Dear referee,

Thank you very much for reviewing our paper titled "Simulating human water impacts on global water resources using VIC-5" and for your valuable comments and suggestions. Below we address your comments (shown in italic), with our responses in blue.

Model performance

The referee suggests that we should *"provide more concrete information about the capability of this model. In particular, the simulation results should be more rigorously compared with observation, not simulation results of other models"*. More specifically (as stated in the specific comments), *"river discharge, terrestrial storage components, and reservoir components should be compared with river gauge, terrestrial water storage of the GRACE satellite estimation and in-situ reservoir operation records respectively"*. These suggestions were also raised by the other reviewer.

We agree with these suggestions and we will include a rigorous evaluation of the hydrological model performance. We will compare model simulations with observations and/or reported data on discharge, total water storage, reservoir storage and sectoral water demands. The following approaches are proposed:

1. Simulated discharge will be compared with monthly timeseries and multi-year average discharge from the GRDC dataset, between 1980 and 2010. Stations are selected within the major river basins of the original VIC calibration paper of Nijssen et al. (2001). Naturalized discharge as well as human-modified discharge simulations will be compared in this manner.
2. Simulated total water storage will be compared with monthly timeseries, multi-year-average total water storage and inter-annual water storage trends from the GRACE satellite dataset, for the period 2004-2016. To do so, a 300km gaussian filter will be applied to the simulated total water storage, as it is in the GRACE dataset. Total water storage will be compared for the same river basins as in the discharge comparison. Naturalized and human-modified total water storage simulations will be compared in this manner. These results will also include the unmet water demands, subsequent non-renewable groundwater abstractions and long-term total water storage exploitation.
3. Simulated sectoral water demand will be compared with monthly timeseries from the Huang et al. (2018) dataset. This is in addition to the comparison to the Shiklomanov (2000) dataset and FAOSTAT (FAO, 2016), EUROSTAT (EC, 2019) and WWDR (Connor, 2015) datasets already used in the paper. Sectoral water demands will be compared for the world and for the 5 regions

used in this paper (Africa, Americas, Asia, Europe and Oceania); and separately for each sector (irrigation, domestic, industrial and livestock) separately.

4. Simulated reservoir inflow, storage and release will be compared with monthly timeseries from Yassin et al. (2019) (assuming this data is shared), Rougé et al. (2019) and Hanasaki et al. (2006) datasets. Dams are selected based on data availability and evaluation will focus on large dams.

Novelty

The referee comments that the model *"includes too few novel aspects"*, since the reservoirs and irrigation modules were already included in previous VIC versions and the water management components were taken from several previous studies. The referee also comments that *"this paper would become better if the authors further emphasize the originality and strength"* of the study. Also, the referee feels that *"the motivation of this study is not well expressed"*.

In response to the issue raised by the referee, we will describe the originality and strength of the model, as well as a clear motivation for our study more clearly. We will clearly to acknowledge that the water management modules are based on previous major works, while describing clearly improvements compared to previous VIC studies, as well as other global hydrological modelling studies.

Compared to previous VIC studies, our model study includes the full range of water-use sectors (including domestic, industrial, energy and livestock), which have been estimated independently. Also, the routing module was fully integrated in VIC-5, which was not possible in previous VIC versions. This heavily decreases computation times for human-impact studies and provides a much improved framework for other future human-impact studies. Water-use sectors can also use groundwater as a resources, which directly impacts baseflow and thus downstream (dry-season) water availability. Compared to other studies, environmental flow requirements from surface- and groundwater systems for terrestrial freshwater ecosystems have been fully integrated. In addition, environmental flow requirements for groundwater into a hydrological model is also a novel component.

Concluding, we do not agree that the study includes too few novel aspects. However, we agree a clearer distinction needs to be made between aspects of model development and scientific development in this study. Therefore we will adjust our manuscript in several places.

Lines 84-88: "Several studies used VIC to simulate the anthropogenic impacts of irrigation and dam operation on water resources (Haddeland et al., 2006a; Haddeland et al., 2006b; Zhou et al., 2015; Zhou et al., 2016) based on the model setup of Haddeland et al. (2006b). However, water withdrawals for other sectors and flow requirements for freshwater ecosystems were ignored in these studies"

Will change to: "Several studies used VIC to simulate the worldwide anthropogenic impacts of irrigation and dam operation on water resources (Haddeland et al., 2006a; Haddeland et al., 2006b; Zhou et al., 2015; Zhou et al., 2016) based on the model setup of Haddeland et al. (2006b). However, groundwater

withdrawals, water withdrawals for other sectors and flow requirements for freshwater ecosystems were not included in these studies."

Lines 89-90: "Our study aims to increase the applicability of the VIC-5 model for water resource assessments, specifically by including human impacts and environmental flow requirements."

Will change to: "Our study aims to increase the applicability of the VIC model for water resource assessments, specifically by including human impacts and environmental flow requirements."

Line 93: "(...) impacts on water resources. These modules include (...)"

Will change to: "(...) impacts on water resources. These modules will integrate the previous major works on anthropogenic-impact modelling into VIC-5. modules include (...)"

Line 95: "(...) systems, and dam operation."

Will change to: "(...) systems, and dam operation. While the study of Haddeland et al. (2006b) already included some offline anthropogenic-impact modules (surface water use for the irrigation sector and dam operation), the new VIC-5 model structure and integrated routing are better suited for global integrated water-resource assessments and substantially decreases computation times (see Section 2.1)."

Line 104: "(...) imposed by EFRs."

Will change to: "(...) imposed by EFRs. This EFR assessment is included to indicate the effects of the newly integrated (groundwater) environmental flow requirements on worldwide water availability. "

Specific comments

"Line 54 "Several models do not yet incorporate all aspects of anthropogenic water withdrawals...": Some models include 'most' of them already (Döll et al., 2014; Wada et al., 2014; Hanasaki et al., 2018). What is the point here?"

We agree with the referee that this sentence (and paragraph) may cause some confusion. Therefore we will rewrite this part of the introduction.

Lines 53-56: "However, further advancements are needed to improve the integration of anthropogenic impacts into hydrological models (Döll et al., 2016). Several models do not yet incorporate all aspects of anthropogenic water withdrawals such as domestic, manufacturing and energy (thermoelectric) water withdrawals from both ground and surface water."

Will change to: "Further advancements are needed to improve the integration of anthropogenic impacts into hydrological models (Döll et al., 2016). The VIC model does not yet incorporate all aspects of anthropogenic water withdrawals such as domestic, manufacturing and energy (thermoelectric) water withdrawals from both ground and surface water."

And will move behind line 88.

"Line 227 "Irrigation demands": Does this model support multiple cropping? This point is worth mentioning since it substantially influences irrigation water estimates in Asia, and eventually the globe"

Irrigation demands support multiple cropping. This was indirectly described in section 3.1 line 299-300 "MIRCA2000 distinguishes the monthly growing area(s) and season(s) of 26 irrigated and rain-fed crop types around the year 2000" and line 303-304: "Cropland coverage (the cropland area actually growing crops) varied monthly based on the crop growing areas of MIRCA2000. The remainder was treated as bare soil". However, this will be explicitly stated.

Lines 234-235: "(...) applied separately (i.e. in different sub-grids)."

Will change to: "(...) applied separately (i.e. in different sub-grids). Note that multiple cropping seasons are included based on the MIRCA2000 land-use dataset (Portmann et al., 2010)."

"Line 238 "who estimated the irrigation efficiency for 22 United Nations sub-regions based on differences between calculated irrigation requirements and reported irrigation withdrawals": Taking at face value, any calculated requirements will perfectly match with reported withdrawals by this method, which sounds a bit odd. Anyway, irrigation efficiency is quite sensitive to the results and performance, please elaborate the background and concept."

The description of the irrigation efficiency implementation will be elaborated upon.

Lines 238-240: “The water loss fraction was based on Frenken and Gillet (2012), who estimated the irrigation efficiency for 22 United Nations sub-regions based on differences between calculated irrigation requirements and reported irrigation withdrawals.”

Will change to: “The water loss fraction was based on Frenken and Gillet (2012), who estimated the irrigation efficiency for 22 United Nations sub-regions. Irrigation efficiencies were estimated based on the differences between the calculated crop water requirements (crop evapotranspiration; consumptive water use) and the reported irrigation water withdrawals (including transportation and application losses). Crop water requirements are estimated based on the FAO Irrigation and Drainage paper (Allen et al., 1998). Low irrigation efficiencies can result in irrigation water withdrawals up to four times higher than the crop water requirements in regions such as east- and west Africa.”

“Line 334 “while the ensemble mean potential and actual withdrawals were only 2200km3 and 1400km3 respectively”: According to Figure 3, the potential withdrawal looks more than 2200 km3. Please revisit the number (or figure).”

The number in the text should be 2460 km3.

Lines 333-335: “Annual potential and actual irrigation withdrawals for VIC-WUR were around 3060 km^3 and 1870 km^3 respectively, while the ensemble mean potential and actual withdrawals were only 2200 km^3 and 1400 km^3 respectively”

Will change to: “Annual potential and actual irrigation withdrawals for VIC-WUR were around 3060 km^3 and 1870 km^3 respectively, while the ensemble mean potential and actual withdrawals were only 2460 km^3 and 1400 km^3 respectively”

“Figure 5: First, domestic water withdrawal of the H08 model is an apparent outlier. It would only make sense if the model reports water consumption, not water withdrawal. Anyway, this figure only tells us that all the models and estimates are different. It doesn’t provide any concrete information how well the performance of VIC-WUR is.”

The data for H08 is the actual domestic water withdrawal as supplied to the ISIMIP2a project. However, to avoid confusion we will remove the model from the analysis of non-irrigation water withdrawals.

The figure was also meant to place the VIC-WUR model in context of the other models. Note that the Shiklomanov (2000) values are based on worldwide reported data (not modelled). However, to provide more concrete information about the performance of VIC-WUR we will compare the model results to Huang et al. (2018), in addition to Shiklomanov (2000) (as described above).

Line 320-321: “H08 additionally provided data for the domestic sector, and PCR-GLOBWB additionally provided data for the domestic and livestock sector.”

Will change to: “PCR-GLOBWB additionally provided data for the domestic and livestock sector.”

“Line 400 “Actual irrigation withdrawals of VIC-WUR are high compared to the other Models...”: The ‘actual irrigation withdrawals’ simulated by global hydrological models are highly dependent on the model components (e.g. groundwater, small irrigation reservoir, aqueducts, etc.) and the settings (e.g. calculation interval, assignment of environmental flow, etc.). Superficial comparison of numbers is simply meaningless. If the authors wish to keep this part, intensively discuss what can (and cannot) be learned from this intercomparison.”

The referee indicates that, without a proper description of the model setup, comparison between different model results is meaningless. Therefore, we will describe most of the model settings and components as well as more rigorously discuss the model differences in the results. Also, we will compare the model results to the worldwide gridded sectoral water withdrawal data of Huang et al. (2018). However, we would still like to include these results since it puts VIC-WUR in the context of the older VIC version of Haddeland et al. (2006b) and other global hydrological models.

The results indicate to what extent the hydrological models are able to use renewable water resources for the anthropogenic water demand (and thus to what extend there would be non-renewable water withdrawals). Also, there is no other way to compare the water resource availability on a global scale, since such observations are not available.

Line 317-318: “(...) and WaterGAP (Muller Schmied et al., 2016). The ISIMIP2a outputs (...)”

Will change to: “(...) and WaterGAP (Muller Schmied et al., 2016). For simulation round 2a the models were required to harmonize their land-use and weather-forcing inputs. Also, no non-renewable water abstractions were allowed, as not to violate the water balance. Of these models only PCR-GLOBLWB includes (renewable) groundwater withdrawals and only the VIC model did not consider paddy rice practices. The ISIMIP2a outputs (...)”

“Line 420-434 “When adhering to EFRs the global water withdrawals are reduced substantially...”: It is hard for me to support the claim here. The Environmental Flow Requirement (EFR) is, unfortunately, seldom taken care in water scarce regions. If it was taken care, we would observe no groundwater depletion, no terminal lake shrinkage, no flow depletion at river mouth at any places in the world. In reality, we do observe such ‘tragedy’ at many places in the world (e.g. the groundwater depletion in the Central Valley in USA, the shrinkage of the Aral Sea, almost complete depletion at the river mouth of

the Colorado River). I feel that EFR brings only uncertainties in the phase of model validation, hence better to put aside in a model description paper."

We did not try to imply that Environmental Flow Requirements (EFRs) are seldom taken care of, rather that the opposite is true. However, since the integrated surface and groundwater EFRs are some of the additions to the hydrological model, we think it wise to discuss some of the impacts of this addition and its implications. However, the discussion will be shortened.

Line 351-352: "Therefore, the impact of the environmental flow requirements was largest in groundwater dependent regions"

Will change to: "Therefore, the potential impact of the environmental flow requirements (if adhered to) would be largest in groundwater dependent regions"

Line 420-421: "When adhering to EFRs the global water withdrawals are reduced substantially, especially due to groundwater withdrawal limitations"

Will change to: "If water-users would adhere to EFRs the global water withdrawals reduce substantially, especially due to constrains in groundwater withdrawals"

Lines 421-425: "This limitation indicates competition between water allocated for anthropogenic uses and environmental purposes. In addition, groundwater withdrawal reductions upstream lead to increased surface water availability downstream. This interaction results in a trade-off between upstream groundwater withdrawals and downstream surface water withdrawals."

Will be removed

"Line 436-448 "However, there are some challenges when applying the methods as described in our paper to future water-food-energy nexus assessments": I am not totally sure whether this paragraph is necessary in this paper. Indeed, the nexus has been extensively studied in the last decade, and some studies have already addressed some of the questions the authors raised. For instance, the community of integrated assessment models have studied on water scarcity on energy generation and manufacturing (Hejazi et al. 2014; Fujimori et al., 2017; Bijl et al. 2018)."

We agree with the reasoning of the referee. This section takes up too much space in the discussion section and we will therefore remove this paragraph.

We hope the referee agrees with our changes made, and are open to any further suggestions or comments.

Sincerely,

Bram Droppers on behalf of all co-authors

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