 of the Supplement.

~~**$S_{\mathrm{R,max,A}}$: Historical root-zone storage capacity from historical land use and observed historical climate**~~

- **$S_{\mathrm{R,max,A}}$: Historical root-zone storage capacity**

  The first set is $S_{\mathrm{R,max,A}}$, which represents the historical meteorological and land-use conditions, derived from observed historical E-OBS data ~~(P_{obs}, $E_{\mathrm{P,obs}}$ for the period 1980-2018)~~ and observed streamflow data (P_{obs}, $E_{\mathrm{P,obs}}$ and Q_{obs} for the period 2005-2017). $S_{\mathrm{R,max,A}}$ is used as parameter for three model runs, each forced with a different dataset: historical E-OBS observations, simulated historical and 2K climate data (Sect. 4.4).

  ~~In this study, we assume that the observed E-OBS historical climate data is the best available estimate of current-day climate conditions and use this data to estimate historical root-zone storage capacities $S_{\mathrm{R,max,A}}$ and to calibrate the hydrological model (Sect. 4.3). The simulated historical climate data is also required to enable a fair comparison with the simulated 2K climate data, as they are both generated with the regional climate model. Despite potential biases in the climate model simulations compared to the observed historical data (here, E-OBS), we do not apply a formal bias-correction of the climate data which may alter the relations between variables in climate models (Ehret et al., 2012). Instead, we force the hydrological model with the native simulated historical climate data, but use the previously determined $S_{\mathrm{R,max,A}}$ parameter. An alternative approach would have been to estimate the root-zone storage capacities using the simulated historical climate data, to directly correct for potential biases in the climate data in the estimation of the root-zone storage capacity parameter but with the downside of affecting spatial patterns across catchments. For comparison, this analysis is performed in Sect. S2 of the Supplement.~~

  ~~**$S_{\mathrm{R,max,B}}$: Adapted root-zone storage capacity from historical land use and 2K climate**~~

- **$S_{\mathrm{R,max,B}}$: Adapted root-zone storage capacity in response to a changing climate**

  We then estimate the root-zone storage capacity $S_{\mathrm{R,max,B}}$ based on the 2K climate and historical land use to reflect ~~vegetation adaptation~~ adaptation of existing vegetation to changing climatic conditions such as differences in seasonality, aridity index (~~Equation~~ Eq. 2) and the resulting runoff coefficient (~~Equation~~ Eq. 3), but under the assumption that the vegetation cover remains unchanged. ~~To account for differences in the observed and simulated historical climate data, $S_{\mathrm{R,max,B}}$ is determined by imposing the difference in storage deficits derived from the 2K and historical climate simulations ($S_{\mathrm{R,def,2K}} - S_{\mathrm{R,def,hist}}$) on the observed storage deficit derived with E-OBS data $S_{\mathrm{R,def,obs}}$, as shown in Table ??.~~

~~**$S_{\mathrm{R,max,C}}$: Adapted root-zone storage capacity from land use conversion to broadleaved forest and 2K climate**~~

- **$S_{\mathrm{R,max,C}}$ and $S_{\mathrm{R,max,D}}$: Adapted root-zone storage capacity in response to a changing climate and land use**

  Subsequently, the root-zone storage capacity is estimated for the 2K climate under two land-use change scenarios, considering that if climate changes, a different vegetation cover might become dominant under natural and anthropogenic influence~~(Table ??). Making use of a space-for-time exchange, we connect the spatially variable ω parameter of the Budyko curve to different land-use categories and use these to evaluate future land-use scenarios. Here, the catchments are categorized according to the areal fraction of broadleaved forest in a catchment (Fig. 1b).~~. In the first scenario, land use in the catchments with mainly coniferous plantations and agriculture (as mainly in the Belgian Ardennes, Sect. 2.2 and Fig. 1) is assumed to be converted to broadleaved forest~~, using sampled $\omega_{\mathrm{broadleaved}}$ values of catchments within the~~. While in the second scenario, the broadleaved forests in the French part of the basin ~~to~~ are converted to coniferous plantations and agriculture. To simulate these land use changes, we first group the ω_{obs} parameter of the Budyko curves of the 35 catchments in three categories according to their areal fraction of broadleaved forest (Fig. 1b). Then, making use of a space-for-time exchange, we randomly sample from ω_{obs} values of one category to represent potential future changes in the other category. In other words, we use ω_{obs} values of catchments with high percentage of broadleaved forest to represent a potential conversion of land use to broadleaved forest in catchments with current-day low percentage of broadleaved forest ($S_{\mathrm{R,max,C}}$) and vice-versa ($S_{\mathrm{R,max,D}}$). These exchanged ω values are used to estimate the 2K runoff coefficient with ~~Equation 3.~~ Eq. 3. We repeat this random sampling several times, which results in several parameter realizations of both $S_{\mathrm{R,max,C}}$ and $S_{\mathrm{R,max,D}}$. The sampling is performed because the variability in ~~ω~~ ω_{obs} values in each category is also influenced by other factors besides the dominant presence of broadleaved forest. ~~The resulting $S_{\mathrm{R,max,C}}$ thus represents an adapted root-zone storage capacity in response to climate change and land-use conversion to broadleaved forest.~~

~~**$S_{\mathrm{R,max,D}}$: Adapted root-zone storage capacity from land use conversion to coniferous plantation and agriculture and 2K climate**~~

~~Similarly, the adapted root-zone storage capacity $S_{\mathrm{R,max,D}}$ is estimated for the 2K climate in a land-use scenario where the broadleaved forest in the French part of the basin are converted to coniferous plantations and agriculture, using sampled $\omega_{\mathrm{coniferous}}$ values of catchments in the Belgian Ardennes.~~

4.2 ~~wflow_FLEX-Topo hydrological~~ Hydrological model

The wflow_FLEX-Topo model (de Boer-Euser, 2017; Schellekens et al., 2020) is a fully distributed process-based model, which uses different flexible model structures for a selection of Hydrological Response Units (HRUs), delineated from the topography and the land use, to represent the spatial variability of hydrological processes. Here, we develop a model with three HRUs for wetlands, hillslopes and plateaus connected through their groundwater storage ~~(schematized in Fig. ?? and model equations in Se~~ (model schematization and equations in Sect. S3 of the Supplement; Savenije, 2010; de Boer-Euser, 2017). Thresholds of 5.9 m for the Height Above the Nearest Drainage (HAND Rennó et al., 2008) and 0.129 for slope are used to delineate the three HRUs~~(Gharari et al., 2011)~~ , as suggested by Gharari et al. (2011), using the MERIT hydro dataset at ∼60 m x 90 m resolution (Yamazaki et al., 2019). ~~Given~~ As additional step, given the high proportion of forest on hillslope and of agriculture on plateau, we here associated hillslope with forest and agriculture with plateau, using the CORINE land cover data (European Environment Agency, 2018). The areal fraction of each HRU are then derived for each cell at the model resolution of 0.00833° (or ∼600 m x 900 m). ~~The model includes snow,~~

The model is forced with precipitation, potential evaporation and temperature. Snow, interception, root-zone, fast and slow storage components ~~.~~ are included in the model. Actual evaporation from the root-zone is linearly reduced when storage is below a certain threshold parameter. This standard formulation to express vegetation water stress (Sect. S3 of the Supplement) is used in many process-based models including NAM, HBV and VHM (Bouaziz et al., 2021). Streamflow is routed through the upscaled river network at the model resolution ~~(?)~~ (Eilander et al., 2021) with the kinematic wave approach. Similar implementations of that model were previously successfully used in a wide variety of environments (e.g. Gharari et al., 2013; Gao et al., 2014; Nijzink et al., 2016b; de Boer-Euser, 2017; Hulsman et al., 2020; Bouaziz et al., 2021).

4.3 Model calibration and evaluation

4.3.1 Calibration and evaluation using the observed historical E-OBS climate data

The wflow_FLEX-Topo model is calibrated using streamflow at Borgharen and the observed historical E-OBS meteorological forcing data for the period 2007-2011, using 2005-2006 as warm-up years. The observed historical E-OBS dataset is used for calibration of the model as it is assumed to most closely represent current-day conditions. The parameter space is explored with a Monte Carlo strategy, sampling 10000 realizations from uniform prior parameter distributions (Sect. S4 of the Supplement). The limited number of samples is due to the high computational resources required to run the distributed model. However, our aim is not to find the "optimal" parameter set, but rather to retain an ensemble of plausible parameter sets based on a multiobjective calibration strategy (Hulsman et al., 2019). To best reflect different aspects of the hydrograph, including high flows, low flows and medium-term partitioning of precipitation into drainage and evaporation, parameter sets are selected based on their ability to simultaneously and adequately represent four objective functions, including the Nash-Sutcliffe efficiencies of streamflow, the logarithm of streamflow and, monthly runoff coefficients as well as the Kling-Gupta efficiency of streamflow. Only parameter sets that exceed a performance threshold of 0.9 for each metric are retained as feasible. The root-zone storage capacity parameter $S_{\mathrm{R,max,A}}$ is a fixed parameter for each subcatchment, which is derived from annual maximum storage deficits with a return period of 2 years for the wetland and plateaus HRUs and 20 years for the hillslopes HRU (Sect. 4.1.2). Next, model performance is evaluated in the 2012-2017 post-calibration period using the same performance metrics, a visual inspection of the hydrographs and the mean monthly streamflow regime. The performance metrics are also evaluated for the 34 remaining nested sub-catchments.

4.3.2 Evaluation using the simulated historical climate data

The performance of the calibrated model for the ensemble of retained parameter sets is also evaluated when the model is forced with the simulated historical climate data, using $S_{\mathrm{R,max,A}}$ for the root-zone storage capacity parameter. This is the reference historical run against which the relative effect of 2K global warming is evaluated for different scenarios to enable a fair comparison (Fig. 2 and Sect. 4.4). In addition, in Sect. ~~S2~~ S5 of the Supplement, we evaluate the performance of the calibrated model forced with the simulated historical climate data but with a root-zone storage capacity parameter derived directly from this data. ~~While this alternative approach enables to correct for potential biases in the simulated historical climate data directly in the estimation of the root-zone storage capacity parameter, it may also affect the spatial patterns of this parameter across catchments.~~

4.4 Hydrological change evaluation

We then force the calibrated wflow_FLEX-Topo model for the ensemble of retained parameter sets with the same 2K climate forcing data in four scenarios each using a different root-zone storage capacity parameter to represent either stationary or adapted conditions in response to a changing climate and land use (Fig. 2 and Sect. 4.1.2). The difference between the modelled historical hydrological response (1980-2018) and the hydrological responses predicted by each of the four model scenarios based on the 2K climate is evaluated in terms of runoff coefficient, evaporative index, annual statistics (runoff coefficient, evaporative index, mean, maximum, minimum 7-days streamflow and median ~~volume deficit~~ annual sum of streamflow below the 90$^{\mathrm{th}}$ percentile ~~reference~~ historical streamflow), and monthly patterns of flux and state variables (streamflow, evaporation, root-zone storage, groundwater storage) for a hypothetical 38-year period. The four scenarios, which each use $S_{\mathrm{R,max,A}}$ as root-zone storage capacity in the historical run, as shown in Fig. 2, are listed below.

~~**Scenario 2K$_{\mathrm{A}}$: Historical land use and historical root-zone storage capacity ($S_{\mathrm{R,max,A}}$)**~~

- **Scenario 2K$_{\mathrm{A}}$: stationarity**
  In scenario 2K$_{\mathrm{A}}$ ~~(Fig. 2)~~, we assume an unchanged land use and that vegetation has not adapted its root-zone storage capacity to the aridity and seasonality of the 2K climate. This scenario implies stationarity of model parameters by using

$S_{\mathrm{R,max,A}}$ in both the historical and 2K runs, a common assumption of many climate change impact assessment studies ~~(Booij, 2005; de Wit et al., 2007; Prudhomme et al., 2014; Hakala et al., 2019; Brunner et al., 2019; Gao et al., 2020; Rottler et al., 2~~ (Booij, 2005; de Wit et al., 2007; Prudhomme et al., 2014; Hakala et al., 2019; Brunner et al., 2019; Gao et al., 2020; Rottler et al., 2 . This is the benchmark scenario against which we compare the hydrological response considering non-stationarity of the system, as in the following three scenarios.

~~**Scenario 2K$_{\mathrm{B}}$: Historical land use and 2K climate adapted root-zone storage capacity ($S_{\mathrm{R,max,B}}$)**~~

- **Scenario 2K$_{\mathrm{B}}$: non-stationarity of the root-zone storage capacity in response to a changing climate**

In scenario 2K$_{\mathrm{B}}$~~(Fig. 2)~~, we again assume an unchanged land use (ω_{obs}). However, we assume that vegetation has adapted its root-zone storage capacity to the aridity and seasonality of the 2K climate conditions by selecting $S_{\mathrm{R,max,B}}$ as parameter for the 2K model run~~, while the historical $S_{\mathrm{R,max,A}}$ is used as parameter in the historical run~~.

~~**Scenario 2K$_{\mathrm{C}}$: Land-use conversion to broadleaved forest and 2K climate adapted root-zone storage capacity ($S_{\mathrm{R,max,C}}$)**~~

- **Scenario 2K$_{\mathrm{C}}$: non-stationarity of the root-zone storage capacity in response to a changing climate and land-use conversion to broadleaved forest**

In scenario 2K$_{\mathrm{C}}$~~(Fig. 2), we adapt~~ , we use the root-zone storage capacity ~~to~~ $S_{\mathrm{R,max,C}}$ to reflect adaptation in response to the changing aridity index and seasonality of the 2K climate ~~. Additionally, we assume a change~~ and changes in vegetation cover for the catchments located mainly in the Belgian Ardennes and dominated by coniferous plantation and agriculture to a land use of broadleaved forest as in the French part of the basin. ~~For this purpose, $S_{\mathrm{R,max,C}}$ is used as parameter in the model run forced with the 2K climate, while $S_{\mathrm{R,max,A}}$ is used as parameter in the historical run.~~

~~**Scenario 2K$_{\mathrm{D}}$: Land-use conversion to coniferous plantation and agriculture and 2K climate adapted root-zone storage capacity ($S_{\mathrm{R,max,D}}$)**~~

- **Scenario 2K$_{\mathrm{D}}$: non-stationarity of the root-zone storage capacity in response to a changing climate and land-use conversion to coniferous plantation and agriculture**

In scenario 2K$_{\mathrm{D}}$~~(Fig. 2)~~, the approach of scenario 2K$_{\mathrm{C}}$ is repeated. However, now the broadleaved forest in the French catchments are assumed to be converted to coniferous plantations or agriculture as in the Belgian Ardennes. The parameter $S_{\mathrm{R,max,D}}$ is used in the model run forced with the 2K climate~~, while $S_{\mathrm{R,max,A}}$ is used in the historical run.~~ .

5 Results

5.1 Adapted root-zone storage capacity $S_{\mathrm{R,max}}$~~from long-term and seasonal water balances and changing land use~~

5.1.1 Long-term water balance characteristics across catchments

In solving the parametric Budyko curve (~~Equation~~ Eq. 1) for the 35 catchments of the Meuse basin using historical E-OBS data and observed streamflow (Fig. 4a), we found that ω_{obs} values tend to be lower~~(median~~ , with a median and standard deviation (subsequent values in next sections represent the same variables) of 2.43 $\pm$ 0.48~~)~~ , for catchments with relatively high percentages of broadleaved forests (25-38 % as in the French part of the basin) as compared to catchments with relatively low percentages of broadleaved forests (1-12 % as in the Belgian part of the catchment) with ~~median ω~~ ω_{obs} values of 3.04 $\pm$ 0.54, as shown in Fig. 4b. Higher values of ω for a same aridity index indicate more water use for evaporation, which is likely related to the increased water use of relatively young coniferous plantations and agriculture as opposed to older broadleaved forests (Fenicia et al., 2009; Teuling et al., 2019).

5.1.2 $S_{\mathrm{R,max,A}}$ ~~from historical land use and historical climate~~Historical root-zone storage capacity

The root-zone storage capacity $S_{\mathrm{R,max,A}}$ derived with observed historical E-OBS climate data and observed streamflow is estimated at values of ~~101~~100 $\pm$ 17 mm and 169 $\pm$ 24 mm across all study catchments for ~~a~~ 2 ~~year~~ and 20 ~~year return period~~years return periods, respectively (Fig. 4c).

~~If instead the simulated historical climate data is used to derive the root-zone storage capacity, this results in slightly higher values with 110 $\pm$ 18 mm and 180 $\pm$ 28 mm for 2 and 20 year return periods, respectively. This overestimation of about +7 % is due to the higher precipitation (on average +9 %) in the simulated historical climate data compared to the observed E-OBS historical data, which leads to relatively lower runoff coefficients and therefore larger evaporative indices and storage deficits in the water balance calculation of the root-zone storage capacity (Sect. S2 of the Supplement).~~

5.1.3 $S_{\mathrm{R,max,B}}$ ~~from historical land use and 2K~~ Adapted root-zone storage capacity in response to a changing climate

The adapted root-zone storage capacity $S_{\mathrm{R,max,B}}$, in response to changing climate conditions and an unchanged land use, strongly increases with respect to historical conditions ($S_{\mathrm{R,max,A}}$) with estimated values of ~~129~~127 $\pm$ 18 mm (+~~28~~27 %) and ~~227~~226 $\pm$ 27 mm (+34 %) for return periods of 2 ~~year~~ and 20 ~~year~~years, respectively (Fig. 4c). This strong increase is explained by larger storage deficits during summer due to an increase of about +10 % in summer potential evaporation in the 2K climate and, therefore, a more pronounced seasonality (Fig. 3b). In contrast, the change in aridity index between the historical and 2K climate simulations is relatively small with a median of +0.01 across all study catchments. This can be explained by a simultaneous increase in mean annual precipitation (+~~5~~4 %) and potential evaporation (+7 %) on average over the basin area in the 2K climate compared to the simulated historical climate data. This increase in precipitation mostly occurs during the winter half year (Nov-Apr). In contrast, there is a relatively large variability in precipitation change in summer, characterized by years with wetter and drier summers.

5.1.4 $S_{\mathrm{R,max,C}}$ ~~from 2K~~ Adapted root-zone storage capacity in response to a changing climate and ~~adapted~~ land use conversion to broadleaved forest

The adapted root-zone storage capacity $S_{\mathrm{R,max,C}}$, in response to changing climate conditions and a land use conversion from coniferous plantation and agriculture to broadleaved forest, results in estimated values of ~~125~~123 $\pm$ 17 mm and ~~219~~216 $\pm$ 27 mm for return periods of 2 ~~year~~ and 20 ~~year~~years, respectively (Fig. 4c). These values are ~~almost~~ similar to $S_{\mathrm{R,max,B}}$, with a difference of about ~~-3~~-4 %. This small decrease is in line with the expected reduced water use of broadleaved forests compared to coniferous plantations.

5.1.5 $S_{\mathrm{R,max,D}}$ ~~from 2K~~ Adapted root-zone storage capacity in response to a changing climate and ~~adapted~~ land use conversion to coniferous ~~plantations~~ plantation and agriculture

In contrast, the root-zone storage capacity $S_{\mathrm{R,max,D}}$, in response to changing climate conditions and a conversion of broadleaved forest to coniferous plantation, result in estimated values of ~~140~~137 $\pm$ 22 mm and ~~243~~235 $\pm$ 35 mm for return periods of 2 ~~year~~ and 20 ~~year~~years, respectively (Fig. 4c). This corresponds to an additional increase of +~~9~~8 % and +~~7~~4 % for both return periods in comparison with $S_{\mathrm{R,max,B}}$, which does not consider additional land-use changes.

~~The difference~~ Therefore, the increase in root-zone storage capacity between the 2K and historical climate simulations ~~as a result of a changing climate (aridity and seasonality) is larger (~~can, here with +~~58~~57 mm or +34 % for a return period of 20 years~~) than the difference between root-zone storage capacity for~~, be mostly attributed to a changing climate ~~and additional~~ (aridity and seasonality) than to changes in land use (~~-8~~-10 mm or ~~-3~~-4 % for $S_{\mathrm{R,max,C}}$ and +~~16~~9 mm or +~~7~~4 % for $S_{\mathrm{R,max,D}}$). This indicates that with the assumed land-use change in scenarios $2\mathrm{K_C}$ and $2\mathrm{K_D}$, the strong increase in water demand during summer as a result of a more pronounced seasonality has greater impact on the estimation of the root-zone storage capacity than a change in ω values. However, note that land use is changed in only part of the catchment for both land use change scenarios and that it is plausible to assume that more pronounced changes in land use will reinforce the observed effects.

5.2 Model evaluation (historical period)

5.2.1 Model forced with observed historical climate data

The modeled streamflow obtained using the ensemble of parameter sets retained as feasible after calibration mimics the observed hydrograph at Borgharen ~~relatively~~ reasonably well for the evaluation period (Fig. 5a). Also the seasonal streamflow regime is ~~relatively~~ well reproduced by the model, except for ~~a slight underestimation of about~~ an underestimation of -9 % in the first half year (Fig. 5b). The four objective functions show a relatively similar performance during calibration and evaluation with median values of ~~approximately~~ 0.93 and 0.78 at Borgharen and for the ensemble of ~~nested catchments~~ 34 additional not individually calibrated nested subcatchments of the Meuse, respectively (Fig. 6a,~~b~~c).

5.2.2 Model forced with simulated historical climate data

When the calibrated model is instead forced with the simulated historical climate data, peaks are slightly overestimated in comparison to the model run forced with the observed historical E-OBS data (Fig. 5c). This is due to the on average +9 % overestimation of precipitation in the simulated historical climate data compared to the observed historical E-OBS climate data. This precipitation overestimation results in an overestimation of about +12 % of modeled mean monthly streamflow during the ~~wettest~~ wet December and January months (Fig. 5d). ~~The~~ However, flows in spring and early summer are better captured when using the simulated historical climate data instead of historical E-OBS data (Fig. 5d). Overall, the streamflow model performance at Borgharen slightly decreases when the simulated historical climate data is used instead of E-OBS, but median values across the ensemble of feasible parameter sets are still above 0.77 for each of the objective functions (Fig. 6~~c~~b). Although a decrease in model performance is found in a few nested catchments, the performance in the ensemble of nested catchments of the Meuse remains ~~relatively high with~~ at median values of around 0.67 (Fig. 6d). The results of the model run forced with the simulated historical data and with the root-zone storage capacity parameter derived directly from this data show a relatively similar behavior, as further detailed in Sect. ~~S2~~ S5 of the Supplement.

The calibrated model forced with the simulated historical climate data shows a plausible behavior with respect to observed streamflow and is also reasonably close to the performance achieved with the observed historical E-OBS climate data. This is important because the effect of the 2K climate on the hydrological response is evaluated with respect to the model run forced with the simulated historical climate data, as they are both generated with the regional climate model. Therefore, the relatively high model performance in the evaluation period ~~enable~~ enables us to use the retained parameter sets from the calibration with E-OBS data for the subsequent analyses with the simulated historical and 2K climate data.

5.3 Hydrological change evaluation (2K warmer climate)

5.3.1 Scenario $2K_A$: ~~Stationarity with historical land use and historical root-zone storage capacity ($S_{R,max,A}$)~~ stationarity

In the $2K_A$ scenario, representing a stationary system with identical parameters in the historical and 2K climate, runoff coefficients are projected to increase with a median of +3 %, the evaporative index (E_A/P) decreases with a median of -2 % and mean annual streamflow increases with a median of +7 %. Maximum annual streamflow is also projected to increase with a median of about +5 %, while the median change in annual minimum of 7-days mean streamflow remains close to zero. The median annual ~~deficit volume~~ sum of streamflow below the 90^{th} percentile historical streamflow increases with +10 %, as shown in Fig. 7.

~~Streamflow~~ From the intra-annual perspective, streamflow is projected to increase from December until August with +8 % ~~and decrease~~ on average and decreases between September and November with -7 % ~~.~~ (Fig. 8a). In the months where evaporation demand exceeds precipitation, the root-zone soil moisture decreases, with a maximum of -22 % in September ~~.~~ (Fig. 8b). Actual evaporation increases throughout the year with around +3 % on average except in July and August (-4 %) when the availability of water in the root-zone of vegetation is not sufficient to supply canopy water demand ~~. Recharge to the~~ (Fig. 8c). The groundwater storage increases with approximately +5 % in all months except November, as shown in Fig. 8d.

5.3.2 Scenario 2K$_{\mathrm{B}}$: ~~Historical land use and adapted~~ non-stationarity of the root-zone storage capacity ~~($S_{\mathrm{R,max,B}}$)~~in response to a changing climate

Changes are substantially different in the 2K$_{\mathrm{B}}$ scenario which considers that the root-zone storage capacity of vegetation has adapted to the change in aridity and seasonality of the 2K climate. ~~Runoff coefficients are instead~~ In contrast to scenario 2K$_{\mathrm{A}}$, runoff coefficients are projected to decrease with a median of -2 %, while the evaporative index increases with a median of +2 % and the median change of mean annual streamflow is close to zero (Fig. 7). ~~Also~~ Similarly, the median change of, both, annual maximum streamflow and minimum 7-days mean streamflow remain close to zero. However, there is a substantial increase of +38 % in ~~median annual deficit volume~~ the median annual sum of streamflow below the 90$^{\mathrm{th}}$ percentile historical streamflow. This result suggests that while the minimum streamflow remains relatively similar, the length of the low flow period strongly increases ~~if we consider that~~ when considering an adaptation of the root-zone storage capacity ~~has adapted~~ to the 2K climate (Fig. 7).

Seasonal changes indicate a decrease in streamflow of -19% between September and November, which is longer and considerably more pronounced than in the 2K$_{\mathrm{A}}$ scenario (Fig. 8a). The root-zone soil moisture increases throughout the year with an average of +34 % due to the larger root-zone storage capacities ~~.~~ (Fig. 8b). Actual evaporation is no longer reduced as a result of moisture stress in the root-zone that has adapted to a changing climate and strongly increases with on average approximately +7 % from May to October to supply canopy water demand ~~. The increase in evaporation during summer~~ (Fig. 8c). However, the considerable increase in spring and summer evaporation strongly reduces the groundwater ~~recharge~~ storage with -5 % from October to February (Fig. 8d).

5.3.3 Scenario 2K$_{\mathrm{C}}$: ~~Land-use~~ non-stationarity of the root-zone storage capacity in response to a changing climate and land-use conversion to broadleaved forest~~and adapted root-zone storage capacity ($S_{\mathrm{R,max,C}}$)~~

The predicted hydrological response in the 2K$_{\mathrm{C}}$ scenario is very similar to the response of the 2K$_{\mathrm{B}}$ scenario, despite considering additional changes in the root-zone storage capacity as a result of a land-use conversion from coniferous plantations and agriculture to broadleaved forest (Figs. 7 and 8). This is in line with the limited differences in root-zone storage capacities of ~~approximately~~ around only +~~3~~4 % between both scenarios (Sect. 5.1).

5.3.4 Scenario 2K$_{\mathrm{D}}$: ~~Land-use~~ non-stationarity of the root-zone storage capacity in response to a changing climate and land-use conversion to coniferous ~~plantations~~ plantation and agriculture~~and adapted root-zone storage capacity ($S_{\mathrm{R,max,D}}$)~~

In contrast, the change in hydrological response is most pronounced for the scenario $S_{\mathrm{R,max,D}}$, which considers land use conversion of the broadleaved forests in the French part of the basin to coniferous plantations and agriculture (Figs. 7 and

8). Runoff coefficients decrease with a median of -4 %, while the evaporative index increases with a median value of +4 % and mean annual streamflow decreases with a median of -2 %~~.~~, as opposed to a +5 % increase in the stationary $2K_A$ scenario (Fig. 7a,b,c). If the median change in streamflow extremes remains relatively close to zero, there is a strong increase of +54 % in the median annual ~~deficit volume~~sum of streamflow below the 90th percentile historical streamflow, suggesting a strong increase in the length of the low flow period (Fig. 7d,e,f).

Streamflow decreases from August to January with an average of -23 % and evaporation strongly increases from May to October with an average of +9 %. This increased evaporation during summer further reduces ~~recharge~~ the groundwater storage from October to February with -7 % (Fig. 8). In comparison with the hydrological response of scenario $2K_B$, the additional land-use conversion in scenario $2K_D$ results in relatively similar patterns of change but with an additional +2 % increase in evaporation, -2 % decrease in streamflow and -2 % decrease in ~~recharge~~ groundwater storage on average throughout the year.

5.3.5 Stationary versus adaptive ecosystems

There is a difference of up to -7 % in the change of mean annual streamflow between the stationary scenario $2K_A$ and the scenarios $2K_B$, $2K_C$, $2K_D$ with adaptive ecosystems ~~and the stationary $2K_A$ scenario.~~(Fig. 7c). Additionally, the scenarios with adaptive ecosystems show a substantially more pronounced decrease in streamflow from September to January and a delay in the occurrence of the lowest streamflow from September to October ~~. The change in mean annual actual evaporation is approximately~~ (Fig. 8a). Associated to these seasonal differences in streamflow, the scenarios with adaptive ecosystems are characterized by summer evaporation that is up to +14 % higher and a mean annual evaporation that is around +4 % higher ~~in the scenarios with adaptive ecosystems and the increase mainly occurs between May and October.~~than in the stationary scenario (Fig. 8c). Instead of a year-round increase in ~~recharge~~ groundwater storage in the $2K_A$ scenario, there is a decrease in winter ~~recharge~~ groundwater storage in the three other scenarios, resulting in a mean annual difference of -6 % between the scenarios with ecosystem adaption and the stationary scenario $2K_A$~~. Hence,~~, expressed as constant model parameters (Fig. 8d). Overall these results suggest that the hydrological response in the 2K climate of the stationary scenario $2K_A$ is substantially different from the responses of the three scenarios $2K_B$, $2K_C$, $2K_D$, which consider a change in the root-zone storage capacity to reflect ecosystem adaptation in response to climate change.

6 Discussion

6.1 Implications

Current practice in many climate change assessment studies is to assume unchanged system properties in the future (benchmark scenario $2K_A$ in our analysis), thereby neglecting potential changes in the system, such as adaption of vegetation to local climate conditions. In addition to this scenario, we suggest a possible approach to consider ecosystem adaptation in response to climate change and test the sensitivity in the resulting hydrological response. Our analysis is, therefore, a first step in evaluating what may happen if we consider ecosystem adaptation in response to climate change in hydrological model predictions. The hydrological response under 2K global warming ~~with respect~~ compared to historical conditions shows distinct patterns of change if we explicitly consider the non-stationarity of climate-vegetation interactions in a process-based hydrological model. ~~We implement a dynamic root-zone storage capacity parameter, which is directly inferred from long-term and seasonal water balances of historical observations in combination with simulated historical and future climate conditions.~~ More specifically, in the non-stationary scenarios, there is an up to -15 % and -10 % stronger decrease in streamflow and groundwater storage respectively after summer due to an up to +14 % stronger increase in actual evaporation during the warmer summers, compared to the stationary scenario.

Our method is based on readily available data and is therefore widely applicable. The choice of hydrological model is open as root-zone storage capacity estimates derived from the water-balance approach are applicable in various hydrological and land surface models, provided that they include a root-zone parameterization, which is the case for most models (Clark et al., 2008; Nijzink et al. . The water-balance approach to estimate the root-zone storage capacity has previously successfully been applied in a variety of climate zones and across various ecosystems (Donohue et al., 2012; Gentine et al., 2012; Gao et al., 2014; Wang-Erlandsson et al., 2016; d . Here, the estimated values of the root-zone storage capacity for the different scenarios have median values below 250 mm for a return period of 20 years, which is within the range of global root-zone storage capacity values estimated by Wang-Erlandsson et al. (2016).

A time-dynamic parameterization of the root-zone storage capacity in the context of deforestation was previously introduced by Nijzink et al. (2016a) and Hrachowitz et al. (2021), who demonstrated that an observed 20 % increase of the runoff coefficient in a catchment can to a large part be attributed to the > 20 % reduction of root zone storage capacity after deforestation. Speich et al. (2020) implemented a time-dynamic root-zone storage capacity in the ~~context of deforestation, while it was implemented by Speich et al. (2020) in the~~ context of climate change. In ~~the latter~~ their study, forest growth in response to climate change leads to a six times higher reduction of streamflow if a dynamic representation of, both, the Leaf Area Index and the root-zone storage capacity is implemented as opposed to a study in which only the Leaf Area Index varies (Schattan et al., 2013). ~~These~~ Although these results are more pronounced than our findings~~but point towards~~ , they point into the same direction of change. As the future is unknown, we cannot test our results against observations, but given the changes in temperature and precipitation, the future predicted hydrological response does not seem implausible. While Speich et al. (2020) combine a forest landscape model with a hydrological model to simultaneously represent the spatio-temporal forest and water balance dynamics, we rely on a simpler approach of movements in the Budyko framework to include potential land-use change.

The ~~concept of trading space-for-time, which uses space as a proxy for time (Singh et al., 2011) could be further explored by selecting a region outside the Meuse basin with a current climate similar to the projected climate. This approach is also commonly referred to as climate-analogue mapping, i.e. statistical techniques to quantify the similarity between the future climate of a given location and the current climate of another location (Rohat et al., 2018; Bastin et al., 2019; Fitzpatrick and Dunn, 2019) . Finding a climate analogue for future projections in present conditions, may allow us to estimate future ω or root-zone storage capacity values in a region where the future climate may resemble today's climate elsewhere.~~

~~These methods are intuitive but not straightforward, as they rely on the selection and combination of relevant climate variables and their relation with vegetation, despite non-linear vegetation responses to climate change (Reu et al., 2014).~~

~~In comparing several scenarios for the root-zone storage capacity parameter, we include some form of system representation uncertainty, which improves our understanding in the modeled changes by placing them in a broader context (Blöschl and Montanari, 2010). Actual evaporation in the study catchments is projected to decrease if the historical root-zone storage capacity is used as a result of moisture stress in the root-zone of vegetation. In contrast, the increased water demand during summer is met when we assume that vegetation has adapted its root-zone storage capacity. This is an indication of disagreements among model representations on processes that become relevant in the future, in line with findings of Magand et al. (2015); Melsen and Guse (2020).~~

~~The~~ impact of climate change on low flows in the Meuse basin has been previously studied by de Wit et al. (2007). Using simulations from regional climate models which project wetter winters and drier summers, they question if the increase in winter precipitation reduces the occurrence of summer low flows due to an increase in groundwater recharge. However, they were unable to address this question with their model due to its poor low-flow performance. Our results indicate an increase in groundwater ~~recharge during winter if the historical root-zone storage capacity parameter is used~~storage during winter in the stationary scenario, as opposed to a decrease for the models with a time dynamic root-zone storage capacity, as a result of an increased water demand for evaporation during summer. ~~This further emphasizes the major impact of vegetation in regulating the water cycle (Luo et al., 2020; Wang et al., 2020; Stephens et al., 2021)~~In comparing several scenarios for the root-zone storage capacity parameter, we include some form of system representation uncertainty, which improves our understanding in the modeled changes by placing them in a broader context (Blöschl and Montanari, 2010).

The ~~land surface scheme HTESSEL, that is used in the regional climate model RACMO2 to generate the historical and 2K climate simulations, assumes, as most land surface models, a fixed~~ conversion to native species may increase biodiversity and the resilience of ecosystems to climate change (Schelhaas et al., 2003; Klingen, 2017; Levia et al., 2020). However, these processes are slow, implying that current management practices shape the forests of decades and centuries to come in an uncertain future. Increasing our understanding on how to include vegetation changes in hydrological models to reliably quantify their impact is a way forward in the development of strategies to mitigate the adverse effects of climate change.

6.2 Limitations and knowledge gaps

6.2.1 On the estimation of adapted root-zone storage capacities

The proposed methodology to estimate future root-zone storage ~~capacity. Ideally, this discrepancy between~~ capacities relies on the underlying assumption that past empirical relations between aridity index and evaporative index (i.e. the Budyko framework) still apply in the future. While the Budyko framework is a well-established concept, recent studies by Berghuijs et al. (2020) and Reaver et al. (2020) show that it should be cautiously applied in changing systems. The Budyko framework reflects the long-term hydrological partitioning under dynamic equilibrium conditions. Therefore, when using the Budyko framework to estimate the future rate of transpiration, we assume that the future vegetation has adapted to the ~~land surface model and the~~

~~hydrological model could be reduced by updating the adapted root-zone storage capacity from one model to the other in several iteration steps, thereby including soil moisture - atmosphere feedback mechanisms.~~

6.3 ~~Limitations and knowledge gaps~~

~~Our study relies on the assumption~~ future climatic conditions and that it is in a state of dynamic equilibrium. The uncertainty of this assumption is considerable because it implies that vegetation has had the time to adapt ~~its root-zone storage capacity in a changing climate.~~ to the rapidly changing environmental conditions. There is increasing evidence that vegetation will eventually adapt to ensure sufficient access to water (Guswa, 2008; Schymanski et al., 2008; Gentine et al., 2012); otherwise, we would not see the hydrological partitioning of catchments around the world broadly plotting along the Budyko curve (Troch et al., 2013). Yet, considering the unprecedented scale and rate of change (Gleeson et al., 2020), it is unclear how ecosystems will cope with climate change, also considering the impact of ~~storms~~potentially increasing storm intensities and frequencies, heatwaves, fires and biotic infestations as a result of water stress on forest ecosystems (Lebourgeois and Mérian, 2011; Allen et al., 2010; Latte et al., 2017; Stephens et al., 2021). ~~Additionally, when exposed to different environmental conditions, ecosystems may adapt their behavior by reducing or increasing their water use to the water availability (Zhang et al., 2020). Similarly, direct human interventions, such as the conversion of natural forests to fast-growing monoculture plantations in many parts of the world has significantly altered forests, making them more susceptible and vulnerable to disturbances (Schelhaas et al., 2003; Levia et al., 2020).However, humans also have the ability to positively influence the water cycle through vegetation, by promoting sustainable agricultural practices and integrated forest management with a simultaneous focus on biodiversity, recreation and timber production. Additionally, the conversion of exotic to native species may also increase biodiversity and the resilience of ecosystems to climate change (Klingen, 2017). However, these processes are slow, implying that current management practices shape the forests of decades and centuries to come in an uncertain future. Increasing our understanding on how to include these changes in hydrological models to reliably quantify their impact is a way forward in~~ In particular, there is considerable uncertainty on how long it will take for vegetation to adapt and how it will adapt, assuming thresholds of adaptability are not exceeded.

In this analysis, we did not explicitly consider that vegetation can adapt to drier conditions by regulating its stomata and hence reduce transpiration. Furthermore, there is evidence that increasing atmospheric CO_2 concentrations may increase both, water use efficiency but also increase green foliage due to fertilization effects (Keenan et al., 2013; Donohue et al., 2013; van der Velde et al., 201 . While the adaptation strategies of individual plants, e.g. root biomass adjustments, anatomical alterations and physiological acclimatisation, depend on vegetation type and species (Brunner et al., 2015; Zhang et al., 2020), here, we determine effective values of the ~~development of strategies to mitigate the adverse effects of climate change~~root-zone storage capacity at the catchment scale to reflect the adaptation of the whole ecosystem. Yet, our ability to predict what will happen is limited, but we can at least test the sensitivity of the hydrological response to changes in the system representation.

Once future transpiration rates are estimated, also the water-balance approach to estimate the root-zone storage capacity is subject to limitations. The method is not suitable in areas where the water table is very close to the surface and where vegetation directly can tap from the available groundwater instead of creating a buffer capacity (e.g Fan et al., 2017). Another limitation of the water-balance approach relates to Eq. 6, in which we scale the daily transpiration estimates with a constant factor to the patterns of potential evaporation minus interception evaporation, implying that vegetation can extract water for transpiration from dry soils as easily as from wet soils.

6.2.1 On the potential land-use change scenarios

We quantify the changes in the hydrological response as a result of a changing climate in combination with several land use scenarios (historical, conversion of broadleaved forests to coniferous plantations and agriculture and vice-versa). The relatively limited additional effects of land-use change on the hydrological response should be understood in the context of the relatively limited areal fraction under potential land-use conversion.

The land-use changes are integrated in the root-zone storage capacity as single parameter. However, climate and land use changes likely affect other aspects of catchment functioning~~(Seibert and van Meerveld, 2016).For example, changes~~ , e.g. interception, infiltration and runoff generation (Seibert and van Meerveld, 2016). Changes in the maximum interception storage capacity (Calder et al., 2003) are not explicitly considered in the estimation of the adapted root-zone storage capacities in the land-use change scenarios, as the impact was shown to be relatively minor in Bouaziz et al. (2020). Additional effects of soil compaction and artificial drainage on peak flows as a result of potential future land conversion (Buytaert and Beven, 2009; Seibert and van Meerveld, 2016) are difficult to quantify but may partly be captured in the changed ω values. As mutual interactions between parameters remain problematic to quantify, we use an ensemble of parameter sets to somehow account for the uncertainty in model parameters and the possibility that parameters compensate for each other due to simplistic process representation.

~~In a first step towards temporally adaptive models, and trading space-for-time for different~~ In the potential land-use change scenarios, we did not ~~consider any additional vertical movements in the Budyko space due to~~ change the percentages of each HRU in our model structure. The top-down approach to estimate the effect of land-use change does not provide the level of detail required to specifically change land-use type at the pixel level. In addition, the same climate forcing was used in each of the ~~effects of increasing CO_2 levels in terms of increased productivity through fertilization, on the one hand, or water use efficiency on the other hand (Keenan et al., 2013; van der Velde et al., 2014; van Der Sleen et al., 2015; Ukkola et al., 2016; Jaramillo et al~~ ~~, as these effects remain problematic to quantify in a meaningful way . Neither did we, for the same reason,~~ 2K scenarios, implying that we did not change potential evaporation as a result of potential land-use changes.

While ω-values are likely a manifestation of multiple climatic, landscape and vegetation characteristics, we assumed that vegetation type is the dominant control to explain differences in ω-values. As this parameter describes the hydrological partitioning and because transpiration is a major continental flux (Jasechko, 2018; Teuling et al., 2019), it is reasonable to assume that the variability in ω-values is largely controlled by the water volume accessible to the roots of vegetation for transpiration (i.e. $S_{\mathrm{R,max}}$). This root-accessible water volume is independent from the soil type, as root systems will develop in a way to ensure sufficient access to water. In clayey soils, the rooting depth might be shallower than in sandy soils for an identical root-zone storage capacity. Topography, geology and soil type are likely implicitly integrated in other model parameters, e.g. the various recession time-scales of the linear reservoirs, which represent subsurface flow resistance throughout the system.

We also did not consider how the relatively high ω values may be related to intercatchment groundwater losses (Bouaziz et al., 2018). Note that as our analyses should be understood in the context of a sensitivity ~~analyses~~ analysis of the impact of potential additional vertical shifts in the Budyko space as a result of a changing land use (Fig. 3), the potential effects on groundwater losses on the results are likely to be minor.

~~In addition~~

6.2.2 On the calibration

Lastly, we performed a limited calibration of the hydrological model to retain an ensemble of plausible solutions and only used a single climate simulation despite the uncertainty in initial and boundary conditions of regional climate models. Our analyses are intended as a ~~proof-of-concept to introduce a top-down methodology to quantify~~ sensitivity analysis to quantify the effect of non-stationarity of the root-zone storage capacity parameter on hydrological model predictions through optimal use of projected climate data, rather than a comprehensive climate change impact assessment of the Meuse basin.

6.3 Outlook

6.3.1 Applications in land surface and ecohydrological models

The land surface scheme HTESSEL, that is used in the regional climate model RACMO2 to generate the historical and 2K climate simulations, assumes, as most land surface models, a fixed root-zone storage capacity over time. Ideally, this discrepancy between the land surface model and the non-stationary hydrological models could be reduced by updating the adapted root-zone storage capacity from one model to the other in several iteration steps, thereby including soil moisture - atmosphere feedback mechanisms. The implementation of the root-zone storage capacity parameter estimated from water-balance data in land surface models is, however, not trivial and requires further research (van Oorschot et al., 2021). Accounting for this climate control on root development and root-zone parameterization in ecohydrological model could potentially also be very interesting, as rooting depth and root distributions estimates are often estimated from fixed look-up tables (Tietjen et al., 2017; Schaphoff et al., 2018).

6.3.2 Climate analogues or trading space-for-time

The concept of trading space-for-time, which uses space as a proxy for time (Singh et al., 2011) could be further explored by selecting regions outside the Meuse basin with a current climate similar to the projected climate. This approach is also commonly referred to as climate-analogue mapping, i.e. statistical techniques to quantify the similarity between the future climate of a given location and the current climate of another location (Rohat et al., 2018; Bastin et al., 2019; Fitzpatrick and Dunn, 2019) . This climate matching could be applied over distant regions, using datasets which combine landscape and climatological data over large samples of catchments (e.g. the various Catchment Attributes and Meteorology for Large-sample Studies (CAMELS) datasets, A

. Despite considerable uncertainties, finding a climate analogue for future projections in present conditions, may allow us to estimate future ω or root-zone storage capacity values in a region where the future climate may resemble today's climate elsewhere. These methods are intuitive but not straightforward, as they rely on the selection and combination of relevant climate variables and their relation with vegetation, despite non-linear vegetation responses to climate change (Reu et al., 2014).

7 Conclusions

Understanding non-stationarity of hydrological systems under climate and environmental changes has been recognized as a major challenge in hydrology (Blöschl et al., 2019). Despite our strong awareness of non-stationarity of hydrological parameters, we often lack knowledge to implement system changes in hydrological models. In this ~~proof-of-concept~~ study in the Meuse basin, we ~~propose a~~ introduce a method to estimate future changes in vegetation model parameters and we evaluate the sensitivity of hydrological model predictions to these changes in vegetation parameters as a results of ecosystem adaptation in response to climate and land-use changes. Our top-down approach ~~to introduce~~ uses readily available regional climate model simulations to allow a time-dynamic representation of the root-zone storage capacity~~parameter within~~ , which is a key parameter in process-based hydrological models~~, using regional climate model simulations~~. Our approach relies, on the one hand, on a space-for-time exchange of Budyko characteristics of dominant land-use types to estimate the hydrological behavior of potential land-use changes and, on the other hand, on the interplay between the long-term and seasonal water budgets to represent climate-vegetation interactions under climate and land-use change. Despite knowledge gaps on future ecosystem water use, we implement potential system changes in a hydrological model based on our current understanding of hydrological systems. The predicted hydrological response to 2K warming is strongly altered if we consider that vegetation has adapted by increasing its root-zone storage capacity with 34 % to offset the more pronounced hydro-climatic seasonality under 2K global warming compared to a stationary system. The increased vegetation water demand under global warming results on average annually in -7 % less streamflow, +4 % more evaporation and -6 % less ~~recharge~~ groundwater storage for the scenarios assuming non-stationary conditions compared to a stationary system. These differences even ~~lead to a distinct change of sign of~~ imply decreasing instead of increasing median annual streamflow ~~.~~ under 2K global warming under non-stationary conditions. More importantly, the seasonal changes are considerable with up to +14 % higher evaporation in summer and up to -15 % and -10 % lower streamflow and groundwater storage respectively in autumn, for the non-stationary scenarios. Our study contributes to the quest for more plausible representations of catchment properties under change and, therefore, more reliable long-term hydrological predictions.

Table 1. Mean annual precipitation P, potential evaporation E_{P}, temperature T and aridity index E_{P}/P for the observed historical E-OBS data and the simulated historical and 2K climate data for the Meuse basin upstream of Borgharen.

	Observed historical climate	Simulated historical climate	Simulated 2K climate
P (mm yr^{-1})	950	1035	1070
E_{P} (mm yr^{-1})	590	670	720
T (°C)	9.6	8.9	10.9
E_{P}/P (-)	0.62	0.64	0.67

~~Root-zone storage capacity description and symbols, derived from long-term transpiration and storage deficits calculations for observed historical E-OBS data (P_{obs}) and simulated historical (P_{hist}) and 2K climate data (P_{2K}) for historical land use (ω_{obs}) and land-use change scenarios ($\omega_{\mathrm{broadleaved}}$ and $\omega_{\mathrm{coniferous}}$). The overline symbol is omitted from P, Q and E_{R} to increase readability. Description Root-zone storage capacity $S_{\mathrm{R,max}}$ mmLong-term transpiration E_{R} mm yr^{-1}(Eq. 5) Storage deficit $S_{\mathrm{R,def}}$ mm(Eq. 7) Observed historical E-OBS climate historical land use (ω_{obs}) $S_{\mathrm{R,max,A}}$ $P_{\mathrm{E,obs}} - Q_{\mathrm{obs}}$ $S_{\mathrm{R,def,obs}}$~~

~~Simulated historical climate historical land use (ω_{obs}) (historical runoff coefficient) - $P_{\mathrm{E,hist}} - Q_{\mathrm{obs}}/P_{\mathrm{obs}} \cdot P_{\mathrm{hist}}$ $S_{\mathrm{R,def,hist}}$~~

~~2K climate historical land use (ω_{obs}) $S_{\mathrm{R,max,B}}$ $P_{\mathrm{E,2K}} - (Q/P)_{\mathrm{2K,B}} \cdot P_{\mathrm{2K}}$ (Eq. 3) $\max(|S_{\mathrm{R,def,obs}} + \min(0, S_{\mathrm{R,def,2K,B}} - S_{\mathrm{R,def,hist}})|)$~~

~~2K climate broadleaved land use ($\omega_{\mathrm{broadleaved}}$) $S_{\mathrm{R,max,C}}$ $P_{\mathrm{E,2K}} - (Q/P)_{\mathrm{2K,C}} \cdot P_{\mathrm{2K}}$ (Eq. 3) $\max(|S_{\mathrm{R,def,obs}} + \min(0, S_{\mathrm{R,def,2K,C}} - S_{\mathrm{R,}}$~~

~~2K climate coniferous land use ($\omega_{\mathrm{coniferous}}$) $S_{\mathrm{R,max,D}}$ $P_{\mathrm{E,2K}} - (Q/P)_{\mathrm{2K,D}} \cdot P_{\mathrm{2K}}$ (Eq. 3) $\max(|S_{\mathrm{R,def,obs}} + \min(0, S_{\mathrm{R,def,2K,D}} - S_{\mathrm{R,def}}$~~

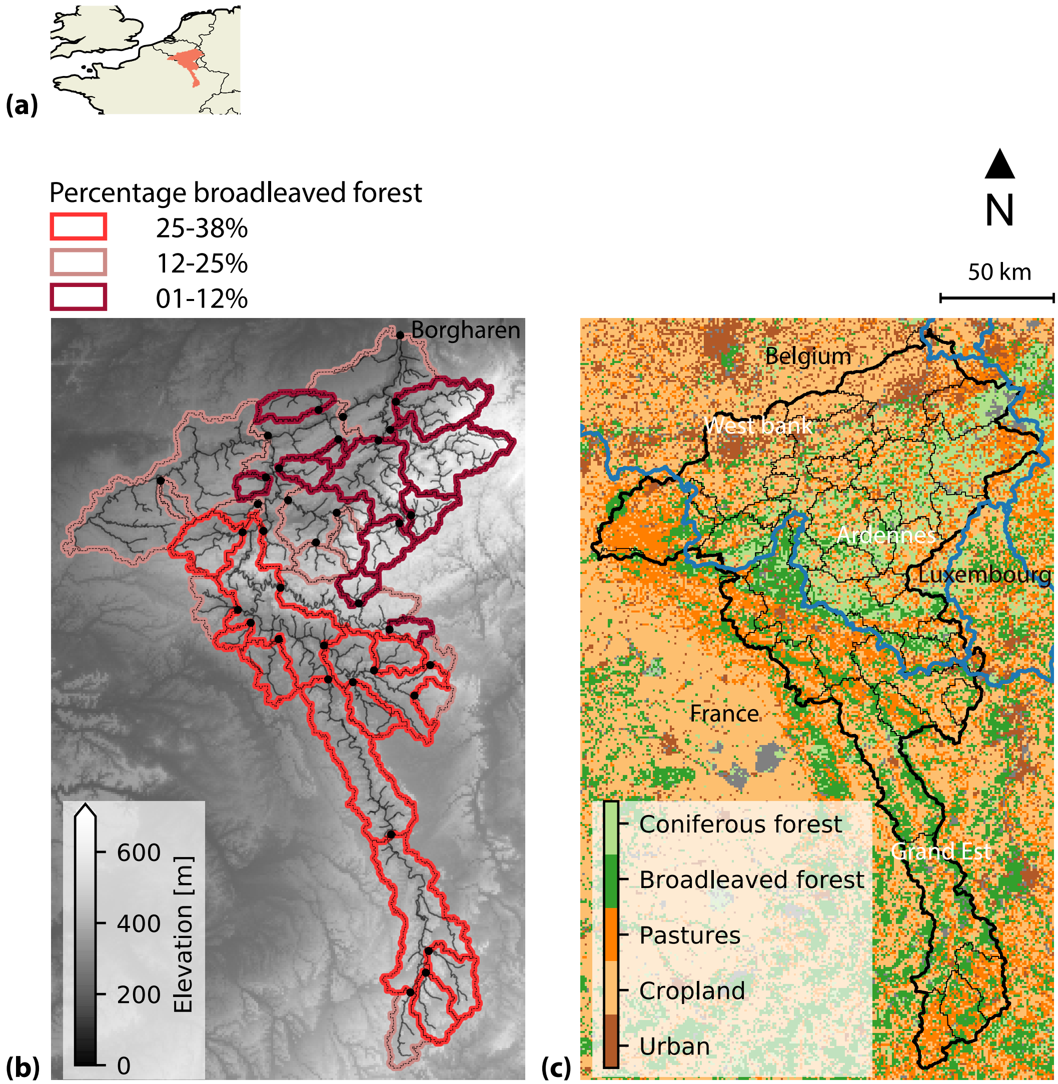

Figure 1. **(a)** Location of the Meuse basin in North-West Europe. **(b)** Elevation in the basin and categorization of catchments according to their areal percentage of broadleaved forest. Black dots indicate the locations where streamflow observations are available. **(c)** Main land-use types according to CORINE Land Cover (European Environment Agency, 2018). The three main zones are the French Southern part of the basin in the Grand Est region, the Ardennes and the area on the West bank of the Meuse.

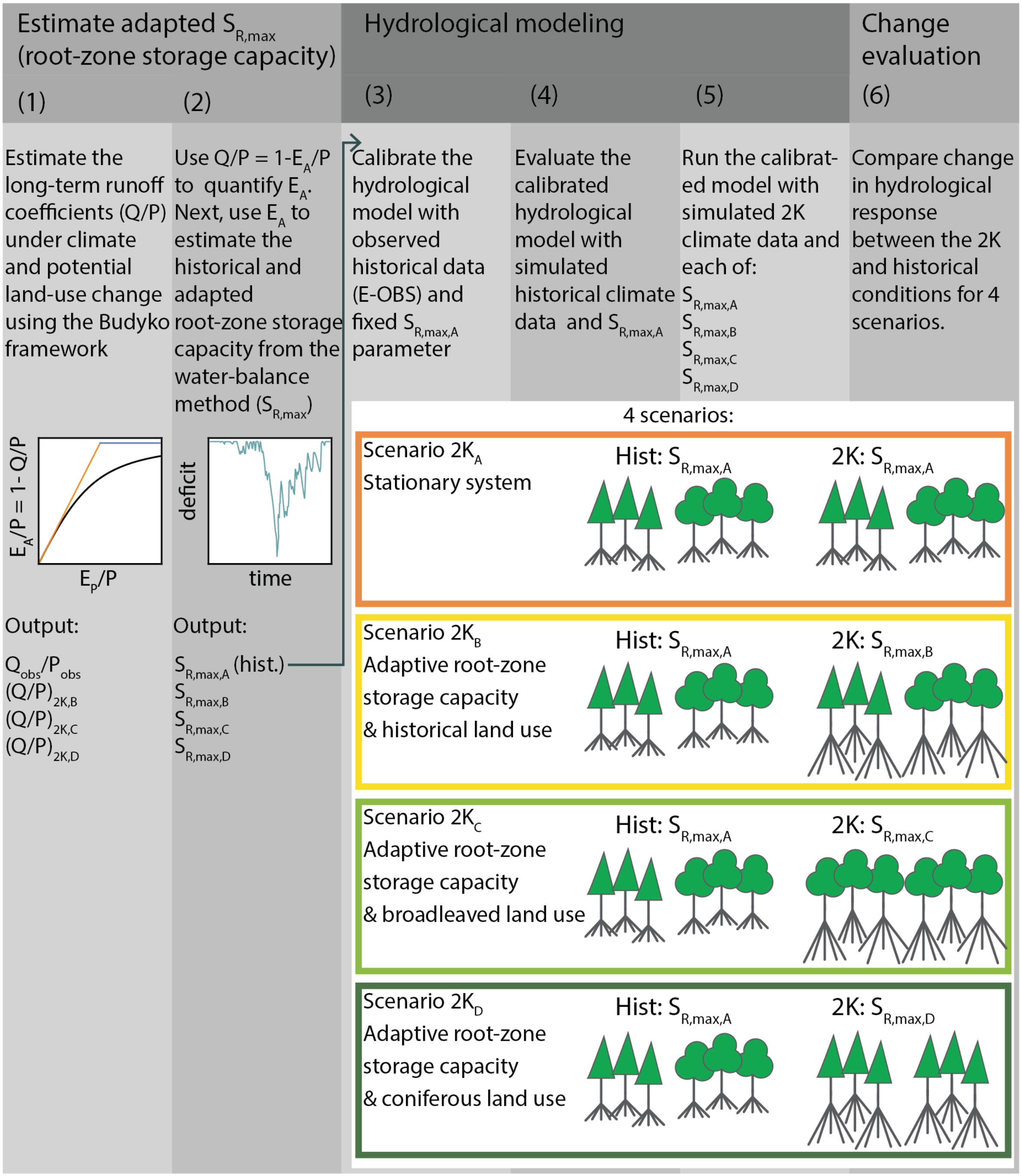

Figure 2. Overview of the methodological procedure and schematic representation of the four model scenarios.

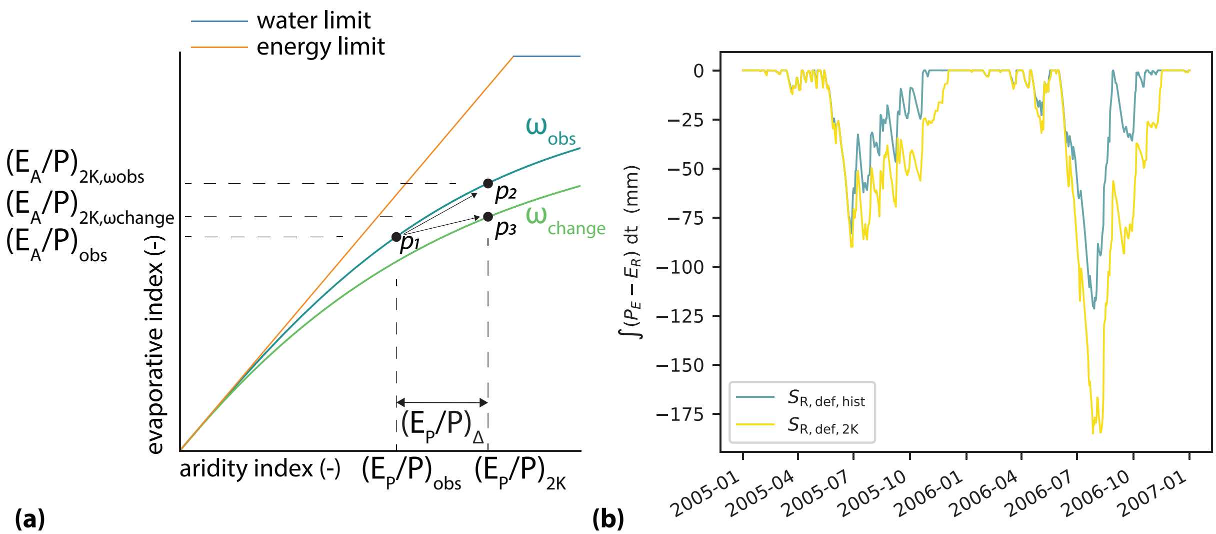

Figure 3. (a) Representation of the Budyko space, which shows the evaporative index (~~E_A/P~~ $E_A/P = 1 - Q/P$) as a function of the aridity index (E_P/P) and the water and energy limit. A catchment with aridity index $(E_P/P)_{obs}$ and evaporative index $(E_A/P)_{obs}$, which is derived from observed historical data assuming $(E_A/P)_{obs} = 1 - (Q/P)_{obs}$, plots at location p_1 on the parametric Budyko curve with ω_{obs}. A movement in the Budyko space towards p_2 along the ω_{obs} curve is shown as a result of a change in aridity index $(E_P/P)_\Delta$ towards a projected $(E_A/P)_{2K,\omega obs}$ associated with aridity $(E_P/P)_{2K}$. An additional ~~vertical~~ shift ~~$\Delta\omega$~~ from the ω_{obs} curve towards a location p_3 on a ω_{change} curve is ~~shown~~ assumed if additional factors (e.g. land use) are projected to change besides aridity index. Here, the represented downward shift in ω reduces the change in evaporative index to $(E_A/P)_{2K,\omega change}$. **(b)** Cumulative storage deficits ($S_{R,def}$) derived from effective precipitation (P_E) and transpiration (E_R) using the simulated historical and 2K climate data. Estimates of transpiration (E_R) are derived from long-term water balance projections as a result of movements within the Budyko framework in response to climate and potential land use changes.

~~Schematic representation of the wflow_FLEX-Topo model with three HRUs for plateau, hillslope and wetland connected through their groundwater storage. The model includes storages for snow S_{W}, interception S_{I}, the root-zone S_{R}, a fast runoff component S_{F} and groundwater S_{S} mm. The total streamflow Q mm d^{-1}is the sum of fast runoff Q_{F} from the three HRUs and groundwater runoff Q_{S}. Evaporation mm d^{-1}occurs from the snow storage (E_{W}), the interception storage (E_{I}) and the root-zone storage (E_{R}). Main parameters for snow processes include a threshold temperature T_{T} $°C$to distinguish precipitation P falling as rain P_{R} or snow P_{S}, a threshold temperature for melt T_{M} mm d^{-1}and a degree-day factor F_{M} mm d^{-1} °C^{-1}. For each HRU, other parameters include a maximum interception capacity I_{max} mm, a maximum root-zone storage capacity $S_{\mathrm{R,max}}$ mm, a shape factor β -, a transpiration water stress factor L_{P} -, a factor for the fraction of preferential groundwater recharge D -, a recession coefficient for the fast storage K_{F} d^{-1}and a combined recession for the slow storage K_{S} d^{-1}. Parameters specific to plateau, hillslope and wetland include a maximum percolation rate $R_{\mathrm{P,max,P}}$ mm d^{-1}, a non-linear coefficient for fast runoff α_{P} and α_{H} -, and a maximum capillary rise rate $R_{\mathrm{C,max,W}}$ mm d^{-1}. Effective precipitation is denoted as P_{E}, fluxes between two stores are denoted as R with subscripts for the stores, and subscripts P, H and W are used to distinguish between the three HRUs.~~

~~Model scenarios using the observed historical and the simulated historical and 2K climate data. The model is calibrated using observed E-OBS data and the historical root-zone storage capacity $S_{\mathrm{R,max,A}}$. The model is then forced with the simulated historical climate data using $S_{\mathrm{R,max,A}}$ as root-zone storage capacity parameter. We then define four scenarios to compare the change in hydrological response to 2K global warming in comparison to historical conditions for the ensemble of feasible parameter sets. In scenario 2K$_{\mathrm{A}}$, we assume an unchanged system (no changes in land use, nor root-zone storage capacity). In scenario 2K$_{\mathrm{B}}$, we assume that vegetation has adapted its root-zone storage capacity to the 2K climate, but no changes in land use. In scenario 2K$_{\mathrm{C}}$, we test the combination of an adapted root-zone storage capacity in response to the changed climate and a hypothetical conversion of coniferous plantations and agriculture to broadleaved forests in part of the catchment. A similar but reversed approach in land-use changes is assumed in scenario 2K$_{\mathrm{D}}$.~~

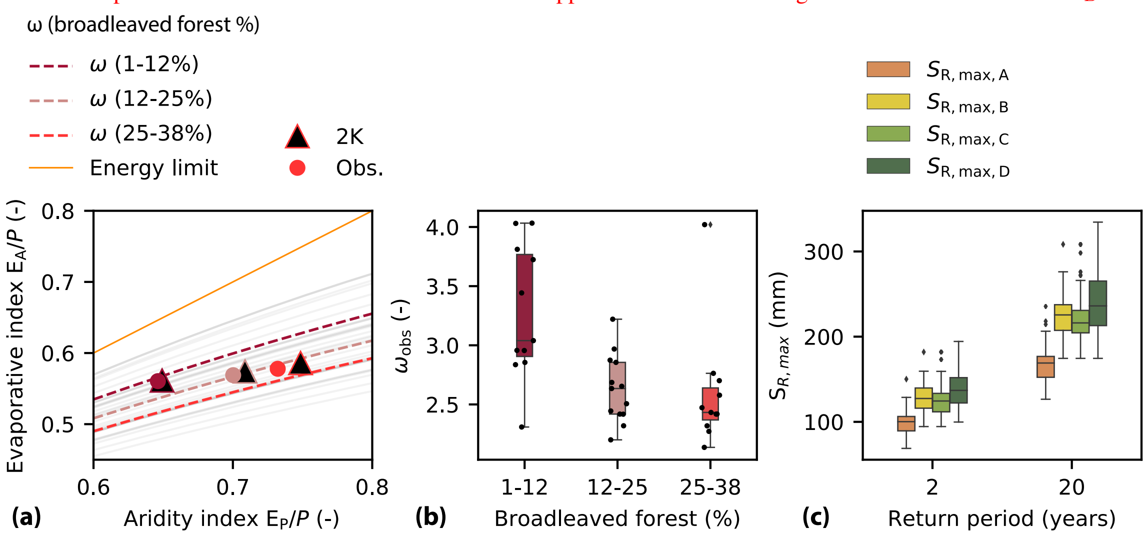

Figure 4. (a) Budyko space with parametric ω_{obs} curves for each of the 35 catchments of the Meuse basin~~, categorized according to their percentage of broadleaved forest~~. The ~~dashes~~ dashed curves represent the median ω_{obs} curves for each category of areal broadleaved forest percentage. The change in median aridity index across catchments of the three categories from historical to 2K climate conditions ~~along each parameterized ω_{obs} curve~~ is ~~also~~ shown ~~for~~ by the ~~median of the three categories~~circles and triangles. **(b)** Parameterized ω_{obs} values for each of the 35 catchments of the Meuse basin, categorized according to their percentage of broadleaved forest. **(c)** Range of root-zone storage capacities across the 35 catchments of the Meuse basin for the four scenarios. $S_{\mathrm{R,max,A}}$ represents the root-zone storage capacity for historical conditions. $S_{\mathrm{R,max,B}}$ represents an adapted root-zone storage capacity in response to the 2K climate but no land use change. In the estimation of $S_{\mathrm{R,max,C}}$, catchments with a low percentage of broadleaved forest (1-12%) receive ω values sampled from catchments with a high percentage of broadleaved forest (25-38%), to represent changes in land use towards a conversion to broadleaved forest. ~~A similar~~ The

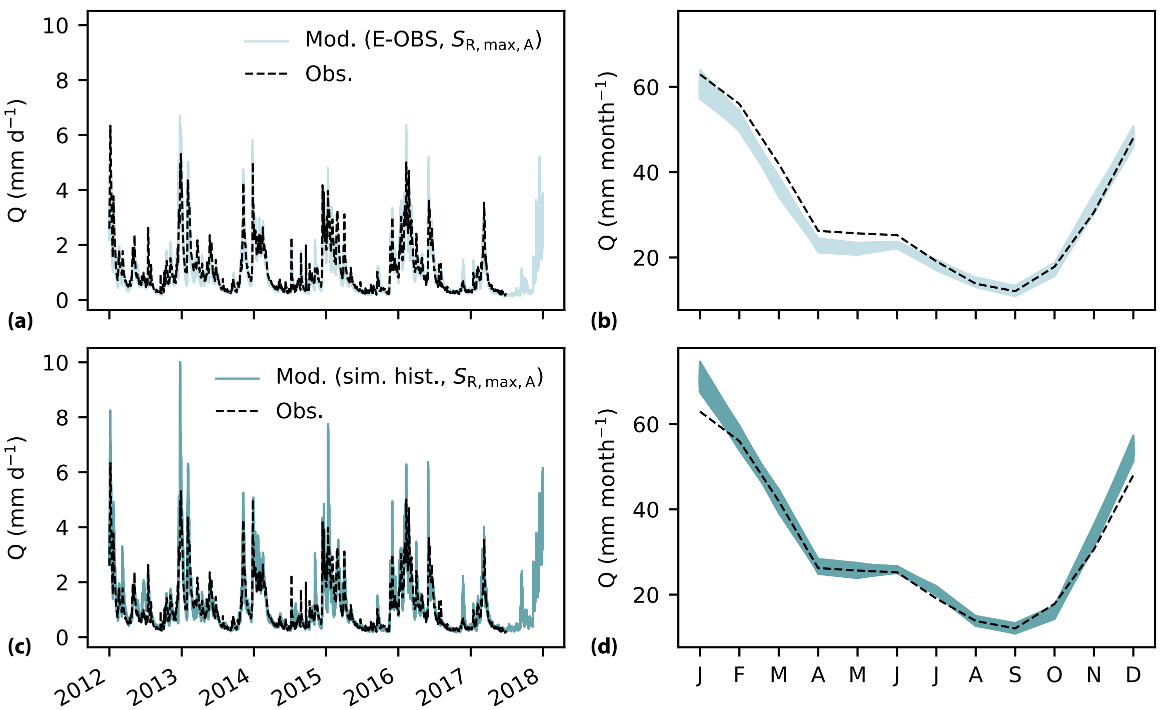

Figure 5. Observed and modeled hydrographs and mean monthly streamflow at Borgharen for the ensemble of parameter sets retained as feasible after calibration when the model is: **(a,b)** forced with E-OBS historical data and using $S_{\mathrm{R,max,A}}$ as model parameter, and **(c,d)** forced with the simulated historical climate data using $S_{\mathrm{R,max,A}}$ as model parameter.

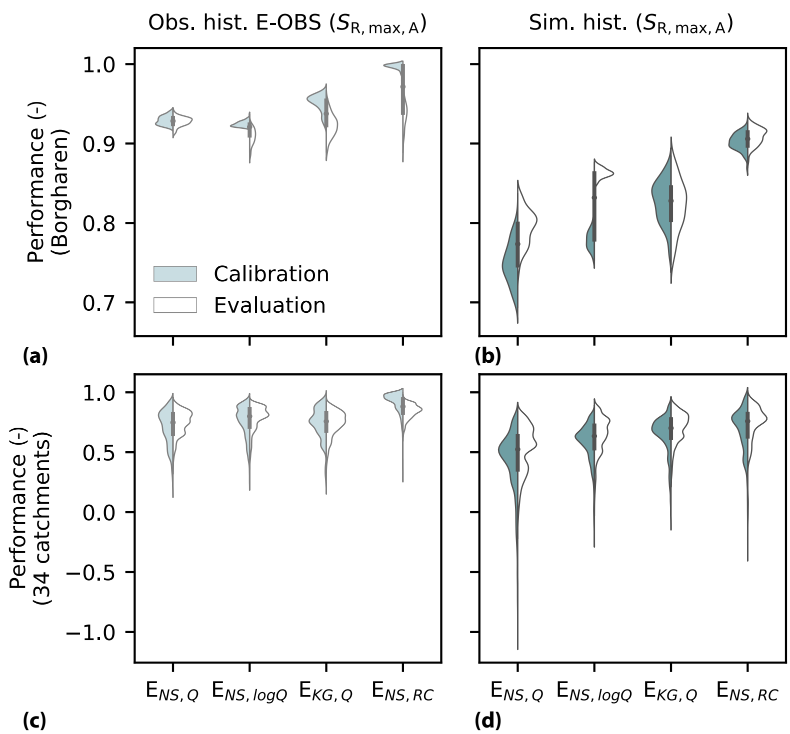

Figure 6. Streamflow model performance during calibration and evaluation for the four objective functions when the model is forced with (~~a,b~~a,c) observed historical E-OBS data and (~~c,d~~b,d) simulated historical climate data at (~~a,c~~a,b) Borgharen and (~~b,d~~c,d) for the ensemble of nested catchments in the Meuse basin. The four objective functions are the Nash-Sutcliffe efficiencies of streamflow, logarithm of streamflow and monthly runoff coefficient ($E_{\mathrm{NS,Q}}$, $E_{\mathrm{NS,logQ}}$, $E_{\mathrm{NS,RC}}$) as well as the Kling-Gupta efficiency of streamflow ($E_{\mathrm{KG,Q}}$). Note the different y-axis scales between rows.

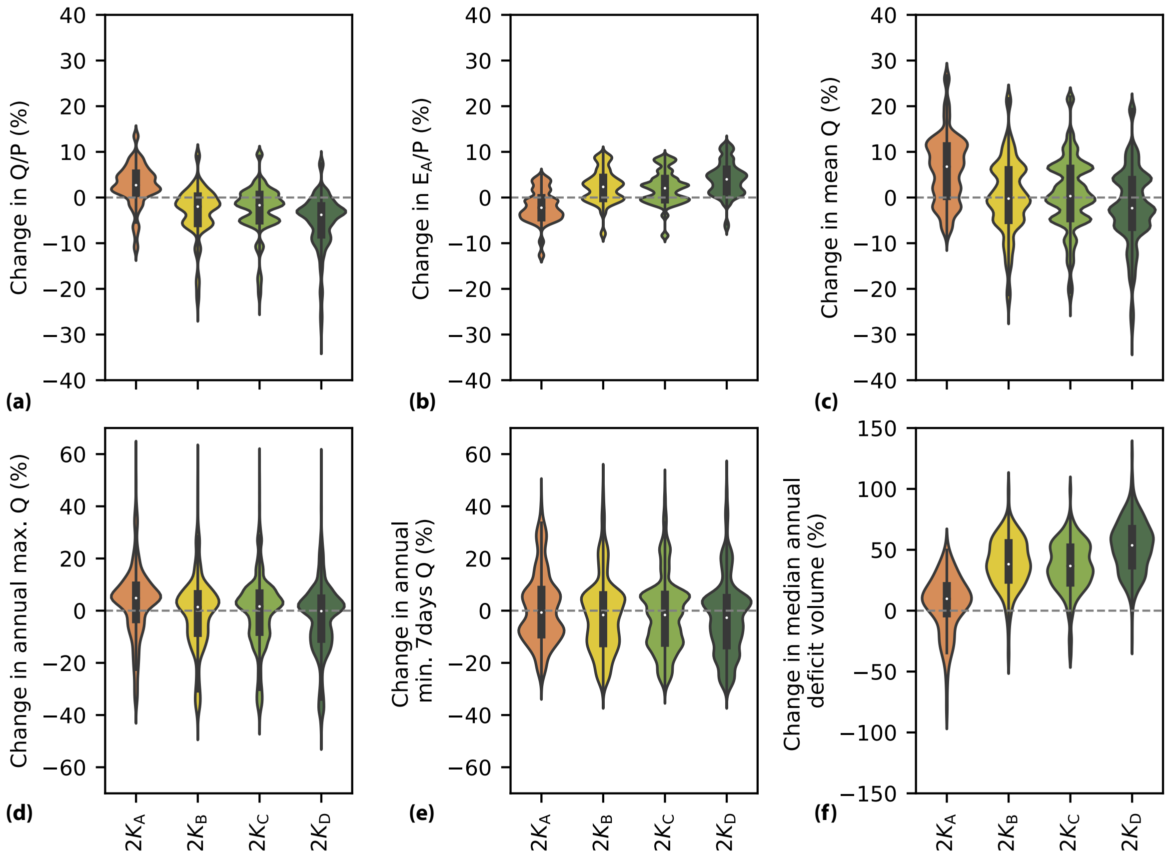

Figure 7. Percentage change in annual hydrological response indicators between the 2K and historical model runs for the four scenarios, each based on different assumptions for the root-zone storage capacity parameter $S_{\mathrm{R,max}}$. Percentage change in **(a)** runoff coefficient Q/P, **(b)** evaporative index E_{A}/P, **(c)** mean annual streamflow, **(d)** mean annual maximum streamflow, **(e)** minimum annual 7-days mean streamflow, **(f)** median annual deficit volume below the reference 90^{th} percentile streamflow. Note the different y-axis scales.

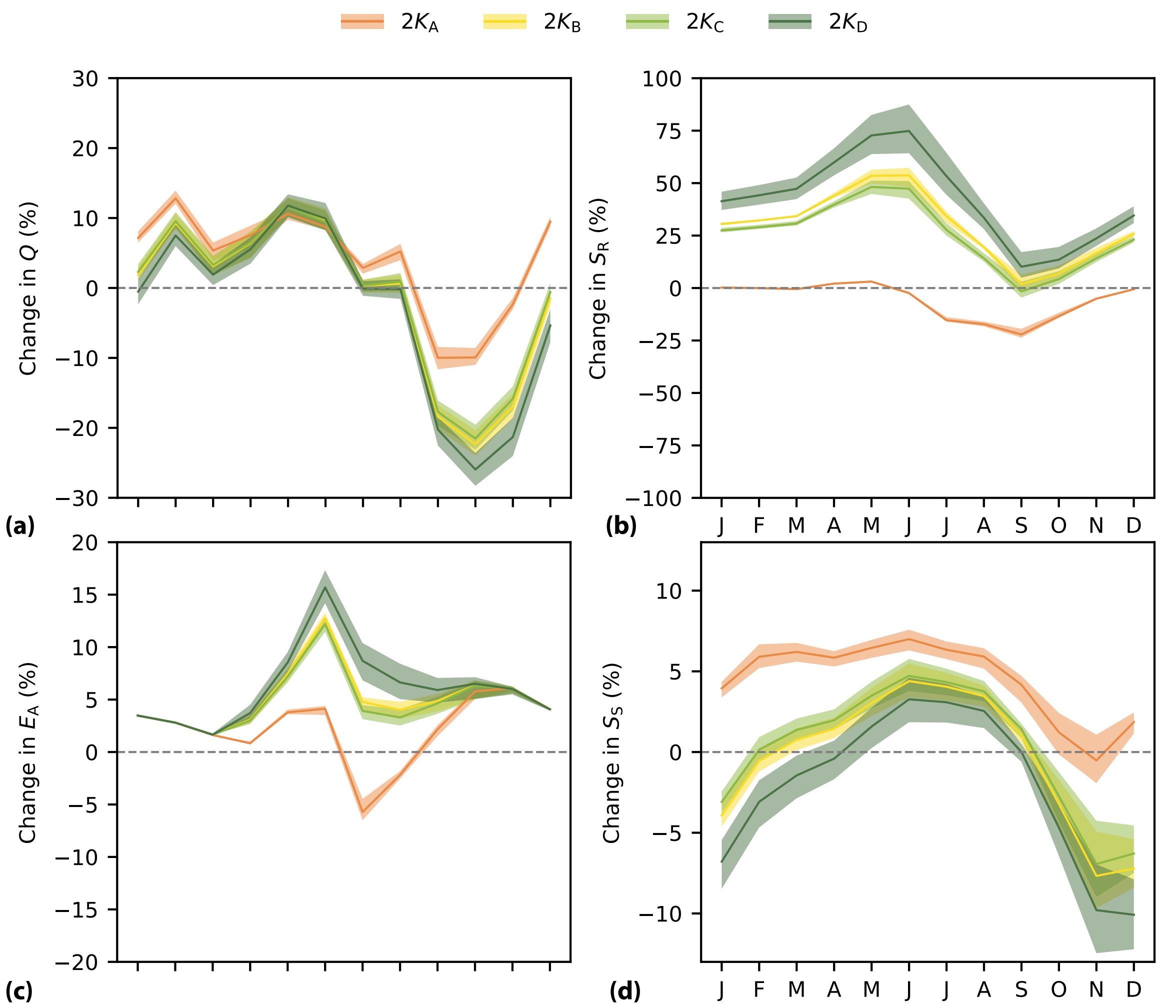

Figure 8. Percentage change in mean monthly hydrological response of several flux and state variables between the 2K and historical model runs for the four scenarios, each based on different assumptions for the root-zone storage capacity parameter $S_{\mathrm{R,max}}$. Percentage change in mean monthly **(a)** streamflow Q, **(b)** ~~actual evaporation E_{A}, (c)~~ root-zone storage S_{R}, **(c)** actual evaporation E_{A}, **(d)** groundwater storage S_{S}. The lines and shaded areas show the median and 5-95$^{\mathrm{th}}$ percentiles from the ensemble of parameter sets retained as feasible.

8 Data availability

Streamflow data for the Belgian stations are provided by the Service Public de Wallonie in Belgium (Direction générale opérationnelle de la Mobilité et des Voies hydrauliques, Département des Etudes et de l'Appui à la Gestion, Direction de la Gestion hydrologique intégrée (Bld du Nord 8-5000 Namur, Belgium)). Streamflow data for the French stations are retrieved from the Banque Hydro portal (http://www.hydro.eaufrance.fr/). The E-OBS dataset (v20.0e) for daily precipitation, temperature and radiation fields for the historical period is used (Cornes et al., 2018) and can be downloaded from https://www.ecad.eu/download/ensembles/download.php. The simulated historical and 2K climate data are provided by the Royal Netherlands Meteorological Institute (KNMI).

Author contributions. HHG, MH, EEA and LJEB designed the study. EEA provided the simulated historical and 2K climate data. LJEB conducted all the analyses and wrote the manuscript. All authors discussed the results and contributed to the final manuscript.

Competing interests. The authors declare that they have no competing interests.

Acknowledgements. We thank Deltares and Rijkswaterstaat for the financial support to conduct this analysis. The authors would like to thank the Service Public de Wallonie, Direction générale opérationnelle de la Mobilité et des Voies hydrauliques, Département des Etudes et de l'Appui à la Gestion, Direction de la Gestion hydrologique intégrée (Bld du Nord 8-5000 Namur, Belgium) for providing the streamflow data. We thank Erik van Meijgaard for performing the historical and 2K climate data simulations. We also thank Wouter Berghuijs for his valuable advice on the Budyko framework.

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