Response to reviews of "Why increased extreme precipitation under climate change negatively affects water security" submitted to *Hydrology and Earth System Sciences* for consideration for publication.

We warmly thank the two reviewers for their positive and constructive reviews of our manuscript. Below we provide a response to their concerns and explain which revisions were implemented and why a certain approach was taken. All changes are indicated in the document with indication of track changes.

Referee #1

The paper "Why increased extreme precipitation under climate change negatively affects water security" explores the redistribution of surface water (blue water) and soil water (green water) under future climate scenarios. The primary result is that increasing precipitation intensity will reduce green water and thus increase plant water stress.

Overall I think that the central questions and technical work in this paper seem to be fine. The primary area in need of improvement is the presentation and discussion of the results. In particular, I feel that: a) some of the conclusions are overstated (or rather not properly qualified), b) the implications of the key results are not discussed in a precise way, and c) there is unnecessary repetition in some sections. Having said this, the paper is generally well written from a grammatical perspective.

I have two broad comments (listed below), and several minor comments (in the attached .pdf) for the authors to address.

We would like to thank the reviewer for his nice comments on the manuscript. We have revised the conclusions and implications of results to be more cautious and revised the manuscript for unnecessary repetitions. Below we have responded to the general and minor comments raised by the reviewer.

1. I find the title/abstract and the results of the paper to be somewhat incongruous. I think that the authors should include more discussion of how the magnitude of the trends that they find impact water security issues in a more precise way. The basic causal narrative that comes across in the abstract is very clear, but the supporting evidence for this narrative is not clear. For example, it is hard to assess whether the impacts on reservoir storage via changing soil erosion are of substantial enough magnitude to significantly change the prospects of irrigation in the study region.

The concept of water security is defined as 'a condition in which the population has access to adequate quantities of clean water to sustain livelihoods and is protected against water related disasters (UN-Water, 2013).' Water security is not a metric in itself; we used four indicators to quantify water security in the Segura River catchment that we considered most relevant in the local context. We acknowledge the need to quantify impacts as much as possible. Therefore, for a more comprehensive discussion of the magnitude of the trends and the impact on water security, we have now included an analysis of the impact of changes in reservoir inflow to irrigation water demand. Unfortunately, we cannot provide the full details of how irrigation water supply will change under future climate conditions. Irrigation water is also supplied from deep aquifers and from the Tagus-Segura water transfer, from which it is very uncertain how *supply will change under future climate conditions. We have included this information in section 2.1 and discussed the future prospects of irrigation in the Discussion and Conclusions section of the revised manuscript.*

Loss of reservoir storage capacity is another aspect affecting water security in Spain and many other areas worldwide (de Vente et al, 2005; Wisser et al., 2013). Therefore, we estimated the capacity loss due to reservoir sedimentation (Figure S9). Under the reference conditions, the annual capacity loss for 14 reservoirs used for irrigation equals 0.11%. This is indeed lower than the global and Spanish national average and not substantial enough to claim that storage capacity is threatened by increased soil erosion under climate change. While this may partly be an artefact of insufficiently accounting for channel erosion processes as explained in the discussion, we have adjusted the claims regarding the impact of sediment yield on the storage capacity of the reservoirs in the abstract, the Discussion and Conclusions sections.

The other two water security indicators (plant water stress and hillslope erosion) can only be interpreted in a qualitative way. It is likely that an increase of plant water stress and hillslope erosion has a detrimental effect on the agricultural productivity due to lack of water availability, of fertile soil and reduced water retention capacity. However, detailed crop-specific information is needed to be able to quantify the impact of these two indicators. While highly relevant, quantitative assessment of impacts on crop yield is beyond the scope of this study.

2. I think that the paper would benefit from a more thorough literature review. There is previous literature that discusses the implications of decreasing precipitation frequency and increasing precipitation intensity on runoff and water stress (e.g. Fay et al. 2003, and Knapp et al. 2008).

We have added a new paragraph to the introduction that discusses the impact of decreasing precipitation frequency and increasing extreme precipitation on natural, arable and urban landuse classes.

Page 2, lines 5-6: There is a moderate amount of repetition here from the last two sentences of the previous paragraph. I think that the presentation could be streamlined, although this point is not critical.

We agree, therefore, we have removed this sentence from the manuscript.

Page 2, lines 22: I believe that this statement should be qualified since it is not the case that there is evidence of increasing extreme precipitation into the future in ALL regions. Perhaps something like: "Considering the estimated [or anticipated] future increase of extreme precipitation in many regions..."

Thanks for the suggestion. We have changed this sentence in the revised manuscript.

Page 2, lines 22-23: Since these are already cited in a previous paragraph for the same reason, I do not think that they are necessary here. This is a very minor concern, however.

We agree. We have removed these references from the manuscript.

Page 3, lines 5-6: It would be good to define SPHY and MMF

We have added a definition of the two models to the revised manuscript.

Page 3, line 15: Likely it would be helpful to include a short definition of these two classifications since some readers may be unfamiliar with the details of the K-G classification system.

The manuscript includes both the description of the climate (Mediterranean and semi-arid) and the Köppen classification (CSa and BSk). Additionally, the manuscript includes information on the annual precipitation and temperature (Figures 2 and S3). We argue that this is sufficient to get an idea of the climate in the study area.

Page 5, line 2: I think that this is more accurately described as two climate scenarios assessed over two time periods, rather than four climate scenarios. (This is a minor point)

Indeed, this would be a more accurate description. However, in the manuscript we refer to these scenarios with the indicators S1-S4. We prefer to keep this logic to increase readability.

Page 5, lines 6-7: The validity of this statement depends on the variable that is being downscaled and bias-corrected as well as the measure of performance that is used to compare methods. Please be more specific.

Indeed. Themeßl et al. (2011) argues that quantile mapping performs particularly well for the highest quantiles. Here we focus on the impact of changes in extreme precipitation, therefore, quantile mapping was selected for the current study. We have added this reasoning to the revised manuscript.

Page 5, lines 7-9: Please elaborate on this and describe the method more precisely. This is particularly important since I presume that your results are somewhat sensitive to this correction process.

We have included a detailed description of quantile mapping to the revised manuscript.

Page 5, lines 13-14: Please provide a brief argument for why this set of parameters provides a good indicator for water security. It seems to me that you are informing some specific areas of water security, but your statement here seems to be a bit more general.

We have added the following sentences to the revised manuscript: "These indicators are specifically important for this study area, which is dominated by rainfed and irrigated agriculture. Changes in plant water stress and hillslope erosion may affect agricultural productivity, while changes in reservoir inflow and reservoir sediment yield affect water availability for irrigated agriculture and drinking water."

Page 5, line 21: I assume that "PWP" should be "PWS"

Indeed. We have changed this in the revised manuscript.

Page 5, line 21: Missing a "."

We have changed this in the revised manuscript.

Page 6, lines 7-13: Both of these measures of uncertainty deal with how certain we are of the sign of the response. This is fine, but it should noted that many readers may also care about whether the magnitude of the response is substantial enough to care about.

We have discussed this issue in the first general comment.

Page 6, line 22: It would be helpful if you were specific about how you define extreme precipitation somewhere in the main text, rather than only in the figure caption.

We have added the following sentences to the revised manuscript to define extreme precipitation and dry spells: "Extreme precipitation is defined as the 95th percentile of daily precipitation, considering only rainy days (>1 mm day^{-1}; Jacob et al., 2014). Dry spells are defined as the 95th percentile of the duration of periods of at least 5 consecutive days with daily precipitation below 1 mm (Jacob et al., 2014)."

Page 7, line 2: It may be interesting to also present and discuss the min and max daily plant water stress under the different scenarios, rather only the seasonal averages.

Plant water stress is determined from soil moisture and potential evapotranspiration, which both do not show much daily variability. Therefore, we argue that a medium-term analysis of this indicator is sufficient to quantify its impact. To increase the understanding of the impact on different landuses, we have added an additional figure to the Supporting Information that shows the temporal variation (monthly) of plant water stress for 9 landuse classes. The figure shows that rainfed agriculture is most affected by climate change, followed by natural land cover and irrigated agriculture. The figure is discussed in the Discussion and Conclusions section of the revised manuscript.

Page 9, line 2: I think that you need to close the loop here and clearly state what the change to storage capacity is for the estimated changes to erosion and sediment yield. This is particularly important because the absrtact states that: "This affects plant water stress and the potential of rainfed versus irrigated agriculture, and increases dependency on reservoir storage, that is increasingly threatened by an increase of soil erosion."

We have responded to this issue in the first general comment.

Page 10, line 5: “a”.

We have changed this in the revised manuscript.

Page 10, line 6: based on Figure 5, I think that this statement needs to be qualified. For example, there are some very large decreases in SY in several of the reservoirs of S4.

We have responded to this issue in the first general comment.

Page 10, lines 7-9: Please provide clear explanations for these assertions of causality. Most importantly, what is the rationale for saying that the decrease in annual volume impacts the distribution of blue/green water to favor blue water?

We argue that changes in annual precipitation volume have a smaller impact on the redistribution of water than changes in extreme precipitation and precipitation frequency. In lines 9-12 (page 10 of the original manuscript) we explain that an increase of extreme precipitation leads to an increase of surface runoff, which is the main cause of the increase of reservoir inflow (blue water). Furthermore, an increase of surface runoff leads to a reduction of infiltration, negatively affecting soil moisture content (green water). To support these claims, we have added a table to the Supporting Information, which shows the changes for a number of hydrological indicators (i.e. precipitation, actual evapotranspiration, surface runoff, infiltration and soil moisture content).

Page 11, lines 1-4: There is a fair bit of repetition in this (already short) discussion. In particular, the authors bring up the lack of consideration of infiltration excess surface runoff and the impact of changing extreme precipitation on surface runoff in consecutive paragraphs. I think that the discussion could be slightly restructured to avoid this repetition.

Thanks for the suggestion. We have critically edited the Discussion and Conclusions section.

Page 11, lines 12-13: I find this portion of the discussion to be inconsistent with the portion of the abstract that states "... increases dependency on reservoir storage, that is increasingly threatened by an increase of soil erosion." Please clarify and/or change the abstract where necessary.

We have responded to this issue in the first general comment.

Page 11, lines 20-21: It is not clear to me how your results illustrate that suitable bias-correction methods are crucial for accurate climate change impact assessments. Please elaborate.

Many studies use the delta change method, which potentially could lead to an opposite direction of change for runoff and soil erosion. We argue that bias-correction methods that explicitly account for projected changes in precipitation distribution, like quantile mapping, are essential in climate change assessments. We have included the following *sentences to the Discussion to clarify this: "Furthermore, we applied a bias-correction method (quantile mapping) that explicitly accounts for changes in the projected precipitation distribution. Many previous studies applied the change factor (or delta change) method, which does not fully account for the changes in rainfall intensity. Studies that apply this method often show that a change of annual rainfall leads to a similar direction of change of runoff and soil erosion (e.g., Shrestha et al., 2013; Correa et al., 2016). Therefore, future studies should consider bias-correction methods that account for changes in frequency and intensity of extreme events that affect both hydrology and soil erosion (Mullan et al., 2012; Li and Fang, 2016)."*

SI, page 5, line 3: Please defend your choice for calibration and validation years. Fitting on 10 years of data and validating on the 14 years prior seems arbitrary and tempts the reader to wonder whether many candidate periods were computed until a satisfactory fit emerged. This would largely defeat the purpose of a validation.

Only a limited amount of data was available for model calibration and validation. Discharge data were available from 1987-2015. NDVI, precipitation and temperature data were only available until 2012. We choose to use individual NDVI images for the calibration period, which were only available from 2000 onwards. Given these limitations, we decided to calibrate the model from 2001-2010 and validate from 1987-2000. We have clarified this in the revised manuscript (SI).

SI, page 5, line 9: I assume that this means minimize. Please clarify what you are optimizing.

Indeed. However, we choose to use "optimized", which is common jargon in hydrological studies.

SI, page 5, line 10: Same as previous comment

In the case of Nash-Sutcliffe, which has a value of 1 in the case of a perfect fit, the model efficiency is maximized. However, we choose to use "optimized", which is common jargon in hydrological studies.

SI, page 5, lines 29-31: Please briefly discuss the impacts of this assumption on your results. Specifically how the results may change for locations with a) higher and b) lower ratios of maximum hourly rainfall to daily rainfall.

We have changed the sentence in the revised manuscript (SI) as follows: "This fraction may vary globally and global extrapolation introduces uncertainty in regions where this fraction differs from our estimate. A higher (lower) fraction may lead to an increase (decrease) of the area prone for infiltration excess surface runoff. Nevertheless, in the absence of better estimates we extrapolated the fraction to illustrate the potential extent of global sensitive areas to infiltration excess runoff."

Referee #2

I have read with interest the manuscript by Eekhout et al. and I believe its subject fits with the content of HESS-D and that its findings are relevant for regional to global scale hydrological impact studies. Eekhout et al. present a comprehensive model study for a sub-humid to semi-arid basin in SE Spain focusing on the effect of increased rainfall intensity on water security for four scenarios of climate change. Strong points of the study are the breadth and coherence of the modelled effects, the use of state-of-the-art climate scenarios, the inclusion of climate change uncertainty and a formal treatment of their outcome in terms of robustness and significance. On these grounds, I'd recommend this manuscript for publication provided several corrections and improvements are made.

We thank the reviewer for his nice and constructive comments on the manuscript. Below we have responded to the specific comments raised by the reviewer.

At its core, I have two problems with the manuscript. First, there is no formal definition of water security and this is expressed in different manners but the relevance of the metrics and their relation to water management are not expressed. I'll address this in more detail below.

In the Introduction we have defined water security "as a condition in which the population has access to adequate quantities of clean water to sustain livelihoods and is protected against water related disasters (UN-Water, 2013)." Water security is not a metric in itself and, indeed, it may be interpreted in different ways. In the manuscript, we use four indicators to quantify water security in the Segura River catchment. In other regions water security may be quantified using different indicators. Therefore, we have added the reasoning why we choose to use these specific indicators to section 2.4.

Second, the study is thorough in its modelling setup and analysis proper but lacks a clear quantification of the effect of increased extreme precipitation. I concur with the authors that this is important in this environment for runoff generation and that changes will have an effect but the exact nature of these changes are not investigated whereas these are important and the effects not necessarily straightforward. Also, I believe that low flows are essential to ensure water security and this is not mentioned or analyzed at all. At the moment the hypothesis is formulated but not fully underpinned and insufficient quantitative analyses are done to isolate the effect of extreme precipitation on water security convincingly.

In the present study we do not aim to isolate the effect of extreme precipitation. However, we aim to apply state-of-the-art future climate projections and take into account all projected climate changes, such as an increase of dry spells and temperature. While the increase of extreme precipitation may be one of the most relevant climate signals, we think that the other climate signals are equally important. By combining all these changes in one comprehensive study, we show that climate change may have significant impact on water security. While an additional sensitivity analysis to isolate the effect of extreme precipitation may be useful, such analysis have already been performed in similar environments and show that runoff and soil erosion are indeed sensitive to extreme precipitation (Pruski & Nearing, 2002; Nunes et al., 2009). In the revised manuscript we refer to these studies in a new paragraph, where we discuss the multiple impacts of extreme precipitation.

Many studies include low flows as an indicator for water security, however, we argue that plant water stress is a more direct indicator for arable and natural land uses. Plant water stress takes both evapotranspiration and soil moisture into account and is crop/plant specific. Low flows, however, only capture the amount of water that is eventually routed to the reservoirs and thus fails to link low water supply to the areas *where it has the most impact, i.e. arable and natural land uses. Low flows may be important for river catchments where navigation is an important economic activity, but here that is not the case.*

In addition, the study has a number of weaknesses that need at least clarification and probably improvement and that I group per category:

Climate and climate change: As we know the rain in Spain does not fall mostly in the plain. Looking at the elevation within the catchment, I am curious to what degree orographic effects are captured by the downscaling of the climate models. This is important as downscaling reproduces the climate but not necessarily the extremes of precipitation in terms of depth, frequency and persistence when compared to the historical period. For this reason, hydrological impact studies in the ISI-MIP project also consider the historical period of the climate models to provide an unbiased reference period (Hempel et al., https://doi.org/10.5194/esd-4-219-2013). It is unclear at the moment how the climate model output and the historical datasets are used consistently (section 2.5) and if the changes in Figure 2 (particularly the lower panel) are indeed truly representing the forecasted change and do not include any bias. In the best possible case clarification is in order and the results of the climate downscaling can be evaluated in the supplementary information (SI).

We use quantile mapping as bias-correction method. Quantile mapping uses historical observations, historical climate model output and future climate model output in its bias-correction routine. First the probability of occurrence of the future precipitation is determined from the empirical cumulative density distribution function (ecdf) of the historical climate model output. Then a correction factor is determined by feeding this probability into the inverse ecdfs of the historical observed and historical climate model output. Finally, the correction factor is added to the future precipitation. The spatial differences in observed annual precipitation sum clearly reflect the orographic effects (compare Figure 1c and Figure 2, upper left). Quantile mapping uses the historical observations. Therefore, the orographic effects are transferred to the bias-corrected future climate projections. Themeßl et al. (2011) argues that quantile mapping performs particularly well for the highest quantiles. Here we focus on the impact of changes in extreme precipitation, therefore, quantile mapping was selected for the current study. We have included a detailed description of quantile mapping in the revised manuscript.

The study overlooks the effect of evaporation completely but this is a non-negligible part of the water balance, affecting both soil moisture and water storage in reservoirs. This driver needs explanation as it becomes more important with higher temperatures and may be decisive in the S4 scenario (RCP 8.5, 2081-2100), more so than precipitation. To analyze this effect and to quantify the effect of precipitation extremes, two control runs with changing only the precipitation and keeping all other factors equal and vice versa, with changing temperature and evaporation but present-day precipitation, is in order. Vegetation change is here a complicating factor, see below on the model setup. In addition, the computation of the potential evaporation and its form in Equation 3 (reference, crop specific?) remain unexplained in the manuscript or the SI.

Indeed, under the most extreme climate conditions of scenario S4, evapotranspiration may become an important contributor to the water balance. However, we argue that the plant water stress indicator captures changes in (potential) evapotranspiration and, *therefore, its effect is included in the model results. In addition to the plant water stress, we have added a table to the Supporting Information, which shows the changes for a number of hydrological indicators (i.e. precipitation, actual evapotranspiration, surface runoff, infiltration and soil moisture content). These results are discussed in a new paragraph in the Discussion and Conclusions section.*

Potential evapotranspiration is determined by multiplying the crop coefficient with the reference evapotranspiration. Crop coefficients are obtained from NDVI, as explained in the Supporting Information. We used a log-linear model to determine NDVI for future climate conditions, hence, potential evapotranspiration is affected by changes in future vegetation conditions. We refer to Terink et al. (2015) and Eekhout et al. (2018), for a comprehensive description of how potential and actual evapotranspiration are determined in the SPHY model.

A remark on the uncertainty analysis (section 2.5): This is well executed but it may be good to indicate that this looks at climate uncertainty only. The other types of uncertainty are also large and relevant but harder to capture, hence my suggestions for additional simulations to capture their effects).

Indeed, our uncertainty analysis only accounts for climate model uncertainty. However, we would like to stress that the current study is a model application, rather than a study on model development. Expressing model uncertainty is indeed important, however, here we focus on the impact of state-of-the-art climate model output and the comprehensive impact on water security. Furthermore, sensitivity analysis on the impact of extreme precipitation has been performed by previous studies (see Introduction of the revised manuscript). Therefore, we restrict our uncertainty analysis to climate model uncertainty only. We have clarified this in section 2.5 of the revised manuscript.

Model setup: The model setup is ambitious and comprehensive. However, some facts are poorly explained and explored. To start with, the interaction between hydrology, erosion, vegetation and soils is a complex one and using an empirical vegetation growth model may complicate the analysis and is sensitive to the underlying assumptions and may insufficiently capture spatio-temporal variations in cover. Thus, a control run with the current vegetation may be necessary to quantify this adequately. Or the differences in vegetation cover should be presented for the four scenarios in the SI and the effect on the crop specific potential evapotranspiration and the actual evapotranspiration analyzed there. Without excluding this effect, rivalling explanations for the simulated changes cannot be excluded a priori and will the conclusion be tentative at best (see below).

We argue that the vegetation model accounts for the spatio-temporal variability of the vegetation cover. The spatial and intra-annual variability was obtained from the long-term average 16-day period NDVI for the period 2000-2012. The inter-annual variability was determined based on a log-linear relationship between the annual precipitation sum, annual average temperature, annual maximum temperature and annual average NDVI for each of the 57 landuse classes for the period 2000-2012, see the Supporting Information. Figure S5 shows the differences in NDVI (vegetation cover) between the reference scenario and the four future scenarios. To account for the plant-specific impact of climate change we have included an additional figure to the Supporting Information that shows the changes of plant water stress for the future scenarios with *respect to the reference scenario. Plant water stress is not only affected by changes in potential evapotranspiration, but also by changes in soil moisture, which is equally important for crop/plant development. The figure shows that rainfed agriculture is most affected by climate change, followed by natural land cover and irrigated agriculture.*

Although there are several weaknesses to the modelling of such a varied landscape, the authors have tried and cover this as well as possible. Still, it would be good to mention the resolution of the model in the text. This remains obscure now.

We have mentioned the resolution in the revised manuscruipt.

Also, the model is calibrated and validated and this has implications for its applicability for scenario modelling when conditions will change from the present-day conditions. Looking at the calibration-validation results, both the hydrological and erosion parts show a decrease in performance in terms of model efficiency and bias when moving from the calibration to the validation period. This suggests over-parameterization and its effect may worsen further in the future. Hence, the calibration and validation should be included in the main text and the implications covered in the discussion.

Accurate model calibration and validation is indeed very important and often one of the main challenges and time-consuming aspects of climate change impact assessments, with a continuous risk of over-parametrization. We have applied a calibration strategy minimizing risk of over-parameterization. To prevent overfitting and achieve most realistic model calibration we set most of the potential calibration parameters at literature values and maintained the other parameters within reasonable physical limits of the parameter domain. We have included this explanation to the revised manuscript (SI).

With regards to the erosion model, I am wondering to what extent the sediment delivery is adequately included when moving from the hillslopes (with fairly coarse resolution I presume) to the channel. The same applies to the transport capacity and whether this can be applied directly for the slopes and channels as sediment transport involves different mechanisms in these domains (bedload v. washload). Clarification of these details would be appreciated.

This is indeed a very important aspect of erosion and sediment yield modelling. The model uses the same equation to determine hillslope and channel erosion while a separate sediment deposition equation is used for channels (see Eekhout et al., 2018). Indeed, hillslope erosion and channel erosion are not captured by the same processes and should be handled with different formulae. However, currently, separated hillslope and channel erosion processes are only captured by detailed soil erosion models (such as WEPP), which cannot be applied at regional scales. This is acknowledged and discussed in more detail in Eekhout et al. (2018). In fact, we are currently working on an additional river module to improve this aspect of the model.

In terms of the scenarios, four scenarios result from a combination of two RCPs and two time periods. But what does this mean in terms of simulations? Are they ran consecutively or are they different simulations, representing a sort of dynamic equilibrium? This aspect is very important as it affects those components that have a memory ranging from short-term effects on the soil to longer term ones in relation to vegetation, groundwater and reservoir storage.

> *The model simulations were performed consecutively and included one start-up year to reach a dynamic equilibrium state for storage components (e.g. reservoirs and soil layers). We have clarified this in the revised manuscript (section 2.3).*

Furthermore, aspects pertaining to water management are not explained. Irrigation is widespread in the basin and water supply the purpose of most of the reservoirs. Yet, there is no information on the extent of irrigated areas, how this is covered by the models and how this interferes with reservoir storage and reservoir operation. Without this vital information, the reader cannot evaluate the merit of the simulations on his/her own.

> *Irrigation is not handled by the model. While large areas of the catchment are irrigated, our results focus on assessment of overall water availability in surface water that could potentially be used by irrigation or other demands. While interesting to assess the role of irrigation water demand, we argue that a separate irrigation module would introduce large uncertainties into the model outcome. There is also little information on additional irrigation water sources, i.e. from deep aquifers and from the Tagus-Segura water transfer. Such additional water supplies are hard to capture in a climate change study, especially, since we have no information on how this supply will change under future climate conditions. We have included more detailed information on other irrigation water sources to section 2.1. Furthermore, we have included discussion on the impact the increase in reservoir inflow, given future projections related to other sources to the Discussion and Conclusions section of the revised manuscript.*

Water security: As mentioned at the start, water security is not defined and only indirect measures of water stress and reservoir inflow are defined.

> *Water security is defined in the first paragraph of the Introduction. Depending on climate and water use, this definition can have different interpretations. Therefore, we have included an explanation why these particular water security indicators are the most relevant to quantify water security in the Segura catchment to section 2.4.*

Yet, one could argue that vegetation in the area is adapted to the adverse climate conditions.

> *Indeed, vegetation in this area is adapted to the current climate conditions. Desertification is a very urgent problem in semi-arid regions. While natural vegetation may be adapted to the current climate, it is doubtful if natural vegetation can resist future extreme climate conditions. A local plot-scale study showed that natural vegetation does not adapt to an increase of climate extremes (Léon-Sánchez et al., 2018).*

On cultivated lands irrigation is widely used to avoid stress conditions. Similar for reservoirs, the inflow may vary (as shown by shift in inflow in the manuscript; Figure 4 and S7) but the overall inflow increases and therefore more water can be stored and used for irrigation.

Indeed, as a result of an increase of reservoir inflow more water would become available for irrigation. However, currently the irrigation infrastructure is already under pressure, due to the increasing demand for irrigation water. Besides, the reservoirs are not the only source of irrigation water, which is also obtained from deep aquifers and from the Tagus-Segura water transfer. We have clarified this in section 2.1 and discussed this in the Discussion and Conclusions section of the revised manuscript.

In terms of water security, the main question is if long periods of drought can be survived (by the vegetation or by the dwindling levels in reservoirs). This facet, however, is not covered at all. This means that more direction should be given to the analysis and intensity, frequency and persistence should be covered as well. In the particular case of the plant water stress (PWS), it is doubtful that it can be averaged in space (natural vs agricultural vegetation) and in time as it is dependent on the growing season that is different for the different species and cultivars. Also, PWS will have different effects depending on the time of the year; water shortage over summer for natural, drought-tolerant species will have little effect and it will be more damaging during the wet season. The same holds for winter wheat. PWS is intuitively a useful metric but it should be handled with care and covered independently for different vegetation types.

We agree that plant water stress should be handled with care. An analysis of crop/plant specific impact of increased plant water stress would indeed be very interesting. Some crop/plant specific information is required to perform such analysis, such as the time a crop/plant can resist a certain (high) level of plant water stress. Unfortunately, this information is very difficult to obtain at regional scale. However, we have included an additional figure to the Supporting Information where we show the intra-annual variation of plant water stress for 9 aggregated landuse classes. This shows that most extreme increases are projected for rainfed agriculture, followed by natural land cover and irrigated agriculture. The figure is discussed in the Discussion and Conclusions section of the revised manuscript.

For the analysis of the sediment yield, I would like to see some further clarification on the yields (1.29 to 6 tonnes per hectare per year) seems quite large and I am wondering how much actually is fed to and trapped by the reservoirs.

The soil erosion values are in the range of the literature data we used to calibrate the soil erosion model (i.e. Cerdan et al., 2010; Maetens et al, 2012). The amount of sediment that is trapped in the reservoirs is shown in Figures 5 and S9. Reservoir sediment yield was calibrated with local reservoir sedimentation data, as described in the Supplementary Information.

Discussion and conclusion: As mentioned at the beginning, the manuscript does not succeed yet in quantifying the effect of extreme precipitation on water security. Overall, the findings agree with earlier studies undertaken at coarser spatial scales but these generally looked at water availability or hydrological extremes without investigating in detail spatial differences or changes in precipitation patterns as the manuscript by Eekhout et al. intends to do at the regional scale. Additional evidence here is needed and this may concentrate on the contribution of direct runoff compared to slow flow, runoff fractions and frequency of different rainfall intensities etc. Without this, the conclusion has too narrow a base and the relevance of the global picture of Figure 6 is not so great, the more so as it does not take the changes in precipitation in the future in account. In terms of the validity of the study, some additional discussion (and analysis) is required on the effect of vegetation, quality of the downscaling, calibration and validation and the coverage of irrigation etc. by the model. At the moment, some information appears quite magically near the end, such as the details on the land cover and the relevance of the findings for water management. While the introduction is succinct and relevant, some reworking of it in light of the discussion and conclusion will be in order.

We would like to stress that not all our findings agree with previous studies. We argue that previous studies may have underestimated the impact of extreme precipitation by not accounting for infiltration excess surface runoff. Many previous studies show a decrease of runoff, as a result of a decrease of annual precipitation. However, for many locations an increase of extreme precipitation is expected, which could lead to an increase of runoff and an important redistribution of water between green and blue water as shown in the current study.

As suggested in the previous comments by the reviewer, we have revised the manuscript with respect to the impact of extreme precipitation on different environments, the impact on the irrigation infrastructure and water demand, the description of the bias-correction method, the calibration strategy and details about the landuse. See previous comments for the specifics regarding these issues.

Overall, it shows care was taken to produce the text, figures and tables, also in the SI. This is much appreciated. Just some minor points:

Page 3, line 21: is the capacity of all 33 reservoirs 866 Hm3 or just the 14 for irrigation? And how does this compare to their inflow (Table S1)?

The total capacity of the 14 reservoirs used to store irrigation water is 866 Hm^3. Under the reference scenario, the total annual reservoir inflow amounts to 400 Hm^3, which is 46% of the total capacity of the 14 considered reservoirs. We have included this information in section 3.2 of the revised manuscript.

Equation 1: add the condition that this holds if theta_t < theta_pws else PWS= 0.

In the text below Equation 1 the following sentence was included: "PWS equals zero when $\theta(t) > \theta_{PWP}$".

Equation 3: what are the values for dtab and what was done for natural vegetation, they are not covered by Allen to my knowledge. Also, clarify ETp here.

The values for the depletion fraction range from 0.2-0.7. Indeed, Allen et al. (1998) mainly covers agricultural crops. For natural vegetation, we adopted values for vegetation types that are most closely related to natural vegetation, i.e. conifer trees for forest and grazing pasture for shrubland. We have clarified this in the revised manuscript. Potential evapotranspiration was obtained from the hydrological model, which is described in Terink et al. (2015).

Section 3.2: Redistribution of water. This is not a logical structure and the term does not connect to the previous part. Divide this into the part on PWS and the reservoir storage.

We have renamed this section: "Impact on Water Security".

Figure 3: what are the dots, next to the daggers and asteriskes? And please explain the design of the box plots. (what do the lines, boxes and bars mean?)

The dots are outliers, we have explained this in the caption, in addition to an explanation of the box plots.

As I said, an interesting read and I hope my comments and suggestions help to improve and publish the manuscript.

We would like to thank the reviewer for his nice comments on the manuscript and appreciate his suggestions that have certainly helped to improve the manuscript.

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List of all relevant changes made in the manuscript

- Adjusted the claims regarding sediment yield in the abstract and Discussion and Conclusion section
- Added relevant implications to the abstract and Discussion and Conclusion section
- Added a paragraph on the impact of extreme precipitation in different environments to the Introduction
- Added detailed information on agriculture and irrigation water supply to the Material & Methods
- Added a description of the quantile mapping method the Material & Methods
- Added information on model simulation to the Material & Methods
- Added reasoning for use of water security indicators to Material & Methods
- Added definition of extreme precipitation and dry spells to Material & Methods
- Added discussion on impact of climate change on hydrological indicators to Discussion and Conclusion section
- Added discussion on sediment yield to Discussion and Conclusion section
- Added discussion on implications of bias-correction to Discussion and Conclusion section
- Added discussion on impact on rainfed crops to Discussion and Conclusion section
- Added discussion on impact on irrigation water demand and supply to Discussion and Conclusion section
- Added information on calibration procedure to Supporting Information
- Added implications of precipitation fraction to Supporting Information
- Added figure of monthly average plant water stress per landuse class to Supporting Information
- Added table with catchment-average change of water security indicators to Supporting Information
- Added table with catchment-average change of hydrological indicators to Supporting Information

Why increased extreme precipitation under climate change negatively affects water security

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Abstract. An increase of extreme precipitation is projected for many areas worldwide in the coming decades. To assess the impact of increased precipitation intensity on water security, we applied a regional scale hydrological and soil erosion model, forced with Regional Climate Model projections. We specifically considered the impact of climate change on the distribution of water between soil (green water) and surface water (blue water) compartments. We show that an increase in precipitation intensity leads to a redistribution of water within the catchment, where water storage in soil decreases and reservoir inflow increases. This affects plant water stress and the potential of rainfed versus irrigated agriculture, and increases dependency on reservoir storage, that is ~~increasingly threatened by an increase of~~ potentially threatened by increased soil erosion. This study demonstrates the crucial importance of accounting for the fact that increased precipitation intensity leads to water redistribution between green and blue water, increased soil erosion, and reduced water security. Ultimately, this has implications for design of climate change adaptation measures, which should aim to increase the water holding capacity of the soil (green water) and to maintain the storage capacity of of reservoirs (blue water), benefiting rainfed and irrigated agriculture.

1 Introduction

For many areas worldwide, increased rainfall intensity and frequency of extreme weather events are projected for the coming decades (Sun et al., 2007; O'Gorman and Schneider, 2009; Sillmann et al., 2013). Yet, there is surprisingly little known about how this will affect water security at regional scales, most relevant for policy making (Nicholson et al., 2009). Water security is defined as a condition in which the population has access to adequate quantities of clean water to sustain livelihoods and is protected against water related disasters (UN-Water, 2013). Accurate quantification of the impacts of climate change on water security is crucial for the design and evaluation of effective adaptation strategies and implementation of the Sustainable Development Goals (SDGs; United Nations General Assembly, 2015), in particular SDG 6 (clean water and sanitation), SDG 13 (climate action) and SDG 15 (life on land). Previous impact studies have indicated how climate change may affect water availability, flood risk (Sperna Weiland et al., 2012; Arnell and Gosling, 2013; Forzieri et al., 2014; Donnelly et al., 2017; Thober et al., 2018) and soil erosion (Li and Fang, 2016), with positive and negative reported impacts. However, these estimates insufficiently account for actual impacts on the redistribution of water between soil and surface water compartments. While water storage potential in soils (green water) and reservoirs (blue water) is increasingly important for climate change adaptation, there is insufficient knowledge of how both are affected by increasing precipitation intensity and how this affects crucial aspects of water security such as plant water stress, reservoir inflow, soil erosion and reservoir storage potential.

~~Most available studies on~~ The expected increase of extreme precipitation will have multiple impacts on urban, natural and arable environments, and may for example cause increased flood frequency (e.g. Thober et al., 2018). However, as a result of increased temperature and, consequently, increased evapotranspiration, antecedent soil moisture conditions may change and affect the impact of ~~climate change on water security do not fully account for the impact of extreme precipitation on water redistribution and crucial hydrological and soil erosion processes. To assess the impact of climate change, hydrological~~ increased flood magnitude (Castillo et al., 2003; Ivancic and Shaw, 2015; Wasko and Sharma, 2017). In urban areas, an increase of extreme precipitation may affect inundation frequency and may pose challenges for stormwater infrastructure, which is often designed under the assumption of a stationary climate (Mishra et al., 2012). In natural environments, a combination of an increase of extreme precipitation and longer dry spells may cause an increase stress conditions for natural vegetation (Fay et al., 2003; Knapp et al., 2008; León-Sánchez et al., 2018). Rainfall intensity is one of the main drivers for soil erosion (Nearing et al., 1990) and is one of the dominant processes that may affect soil erosion under future climate conditions (Nearing et al., 2004 . In fact, both runoff and soil erosion are among the processes most sensitive to changes in rainfall intensity (Pruski and Nearing, 2002; Nune . Soil erosion of arable land and related loss of organic matter and nutrients is a major threat for agricultural productivity, which is already under pressure by increasing food demands (Pimentel et al., 1995).

Hydrological and soil erosion ~~models~~ studies on the impact of climate change are generally forced with future projected climate data from Global Circulation Models (GCMs). To enhance accuracy and spatial resolution of climate projections some studies adopt Regional Climate Models (RCMs) to downscale GCM output (Jacob et al., 2014) and apply bias-correction methods to overcome the bias between historical observed and modelled data. While the change factor (or delta change) approach is the most popular bias-correction method, other bias-correction methods that consider the change in future precipitation distribution are needed to assess the effects of changes in frequency and intensity of extreme events (Mullan et al., 2012; Li and Fang, 2016). The selection of climate models, downscaling and bias-correction methods strongly affects the climate projections (Maraun et al., 2017) and consequently also the simulated hydrological and erosional response. Moreover, most global and regional studies only consider saturation excess surface runoff and disregard infiltration excess surface runoff, which may lead to an underestimation of the actual impact of extreme precipitation on surface runoff generation. Saturation excess and infiltration excess are the main mechanisms causing surface runoff. They may co-exist within a catchment and occur at different times or places due to differences in spatio-temporal conditions, i.e. antecedent soil moisture, soil characteristics or precipitation intensities (Beven, 2012). Infiltration excess surface runoff is mainly driven by precipitation intensity and is responsible for major parts of surface runoff generation in many parts of the world, such as the Mediterranean (Merheb et al., 2016; Manus et al., 2008) and semi-arid environments (Lesschen et al., 2009; García-Ruiz et al., 2013), due to steep slopes, low infiltration rates and frequent intense precipitation events. Considering the estimated future increase of extreme precipitation ~~(Sun et al., 2007; O'Gorman and Schneider, 2009; Sillmann et al., 2013)~~in many regions, infiltration excess surface runoff will become increasingly more important.

Climate change will affect soil erosion through changes in precipitation volume and intensity and through climate change induced changes in vegetation cover. Climate change induced increase in extreme precipitation is likely to be a dominant factor causing future increase of soil erosion (Nearing et al., 2004; Nunes et al., 2008), as was demonstrated in various hillslope scale (Zhang et al., 2012; Mullan et al., 2012; Routschek et al., 2014) and catchment-scale event-based model studies (Baartman et al., 2012; Paroissien et al., 2015). Given the relevance of precipitation intensity, appropriate bias-correction methods and accounting for infiltration excess surface runoff are particularly important to assess the impact of climate change. However, large-scale assessments rarely consider the impact of increased extreme precipitation frequency on soil erosion rates. They are either applied at a low temporal resolution (e.g. monthly time steps), hence, focusing on changes in precipitation volume, or use bias-correction methods that do not consider changes in the frequency distribution (e.g. the delta change method), leading to strong underestimation of the impact of climate change. Furthermore, vegetation cover mitigates soil erosion through canopy interception and flow resistance (Nearing et al., 2004; Nunes et al., 2013). However, the interactions between reduced precipitation, increased temperature and changes in the vegetation cover are rarely assessed in soil erosion impact studies, while the change in vegetation cover may have a significant impact on hydrological and soil erosion processes (Nunes et al., 2009a).

Due to the inherent nature of the processes involved, such as infiltration excess surface runoff and soil erosion, the impact of extreme precipitation can only be assessed at a sufficiently detailed spatial and temporal scale. Therefore, the objective of this study was to examine the effect of climate change on water security through application of a spatially-distributed hydrological model (SPHY; Terink et al., 2015), coupled with a soil erosion model (MMF; Morgan and Duzant, 2008), that runs at a daily time step. The hydrological model simulates the main hydrological processes, including infiltration excess surface runoff. The model was applied to the Segura River catchment, a typical large Mediterranean river catchment, highly regulated by reservoirs. We applied the model to a reference scenario and 4 future climate scenarios, where we accounted for the multiple effects of climate change, including precipitation intensity, and seasonal and inter-annual vegetation development.

2 Material & Methods

2.1 Study Area

The study is performed in the Segura River catchment in the southeast of Spain (Figure 1). The catchment area covers 15,978 km^2 and has an elevation ranging between sea level and 2055 $\mathrm{m.a.s.l.}$ (Figure 1c). The climate in the catchment is classified as ~~temperate (Cfa and Cfb~~ Mediterranean (Csa according to the Köppen-Geiger climate classification) in the headwaters (19%) and semi-arid (BSk) in the rest of the catchment (81%). Catchment-averaged mean annual ~~rainfall~~ precipitation amounts to 361 mm (for the period 1981-2000) and mean annual temperature ranges between 9.3 and 18.7 $^{\circ}\mathrm{C}$ (1981-2000) in the headwaters and downstream area, respectively.

The main landuse types are shrubland (28%), forest (26%), cereal fields (14%) and almond orchards (9%) (Figure 1d). Agriculture accounts for 44% of the catchments surface area and can be subdivided into rainfed crops (31%; cereal fields, almond orchards, vineyards and olive orchards), irrigated crops (12%; fruit trees and horticulture) and other agriculture (1%). The main soil classes are Calcisols (41%), Leptosols (35%), Luvisols (4%) and Kastanozems (4%) (Figure 1e). There are 33 reservoirs in the catchment, from which 14 are allocated exclusively for irrigation purposes (Figure 1b and Table ~~S1~~S1) with a total capacity of 866 Hm^3. The other reservoirs have mixed functions for electricity supply and flood prevention. Besides reservoirs, irrigation water demand is also met with water from deep aquifers and the Tagus-Segura water transfer.

2.2 Model Description

We applied ~~a~~ the spatially-distributed ~~hydrological~~ Spatial Processes in HYdrology model (SPHY; Terink et al., 2015), coupled with ~~a~~ the Morgan-Morgan-Finney soil erosion model (MMF; Morgan and Duzant, 2008), described in detail in Eekhout et al. (2018). The hydrological model simulates the most relevant hydrological processes, such as interception, evapotranspiration, dynamic evolution of vegetation cover, including seasonal patterns and response to climate change, surface runoff, and lateral and vertical soil moisture flow at a daily timestep, here implemented at 200 m spatial resolution. The model simulates infiltration excess surface runoff based on the Green-Ampt formula (Heber Green and Ampt, 1911). The soil erosion model is based on the ~~Modified Morgan-Morgan-Finney~~ MMF model (Morgan and Duzant, 2008), runs at a daily time-step and is fully coupled with the hydrological model. Soil detachment is determined as a function of raindrop impact and accumulated runoff. In-field deposition is a function of the abundance of vegetation and soil roughness. The remainder will go into transport, considering the transport capacity of the flow and a sediment trapping formula to account for the deposition of sediment in reservoirs. The model incorporates a vegetation module that considers inter- and intra-annual vegetation development and provides vegetation input to both the hydrological and the soil erosion model (see SI and Eekhout et al. (2018) for a detailed description of the model, input data and calibration).

2.3 Climate scenarios

We applied four different future climate scenarios, divided over two future periods (i.e. 2031-2050 and 2081-2100) and two Representative Concentration Pathways (i.e. RCP4.5 and RCP8.5), describing an emission scenario peaking in 2040 followed by a decline (RCP4.5) and ~~one~~ an emission scenario with continuous increase of emissions throughout the 21st century (RCP8.5). We obtained data from a total of nine climate models (Table ~~S2~~S2) from the EURO-CORDEX initiative (Jacob et al., 2014), with a 0.11° resolution. Quantile mapping has been recognized as the empirical-statistical downscaling and bias-correction method that shows the best performance~~(Themeßl et al., 2011).~~, particularly for the highest quantiles (Themeßl et al., 2011). Changes in extreme precipitation may have a large impact on the hydrological and soil erosion processes, therefore, quantile mapping was selected for the current study. Quantile mapping first determines the probability of occurrence of the future precipitation from the empirical cumulative density distribution function (ecdf) of the historical climate model output. Then a correction factor is determined by feeding this probability into the inverse ecdfs of the historical observed and historical climate model output. Finally, the correction factor is added to the future precipitation. We adopted the method

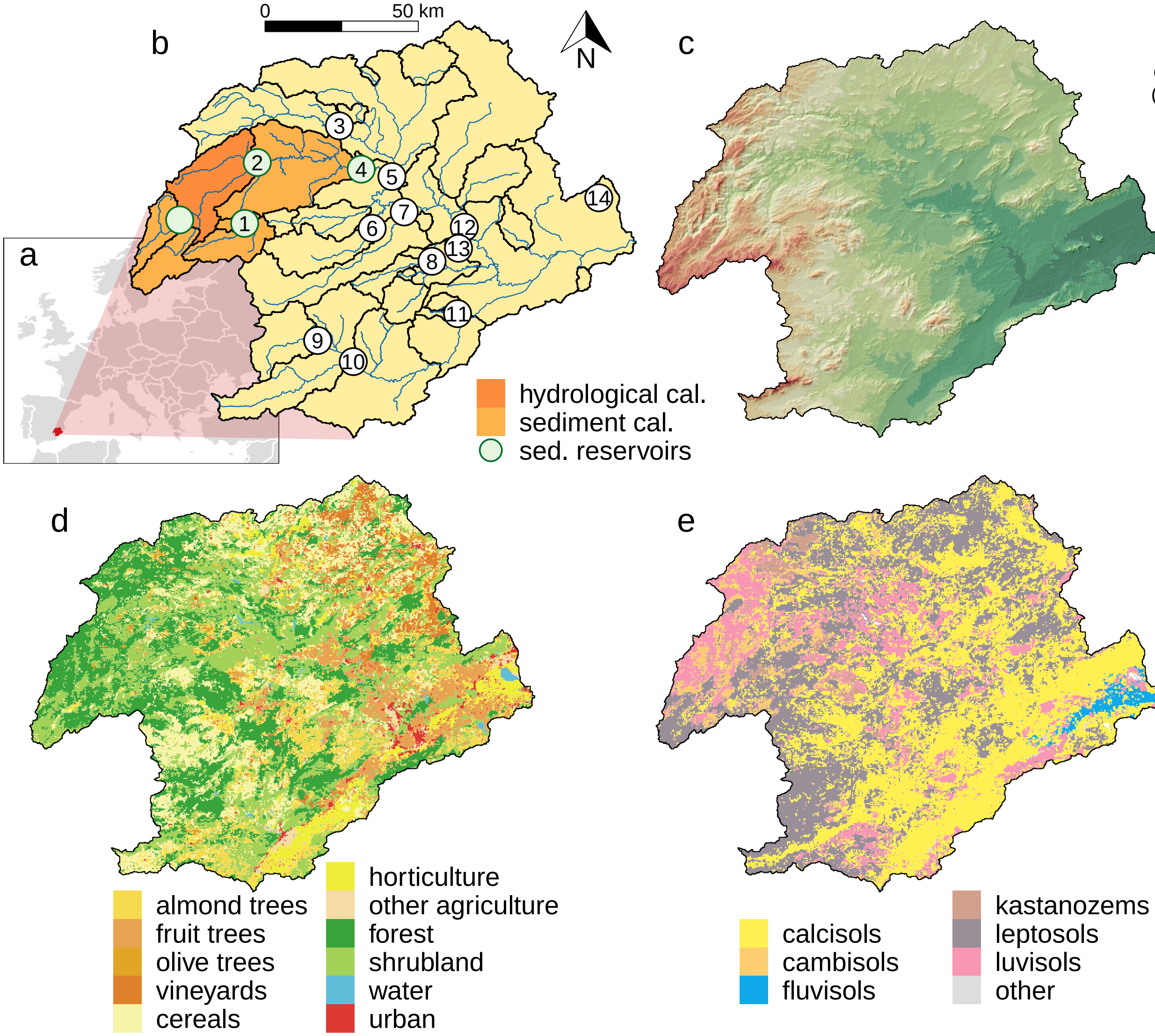

Figure 1. Location and characteristics of the Segura River catchment: (a) location of the catchment within Europe, (b) location of the subcatchments (yellow), the hydrological calibration area (dark orange), the soil erosion calibration area (light orange), the channels (blue), the reservoirs (numbers 1-14), and the calibration reservoirs (green dots), (c) Digital Elevation Model (Farr et al., 2007), (d) landuse map (MAPAMA, 2010), and (e) soil texture map (Hengl et al., 2017).

proposed by Themeßl et al. (2012) ~~, which utilizes Frequency Adaptation and~~ that accounts for the dry-day frequency, which could lead to uncertainties when the dry-day frequency of the historical climate model output is greater than in the historical observations. Furthermore, this method accounts for new extremes, ~~respectively,~~ to correct for ~~the dry-day effect and to correct for~~ new extreme precipitation values that do not occur in the ~~reference period~~historical observations. Daily precipitation and temperature data for the reference scenario (1981-2000) were, respectively, obtained from the SPREAD dataset (Serrano-Notivoli et al., 2017), with a 5 km resolution, and the SPAIN02 dataset (Herrera et al., 2016), with a 0.11° resolution. The model simulations were performed consecutively and included one start-up year, which was sufficient to reach a dynamic equilibrium state for storage components (e.g. soil moisture compartments and reservoir storage).

2.4 Water Security Indicators

We evaluated the impact of climate change on water security using plant water stress, reservoir inflow, hillslope erosion and reservoir sediment yield as impact indicators. These indicators are specifically important for this study area, which is dominated by rainfed and irrigated agriculture. Changes in plant water stress and hillslope erosion may affect agricultural productivity, while changes in reservoir inflow and reservoir sediment yield affect water availability for irrigated agriculture and drinking water.

Plant water stress, defined as an indicator between no stress (0) and fully stressed (1), was determined by comparing the soil moisture content in the root layer with the plant specific soil moisture content from which stress starts to occur and soil moisture at wilting point. Plant water stress is determined using the following equation (adapted from Porporato et al., 2001)):

$$\mathrm{PWS} = \frac{\theta_{\mathrm{PWS}} - \theta(t)}{\theta_{\mathrm{PWS}} - \theta_{\mathrm{PWP}}} \tag{1}$$

where PWS is the dimensionless plant water stress, $\theta(t)$ is the soil moisture content at timestep t, θ_{PWS} is the plant and soil specific soil moisture content from which plant water stress starts to occur and θ_{PWP} is the soil moisture content at permanent wilting point. ~~PWP~~ PWS equals zero when $\theta(t) > \theta_{\mathrm{PWP}}$. The value of θ_{PWS} is determined as follows (adapted from Allen et al., 1998):

$$\theta_{\mathrm{PWS}} = \theta_{\mathrm{FC}} - d(\theta_{\mathrm{FC}} - \theta_{\mathrm{PWP}}) \tag{2}$$

where θ_{FC} is the soil moisture content at field capacity, and d is the depletion fraction. The depletion fraction is a plant specific factor ~~, which~~ and is a function of the potential evapotranspiration (Allen et al., 1998):

$$d = d_{\mathrm{tab}} + 0.04(5 - ET_{\mathrm{P}}) \tag{3}$$

where d_{tab} is the tabular value of the depletion fraction and ET_{P} is the potential evapotranspiration obtained from the hydrological model. Values for d_{tab} were obtained from Allen et al. (1998). Allen et al. (1998) mainly focusses on agricultural crops. For natural vegetation, we adopted values for vegetation types that are most closely related to natural vegetation, i.e. conifer trees for forest and grazing pasture for shrubland.

Reservoir inflow of the 14 reservoirs used for irrigation is defined as the cumulative discharge sum in the upstream area of a reservoir. In this calculation, only the area is considered that belongs to one reservoir. If the upstream area of a reservoir contains one or more other reservoirs, the discharge originating from these areas is omitted. Hillslope erosion was determined from the long-term average soil erosion map. Per subcatchment we determined the average of all the cells with an upstream area smaller than 10 km^2, representing hillslope erosion. Reservoir sediment yield was determined from the sediment yield timeseries obtained at each reservoir. Per reservoir we determined the average yearly sediment yield. From reservoir sediment yield we determined annual capacity loss, by dividing the reservoir sediment yield by the storage capacity of the reservoir.

2.5 Uncertainty Analysis

To account for uncertainty we evaluated the robustness and significance of the climate projections and the model predictions ~~between the~~ within the climate model ensemble of 9 climate models. This only reflects climate model uncertainty, not the uncertainty related to other sources, such as the SPHY-MMF model. Robustness is defined as the agreement of the simulations in terms of the direction of change, i.e. changes in which more than 66% of the models agree in the direction of change were called robust changes. A paired U-test (Mann–Whitney–Wilcoxon test, with a significance level of 0.05) was applied to test the significance of model outcomes for the 9 climate models. The pairs consisted of the model output for (1) the reference scenario and (2) the 9 climate models. The paired U-test is also applied to determine the significance of the catchment-averaged change with respect to the reference scenario.

3 Results

3.1 Climate Change Signal

The future climate scenarios predict a significant 20-135 mm decrease of annual precipitation in the headwaters of the catchment, corresponding to a decrease of 3 to 24%, with respect to the reference scenario (Figures 2 (upper row) and 3). Scenario S4 predicts significant decreases in the entire catchment, with a catchment-average decrease of 18% ($p<0.01$). All future scenarios show a robust and significant increase of annual average temperature, with changes from 1.2 °C (scenario S1) to 3.9 °C (scenario S4) (Figures 3 and ~~S3~~S3).

Changes in the intensity and frequency of precipitation may be the most relevant climate signal affecting water security, which we assessed through the intensity of extreme precipitation and the duration of dry spells. Extreme precipitation is defined as the 95th percentile of daily precipitation, considering only rainy days (>1 mm day^{-1}; Jacob et al., 2014)). Dry spells are defined as the 95th percentile of the duration of periods of at least 5 consecutive days with daily precipitation below 1 mm (Jacob et al., 2014). Under future climate conditions, extreme precipitation is likely to increase significantly in almost the entire catchment, with largest increases found for scenario S4 (Figures 2 (lower row) and 3). The duration of dry spells ~~, periods of 5 consecutive days with less than 1 precipitation (Jacob et al., 2014),~~ is likely to significantly increase by 7-9 days (catchment-average, $p<0.02$) for scenarios S1-3 and by 26 days for scenario S4 ($p<0.01$) (Figures 3 and ~~S4~~S4). These results suggest a significant decrease of precipitation frequency in all 4 scenarios.

3.2 ~~Redistribution of~~ Impact on Water Security

In the reference scenario, water availability shows a distinct seasonal pattern (Figures 4, ~~S6 and S7~~S6 and S8). Reservoir inflow peaks in the autumn and winter months. ~~In those two seasons~~The total annual reservoir inflow equals 400 Hm^3, which is 46%

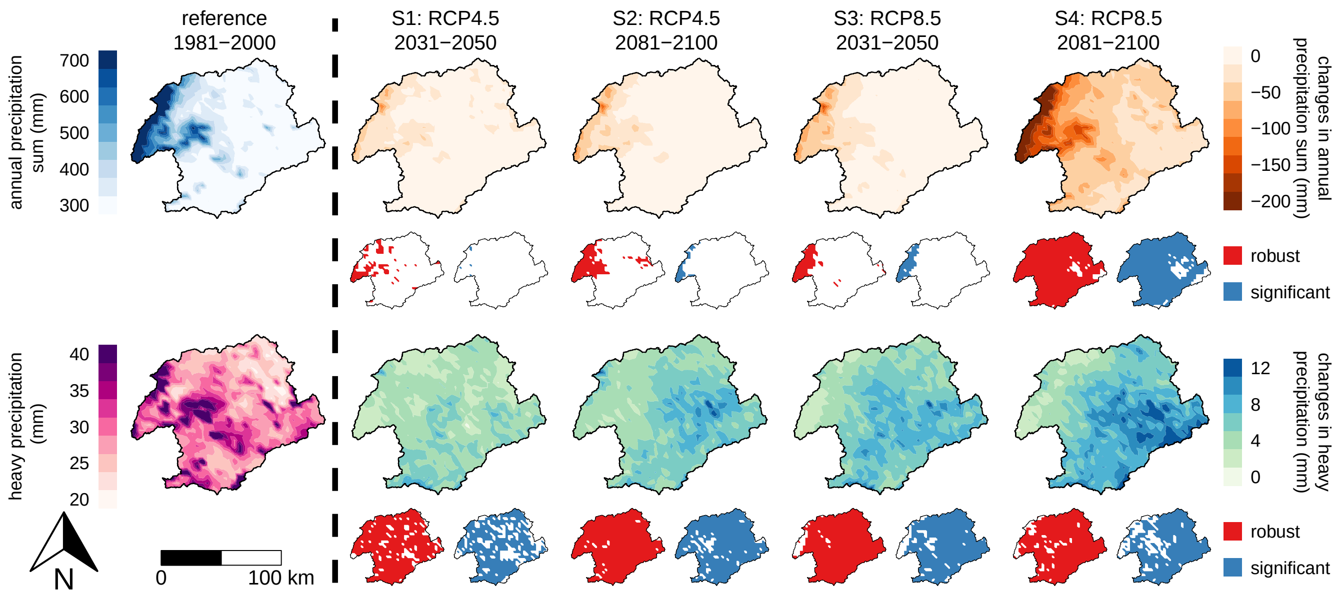

Figure 2. Ensemble average annual precipitation sum (mm, upper row) and ensemble average heavy precipitation (mm, lower row) defined as the 95th percentile of daily precipitation, considering only rainy days ($>1\ \mathrm{mm\,day^{-1}}$; Jacob et al., 2014)), for the reference scenario (left) and changes between the reference scenario and the four future scenarios (right).

of the total capacity of the fourteen reservoirs used for irrigation. In the autumn and winter months, the plant water stress is low, except in the downstream part of the catchment. In the spring and more pronounced in the summer, reservoir inflow decreases and plant water stress increases. Plant water stress reaches a maximum in the summer, where the catchment-average equals 0.88.

Changes in water availability under future climate conditions show a seasonal pattern as well. In the winter months (DJF) the catchment-total reservoir inflow decreases in all scenarios, up to 36% (p<0.01) in scenario S4. Significant changes in plant water stress are projected for scenarios S2-S4 showing a catchment-average increase of 0.04 (p=0.03) to 0.11 (p<0.01). In contrast, reservoir inflow in spring (MAM) increases in all scenarios, most markedly in scenario S3 with an increase of 85% (p=0.07). A small increase in plant water stress is observed in scenarios S1-3, however, scenario S4 shows a significant catchment-average increase of 0.09 (p<0.01).

Similar results are projected for the summer months, with significant changes in plant water stress in scenario S4, showing a catchment-average increase of 0.04 (p<0.01). Surprisingly, despite of the decreasing annual precipitation, in the summer months (JJA) reservoir inflow increases, with a maximum of 119% (scenario S3, p=0.01). In the autumn months (SON) catchment-average plant water stress increases most of all seasons, ranging from 0.05 to 0.11 (p<0.01). In autumn, reservoir inflow increases in all scenarios, with a maximum of 37% (scenario S2, p=0.16). Overall, a significant yearly increase of reservoir inflow is projected for scenarios S1-3, with a maximum in scenario S3 of 28% (p<0.01) with respect to the reference

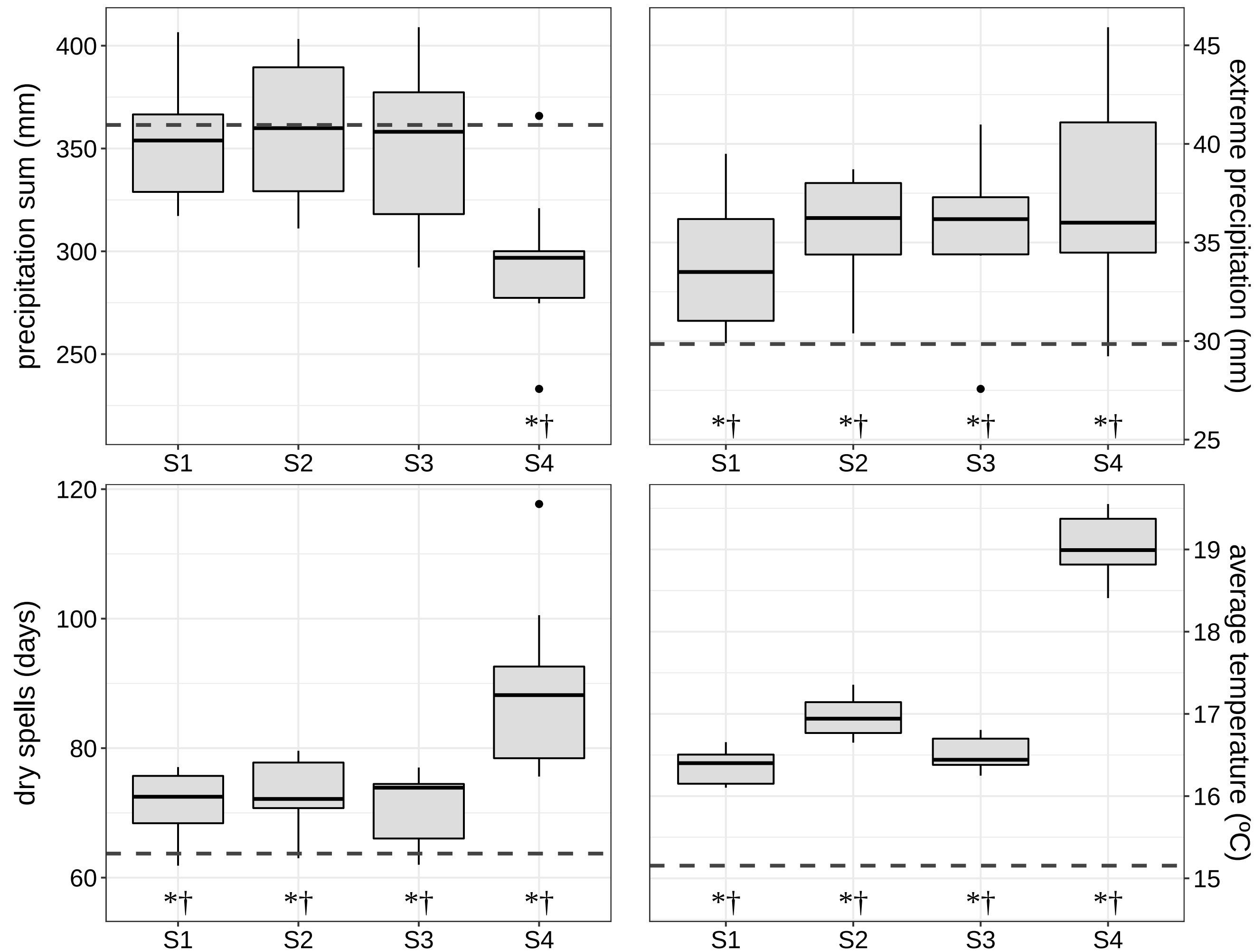

Figure 3. Catchment-average climate signal indicators, i.e. precipitation sum (mm), extreme precipitation (mm), dry spells (days) and average temperature (°C). The boxplots indicate the spread of the catchment-average among the nine climate models. In each panel the horizontal dashed line represents the catchment-average value for the reference scenario. An asterisk ($*$) indicates a robust change and a dagger (†) indicates a significant change ($p<0.05$). The hinges indicate the 25th and 75th percentiles, the thick horizontal line indicates the median, the whiskers indicate 1.5 times the inter quantile range from each of the two hinges and the dots indicate outliers.

scenario (Table S3). The yearly catchment-average plant water stress increases significantly in all scenarios ($p<0.01$), ranging from 0.03 (scenario S1) to 0.09 (scenario S4), equivalent to a 5-14% increase (Table S3).

To understand water security and assess the potential for climate change adaptation, it is important to consider water storage capacity in reservoirs, and storage capacity loss due to soil erosion. In the reference scenario, reservoir sediment yield (SY) corresponds to a total annual capacity loss of 0.11% (Figures 5 and ~~S8~~S9). The average hillslope erosion (SSY) in the sub-catchments ranges between 129 and 622 $\mathrm{Mg\,km^{-2}\,yr^{-1}}$. Under future climate conditions, an increase of hillslope erosion is

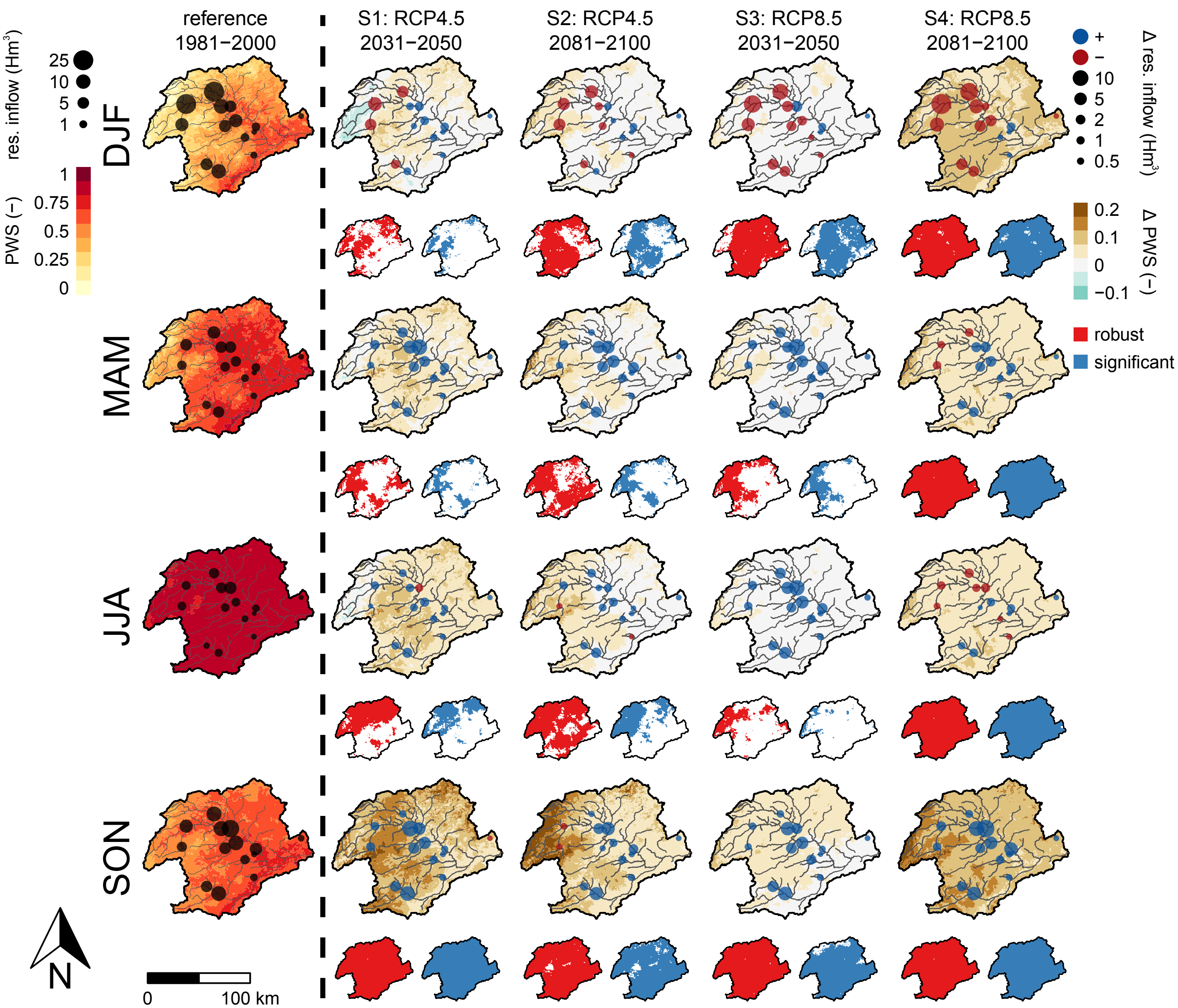

Figure 4. Ensemble average seasonal reservoir inflow (dots, Hm^3) and plant water stress (PWS) (-) for the reference scenario (left) and changes between the reference scenario and the four future scenarios (right), differentiated by season: winter (DJF), spring (MAM), summer (JJA), and autumn (SON). For the future scenarios, the reservoir inflow is presented as an increase (blue) or a decrease (red).

observed in all scenarios (~~S1–S4~~S1-4). Hillslope erosion mainly increases in the central and downstream located subcatchments. In the headwaters, hillslope erosion decreases due to a decrease of annual precipitation (Figure 2) and an increase in vegetation cover (Figure ~~S5~~S5). The increase in catchment-average hillslope erosion ranges from ~~23~~24% (p=0.13) to ~~45~~46% (p=0.01). Reservoir sediment yield increases in scenarios ~~S1–S3~~ S1-3 and decreases in scenario S4. However, significant changes in

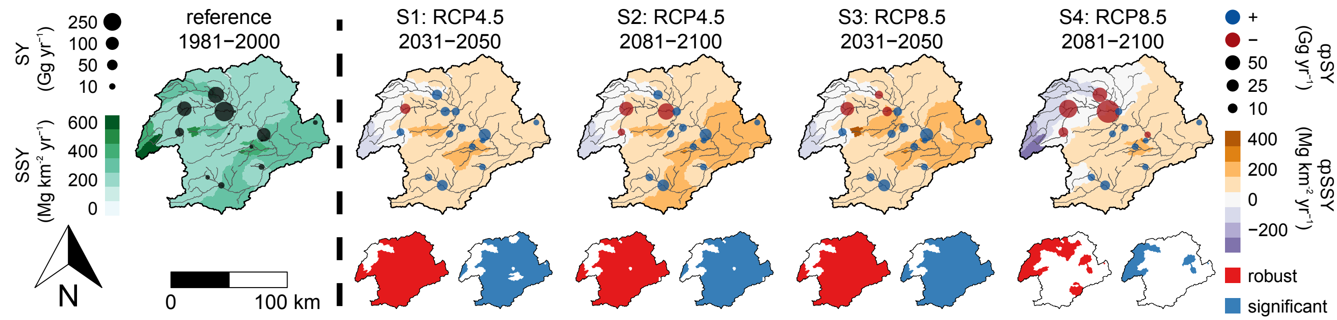

Figure 5. Ensemble average sediment yield (SY) at the reservoirs (dots, $\mathrm{Gg\,yr^{-1}}$) and average hillslope erosion (SSY) per subcatchment ($\mathrm{Mg\,km^{-2}\,yr^{-1}}$) for the reference scenario (left) and changes between the reference scenario and the four future scenarios (right). For the future scenarios, the SY is presented as an increase (blue) or a decrease (red).

sediment yield are only observed in scenario S4, with a decrease of ~~22~~33% ($p<0.01$) due to decreasing sediment transport capacity in channels.

4 Discussion and Conclusions

Previous studies concluded that climate change leads to reduced water availability in those areas where lower future annual precipitation sums are projected, evidenced by increased drought indices and reduced streamflow (Sperna Weiland et al., 2012; Arnell and Gosling, 2013; Lopez-Bustins et al., 2013; Forzieri et al., 2014). Our results confirm this, but more importantly we show ~~an~~ a significant redistribution of water under future climate conditions, resulting in increased plant water stress due to a reduction of soil water content (green water), ~~and increased water and sediment~~ increased soil erosion and water inflow into streams and reservoirs (blue water), leading to an overall reduced water security. The redistribution of water is mainly driven by an increase in extreme precipitation ~~(Figure 2)~~ and a decrease of precipitation frequency~~(Figure S4)~~, and to a lesser extent by a change in annual precipitation volume (~~Figure 2~~ Figures 2 and S4). The increase in extreme precipitation causes an increase in surface runoff and, subsequently, an increase in reservoir inflow and soil erosion. As such, climate change eventually leads to a reduction of infiltration into the soil, which negatively affects soil moisture content (Table S4) and, subsequently, leads to an increase in plant water stress (Figure 4 and Table S3), which is a crucial impact indicator for ~~rainfed agricultural~~ agriculture and natural ecosystems, and may point towards reduced crop yield and natural vegetation cover (Allen et al., 1998).

The four climate change scenarios can be subdivided into moderate (scenarios S1-3) and extreme (scenario S4) climate conditions and related impacts. The moderate climate conditions are mainly characterized by limited reductions of annual precipitation sum and increased temperature (Figure 3). This results in increase of plant water stress, due to a decrease of (actual) evapotranspiration and soil moisture content (Table S4). The extreme climate conditions (scenario S4) are characterized by a significant decrease of precipitation and an increase of dry spells and average temperature (Figure 3). An increase of temperature often leads to an increase of evapotranspiration, however, less water will infiltrate into the soil due to the significant decrease of precipitation and its increased intensity. As a result, actual evapotranspiration and soil moisture content significantly decrease under these extreme conditions (Table S4), leading to a significant increase of plant water stress in all seasons (Figure 4).

Previous studies indicated that soil erosion can either decrease or increase under climate change due to the combined effect of decreasing precipitation, increasing intensity and changing vegetation cover (Li and Fang, 2016). ~~However, most previous studies do not, or insufficiently, account for crucial processes like infiltration excess surface runoff, and intra- and inter-annual vegetation development as affected by climate change.~~ Our results show an increase in hillslope erosion due to increased precipitation intensity in the majority of the subcatchments, leading to an increase of sediment yield ~~towards streams and~~ in most reservoirs (Figure 5). ~~However, the~~ Increased soil erosion may affect water security directly due to its effect on soil depth, loss of soil organic matter content, and reduced water retention capacity. However, despite the increased soil erosion rates, the catchment-total reservoir sediment yield remains constant or even decreases, due to a decrease in the transport capacity of the flow resulting from a decrease in runoff in the headwaters, most pronounced in scenario S4. This further illustrates the importance of accounting for sediment transport capacity and the different response of hillslope erosion as compared to catchment sediment yield~~.~~, which is still insufficiently accounted for in the current model and one of the main challenges in soil erosion and sediment yield models (de Vente et al., 2013). So, although we did not find significantly increased reservoir storage capacity loss due to climate change in our study, loss of reservoir storage capacity is an important aspect affecting water security in many areas worldwide and requires attention when assessing water security (de Vente et al., 2005; Wisser et al., 2013).

~~Our results show that increased~~ Increased precipitation intensity leads to increased surface runoff, soil erosion, and redistribution of water within the catchment. While it is well established that extreme precipitation leads to surface runoff Beven (2012) and significantly contributes to soil erosion (Favis-Mortlock and Mullan, 2011), most large-scale impact assessments do not consider the most relevant process involved, i.e. infiltration excess surface runoff. A rough preliminary estimate indicates infiltration excess ~~overland flow~~ surface runoff actually plays a substantial role in about one quarter of the global land surface (Figure 6) where extreme precipitation intensity exceeds the infiltration capacity of the soil. Therefore, we argue that, to account for the impact of increased extreme precipitation on water security, it is crucial to consider infiltration excess surface runoff in hydrological and soil erosion assessments. Furthermore, we applied a bias-correction method (quantile mapping) that explicitly accounts for changes in the projected precipitation distribution. Many previous studies applied the change factor (or delta change) method, which does not fully account for the changes in rainfall intensity. Studies that apply this method often show that a change of annual rainfall leads to a similar direction of change of runoff and soil erosion (e.g., Shrestha et al., 2013; Correa et al., 2016). Therefore, future studies should consider bias-correction methods that account for changes in frequency and intensity of extreme events that affect both hydrology and soil erosion (Mullan et al., 2012; Li and Fang, 2016).

Our analysis further shows that, in general, plant water stress and reservoir inflow both increase under future climate conditions. For agriculture, which amounts to more than 40% of the catchment surface area, this may have significant consequences. ~~An increase of~~ Rainfed crops (covering 31% of the catchment) are most affected by increases in plant water stress ~~for~~ (Figure S7). Seasonal changes in plant water stress (i.e. increase plant water stress in autumn), will strongly affect the harvest and

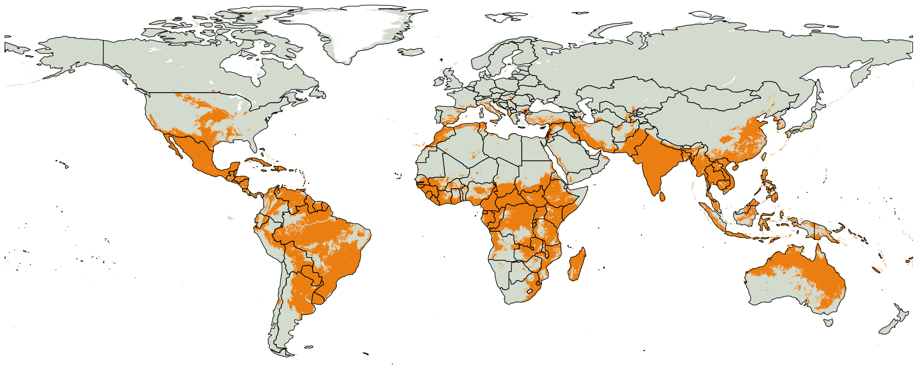

Figure 6. Global map indicating the areas (in orange) prone for infiltration excess surface runoff, defined as those areas where extreme precipitation exceeds the infiltration rate (Figure S2). See SI for more details.

seeding period of the dominant rainfed crops (e.g. ~~cereals and almond trees, covering 29% of the catchment)~~(winter) cereal and almonds), which may lead to decreasing crop yields (Allen et al., 1998). On the other hand, increased reservoir inflow may be beneficial for irrigated agriculture (~~e.g. horticulture and fruit, covering 19~~covering 12% of the catchment). ~~These changes have short-term and long-term consequences. On the short-term seasonal changes in plant water stress (i. e. increase~~ The current annual irrigated water demand equals 1101 Hm^3 (Confederación Hidrolgráfica del Segura, 2015). Hence, 36-46% of the irrigated water demand can be met with the annual natural reservoir inflow under future climate conditions. However, an increase of plant water stress ~~in autumn), will strongly affect the harvest and seeding period of the dominant crops (e. g. winter cereal and almonds; Figure 4). Long-term consequencesmay include~~ is also projected for irrigated crops (Figure S7), which would lead to increasing water demand. Currently, irrigation water demand is partly met with water abstractions from deep aquifers and from the Tagus-Segura water transfer. Previous studies have shown that the deep aquifers in the study area are already overexploited (Rupérez-Moreno et al., 2017; Pellicer-Martínez and Martínez-Paz, 2018), which reduces the prospects for future irrigation water extraction. Furthermore, the already highly debated Tagus-Segura water transfer will most likely suffer from reduced water supply under future climate conditions (Lobanova et al., 2017). While increasing water supply from reservoirs is projected, the future sustainability of irrigated crops will most likely decrease due to increased plant water stress, depleted aquifers and reduced water supply from the Tagus-Segura water transfer.

These changes also have other long-term consequences. Increasing plant water stress in rainfed agriculture may cause a shift from rainfed to irrigated agriculture, a trend that is already taking place (Nainggolan et al., 2012) and that would increase the dependency on reservoir storage and irrigation infrastructure. Further land abandonment can be foreseen in areas without access to irrigation water, leading to an increase of shrubland and forest, with significant consequences for ecosystem functioning and rural livelihoods and possible decreased streamflow (Beguería et al., 2003; García-Ruiz et al., 2011). On the other hand, our findings illustrate that careful design of land management in rainfed areas can directly affect water availability for irrigated agriculture, i.e. water available in reservoirs. The design of climate change adaptation strategies should therefore consider their effect on the redistribution of water from green to blue water and the long-term socio-economic consequences. For example, sustainable land management can possibly form a more cost-effective adaptation option to increased extreme precipitation than investing in larger reservoirs and irrigation infrastructure (Sanz et al., 2017).

~~Our~~ Overall, our results illustrate that representation of pertinent hydrological processes and suitable bias-correction methods are crucial for accurate climate change impact assessments. To increase water security under climate change we show there is a need for effective adaptation strategies that aim to increase the water holding capacity of the soil (green water) and to reduce soil erosion in order to enhance soil quality and maintain the storage capacity of reservoirs (blue water), benefiting rainfed and irrigated agriculture.

Competing interests. The author declares that they have no conflict of interest.

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1 Model Description

We applied the Spatial Processes in HYdrology (SPHY) hydrological model (Terink et al., 2015), which is a spatially distributed leaky-bucket type of model applied on a cell-by-cell basis at a daily time step. The SPHY model is fully coupled with the Morgan-Morgan-Finney soil erosion model (MMF; Morgan and Duzant, 2008). The SPHY-MMF model is described in detail in Eekhout et al. (2018) and can be accessed at this location: https://github.com/JorisEekhout/SPHY/tree/SPHY2.1-MMF.

1.1 Hydrological Model

SPHY simulates most relevant hydrological processes, such as interception, evapotranspiration, dynamic evolution of vegetation cover (including seasonal patterns and response to climate change), surface runoff, and lateral and vertical soil moisture flow. Here we describe the main modification we made for this study, i.e. the inclusion of a infiltration excess surface runoff equation. See Terink et al. (2015) for a detailed description of the model.

We incorporated an infiltration excess equation, which runs at a daily time step. The equation is inspired by the Green-Ampt formula (Heber Green and Ampt, 1911). We assumed a constant infiltration rate f $(\mathrm{mm\,hr^{-1}})$, which is determined for each cell and each day by:

$$f = \frac{K_{\mathrm{eff}}}{24}\left[1+\frac{\theta_{\mathrm{sat}}-\theta}{\theta_{\mathrm{sat}}}\right]^{\lambda} \tag{1}$$

where K_{eff} is the effective hydraulic conductivity, θ_{sat} is the saturated water content, θ is the actual water content, and λ is a calibration parameter. Bouwer (1969) suggested an approximation of $K_{\mathrm{eff}} \approx 0.5\,K_{\mathrm{sat}}$.

Infiltration excess surface runoff occurs when the precipitation intensity exceeds the infiltration rate f (Beven, 2012). Analysis of hourly precipitation time series for 25 years (1991-2015) from 5 precipitation stations in the catchment showed that, on average, the highest precipitation intensity was recorded in the first hour of the rain storm and decreases linearly until the end of the storm. We assumed a triangular-shaped precipitation intensity $p(t)$ $(\mathrm{mm\,hr^{-1}})$ according to:

$$p(t) = -\frac{1}{2}\alpha^2 P t + \alpha P \tag{2}$$

where α is the fraction of daily rainfall that occurs in the hour with the highest intensity, P is the daily rainfall (mm), and t is an hourly time step. Daily infiltration excess surface runoff Q_{surf} is determined as follows:

$$Q_{\mathrm{surf}} = \begin{cases} \dfrac{(\alpha P - f)^2}{\alpha^2 P} & \text{if } \alpha P > f \\ 0 & \text{if } \alpha P \leq f \end{cases} \tag{3}$$

When the hourly precipitation intensity αP is higher than the infiltration rate f, surface runoff equals the triangular shaped area of the precipitation above the infiltration rate. The amount of precipitation below the infiltration rate will infiltrate into the rootzone. Parameter α was set to 0.34, which follows from the analysis of the hourly rainfall data.

1.2 Daily Morgan-Morgan-Finney soil erosion model

We integrated the Morgan-Morgan-Finney (MMF; Morgan and Duzant, 2008) soil erosion model into the SPHY hydrological model. MMF is a conceptual soil erosion model that originally is applied at an annual time step. We modified the original MMF model such that it runs at a daily time step and is fully integrated into the SPHY model. This means that MMF receives input from the SPHY model, such as effective precipitation (throughfall), runoff and canopy cover.

Detachment of soil particles is determined separately for raindrop impact and surface runoff. The detachment of soil particles by raindrop impact (F; $\mathrm{kg\,m^{-2}}$) is a function of the kinetic energy of the effective rainfall, the detachability of the soil (K; $\mathrm{J\,m^{-2}}$) and the ground cover (GC; expressed as a proportion between zero and unity). The kinetic energy of the effective rainfall is in turn determined separately for direct throughfall and leaf drainage, and is subsequently summed to obtain the total rainfall energy KE. Canopy cover (fraction between 0 and 1 and obtained from the dynamic vegetation module) is used to separate direct throughfall and leaf drop from effective precipitation. The ground cover protects the soil from detachment and includes the proportion of vegetation and stones covering the surface and is set to 1 in case of the presence of snow. In order to allow for the particle-size distribution of the soil, the effective rainfall is proportioned according to the proportion of clay (c), silt (z) and sand (s) particles in the soil and subsequently summed:

$$F_i = K_i \frac{\%i}{100}(1-GC)KE \times 10^{-3} \tag{4}$$

With i the textural class, ~~with~~ i.e. c for clay, z for silt and s for sand. Based on data from Quansah (1982), values of K_c, K_z and K_s are taken respectively as 0.1, 0.5 and 0.3 $\mathrm{g\,J^{-1}}$.

The detachment of soil particles by runoff (H; $\mathrm{kg\,m^{-2}}$) is a function of the volume of accumulated runoff (Q; mm), the detachability of the soil by runoff (DR; $\mathrm{g\,mm^{-1}}$), the slope angle (S; °) and the ground cover (GC; -). The detachment by runoff is also proportioned by texture class and subsequently summed:

$$H_i = DR_i \frac{\%i}{100} Q^{1.5}(1-GC)\sin^{0.3} S \times 10^{-3} \tag{5}$$

Based on data from Quansah (1982), values of DR_c, DR_z and DR_s are taken respectively as 1.0, 1.6 and 1.5 $\mathrm{g\,mm^{-1}}$.

The detachment of soil particles by raindrop impact (F) and runoff (H) are subsequently summed. Only a proportion of the detached soil will be delivered to the runoff for transport, the remainder will be deposited within the cell of its origin. The percentage of the detached sediment that is deposited within the cell of its origin is estimated from the relationship obtained by Tollner et al. (1976), calculated separately for each particle size:

$$DEP_{c,z,s} = 44.1 N_{f_{c,z,s}}^{0.29} \tag{6}$$

Where N_f is the particle fall number and DEP is maximized by 100. The particle fall number is a function of the flow velocity, which is a function of the presence and abundance of vegetation and the surface roughness.

The amount of soil particles that will be delivered to the runoff for transport is calculated as follows:

$$G = \sum_{c,z,s}(F_{c,z,s} + H_{c,z,s})(1-(DEP_{c,z,s}/100)) \tag{7}$$

1.3 Sediment Routing

Transport of sediment by runoff is restricted by the transport capacity of the flow. We modified the transport capacity equation as proposed by Prosser and Rustomji (2000) by introducing a landuse-specific roughness factor:

$$TC = \mathrm{flow_{factor}} q^{\beta}\, S^{\gamma} \tag{8}$$

Where $\mathrm{flow_{factor}}$ is a spatially distributed roughness factor, q is the accumulated runoff per unit width ($\mathrm{m^2\,day^{-1}}$), S is the local energy gradient, approximated by the slope, and β and γ are model parameters. As suggested by Prosser and Rustomji (2000) we set $\gamma = 1.4$ and we used β in the calibration procedure. The landuse-specific roughness factor $\mathrm{flow_{factor}}$ is a function of the presence and abundance of vegetation and the surface roughness.

Reservoir sediment trapping efficiency, the percentage of sediment trapped by the reservoir, is calculated according to Brown (1943):

$$TE = 100\left[1 - \frac{1}{1+0.0021D\frac{C}{A_{\mathrm{basin}}}}\right] \tag{9}$$

where TE is the trapping efficiency (%), D is a constant within the range 0.046-1, we adopted the mean value of 0.1, C is the reservoir capacity ($\mathrm{m^3}$), and A_{basin} is the drainage area of the subcatchment ($\mathrm{km^2}$).

1.4 Dynamic Vegetation Module

SPHY-MMF includes a dynamic vegetation module that allows characterization of the seasonal and inter-annual differences in vegetation cover. A time series of the Normalized Difference Vegetation Index (NDVI) images is used as input for the dynamic vegetation module. The Leaf Area Index (LAI) is determined from the individual NDVI images using a logarithmic relation (Sellers et al., 1996). The LAI is used in the hydrological model to determine canopy storage, interception and the resulting precipitation throughfall. The latter is subsequently used in both the hydrological and soil erosion model. The canopy cover, from the soil erosion model, is defined as the LAI maximized by 1. The NDVI is also used to determine the crop coefficients, which are used in the calculation of the potential evapotranspiration. Crop coefficients are determined from NDVI with a linear relation. See Terink et al. (2015) for a detailed description of the dynamic vegetation module.

1.5 Model input data

All model input data were prepared at a 200 m resolution. Textural fractions (sand, clay and silt) and organic matter content were obtained from the global SoilGrids dataset (Hengl et al., 2017) at 250 m resolution. The soil hydraulic properties (saturated hydraulic conductivity, saturated water content, field capacity, and wilting point) were obtained by applying pedotransfer functions (Saxton and Rawls, 2006).

The SRTM dataset (Farr et al., 2007) at 30 m resolution was resampled to the model grid to obtain a Digital Elevation Model (Figure 1d). The spatially distributed rock fraction map was obtained by applying the empirical formulations from Poesen et al. (1998), which determines rock fraction based on slope.

Both the hydrological and the soil erosion model require landuse-specific input. We used a national landuse map (MAPAMA, 2010), which provides 57 landuse classes within the study area. Values for the landuse-specific tabular value of the depletion fraction were obtained from Allen et al. (1998) (Table 22). Values for the maximum LAI were obtained from Sellers et al. (1996). The soil erosion model requires landuse-specific input for plant height, stem density, stem diameter, canopy cover fraction, ground cover fraction and Manning's roughness coefficient for vegetation. We obtained values for each of these parameters through observations from aerial photographs, expert judgement and as part of the calibration procedure.

NDVI images were obtained from bi-monthly Moderate Resolution Imaging Spectroradiometer (MODIS) data for the period 2000-2012. For model calibration (2001-2010) we used each of the individual NDVI images, after gap-filling (mainly due to cloud cover) with the long-term average 16-day period NDVI for the period 2000-2012.

For the reference and future scenarios no NDVI images of sufficient quality and resolution were available, therefore we prepared the NDVI model input, accounting for the intra- and inter-annual variability. The intra-annual variability was obtained from the long-term average 16-day period NDVI for the period 2000-2012. The inter-annual variability was determined based on a log-linear relationship between the annual precipitation sum, annual average temperature, annual maximum temperature and annual average NDVI for each of the 57 landuse classes for the period 2000-2012:

$$\begin{aligned} NDVI_{\text{year}} = & \beta_0 + \log(P_{\text{year}})\beta_1 + \log(P_{\text{year-1}})\beta_2 + \log(Tavg_{\text{year}})\beta_3 \\ & + \log(Tavg_{\text{year-1}})\beta_4 + \log(Tmax_{\text{year}})\beta_5 + \log(Tmax_{\text{year-1}})\beta_6 \end{aligned} \tag{10}$$

Where $NDVI$ is the annual average NDVI, P the annual precipitation sum, $Tavg$ the annual average temperature, $Tmax$ the annual maximum temperature, and β_{0-6} coefficients of the log-linear regression model. We used the annual climate indices of two years, the current year and the previous year, to account for the climate lag that may influence the vegetation development. A stepwise model selection procedure was applied for each of the 57 landuse classes, selecting the best combination of variables from equation 10 with the lowest AIC (Akaike Information Criterion) in R (version 3.4.0), using the stepAIC algorithm from the MASS package (Venables and Ripley, 2002).

1.6 Model Calibration & Validation

Model calibration and validation were performed in five headwater subcatchments that are not affected by water extractions for irrigation (Figure 1b). To prevent overfitting and achieve most realistic model calibration we set most of the potential calibration parameters at literature values and maintained the other parameters within reasonable physical limits of the parameter domain.

Calibration and validation were performed for the periods 2001-2010 and 1987-2000, respectively. These periods were chosen such that we could make best use of the limited available data, i.e. daily discharge, precipitation, temperature and NDVI images.

Daily discharge time series were used to determine model performance. Data were obtained from the Segura River Basin Agency for the Fuensanta reservoir (Figure 1b). We only considered the discharge originating from the Fuensanta subcatchment, by subtracting the discharge from the upstream located subcatchments, both for the observed and the simulated time series. The calibration procedure consisted of two steps. First, we optimized the water balance by comparing the observed and simulated discharge sum (percent bias). We adjusted the calibration parameter λ from equation 3 and model parameters from the dynamic vegetation module and soil hydraulic properties to optimize the percent bias of the discharge. In the second step we optimized the Nash-Sutcliffe model efficiency (NSE; Nash and Sutcliffe, 1970) ~~)~~ by adjusting a model parameter from the routing module. The calibration resulted in a NSE of 0.47 for the daily discharge, a NSE of 0.76 for the monthly discharge and a percent bias of 2.3% (Figure S1a). Model validation resulted in a NSE of 0.25 for the daily discharge, a NSE of 0.39 for the monthly discharge and a percent bias of -18.7% (Figure S1b).

Next, we calibrated the soil erosion model. First, we optimized the detached material going into transport G for 8 aggregated landuse classes, based on literature data (Cerdan et al., 2010; Maetens et al., 2012). We optimized sediment yield at the reservoirs with reservoir sediment yield data from 4 reservoirs (Avendaño-Salas et al., 1997) (Figure 1b). Model performance was evaluated based on percent bias. The calibration procedure focused on a model parameter from the sediment transport module. We obtained a percent bias of 0.0% in the calibration and -19.8% in the validation.

2 Global Infiltration Excess Surface Runoff

Infiltration excess surface runoff occurs when the precipitation intensity exceeds the soil infiltration rate (Beven, 2012). Based on global precipitation and soil data, we determined a global map indicating the areas prone for infiltration excess runoff during extreme precipitation events.

Global daily precipitation data were obtained from the Global Precipitation Climatology Centre (GPCC; Schamm et al., 2016). The GPCC dataset contains daily global land-surface precipitation data, interpolated on a regular 1° grid for the period 1988-2013. For each grid cell we determined the extreme precipitation (Figure S2a), defined as the 95th percentile of daily precipitation, considering only rainy days ($>1\ \mathrm{mm\,day^{-1}}$, Jacob et al., 2014). Infiltration excess runoff is a sub-daily process. While no global sub-daily precipitation data were available, we assumed that 34% of the daily rainfall occurs in the hour with the highest intensity. This fraction we obtained from analysis of hourly precipitation data from 5 precipitation stations within the Segura River catchment covering a period of 25 years (1991-2015). ~~While this~~ This fraction may vary globally and global extrapolation introduces uncertainty in regions where this fraction differs from our estimate. A higher (lower) fraction may lead to an increase (decrease) of the area prone for infiltration excess surface runoff. Nevertheless, in the absence of better estimates we extrapolated the fraction to illustrate the potential extent of global sensitive areas to infiltration excess runoff.

Infiltration rate was estimated based on the saturated hydraulic conductivity. We obtained global sand, clay and organic matter maps at 10 km resolution from the SoilGrids dataset (Hengl et al., 2017). Saturated hydraulic conductivity (Figure S2b) was obtained by applying pedotransfer functions (Saxton and Rawls, 2006). To obtain an estimate of the infiltration rate we determined the effective saturated hydraulic conductivity K_{eff}. Bouwer (1969) showed that, because of entrapped air, K_{eff} should be smaller than K_{sat} and suggested an approximation of $K_{\mathrm{eff}} \approx 0.5\, K_{\mathrm{sat}}$.

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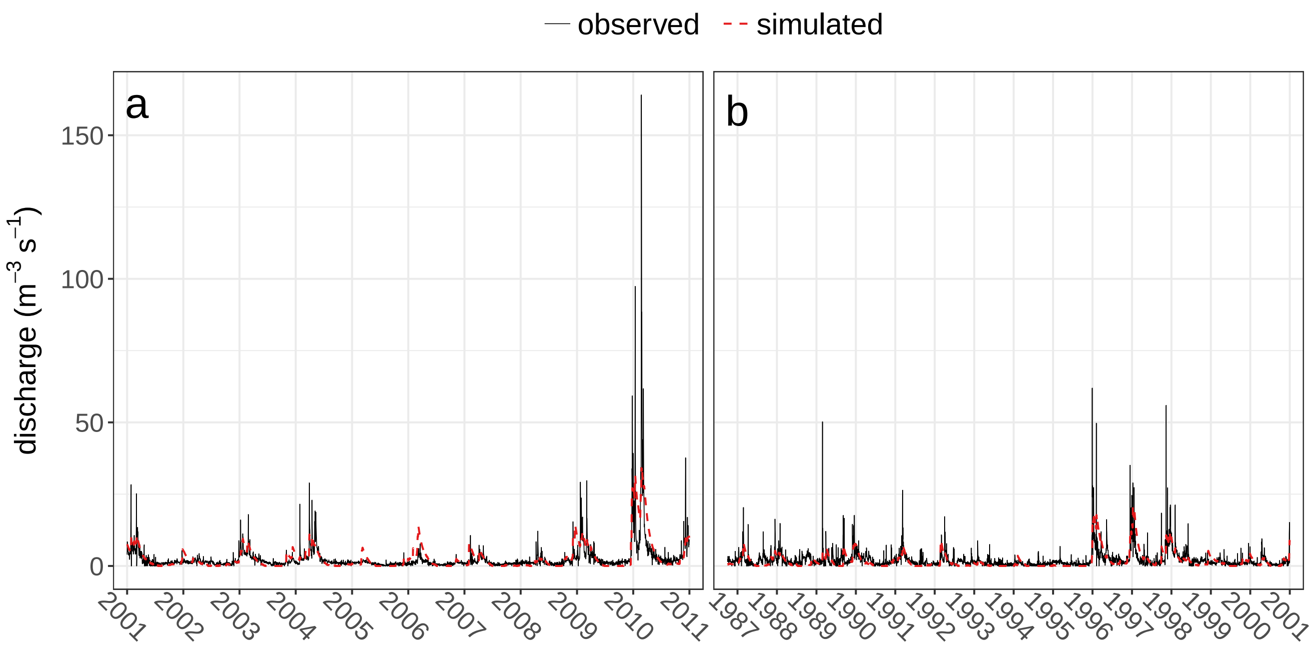

Figure S1. Discharge time series for the calibration (a) and validation period (b). The dashed red line correspond to the simulated time series and the solid black line corresponds to the observed time series.

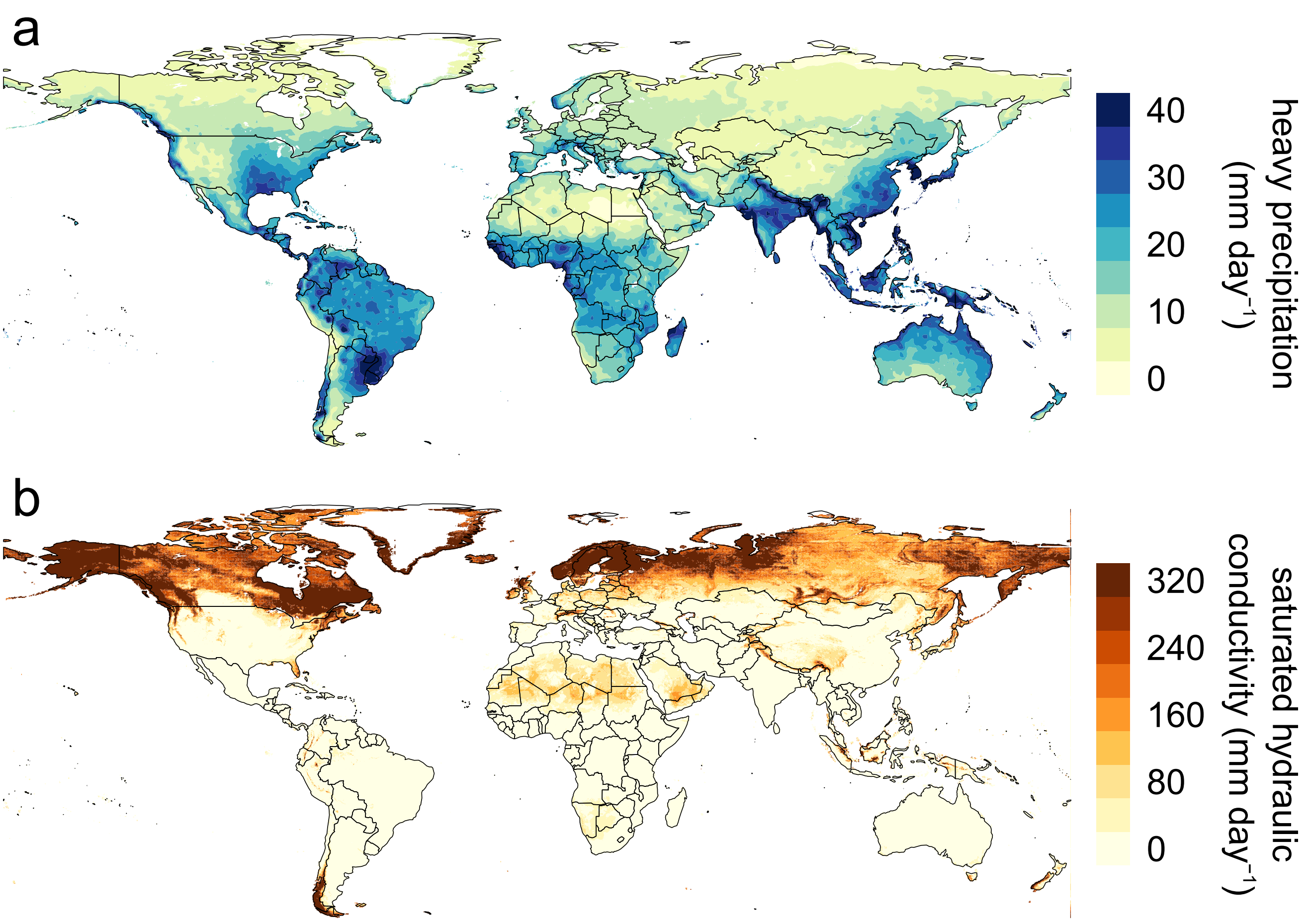

Figure S2. (a) Global heavy precipitation $(\mathrm{mm\,day}^{-1})$ and (b) global saturated hydraulic conductivity map $(\mathrm{mm\,day}^{-1})$.

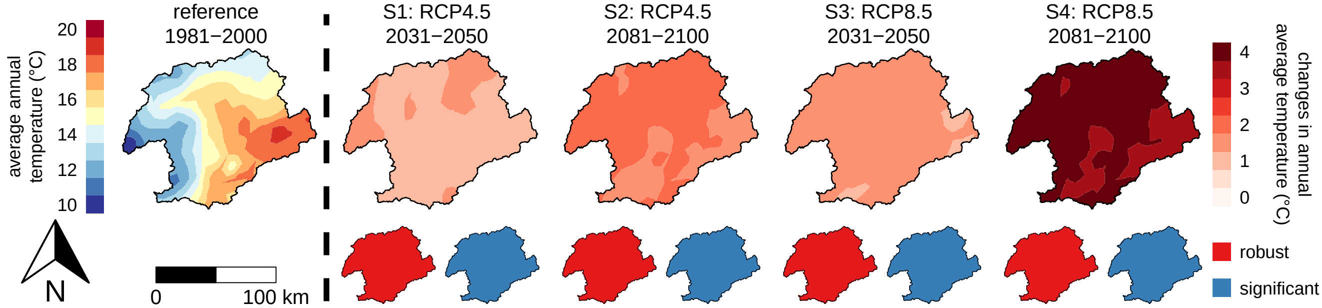

Figure S3. Ensemble average annual-average temperature (°C) for the reference scenario (left) and changes between the reference scenario and the four future scenarios (right).

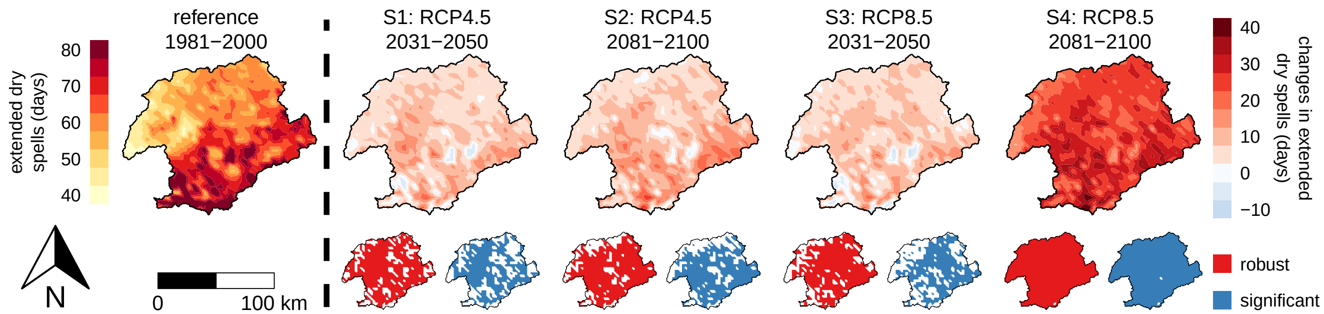

Figure S4. Ensemble average dry spells (days) defined as the 95th percentile of the duration of ~~dry spells, which is defined as~~ periods of at least 5 consecutive days with daily precipitation below 1 mm, for the reference scenario (left) and changes between the reference scenario and the four future scenarios (right).

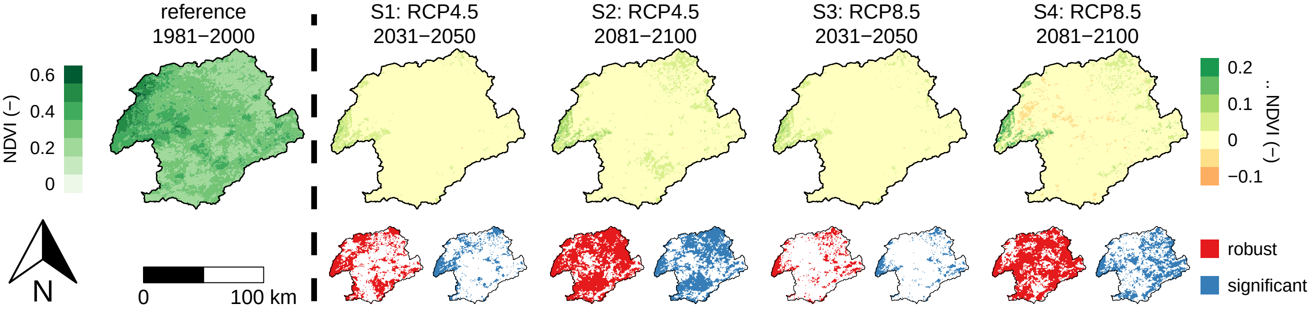

Figure S5. Ensemble average NDVI (-) for the reference scenario (left) and changes between the reference scenario and the four future scenarios (right).

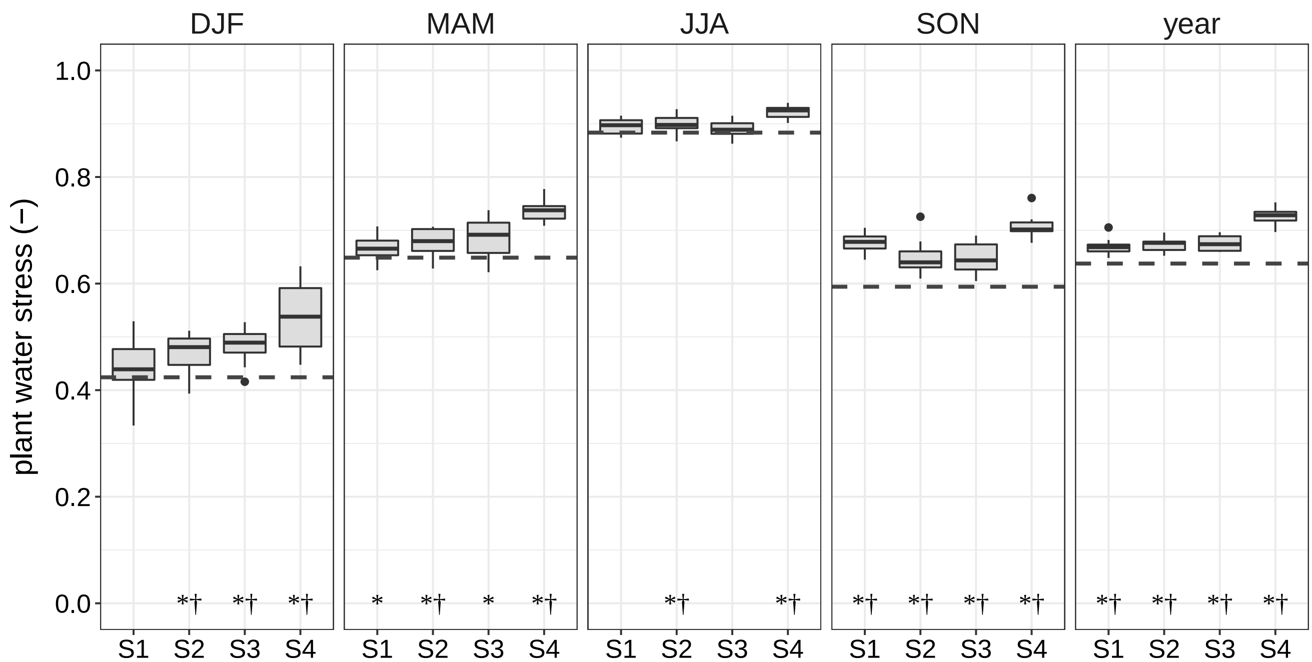

Figure S6. Catchment-average plant water stress (-), averaged by season: winter (DJF), spring (MAM), summer (JJA), autumn (SON), and for the whole year. The boxplots indicate the spread of the catchment-average among the nine climate models. In each panel the horizontal dashed line represents the catchment-average value for the reference scenario. An asterisk (∗) indicates a robust change and a dagger (†) indicates a significant change ($p<0.05$). The boxplots are described as follows: the hinges indicate the 25th and 75th percentiles, the thick horizontal line indicates the median, the whiskers indicate 1.5 times the inter quantile range from each of the two hinges and the dots indicate outliers.

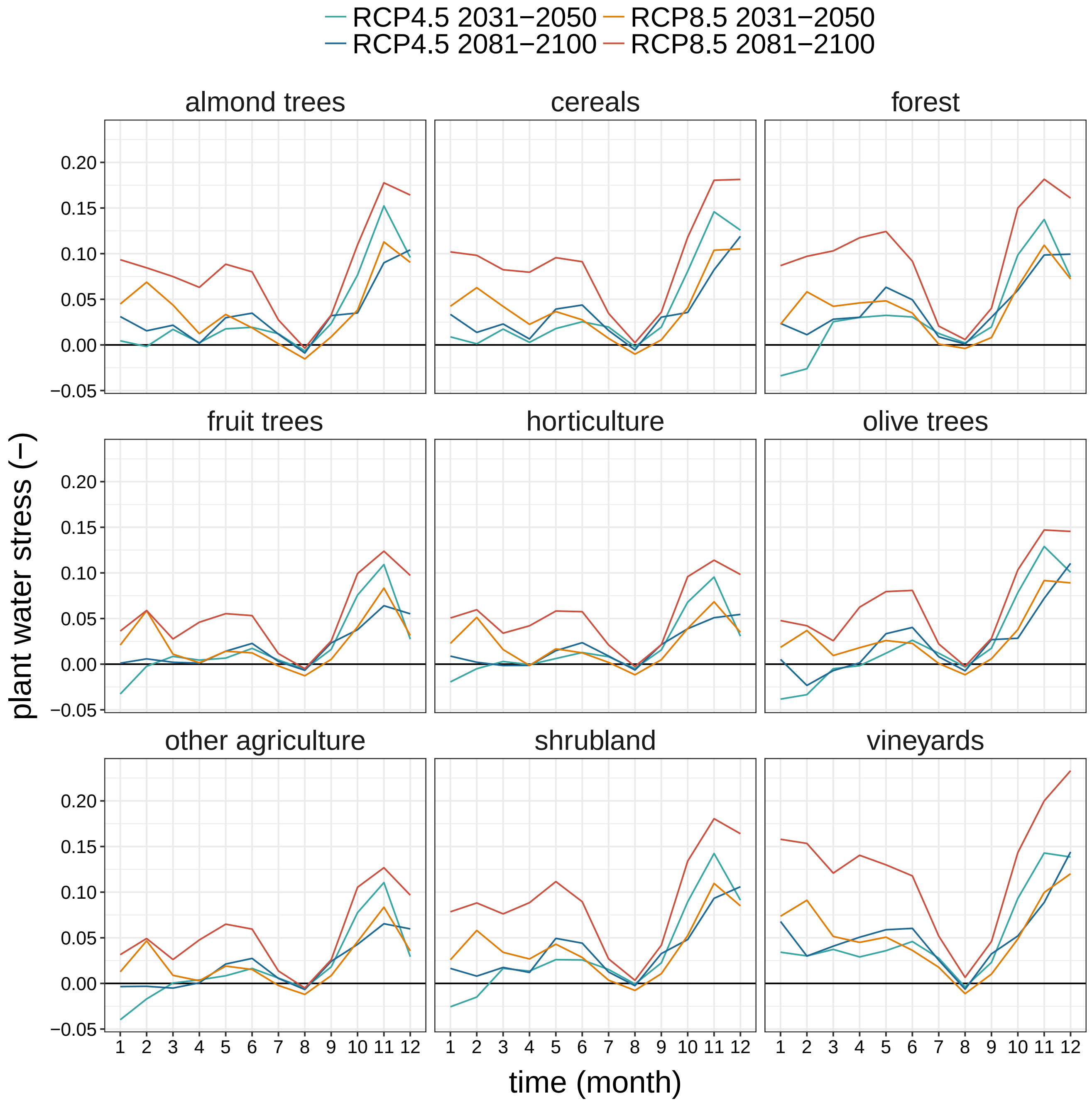

Figure S7. Monthly average plant water stress (-) per landuse class. The plant water stress is shown as a difference with respect to the reference scenario.

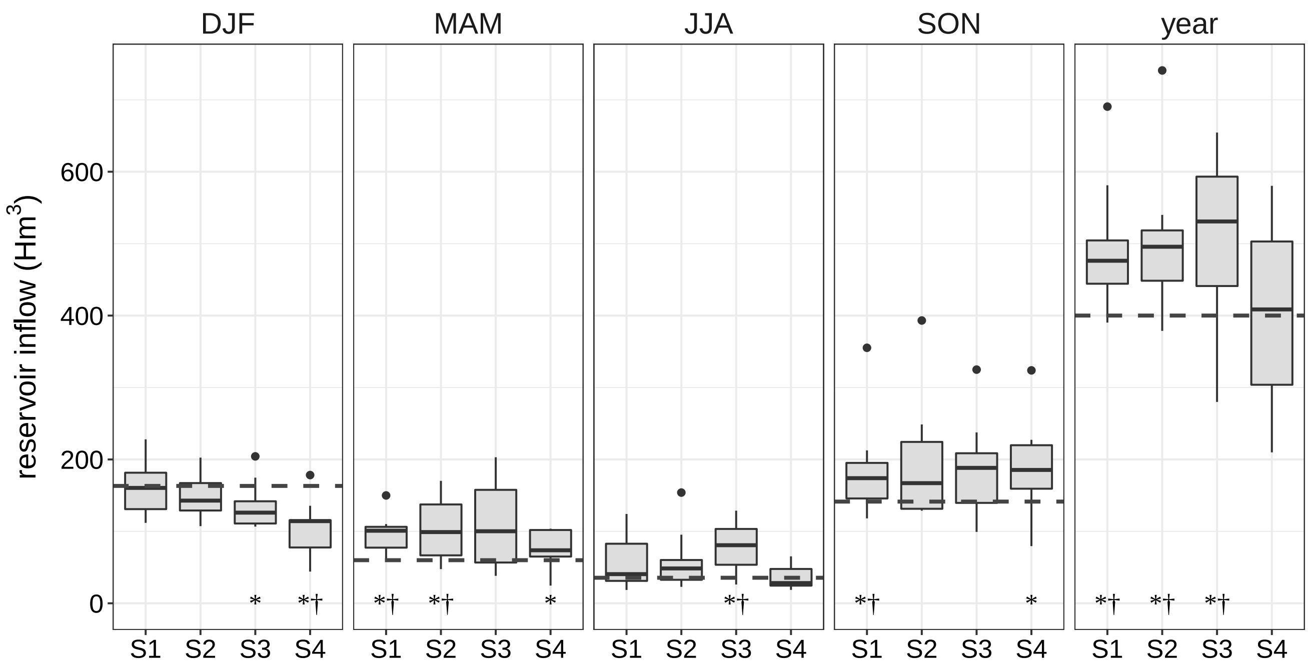

Figure S8. Catchment-average reservoir inflow (Hm^3), averaged by season: winter (DJF), spring (MAM), summer (JJA), autumn (SON), and for the whole year. The boxplots indicate the spread of the catchment-average among the nine climate models. In each panel the horizontal dashed line represents the catchment-average value for the reference scenario. An asterisk ($*$) indicates a robust change and a dagger (†) indicates a significant change ($p<0.05$). The boxplots are described as follows: the hinges indicate the 25th and 75th percentiles, the thick horizontal line indicates the median, the whiskers indicate 1.5 times the inter quantile range from each of the two hinges and the dots indicate outliers.

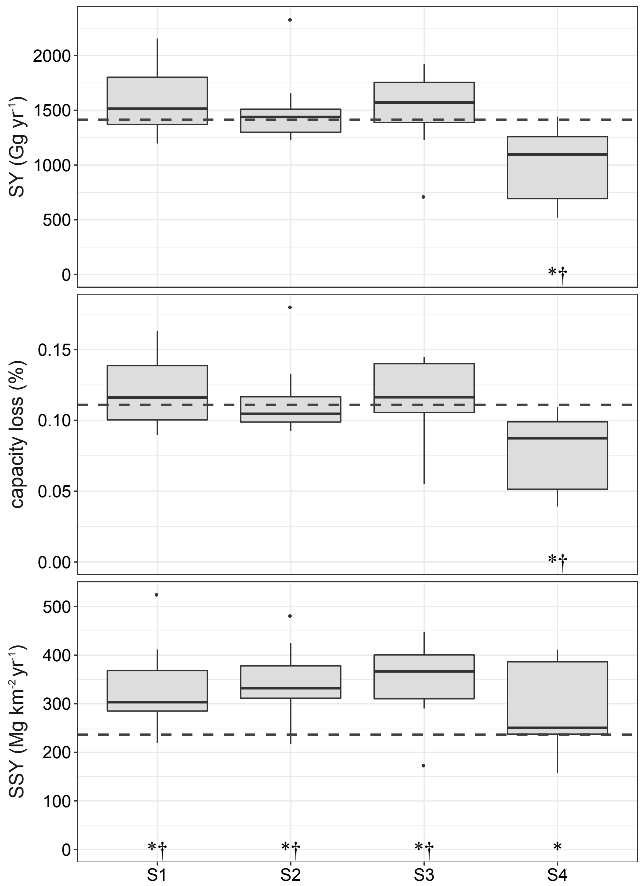

Figure S9. Catchment-average reservoir sediment yield (SY) ($\mathrm{Gg\,yr^{-1}}$), capacity loss (%) and hillslope erosion (SSY) ($\mathrm{Mg\,km^{-2}\,yr^{-1}}$). The boxplots indicate the spread of the catchment-average among the nine climate models. In each panel the horizontal dashed line represents the catchment-average value for the reference scenario. An asterisk ($*$) indicates a robust change and a dagger (†) indicates a significant change ($p<0.05$). The boxplots are described as follows: the hinges indicate the 25th and 75th percentiles, the thick horizontal line indicates the median, the whiskers indicate 1.5 times the inter quantile range from each of the two hinges and the dots indicate outliers.

Table S1. The name and capacity of the 14 reservoirs considered in this study. The reservoir number corresponds to the numbers in Figure ~~1b~~1b.

nr	name	capacity (Hm^3)
1	Taibilla	9
2	Fuensanta	210
3	Talave	35
4	Cenajo	437
5	Camarillas	36
6	Argos	10
7	Alfonso XIII	22
8	La Cierva	7
9	Valdeinfierno	13
10	Puentes	26
11	Algeciras	45
12	Ojós	1
13	Mayes	2
14	Crevillente	13

Table S2. The nine climate models used in this study, with their corresponding RCM, GCM and research institute.

RCM GCM	CCLM[a]	HIRHAM5[b]	RACMO[c]	RCA[d]	WRF[e]
CNRM-CM5	X			X	
EC-EARTH	X	X	X	X	
IPSL-CM5A-MR					X
MPI-ESM-LR	X			X	

[a]Climate Limited-area Modelling-Community (CLMcom), [b]Danish Meteorological Institute (DMI), [c]Royal Netherlands Meteorological Institute (KNMI), [d]Swedish Meteorological and Hydrological Institute (SMHI), [e]Institut Pierre Simon Laplace (IPSL)

Table S3. Catchment-average change of the water security indicators. Values for the reference scenario are presented in absolute values. All other values are differences with respect to the reference scenario and are accompanied with percentages in parentheses. Values marked in bolt are significantly different ($p < 0.05$).

scenario	period	plant water stress (-)	hillslope erosion ($Mg\,km^{-2}\,yr^{-1}$)	reservoir inflow (Hm^3)	sediment yield ($Gg\,yr^{-1}$)	capacity loss (%)
reference	1981-2000	0.64	227.3	400.0	1082.4	0.11
RCP 4.5	2031-2050	**0.03 (5.2)**	**89.0 (39.1)**	**99.6 (24.9)**	88.6 (8.2)	0.01 (8.5)
RCP 4.5	2081-2100	**0.04 (5.6)**	**101.4 (44.6)**	**103.9 (26.0)**	43.9 (4.1)	0.00 (4.4)
RCP 8.5	2031-2050	**0.04 (5.9)**	**104.2 (45.9)**	**111.7 (27.9)**	39.8 (3.7)	0.00 (4.0)
RCP 8.5	2081-2100	**0.09 (13.7)**	53.5 (23.5)	1.1 (0.3)	**-352.6 (-32.6)**	**-0.04 (-32.2)**

Table S4. Catchment-average change of hydrological indicators. Values for the reference scenario are presented in absolute values. All other values are differences with respect to the reference scenario and are accompanied with percentages in parentheses. Values marked in bolt are significantly different ($p < 0.05$).

scenario	period	precipitation (mm)	actual evapotranspiration (mm)	surface runoff (mm)	infiltration (mm)	soil moisture content (mm)
reference	1981-2000	361.5	314.2	38.0	262.9	11.6
RCP 4.5	2031-2050	-8.0 (-2.2)	**-19.4 (-6.2)**	14.9 (39.1)	**-13.7 (-5.2)**	-0.8 (-6.6)
RCP 4.5	2081-2100	-3.5 (-1.0)	-16.9 (-5.4)	**19.1 (50.2)**	-11.9 (-4.5)	**-1.1 (-9.9)**
RCP 8.5	2031-2050	-8.9 (-2.4)	-21.8 (-6.9)	**19.0 (50.0)**	-16.8 (-6.4)	**-1.2 (-10.5)**
RCP 8.5	2081-2100	**-65.2 (-18.0)**	**-66.6 (-21.2)**	12.8 (33.6)	**-57.6 (-21.9)**	**-3.3 (-28.6)**