Global water resources affected by human interventions and climate change

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Humans directly change the dynamics of the water cycle through dams constructed for water storage, and through water withdrawals for industrial, agricultural, or domestic purposes. Climate change is expected to additionally affect water supply and demand. Here, analyses of climate change and direct human impacts on the terrestrial water cycle are presented and compared using a multimodel approach. Seven global hydrological models have been forced with multiple climate projections, and with and without taking into account impacts of human interventions such as dams and water withdrawals on the hydrological cycle. Model results are analyzed for different levels of global warming, allowing for analyses in line with temperature targets for climate change mitigation. The results indicate that direct human impacts on the water cycle in some regions, e.g., parts of Asia and in the western United States, are of the same order of magnitude, or even exceed impacts to be expected for moderate levels of global warming (+2 K). Despite some spread in model projections, irrigation water consumption is generally projected to increase with higher global mean temperatures. Irrigation water scarcity is particularly large in parts of southern and eastern Asia, and is expected to become even larger in the future.

ISI-MIP | WaterMIP

Terrestrial water fluxes are affected by both climate and direct human interventions, e.g., dam operations and water withdrawals. Climate change is expected to alter the water cycle and will subsequently impact water availability and demand. Several hydrologic modeling studies have focused on climate change impacts on discharge in large river basins or global terrestrial areas under naturalized conditions using a single hydrologic model forced with multiple climate projections (1, 2). Recently, hydrological projections from eight global hydrological models (GHMs) were compared (3). In many areas, there was a large spread in projected runoff changes within the climate–hydrology modeling chain. However, at high latitudes there was a clear increase in runoff, whereas some midlatitude regions showed a robust signal of reduced runoff. The study also concluded that the choice of GHM adds to the uncertainty for hydrological change caused by the choice of atmosphere–ocean general circulation models (hereafter called GCMs) (3). Expected runoff increases in the north and decreases in parts of the middle latitudes have been found also when analyzing runoff from 23 GCMs (4).

These studies focused on the naturalized hydrological cycle, i.e., the effects of direct human interventions were not taken into account. However, in many river basins humans substantially alter the hydrological cycle by constructing dams and through water withdrawals. Reservoir operations alter the timing of discharge, although mean annual discharge does not necessarily change much. A study with the water balance model (WBM) showed that the impact of human disturbances, i.e., dams and water consumption, in some river basins is equal to or greater than the impact of expected climate changes on annual runoff over the next 40 y (5). Also, rising water demands are found to outweigh global warming in defining the state of global water systems in the near future (6). Water for irrigation is the largest water use sector, currently accounting for about 70% of global water withdrawals and nearly 90% of consumptive water use (7). A recent synthesis of simulations from seven GHMs found that irrigation water consumption currently amounts to 1,250 $\text{km}^3 \cdot \text{y}^{-1}$ (±25%) and that considerable differences among models appear in the spatiotemporal patterns of water consumption (8).

Direct comparisons of the climate impact and human intervention modeling studies can be difficult given that the setups are not identical, i.e., the input forcing data and climate models vary. Also, because of the uncertainty of model-specific results, a multimodel approach is preferable in impact modeling studies (3, 9). This approach is similar to assessments performed within the climate community. Here, multimodel results on current and future water availability and consumption at the global scale from the Water Model Intercomparison Project (WaterMIP) within the European Union Water and Global Change (EU WATCH) project (9, 10), and Inter-Sectoral Impact Model Intercomparison Project (ISI-MIP) (11) are presented. (Information

Significance

Humans alter the water cycle by constructing dams and through water withdrawals. Climate change is expected to additionally affect water supply and demand. Here, model analyses of climate change and direct human impacts on the terrestrial water cycle are presented. The results indicate that the impact of man-made reservoirs and water withdrawals on the long-term global terrestrial water balance is small. However, in some river basins, impacts of human interventions are significant. In parts of Asia and the United States, the effects of human interventions exceed the impacts expected for moderate levels of global warming. This study also identifies areas where irrigation water is currently scarce, and where increases in irrigation water scarcity are projected.

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on how to get access to WaterMIP and ISI-MIP simulation results can be found at www.eu-watch.org and www.isi-mip.org, respectively.) Results from these two projects are synthesized to obtain a large ensemble of impact model results. The integration of results from the different projects is achieved by extracting impacts for time periods of global mean temperature (GMT) increases of 2 and 3 K from the simulations, largely following the method of Tang and Lettenmaier (4). The advantage of this approach is that it allows presenting results in a way that is in line with temperature targets used in climate mitigation discussions.

Other studies have focused on future water scarcity using results from WaterMIP and ISI-MIP, but have analyzed changes of naturalized runoff only (3, 12). We here aim to fill this knowledge gap by comparing the different impacts from climate change and direct human impacts and analyzing their interplay. The models included take into account water withdrawals and consumption in different sectors; for more information, see *Models and Data* and *Supporting Information, SI Models and Data*. The objectives of this study are to (*i*) assess the relative contribution of anthropogenic impacts and climate change to river basin scale water fluxes, and (*ii*) identify areas where climate change can be expected to cause substantial changes in water consumption and water scarcity, focusing on water for irrigation. The effects of future changes in irrigated areas or irrigation practices are not taken into account, and only dams that currently exist are included in the analyses. In this paper, simulations considering man-made reservoirs, water withdrawals, and water consumption are referred to as human impact simulations, whereas the simulations without these disturbances are referred to as naturalized simulations. The results are mainly presented in a way intended to give an overview of impacts at larger spatial scales (river basin and country levels). However, some finer-scale results are included to reveal effects that can be concealed at coarse spatial scales.

Results

Human Impacts Versus Climate Change. Anthropogenic water consumption results in mean annual runoff decreases of 5% or more in many river basins during the control period (1971–2000) (Fig. 1*A* and *Supporting Information, River Basin Information and Results*). The effect is especially noticeable in heavily irrigated regions at middle latitudes across Asia, and in the western part of the United States. In some river basins in the Middle East, central Asia, and the Indian subcontinent, the median ensemble runoff decrease is more than 15% as a result of water consumption within the river basin. In several other Asian river basins, and in the Colorado, Nile, Orange, Murray–Darling River basins, the ensemble median decrease in runoff resulting from anthropogenic water consumption is between 5% and 15%.

Water consumption always results in runoff decreases, whereas the climate change signal can be in both directions. Climate change affects naturalized runoff in river basins in all parts of the world. Projected runoff decreases are especially noticeable in the Mediterranean area and in the Middle East, but also in Central and South America and parts of Australia (Fig. 1*B*). Runoff is projected to increase at northern latitudes, corresponding to areas with large projected increases in precipitation (13). Runoff increases are also projected in parts of the Arabian Peninsula, the Horn of Africa, and the Indian subcontinent (Fig. 1*B*).

The pattern of the total impacts, i.e., runoff changes caused by both 2 K GMT increase and human impacts (Fig. 1*C*), is dominated by the impacts of climate change alone (Fig. 1*B*). However, noticeable differences exist in southwestern United States and central Asia. To highlight the relationship between the human impacts and climate change effects, differences between the absolute values of the individual impacts are presented (Fig. 2). This comparison shows that, in several river basins, current water consumption affects annual averaged runoff more than climate change (2 K) is expected to impact naturalized runoff. Fig. 2*A* shows the river basins in which the climate signal mitigates the human impact signal to some extent or even exceeds it, e.g., in the Nile River basin. Fig. 2*B* shows the river basins in which the impact of climate change adds to the human impact signal. The combined effect is hence enhancement, e.g., in the Colorado and the Indus River basin.

Despite the locally significant decreases in runoff, anthropogenic water consumption amounts to only 1.3% of median global terrestrial runoff (Fig. 3*A*). Among the world's large river basins, and according to the model ensemble included in this study, the Indus River basin is the most affected by human impacts at the annual level. According to the median ensemble result, as much as 47% of current runoff is consumed within the Indus River basin (Fig. 3*F*). Fig. 3 also shows that the results across the model ensemble for the human impact simulations are significantly different at the river basin level. The interquartile range for the Indus River basin is from 29% to 62%, and the individual model results vary between 18% and 79%. Large intermodel variations are also found in the Huang He River basin (Fig. 3*G*), where the simulated anthropogenic water consumption varies between 7% and 51% of current naturalized runoff. Moreover, for most of the river basins presented, the impact of a 3 K GMT increase is more pronounced than a 2 K GMT increase, both when looking at the total effect of climate change and human impacts and when looking at the decomposed effects separately (Fig. 3). In the Colorado and Mississippi River basins, and in several river basins in Asia, the human impact effect is larger than the climate effect (Figs. 2 and 3). In the Mediterranean area, both the climate and human impact signals are negative, but the climate signal dominates (Fig. 2*B*).

Irrigation Water Consumption and Scarcity. The number of water use sectors included in the results presented so far varies between

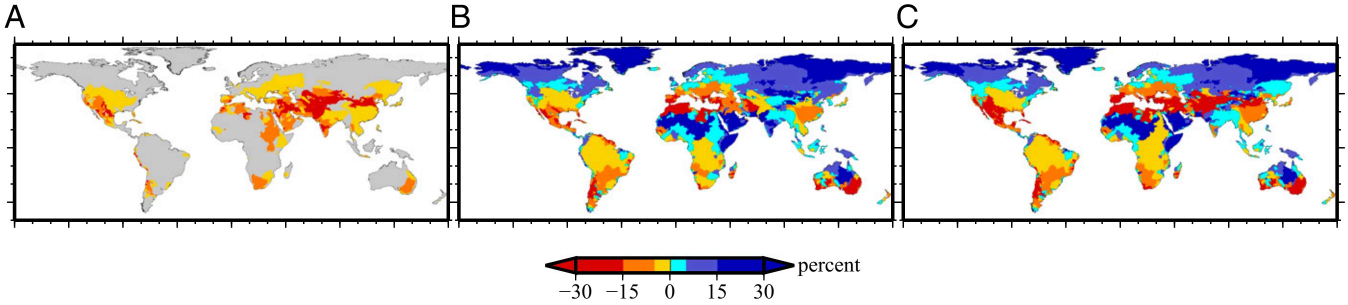

Fig. 1. Comparison of human impact and climate change effects on runoff at the river basin level. Basin averaged runoff values are calculated based on simulated discharge at the outlet of the river basins, and the median ensemble results are shown. (*A*) Control period (1971–2000) human impact simulations compared with control period naturalized simulations. (*B*) Basin averaged naturalized runoff for 2 K GMT increase, compared with control period naturalized simulations. (*C*) Basin averaged human impact runoff for 2 K GMT, compared with control period naturalized simulations.

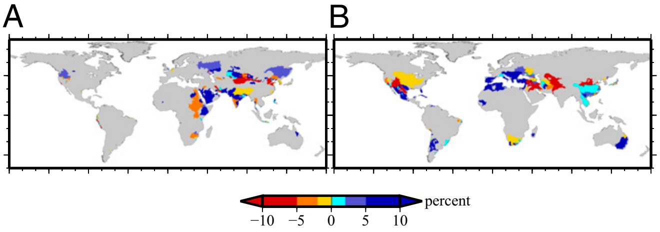

Fig. 2. (*A*) The difference between the absolute values in Fig. 1 *A* and *B* in basins where the human impact and climate signals are opposite, i.e., naturalized runoff increases. (*B*) The differences between the absolute values in Fig. 1 *A* and *B* in basins where both the climate signal and human impact signal are negative, i.e., runoff decreases. The red and yellow colors indicate that the control period human impacts are larger than future climate effects on naturalized runoff.

the different GHMs (*Models and Data*). However, all GHMs include the agriculture sector, i.e., water used for irrigation, which is the largest water consumer globally (7). Here, an index called the cumulative abstraction-to-demand (CAD) ratio (14) is used as a measure of irrigation water scarcity. The higher this number is, the closer the crops are to having their water requirements fulfilled. Thus, a decrease in CAD represents an increase in water scarcity. The highest potential irrigation water consumption numbers (water consumed given water is freely available) during the control period (1971–2000) are found in the Indian subcontinent (Fig. 4*A*). Although the CAD ratio is low in the Indian subcontinent (Fig. 4*B*), actual water consumption (water consumed taking water availability into account) in the area is still considerable, which is reflected in the human impact results for the Indus River basin (Figs. 1*A* and 3).

The CAD ratio is projected to decrease with increasing GMT in most areas where irrigation exists today (Fig. 4*C*), meaning an increase in irrigation water scarcity. The CAD ratio is projected to increase in only a few scattered areas, e.g., western India. This increase in the CAD ratio can be linked to increased water availability in this area (Fig. 1*C*). Fig. 4 reveals some areas impacted by direct human interventions that are not revealed in Fig. 1, because subbasin variations can be concealed when presenting basin averaged results. For example, in parts of the Mississippi River basin, water consumption is considerable, whereas the effect at the basin total level is small (Figs. 1–3). A decrease in the CAD ratio is projected in the United States, southwestern Europe, Pakistan, India, and China (Fig. 4*C*). Some statistics on the impact of 2 and 3 K of global warming on irrigation water in these areas, in addition to the global total numbers, are presented in Fig. 5. The global median potential irrigation water consumption for the entire ensemble (47 members) is 1,171 km^3·y^{-1} in the control period (Fig. 5*A*). The interquartile range for the same time period ranges from 940 to 1,284 km^3·y^{-1}. The corresponding number for the subensemble, i.e., for those models simulating both potential and actual water consumption (29 of the 47 members; *Models and Data*), is 1,174 km^3·y^{-1} (942–1,292 km^3·y^{-1}). These numbers are close to the 1,250 km^3·y^{-1} (±25%) reported previously (8), and represent about 1% of mean annual terrestrial precipitation in the forcing datasets used here, and between 1% and 2% of simulated annual terrestrial runoff.

Substantial differences exist in the ensemble estimates of the amount of potential irrigation water consumed, i.e., when water demands are always met (Fig. 5). However, potential irrigation water consumption will increase with increasing GMT, both globally and regionally (Fig. 5). Irrigation water consumed when water availability is taken into account is more similar across the ensemble, despite the differences in human impact parameterizations (*Models and Data*). Global actual irrigation water consumption increases slightly with increasing GMT (Fig. 5*A*). The projected changes in actual irrigation water consumption are less apparent than the projected changes in potential irrigation water consumption (Fig. 5). The spread in irrigation water consumption numbers for a given time period reflects the spread in human impacts seen for the river basins presented in Fig. 3. More importantly, there is a general agreement that the CAD ratio will decrease in the areas in question, and more so the more GMT increases. The global CAD ratio varies from 0.4 to 0.7 across the simulations, decreasing to 0.35–0.68 at 3 K GMT increase. The corresponding median number decreases from 0.58 to 0.52. The smallest change in the CAD ratio is found in India. Here, increased water availability (Fig. 1) results in almost constant water scarcity, despite a slight increase in potential irrigation water consumption (Fig. 4). Among the areas presented in Fig. 5, the relative decrease in the CAD ratio is most pronounced in southwestern Europe. Here, the control period median CAD ratio is simulated at 0.69, whereas the median result at 3 K GMT is 0.5. Actual irrigation water consumption does not change much with increasing GMT, indicating that the decrease in the CAD ratio for the areas considered is mainly caused by an increase in water demands.

Discussion

The climate effects on naturalized runoff presented here are broadly consistent with results presented elsewhere (3, 4, 12). In large parts of the world, the additional impact on runoff caused by anthropogenic water consumption does not contribute much to the total changes. However, this study emphasizes the importance of taking anthropogenic water consumption into account in areas where direct human interventions are large, and highlights areas where water consumption leads to substantial changes in land surface water fluxes. It has previously been indicated that it is unlikely that irrigation has a significant global-scale impact on the Earth's climate (15), but regional predictions

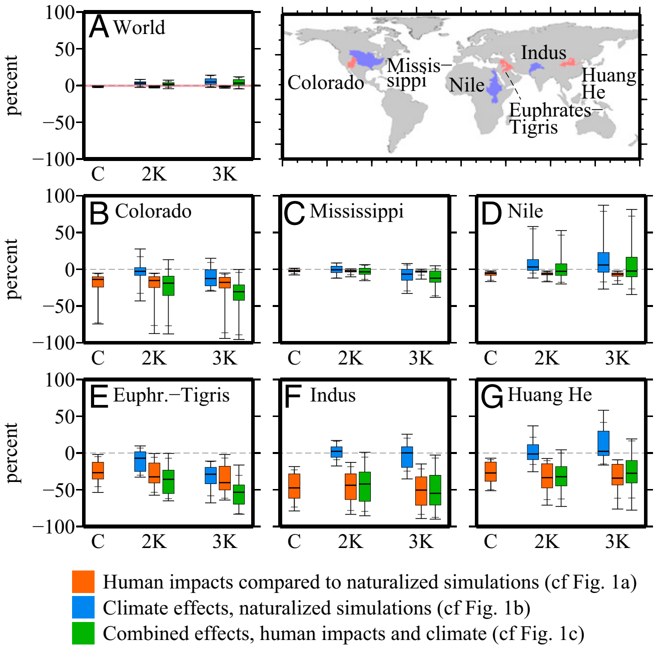

Fig. 3. Box plots of relative changes in runoff for (*A*) the world, (*B*) Colorado, (*C*) Mississippi, (*D*) Nile, (*E*) Euphrates-Tigris, (*F*) Indus, and (*G*) Huang He for the control period (C) (1971–2000), 2 and 3 K GMT increases. The boxes illustrate the 25th, 50th, and 75th percentiles of the ensemble (47 members). The whiskers represent the total sample spread, and in addition the 5th and 95th percentiles are marked. The human impact results (orange bars) are compared with the naturalized simulations during the same time period, e.g., 2 K human impacts are compared with 2 K naturalized simulations. All climate and combined effects (blue and green bars) are compared with the control period naturalized simulations.

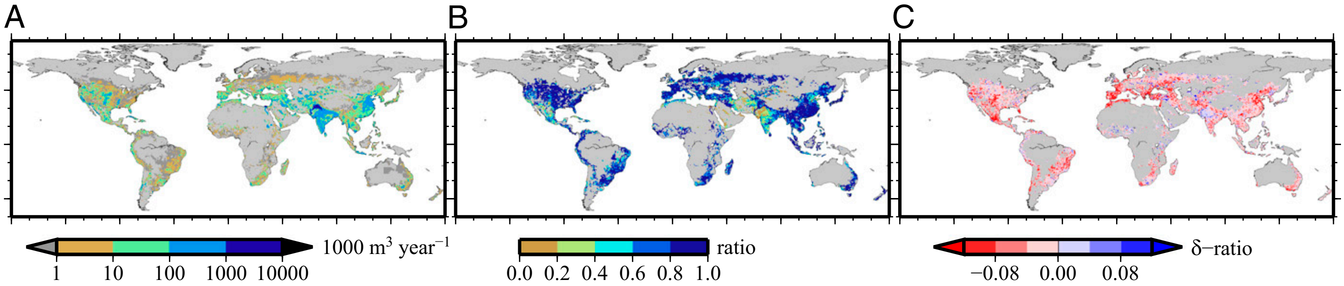

Fig. 4. Irrigation water consumption and cumulative abstraction-to-demand (CAD) ratio at the grid cell level. (*A*) Ensemble median potential irrigation water consumption, control period (1971–2000). Light gray color represents areas where there is no, or very little, irrigation. (*B*) Ensemble median CAD, control period. (*C*) Differences in CAD between the control period and the 2 K GMT increase period. Negative numbers mean the CAD ratio decreases.

within global climate models can be improved by taking into account local-scale processes (15).

Surface water evaporation from man-made reservoirs and reservoir operations causing seasonal regime shifts across multiyears can cause slight changes in annual runoff numbers. However, reservoirs influence the shape of the hydrograph profoundly in many areas of the world and seasonally impact discharge much more than the reduction caused by water consumption (16, 17). Seasonal changes in discharge caused by storing and releasing of water in reservoirs are not presented in this study, which focuses on annual runoff numbers. Also, because only annual results are presented, it is not revealed whether water scarcity is constant over the time period considered, or whether interannual or intraannual variations exist. The reservoir storage capacity within a river basin indirectly impacts annual runoff numbers through its ability to accommodate seasonal variations in flow volume and hence to satisfy irrigation water requirements. This effect has not been specifically studied here, but it has previously been indicated that nearly one-half of the irrigation water extracted globally originates from reservoirs built for irrigation purposes (16).

The model ensemble indicates that irrigation water scarcity is expected to increase with increasing GMT. About 40% of total agricultural production relies on irrigation (18). In light of this, the increase in water scarcity and potential decline in food production could affect people worldwide through food price changes on the global market (19). In areas with a projected increase in irrigation water scarcity, and hence possible decreases in food productivity, adaptation measures need to be addressed. To increase food production, better water management and improved irrigation practices (reduced losses) have been suggested (8). Irrigation area expansion in regions with sufficient freshwater is also projected to increase food production (20). These issues must all be discussed in light of other water demands, including environmental flow requirements (8).

The areas for which irrigation water consumption and water scarcity are presented in Figs. 4 and 5 do not overlap directly with the river basins presented in Figs. 1–3. However, Figs. 4 and 5 still indicate that, if more water was available for use, the anthropogenic impacts on river basin runoff seen in Figs. 1–3 would have been even larger. The range in estimates in Fig. 3 is a result of both differences in the baseline runoff (naturalized simulations) and amount of water consumed. Parameterization differences among GHMs that influence naturalized simulation results (9) will subsequently influence the human impact simulations. Reservoir operations and water withdrawal parameterizations further influence the results and contribute to the rather large differences (Figs. 3 and 5). The largest relative runoff decreases for the human impact simulations in the Colorado River basin, for example, originate from the hydrologic model simulating the lowest naturalized runoff and among the highest water consumption numbers within the river basin. In other areas, e.g., in the Indus and Huang He River basins, the differences are also influenced by whether or not multicropping is taken into account in the hydrologic model.

It should be noted that none of the models considers water transportation between river basins, e.g., water transported from the Colorado River basin to California, and groundwater extractions are poorly represented in most models. Hence, the actual irrigation water consumption numbers might be somewhat underestimated. However, three of the GHMs assume that anthropogenic water demands are always met (*Models and Data*). Furthermore, not all models take into account water consumption in sectors other than agriculture, although the impact may be small because those sectors currently account for only a small fraction of the total. In addition, irrigation water withdrawals and consumption depend on the

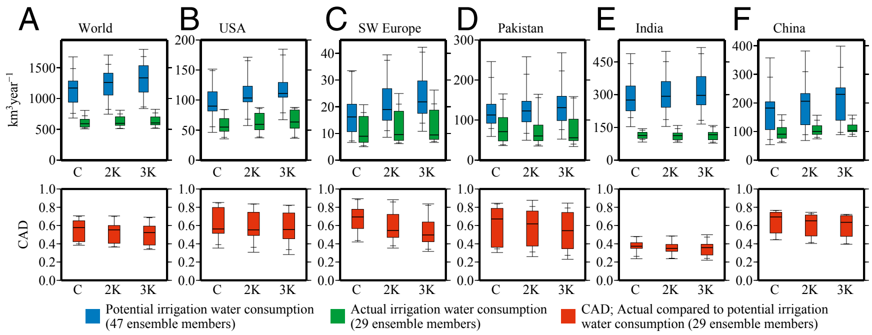

Fig. 5. Ensemble statistics on irrigation water consumption for the control period (C) (1971–2000), 2 and 3 K GMT increases for (*A*) the world, (*B*) United States, (*C*) southwest Europe (here comprising Portugal, Spain, and France, (*D*) Pakistan, (*E*) India, and (*F*) China. The upper panels show annual potential and actual irrigation water consumption. The lower panels show CAD, i.e., the relationship between the actual and potential irrigation water consumption. The boxes illustrate the 25th, 50th, and 75th percentiles of the ensemble. The whiskers represent the total sample spread, and in addition the 5th and 95th percentiles are marked.

Table 1. Hydrologic models

Model name	Human impact parameterizations
H08 (27)	Two-purpose reservoir scheme (irrigation and nonirrigation). Potential and actual irrigation water withdrawals and consumption. Irrigation water extracted from nearby river. Actual industrial and domestic water withdrawals and use. Water withdrawals and consumption for industrial and domestic sectors (16, 27).
LPJmL (28)	Multipurpose reservoir scheme. Potential and actual irrigation water withdrawals and consumption. Irrigation water extracted locally and from reservoirs. Actual water withdrawals and consumption in other sectors taken from WaterGAP estimates (17, 29).
MPI-HM (30)	Potential irrigation water consumption. Irrigation water extracted from nearby river and from a hypothetical aquifer if needed. No reservoirs. No published references.
PCR-GLOBWB (31)	Two-purpose reservoir scheme (water supply and nonwater supply). Potential and actual irrigation water withdrawals and consumption. Irrigation water extracted locally from surface water and groundwater, and from reservoirs. Potential water withdrawals and consumption for domestic and industrial sectors (31, 32).
VIC (33)	Multipurpose reservoir scheme. Potential and actual irrigation water withdrawals and consumption. Irrigation water extracted from nearby river and from reservoirs (34).
WaterGAP (35)	Two-purpose reservoir scheme (irrigation and nonirrigation) (16). Potential irrigation water withdrawals and consumption (36). Potential water withdrawals and consumption for domestic and industrial sectors (37).
WBMplus (21)	Reservoir operation is a function of current inflow compared with long-term inflow. Potential irrigation water withdrawals and consumption. Irrigation water extracted locally (small local reservoirs, groundwater and nearby river) (21).

LPJmL, Lund-Potsdam-Jena managed land dynamic global vegetation and water balance model; MPI-HM, Max Planck Institute – hydrology model; PCR-GLOBWB, PCRaster global water balance model; VIC, variable infiltration capacity macroscale hydrologic model; WaterGAP, water – a global assessment and prognosis model; WBMplus, water balance/transport model.

irrigation map used (21). These differences in human impact parameterization clearly contribute to the spread in runoff changes and water consumption numbers, in addition to naturalized simulation differences. In addition, both GCMs and GHMs contribute substantially to the spread in future projections (3, 12).

Only climate change effects on water demands and consumption are accounted for in this study, whereas other variables, such as irrigated area and irrigation efficiencies are kept constant at the year 2000 level. Also, the indirect effect of rising CO_2 concentrations on runoff and irrigation water consumption through its direct effect on evaporative demand is not considered. Increasing CO_2 can lead to lower irrigation water demands (20, 22). However, nutrient limitations may influence crop growth. The combined effect on crop growth, irrigation water demands, and resulting food production is still somewhat uncertain (22). The positive trend in potential irrigation water consumption presented here is more profound than for specialized crop models (20). Possible reasons for this lie in the different representation of agricultural land and agrohydrological processes in the models (20). These and other impacts on the hydrological cycle should be addressed in future hydrological model developments and multimodel studies. Note also that bias correction has been applied to the GCM data (23, 24). The assumptions and implications of bias correction on forcing data used in hydrological simulations are thoroughly discussed in the study by Ehret et al. (25). Bias correction can impact present-day simulated runoff numbers strongly, but the impact on projected relative water flux changes, which is the focus in this paper, are much smaller (23, 26).

Conclusions

Based on a large ensemble of simulations using eight GCMs and seven GHMs, this study provides a comprehensive assessment of the effects of climate change and direct anthropogenic disturbances on the terrestrial water cycle. Despite considerable spread in the individual results, a number of robust conclusions can be drawn at the regional and global scale. The results indicate that the impacts of man-made reservoirs, water withdrawals, and water consumption on the long-term global terrestrial water balance are small. However, impacts of anthropogenic interventions are significant in several large river basins. In particular, in irrigation-rich areas in Asia and in the western United States, the effect of current anthropogenic interventions on mean annual runoff is stronger than the projected changes for a 2 or 3 K increase in GMT. Climate change tends to increase potential irrigation water consumption on currently irrigated lands with further detrimental effects in regions with significant irrigation. The climate change signal on runoff can be positive or negative, and hence has the potential to alleviate or aggravate irrigation water scarcity. Globally,

Table 2. First year of 30-y periods for each GCM and mean GMT increases above preindustrial level

Mean GMT increases	CMIP3–A2			CMIP5–RCP8.5				
	CNRM-CM3	ECHAM5/MPI-OM	IPSL-LMDZ-4	GFDL-ESM2M	HadGEM2-ES	IPSL-CM5A-LR	MIROC-ESM-CHEM	NorESM1-M
+2 K	2037	2041	2032	2039	2016	2019	2018	2032
+3 K	2058	2059	2055	2068	2036	2039	2037	2058
GHM simulations	*H08, LPJmL, VIC*, WaterGAP			*H08*, *LPJmL,* MPI-HM, *PCR-GLOBWB, VIC,* WBMplus, WaterGAP				

The table includes information on which GCM–GHM combinations that have been simulated (ensemble size is 47). GHM names in italics denote those that have performed both the actual and potential human impact simulations (ensemble size is 29). CMIP3-A2, Coupled Model Intercomparison Project 3, A2 emission scenario; CMIP5-RCP8.5, Coupled Model Intercomparison Project 5, Representative Concentration Pathway 8.5; CNRM-CM3, Centre National de Recherches Météorologiques Coupled global climate Model, version 3; ECHAM5/MPI-OM, European Centre for medium range weather forecasts, HAMburg, version 5, Max Planck Institute for meteorologi, Ocean Model; IPSL-LMDZ-4, Institut Pierre Simon Laplace, Laboratoire de Meteorologie Dynamique, Zoom capability, 4th assessment report; GFDL-ESM2M, Geophysical Fluid Dynamics Laboratory, Earth System Model version 2, Modular ocean model; HadGEM2-ES, Hadley centre Global Environment Model version 2, Earth System model; IPSL-CM5A-LR, Institut Pierre Simon Laplace, CMip5 version A, Low Resolution; MIROC-ESM-CHEM, Model for Interdisciplinary Research on Climate, Earth System Model, Chemistry; NorESM1-M, Norwegian Earth System Model version 1, interMediate resolution.

the relationship between actual and potential irrigation water consumption is expected to decrease, indicating an increase in irrigation water scarcity.

Models and Data

Seven GHMs are included in this study. The nature and magnitude of human disturbances at which direct anthropogenic impacts like dams, water withdrawals, and water consumption are included in the models vary (Table 1 and *Supporting Information, SI Models and Data*). All models were forced with climate data from a total of eight GCMs included in the Coupled Model Intercomparison Project 3 (CMIP3) and CMIP5 archives (Table 2). CMIP3 data were prepared for the hydrological model simulations within the WATCH project (3, 23), and the CMIP5 data were prepared for ISI-MIP (24). Included in the analyses presented here are results when using forcing data from the A2 emission scenario (CMIP3 models) and RCP8.5 (CMIP5 models). Thirty-year periods of GMTs at 2 and 3 K above preindustrial level are extracted from the GCMs (Table 2). The control period (1971–2000) is assumed to be 0.4 K above preindustrial level for all GCMs.

All hydrological models are run at a daily time step at a spatial resolution of 0.5° latitude by longitude, and runoff is routed through the DDM30 river network (38). Simulation results are submitted for the period 1971–2099. Not all GHMs are run using input data from all GCMs (Table 2). Simulated discharge at the basin outlets are used when calculating basin averaged, or world total, runoff numbers. In this paper, potential water consumption represents water consumed given water is freely available. All models included in the study simulate this quantity. Four of the models—H08, the Lund-Potsdam-Jena managed land dynamic global vegetation (LPJmL), the PCRaster global water balance model (PCR-GLOBWB), and the variable infiltration capacity macroscale hydrologic model (VIC)—also simulate actual water consumption, which is defined as water consumed when water availability is taken into account. The CAD ratio (14) is used as a measure of irrigation water scarcity (*Supporting Information, Glossary*). Both actual and potential irrigation water consumption are calculated at a daily temporal resolution, and hence subannual variations are imbedded in the final CAD numbers.

Annual runoff and water consumption numbers are calculated for each GCM–GHM combination independently, creating an ensemble of up to 47 annual time series for the period 1971–2099. Differences between simulations are thereafter calculated for each time period of interest (Table 2) for each ensemble member. Finally, median numbers and other statistic measures are calculated. All results are treated equally, and no attempt to give weights to GCMs or GHMs based on performance has been made.

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