A point-by-point response to the editor and reviewers for “Reconstruction of global gridded monthly sectoral water withdrawals for 1971–2010 and analysis of their spatiotemporal patterns” by Zhongwei Huang et al

Manuscript Details: Reconstruction of global gridded monthly sectoral water withdrawals for 1971-2010 and analysis of their spatiotemporal patterns, https://doi.org/10.5194/hess-2017-551

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We thank the editor and the three reviewers for their very valuable comments and suggestions to improve the manuscript. Below we are our point-by-point responses.

Response to Anonymous Referee #1

Referee comments in Italics

In this study, the authors reconstructed the global water withdrawal patterns from collected data by statistical downscaling. The spatial and temporal patterns of water withdrawal, along with sectoral divisions were analyzed. This work is not trivial. Estimating water withdrawal in a small watershed and considering various sectors is hard enough, not to say at the global scale. As a result, I do not think readers should blame the simplifications taken here.

Response: We appreciate the positive and constructive feedback from the referee on our manuscript.

However, I do have a concern of the irrigation part. It seems that the observations used for calibration is very sparse, especially in developing countries. For example, in the two major countries with water withdrawal – China and India, only data from West Bengal and Beijing were used. The result might be very biased because of the spatial variability of climate, water resources, and population density. Considering that 68% of water withdrawal is used for irrigation, this might lead to large errors in the final result.

Response: We agree with the reviewer that irrigation is the largest water withdrawer and consumer of water globally and certainly in countries such as China and India. The mentioned example of using sparse data was specifically for the temporal downscaling of domestic water withdrawals, and not irrigation. For irrigation, we used the gridded irrigation water withdrawal estimates from Global Hydrological Models (GHMs) as a base layer to spatially and temporally downscale the reported country-level irrigation data from FAO AQUASTAT and USGS. As for the domestic sector, we collected monthly domestic water withdrawal from various sources (Table 2) to guide the temporal downscaling of domestic water withdrawals. As the referee mentioned, in the two major countries with water withdrawal – China and India, only data from West Bengal and Beijing were used. Given that domestic water withdrawal is roughly 7% of total water withdrawal in India and 12% in China, we acknowledge that more data would help improve the temporal downscaling of domestic water withdrawals, and future work should focus on collecting high resolution water withdrawal data both spatially and temporally. In the revised version of our manuscript, we discuss these aspects in detail.

Also in Table 2: The second column is a mixture of cities, counties and states. In addition, it is better to indicate which state the city is located as it is not uncommon for multiple cities to have the same name.

Response: Thanks for your kind comment. We have revised Table 2 as suggested.

In Table 3, did you calibrate the R value in Japan and Spain too, or you just adopted the value from literature?

Response: We just adopted the R value in Japan and Spain from literature because we don't have monthly water withdrawal data for these two countries. We clarify this distinction in the revised manuscript.

Overall, the study is novel, the topic is suitable to HESS, and the manuscript is well written. I suggest a minor revision addressing my concerns mentioned above.

Response: Thanks to referee for the positive feedback. We will revise our manuscript based on the suggestions and comments.

Response to Anonymous Referee #2

Referee comments in Italics

GENERAL COMMENTS

*This manuscript reconstructs gridded monthly water withdrawals globally for 6 sectors for 1971-2010 in a spatial resolution of 0.5*0.5 degrees. The authors make this water* *withdrawal dataset publicly available, which makes the manuscript more valuable and is in the line of the open-access philosophy of HESS.*

Such a detailed global dataset is indeed to my knowledge the first in its kind and very useful. The statement at the end of the document (page 14 lines 3-5) "In whole, despite the uncertainties and limitations, this study is of great significance not only for cross comparison and validation for modeling and analyzing the impacts of human water use, but also for investigating water use related issues at finer spatial, temporal and sectoral scales" is very true.

I also appreciate that the authors include an extensive part in their manuscript on uncertainty (Section 4), as they acknowledge the uncertainty and limitations of their study.

The manuscript is novel, well written and in the scope of HESS. I recommend for moderate revision, as some issues need to be additionally addressed/discussed first.

Response: We appreciate the positive and constructive feedback from the referee on our manuscript.

MODERATE COMMENTS

1) The authors use as basis FAO AQUASTAT data and state-scale estimates of USGS for the US as basis for downscaling. Yet, on page 3 Lines 1-15 they argue that particular countries provide more detailed (especially spatially) data than the FAOSTAT data. This is indeed true for Germany as the authors point out, but also for many other European countries. These data (and additionally from Canada, China, ...) could have been used to optimise the downscaling methodology the authors use. Why was this choice made for the US but not for these other sources? I find this a bit a missed opportunity. I acknowledge that this means a lot more work, but you could have used all best data available instead of the US selection. Nevertheless, this does not have to be done within this paper, but maybe in future work. Please discuss shortly in the limitations section (section 4) of your manuscript.

Response: Thanks for your thoughtful comments. We agree with the reviewer that we could have improved the spatial downscaling if we were to collect subnational sectoral water withdrawals based on the USGS equivalent agencies in these countries. We also agree with the reviewer that such an extension would amount for a lot of additional work and should be tackled in future research. Such an effort would also raise some additional challenges. For example, the definitions of sectoral water use are potentially inconsistent because these data are reported by various organizations and institutions. We only use

FAOSTAT and USGS data in this study, but we can update the open-access datasets when we get the subnational sectoral water withdrawal data in other regions or countries. In the revised manuscript, we further discuss the limitation and potential future work to improve the reconstructed dataset.

*2) SPATIAL DOWNSCALING TECHNIQUES: For some sectors (domestic, irrigation, livestock) the downscaling techniques are state of the art, for other sectors (electricity for cooling, mining and manufacturing) they are very rough. The three latter are based upon population-density maps. This is a very rough approach, as these sectors are in my opinion not always highly correlated with population densities. Water abstractions for cooling can very well be concentrated outside urban centres, for security reasons (e.g. nuclear power plants) and the availability of large water quantities (e.g. along rivers). Nulear water abstraction which can be substantial can thus be concentrated as point intake in a more rural area. Manufacturing industries have in developed countries often moved outside urban centres (where in the past they were often in city centres). Last but not least, mining activities often take place in remote areas, and large water abstractions can be very concentrated on a small rural spatial scale. When you produce a 0.5*0.5 degree geo-dataset, these considerations can be very relevant. I acknowledge that the authors briefly describe limitations on page 12 lines 24-27. They also say this is a topic for further research. But please elaborate more on this, in the line with the argumentation I just made.*

Response: Thanks for your thoughtful comments. We agree with the referee that the spatial downscaling techniques for some sectors (e.g. electricity generation, mining and manufacturing) are rough. Water withdrawal for electricity generation are affected by many factors, including the location of power plants, the amount of generated electricity, generation type, cooling technology, and fuel types. As mentioned by referee, water withdrawal for cooling can be concentrated outside urban centres for security reasons (e.g. nuclear power plants) and the availability of large water quantities (e.g. along rivers), and water withdrawal for mining and manufacturing are also related to the geographic locations of manufacturing centers, and mines. In our revised manuscript, we elaborate more on the limitations and future work of the spatial downscaling techniques.

3) MISSING SECTOR TOURISM: The authors include 6 sectors, the ones which are typically identified for abstracting water. However, as in most studies, some particular water abstraction sectors are excluded. As indicated in the publication https://doi.org/10.1016/j.ecoser.2015.08.003, an important generally neglected sector is tourism. This includes water abstractions for snowmaking, which during winter months in mountain areas can be the largest regional water user (https://doi.org/10.2166/wst.2009.211). This water is generally taken from surface water, and is not accounted for in municipal water abstraction statistics. But this also includes water abstractions for hotels/swimming pools/spas both in winter and summer tourist *areas (e.g. https://doi.org/10.1016/j.tourman.2013.05.010). These water users often have own private water abstractions, which are not accounted for in domestic/ municipal water use statistics. E.g. in Mediterranean regions during summer months these water abstractions can become shortly the dominant water use. Another touristic water user are golf courts (e.g. https://doi.org/10.1094/ATS-2009-0129-01-RS). These touristic water abstractions can on a local (0.5*0.5 degree) and temporal (monthly) level be very significant. Please include in your discussion section a short subsection on this topic, based upon my input. Future research should include the sector tourism.*

Response: Thanks for your thoughtful input. We didn't consider tourism sector due to lack of global water withdrawal dataset on tourism. In the revised manuscript, we discuss the need for considering the missing sectors (e.g. tourism).

*4) SECTORS FORESTRY and AQUACULTURE: As indicated in the publication https://doi.org/10.1016/j.ecoser.2015.08.003, these sectors also account for water abstractions. Again, on a global level they may not be very significant in quantity, but on a local (0.5*0.5 degree) and temporal (monthly) level, they can be very significant. Is forestry accounted for in your irrigation sector? Aquaculture can be very significant in a country like China. Please include in your discussion section a short subsection on this topic.*

Response: Thanks for your valuable inputs. Water use for forestry and aquaculture sector are important components of total water use. Here, aquaculture water withdrawal is included in livestock sector in our study, because FAO AQUASTAT provides water withdrawal for agricultural (i.e. water withdrawn for irrigation, livestock and aquaculture purposes) and livestock water withdrawal are calculated by the difference of agricultural and irrigation water withdrawal. We ignore water withdrawal for forestry sector in this study. In the revised manuscript, we will present the definition of water withdrawal by sectors, and further discuss the significance of considering the forestry and aquaculture sectors in our future work.

5) DOMESTIC WATER ABSTRACTION: Please define in your paper what you mean with this. There is often confusion in the terminologies domestic and municipal water abstractions. There is a difference in water abstractions by households (generally defined as domestic water abstractions) and municipal water use, which additionally includes water use by shops, schools, public buildings ... and even for the cleaning of streets or public parks. As I understand your definition of "domestic sector" also includes these water users. Include a definition.

Response: Thanks for your kind comments. Domestic water withdrawal in this study is the water use for indoor household purposes such as drinking, food preparation, bathing, washing clothes and dishes, flushing toilets, and outdoor purposes such as watering lawns and gardens, and also includes water use for the part of the industries and urban agriculture (e.g. water use by shops, schools, public buildings, and for the cleaning of streets or public parks). We will add the definition of water withdrawal by sectors in the revised version.

MINOR COMMENTS

Page 2 line 19: You discussed the impact on the hydrological cycle and humans. Please add a sentence about the negative impact on the environment

Response: Thanks for your kind comment, and we will revise the manuscript as suggested.

page 2 Line 22 'We focus in this study on water withdrawal" - This is a choice, as also water consumption is an important statistic of water use. Water stress e.g. can be computed with both, as discussed in a recent publication https://doi.org/10.1016/j.scitotenv.2017.09.056

Response: We agree. Water consumption is an important statistic of water use, and we also reconstructed the global gridded sectoral water consumption dataset, which will be also published together with water withdrawal data through an open-access link. Because the methods for reconstructing water consumption data are simple, we focus in this study on water withdrawal. The details of water consumption data will be represented in supplement materials.

Page 3 line 7: Please add that also other selected European countries provide more detailed water use statistics (especially spatial data).

Response: Thanks for your kind comment, and we will revise the manuscript as suggested.

Page 3 Lines 18, 19: GHM and LSM - define abbreviation first

Response: Thanks for your kind comment, and we will define abbreviation first in revised manuscript.

Page 4 Line 14 ... (GCAM): please add ref

Response: Thanks for your kind comment, and we will add the references.

Page 6 Line 14: ... 30 urban centers ... : Urban water use characteristics can actually be quite different from rural water characteristics. By only downscaling based upon urban *water use characteristics, the resulting dataset could be biased in temporal representation for more rural areas*

Response: That is an excellent suggestion, and future work should certainly capture such a distinction between rural and urban seasonal patterns. This obviously will hinge on the availability of such data to facilitate such an exercise. As far as we know, there is not such a product, and collecting monthly data for this sector proved to be challenging as apparent by the number of countries with such data (Table 2). We will discuss this limitation in our revised manuscript.

Page 8 Lines 17-21: Water abstraction for livestock: there are actually formulas that relate livestock water use to temperature.

Response: Thanks for your comments. There are possible formulas that relate livestock water use to temperature. But we don't have monthly livestock water use data to parameterize such formulas. Thus, we use the uniform distribution in this study.

Table 1: Please add a column with the spatial resolution of these datasets

Response: Thanks for your comments. We will revise the table as suggested.

Figure 3: (c) Electricity and not elecreicity.

Response: Thanks for your comments. We will revise this in new manuscript.

Response to Anonymous Referee #3

Referee comments in Italics

This manuscript aims to reconstruct a global monthly gridded (0.5 degree) sectoral water withdrawal dataset for six water use sectors (irrigation, domestic, electricity generation (cooling of thermal power plants), livestock, mining, and manufacturing) for the period 1971-2010. And the reconstructed gridded water withdrawal dataset is open access. This paper is suitable for the HESS scope and also a valuable contribution to examining issues related to water withdrawals at fine spatial, temporal and sectoral scales.

Response: We appreciate the positive and constructive feedback from the referee on our manuscript.

The spatial distribution of water withdrawal for electricity generation depends on the distribution of the power plants. Most of the power plants are not concentrated in densely populated area. However, in this paper, spatial downscaling of water withdrawal for *electricity generation (water withdrawal for cooling of thermal power plants) is based on population density maps. It should be future explained and discussed.*

Response: We agree that there are some limitations in the spatial downscaling of water withdrawal for electricity generation, and future research should look into constructing a global database of power plants with details about their locations, construction year, fuel type, cooling technology, water source, generation capacity, capacity factor, etc. We discuss this in details in the revised manuscript.

In this paper, the spatial downscaling of water withdrawal for water withdrawal of electricity generation, domestic, mining and manufacturing was based on the population density maps. According to the gridded population map of the world (Center for International Earth Science Information Network (CIESIN) Columbia University), there are no people in Taklimakan Desert, some "no man's land" areas in Qinghai-Tibet Plateau, Sahara Desert. However, there are some water withdrawal of those sectors (please see Figure 5, 6, and 7). And in Figure S3, the dominant water withdrawal sector is manufacturing in Taklimakan Desert and some "no man's land" areas in Qinghai-Tibet Plateau, and is domestic in Sahara Desert. Please check it.

Response: Thanks for your thoughtful comments. The gridded population maps we used for spatial downscaling are from HYDE during 1971-1989 and GPW during 1990-2010. Upon reassessing the two population products, we found that HYDE generally shows no population while GPW shows some population in these places (e.g., deserts and no-man lands). And since the results in Figure 5, 6 and 7 were all calculated based on the long-term annual mean value (1971-2010), the domestic, manufacturing, mining and electricity generations sectors which depend on population density will have water withdrawals in these "no-man" grids, but the withdrawals are very small. In the revised manuscript, we will revise the figures with consideration of "no man's land" area based on your suggestions, and further discuss the limitation in spatial downscaling techniques.

A list of all relevant corrections made in the manuscript for "Reconstruction of global gridded monthly sectoral water withdrawals for 1971–2010 and analysis of their spatiotemporal patterns" by Zhongwei Huang et al

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We thank three reviewers and editor for their very valuable comments. Below is a list of all relevant changes made in the manuscript.

Relevant changes made in the manuscript are as follows:

1) A co-author was added due to his great contribution to data publication and the manuscript revision.
2) The reconstruction dataset are available online, and a link was added in the manuscript.
3) More details about the definition of the sectoral water withdrawal were added in the manuscript.
4) Limitations and future works in data source and the methods we used were further discussed.
5) Some figures were corrected by ignoring area with annual sectoral water withdrawal less than 0.01mm when analysis the temporal pattern and changing trend of sectoral water withdrawal.
6) In the supplement material, methods used for generating sectoral water consumption data are represented; and a new figure about the changes in global water withdrawal by 6 sectors during 1971-2010 was added.

The following pages are a marked-up manuscript version and supplementary. We hope that the revisions in the manuscript and our accompanying responses will be sufficient to make our manuscript suitable for publication in HESS.

Reconstruction of global gridded monthly sectoral water withdrawals for 1971-2010 and analysis of their spatiotemporal patterns

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Abstract

Human water withdrawal has increasingly altered the global water cycle in past decades, yet our understanding of its driving forces and patterns is limited. Reported historical estimates of sectoral water withdrawals are often sparse and incomplete, mainly restricted to water withdrawal estimates available at annual and country scale, due to a lack of observations at local and seasonal time scales. In this study, through collecting and consolidating various sources of reported data and developing spatial and temporal statistical downscaling algorithms, we reconstruct a global monthly gridded (0.5 degree) sectoral water withdrawal dataset for the period 1971–2010, which distinguishes six water use sectors, i.e. irrigation, domestic, electricity generation (cooling of thermal power plants), livestock, mining, and manufacturing. Based on the reconstructed dataset, the spatial and temporal patterns of historical water withdrawal are analyzed. Results show that global total water withdrawal has increased significantly during 1971-2010, mainly driven by the increase of irrigation water withdrawal. Regions with high water withdrawal are those densely populated or with large irrigated cropland production, e.g., the United States (US), eastern China, India, and Europe. Seasonally, irrigation water withdrawal in summer for the major crops contributes a large percentage of annual total irrigation water withdrawal in mid and high-latitude regions, and the dominant season of irrigation water withdrawal is also different across regions. Domestic water withdrawal is mostly characterized by a summer peak, while water withdrawal for electricity generation has a winter peak in high-latitude regions and a summer peak in low-latitude regions. Despite the overall increasing trend, irrigation in the western US and domestic water withdrawal in western Europe exhibit a decreasing trend. Our results highlight the distinct spatial pattern of human water use by sectors at the seasonal and annual scales. The reconstructed gridded water withdrawal dataset is open-access, and can be used for examining issues related to water withdrawals at fine spatial, temporal and sectoral scales.

1. Introduction

With the rapid growth in population, income, and demand for energy, feed, and food, global freshwater withdrawal increased from ~2500 km^3 yr^{-1} in 1970 to ~4000 km^3 yr^{-1} in 2010 (Shiklomanov, 2000; Döll et al., 2009; Wada and Bierkens, 2014). Such large-scale human water withdrawals have significant impacts on ~~both~~ the water cycle, the associated ecosystems, and society. For example, irrigation has redistributed surface water and groundwater resources, and perturbed terrestrial hydrology via changes in evapotranspiration and streamflow (White et al., 1972; Stohlgren et al., 1998; Haddeland et al., 2006; Tang et al., 2008; Kustu et al., 2011; Wang and Hejazi, 2011; Döll et al., 2012; Taylor et al., 2013; Döll et al., 2014), which has in turn altered surface air temperature and precipitation at regional and global scale (Adams et al., 1990; Boucher et al., 2004; Kueppers et al., 2007; Lobell et al., 2009; DeAngelis et al., 2010). Rost et al. (2008) stated that irrigation increased global evapotranspiration by ~2% and decreased river discharge by 0.5% during 1971-2000, while Müller Schmied et al. (2014) computed an increase of global evapotranspiration due to human water use (with approx. 90% being due to irrigation) of about 1.3% and a decrease of river discharge of about 1.8 %. Furthermore, increasing human water withdrawals can intensify water stresses and further limit ~~further~~ economic development, particularly in arid or semi-arid regions, e.g., northern China, India, Middle East (Rodell et al., 2009; Wada et al., 2011; Taylor et al., 2013; Yin et al., 2017). Although characterizing the impact of human water use on the hydrological cycle would entail a comprehensive assessment of the water lifecycle from source (surface vs groundwater), to end use sectors (irrigation, industrial, domestic), to changes to its quality (waste water), to its eventual return to the environment (return flow) or consumption (consumptive use) (Wada et al., 2014), we focus in this study on water withdrawal.

During the past years, many global hydrological models (GHMs), land surface models (LSMs) and integrated assessment models (IAMs) have incorporated water management modules to assess global water withdrawal by sectors (Döll and Siebert, 2002; Tang et al., 2007; Hanasaki et al., 2008b; Rost et al., 2008; Wada et al., 2011; Pokhrel et al., 2012; Flörke et al., 2013; Hejazi et al., 2014). However, large discrepancies exist among different modeling studies with respect to the magnitudes of water withdrawals, due to differences in model structure, input parameters, climate forcing, and assumptions to supplement the data deficiencies (Wada et al., 2016). Therefore, cross-comparison of estimated water withdrawal from large-scale models is critical for quantifying the impacts of human water withdrawal, which was hampered so far due to a lack of water withdrawal benchmark at fine spatial and temporal scales (Barnett et al., 2005; Wada et al., 2011; Voisin et al., 2013; Hejazi et al., 2015; Leng et al., 2016).

Historical water withdrawal records by sectors are reported by many agencies or organizations. Shiklomanov and Rodda (2003) published a global water resources assessment (including water withdrawal and consumption data) for 26 regions according to literature review and statistical surveys. Additionally, estimated water use by sectors (irrigation, livestock, domestic, industry, and hydroelectric power) at state and county level in the United States has been reported by the US Geological Survey (USGS) every 5 years since 1950, and 1985, respectively. Similar historical water use reports are also published by the Ministry of Water Resources of China, the Statistisches Bundesamt of Germany, the Ministry of Land Infrastructure and Transportation in Japan, and the Water Security Agency of Canada. Consolidating these subnational water withdrawal data which are reported by various organizations and institutions can be challenging due to the potential inconsistencies in the definition of sectoral water withdrawals. Another global water use inventory, AQUASTAT, which has been developed by the Food and Agriculture Organization (FAO), provides historical water withdrawals in particular sectors (agriculture, irrigation, domestic, and industry) every 5-year at country level. Unfortunately, these historical records in some regions or water use sectors are often incomplete or missing. Recently, Liu et al. (2016) developed a country scale water withdrawal dataset by sector at 5-year interval for 1973-2012 by filling the missing values in FAO AQUASTAT dataset. Furthermore, most existing water withdrawal inventories have been published at annual scale or 5-year interval for a particular region, which ignores the seasonal and spatial variations (aside from the irrigation estimates by models). The coarseness in data granularity may cause inadequate understanding for finer scale water use and hold back water management policy development.

Thus, establishing a comprehensive and consistent global dataset of historical water withdrawal time series, capturing both the seasonality and spatial variations, is important for multiple reasons. First, the reconstructed global historical gridded water withdrawal dataset can be used for cross–comparison of water withdrawal estimates of GHMs and also to supplement the water withdrawal estimates in LSMs due to lack of domestic and industrial water withdrawal simulation in most LSMs. Furthermore, such a dataset is important for investigating water use related issues and patterns at high spatial, temporal and sectoral resolutions, which is critical for developing sound water management strategies. The overarching goal of this study was to generate such a historical global monthly gridded water withdrawal data (0.5x0.5 degrees) for the period 1971-2010, distinguishing six water use sectors (irrigation, domestic, electricity generation, livestock, mining, and manufacturing).

The dataset constitutes the first reconstructed global water withdrawal data product at sub-annual and sub-national/gridded resolution that is derived from different models and data sources; it was generated by spatially and temporally downscaling country-scale estimates of sectoral water withdrawals from FAO AQUASTAT (and state-scale estimates of USGS for the US). In addition, the industrial sector was disaggregated into manufacturing, mining and cooling of thermal power plants. Downscaling was performed using the output of various models and new modeling approaches. This study adopts the spatial and temporal downscaling methodologies for water withdrawal in previous studies (Wada et al., 2011; Voisin et al., 2013; Hejazi et al., 2014; Wada and Bierkens, 2014), and further validates the temporal downscaling for water withdrawal domestic and electricity generation globally. Thus, with the application of the spatial and temporal downscaling methodologies, a reconstruction of global monthly gridded water withdrawal dataset for the period 1971-2010 is generated based on multiple reported data sources. Then the spatial and temporal patterns of global water withdrawal by sectors as provided by the newly developed dataset are analyzed. In this paper, data and methods are described in section 2. Section 3 presents the spatiotemporal patterns of water withdrawal by sectors based on the newly developed dataset, and section 4 discusses the uncertainty and limitation of our work. Conclusions are presented in section 5.

2 Data and Methodology

2.1 Data

Water withdrawal in US is obtained from the USGS (http://water.usgs.gov/watuse/) at the state level for every 5 years since 1950, and by sector (irrigation, livestock, domestic, thermoelectric power, mining and manufacturing). In addition, FAO AQUASTAT provides water withdrawal data for agriculture, irrigation, domestic and industrial per 5-year interval for 200 countries (http://www.fao.org/nr/water/aquastat/data/query/), and the missing values were filled by Liu et al. (2016) using several techniques such as inverse weighting, linear interpolation, and proxies (e.g. irrigated land area, industrial value added, and population). Water withdrawal for electricity generation, mining and manufacturing are retrieved from the industrial sector in FAO AQUASTAT in combination with the sectoral water withdrawal simulation of the Global Change Assessment Model (GCAM) (Edmonds et al., 1997; Kim et al., 2006). Here, water withdrawal datasets from USGS and FAO AQUASTA, which are used to reconstruct the global gridded monthly water withdrawal dataset, are applied in the US and in the rest of world, respectively. In this study, irrigation water withdrawal is defined as the water withdrawn for irrigation purposes, and is part of agricultural water withdrawal, together with water withdrawal for livestock (watering and cleaning) and for aquaculture (here lumped as is generally done in existing datasets). According to USGS and FAO definitions (Maupin et al., 2014; FAO, 2106), domestic water withdrawal here represents the water use for indoor household purposes (e.g., drinking, food preparation, bathing, washing clothes and dishes, and flushing toilets), outdoor purposes (e.g., watering lawns and gardens), and for industries and urban agriculture that are connected to the municipal system (e.g. water use by shops, schools, and public buildings). Electricity water withdrawal is the water use for the cooling of thermoelectric and nuclear power plants. Water withdrawal for mining is for the extraction of minerals that may be in the form of solids, liquids, and gases, such as coal, iron, and natural gas. Water withdrawal for manufacturing is for such purposes as fabricating, processing, washing, cooling or transporting a product, incorporating water into a product; or for sanitation need within the manufacturing facility. These sectoral water withdrawal categories are consistent with the work of Liu et al. (2016).

The data sets used for spatial and temporal downscaling of sectoral water withdrawal are listed in Table 1. Global population density maps, which are applied for spatial downscaling of domestic, electricity generation, mining and manufacturing sectors, were obtained from the History Database of the Global Environment (HYDE) during 1970-1980 and Gridded Population of the World (GPW) during ~~1985~~1990-2010 in Socioeconomic Data and Application Center (SEDAC). Global livestock densities maps for 6 species (i.e. cattle, buffalo, goat, sheep, pig and poultry) for the year 2005 were collected from the FAO's Animal Production and Health Division. The gridded daily air temperature data from WATCH Forcing Data methodology applied to ERA Interim reanalysis data (WFDEI) from 1971 to 2010 is used for temporal downscaling of electricity and domestic water withdrawal from annual to monthly (Weedon et al., 2014). Other sources of air temperature data, from WATCH (Weedon et al., 2010), Princeton (Sheffield et al., 2006) and GSWP3 (Compo et al., 2011), are also adopted to examine the uncertainty of different climate forcing on simulated global monthly water withdrawal for electricity and domestic sectors. In addition, four global gridded monthly irrigation water withdrawal simulations for the period 1971-2010, which are obtained from the Inter-Sectoral Impact Model Inter-comparison Project (ISI-MIP) (Warszawski et al., 2014), are utilized for the reconstruction of irrigation water withdrawal. The four products were generated by 4 GHMs, i.e. WaterGAP (Döll and Siebert, 2002; Alcamo et al., 2003; Döll et al., 2009; Müller Schmied et al., 2014), LPJmL (Rost et al., 2008), H08 (Hanasaki et al., 2008a, b), and PCR-GLOBWB (Van Beek et al., 2011; Wada et al., 2011; Wada et al., 2014), and they are all forced by WFDEI climate data. To investigate the uncertainty derived from forcing data, we also use other three simulated irrigation water withdrawal by WaterGAP forced by three datasets (i.e. Princeton, GSWP3 and WATCH).

2. 2 Methodology

Water withdrawal datasets from FAO AQUASTA and USGS need to be spatially downscaled from country (or state) level to grid scale, and temporally downscaled from 5-year interval to monthly scale. As for irrigation sector, correction factors are used to scale the irrigation water withdrawal estimates by GHMs according to reported data. For the other sectors, the spatial and temporal downscaling is applied to FAO AQUASTA and USGS estimates independently to get the monthly gridded dataset following 3 steps: firstly the individual sectoral water withdrawal is downscaled from country (or state) level to grid (0.5°x0.5°) level by using spatial downscaling algorithms; then annual time series of sector water withdrawal is obtained by using linear interpolation between the 5-year interval from reports; and finally a temporal downscaling procedure is adopted to generate monthly gridded water withdrawal data by sector. The sector-specific methodologies for the reconstruction of water withdrawal are described below in details.

2.2.1 Irrigation

Global gridded monthly irrigation water withdrawals during the period 1971-2010 are generated based on FAO AQUASTAT and USGS estimates and values of gridded monthly irrigation water withdrawals as simulated by four GHMs. Irrigation water withdrawals simulated by these four GHMs all have reasonable agreement (correlation coefficient (r) more than 0.7) with FAO AQUASTAT and USGS estimates at the country level and US state level, respectively (Figure S1). Large discrepancies exist among GHMs at the seasonal and regional scale (Figure S2) due to differences in model structure and parameters (Wada et al., 2013; Liu et al., 2017), so multiple GHMs are taken into account. By applying the correction factors between model estimates and reported estimates to the monthly gridded irrigation water withdrawals simulated by GHMs within a specific country (or state) (i.e. FAO AQUASTAT and USGS datasets), the reconstructed monthly gridded irrigation water withdrawals are calculated as follows:

$$Wir_{i,j,g} = Wir\_sim_{i,j,g} \times f_{m,p}, \qquad (1)$$

where $Wir_{i,j,g}$ is the reconstructed irrigation water withdrawal for the month i of year j at grid g (m^3), and $Wir\_sim_{i,j,g}$ is the irrigation water withdrawal for the month i of year j at grid g simulated by four GHMs (m^3); $f_{m,p}$ is the correction factor for the simulation by GHMs, calculated by $f_{m,p} = Wir\_obv_{m,p} / Wir\_sim_{m,p}$, where $Wir\_obv_{m,p}$ and $Wir\_sim_{m,p}$ are the 5-year irrigation water withdrawal (m^3) reported by AQUASTAT (or USGS) and simulated by GHMs, respectively, for country (or state) m (where grid g is located in country m) and time period p (year j is in the period p). Thus, four reconstructed irrigation water withdrawal datasets are generated based on simulations from the four GHMs. The spatial and temporal pattern of the ensemble mean of these four datasets, and the disagreement among them are discussed in results and discussion sections, respectively.

2.2.2 Domestic

The spatial downscaling of domestic water withdrawal follows the methods in Hejazi et al. (2014), which used the population density maps as the proxy for disaggregating domestic water withdrawal from country (or state) level to grid level. Temporal downscaling algorithm for domestic water withdrawal are also used by Wada et al. (2011) and Voisin et al. (2013):

$$\mathrm{W_{dij}} = \frac{\mathrm{W_{dj}}}{12}\left(\frac{\mathrm{T_{ij}}-\mathrm{T_{avg}}}{\mathrm{T_{max}}-\mathrm{T_{min}}}\mathrm{R}+1\right), \qquad (2)$$

where $\mathrm{W_{dij}}$ is domestic water withdrawal in month i of year j (m^3); $\mathrm{W_{dj}}$ is domestic water withdrawal in year j (m^3); $\mathrm{T_{ij}}$ is the average temperature in month i of year j; $\mathrm{T_{avg}}$, $\mathrm{T_{max}}$ and $\mathrm{T_{min}}$ are the average, the maximum and the minimum monthly temperature in year j (all in °C), respectively; parameter R is the amplitude (dimensionless), which measures the relative difference of domestic water withdrawal between the warmest and coldest months in a given year.

Wada et al. (2011) reported that R=0.1 could fit the variation of domestic water use in Japan and Spain. However, this term is different across regions as domestic water withdrawal is influenced not only by socioeconomic and climatic conditions but also by water policies and strategies (Babel et al., 2007). Here, we use the observed monthly water use data in 30 urban centers and counties (Table 2) to calibrate *R* in different regions. Table 3 shows the range of calibrated *R* values for each country, and we use the median value for the temporal downscaling of domestic water withdrawal for the remaining countries with unavailable historical observation. For Japan and Spain we used $R=0.1$ as reported by Wada et al. (2011) (Table 3). Monthly domestic water withdrawal was calculated using Eq. (2) for the 30 urban centers and counties, and the simulated mean monthly domestic water withdrawal shows reasonable agreement with observations with correlation coefficient (r) more than 0.8 and mean absolute percentage error (MAPE) less than 15% in most urban centers and counties (Fig. 1).

2.2.3 Electricity

Similar to the domestic sector, spatial downscaling of water withdrawal for electricity generation (water withdrawal for cooling of thermal power plants) is based on population density maps (Hejazi et al., 2014). The temporal downscaling of water withdrawal for electricity generation follows Voisin et al. (2013) and Hejazi et al. (2015), which assume that the amount of water withdrawal for electricity generation is proportional to the amount of electricity generated. Here, the generated electricity is assumed to be consumed by three sectors, i.e., building, industry and transportation. Electricity consumption by building is further divided into three categories: heating, cooling and other home utilities. Electricity consumption for industry and transportation is assumed to be a uniformly distributed within a year, while water withdrawal for building electricity use is dependent on heating degree days (HDD) and cooling degree days (CDD). HDD and CDD, which are derived from outdoor air temperature, are robust indicators for representing heating- and cooling-related energy consumption (Allen, 1976; Karimpour et al., 2014). Here, only electricity use for heating and cooling are assumed to be sensitive to the climatic factors. Equation (3) represents for the temporal downscaling of electricity generation from annual to monthly:

$$E_{ij} = E_j \times (p_b \times (p_h \frac{HDD_{ij}}{\sum HDD_{ij}} + p_c \frac{CDD_{ij}}{\sum CDD_{ij}} + p_u \times \frac{1}{12}) + p_{it} \times \frac{1}{12}) \ , \qquad (3)$$

where E_{ij} is the electricity use for the month of *i* and year of *j*; E_j is the annual electricity use; p_b and p_{it} are the proportions of total electricity use for building and transportation and industry together, respectively, with $p_b + p_{it} = 1$; p_h, p_c and p_u are the proportions of total building electricity use for heating, cooling and other home utilities, respectively, with $p_h + p_c + p_u = 1$; HDD_{ij} and CDD_{ij} are the *HDD* and *CDD* of month *i* in year *j*, respectively, and were calculated by using a base temperature of 18 $^{\circ}C$:

$$HDD_{ij} = \sum_1^n (18 - T_{d_{ij}}) \forall T_{d_{ij}} < 18^{\circ}C \ , \qquad (4)$$

$$CDD_{ij} = \sum_1^n (T_{d_{ij}} - 18) \forall T_{d_{ij}} > 18°C, \tag{5}$$

where $T_{d_{ij}}$ is the average temperature of the day d of month i in year j. Thus, the monthly water withdrawal for electricity generation is then calculated as follows:

$$W_{ij} = W_j \times (p_b \times (p_h \frac{HDD_{ij}}{\sum HDD_{ij}} + p_c \frac{CDD_{ij}}{\sum CDD_{ij}} + p_u \times \frac{1}{12}) + p_{it} \times \frac{1}{12}), \tag{6}$$

where W_{ij} is the water withdrawal of electricity generation for the month of i and year of j; and W_j is the annual total water withdrawal for electricity generation. The parameters p_b, p_{it}, p_h, p_u and p_c are obtained from the International Energy Agency (IEA) (IEA, 2012b, a). For some counties with low annual CDD (or HDD), there are almost no cooling (or heating) services. However, the parameters p_c and p_h (the proportions of total building electricity use for cooling and heating, respectively) are not equal to 0, which can lead to a failure in reproducing summer or winter peaks. Thresholds for annual HDD and CDD are defined, by assuming that if $\sum HDD_{ij}$ <650 °C or $\sum CDD_{ij}$ <450 °C, then there is no electricity use for heating or cooling, respectively. Note, thresholds for annual HDD and CDD are obtained by calibration against reported monthly electricity generation data. The monthly water withdrawal for electricity generation is calculated as follows:

If $\sum HDD_{ij}$ <650 and $\sum CDD_{ij}$ <450:

$$W_{ij} = W_j \times \frac{1}{12}; \tag{7}$$

If $\sum HDD_{ij}$ >650 and $\sum CDD_{ij}$ <450:

$$W_{ij} = W_j \times (p_b \times ((p_h + p_c) \frac{HDD_{ij}}{\sum HDD_{ij}} + p_u \times \frac{1}{12}) + p_{it} \times \frac{1}{12}); \tag{8}$$

If $\sum HDD_{ij}$ <650 and $\sum CDD_{ij}$ >450:

$$W_{ij} = W_j \times (p_b \times ((p_h + p_c) \frac{CDD_{ij}}{\sum CDD_{ij}} + p_u \times \frac{1}{12}) + p_{it} \times \frac{1}{12}); \tag{9}$$

If $\sum HDD_{ij}$ >650 and $\sum CDD_{ij}$ >450:

$$W_{ij} = W_j \times (p_b \times (p_h \frac{HDD_{ij}}{\sum HDD_{ij}} + p_c \frac{CDD_{ij}}{\sum CDD_{ij}} + p_u \times \frac{1}{12}) + p_{it} \times \frac{1}{12}). \tag{10}$$

Voisin et al. (2013) and Hejazi et al. (2015) validated this method against observed data for the year 2005 in US. To further validate this method globally, monthly electricity generation data during 2000-2012 in 33 OECD countries reported by IEA (http://www.iea.org/statistics/topics/Electricity/) were collected. Figure 2 shows the comparison between simulated and observed monthly mean electricity generation during 2000-2012 in 33 OECD countries. It is found that the simulations agree well (with the correlation coefficient above 0.6 and MAPE under 15%) with observations in most of the countries. However, electricity generation shows considerable underestimation in summer for some regions (e.g. Austria, Chile, and Switzerland) where hydropower accounts for a large portion of the total electricity generations in summer and parts of electricity are exported to other countries (Bauer, 2009; Wagner et al., 2015; IEA, 2016). In general, the reasonable agreement between simulation and observation suggests the effectiveness of Eq. (7-10) to temporally downscale water withdrawal for electricity generation.

2.2.4 Livestock, mining and manufacturing

For the spatial downscaling, we apply the global maps of estimated livestock density to downscale water withdrawal of livestock (Alcamo et al., 2003; Hejazi et al., 2014), and population density to downscale water withdrawal of mining and manufacturing sectors. For the temporal downscaling of water withdrawal of livestock, mining and manufacturing, a uniform distribution (i.e. the monthly value are the same within the year) is adopted following Voisin et al. (2013).

3 Results

3.1 Spatial distribution of global water withdrawal by sectors

Figure 3 shows the spatial distribution of long-term mean annual water withdrawal by sector during 1971-2010. Total global water withdrawal has increased during the past 40 years, and on average 68% of global water withdrawal has been used for irrigation, followed by electricity generation (11%), domestic (9%) and manufacturing (7%) while less than 5% of global total water withdrawal is for livestock and mining purposes (Fig.S3&S4). Irrigation water withdrawal is highest in the western US, eastern China, and India due to low water availability during the crop growing season and the massive crop productions in these regions. For example, in the western US, the average annual precipitation is less than 400 mm, resulting in water stress for optimal crop growth without irrigation. Different irrigation techniques for crops contribute to the large spatial heterogeneity of water withdrawal (Jägermeyr et al., 2015). For example, large amounts of water are withdrawn for maintaining a certain water level on rice fields in South China and Southeast Asia (Shahid, 2011). In addition, there is almost no irrigation in cold or sparsely populated regions (e.g. North Canada and Sahara). Domestic water withdrawals are high in the eastern US, eastern China, European countries, coastal regions of South America and India, but are limited in northern

Canada, northern Russia and Sahara due to spare population. The spatial distributions of water withdrawal for electricity generation, mining and manufacturing are broadly similar to that of domestic, and consistent with the global population distribution that water withdrawal regions concentrating in urban areas or regions with denser population. As for the livestock sector, water withdrawal is mainly used in India, eastern China and the eastern US where livestock is densely concentrated (Robinson et al., 2014). Generally, the dominant water withdrawal sectors by land area are irrigation in the western US, eastern China, southern Brazil and India, domestic in the northern Brazil and most of the Africa, electricity generation in Russia, Canada, and the eastern US, and livestock in Australia (Fig.S3).

3.2 Seasonal patterns of water withdrawal for irrigation, domestic and electricity generation

An evident seasonal pattern is identified for irrigation water withdrawal during 1971-2010 (Fig. 4), concentrated in June to August (JJA) in the northern hemisphere and December to February (DJF) in the southern hemisphere. In the US and European countries, due to large water requirement in crop growing stages, more than 75% of annual irrigation water withdrawal occurs in JJA, while no irrigation takes place in DJF. In contrast, in the southern parts of South America and southern Africa, irrigation water is mainly withdrawn in DJF and accounts for about 70 percent of annual total irrigation. In general, irrigation water withdrawal exhibits an evident seasonal pattern in mid and high-latitude regions, but not in the tropical zone (e.g. Brazil and the Southeast Asia) where irrigation is applied year-around due mainly to multi-cropping practices. The seasonal variation of irrigation water withdrawal is determined not only by crop calendar but also the climate conditions. For example, in India, most of precipitation occurs in rainy seasons (monsoon) but crop water requirement is still large in September to November (SON), leading to a peak of irrigation water withdrawal in SON, especially in northwest India (Rodell et al., 2009; Famiglietti, 2014). The seasonal pattern of domestic water withdrawal (Fig. 5) is largely related to the seasonal temperature variation and the parameter R (i.e. representing the relative difference of domestic water withdrawal between the warmest and coldest months). On both hemispheres, domestic water withdrawal is larger in the respective summer seasons compared to winter, consistent with the seasonal evolution of temperatures. Water withdrawal for lawn and garden, which will take a large part of total domestic water withdrawal in summer, is the dominant factor for the summer peak, especially in developed countries (e.g. the US and Australia) (Loh and Coghlan, 2003; Shaffer, 2009). Figure 6 shows the seasonal pattern of water withdrawal for electricity generation. Higher water withdrawal is found in winter than in summer in high-latitude regions (e.g. Canada, Western Europe and southern Australia), where heating is normally adopted in winter while cooling is rarely applied in summer time. On the contrary, electricity for heating is rarely used in winter in tropical regions (e.g. northern Africa and western Asia) as cooling is frequently applied in summer, resulting in dominant water withdrawal for electricity generation in summer. In fact, homes that have air conditions use electricity as the main source of cooling in the summer, while electricity is also one of the main sources for heating in winter (e.g. the application of furnace, boiler circulation pumps, and compressor) (EIA, 2017), which leads to the summer and winter peak of electricity generation.

3.3 Trend in water withdrawal in 1971-2010 by sectors

Global total water withdrawal has increased significantly from 2500 to 4000 km^3 yr^{-1} during 1971-2010 (Fig. ~~S4~~S5). A particularly strong increasing trend is found in China (from ~400 to ~550 km^3 yr^{-1}) and India (from ~300 to ~800 km^3 yr^{-1}). In contrast, total water withdrawal in the US increased before 1980 but then decreased during 1985-2010, and similar evolution is found for the European Union (EU27). Water withdrawal increased during the past 40 year in most regions (Fig. 7, Fig. ~~S4~~S5-~~8~~9) as a result of the increasing population, urbanization, the growing food demand and expansion of irrigated cropland, which are in line with previous studies (Shiklomanov, 2000; Wada and Bierkens, 2014). However, sectoral water withdrawal also shows decreasing trend in specific regions. Irrigation water withdrawal has exhibited a decreasing trend (about -0.3 mm/year) in western US and west Europe, partly due to the application of sprinkler and micro-irrigation systems (Pereira et al., 2002). A significant decreasing trend of domestic water withdrawal is found in most of European countries (e.g. Sweden, Germany, and Poland), because of the low growth rate of population and the improvement of domestic water use efficiency and water management (e.g. water price and water meters) (Herrington, 1997; Gleick, 2000; Dalhuisen et al., 2003). In addition, in part of European countries and US, water withdrawal for electricity generation showed a decreasing trend, which could be attributed to shifts in cooling technologies and fuel mix. For instance, the penetration of more recirculating cooling technologies than once-through, and the shift to less-water intensive fuel mixes (e.g., wind, solar, and natural gas) improved the overall water use efficiency of the electricity sector (Liu et al., 2015).

4 Discussion

The reconstructed global gridded monthly water withdrawal dataset by sector is generated by spatially and temporally downscaling country-scale estimates of sectoral water withdrawals from FAOSTAT (and state-scale estimates of USGS for the US). In this section, the uncertainties in the data sources (FAO AQUASTAT and USGS) including model estimates, and in the applied spatial and temporal downscaling methods by sectors are discussed.

4.1 Uncertainties in data sources

Water withdrawal estimates by sectors in the US are provided by the USGS at a high spatial resolution (state and county), and are often treated as a benchmark for model calibration and validation (Vassolo and Döll, 2005; Hejazi et al., 2014; Leng et al., 2016). Water withdrawal estimates from FAO AQUASTAT are mainly from national surveys and assessments (e.g. national yearbook, statistics and reports) or model simulations (e.g. irrigation water withdrawal). Missing values in FAO AQUASTAT water withdrawal dataset were filled by Liu et al. (2016) with empirical techniques (e.g. population and irrigated area). Water withdrawals for electricity generation, mining and manufacturing were broken down from industrial estimates from FAO AQUASTAT with the aid of model simulations. Thus, uncertainties may arise from these procedures. To assess the level of uncertainty in the country-level data, we compared the domestic and industrial water withdrawal time series from 1971-2010 by with estimates of Flörke et al. (2013) and Shiklomanov (2000) (Fig. ~~S9~~S10). Global domestic water withdrawal agrees well among these estimates both in trend and average value. Global industrial water withdrawal estimates by Flörke et al. (2013) and Shiklomanov (2000) are higher than estimates used in this study, but they all show similar changing trend during 1970-2010. Estimates of thermoelectric water withdrawal in this study is lower than estimates from Flörke et al. (2013), and water withdrawal for manufacturing agrees well among these two datasets. In this study, only country-scale estimates from FAO AQUASTAT data and state-scale estimates of USGS for the US are used as basis for downscaling. Future research could explore the collection and consolidation of subnational and sub-regional sectoral data for other countries or regions, as well as include other sectors beyond the six considered here. For example, water withdrawal for aquaculture is included in livestock, but separating the two sectors can be useful in countries with large freshwater fish production, e.g. China. Other sectors that can be distinguished, include water withdrawal for forestry (e.g., production of papers, furniture) and tourism (e.g., snowmaking, hotels, swimming pools, spas and golf courts) (Cazcarro et al., 2014; Vanham et al., 2009; Vanham, 2016).

4.2 Uncertainties in reconstructed irrigation water withdrawal

The global gridded monthly irrigation water withdrawal data as produced in this study is based on various data sources, including both census national/state data and model estimates. Specifically, correction factors are used to adjust the irrigation water withdrawal estimates by GHMs to match the reported data at the country/state level. Therefore, besides the reliability of the data source, uncertainties among GHMs and different climate forcing would propagate into the newly developed dataset at the monthly time scale (Wada et al., 2013; Liu et al., 2017). Here, firstly four reconstructed irrigation water withdrawal datasets based on simulations of 4 GHMs, i.e. WaterGAP, H08, LPJmL, PCR-GLOBWB, forced by WFDEI, are compared to examine the uncertainties induced by model structure; then another four reconstructed irrigation water withdrawal based on simulations of WaterGAP forced by four climatic data, namely WFDEI, WATCH, GSWP3, Princeton, are used to investigate the uncertainties in reconstructed products induced by climate forcing. The coefficient of variation (CV) defined as the standard deviation divided by the ensemble mean value of these four generated datasets are used to evaluate the uncertainty. As shown in Fig. 8, the uncertainties arising from GHMs are rather high (CV>0.5) in the southeast China, the west coast of South America, the southeast of Brazil and part of the US. Seasonally, CVs in the northern hemisphere are larger than these in the southern hemisphere in DJF and vice versa in JJA (Fig. ~~S10~~S11). Uncertainties among GHMs in irrigation water withdrawal simulation mainly come from the parameterization and assumptions of irrigation scheme, such as the crop calendar, irrigation area and crops types (Wada et al., 2016). Although all four GHMs rely on approximately the same data set of irrigated areas from Siebert et al. (2005) (GMIA, http://www.fao.org/nr/water/aquastat/irrigationmap/index.stm), the crop types and the crop calendar definition in these

GHMs are different. For example, LPJmL, H08 and WaterGAP use climate conditions to simulate crop calendars (Bondeau et al., 2007; Hanasaki et al., 2010), while PCR-GLOBWB use the crop calendar data from Portmann et al. (2010). In addition, the uncertainty arising from climate forcing is small in most of regions (CV<0.25) due to the high agreement of historical climate datasets (Müller Schmied et al., 2016). Therefore, it is evident that the uncertainty from model structure is larger than that induced by forcing data. To improve the reconstruction of irrigation water withdrawal data, more realistic irrigation parameterization in GHMs and more reliable input data are needed.

4.3 Uncertainties in the spatial and temporal downscaling methods

Although the applied spatial and temporal downscaling methods possess some level of uncertainty in how water withdrawals are distributed spatially within a region or within a year, we did not explore the role of different downscaling methods on the gridded water withdrawal results. Instead we relied on a set of methods that have been used in the literature (Wada et al., 2011; Voisin et al., 2013; Hejazi et al., 2014; Wada and Bierkens, 2014) due to the general lack of multiple methods. Thus, we limit our discussion here to some of the potential sources of uncertainties associated with the spatial and temporal downscaling methods.

The spatial downscaling of water withdrawal by sectors can benefit from considering additional factors to represent the spatial distribution of global water withdrawal. T~~For example, t~~he spatial distribution of domestic water withdrawal is related not only to population density but also to incomes (GDP per capita) (Flörke et al., 2013), which varies region by region. ~~In addition, water~~ Water withdrawal for electricity generation is mainly for cooling purpose in thermoelectric power plant, and can also be affected by many factors besides population, including the location of power plants, the amount of generated electricity, generation type, cooling technology, and fuel type (Byers et al., 2014; Hejazi et al., 2014; Liu et al., 2015). ~~-~~For example, thermoelectric power plants are concentrated outside urban centers, for security reasons (e.g. nuclear power plants) and in proximity to large water quantities (e.g. along the rivers). As for mining and manufacturing sectors, Vassolo and Döll (2005) found that the consideration of city nighttime lights works better ~~that~~ than urban population. In addition, water withdrawals for manufacturing ~~and mining~~ are also dependent on the location of industry, the purpose for water use (e.g. cleaning, diluting and cooling), the outputs type (e.g. food and beverages), the raw materials~~GDP~~, and the technical system of water use (Flörke et al., 2013).~~.~~ Thus, future research should also consider using other ancillary data in addition to population density maps for the spatial downscaling of domestic and industry water withdrawals, such as the geographic locations and characteristics of power plants, manufacturing centers, and mines, and their historical evolutions.

The temporal downscaling methods by sectors can benefit from accounting for the intra-seasonal and inter-annual pattern of water withdrawal~~.~~ ~~That is the i~~Inter-annual variation of water withdrawal by sectors need to be considered when downscaling FAO AQUASTAT and USGS data from of 5-yr interval to annual scale. The inter-annual variability of human water withdrawal is of great significance for understanding the impacts of climate change (e.g. El Niño-Southern Oscillation, drought, and flood) on human behavior and economy (Vörösmarty et al., 2000; Jacob, 2001; Piao et al., 2010; Haddeland et al., 2014). Furthermore, temporal downscaling of domestic water withdrawal can benefit from considering additional factors besides air temperature , such as precipitation, population, and water availability to represent the seasonality of domestic water withdrawal (White et al., 1972; Hoekstra and Chapagain, 2006). Urban water use characteristics can actually be quite different from rural water characteristics. By only downscaling based upon urban water use characteristics, the reconstructed dataset could thus be biased in rural areas in terms of the temporal pattern. Also, the calibration of the parameter *R* in this study is rough due to the limitation of reported monthly water withdrawal data. For example, in the two major countries with water withdrawal, China and India, only data from West Bengal and Beijing were available. Given that domestic water withdrawal is roughly 7% of total water withdrawal in India and 12% in China, we acknowledge that more data would help improve the temporal downscaling of domestic water withdrawals, and future work should focus on collecting high resolution water withdrawal data both spatially and temporally. ~~Also, observed monthly domestic water withdrawal data will be of great importance for the calibration and validation of the parameter *R* in regions without historical observations.~~ As for electricity generation, the effects of electricity trade and hydropower generation need to be taken into account in future research. Although air temperature datasets used for temporal downscaling may add another source of uncertainty to the reconstructed water withdrawal data, our results show that the uncertainty induced by air temperature datasets is small in the temporal downscaling of water withdrawal for domestic and electricity generation (Fig.~~S11~~S12). This is mainly because of the high agreement in monthly variation of air temperature among the four different data sources (i.e. WFDEI, WATCH, GSWP3, Princeton) as all of them are bias corrected to (different) versions of the CRU time series (Müller Schmied et al., 2016). For livestock, mining, and manufacturing sectors, uniform distribution is applied for temporal downscaling. Incorporating the sub-annual variations in these sectors would require collecting monthly water withdrawal datasets to establish formulas that relate monthly water withdrawal for livestock, mining, and manufacturing to climate signals (e.g. temperature, precipitation).

5 Conclusions

In this study, a reconstructed global gridded monthly sectoral water withdrawal dataset, which is open-access online (https://doi.org/10.5281/zenodo.897933), was produced for the period 1971-2010 by temporally and spatially downscaling country-level (FAO AQUASTAT) and state-level (USGS, only for USA) datasets using various models and new modeling approaches. Correction factors are used to scale irrigation water withdrawal estimates by GHMs to annual country/state estimates from FAO and USGS. Global population density maps are used for the spatial downscaling for water withdrawal for domestic, electricity generation, mining and manufacturing; while livestock density maps are used for livestock sector. In addition, air temperature are used to present the monthly variation of water withdrawal by domestic and electricity generation, which are validated against observations, and simulation results show reasonable agreements with observations in selected regions.

The reconstructed dataset, at 0.5 degree spatial resolution and monthly temporal resolution, includes water withdrawal by sector, i.e. irrigation, domestic, electricity generation, livestock, mining and manufacturing. Based on the reconstruction dataset, the spatial and temporal change patterns of global water withdrawal by sectors were analyzed. Globally, most of global water withdrawal is used for irrigation, followed by electricity generation and domestic. Spatially, the dominant irrigation water withdrawal area are regions with large irrigated cropland and massive crop productions, e.g. the western US, eastern China, and India. Water withdrawal for domestic, electricity generation, mining and manufacturing are high in urban areas or regions with denser population. Seasonally, irrigation water withdrawal exhibits an evident seasonal pattern in mid and high-latitude regions, but not in the tropical zone. Domestic water withdrawal is larger in JJA than in DJF in northern hemisphere, and vice versa in southern hemisphere. Water withdrawal for electricity generation showed a winter peak in high-latitude regions and a summer peak in low-latitude regions.

In addition, the uncertainties in the reconstructed water withdrawal data are analyzed, and limitations for spatial and temporal downscaling of other sector are discussed. Results show that the uncertainties arising from model structure are larger than that induced by forcing data in the reconstructed irrigation water withdrawal. More advanced models that capture the spatial pattern and intra- and inter-annual variabilities of sectoral water withdrawal are prospect, and more frequently and spatially resolved observed water withdrawal data at country or region scale are also required for improving the quality of the reconstructed dataset. In whole, despite the uncertainties and limitations, this study is of great significance not only for cross-comparison and validation for modeling and analyzing the impacts of human water use, but also for investigating water use related issues at finer spatial, temporal and sectoral scales.

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Table 1 Datasets for spatial and temporal downscaling of reported water withdrawal by sectors

Sectors	Spatial downscaling	Temporal downscaling
Irrigation	Global irrigation water withdrawal simulation by 4 GHMs (namely WaterGAP, H08, LPJmL, and PCR-GLOBWB) for the period 1971-2010	
Domestic	Global population density maps from HYDE during 1970-~~1980~~ 1989 and GPW during ~~1985~~1990-2010	The gridded daily air temperature data from WFDEI during 1971-2010
Electricity		
Mining		uniform distribution
Manufacturing		
Livestock	Global livestock density maps in 2005 from FAO	uniform distribution

Table 2 Details of the observed monthly domestic water withdrawal for calibration of parameter R.

Country	State/Province	City	Period	Source
Canada	Saskatchewan	Kindersley	2001-2015	Saskatchewan community water use records, Water security agency(2016)
		Assiniboia	2001-2015	
		Yorkton	2001-2015	
		Prince Albert	2003-2015	
		Stanley Mission	2005-2014	
		Estevan	2001-2015	
		Swift Current	2001-2015	
		Estend	2001-2015	
		Regina	2001-2015	
USA	Indiana	Indiana	1999-2004	Shaffer (2009)
	Ohio	Ohio	1999-2004	
	Arizona	Canyon	1971-1978	Maidment and Parzen (1984)
	Indiana	Phoenix	1995-2004	Balling et al. (2008)
	Arizona	Tucson	1990	Voisin et al. (2013)
	Washington	Seattle	1990	
	California	Orange	1990	
	South Carolina	Clemson University	1990	
	California	Fortuna	2013, 2015	State Water Resources Control Board of California (http://projects.scpr.org/applications/onthly-water use/)
		Imperial		
		Galt		
		Ripon		
		Greenfield		
		Riverbank		
		Truckee-Donner		
		Fillmore		
		Hanford		
		Adelanto		
India	West Bengal	West Bengal	2006	Hossain et al. (2013)
China	Beijing	Beijing	2013-2014	Beijing Water Authority (https://www.bjwater.gov.cn/pub/bjwater/bmfw/)
Australia	Western Australia	Perth	2000-2001	Loh and Coghlan (2003)

Table 3 Calibrated R in different counties and their median value for temporal downscaling of domestic water withdrawal.

	Canada	USA	Australia	India	China	Japan	Spain	Global
City number	9	18	1	1	1	1	1	32
Range of R	0.15~0.79	0.11~1.14	-	-	-	-	-	0.1~1.14
Median R	0.36	0.52	0.8	0.29	0.2	0.1	0.1	0.45

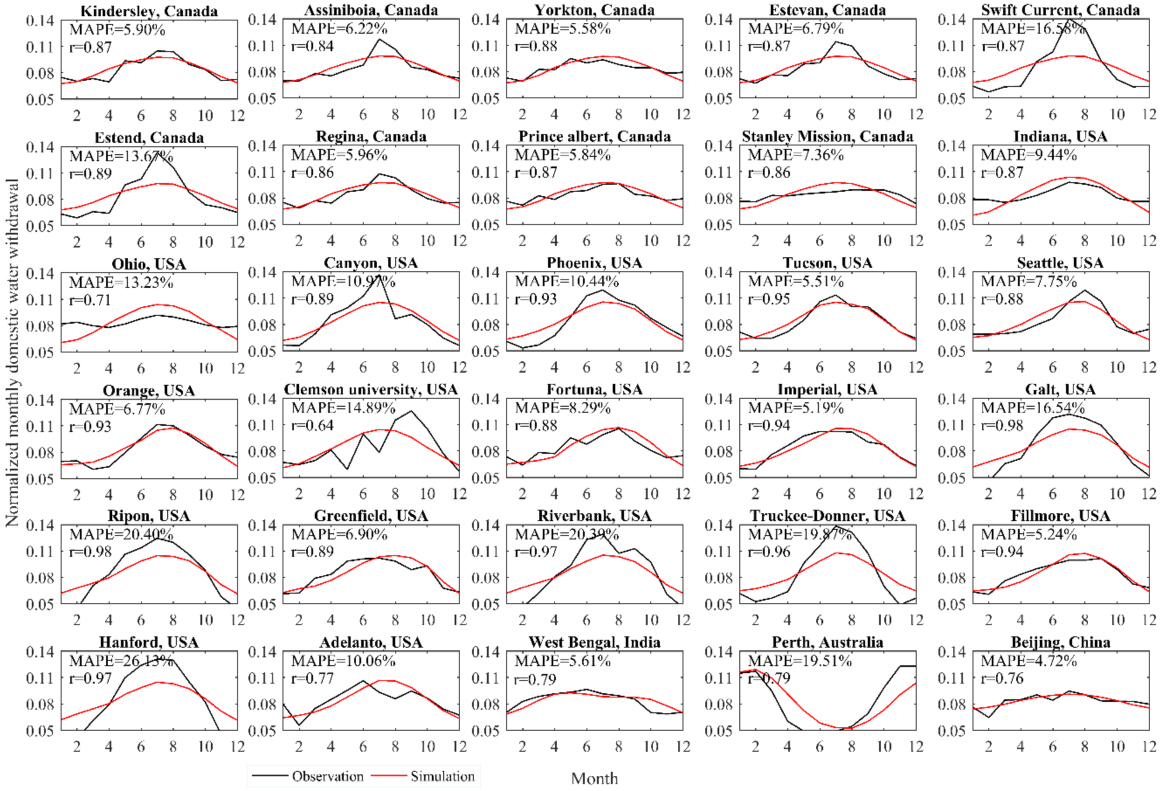


Figure 1 Comparison between simulated and observed monthly domestic water withdrawal in global 30 regions: the normalized monthly water withdrawal is the proportion of monthly water withdrawal to the total annual water withdrawal.

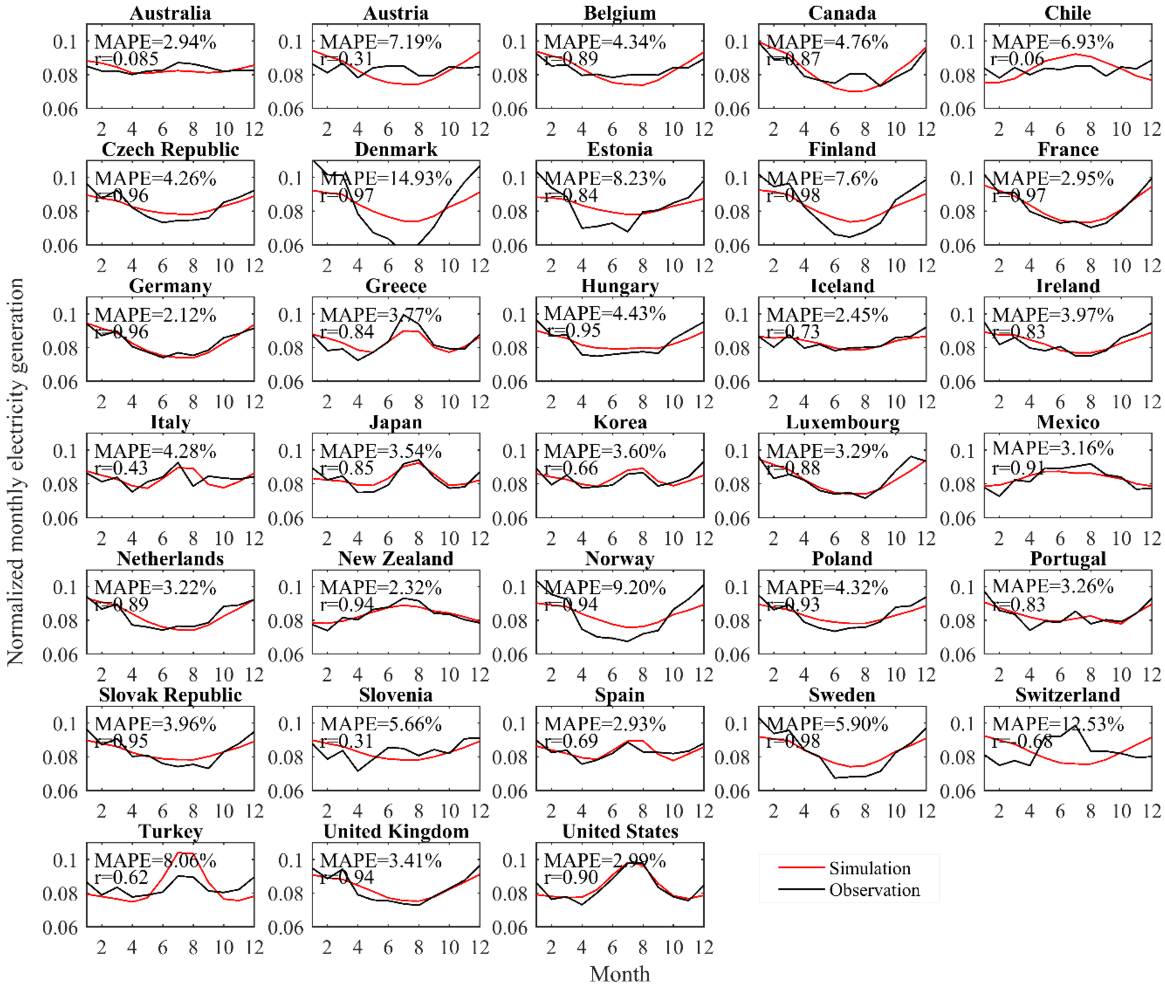
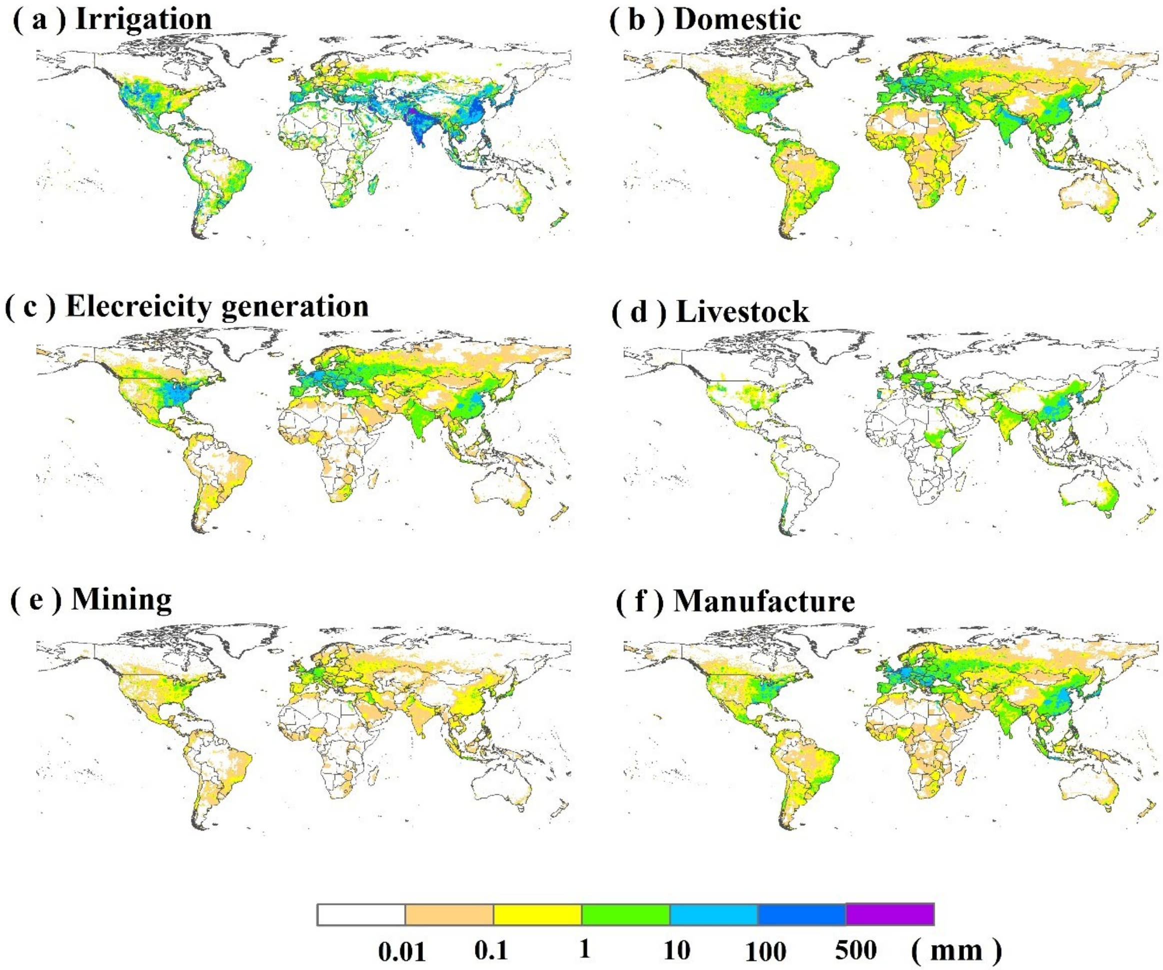


Figure 2 Comparison between simulation and observation of normalized monthly mean electricity generation in 33 OECD countries during 2000-2012: the normalized monthly electricity generation is the proportion of monthly water withdrawal to the total annual electricity generation.


(a) Irrigation
(b) Domestic
(c) Elecreicity generation
(d) Livestock
(e) Mining
(f) Manufacture
0.01
0.1
1
10
100
500
(mm)

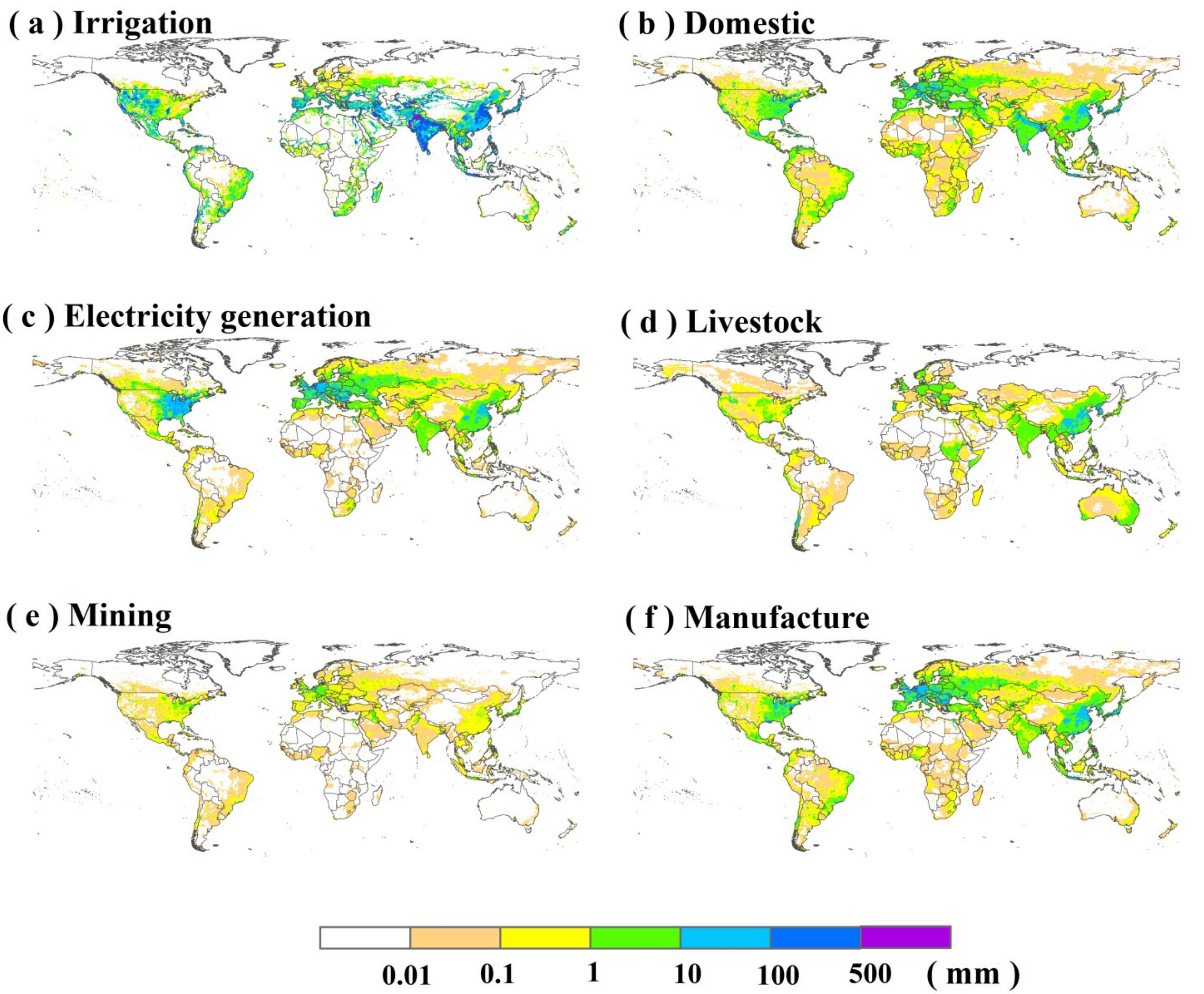
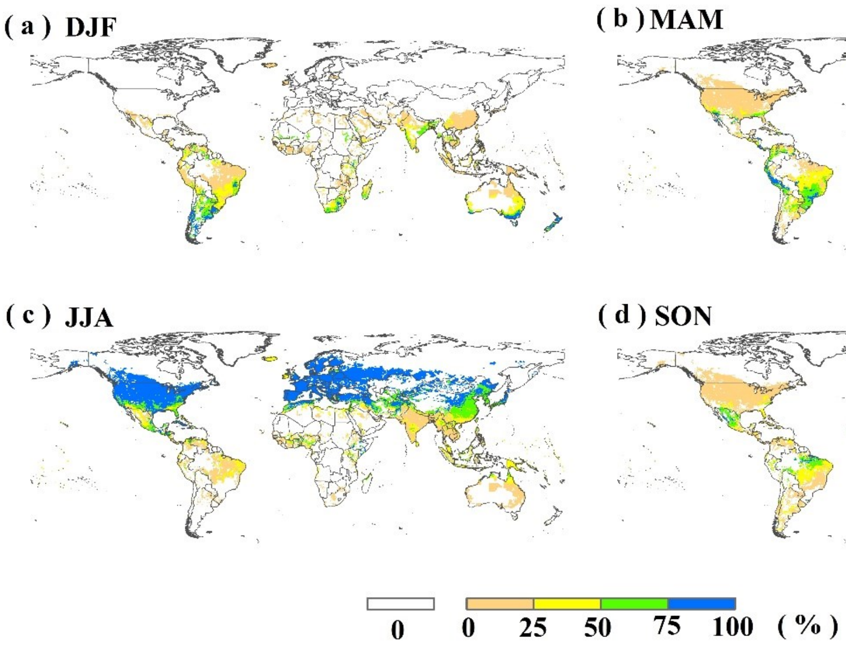


Figure 3 Spatial distribution of annual mean water withdrawal by 6 sectors: (a) irrigation, (b) domestic, (c) electricity generation, (d) livestock, (e) mining and (f) manufacturing during 1971-2010.

5


(a) DJF
(b) MAM
(c) JJA
(d) SON
0
0
25
50
75
100
(%)

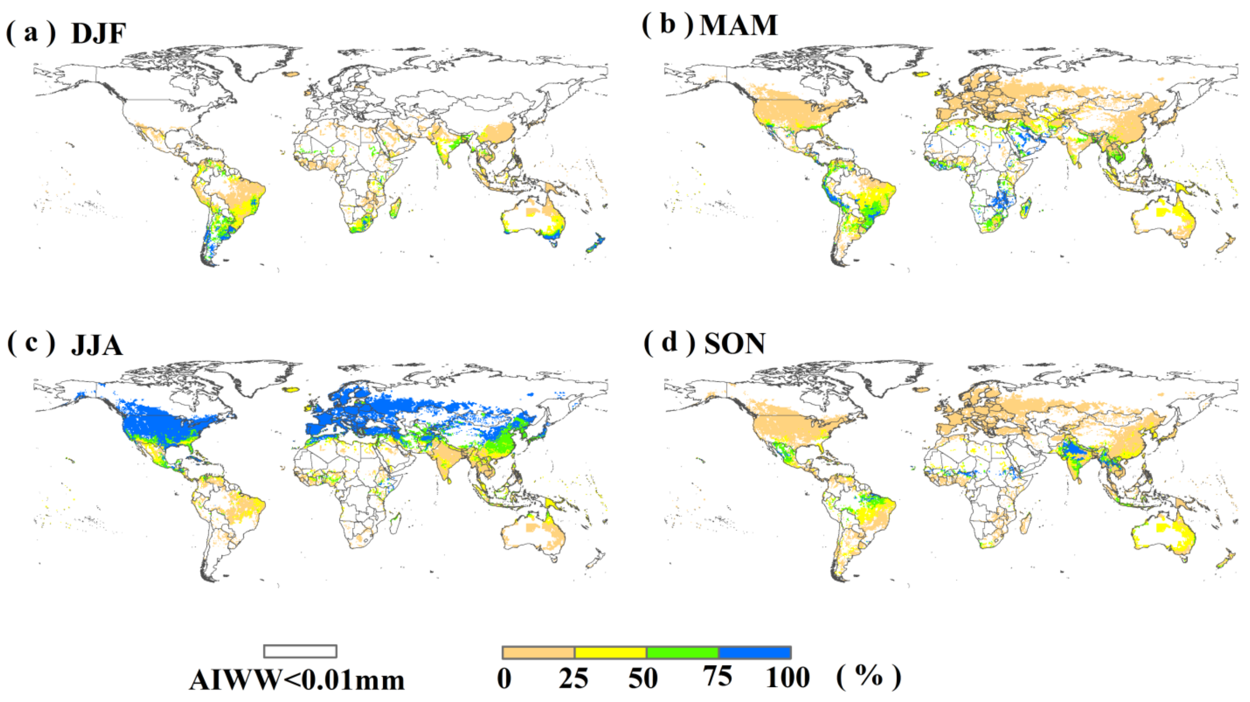
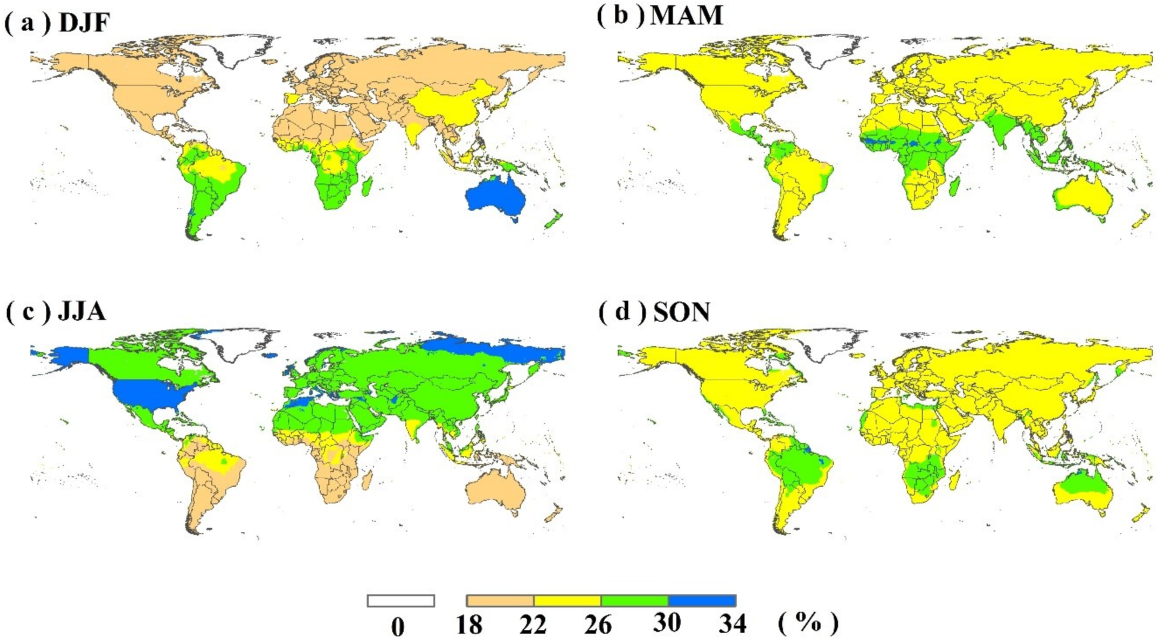


Figure 4 Relative seasonal distribution of global irrigation water withdrawal over the period 1971-2010 based on the ensemble mean of four GHMs: December to February (DJF), March to May (MAM), June to August (JJA) and September to November (SON), and grids with annual irrigation water withdrawal (AIWW) less than 0.01mm are not taken into consideration.~~.~~


(a) DJF
(b) MAM
(c) JJA
(d) SON
0
18
22
26
30
34
(%)

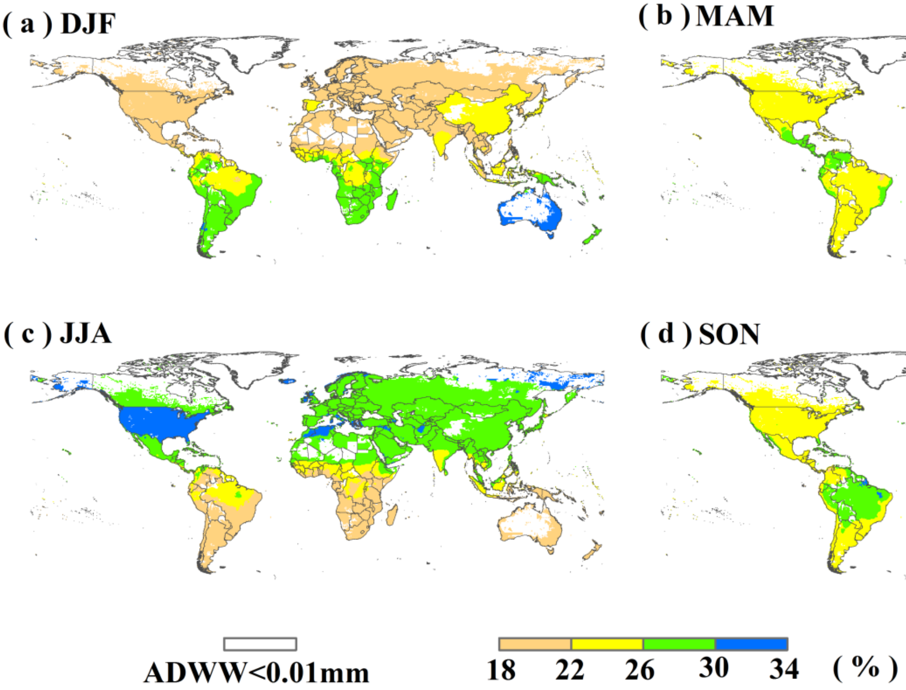
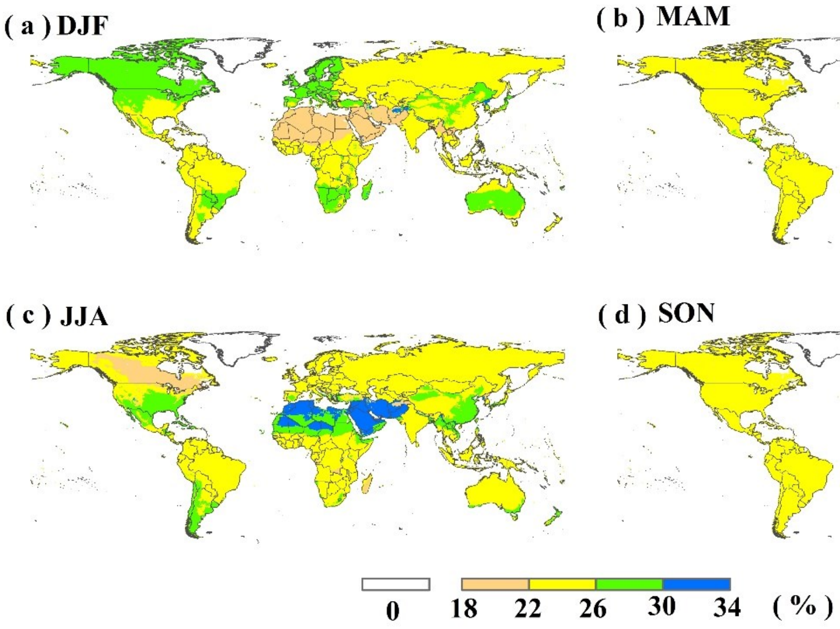


Figure 5 Relative seasonal distribution of global domestic water withdrawal over the period 1971-2010: December to February (DJF), March to May (MAM), June to August (JJA) and September to November (SON), and grids with annual domestic water withdrawal (ADWW) less than 0.01mm are not taken into consideration.~~.~~


(a) DJF
(b) MAM
(c) JJA
(d) SON
0
18
22
26
30
34
(%)

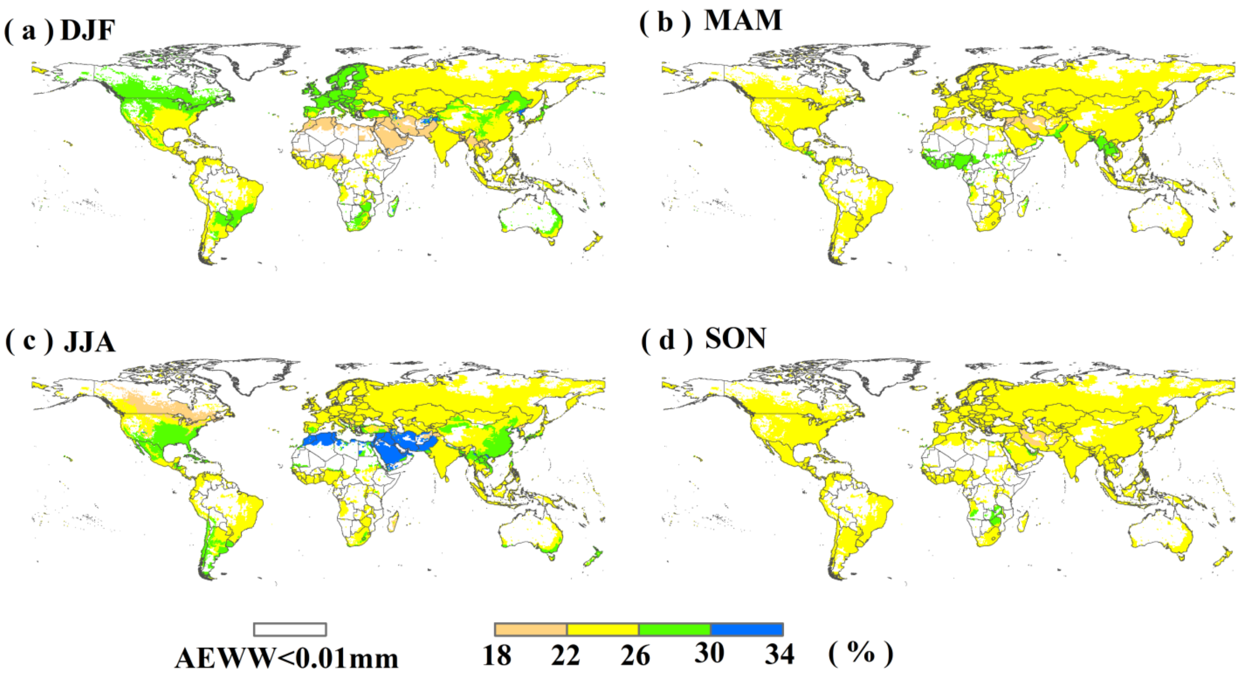
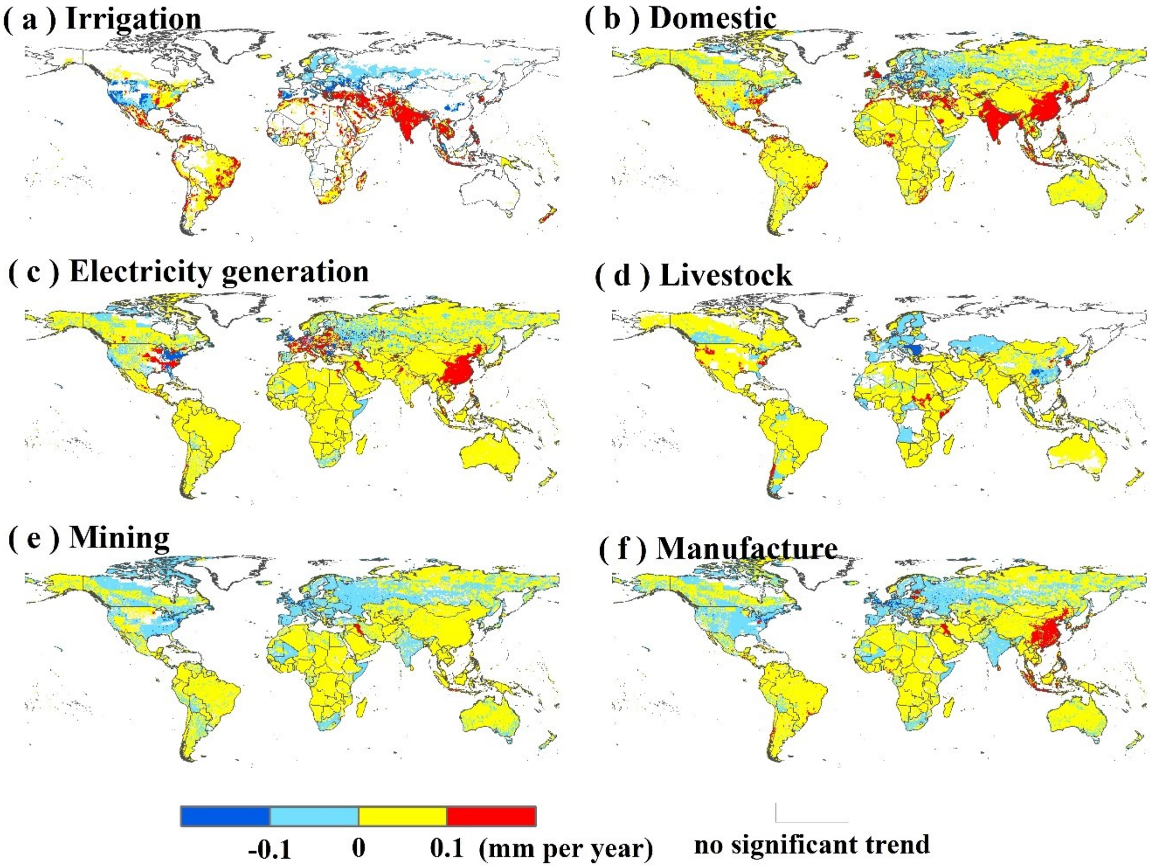


Figure 6 Relative seasonal distribution of global electricity generation water withdrawal over the period 1971-2010: December to February (DJF), March to May (MAM), June to August (JJA) and September to November (SON), and grids with annual electricity water withdrawal (AEWW) are not taken into consideration.~~.~~



(a) Irrigation

(b) Domestic

(c) Electricity generation

(d) Livestock

(e) Mining

(f) Manufacture

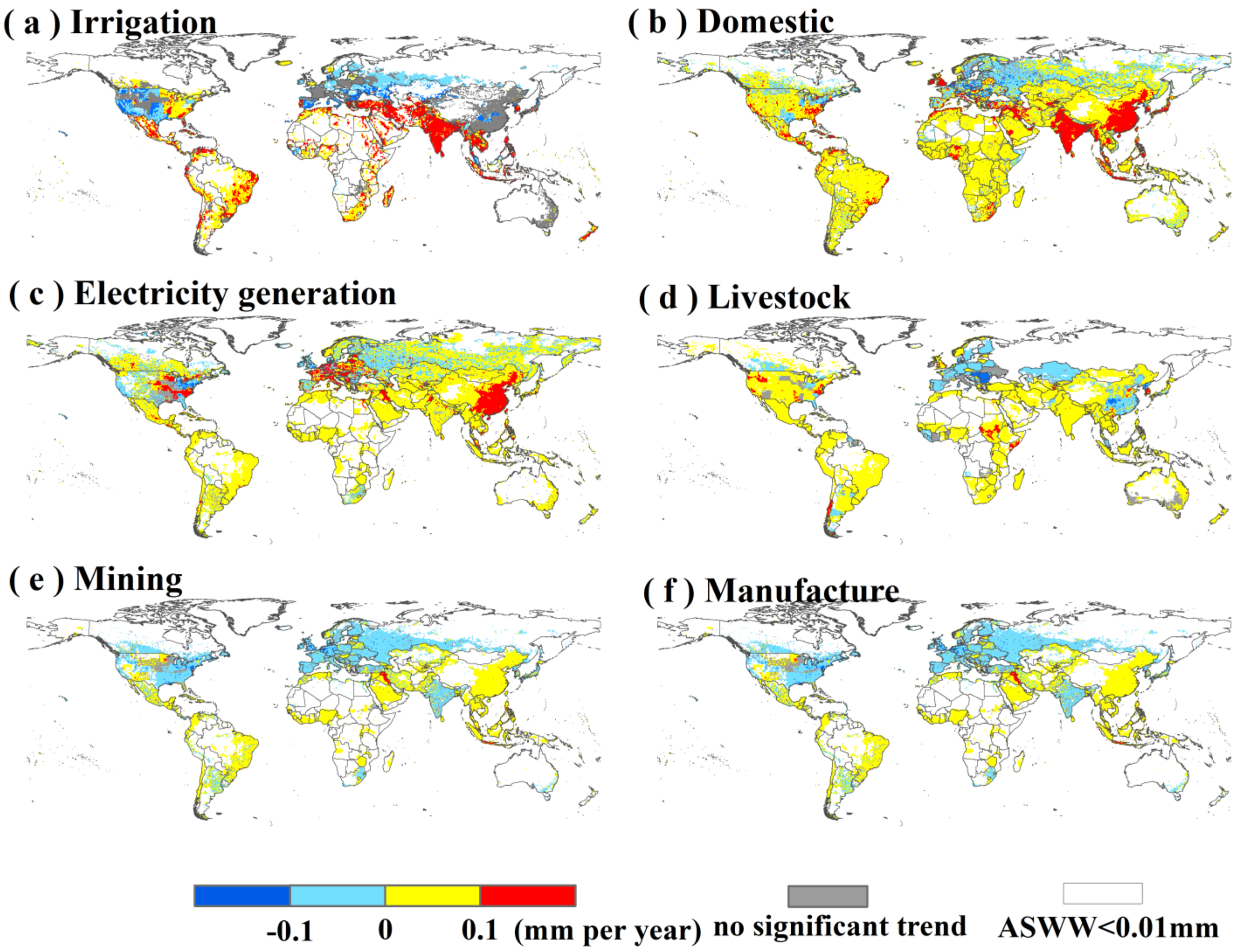


Figure 7 Trend of global gridded water withdrawal by sectors: (a) irrigation, (b) domestic, (c) electricity generation, (d) livestock, (e) mining and (f) manufacturing, grids with annual sectoral water withdrawal (ASWW) less than 0.01mm are not taken into consideration.

5

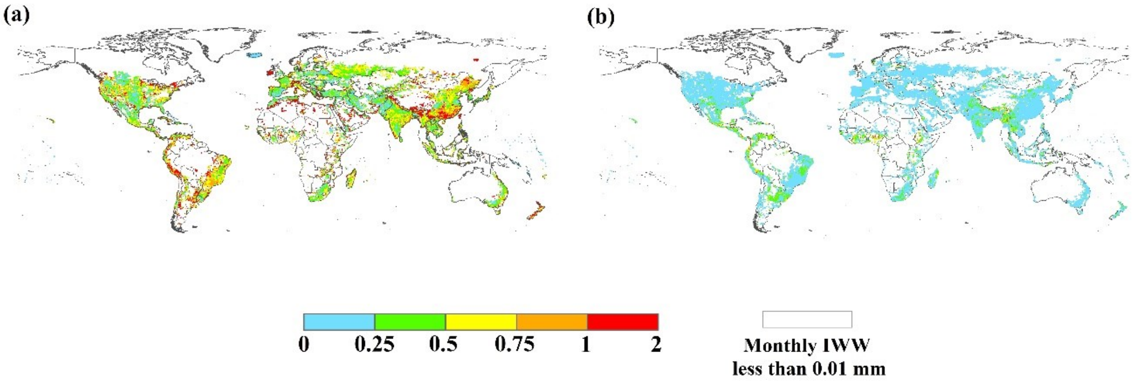


Figure 8 Coefficient of variation (CV) in multi-annual average irrigation water withdrawal caused by (a) multi-model framework and by (b) multi-forcing data, and area with ~~annual~~ monthly mean irrigation water withdrawal (IWW) less than 0.01 mm are not taken into consideration.

Supplement of "Reconstruction of global gridded monthly sectoral water withdrawals for 1971-2010 and analysis of their spatiotemporal patterns"

Huang et al.

Supplement material

1. Methods used for generating sectoral water consumption data

Besides the global gridded monthly sectoral water withdrawal data during 1971-2010, sectoral water consumption data were also produced at grid scale and monthly time step and are available online (https://doi.org/10.5281/zenodo.897933). For the irrigation sector, irrigation water consumption was generated by reapplying the correction factor in Eq.(1) to irrigation water consumptions simulated by four GHMs (i.e. WaterGAP, LPJmL , H08, and PCR-GLOBWB):

$$Cir_{i,j,g} = Cir\_sim_{i,j,g} \times f_{m,p};\qquad (S1)$$

Where $Cir_{i,j,g}$ is the reconstructed irrigation water consumption for the month *i* of year *j* at grid *g* (m3), and $Cir\_sim_{i,j,g}$ is the irrigation water consumption for the month *i* of year *j* at grid *g* simulated by four GHMs (m3); $f_{m,p}$ is the correction factor calculated in Eq.(1). For the remaining sectors, consumptive water use efficiency (the proportion of water consumption to water withdrawal) was used. Based on the simulation of Flörke et al (2013), consumptive water use efficiencies for electricity generation, domestic and manufacturing sector were calculated at country level, and global consumptive water use efficiencies for livestock and mining adopted the value in the US which was estimated by USGS. Thus, water consumptions by these 5 sectors were calculated by the products of reconstructed water withdrawal data and the consumptive water use efficiencies.

2. Supplement figures

Figure S1. Simulated annual irrigation water withdrawal using each of the following four GHMs (i.e., WaterGAP, H08, LPJmL, and PCR-GLOBWB) in comparison with FAO AQUASTAT data at country level and USGS estimation at state level.

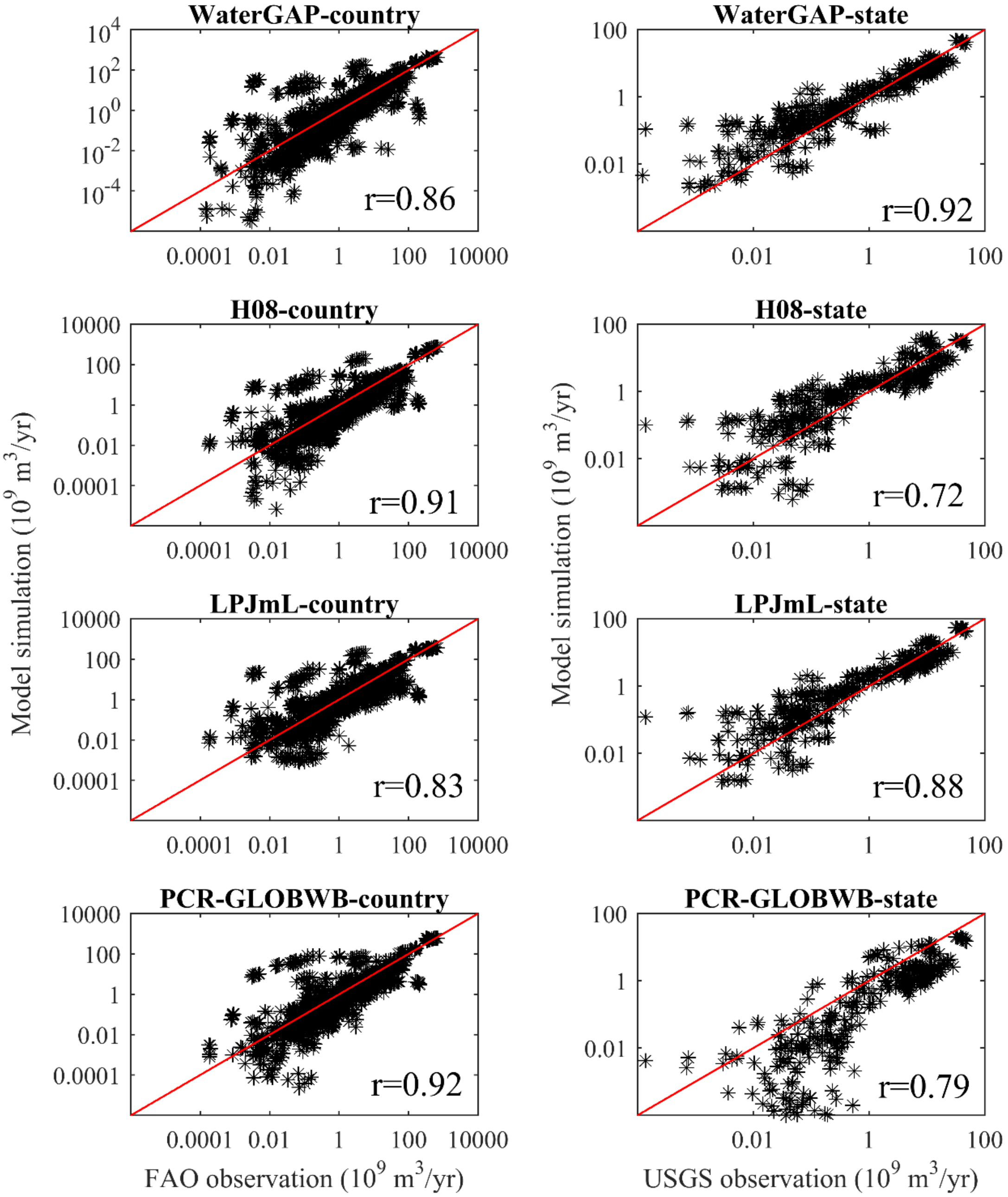


Figure S2. Mean monthly irrigation water withdrawal (normalized in percentage) in 32 GCAM regions simulated by four GHMs (i.e., WaterGAP, H08, LPJmL, and PCR-GLOBWB).

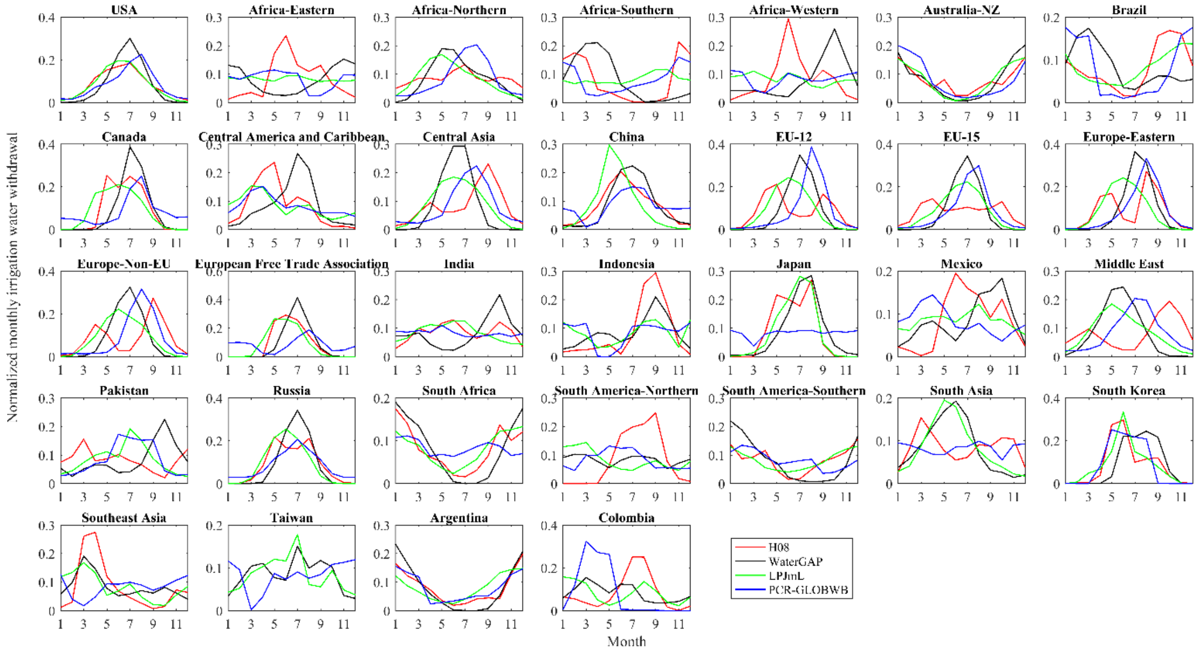


Figure S3. Spatial distribution of global dominant water withdrawal sectors.

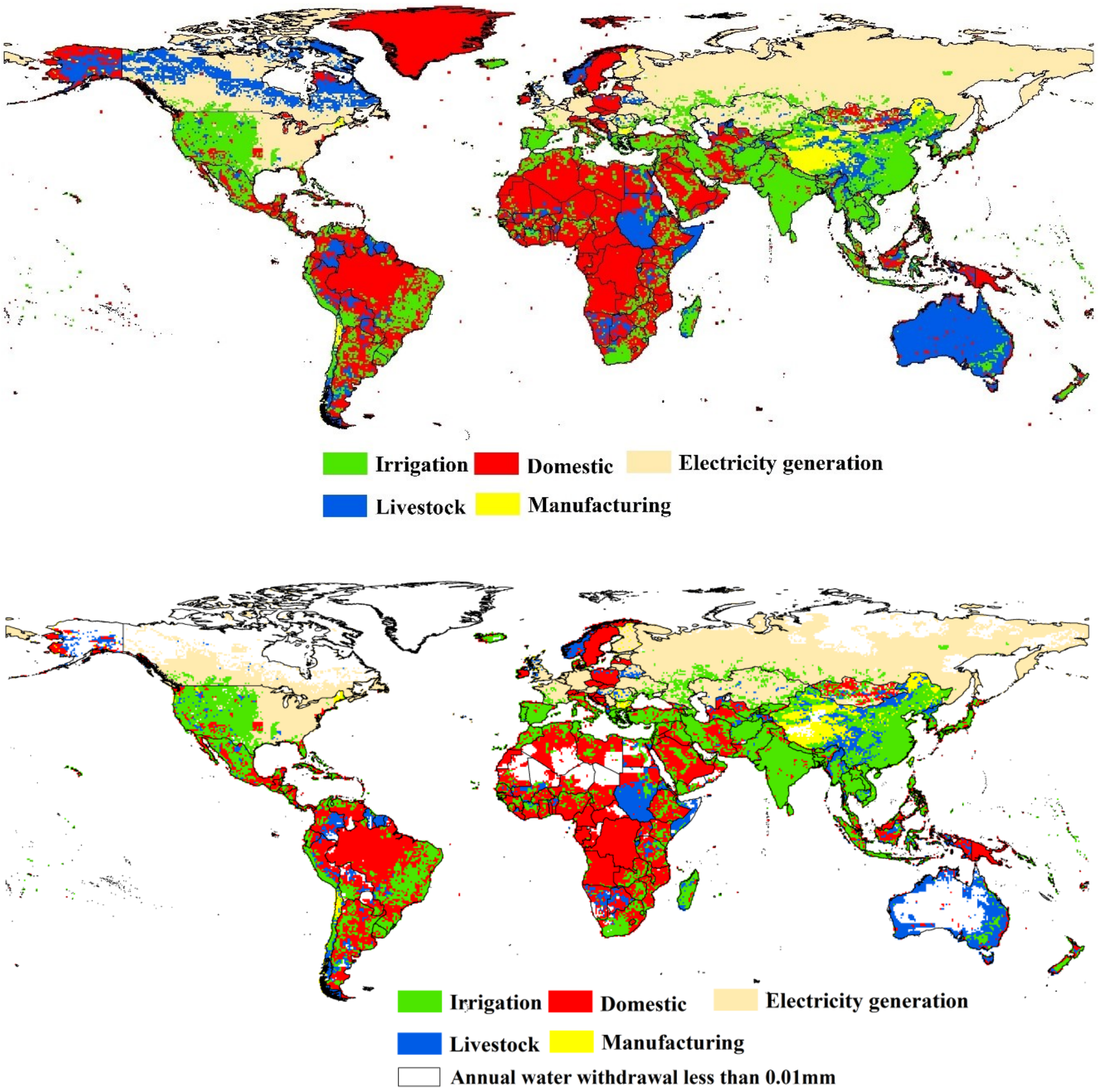


Figure S4. Water withdrawal by 6 sectors during 1971-2010 in (a) Global, (b) China, (c) the US, (d) India and (e) EU27.

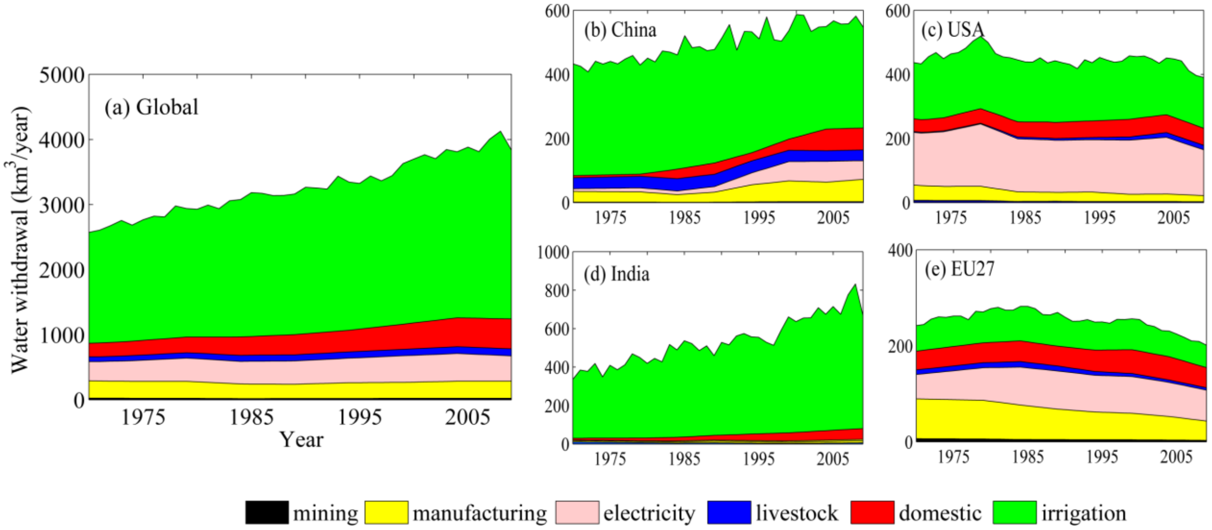


Figure ~~S4~~ S5 Monthly and annual time-series of total water withdrawal for global, China, the US, India and EU27 during 1971-2010

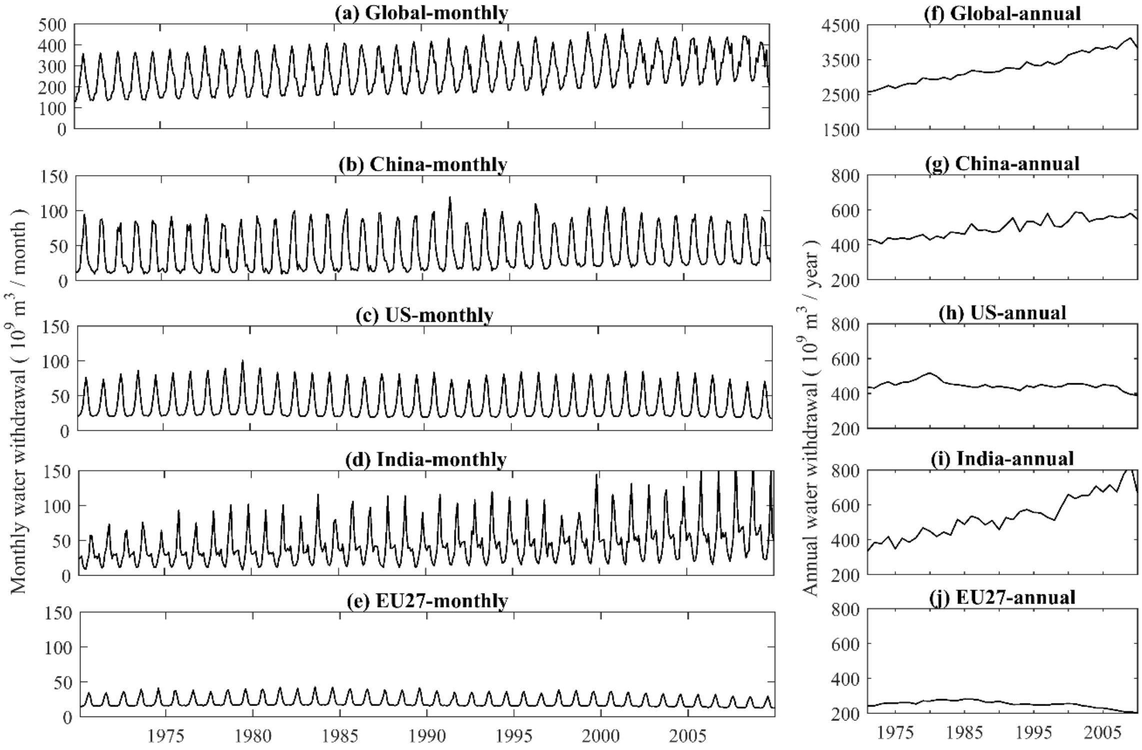


Figure ~~S5~~S6. Monthly and annual time-series of irrigation water withdrawal for global, China, US, India and EU27 during 1971-2010.

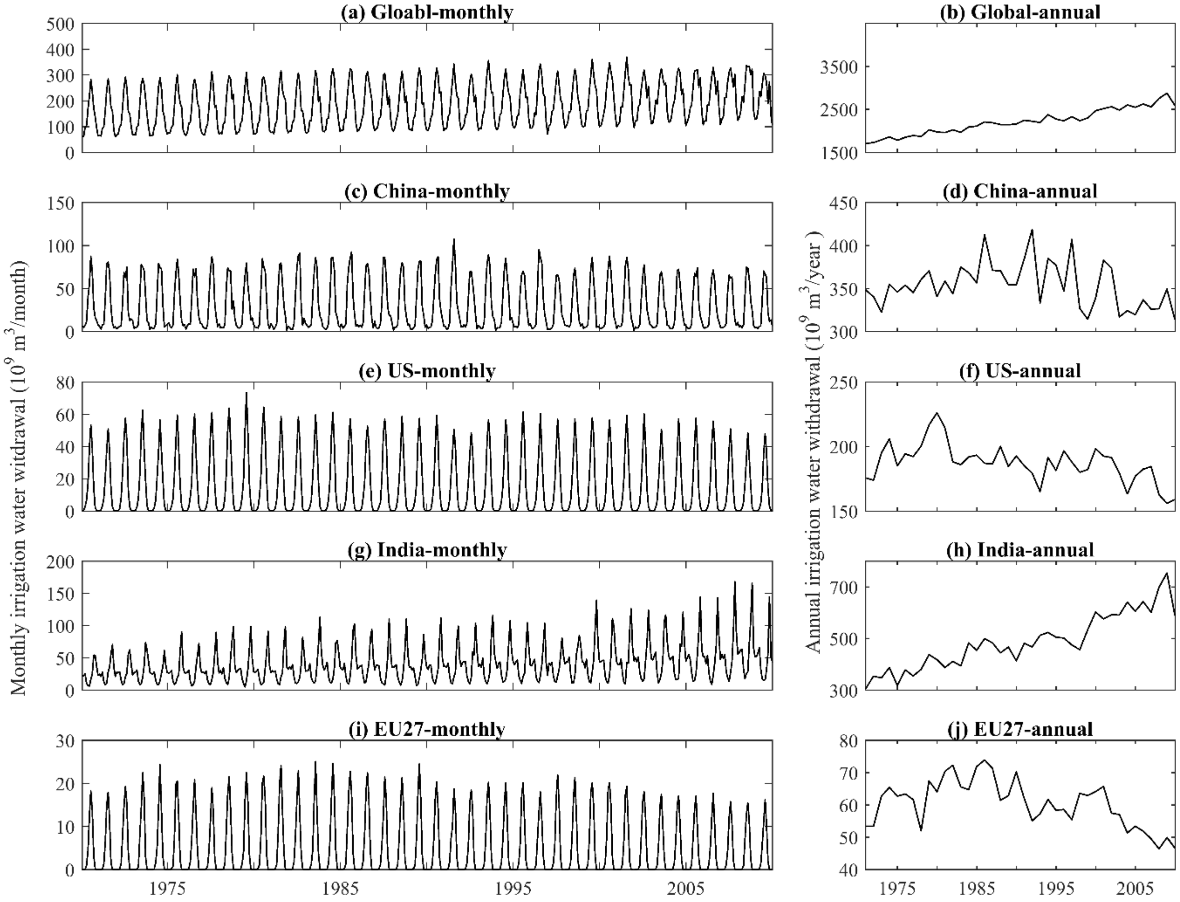


Figure ~~S6~~S7. Monthly and annual time-series of domestic water withdrawal for global, China, US, India and EU27 during 1971-2010.

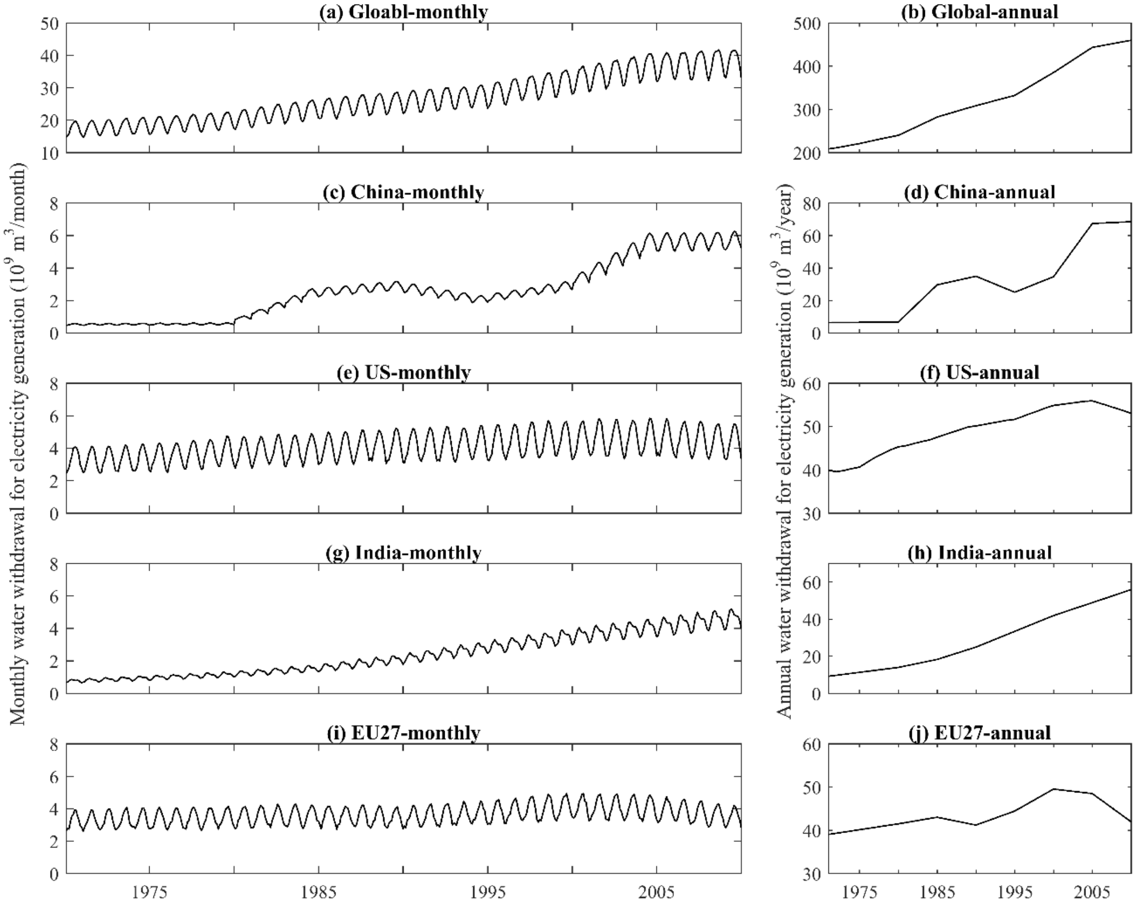


Figure ~~S7~~ S8 Monthly and annual time-series of electricity generation water withdrawal for global, China, US, India and EU27 during 1971-2010

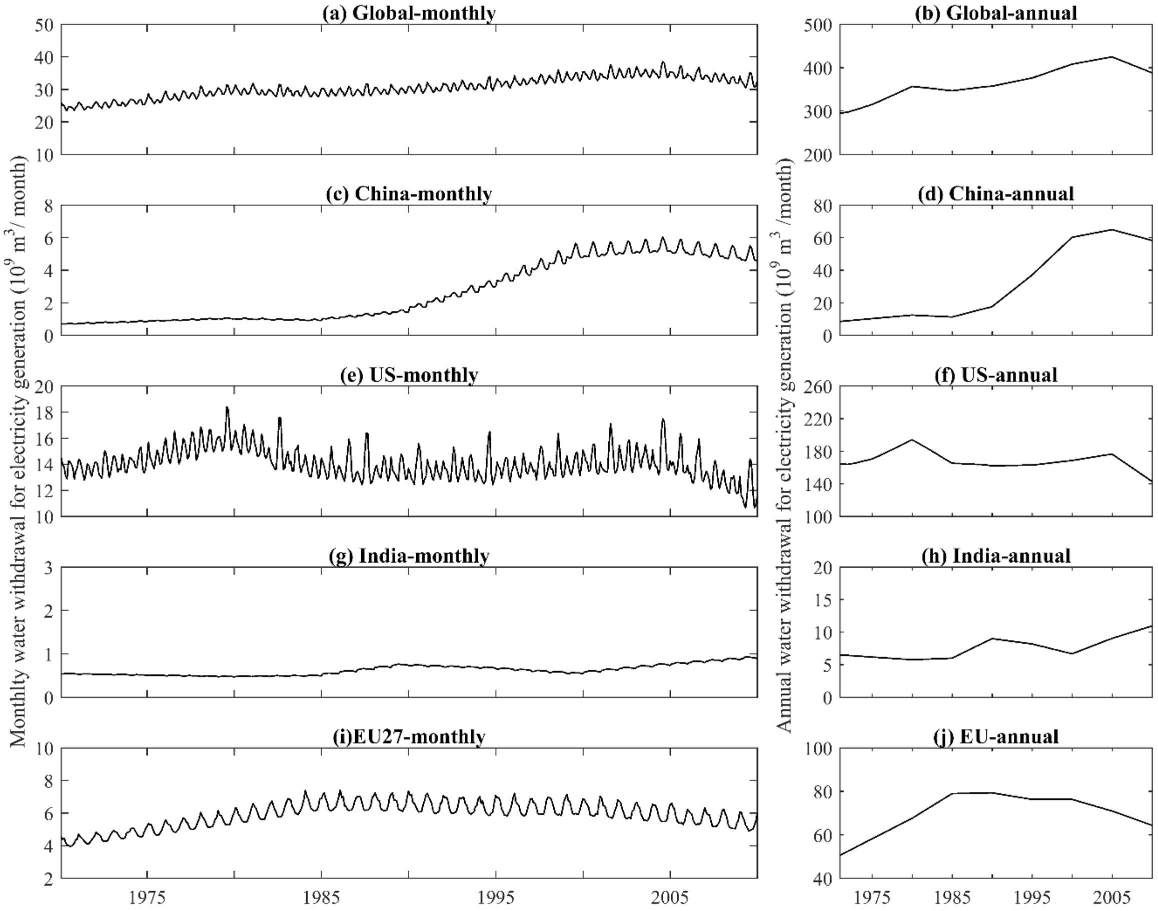


Figure ~~S8~~S9. Annual time-series of water withdrawal by sector (mining, livestock, and manufacturing) for global, China, US, India and EU27 during 1971-2010.

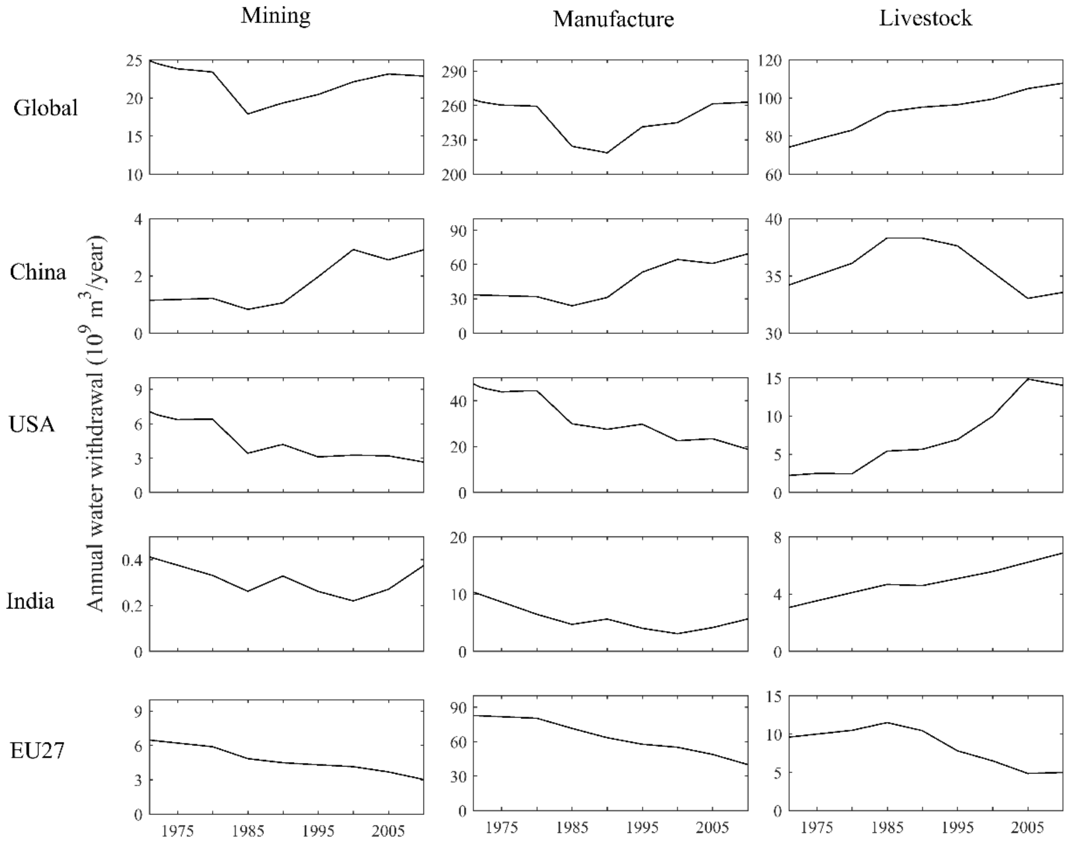


Figure ~~S9~~ S10 comparison of global water withdrawal used in this study with estimates from Flörke et al. (2013) and Shiklomanov (2000) for domestic and industrial sectors.

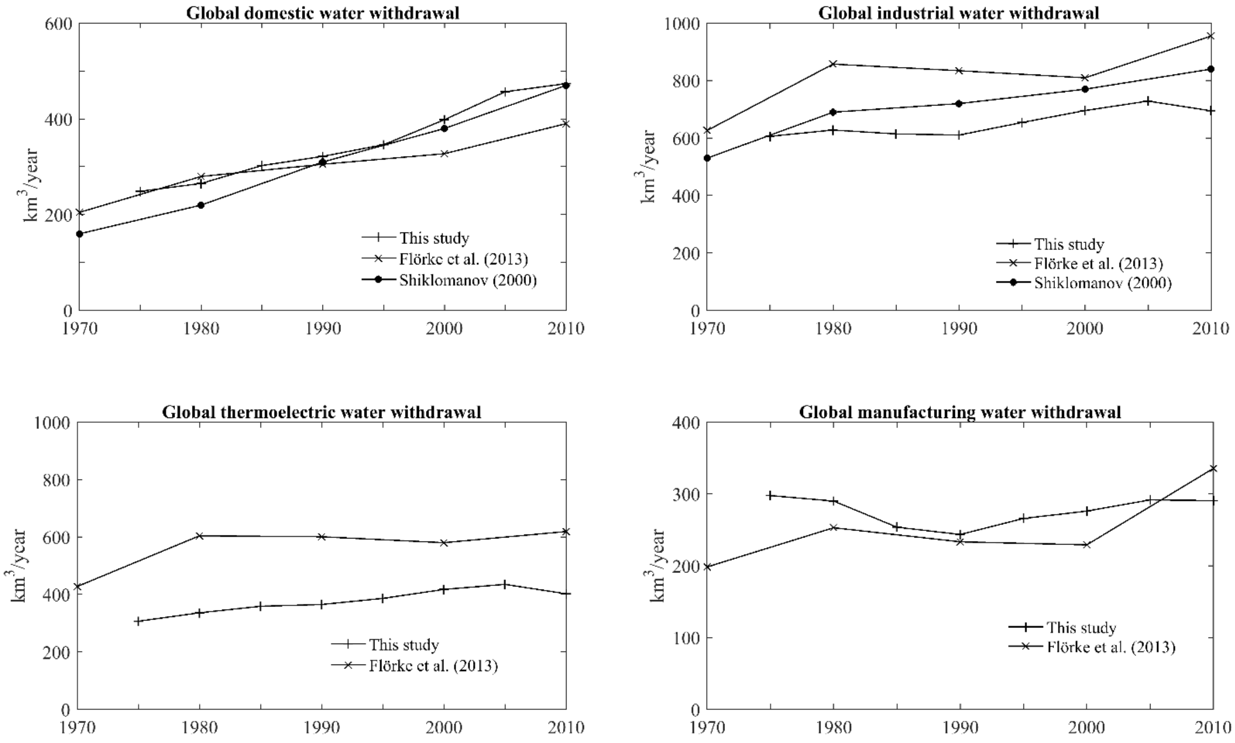


Figure ~~S10~~ S11 coefficient of variation (CV) of irrigation water withdrawal in JJA and DJF caused by multi-model framework and by multi-forcing data: December to February (DJF) and June to August (JJA)-.

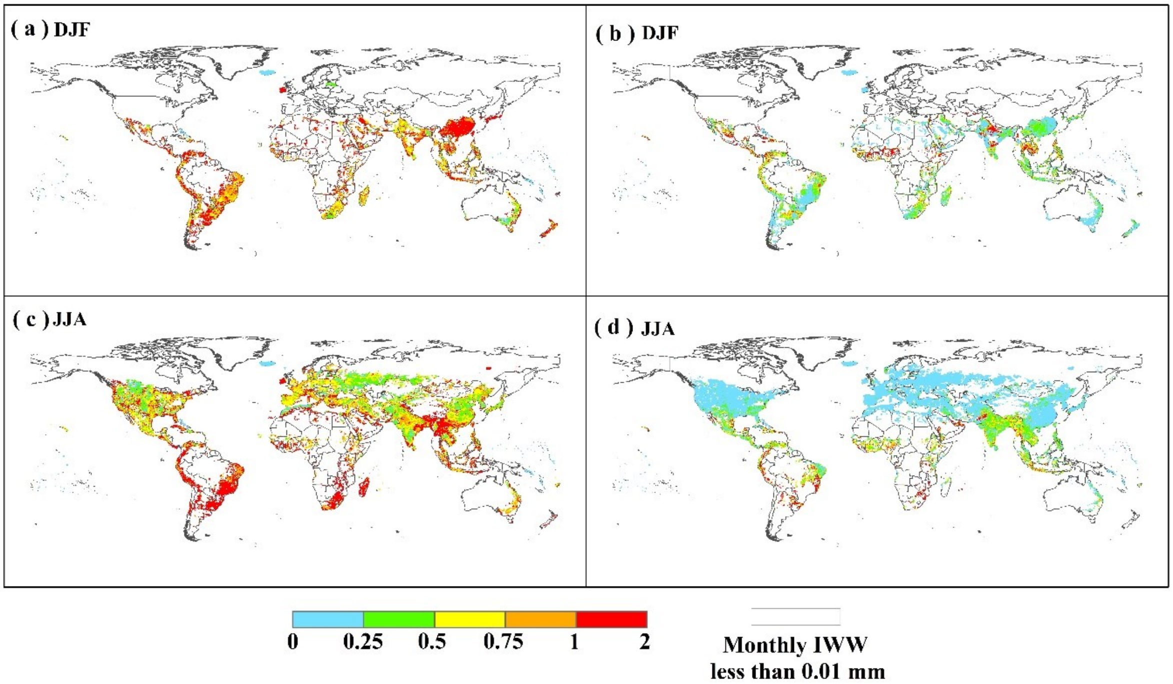


Figure ~~S11~~ S12 coefficient of variation (CV) caused by different climate forcing in temporal downscaling of (a) domestic and (b) electricity generation in 4 seasons: : December to February (DJF), March to May (MAM), June to August (JJA) and September to November (SON).