Dear editor,

Thank you very much for handling our manuscript titled “Simulating human water impacts on global water resources using VIC-5”. Below we provided a list of all the relevant changes made in the manuscript. The referee responses and a mark-up of the new manuscript version are also included.

Model performance

The largest manuscript change is in line with the request for further model validation by the referees. The referees requested a rigorous validation based on observed discharge and terrestrial total water storage anomalies as well as water withdrawal per sector (irrigation, industrial, domestic), per source (groundwater, surface water) and dam operation. The model validation now has the main focus of the paper, which changed the manuscript substantially:

1. Non-renewable groundwater withdrawals are now included in the methodology, which was required in order to validate the terrestrial total water storage anomalies. This changed Figure 1 and the description of the methods in Section 2.2.1.
2. Model validation has replaced the original inter-model comparison as the main result of the manuscript. Section 3.2 has been completely re-written and inter-model comparisons are only shown in Table 1 and 2.
3. The discussion (previously Section 4) has been incorporated in Section 3 to increase readability. Due to the wide range of validation metrics, a separate discussion section would need to repeat information in order to provide the reader with context, which became tedious to read.
4. Since the main manuscript results have changed, the conclusions, abstract and introduction have been adjusted accordingly.
5. Appendix E was included to provide a general model validation for several major river basins. These results have not been included in the main text, since the main text is focussed on the performance of the model additions instead of the original model performance.

Referee changes

Based on the comments and suggestions of the referees (see referee responses below for more details), several other changes have been made as well:

1. The introduction now focusses more clearly on the model additions to the VIC model, instead of to the general modelling community. As indicated by the referees, it was unclear what the specific aim of our study was and how this related to previous major developments within the modelling community.

2. Further explanation was given to: water allocation, irrigation efficiency, multi-cropping, the model setup and energy water demands. Also, further citations were added to: previous VIC model usage, similar groundwater partitioning studies, various dam operation schemes, socio-economic data sources and energy sector data sources.
3. Textual changes as discussed in the referee responses.

Other changes

1. The sensitivity analysis in Appendix D was removed and data used for calibration was instead included in Figure 2 of the main text.
2. Minor textual changes in the description of the irrigation module, environmental flow module and model setup to increase readability.

We hope this list (and attached referee responses and manuscript mark-up) sufficiently describes the manuscript changes made.

Sincerely,

Bram Droppers on behalf of all co-authors

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 further evaluate model performance, such as *"flow regulation and overall redistribution of water resources and performance of the model in meeting sectoral demands"*. Later it is mentioned with respect to water stores and/or fluxes: *"there is no evaluation of the terrestrial water storage with respect to GRACE as performed in other equivalent models valuations, or in flow (Yassin et al., 2019), or in supply deficit metrics as "accounting for supply from unsustainable sources" (Döll et al., 2012) or as unmet demand (Voisin et al., 2013), which allows to evaluate the overall performance of the sectoral water management model"*, and with respect to sectoral water demands: *"The sectoral demand models: (Huang et al., 2018) provides an evaluation of the different water demand models for different sectors. The set up and computed sectoral water demands would need to be further evaluated to support the sectoral water demand models in VIC5-WUR"*, and with respect to reservoir operation: *"Appropriate figures and validation should be provided"*. These suggestions were also addressed by the other reviewer.

We agree with these suggestions and will include a rigorous evaluation of the hydrological model performance. More specifically 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. (2001b). Naturalized discharge as well as human-modified discharge simulations will be compared in this manner.
2. Simulated total water storage will be compared against monthly timeseries, multi-year-average total water storage and inter-annual water storage trends from the GRACE satellite dataset, between 2004 and 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 discharge as well as 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.

Specific comments

"Please note that the assumption for power plants to run at maximum capacity constantly is not realistic. Capacity factors (ratio of generation over maximum capacity) and generation portfolio are available through the EIA and IEA datasets"

Thanks for this comment. Capacity factors on a per-plant basis as mentioned by the referee are not fully available to us, unfortunately. Country-based analysis, based on the EIA dataset, shows that the capacity factors vary per country (fossil: between 1% and 73%; nuclear: between 37% and 88%; biomass: between 15% and 100%) and over time (fossil: between 44% and 48%; nuclear: between 56% and 82%; biomass: between 53% and 58%). These factors may also be cooling system dependent. Due to these data limitations we will use a global mean factor of 46% for fossil, 72% for nuclear and 56% for biomass based power plants.

Line 669-671: "Since there was no observed data about the actual annual generation, each plant was assumed to be running at its installed generation capacity throughout the year, similar to van Vliet et al. (2016)."

Will change to: "Actual generation is estimated by adjusting the installed generation capacity by 46% for fossil, 72% for nuclear and 56% for biomass power plants (based on country-based data of the EIA (EIA, 2013))."

Line 677-681: "In cases where even the national industrial water demands were less than the national energy water demand (5 countries), the energy water demands were lowered instead. This could be the case in countries where power plants do not operate at their installed capacity, as globally around 45% of the installed capacity is actually generated (based on data of van Vliet et al. (2016))."

Will change to: "In cases where even the national industrial water demands were less than the national energy water demand (4 countries), the energy water demands were lowered instead."

"Enhancement of reservoir releases based on storage levels. (Yassin et al., 2019) and (Rougé et al., 2019) provided a new reservoir operation formulation that modulates releases based on storage levels. While the manuscript is not a review of existing models, the proposed citations should help further support the "model enhancement and improvement" with respect to existing models"

We have included the citations mentioned by the referee, which also describe generic dam operation schemes developed for large-scale hydrological modelling.

<u>Line 197-199</u>: "Due to the lack of globally available information on local dam operations, several generic dam operation schemes were developed for macro-scale hydrological models to reproduce the effect of dams on natural streamflow (Haddeland et al., 2006; Hanasaki et al., 2006; Zhao et al., 2016)"

Will change to: "Due to the lack of globally available information on local dam operations, several generic dam operation schemes were developed for macro-scale hydrological models to reproduce the effect of dams on natural streamflow (Haddeland et al., 2006; Hanasaki et al., 2006; Zhao et al., 2016; Rougé et al., 2019; Yassin et al., 2019)"

"(Nazemi & Wheater, 2015a, 2015b) provides an overview of existing challenges in large scale water management models. Those papers should be cited in the introduction to complement the authors identified challenges (the environmental flow) with other identified challenges"

We have included the citations mentioned by the referee, as well as Pokhrel et al. (2016) to include a wider range of review papers that identify the challenges in large-scale hydrological modelling.

<u>Lines 53-54</u>: "However, further advancements are needed to improve the integration of anthropogenic impacts into hydrological models (Döll et al., 2016)"

Will change to: "However, further advancements are needed to improve the integration of anthropogenic impacts into hydrological models (Nazemi and Wheater, 2015a, b; Döll et al., 2016; Pokhrel et al., 2016)"

"The allocation of sectoral water demand to surface and ground-water systems as well as the sectoral return flow into the surface water system seems to be equivalent to (Voisin et al., 2017), which should then be cited."

We have included the citation mentioned by the referee, as well as other studies (Hanasaki et al., 2018) that used the same approach in allocation sectoral water demands to surface and groundwater systems.

Line 150-153: “The partitioning of water withdrawals between surface and ground water resources was based on the study of Döll et al. (2012), who estimated the groundwater withdrawal fraction for each sector in around 15.000 national and sub-national administrative units.”

Will change to: “The partitioning of water withdrawals between surface and ground water resources is data driven, similar to other studies (e.g. Döll et al., 2012; Voisin et al., 2017; Hanasaki et al., 2018). Groundwater withdrawal fraction were based on the study of Döll et al. (2012), who estimate fractions for each sector in around 15.000 national and sub-national administrative units.”

“The description of how the supply is allocated to the different sectoral water demands needs to be specified in this manuscript. A missing description is how the priority is set between sectoral demands. For example , are thermo-electric plants getting their demand met first before domestic or irrigation demand?”

The priority between sectoral water demands was described in section 2.2.1 (water withdrawal and consumption) on lines 162-163: “When water demands cannot be met, water withdrawals are allocated to the domestic, energy, manufacturing, livestock and irrigation sector in that order”. However, we will make this more clear.

Lines 162-163: “When water demands cannot be met, water withdrawals are allocated to the domestic, energy, manufacturing, livestock and irrigation sector in that order”

Will change to: “In terms of water allocation, under conditions where water demands cannot be met, water withdrawals are allocated to the domestic, energy, manufacturing, livestock and irrigation sector in that order”

“Is there any priority for supply allocation based on spatial location? Which grid cells can request water from a mainstream if the main channel is not within this grid cell?”

There is no priority for supply allocation based on location, inside or outside the delta. Water requests from the mainstream (if the main channel is not within the grid cell) are allocated based on demand. This will be explicitly stated.

Line 159-160: “Therefore, streamflow at the river mouth is available for use in delta areas to simulate the actual water availability.”

Will change to: “Therefore, streamflow at the river mouth is available for use in delta areas (partitioned based on demand) to simulate the actual water availability.”

“Was the Hanasaki et al. (2006) “dependence” database used?”

The Hanasaki et al. (2006) dependence method is not used in this study, which will be explicitly stated. Rather our study used the controlled discharge fraction as the fraction of downstream demands taken into account. This is described in section 7.3 (appendix c: dam operation scheme) on lines 566-567: "Water demands were based on the water demands of downstream cells. Only a fraction of water demands were taken into account, based on the fraction of upstream area the dam controlled". However, there was an error which causes confusion; "upstream area" should read "upstream discharge".

Line 566-567: "Only a fraction of water demands were taken into account, based on the fraction of upstream area the dam controlled."

Will change to: "Only a fraction of water demands were taken into account, based on the fraction of upstream discharge the dam controlled."

"While authors indicate that it will be the subject of further research, what is the default implementation that was used in the presented simulations?"

We are not fully sure if we understand the referee correctly. However, assume the referee is referring to which modules were used to generate the results in this study. We will explicitly add this information to section 3.1 (setup).

Line 299: "(...) soil layers per grid cell. Soil and (natural) vegetation (...)"

Will change to: "(...) soil layers per grid cell. The routing, reservoir, irrigation and water-use modules were all used in the simulations. The environmental flow requirements were only used where this is specifically indicated. Soil and (natural) vegetation (...)"

"the introduction is missing a range of large scale studies where such a large scale water management model has been used with the VIC model, albeit not VIC5. While the proposed set up seems more complete, it seems that the paper should still cite those studies as they represent to a certain extent an earlier version of this integrated model (Voisin et al., 2017; Voisin et al., 2018; Zhou, Voisin, Leng, Huang, & Kraucunas, 2018)"

We have included almost all of the citations mentioned by the referee as they represent a wider range of VIC model applications. Voisin et al. (2017) was excluded since this study seems to use the Community Land Model (CLM) instead of the Variable Infiltration Capacity model (VIC).

Lines 80-84: "VIC has been used extensively in studies ranging from: coupled regional climate model simulations (Zhu et al., 2009; Hamman et al., 2016), combined river discharge and water-temperature simulations (van Vliet et al., 2016), hydrological sensitivity to climate change (Hamlet and Lettenmaier, 1999; Nijssen et al., 2001a; Chegwidden et al., 2019), global streamflow simulations (Nijssen et al., 2001b), and real-time drought forecasting (Wood and Lettenmaier, 2006; Mo, 2008)."

Will change to: "VIC has been used extensively in large-scale studies ranging from: coupled regional climate model simulations (Zhu et al., 2009; Hamman et al., 2016), combined river discharge and water-temperature simulations (van Vliet et al., 2016), hydrological sensitivity to climate change (Hamlet and Lettenmaier, 1999; Nijssen et al., 2001a; Chegwidden et al., 2019), global streamflow simulations (Nijssen et al., 2001b), sensitivity in flow regulation and redistribution (Voisin et al., 2018; Zhou et al., 2018), and real-time drought forecasting (Wood and Lettenmaier, 2006; Mo, 2008)."

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

Sincerely,

Bram Droppers on behalf of all co-authors

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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 further evaluate model performance *“compared to observed sectoral and/or global water withrdrawals”*. These suggestions were also addressed by the other reviewers.

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. As included in the response to the other reviewers, 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 *"methodology itself lacks in novel advancements"* and, in the specific comments, that *"It should be more carefully noted throughout the text the novelty of what is being added to the modeling community"*. Claims regarding its use in modelling the water-food-energy nexus *"may be misleading"* and, in the specific comments, that such conclusions *"should be clarified"*. This was also commented by another reviewer.

With regard to the notions of methodological novelty: we agree that the incorporated modules are based on previous major works. However, the integration of these modules is a clear improvement 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.

With regard to the notions of the water-food-energy nexus: we agree with the referee that notions towards the modelling of the water-food-energy nexus may be misleading. We will therefore remove these sentences from the manuscript, and rewrite part of the discussion.

For a full description of all proposed changes we refer to our responses to referee 1.

Specific comments

"Line 328: the study is mentioned to use varying socioeconomic predictors. These could be better explained in section 2.3.2 in order to specify where GDP and GVA are obtained."

We will add an explanation to section 2.3.2, based on section 7.4.1.

<u>Lines 243-244</u>: "Domestic and industrial water withdrawals were estimated based on Gross Domestic Product (GDP) per capita and Gross Value Added (GVA) by industries respectively."

Will change to: "Domestic and industrial water withdrawals were estimated based on Gross Domestic Product (GDP) per capita and Gross Value Added (GVA) by industries respectively (from Bolt et al. (2018), Feenstra et al. (2015) and World bank (2010); see section 7.4.1 for more details)."

"Lines 406-408: "To our knowledge no previous study has estimated the amount of

global non-renewable groundwater withdrawals without using on the the models mentioned above" - see Turner et al. (2019) or Kim et al. (2016) for additional groundwater withdrawal modeling capabilities.”

We thank the referee for these useful citations, which we will incorporate into the text.

“Line 426: "Note that VIC-WUR does not include non-renewable groundwater withdrawals, while these withdrawals would affect baseflow to a lesser degree" - I am confused, then why was there a discussion on about this in paragraph starting at line 400? Maybe consider reorganizing these thoughts..”

The discussion in the paragraph starting at line 400 assumes that all unmet water withdrawals originate from non-renewable sources. However, this does not mean that models actually include simulations of non-renewable groundwater withdrawals. To make this distinction clearer we will include more detail about the model setup used in the results, and we will reorganize the discussion.

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

Sincerely,

Bram Droppers on behalf of all co-authors

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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.

<u>Lines 84-88</u>: "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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Simulating human impacts on global water resources using VIC-5

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Abstract. Questions related to historical and future water resources and ~~water~~ scarcity have been addressed by several macro-scale hydrological models ~~over~~. One of these models is the ~~last few decades.~~Variable Infiltration Capacity (VIC) model. However, further ~~advancements are~~ model developments were needed to ~~improve the integration of~~ holistically assess anthropogenic impacts ~~and environmental flow requirements into hydrological models. The newly developed VIC-WUR model aims to increase the applicability of the~~on global water resources using VIC~~-5 model for water resource assessments, specifically by including human impacts and environmental flow requirements. To this end, VIC-WUR extends VIC-5 with modules for irrigation, domestic, industrial, energy and livestock water use, environmental flow requirements for surface and groundwater systems, and dam operation. Model inputs of sectoral water demand were estimated independently and correlated well to reported national water withdrawals~~.

~~VIC-WUR results, based on the newly developed modules, corresponded with results from reported global water withdrawals and other hydrological models, although differences exist. The VICWUR irrigation withdrawals were high compared to the other models but closer to the reported values, decreasing the gap between simulated and reported withdrawals. Irrigation withdrawals were probably high due to the inclusion of groundwater withdrawals and paddy irrigation in the model. Domestic and industrial water withdrawals were slightly lower than the reported values. Domestic and industrial withdrawals were probably insufficient due to low water availability, as the potential water withdrawals are more in line with reported values. Livestock water withdrawals were within the range of reported values and other models.~~

~~The model additions comprehensively incorporate anthropogenic and environmental water use, which provides new opportunities for global water resource assessments. A preliminary assessment of environmental flow requirements shows competition between water resources allocated for human consumption and the environment, from ground and surface water sources. The improvements made here are a first step towards integrated water-food-energy nexus modelling.~~

Our study developed VIC-WUR, which extends the VIC model with: (1) integrated routing, (2) surface and groundwater use for various sectors (irrigation, domestic, industrial, energy and livestock), (3) environmental flow requirements for both surface and groundwater systems, and (4) dam operation. Global gridded datasets on sectoral demands were developed separately and used as an input to the VIC-WUR model.

Simulated national water withdrawals were in line with reported FAO national annual withdrawals (R^2 adjusted > 0.8), both per sector as well as per source. However, trends in time for domestic and industrial water withdrawal were mixed compared to other previous studies. GRACE monthly terrestrial water storage anomalies were well represented (global mean RMSE of 1.9 and 3.5 for annual and interannual anomalies respectively), while groundwater depletion trends were overestimated. The implemented human impact modules increased simulated streamflow performance for 370 out of 462 human-impacted GRDC monitoring stations, mostly due to the effects of reservoir operation. An assessment of environmental flow requirements indicates that global water withdrawals have to be severely limited (by 39 %) to protect aquatic ecosystems, especially for groundwater withdrawals.

VIC-WUR has potential for studying impacts of climate change and anthropogenic developments on current and future water resources and sectoral specific-water scarcity. The additions presented here make the VIC model more suited for fully-integrated worldwide water-resource assessments and substantially decrease computation times compared to previous versions.

1 Introduction

Questions related to historical and future water resources and scarcity have been addressed by several macro-scale hydrological models over the last few decades (Liang et al., 1994; Alcamo et al., 1997; Hagemann and Gates, 2001; Takata et al., 2003; Krinner et al., 2005; Bondeau et al., 2007; Hanasaki et al., ~~2008~~2008a; Van Beek and Bierkens, 2008; Best et al., 2011). Early efforts focussed on the simulation of natural water resources and the impacts of land cover and climate change on water availability (Oki et al., 1995; Nijssen et al., 2001a; Nijssen et al., 2001b). Recently, a larger focus has been on incorporating anthropogenic impacts, such as water withdrawals and dam operations, into water resource assessments (Alcamo et al., 2003; Haddeland et al., 2006b; Biemans et al., 2011; Wada et al., 2011b; Hanasaki et al., 2018).

Global water withdrawals increased eight-fold over the last century and are projected to increase further (Shiklomanov, 2000; Wada et al., 2011a). Although water withdrawals are only a small fraction of the total global runoff (Oki and Kanae, 2006), water scarcity can be severe due to the variability of water in both time and space ~~(Postel et al., 1996). Already severe water scarcity is experienced by two-thirds of the global population for at least part of the year (Mekonnen and Hoekstra, 2016). To stabilize water availability for different sectors (e.g. irrigation, hydropower, and domestic uses) dams and reservoirs were built, which are able to strongly affect global river discharge (Nilsson et al., 2005; Grill et al., 2019)~~(Postel et al., 1996). Already severe water scarcity is experienced by two-thirds of the global population for at least part of the year (Mekonnen and Hoekstra, 2016). To stabilize water availability for different sectors (e.g. irrigation, hydropower, and domestic uses) dams and reservoirs were built, which are able to strongly affect global river streamflow (Nilsson et al., 2005; Grill et al., 2019). In addition, groundwater resources are being extensively exploited to meet increasing water demands (Rodell et al., 2009; Famiglietti, 2014).

~~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. Although these sectors use less water than irrigation~~

~~(Shiklomanov, 2000; Grobicki et al., 2005; Hejazi et al., 2014) they are locally important actors (Gleick et al., 2013), especially for the water-food-energy nexus (Bazilian et al., 2011). Sufficient water supply and availability are essential for meeting a range of local and global sustainable development goals related to water, food, energy and ecosystems (Bijl et al., 2018).~~

~~Environmental flow requirements (EFRs) are also often neglected in global water resource assessments (Pastor et al., 2014), even though they are "(...) necessary to sustain aquatic ecosystems which, in turn, support human cultures, economies, sustainable livelihoods, and well-being" (Brisbane Declaration, 2017). Various EFR methods are available for streamflow (Smakhtin et al., 2004; Richter et al., 2012; Pastor et al., 2014) and groundwater (Gleeson and Richter, 2018), although environmental limits for groundwater withdrawal have only recently been considered explicitly. Anthropogenic alterations already strongly affect freshwater ecosystems (Carpenter et al., 2011), with more than a quarter of all global rivers experiencing very high biodiversity threats (Vorosmarty et al., 2010). By neglecting EFRs, water availability for anthropogenic uses is likely over-estimated (Gerten et al., 2013).~~

One of widely-used macro-scale hydrological models is the Variable Infiltration Capacity (VIC) model. The model was originally developed as a land-surface model ~~(Liang et al., 1994)~~(Liang et al., 1994), but has been mostly used as a stand-alone hydrological model (Abdulla et al., 1996; Nijssen et al., 1997) using an offline routing module (Lohmann et al., 1996; Lohmann et al., ~~1998b, a~~1998a, b). Where land-surface models focus on the vertical exchange of water and energy between the land surface and the atmosphere, hydrological models focus on the lateral movement and availability of water. By combining these two approaches, VIC simulations are strongly process-based and this, in turn, provides a good basis for climate-impact modelling. ~~Recently version 5 of the VIC model (VIC-5) was released (Hamman et al., 2018), which focussed on improving the model infrastructure. These improvements are highly relevant when simulating anthropogenic impacts on global water resources.~~

VIC has been used extensively in studies ranging from: coupled regional climate model simulations (Zhu et al., 2009; Hamman et al., 2016), combined river ~~discharge~~streamflow and water-temperature simulations (van Vliet et al., 2016), hydrological sensitivity to climate change (Hamlet and Lettenmaier, 1999; Nijssen et al., 2001a; Chegwidden et al., 2019), global streamflow simulations ~~(Nijssen et al.,~~

~~2001b)~~(Nijssen et al., 2001b), sensitivity in flow regulation and redistribution (Voisin et al., 2018; Zhou et al., 2018), and real-time drought forecasting (Wood and Lettenmaier, 2006; Mo, 2008). 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.~~However, further developments were needed to holistically assess anthropogenic impacts on global water resources using VIC (Nazemi and Wheater, 2015a, b; Döll et al., 2016; Pokhrel et al., 2016).

~~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.~~Firstly, the VIC model did not yet include groundwater withdrawals or water withdrawals from domestic, manufacturing and energy (thermoelectric) sources. Although these sectors use less water than irrigation (Shiklomanov, 2000; Grobicki et al., 2005; Hejazi et al., 2014) they are locally important actors (Gleick et al., 2013), especially for the water-food-energy nexus (Bazilian et al., 2011). Sufficient water supply and availability are essential for meeting a range of local and global sustainable development goals related to water, food, energy and ecosystems (Bijl et al., 2018). Secondly, environmental flow requirements (EFRs) were often neglected (Pastor et al., 2014), even though they are "necessary to sustain aquatic ecosystems which, in turn, support human cultures, economies, sustainable livelihoods, and well-being" (Brisbane Declaration, 2017). Anthropogenic alterations already strongly affect freshwater ecosystems (Carpenter et al., 2011), with more than a quarter of all global rivers experiencing very high biodiversity threats (Vorosmarty et al., 2010). By neglecting EFRs, sustainable water availability for anthropogenic uses is overestimated (Gerten et al., 2013). Lastly, while the model setup of Haddeland et al. (2006b) already included important anthropogenic impact modules (i.e. irrigation and dam operation), these were not fully integrated yet. Therefore multiple successive model runs were required which was computationally expensive, especially for global water resources assessments.

Recently version 5 of the VIC model (VIC-5) was released (Hamman et al., 2018), which focussed on improving the VIC model infrastructure. These improvements provide the opportunity to fully integrate human-impacts into the VIC model framework, while reducing computation times. Here the newly developed VIC-WUR model is presented (named after the developing team at Wageningen University and Research). The VIC-WUR model extends the existing VIC-5 model with several modules that simulate the anthropogenic impacts on water resources. These modules will implement previous major works on anthropogenic impact modelling as well as integrate environmental flow requirements into VIC-5. The modules include: (1) integrated routing, ~~water~~ (2) surface and groundwater use for various sectors (irrigation, domestic, industrial, energy and livestock), (3) environmental flow requirements for both surface and groundwater systems, and (4) dam operation.

~~The next section first describes the original VIC-5 hydrological model (Section 2.1), which calculates natural water resource availability. Subsequently the integration of the anthropogenic impact modules, which modify the water resource availability, are described (Section 2.2). Global anthropogenic water uses for each sector are also estimated (Section 2.3). To assess the performance of the newly developed modules, the VIC-WUR results were compared with reported global withdrawal data from Shiklomanov (2000) and Steinfeld et al. (2006) as well as various other state-of-the-art global hydrological models used in the Inter-Sectoral Impact Model Intercomparison Project (ISIMIP; Warszawski et al., 2014) and Water and Global Change project (WATCH; Harding et al., 2011) (Section 3.1). The results also contain a preliminary assessment of the water availability constrains imposed by EFRs.~~

The next section first describes the original VIC-5 hydrological model (Section 2.1), which calculates natural water resource availability. Subsequently the integration of the anthropogenic impact modules, which modify the water resource availability, are described (Section 2.2). Global anthropogenic water uses for each sector are also estimated (Section 2.3). To assess the capability of the newly developed modules, the VIC-WUR results were compared with FAO national water withdrawals by sector and by source (FAO, 2016); Huang et al. (2018), Steinfeld et al. (2006), and Shiklomanov (2000) data on water withdrawals by sector; GRACE terrestrial water storage anomalies (NASA, 2002); GRDC streamflow timeseries (GRDC, 2003); and Yassin et al. (2019) and Hanasaki et al. (2006) data on reservoir operation (Section 3.2). VIC-WUR simulations results are also compared with various other state-of-the-art global hydrological models. Lastly, the impacts of adhering to surface and groundwater environmental flow requirements on water availability are assessed (Section 3.3). This assessment is included to indicate the effects of the newly integrated surface and groundwater environmental flow requirements on worldwide water availability.

2 Model development

2.1 VIC hydrological model

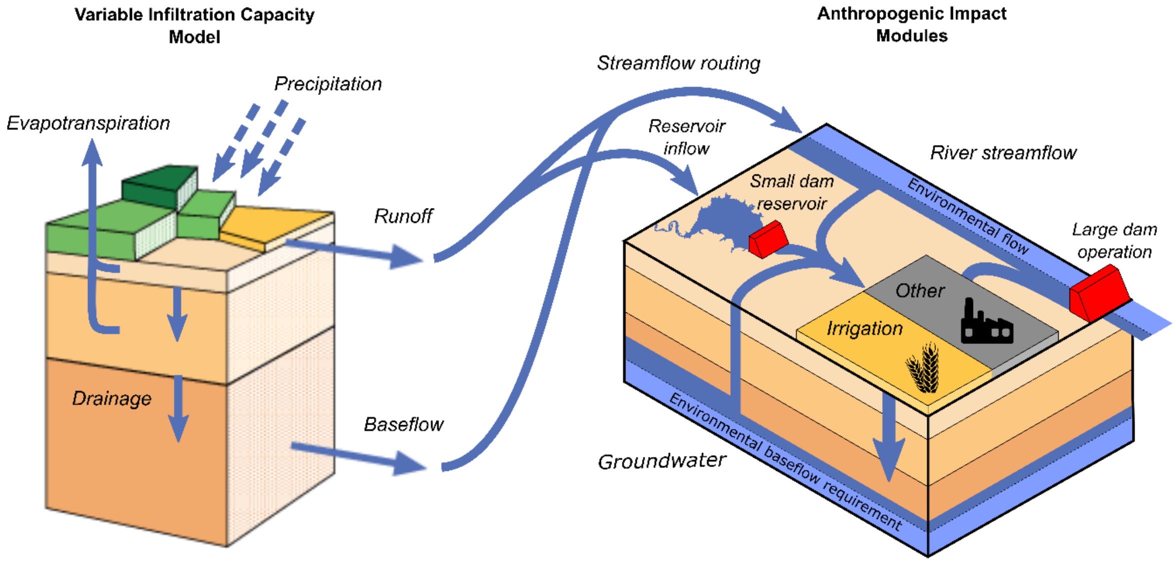
The basis of the VIC-WUR model is the Variable Infiltration Capacity model version 5 (VIC-5) (Liang et al., 1994; Hamman et al., 2018). VIC-5 is an open source macro-scale hydrological model that simulates the full water and energy balance on a (latitude – longitude) grid. Each grid cell accounts for sub-grid variability in land cover and topography, and allows for variable saturation across the grid cell. For each sub-grid the water and energy balance is computed individually (i.e. sub-grid do not exchange water or energy between one another). The methods used to calculate the water and energy balance are summarized in Appendix A, mainly based on the work of ~~Liang et al. (1994)~~Liang et al. (1994). For the description of the global calibration and validation of the water balance one is referred to ~~Nijssen et al. (2001b)~~Nijssen et al. (2001b).

VIC version 5 (Hamman et al., 2018) upgrades did not change the model representation of physical processes, but improved the model infrastructure. Improvements include the use of NetCDF for input/output and the implementation of parallelization through Message Passing Interface (MPI). These changes increase computational speed and make VIC-5 better suited for (computationally expensive) global simulations. The most significant modification that enables new model applications is that VIC-5 also changed the processing order of the model. In previous versions all timesteps were processed for a single grid cell before continuing to the next cell (time-before-space). In VIC-5 all grid cells are processed before continuing to the next timestep (space-before-time). This development allows for interaction between grid cells every timestep, which is important for full integration of the anthropogenic impact modules, especially water withdrawals and dam operation.

For example, surface and subsurface runoff routing to produce river streamflow was typically done as a post-process operation (Lohmann et al., 1996; Hamman et al., 2017), due to the time-before-space processing order of previous versions. Therefore, water withdrawals could not be taken into account directly and studies using the model setup of Haddeland et al. (2006b) required multiple successive model runs. Since VIC-5 uses the space-before-time processing order, runoff routing could be simulated each timestep. The routing post-process was replaced by our newly developed routing module which simulates routing sequentially (upstream-to-downstream) to facilitate water withdrawals between cells.

2.2 Anthropogenic-impact modules

VIC-WUR extends the existing VIC-5 though the addition of several newly developed anthropogenic-impact modules (Figure 1). These modules include sector-specific water withdrawal and ~~consumptions~~consumption, environmental flow requirements for both surface and groundwater systems and dam operation for large and small (within-grid)~~ and large~~ dams.



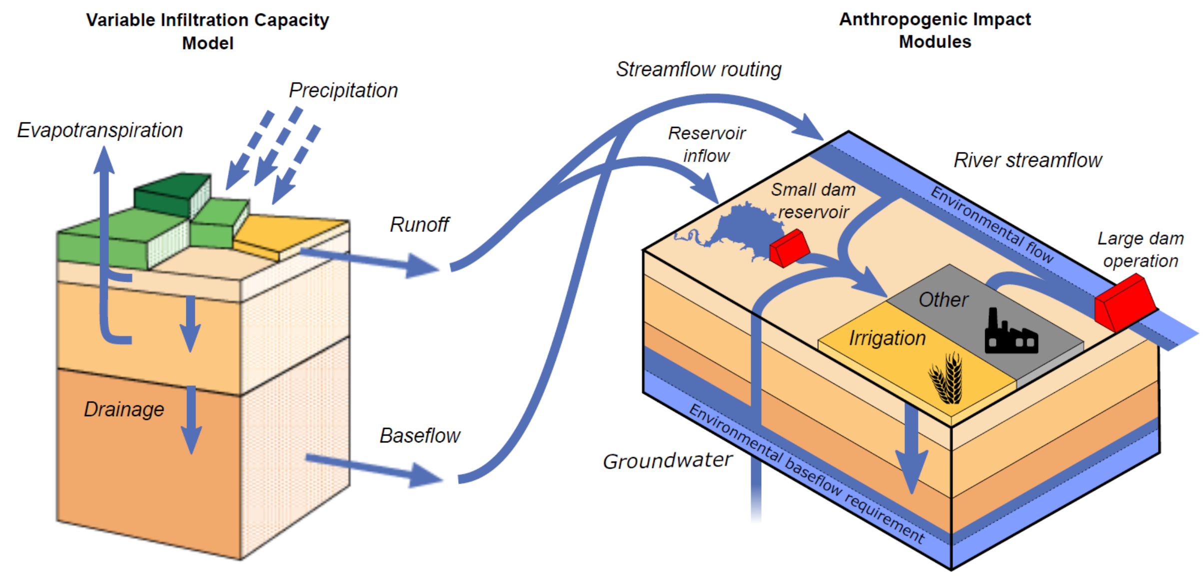


Figure 1: Schematic overview of the VIC-WUR model that includes the VIC-5 model and several anthropogenic impact modules. Water from river streamflow, groundwater and small (within-grid) reservoirs are available for withdrawal. Surface and groundwater withdrawals are constrained by environmental flow requirements. Withdrawn water is available for irrigation, domestic, industrial, energy and livestock use. Unconsumed irrigation water is returned to the soil column of the hydrological model. Unconsumed water for the other sectors is returned to the river streamflow. Small reservoirs fill using surface runoff from the cell they are located, while large dam reservoirs operate solely on rivers streamflow.

2.2.1 Water withdrawal and consumption

In VIC-WUR, sectoral water demands need to be specified for each grid cell (Section 2.3). To meet water demands, water can be withdrawn from river streamflow, small (within-grid) reservoirs, and groundwater resources. Streamflow withdrawals are abstracted from the grid cell discharge (as generated by the routing module~~),~~) and reservoir withdrawals are abstracted from small dam reservoirs (located in the cell~~) and groundwater~~). Groundwater withdrawals are abstracted from the third layer soil moisture~~.~~ and an (unlimited) aquifer below the soil column. Aquifer abstractions represent renewable and non-renewable abstractions from deep groundwater resources. Subsurface runoff is used to fill the aquifer if there is a deficit.

The partitioning of water withdrawals between surface and ground water resources is data driven (similar to e.g. Döll et al., 2012; Voisin et al., 2017; Hanasaki et al., 2018). Partitioning was based on the study of Döll et al. (2012), who estimated ~~the~~ groundwater withdrawal ~~fraction~~fractions for each sector in around 15.000 national and sub-national administrative units. ~~Groundwater~~These groundwater fractions were based mainly on information from the International Groundwater Resources Assessment

Centre (IGRAC; un-igrac.org) database. Surface water withdrawals ~~are partitioned between river streamflow and small reservoirs relative to water availability~~were partitioned between river streamflow and small reservoirs relative to water availability. Groundwater withdrawals were first withdrawn from the third soil layer, second from the (remaining) river streamflow resources and lastly from the groundwater aquifer. This order was implemented to avoid overestimation of non-renewable groundwater withdrawals as a result of errors in the partitioning data. Aquifer withdrawals are additionally limited by the pumping capacity from Sutanudjaja et al. (2018), who estimated regional pumping capacities based on information from IGRAC.

Water ~~could~~can also be withdrawn from the river streamflow of other ‘remote’ cells in delta areas. Since rivers cannot split in ~~our~~the routing module, the model is unable to simulate the redistribution of water resources in dendritic deltas. Therefore, streamflow at the river mouth is available for use in delta areas (partitioned based on demand) to simulate the actual water availability. Delta areas were delineated by the global delta map of Tessler et al. (2015).

~~When~~In terms of water allocation, under conditions where water demands cannot be met, water withdrawals are allocated to the domestic, energy, manufacturing, livestock and irrigation sector in that order. Withdrawn water is partly consumed, meaning the water evaporates and does not return to the hydrological model. Consumption rates were set at 0.15 for the domestic and 0.10 for the ~~domestic and~~ industrial ~~sectors respectively~~sector, based on the data of Shiklomanov (2000). The water consumption in the energy sector was based on Goldstein and Smith (2002) and varies per thermoelectric plant based on the fuel type and cooling system. For the livestock sector the assumption was made that all withdrawn water is consumed. Unconsumed water withdrawals for these sectors are returned as river streamflow. For the irrigation sector, consumption was determined by the calculated evapotranspiration. Unconsumed irrigation water remains in the soil column and eventually returns as subsurface runoff.

2.2.2 Environmental flow requirements

Water withdrawals can be constrained by environmental flow requirements (EFRs). These EFRs specify the timing and quantity of water needed to support terrestrial river ecosystems (Smakhtin et al., 2004;

Pastor et al., 2019). Surface and groundwater withdrawals are constrained separately in VIC-WUR, based on the EFRs for streamflow and baseflow respectively. EFRs for streamflow specify the minimum river streamflow requirements while EFRs for baseflow specify the minimum subsurface runoff requirements (from groundwater to surface water). Since baseflow is a function groundwater availability ~~in the hydrological model~~, baseflow requirements are used to constrain groundwater (including aquifer) withdrawals.

Various EFR methods are available (Smakhtin et al., 2004; Richter et al., 2012; Pastor et al., 2014). Our study used the Variable Monthly Flow (VMF) method (Pastor et al., 2014) to calculate the EFRs for streamflows. VMF calculates the required streamflow as a fraction of the natural flow during high (30 %), intermediate (45 %) and low (60 %) flow periods, as described in Appendix B. The VMF method performed favourably compared to other hydrological methods, ~~such as the method proposed by Smakhtin et al. (2006) or the Q90-Q50 method,~~ in 11 case studies where EFRs were calculated locally (Pastor et al., 2014). The advantage of the VMF method is that the method accounts for the natural flow variability, which is essential to support freshwater ecosystems (Poff et al., 2010).

EFR methods for baseflow have been rather underdeveloped compared to EFR methods for streamflow. However, a presumptive standard of 90 % of the natural subsurface runoff through time was proposed by Gleeson and Richter (2018), as described in Appendix B. This standard should provide high levels of ecological protection, especially for groundwater dependent ecosystems.

Note that part of the EFRs for baseflow are already captured in the EFRs for streamflow, especially during low-flow periods that are usually dominated by baseflows. However, the EFRs for baseflow specifically limit local groundwater withdrawals while EFRs for streamflow include the accumulated runoff from upstream areas. Also, the chemical composition of groundwater derived flows is inherently different, making them a non-substitutable water flow for environmental purposes (Gleeson and Richter, 2018).

2.2.3 Dam operation

Due to the lack of globally available information on local dam operations, several generic dam operation schemes were developed for macro-scale hydrological models to reproduce the effect of dams on natural streamflow (Haddeland et al., 2006a; Hanasaki et al., 2006; Zhao et al., 2016; Rougé et al., 2019; Yassin et al., 2019). In VIC-WUR a distinction is made between 'small' dam reservoirs (with an upstream area smaller than the cell area) and 'large' dam reservoirs, similar to Hanasaki et al. (2018), Wisser et al. (~~2010~~2010a)~~ and Döll et al. (2009)~~ and Döll et al. (2009). Small dam reservoirs act as buckets that fill using surface runoff of the grid-cell they are located in and reservoirs storage can be used for water withdrawals in the same cell. Large dam reservoirs are located in the main river and used the operation scheme of Hanasaki et al. (2006)~~.~~, as described in Appendix C.

The scheme distinguishes between two dam types: (1) dams that do not account for water demands downstream (e.g. hydropower dams or flood protection dams) and (2) dams that do account for water demand downstream (e.g. irrigation dams). For dams that do not account for demands, dam release is aimed at reducing annual fluctuations in discharge. For dams that do account for demands, dam release is additionally adjusted to provide more water during periods of high demand. The operation scheme was validated by Hanasaki et al. (2006) for 28 reservoirs and was used in various other studies (Hanasaki et al., ~~2008~~2008a; Döll et al., 2009; Pokhrel et al., ~~2012~~2012b; Voisin et al., 2013; Hanasaki et al., 2018). Here, the scheme was adjusted slightly to account for monthly varying EFRs and to reduce overflow releases~~. The full operation scheme~~, which is described in Appendix C.

The Global Reservoir and Dam (GRanD) database (Lehner et al., 2011) was used to specify location, capacity, function (purpose), and construction year of each dam. The capacity of multiple (small- and large) dams located in the same cell were combined.

2.3 Sectoral water demands

~~Water~~VIC-WUR water withdrawals are based on the irrigation, domestic, industry, energy and livestock water demand in each grid-cell. Water demands represent the potential water withdrawal, which is reduced when insufficient water is available. Irrigation demands were estimated based on the hydrological model while water demands for other sectors are provided to the model as an input. Domestic and industrial were estimated based on several socioeconomic predictors, while energy and livestock water demands were ~~mostly data-driven (i.e. ~~derived from power plant and livestock distribution data~~)~~. Due to data limitations the energy sector was incomplete, and energy water demands were partly included in the industrial water demands (which combined the remaining energy and manufacturing water demands). For more details concerning sectoral water demand calculations the reader is referred to Appendix D.

2.3.1 Irrigation demands

Irrigation demands were set to increase soil moisture in the root zone so that water availability is not limiting crop evapotranspiration and growth. ~~Preferably, irrigation was supplied to fill the soil to field capacity (Allen et al., 1998), which is the moisture content where water leaching is minimized. ~~The exception is paddy rice irrigation (Brouwer et al., 1989), where irrigation was also supplied to keep the upper soil layer saturated. Water demands for paddy irrigation practices are relatively high compared to conventional irrigation practices due to increased evaporation and percolation. Therefore, the crop irrigation demands for these two irrigation practices were calculated and 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) (see Section 3.1 for more details).

Total irrigation demands also included transportation and application losses. Note that transportation and application losses are not 'lost' but rather returned to the soil column without being used by the crop. 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. Potential total irrigation demands were validated independently and correlated well with reported withdrawals (adjusted R^2 > 0.8; Figure 2a)~~. 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.

2.3.2 Domestic and industrial demands

Domestic and industrial water withdrawals were estimated based on Gross Domestic Product (GDP) per capita and Gross Value Added (GVA) by industries respectively~~.~~ (from Bolt et al. (2018), Feenstra et al. (2015) and World bank (2010); see Appendix D for more details). These drivers do not fully capture the multitude of socioeconomic factors that influence water demands (Babel et al., 2007). However, the wide availability of data allows for extrapolation of water demands to data-scarce regions and future scenarios (using studies such as Chateau et al. (2014)).

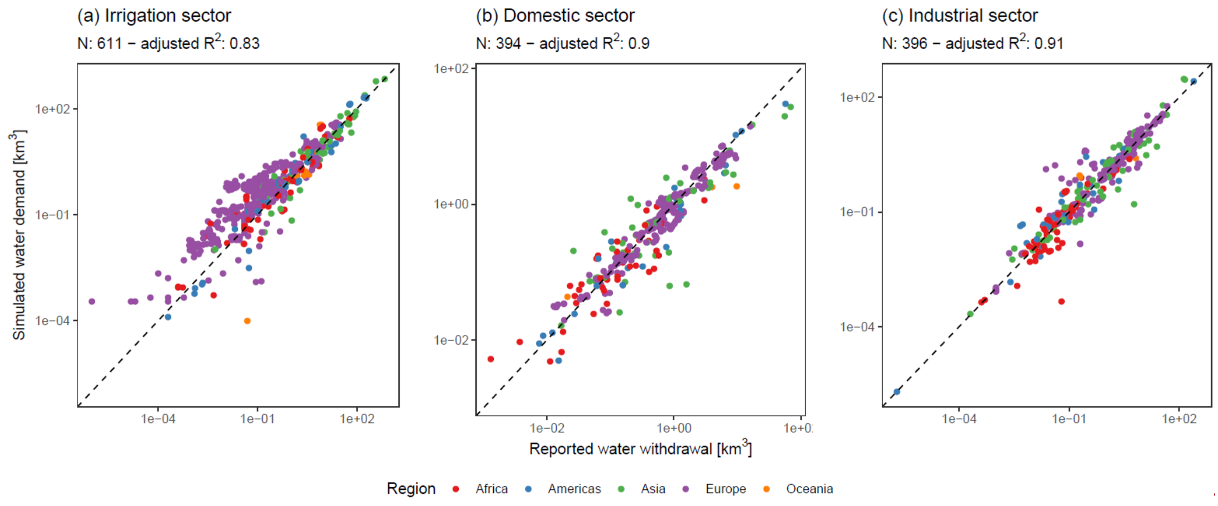
Domestic water demands per capita (used for drinking, sanitation, hygiene and amenity uses) were estimated similar to Alcamo et al. (2003). Demands increased non-linearly with GDP per capita due to the acquisition of water using appliances as household become richer. A minimum water supply is needed for survival, and the saturation of water using appliances sets a maximum on domestic water demands. Industrial water demands (used for cooling, transportation and manufacturing) were estimated similar to Flörke et al. (2013) and Voß and Flörke (2010). Industrial demands increased linearly with GVA (as an indicator of industrial production). Since industrial water intensities (i.e. the water use per production unit) vary widely between different industries (Flörke and Alcamo, 2004 ; Vassolo and Döll, 2005; Voß and Flörke, 2010), the average water intensity was estimated for each country. Both domestic and industrial water demands were also influenced by technological developments that increase water-use efficiency over time, as in Flörke et al. (2013). ~~Estimated domestic and industrial water demands were validated independently and correlated well to reported withdrawals (adjusted $R^2 > 0.8$; Figure 2b and Figure 2c).~~

~~Domestic water demands varied monthly based on air temperature variability as in Wada et al. (2011b).~~Domestic water demands varied monthly based on air temperature variability as in Huang et al. (2018) (based on Wada et al. (2011b)). Using this approach, water demands were higher in summer than in winter, especially for counties with strong seasonal temperature differences. Domestic water demand per capita were downscaled using the HYDE3.2 gridded population maps (Goldewijk et al., 2017). Industrial water demands were kept constant throughout the year. Industrial demands were downscaled from national to grid cell values using the NASA Back Marble night-time light intensity map (Roman et al., 2018). National industrial water demands were allocated based on the relative light intensity per grid cell for each country.

2.3.3 Energy and livestock demands

Energy water demands (used for cooling of thermoelectric plants) were estimated using data from van Vliet et al. (2016). Water use intensity for generation (i.e. the water use per generation unit) was estimated based on the fuel and cooling system type (Goldstein and Smith, 2002), which was combined with the ~~installed~~ generation capacity. Note that the data only covered a selection of the total number of thermoelectric power plants worldwide. Around 27 % of the total (non-renewable) global installed capacity between 1980 and 2011 was included in ~~this~~the dataset due to lack of information on cooling system types for the majority of thermoelectric plants. To avoid double counting, energy water demands were subtracted from the industrial water demands.

Livestock water demands (used for drinking and animal servicing) were estimated by combining the Gridded Livestock of the World (GLW3) map (Gilbert et al., 2018) with the livestock water requirement reported by Steinfeld et al. (2006). Eight varieties of livestock were considered: cattle, buffaloes, horses, sheep, goats, pigs, chicken and ducks. Drinking water demands varied monthly based on temperature as described by Steinfeld et al. (2006), whereby drinking water requirements were higher during higher temperatures.



~~**Figure 2: Comparison between reported and estimated national water withdrawal per year for the irrigation (a), domestic (b) and industrial (c) sector. Reported values are from the validation dataset. Note the log-log axis which is used to display the wide range of water withdrawals. The adjusted R squared is also based on the log-log values.**~~

3 Model application

3.1 Setup

VIC-WUR results were generated between 1979 and 2016, excluding a spin-up period of one year (analysis period from 1980 to 2016). The model used a daily timestep (with a 6-hourly timestep for snow processes) and simulations were executed on a 0.5° by 0.5° grid (around 55 km at the equator) with three soil layers per grid cell. Soil and (natural) vegetation parameters were the same as in ~~Nijssen et al. (2001c)~~Nijssen et al. (2001c) (disaggregated to 0.5°), who used various sources to determine the soil (Cosby et al., 1984; Carter and Scholes, 1999) and vegetation parameters (Calder, 1993; Ducoudre et al., 1993; Sellers et al., 1994; Myneni et al., 1997).

~~Nijssen et al. (2001c)~~Nijssen et al. (2001c) used the Advanced Very High Resolution Radiometer vegetation type database (Hansen et al., 2000) to spatially distinguish 13 land cover types. The land cover type ‘cropland’ in the original land-cover dataset was replaced by cropland extents from the MIRCA2000 cropland dataset (Portmann et al., 2010). MIRCA2000 distinguishes the monthly growing area(s) and season(s) of 26 irrigated and rain-fed crop types around the year 2000. Crop types were aggregated into three land cover types: rain-fed, irrigated and paddy rice cropland. The natural vegetation was proportionally rescaled to make up discrepancies between the natural vegetation and cropland extents.

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. Cropland vegetation parameters (e.g. Leaf Area Index (LAI), displacement, vegetation roughness and albedo) vary monthly based on the ~~monthly~~ crop growing seasons and the development-stage crop coefficients of the Food and Agricultural Organisation (Allen et al., 1998).

The latest WATCH forcing data Era Interim (aggregated to 6 hourly), developed by the EU Water and Global Change (WATCH; Harding et al., 2011) project, was used as climate forcing (WFDEI; Weedon et al., 2014). The dataset provides gridded historical climatic variables of minimum and maximum air temperature, precipitation (as the sum of snowfall and rainfall, GPCC bias-corrected), relative humidity, pressure and incoming shortwave and longwave radiation.

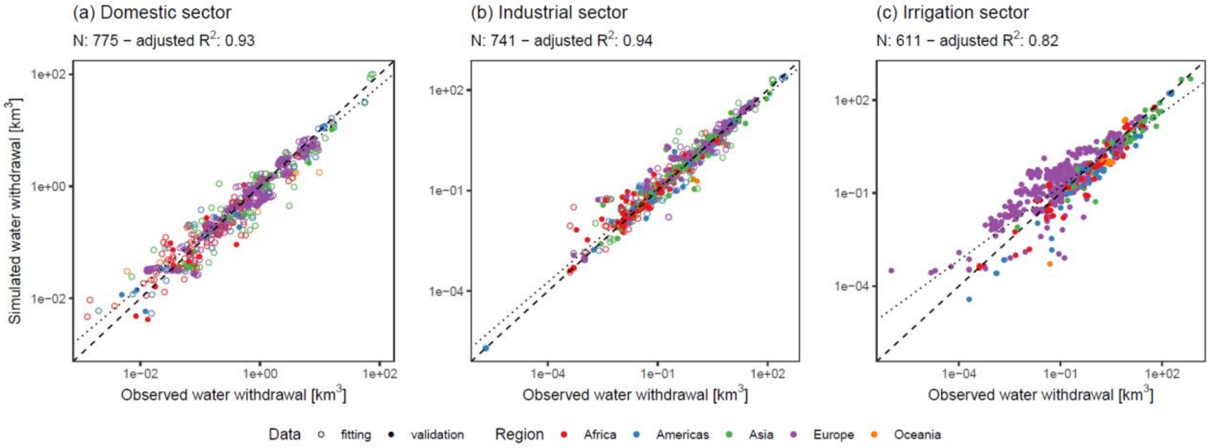
For naturalized simulations only the routing module was used. For the human-impact simulations the sectoral water withdrawals and dam operation modules were turned on in the model simulations. For the EFR-limited simulations water withdrawals and dam operations were constrained as described.

3.2 Validation and evaluation

In order to validate the VIC-WUR human-impact modules, water withdrawal, terrestrial total water storage anomalies, streamflow and reservoir operation simulations were compared with observations. The validation specifically focused on the effects of the newly included human-impact modules, meaning that streamflow and total-water storage anomaly results are shown for river basins that are strongly influenced by human activities. A general validation for streamflow and terrestrial total water storage anomalies (including basins with limited human activities) is shown in Appendix E.

3.2.1 Sectoral water withdrawals

Simulated global domestic, industrial, livestock and irrigation mean water withdrawals were 310, 771, 36 and 2202 km^3 year^{-1} respectively for the period of 1980 to 2016. Sectoral water withdrawals were compared with FAO national annual water withdrawals (FAO, 2016), monthly withdrawal data from Huang et al. (2018) and annual withdrawal data from Shiklomanov (2000) and Steinfeld et al. (2006). For the latter studies, water withdrawals were aggregated by region (world, Africa, Asia, Americas, Europe and Oceania). Note that Huang et al. (2018) irrigation water withdrawals integrate results of four other macro-scale hydrological models (WaterGAP, H08, LPJmL, PCR-GLOBWB), using the same land-use and climate setup as our study. Results from individual macro-scale hydrological models are also shown.



~~3.2~~ **Figure 2: Comparison between simulated and reported national annual water withdrawals for the (a) domestic, (b) industrial and (c) irrigation sector. Colours distinguish between regions. Open circles were also used in the calibration of the water withdrawal demands. The dashed line indicates the 1:1 ratio and the spotted line indicates the simulated best linear fit. Note the log-log axis which is used to display the wide range of water withdrawals.**

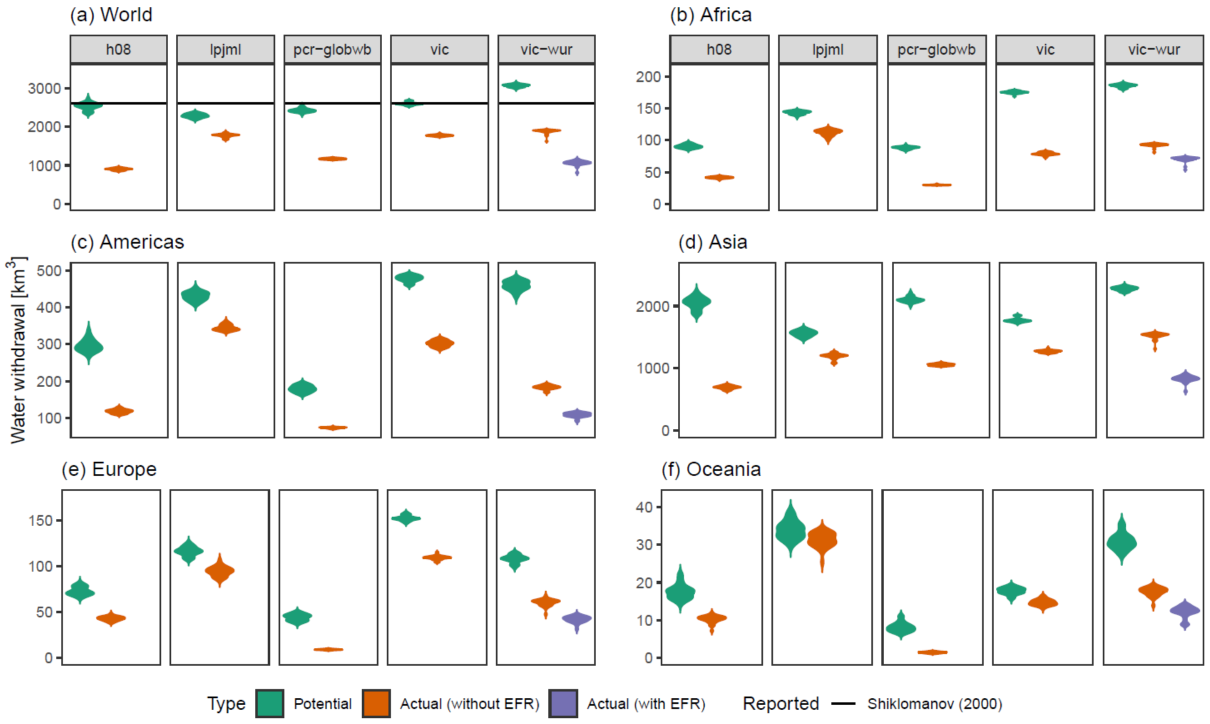
~~**Results**~~

~~The VIC-WUR model results were compared to several of the Inter-Sectoral Impact Model Intercomparison Project (Warszawski et al., 2014) simulation round 2a global hydrological impact models: H08 (Hanasaki et al., 2008), LPJmL (Sitch et al., 2003), VIC (Liang et al., 1994), PCR-GLOBWB (Wada et al., 2014) and WaterGAP (Muller Schmied et al., 2016). The ISIMIP2a outputs are comparable to the results of our study since the same meteorological and land cover inputs were used. The VIC and LPJmL models only provided data on the actual and potential irrigation withdrawal and consumption. H08 additionally provided data for the domestic sector, and PCR-GLOBWB additionally provided data for the domestic and livestock sector. To increase the number of models to compare to, the WaterGAP (Alcamo et al., 2003) output for the domestic and industrial (manufacturing plus energy) sector from the Water and Global Change project (Harding et al., 2011) was included as well. Note that the WaterGAP simulations were based on a different WATCH forcing dataset (WFD) (Weedon et al., 2011). Since our study used a present-day land-cover map, the actual and potential irrigation~~

~~withdrawals were compared based on the so-called ‘pressoc’ (present-day land cover) simulations. Domestic, industrial and livestock sectors were compared based on the ‘varsoc’ (variable human influences) simulations, since our study used varying socioeconomic predictors to estimate the water demand in these sectors. Results were compared between the years 1980 to 2005. The reported global water withdrawal of Shiklomanov (2000) and Steinfeld et al. (2006) are included as a reference.~~

~~3.2.1 Irrigation sector~~

~~Compared to other models the VIC-WUR potential and actual water withdrawals (without EFRs) were at the high end (Figure 3). 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. Especially in the African and Asian regions the irrigation withdrawals were high compared to the model ensemble. Irrigation withdrawals were probably high due to the inclusion of groundwater withdrawals and paddy irrigation in the model. All models (VIC-WUR included) indicated a lower actual irrigation withdrawal than reported. Due to the increased irrigation withdrawal, the deficit for VIC-WUR (around 710 km^3) was lower than the ensemble mean deficit (around 1170 km^3). This difference is often assumed to be met by non-renewable and/or unspecified withdrawals (Wada et al., 2010; Hanasaki et al., 2018).~~



~~**Figure 3: Irrigation withdrawals for the world (a) and each region (b-f) for five hydrological models between 1980 and 2005. Colours differentiate between the potential (green), actual excluding EFRs (orange) and actual including EFRs (purple) withdrawals. The spread indicates the inter-annual variation of the simulated irrigation withdrawals. Data was obtained from the ISIMIP project, except for the VIC-WUR model. The black line indicates the reported total irrigation withdrawal as estimated by Shiklomanov (2000). Note that the y-axis varies for each graph, making Asia is by far the largest contributor to irrigation withdrawals.**~~

~~Limitations imposed by the~~The R^2 adjusted is also based on the log values.

Simulated domestic, industrial and irrigation water withdrawals correlated well to reported national water withdrawals, with adjusted R^2 of 0.93, 0.94 and 0.82 for domestic, industrial and irrigation water withdrawal respectively (Figure 2a-c). Generally, smaller water withdrawals were overestimated and larger water withdrawals were underestimated. Differences for the domestic and industrial sector were small and probably related to the fact that smaller countries were poorly delineated on a 0.5° by 0.5° grid. However, irrigation differences were larger with overestimations of irrigation water withdrawals in (mostly) Europe. Since irrigation water demands are the results of the simulated water balance, overestimations would indicate a regional underestimation of water availability for Europe or differences in irrigation efficiency.

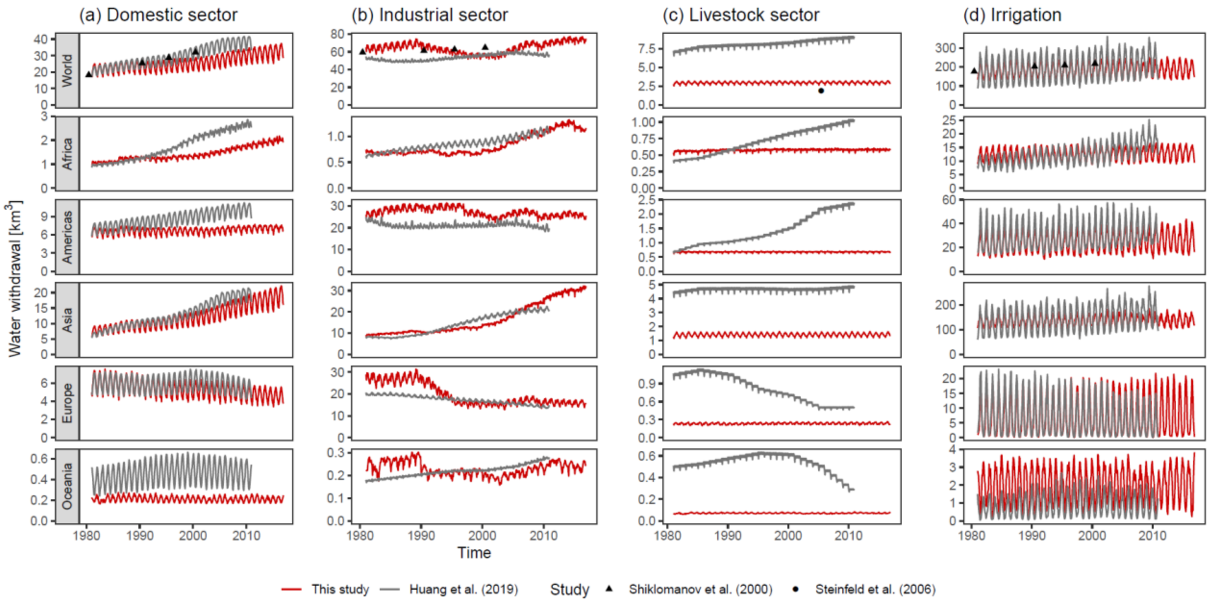


Figure 3: Comparison between simulated and compiled monthly and annual regional water withdrawals for the (a) domestic sector, (b) industrial sector and (c) irrigation. Colours and shapes distinguish between studies. Note that the jitter in livestock withdrawals is due to the different days per month.

When domestic, industrial and livestock water withdrawals were compared to other studies, results were mixed (figure 3a-c). Simulated domestic withdrawals followed a similar trend in time. However, simulated domestic water withdrawals trends were overall somewhat underestimated with a mean bias of 54 km^3 year^{-1} compared to Huang et al. (2018). Asia is the main contributor to the global underestimation, but results are similar in most regions. Simulated industrial water withdrawal were (mostly) higher in our study with a mean bias of 107 km^3 year^{-1} compared to Huang et al. (2018) but only a mean bias of 5 km^3 year^{-1} compared to Shiklomanov (2000). Also, industrial water withdrawal trends in time were less consistent.

Withdrawal differences for the domestic and industrial sector are probably due to the limited data availability. Our approach to compute water demands was data-driven and sensitive to data gaps (as opposed to Huang et al. (2018) who also combined model results). For example, domestic withdrawal data for China was not available before 2007 and industrial withdrawal data was limited before 1990.

For livestock water withdrawals there is a large discrepancy between the Huang et al. (2018) and Steinfeld et al. (2006). Both studies used similar livestock maps, but there was large differences in livestock water intensity [litre animal^{-1} year^{-1}]. Since our study used Steinfeld et al. (2006) to estimate livestock water intensity, our results were closer to their values (slightly higher due to the inclusion of buffaloes, horses and ducks). Note that Huang et al. (2018) shows trends in livestock water withdrawals while our study used static livestock maps.

Table 1: Global irrigation water withdrawals as calculated by several global hydrological models. **Includes livestock withdrawals.

Model	**Irrigation withdrawal [km^3 year^{-1}]**	**Representative years**	**Reference**
VIC-WUR	2202 (± 60)	1980-2016	Our study
H08	(a) 2810 (b) 2544 (± 75)	(a) 1995 (b) 1984 - 2013	(a) Hanasaki et al. (2008b) (b) Hanasaki et al. (2018)
MATSIRO	(a) 2158 (± 134) (b) 3028 (± 171)	(a) 1983 - 2007 (b) 1998 - 2002	(a) Pokhrel et al. (2012a) (b) Pokhrel et al. (2015)
LPJmL	2555	1971 - 2000	Rost et al. (2008)
PCR-GLOB	(a) 2644 (b) 2309 **	(a) 2010 (b) 2000 - 2015	(a) Wada and Bierkens (2014) (b) Sutanudjaja et al. (2018)
WaterGAP	(a) 3185 (b) 2400	(a) 1998-2002 (b) 2003 - 2009	(a) Döll et al. (2012) (b) Döll et al. (2014)
WBM	2997	2002	Wisser et al. (2010b)

Simulated irrigation water withdrawals were within range of other macro-scale hydrological model estimates (Table 1). Simulated monthly variability in irrigation water withdrawals is reduced compared to the compiled results of Huang et al. (2018) (Figure 3d), especially in Asia. Also, trends in time are less pronounces as can be seen in Africa. These differences may indicate a relative low weather/climate sensitivity of evapotranspiration in VIC-WUR, as annual and interannual weather changes affect irrigation water demands to a lesser degree.

3.2.2 Groundwater withdrawals and depletion

Simulated global mean withdrawals were 2327 and 992 km^3 year^{-1} for surface and groundwater respectively for the period of 1980 to 2016. Of the global groundwater withdrawals, 334 km^3 year^{-1} contributed to groundwater depletion. Simulated ground and surface water withdrawals and terrestrial total water storage anomalies were compared FAO national annual water withdrawals (FAO, 2016) and monthly storage anomaly data from the GRACE satellite (NASA, 2002). GRACE satellite total water storage anomalies were used to validate total water storage dynamics as well as groundwater exploitation contributing to downward trends in total water storage. Groundwater depletion results from other macro-scale hydrological models are shown as well. In order to compare the simulation results to the GRACE dataset, a 300km gaussian filer was applied to the simulated data (similar to Long et al. (2015)).

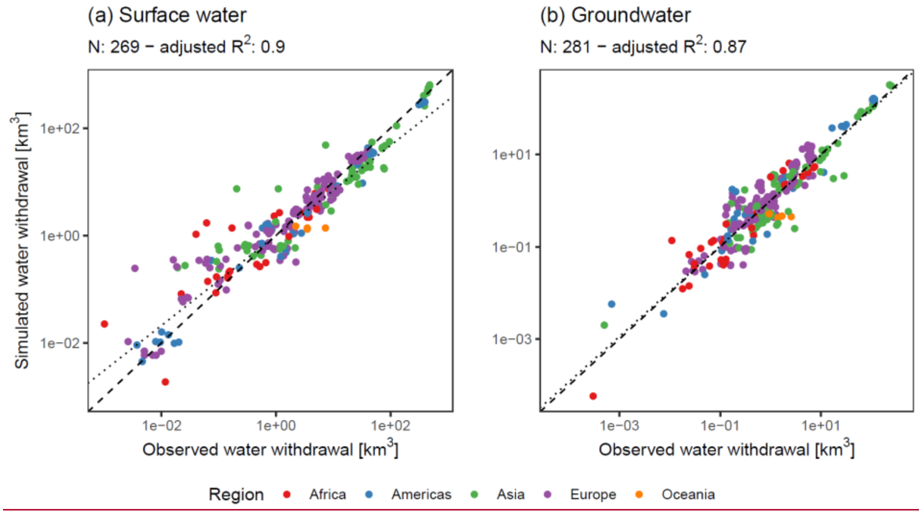


Figure 4: Comparison between simulated and reported national annual water withdrawals from (a) surface water and (b) groundwater. Colours distinguish between regions. The dashed line indicates the 1:1 ratio and the spotted line indicates the simulated best linear fit. Note the log-log axis which is used to display the wide range of water withdrawals. The R^2 adjusted is also based on the log values.

Simulated surface and groundwater withdrawals correlated well to the reported national water withdrawals, with adjusted R^2 of 0.90 and 0.87 for surface and groundwater respectively (Figure 4a-b). Surface water withdrawals were overestimated for low withdrawals and underestimated for large withdrawals. There is a weak correlation (-0.35) between the underestimations in surface water withdrawals and the overestimation in groundwater withdrawals, meaning water withdrawal differences could be related to the partitioning between surface and groundwater resources. Also, it is likely that low water demands are overestimated (as discussed in Section 3.2.1), resulting in an overestimation of low surface water withdrawals.

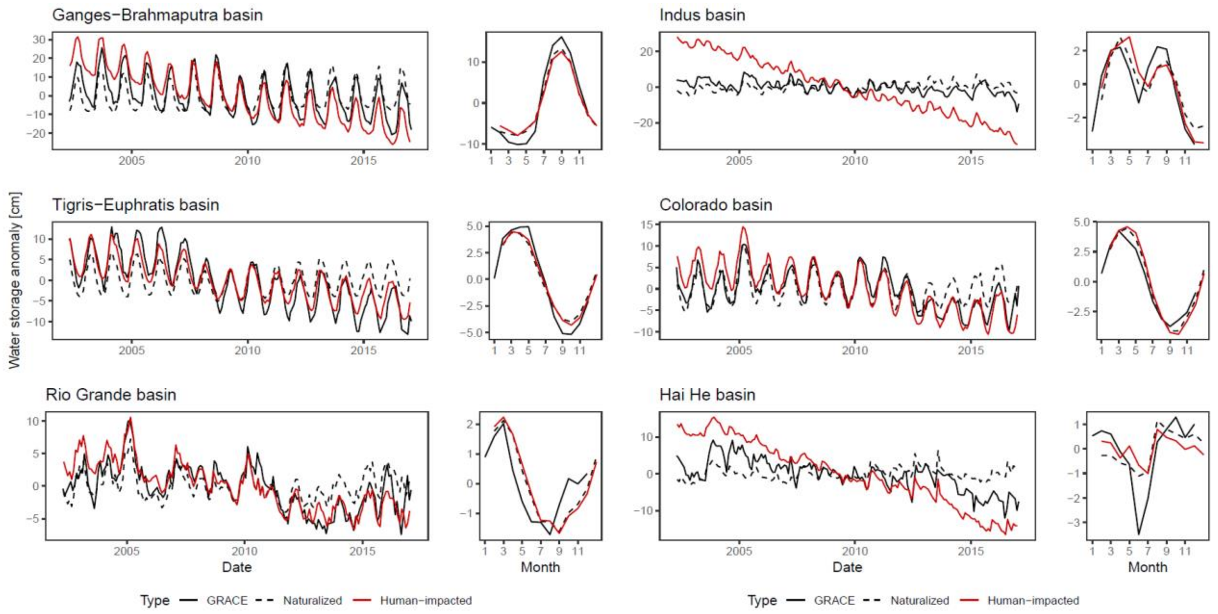


Figure 5: Comparison between simulated and observed monthly terrestrial total water storage anomalies. Figures indicate timeseries and multi-year mean average for naturalized simulations (dashed), human-impacted simulations (red) and observed (black) terrestrial total water storage anomalies.

Simulated monthly terrestrial water storage anomalies correlated well to the GRACE observations, with mean annual and inter-annual Root Mean Squared Error (RMSE) of 1.9 mm and 3.5 mm respectively. The difference between annual and inter annual performance was primarily due to the groundwater depletion process (Figure 5). Simulated groundwater depletion was (mostly) overestimated (e.g. Indus and Hai He basins), with higher declining trends in terrestrial total water storage for most basins. However, compared to other macro-scale hydrological models, simulated groundwater withdrawal and exploitation was within range (Table 2), even though total groundwater withdrawals were relatively high.

As with the FAO comparison, these results seems to indicate that withdrawal partitioning towards groundwater is overestimated. However, conclusions regarding groundwater depletion are limited by the relatively simplistic approach to groundwater used in our study (as discussed by Konikow (2011) and de Graaf et al. (2017)). For example, processes such as wetland recharge and groundwater flows between cells are not simulated, even though these could decrease groundwater depletion.

Table 2: Global groundwater withdrawals and depletion as calculated by several global hydrological models.

Model	**Groundwater withdrawal [km3 year-1]**	**Groundwater depletion [km3 year-1]**	**Representative years**	**Reference**
VIC-WUR	992 (± 51)	316 (± 63)	1980 - 2016	Our study
H08	789 (± 30)	182 (± 26)	1984 - 2013	Hanasaki et al. (2018)
MATSIRO	570 (± 61)	330	1998 - 2002	Pokhrel et al. (2015)
GCAM		(a) 600 (b) 550	(a) 2005 (b) 2000	(a) Kim et al. (2016) (b) Turner et al. (2019)
PCR-GLOB	(a) 952 (b) 632	(a) 304 (b) 171	(a) 2010 (b) 2000 - 2015	(a) Wada and Bierkens (2014) (b) Sutanudjaja et al. (2018)
WaterGAP	(a) 1519 (b) 888	(a) 250 (b) 113	(a) 1998-2002 (b) 2000 - 2009	(a) Döll et al. (2012) (b) Döll et al. (2014)

3.2.3 Discharge modification

Simulated discharge was compared to GRDC station data (GRDC, 2003) for various human-impacted rivers. Stations were selected if the upstream area was larger than 20,000 km2, matched the simulated upstream area at the station location, and the available data spanned more than 2 years. Subsequently, stations where the human-impact modules did not sufficiently impacted discharge were omitted. In order validate the reservoir operation more thoroughly, simulated reservoir inflow, storage and release was compared with operation data from Hanasaki et al. (2006) and Yassin et al. (2019). Reservoirs were included if the simulated storage capacity (which is the combined storage capacity of all large dams in a grid) was similar to observed storage capacity.

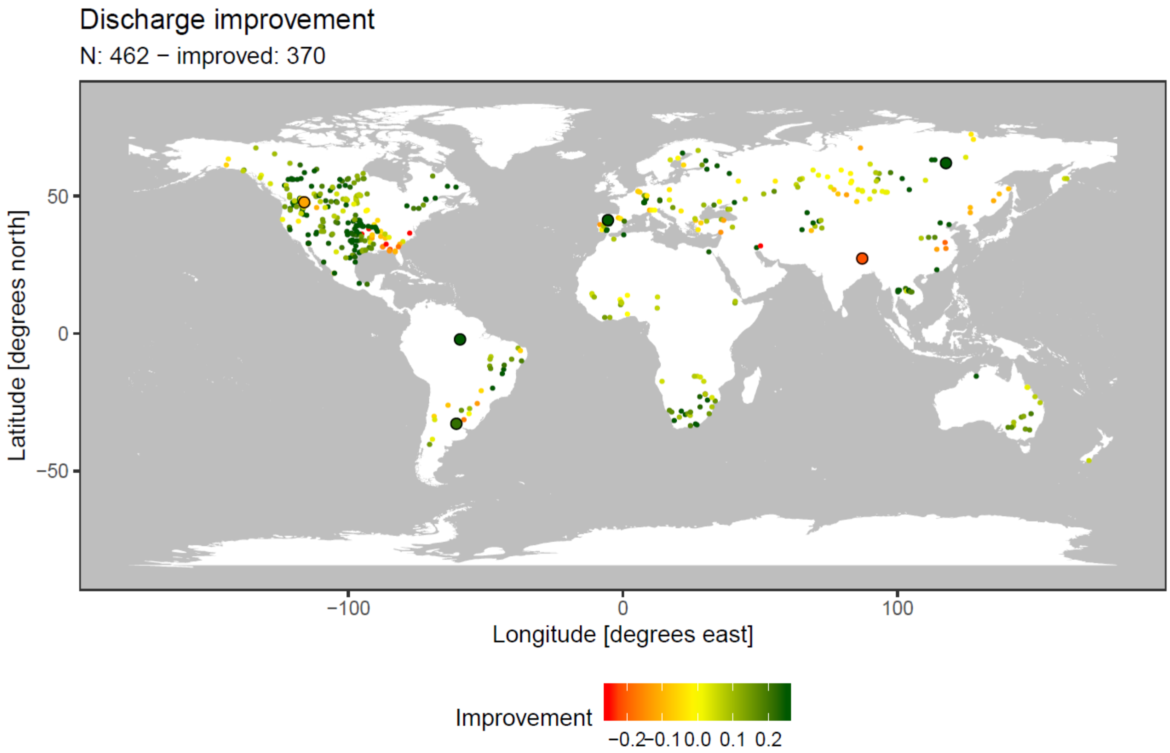


Figure 6: Discharge improvement from naturalized to human-impacted simulations (as a fraction of the naturalized RMSE). Circled larger stations are shown in Figure 7.

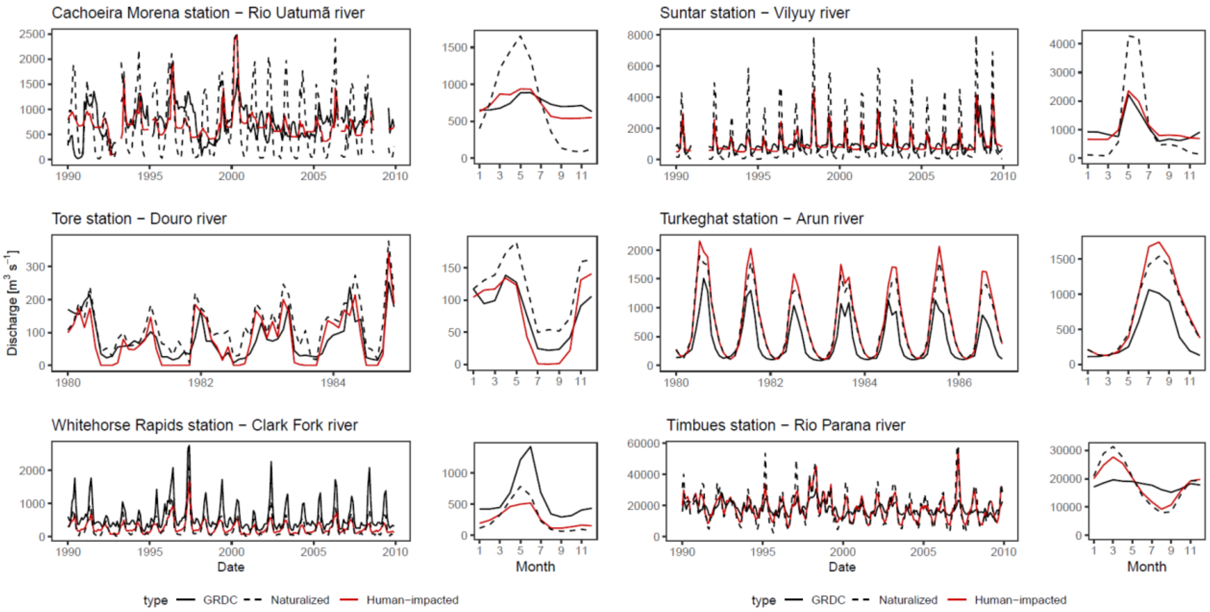


Figure 7: Comparison between simulated and observed discharge. Figures indicate timeseries and multi-year average of for naturalized simulations (dashed), human-impacted simulations (red) and observed (black) discharge.

The inclusion of the human-impact modules improved discharge performance, measured in RMSE, for 370 out of 462 stations (80 %; Figure 6 and 7). Improvements were mainly due to the effects of reservoir operation on discharges (e.g. Cachoeira Morena and Suntar stations), but also due to withdrawal reductions (e.g. Tore station). Reservoir effects on discharge were sometimes underestimated however (e.g. Timbues station).

Decreased performance was mostly related to under or overestimations of (calibrated) natural streamflow which was subsequently exacerbated by reservoir operation and water withdrawals. For example, the Clark Fork river naturalized streamflow was underestimated, which was subsequently further underestimated by the human-impact modules (Whitehorse Rapids station). Also, increases in discharge due to groundwater withdrawals could increase naturalized streamflow (e.g. Turkeghat station). Further improvements to discharge performance would most likely require either a recalibration of the VIC model parameters.

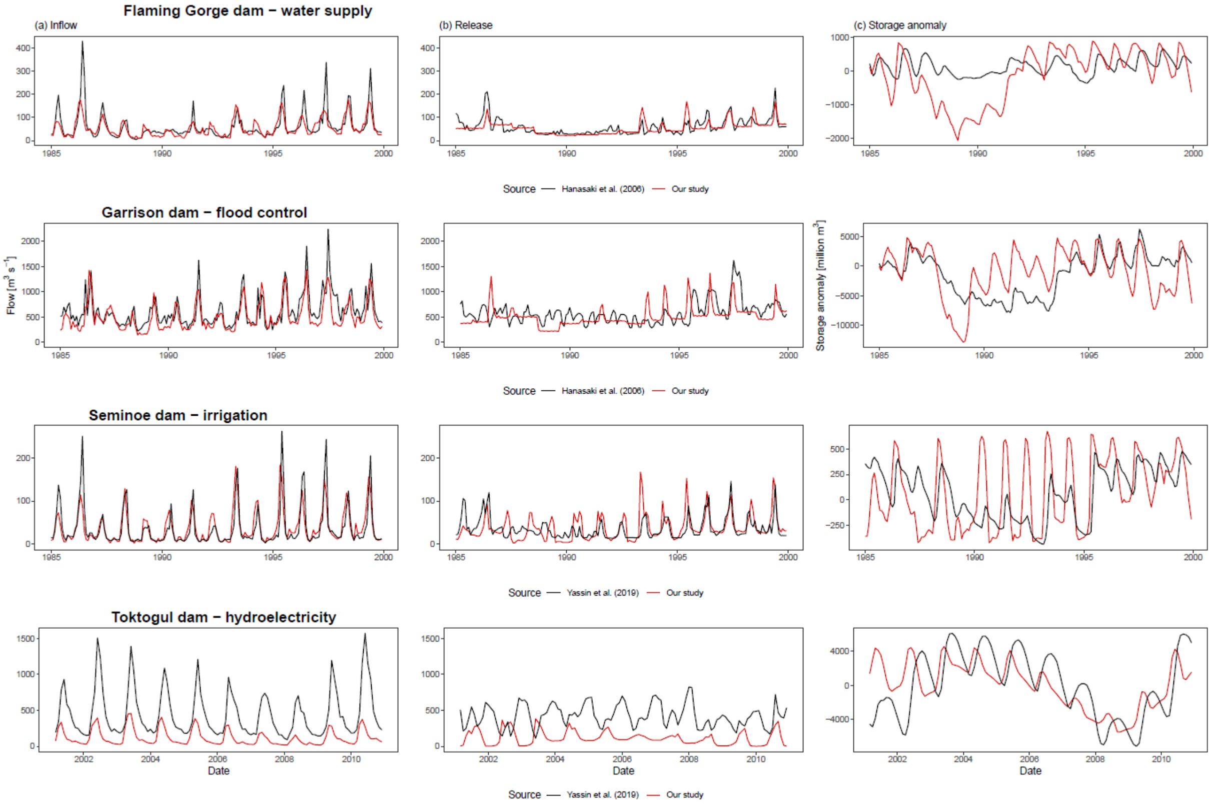


Figure 8: Comparison between simulated and observed reservoir operation. Figures indicate timeseries and multi-year averages of (a) inflow, (b) release and (c) storage anomalies for human-impacted simulations (red) and observations (black).

For individual reservoirs, operation characteristics were generally well simulated (Figure 8), with reductions in annual discharge variations (e.g. Flaming Gorge and Garrison dams) and increased water release for irrigation (e.g. Seminoe dam). However, due to changes in locally simulated and actual inflow, dam operation can take on different characteristics (e.g. Toktogul dam). Also, peak discharge events caused by reservoir overflow (as also described by Masaki et al. (2018a)) were not always sufficiently represented in the observations (e.g. Garisson dam). These differences indicate locally varying reservoir operation strategies. Several studies have developed reservoir operation schemes that can be calibrated to the local situation (Rougé et al., 2019; Yassin et al., 2019). However, worldwide implementations of these operation schemes remains limited by data availability.

3.3 Integrated environmental flow requirements ~~reduced the actual (irrigation) water withdrawals~~

In order to assess the impact and capabilities of the newly integrated environmental flow requirements (EFRs) module, simulated water withdrawals with and without adhering to EFRs were compared.

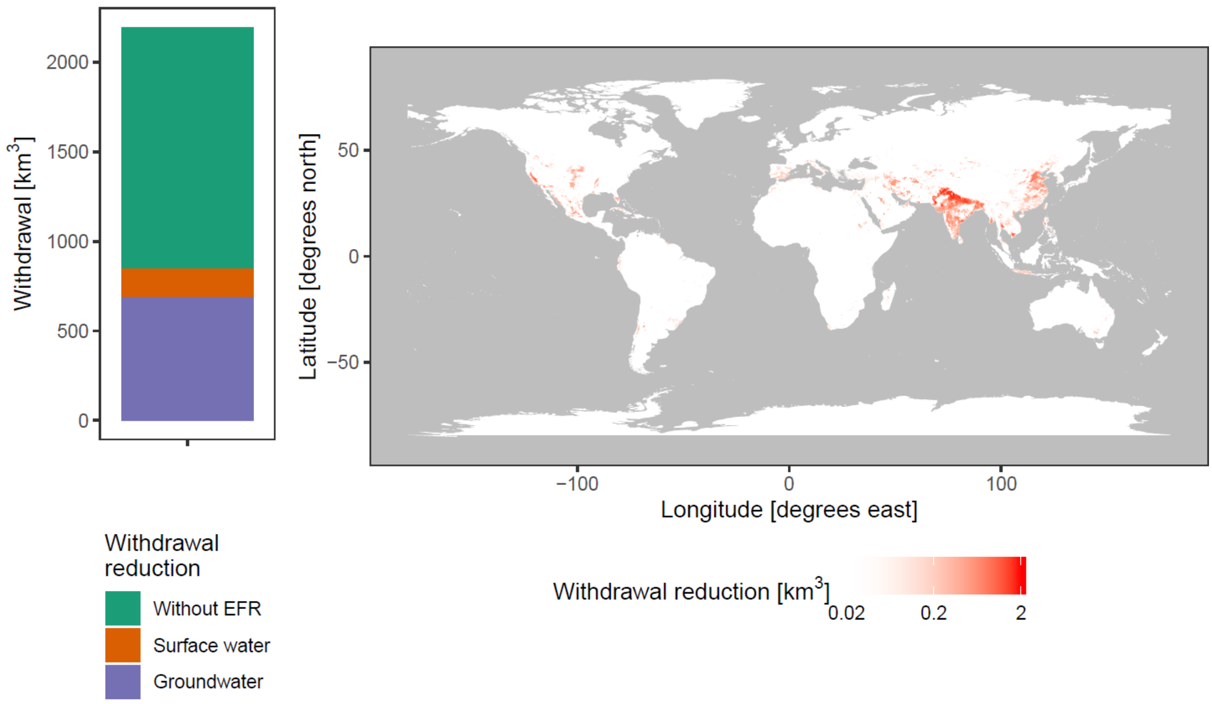
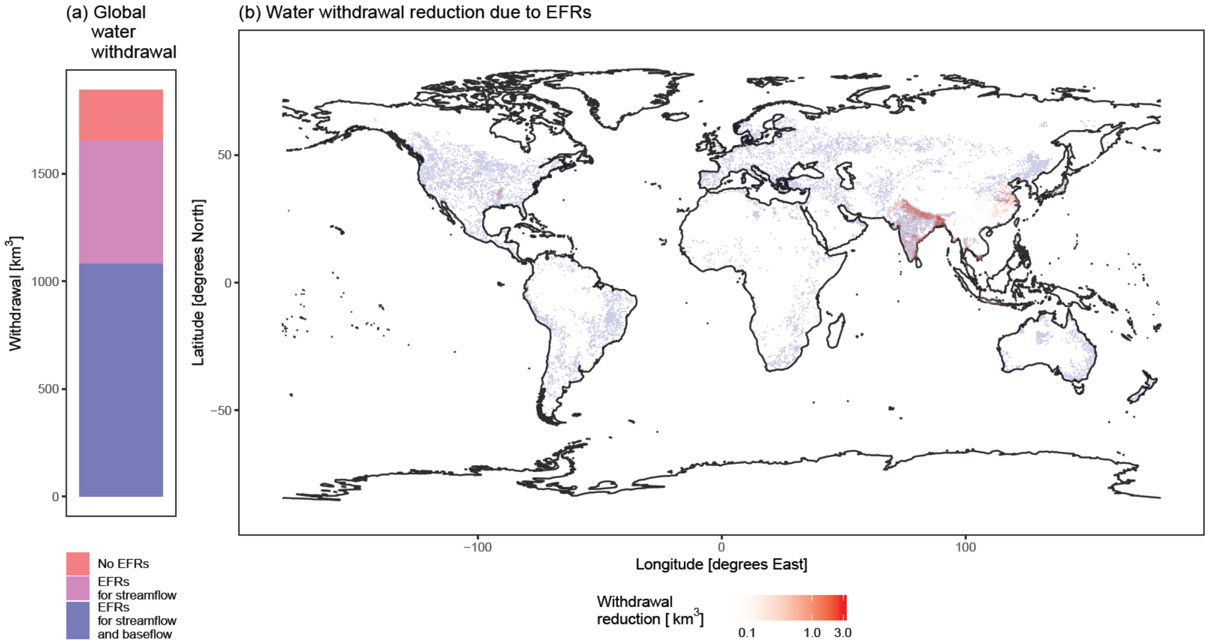


Figure 9: Average annual irrigation water withdrawal reductions when adhering to EFRs as (left) global gross total and (right) spatially distributed. Global gross totals are separated into withdrawals without any reduction (green), surface water withdrawal reductions (orange) and groundwater withdrawal reductions (purple). Note the log axis for the spatially distributed withdrawal reductions to better display the spatial distribution of the reductions.

If water-use would be limited to EFRs, irrigation withdrawals would need to be reduced by about ~~43% (Figure 4a). In total, 71%~~39 % (851 km^3 year^{-1}) (Figure 9a). Under the strict requirements used in our study, 81 % (693 km^3 year^{-1}) of the reduction could be attributed to limitations imposed on groundwater withdrawals. ~~Therefore~~Subsequently, the impact of the environmental flow requirements ~~was~~(if adhered to) would be largest in groundwater dependent regions (Figure ~~4b). However, ~~9b). Note that, due to the full integration of EFRs, downstream surface water withdrawals increased by ~~11 %~~98 km^3 year^{-1} when limiting groundwater withdrawals on top of limiting surface water withdrawals, due to increase subsurface runoff.

Reductions due to EFRs were similar to Jägermeyr et al. (2017), who calculated irrigation withdrawal reductions of 41 % (997 km^3 year^{-1}) assuming only surface water abstractions. In our study, surface water reductions were smaller since the strict groundwater requirements increases subsurface runoff ~~increases.~~

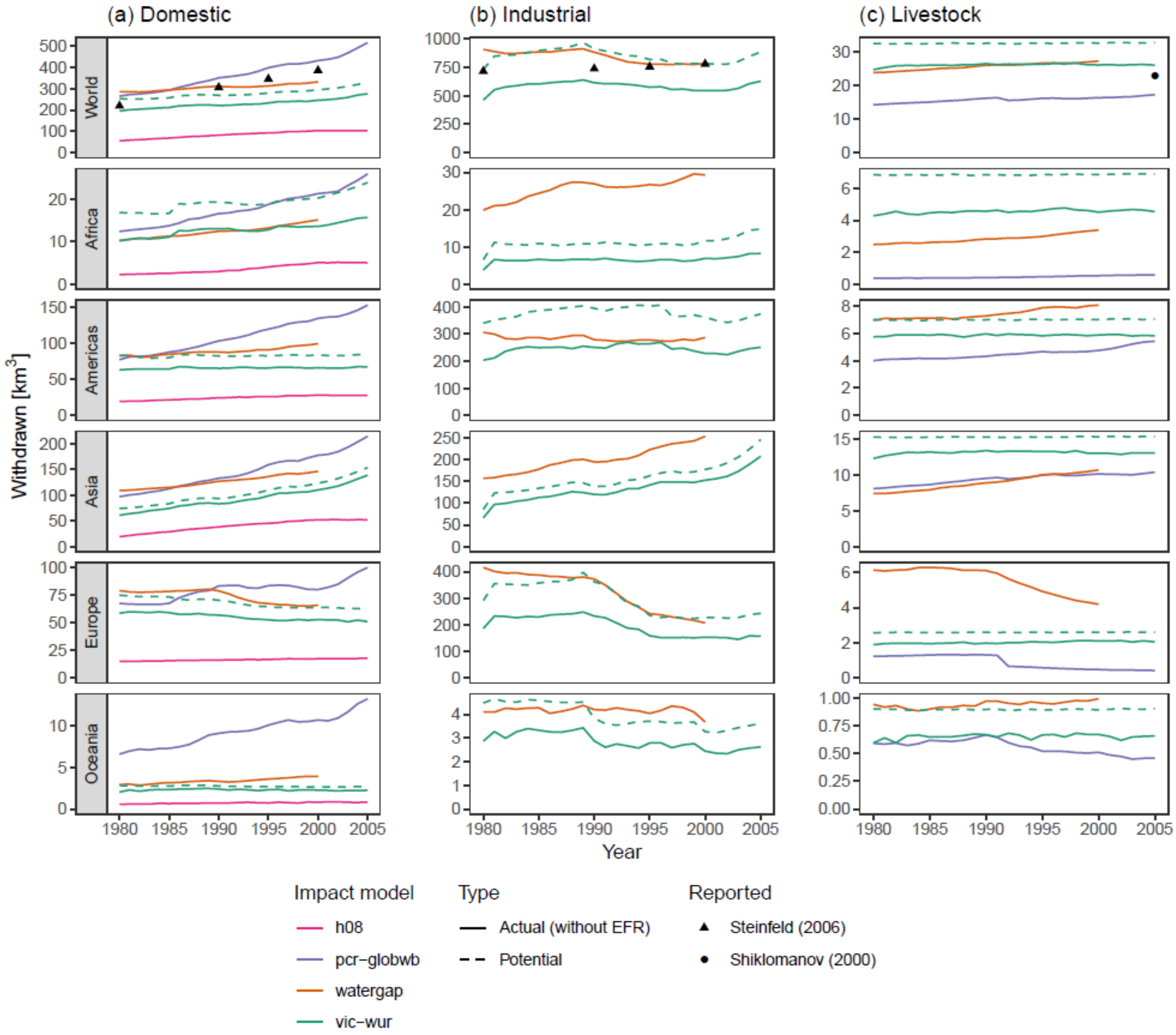


~~Figure 4: Average annual water withdrawals reductions when adhering~~ to ~~EFRs as (a) global gross total and (b) spatially distributed. Global gross totals (a) are separated into withdrawals without EFRs (red), withdrawals with EFRs for streamflow (purple) and withdrawals with EFRs for both streamflow and baseflow (blue). Note the log axis for the spatially distributed withdrawal reductions (b) to better display the spatial distribution of the reductions. Blue regions indicate areas where the withdrawal reduction is largely (> 75 %) caused by the EFRs for baseflow.~~

~~3.2.2 Domestic, industrial and livestock sector~~

~~In contrast to the irrigation withdrawals, the annual domestic (ranging from 195 km^3 to 275 km^3) and industrial (ranging from 461 km^3 to 637 km^3) withdrawals of VIC-WUR were slightly lower than that of reported values and other models (Figure 5a; Figure 5b). Domestic and industrial withdrawals were probably low due to insufficient water availability, as the potential water withdrawals are more in line with reported values. Note that the rising trend of the VIC-WUR domestic water withdrawals (on~~

~~average 2.5 km^3 year^{-1}), WaterGAP (on average 2.3 km^3 year^{-1}) and H08 (on average 2.4 km^3 year^{-1}) was more gradual than that of PCR-GLOBWB (on average 8.3 km^3 year^{-1}) and Shiklomanov (2000) (on average 8.1 km^3 year^{-1}) between 1980 and 2000. This slope difference resulted from the different methods used to calculate domestic water demand. The annual livestock withdrawals of VIC-WUR (ranging from 25 km^3 to 27 km^3) were within range of reported values and other models (Figure 5c).~~



~~Figure 5: Domestic (a), industrial (b) and livestock (c) water withdrawals for the world and each region for five hydrological models between 1980 and 2005. Colours differentiate between models. Data was obtained from the ISIMIP project (for H08 and PCR-GLBOWB) and WATCH project (for WaterGAP), except for the VIC-WUR model. The black points indicates the reported total water withdrawals for each sector as estimated by Shiklomanov (2000) (for domestic and industrial sectors) and (Steinfeld et al., 2006) (for livestock sector). Note that the y-axis varies for each graph, making Asia, Europe and Asia the largest contributors to the domestic, industrial and livestock water withdrawals respectively.~~

~~4 Discussion~~

~~Our paper presents the newly developed VIC-WUR model that aims to provide new opportunities for global water resource assessments by integrating several anthropogenic-impact modules. The results of the VIC-WUR model are in line with reported water withdrawal values of Shiklomanov (2000) and (Steinfeld et al., 2006), as well as the results of other hydrological models available via the ISIMIP and WATCH projects. However, there are some important differences.~~

~~Potential irrigation withdrawal differences between models reflect the differences in the representation of hydrological processes as well as the method used to calculate irrigation demands. Especially the differences between VIC and VIC-WUR are interesting since they both employ the same hydrological model. The increase in potential irrigation withdrawal between VIC and VIC-WUR can be attributed to the inclusion of paddy irrigation by VIC-WUR. VIC irrigates crops only when they experience water stress, while in VIC-WUR paddy irrigation is also used to saturate the top soil layer. The VIC-WUR potential withdrawals are 56 % higher than the VIC potential withdrawals for cells where rice is the major crop (> 50 % of cropland). Potential irrigation withdrawals for convention irrigation is actually higher for VIC than VIC-WUR, since the field capacity in VIC-WUR is tuned lower than that the field capacity in VIC (see Appendix D). The lower field capacity results in reduced percolation for conventional irrigation. The VIC potential withdrawals are 33 % higher than the VIC-WUR potential withdrawals for cells where no rice is present. This difference is reflected in the spatial distribution of water demands. Potential irrigation withdrawals of VIC-WUR are higher than those of VIC, except for the Americas and Europe where paddy irrigation is relatively limited.~~

~~Actual irrigation withdrawals of VIC-WUR are high compared to the other models. This difference can be explained, in part, since some models (LPJmL, VIC and H08) did not (yet) include groundwater withdrawals in their simulations. The high irrigation withdrawals of VIC-WUR decrease the gap between the reported and simulated irrigation withdrawals often assumed to be met by (non-renewable) groundwater withdrawals, in particular fossil groundwater stores (Wada et al., 2010). Often the regions where the simulated withdrawals are lower than the actual withdrawals are regions where unsustainable groundwater exploitation is reported by several studies (Gleeson et al., 2012; Rodell et al., 2018). To~~

~~our knowledge no previous study has estimated the amount of global non-renewable groundwater withdrawals without using one of the models mentioned above. Therefore, the accuracy of actual irrigation withdrawal results cannot be verified.~~

~~Differences in domestic, industrial and livestock actual water withdrawals between models are difficult to explain since most studies use different methods to calculate and downscale sectoral water demands. Therefore, water availability is not the only factor affecting the actual water withdrawals. Inputs of potential domestic and industrial water withdrawals are close to the values reported by Shiklomanov (2000). However, the actual water withdrawals are lower, indicating limited water availability. The lack of water availability could be due to a number of factors: (1) The spatial distribution of water demands, (2) the division between groundwater and~~ surface ~~water withdrawals, and/or (3) simulations of water availability are insufficient in certain regions. Improvements would require more data to improve groundwater and surface water demands and/or regional verification of water availability.~~

~~Environmental Flow Requirements (EFRs) for both baseflow and streamflow are used to assess the water requirements for terrestrial river ecosystems. When adhering to EFRs the global water withdrawals are reduced substantially, especially due to groundwater withdrawal limitations. 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. Note that VIC-WUR does not include non-renewable groundwater withdrawals, while these withdrawals would affect baseflow to a lesser degree.~~

waters. It can be discussed to what extent the EFRs for baseflow ~~are~~were too constricting, ~~because it is~~since they were based on the relatively stringent EFR for streamflow of Richter et al. (2012) (10 % of the natural streamflow). However, in the absence of any other standards, this baseflow standard remains the best available. ~~However, the model setup allows for the evaluation of other standards as well.~~ Note that, even when accounting for EFRs for baseflow on a grid scale, withdrawals ~~can~~could still have local and long-term impacts that are not captured by the model. The timing, location and depth of groundwater

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withdrawals are ~~also~~ important factors due to their interactions with the local geohydrology, as discussed by Gleeson and Richter (2018).

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~~The newly developed model will be used for the assessment of trade-offs and synergies between the sectors in the water-food-energy nexus. However, there are some challenges when applying the methods as described in our paper to future water-food-energy nexus assessments. Firstly, an holistic approach is needed to assess trade-offs and synergies in the water-food-energy nexus. This approach should account for competition between resources in an integrated way and should also be captured in consistent scenarios. These scenarios should, for example, define future developments of manufacturing subsectors, hydropower and thermoelectric developments and water efficiencies. Secondly, the energy sector should be expanded upon. Currently only a limited number of thermoelectric power plants are included in the analysis while the rest is incorporated in the industrial water demands. By explicitly accounting for the energy water demand one is able to assess the impact of water scarcity on energy generation and manufacturing separately. Lastly, developments are needed to translate water scarcity into production losses. Currently, only the lack of water is assessed, while the interest is in determining the impact on food and energy production. Therefore, new modules have to be developed that estimate energy generation and food production based on the water availability of the VIC-WUR model.~~

~~5~~4 Conclusion

~~The VIC-WUR model introduced in this paper aimed to provide new opportunities for global water resource assessments. Accordingly, several newly developed anthropogenic impact modules were integrated into the VIC-5 macro-scale hydrological model. The additions presented here comprehensively include anthropogenic and environmental water requirements and expand upon the previous efforts of Haddeland et al. (2006b).~~

~~The performance of the modules is in line with reported global water withdrawals and results of other hydrological models. While these additions are sufficient for global water resource assessments, further development is required in order to holistically assess trade-offs and synergies in the water-food-energy nexus. A preliminary assessment of environmental flow requirements already shows competition~~

~~between water resources allocated for human consumption and the environment, from both ground and surface water sources.~~

The VIC-WUR model introduced in this paper aims to provide new opportunities for global water resource assessments using the VIC model. Accordingly, several anthropogenic impact modules, based on previous major works, were integrated into the VIC-5 macro-scale hydrological model: domestic, industrial, energy, livestock and irrigation water withdrawals from both surface water and groundwater as well as an integrated environmental flow requirement module and dam operation module. Global gridded datasets on domestic, industrial, energy and livestock demand were developed separately and used to force the VIC-WUR model.

Simulated national water withdrawals were in line with reported national annual withdrawals (R^2 adjusted > 0.8; both per sector as per source). However, the data-oriented methodology used to derive sectoral water demands resulted in different withdrawal trends over time compared to other studies (Shiklomanov, 2000; Huang et al., 2018). However, note that the model setup of VIC-WUR allows for the evaluation of other sectoral water demand inputs, on various temporal aggregations. Terrestrial water storage anomaly trends were well simulated (mean annual and inter-annual RMSE of 1.9 mm and 3.6 mm respectively), while groundwater exploitation was overestimated. Overestimated groundwater depletion rates are likely related to an over-partitioning of water withdrawals to groundwater. The implemented human impact modules increased simulated discharge performance (370 out of 462 stations), mostly due to the effects of reservoir operation.

An assessment of the effect of EFRs shows that, when one would adhere to these requirements, global water withdrawals would be severely limited (39 %). This limitation is especially the case for groundwater withdrawals, which, under the strict requirements used in our study, need to be reduced by 81 %.

VIC-WUR has potential for studying impacts of climate change and anthropogenic developments on current and future water resources and sectoral specific-water scarcity. The additions presented here make the VIC model more suited for fully-integrated worldwide water-resource assessments and substantially decrease computation times compared to previous versions.

~~6~~5 Code availability

All code for the VIC-WUR model is freely available at github.com/wur-wsg/VIC (tag VIC-WUR.2.0.0; DOI 10.5281/zenodo.3399450) under the GNU General Public License, version 2 (GPL-2.0). VIC-WUR documentation can be found at vicwur.readthedocs.io. The original VIC model is freely available at github.com/UW-Hydro/VIC (tag VIC.5.0.1; DOI 10.5281/zenodo.267178) under the GNU General Public License, version 2 (GPL-2.0). VIC documentation can be found at vic.readthedocs.io. Documentation and scripts concerning inputs, configurations and analysis used in ~~this~~our study is freely available at github.com/bramdr/VIC-WUR_support (tag VIC-WUR.2.0.0; DOI 10.5281/zenodo.3401411) under the GNU General Public License, version 3 (GPL-3.0).

~~7~~6 Appendix

~~7.1~~6.1 Appendix A: VIC water and energy balance

In VIC each sub-grid computes the water and energy balance individually (i.e. sub-grid do not exchange water or energy between one another). For the water balance, incoming precipitation is partitioned between evapotranspiration, surface and subsurface runoff, and soil water storage. Potential evapotranspiration is based on the Penman-Monteith equation without the canopy resistance (Shuttleworth, 1993). The actual evapotranspiration is calculated by two methods, based on whether the land cover is vegetated or not (bare soil). Evapotranspiration of vegetation is constrained by stomatal, architectural and aerodynamic resistances and is partitioned between canopy evaporation and transpiration based on the intercepted water content of the canopy (Deardorff, 1978; Ducoudre et al., 1993). Bare soil evaporation is constrained by the saturated area of the upper soil layer. The saturated area is variable within the grid since (as the model name implies) the infiltration capacity of the soil is assumed heterogeneous (Franchini and Pacciani, 1991). Saturated areas evaporate at the potential evaporation rate while in unsaturated areas evaporation is limited. Surface runoff is produced by precipitation over saturated areas. Precipitation over unsaturated areas infiltrates into the upper soil layer and drains through the soil layers based on the gravitational hydraulic conductivity equations of Brooks and Corey (1964). In the first and second layer water is available for transpiration, while the third layer is assumed to be below the root zone. From the third layer baseflow is generated based on the non-linear Arno conceptualization (Franchini and Pacciani, 1991). Baseflow increases linearly with soil moisture content when the moisture content is low. At higher soil moisture contents the relation is non-linear, representing subsurface storm-flows.

For the energy balance, incoming net radiation is partitioned between sensible, latent, and ground heat fluxes and energy storage in the air below the canopy. The energy storage below the canopy is omitted if it is considered negligible (e.g. the canopy surface is open or close to the ground). The latent heat flux is determined by the evapotranspiration as calculated in the water balance. The sensible heat flux is calculated based on the difference between the air and surface temperature and the ground heat flux is calculated based on the difference between the soil and surface temperature. Since the incoming net radiation is also a function of the surface temperature (specifically the outgoing longwave radiation), the surface temperature is solved iteratively. Subsurface ground heat fluxes are calculated assuming an exponential temperature profile between the surface and the bottom of the soil column, where the bottom temperature is assumed constant. Later model developments included options for finite difference solutions of the ground temperature profile ~~(Cherkauer and Lettenmaier, 1999)~~(Cherkauer and Lettenmaier, 1999), spatial distribution of soil temperatures (Cherkauer and Lettenmaier, 2003), a quasi-2-layer snow-pack snow model (Andreadis et al., 2009), and blowing snow sublimation ~~(Bowling et al., 2004)~~(Bowling et al., 2004).

~~7.2~~6.2 Appendix B: EFRs for ~~streamflow~~surface and ~~baselow~~groundwater

VIC-WUR used the Variable Monthly Flow (VMF) method (Pastor et al., 2014) to limit surface water withdrawals. The VMF method (Pastor et al., 2014) calculates the EFRs for streamflow as a fraction of the natural flow during high (Eq. A.1), intermediate (Eq. A.2) and low (Eq. A.3) flow periods. The presumptive standard Gleeson and Richter (2018) is used to limit groundwater withdrawals~~.~~ (including aquifer groundwater withdrawals). This standard calculates the EFRs for baseflow as 90 % of the natural subsurface runoff through time (Eq. A.4). Here, daily instead of monthly EFRs were used to better capture the monthly flow variability.

$$EFR_{s,d} = 0.6 \cdot NF_{s,d} \qquad \text{Eq. (A.1)}$$

$$where\ NF_{s,d} \leq 0.4 \cdot NF_{s,y}$$

$$EFR_{s,d} = 0.45 \cdot NF_{s,d} \qquad \text{Eq. (A.2)}$$

$$where\ 0.4 \cdot MF_{s,y} < NF_{s,d} \leq 0.8 \cdot NF_{s,y}$$

$$EFR_{s,d} = 0.3 \cdot NF_{s,d} \qquad \text{Eq. (A.3)}$$

$$where\ NF_{s,d} > 0.8 \cdot NF_{s,y}$$

$$EFR_{b,d} = 0.9 \cdot NF_{b,d} \qquad \text{Eq. (A.4)}$$

Where $EFR_{s,d}$ is the daily EFRs for streamflow [m^3 s^{-1}], $EFR_{b,d}$ the daily EFRs for baseflow [m^3 s^{-1}], $NF_{s,d}$ is the average natural daily streamflow [m^3 s^{-1}], and $NF_{s,y}$ is the average natural yearly streamflow [m^3 s^{-1}], and $NF_{b,d}$ is the average natural daily baseflow [m^3 s^{-1}].

EFRs for streamflow and baseflow were based on VIC-WUR naturalized simulations between 1980 and 2010. Average natural daily flows were calculated as the interpolated multi-year ~~daily~~monthly average flow over the simulation period~~, followed by a 30-day moving average smoother~~.

~~7.3~~6.3 Appendix C: Dam operation scheme

VIC-WUR used a dam operation scheme based on Hanasaki et al. (2006). Target release (i.e. the estimated optimal release) was calculated at the start of the operational year. The operational year starts at the month where the inflow drops below the average annual inflow, and thus the storage should be at its desired maximum. The scheme distinguished between two dam types: (1) dams that did not account for water demands downstream (e.g. hydropower dams or flood control) and (2) dams that did account for water demands downstream (e.g. irrigation dams). The original scheme of Hanasaki et al. (2006) also accounts for EFRs, which were fixed at half the annual mean inflow. Other studies lowered the requirements to a tenth of the mean annual inflow, increasing irrigation availability and preventing excessive releases (Biemans et al., 2011; Voisin et al., 2013). In our study the original dam operation scheme was adapted slightly to account for monthly varying EFRs.

For dams that did not account for demands, the initial release was set at the mean annual inflow corrected by the variable EFRs (Eq. A.~~1~~5). For dams that did account for demands, the initial release was increased during periods of higher water demand. If demands were relatively high compared to the annual inflow, the release was corrected by the demand relative to the mean demand (Eq. A.~~2~~6). If demands were relatively low compared to the annual inflow, release was corrected based on the actual water demand (Eq. A.~~3~~7).

$$R'_m = EFR_{s,m} + (I_y - EFR_{s,y})$$ Eq. (A~~.1)~~.5)

$$where\ D_y = 0$$

$$R'_m = \ EFR_{s,m} + \left(I_y - EFR_{s,y}\right) * \frac{D_m}{D_y}$$ Eq. (A~~.2)~~.6)

$$where\ D_y > 0\ and\ D_y > (I_y - EFR_{s,y})$$

$$R'_m = EFR_{s,m} + (I_y - EFR_{s,y}) - D_y + D_m$$ Eq. (A.~~3~~7)

$$where\ D_y > 0\ and\ D_y \leq (I_y - EFR_{s,y})$$

Where R'_m is the initial monthly target release [m^3 s^{-1}], $EFR_{s,m}$ is the average monthly EFR for streamflow demand [m^3 s^{-1}], I_y is the average yearly inflow [m^3 s^{-1}], $EFR_{s,y}$ is the average yearly EFR for streamflow [m^3 s^{-1}], D_m is the average monthly water demand [m^3 s^{-1}] and D_y is the average yearly water demand [m^3 s^{-1}].

As in Hanasaki et al. (2006), the initial target release was adjusted based on storage and capacity. Target release was adjusted to compensate differences between the current storage and the desired maximum storage (Eq. A.~~4~~8). Target release was additionally adjusted if the storage capacity is relatively low compared to the annual inflow, and unable to store large portions of the inflow for later release (Eq. A.~~5~~9).

$$R_m = k \cdot R'_m$$ Eq. (A.~~4~~8)

$$where\ c \geq 0.5$$

$$R_m = \left(\frac{c}{0.5}\right)^2 \cdot k \cdot R'_m + \left\{1 - \left(\frac{c}{0.5}\right)^2\right\} \cdot I_m$$ Eq. (A.~~5~~9)

$$where\ 0 \leq c \leq 0.5$$

Where I_y is the average monthly inflow [m^3 s^{-1}], c the capacity parameter [-] calculated as the storage capacity divided by the mean annual inflow and k the storage parameter [-] calculated as current storage divided by the desired maximum storage. The desired maximum storage was set at 85 % of the storage capacity as recommended by Hanasaki et al. (2006).

Water inflow, demand and EFRs were estimated based on the average of the past five years. Water demands were based on the water demands of downstream cells. Only a fraction of water demands were taken into account, based on the fraction of ~~upstream area~~discharge the dam controlled. For example: if a dam controlled 70 % of the ~~upstream area~~discharge of a downstream cell, than 70 % of its demands were taken into account. Fractions smaller than 25 % were ignored.

The original dam operation scheme of Hanasaki et al. (2006) was shown to produce excessively high discharge events due to overflow releases (Masaki et al., ~~2018~~2018b). These overflow releases occurred due to a mismatch between the expected and actual inflow. In our study, dam release was increased during high-storage events to prevent overflow and accompanying high discharge events. If dam storage was above the desired maximum storage, target dam release was increased to negate the difference (Eq. A.~~6~~10). If dam storage was below the desired minimum storage, release is decreased (Eq. A.~~7~~11). Dam release was adjusted exponentially based on the relative storage difference: small storage differences were only corrected slightly, but if the dam was close to overflowing or emptying, the difference was corrected strongly.

$$R_a = R_m + \frac{(S - C\alpha)}{\gamma} \cdot \left(\frac{\frac{S}{C} - \alpha}{1 - \alpha}\right)^b$$ Eq. (A.~~6~~10)

$$where\ S > C\alpha$$

$$R_a = R_m + \frac{(S - C(1-\alpha))}{\gamma} \cdot \left(\frac{(1-\alpha) - \frac{S}{C}}{1-\alpha} \right)^b \qquad \text{Eq. (A.}\cancel{7}\text{11)}$$

$$where\ S < C(1-\alpha)$$

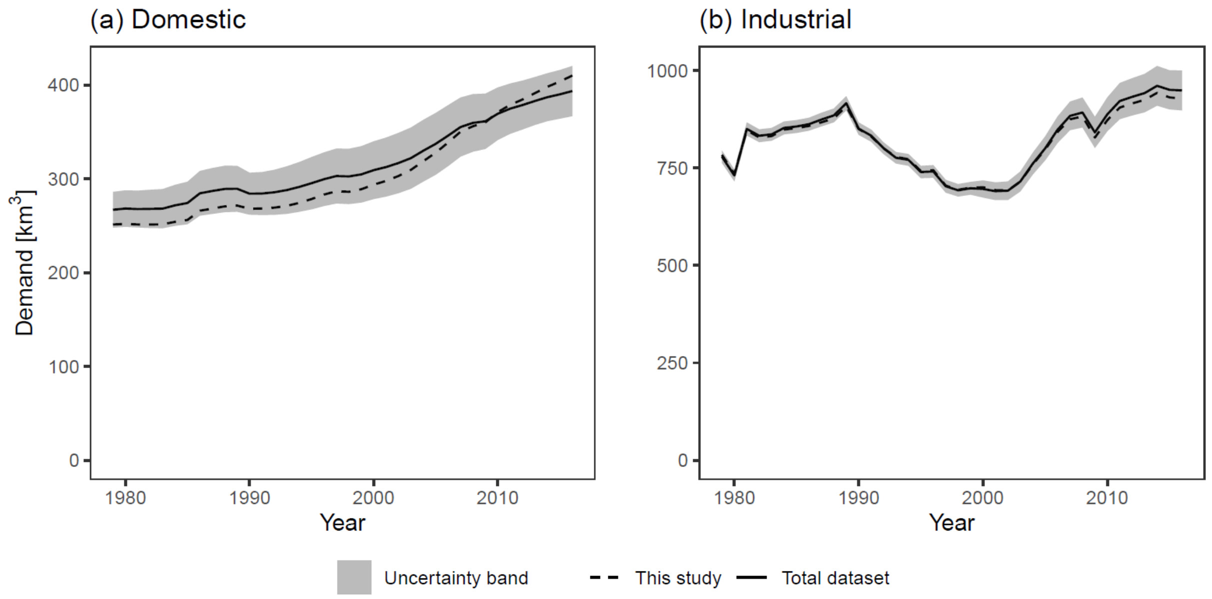
Where R_a is the actual dam release [$m^3\ s^{-1}$], S the dam storage capacity [m^3], α the fraction of the capacity that is the desired maximum [-], β the exponent determining the correction increase [-] and γ the parameter determining the period when the release is corrected [s^{-1}]. In testing the exponent and period were tuned to 0.6 and 5 days respectively.

~~7.4~~6.4 Appendix D: Water demand

~~7.4.1~~6.4.1 Fitting and validation data

Data on irrigation, domestic and industrial water withdrawals were based on the AQUASTAT database (FAO, 2016), EUROSTAT database (EC, 2019) and United Nations World Water Development Report (Connor, 2015). Data on GDP per capita and GVA was abstracted from the Maddison Project Database 2018 (Bolt et al., 2018), Penn World Table 9.0 (Feenstra et al., 2015) and World Bank Development Indicators (World bank, 2010).

Available data for domestic an industrial withdrawals were divided into a dataset used for parameter fitting (80 %) and a dataset used for validation~~.~~ (20 %). Domestic water demands were estimated for each United Nations sub-region, and thus data was divided per sub-region to ensure a good global coverage of data. In the same manner industrial water demand were divided per country. In case there is only a single data point, the data was added to both the fitting and validation data. ~~To assess uncertainty introduced by dividing the dataset, a sensitivity analysis was performed. The dataset was divided into partial datasets 100 times at random. Each partial dataset was used to generate and map domestic and industrial water demands. Domestic water demands based on the partial datasets had a standard deviation of around 9% compared to water demands based on the total dataset (Figure A.1a). Industrial water demands based on the partial datasets had a standard deviation of around 3% compared to water demands based on the total dataset (Figure A.1b).~~



~~**Figure A1: Sensitivity analysis of dividing the available data into a fitting and validation dataset for the domestic (a) and industrial (b) water demand estimations. Uncertainty bands are based on the standard deviation of 100 divisions. The solid line is the water demand estimation based on the total data. The striped line is the water demand estimation used in this study.**~~

~~7.4.2~~6.4.2 Irrigation sector

Conventional irrigation demands were calculated when soil moisture contents drop below the critical threshold where evapotranspiration will be limited. Demands were set to ~~fill the soil up to field capacity~~relieve water stress (Eq. A.12). Paddy irrigation demands were set to always keep the soil moisture content of the upper soil layer saturated (Eq. A.13), similar to Hanasaki et al. (~~2008~~2008a) and Wada et al. (2014). For paddy irrigation, the saturated hydraulic conductivity of the upper soil layer was reduced by its cubed root to simulate puddling practices, as recommended by the CROPWAT model (Smith, 1996). Total irrigation demands were adjusted by the irrigation efficiency (Eq. A.14). Paddy irrigation used an irrigation efficiency of 1 since the water losses were already incorporated in the water demand calculation.

$$ID'_{conventional} = \cancel{FC - (W_1}(W_{cr,1} + \cancel{W_2)}\,W_{cr,2}) - (W_1 + W_2)$$

Eq. (A.12)

$$where\ W_1 + W_2 < W_{cr,1} + W_{cr,2}$$

$$ID'_{paddy} = W_{max,1} - W_1$$ Eq. (A.13)

$$\text{where } W_1 < W_{max,1}$$

$$ID = ID' * IE \qquad \text{Eq. (A.14)}$$

Where $ID'_{conventional}$ is the conventional crop irrigation demand [mm], ID'_{paddy} is the paddy crop irrigation demand [mm], *ID* is the total irrigation demand [mm], W_1 and W_2 are the soil moisture contents of the first and second soil layer respectively [mm], W_{cr} is the critical soil moisture content [mm], ~~*FC* is the field capacity [mm], W_{max} the maximum soil moisture content [mm], and *IE* is the irrigation efficiency [mm mm^{-1}]. The field capacity was tuned to tuned to (Wcr_1 + Wcr_2) / 0.8. Note that our study used a lower field capacity compared to the (Haddeland et al., 2006b) model setup, since this provided a better fit.~~ W_{max} the maximum soil moisture content [mm], and *IE* is the irrigation efficiency [mm mm^{-1}].

~~7.4.3~~6.4.3 Domestic sector

Domestic water demands were represented by using a sigmoid curve for the calculation of structural domestic water demands (Eq.A.15) and a efficiency rate for the calculation of water-use efficiency increases (Eq. A.16). These equations differ slightly from Alcamo et al. (2003) since our study used the base 10 logarithms of GDP and water withdrawals per capita as they provided a better fit.

$$DSW_y = DSW_{min} + (DSW_{max} - DSW_{min}) * \frac{1}{1+e^{-f(GDP_y - o)}} \qquad \text{Eq. (A.15)}$$

$$DW_y = 10^{DSW_y} \cdot TE^{y - y_{base}} \qquad \text{Eq. (A.16)}$$

Where *DSW* is the yearly structural domestic withdrawal [log10 m^3 cap^{-1}], *DW* the yearly domestic withdrawal [m^3 cap^{-1}], DW_{min} the minimum structural domestic withdrawal [log10 m^3 cap^{-1}], DW_{max} the maximum structural domestic withdrawal (without technological improvement) [log10 m^3 cap^{-1}], *GDP* the yearly gross domestic product [log10 USD$_{\text{equivalent}}$ cap^{-1}], *f* [-] and *o* [log10 USD$_{\text{equivalent}}$] the parameters that determine the range and steepness of the sigmoid curve, *y* the year index, *TE* the technological efficiency rate [-], and y_{base} the base year (taken to be 1980).

DW_{min} was set at 7.5 l cap^{-1} d^{-1} based on the World Health Organisation standard (Reed and Reed, 2013), DW_{max} was estimated at around 450 l cap^{-1} y^{-1} based on a global curve fit, and *TE* was set at 0.995, 0.99, and 0.98 for developing, transition and developed countries respectively (United Nations development status classification) based on Flörke et al. (2013). Curve parameters f and o were estimated for the 23 United Nations sub-regions based on the GDP per capita and domestic water withdrawal data. In case insufficient data was available to calculate parameters values, regional (4 sub-regions) or global (~~5~~4 sub-regions) parameter estimates were used.

~~7.4.4~~6.4.4 Industrial sector

Industrial water demands were represented by using a linear formula for the calculation of structural industrial water demands (Eq. A.17) and a efficiency rate for the calculation of water-use efficiency increases (Eq. A.18).

$$ISW_y = ISW_{int} \cdot GVA_y \qquad \text{Eq. (A.17)}$$

$$IW_y = \mathrm{ISW_y} \cdot TE^{y-y_{base}} \qquad \text{Eq. (A.18)}$$

Where *ISW* is the yearly structural industrial withdrawal [m^3], IW_{int} the country specific industrial water intensity [m USD$_{\mathrm{equivalent}}^{-1}$], *IW* the yearly industrial withdrawal [m^3], *GVA* the yearly gross value added by industry [USD$_{\mathrm{equivalent}}$], *y* the year index, y_{base} the base year (taken to be the year when the industrial water intensity is determined), and *TE* the technological efficiency rate [-].

TE was set at 0.976 and 1 for OECD and non-OECD countries respectively before the year 1980, 0.976 between the years 1980 and 2000 and 0.99 after the year 2000 based on Flörke et al. (2013). Industrial water intensities were estimated for the 246 United Nations countries based on the GVA and industrial water withdrawal data. In case insufficient data was available to calculate the industrial water intensities, either sub-regional (~~76~~56 countries), regional (17 countries) or global (~~6~~9 countries) intensities estimates were used.

~~7.4.5 Energy sector~~

~~For each thermoelectric power plant the water intensity was combined with their generation to calculate the water demands (Eq. A.19). Since there was no observed data about the actual annual generation, each plant was assumed to be running at its installed generation capacity throughout the year, similar to van Vliet et al. (2016).~~

6.4.5 Energy sector

For each thermoelectric power plant the water intensity was combined with their generation to calculate the water demands (Eq. A.19). Actual generation is estimated by adjusting the installed generation capacity by 46 % for fossil, 72 % for nuclear and 56 % for biomass power plants (based on EIA national annual generation data (EIA, 2013))

$$EW_y = EW_{int} \cdot G_y \qquad \text{Eq. (A.19)}$$

Where *EW* is the yearly energy withdrawal [m^3], EW_{int} the energy water intensity [m^3 MWh^{-1}], *G* the yearly generation for each plant [MWh], and *y* the year index.

The energy water demands were subtracted from the industrial water demands at the location of each power plant. In cases where the grid cell industrial water demand was less than the energy water demand, national industrial water demands were lowered. In cases where even the national industrial water demands were less than the national energy water demand (~~5 countries), the energy water demands were lowered instead. This could be the case in countries where power plants do not operate at their installed capacity, as globally around 45% of the installed capacity is actually generated (based on data of van Vliet et al. (2016)). Energy demands were lowered until 10~~3 countries), the energy water demands were lowered instead. Energy demands were lowered until 10 % of the national industrial water demand remains, to ensure some spatial coverage of industrial and energy water demands.

~~7.4.6~~6.4.6 Livestock sector

Livestock water demands were estimated by combining the livestock population with the water requirements for each livestock variety (Eq. A.20).

$$LW_y = LW_{int} \cdot L \qquad \text{Eq. (A.20)}$$

Where LW is the yearly livestock withdrawal [m^3], LW_{int} the livestock water intensity [m^3 $livestock^{-1}$], L the livestock number for each variety [livestock].

6.5 Appendix E: General performance

VIC-WUR monthly discharge and monthly terrestrial total water storage anomalies were compared with observations from the GRDC dataset (GRDC, 2003) and GRACE satellite dataset (NASA, 2002) for eight major river basins (not included in the main text). Discharge stations were selected if the upstream area was larger than 10000 m2, matched the simulated upstream area at the station location,): Amazon, Congo, Lena, Volga, Yangtze, Danube, Columbia and Mississippi river basins. A 300km gaussian filer has been applied to the total water storage simulation data (similar to Long et al. (2015)).

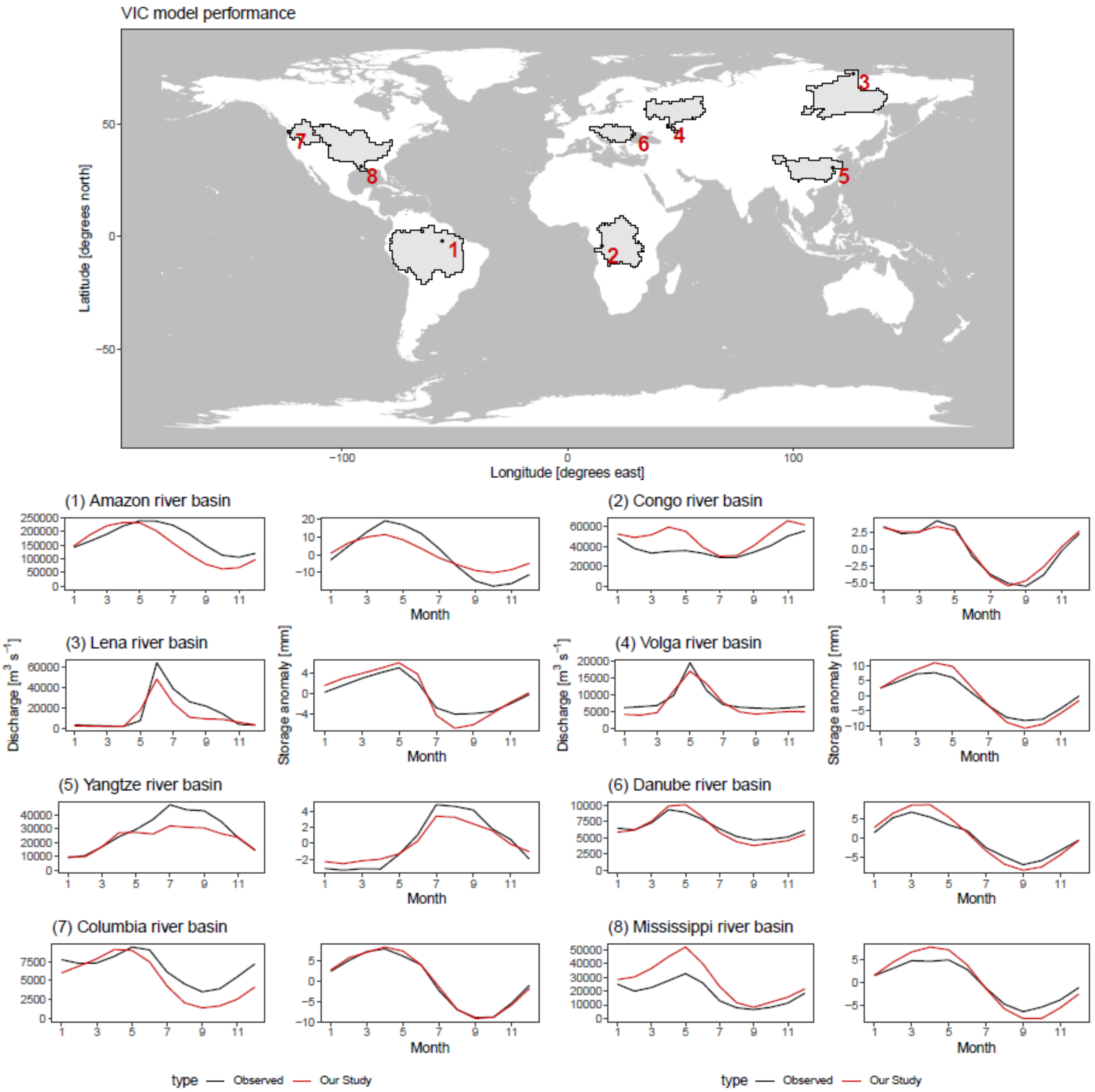


Figure A1: Comparison between simulated and observed discharge and terrestrial total water storage anomalies. Figures indicate multi-year averages of human-impacted simulations (red) and observations (black).

~~8~~7 Author contribution

Bram Droppers and Wietse H.P. Franssen developed and tested the model additions introduced in VIC-WUR. Bram Droppers generated and analysed the results. Michelle T.H. van Vliet, Bart Nijssen and Fulco Ludwig provided overall oversight and guidance. Bram Droppers prepared the manuscript with contributions from all co-authors.

~~9~~8 Competing interests

The authors declare that they have no conflict of interest.

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