Human induced changes in the global water cycle

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1.0 Introduction

Humans have heavily impacted the land surface. Perhaps the greatest manifestation of human alterations is land cover change. *Hooke and Martin-Duque [2002]* estimate that over 50% of the land surface globally has been affected by man's activities. Other estimates are much higher. *Sanderson et al. [2002]* estimate, for instance, that "Overall, 83% of the land's surface, and 98% of the area where it is possible to grow rice, wheat, or maize is directly influenced by human beings." These changes affect the water cycle in a number of ways. Changes in vegetation (or between vegetated and non-vegetated, e.g., urban areas) change evapotranspiration. Changes in land cover also affect the runoff response, for instance less permeable (or impervious) surfaces result in more rapid runoff response during storms, and generally reduced infiltration (hence groundwater recharge). Land cover change can also affect channel network characteristics and in turn runoff response.

A more direct means by which humans have affected the water cycle is through construction of water management structures. These range from channel modifications (generally to protect riverside property and/or for flood management) to river diversion structures (e.g., the massive All American Canal between Arizona and Southern California, which diverts almost 6 km^3 of water per year from the Colorado River Basin), to dams and reservoirs. Globally, the total constructed reservoir storage capacity is estimated to be around 7000 km^3 *[Vörösmarty et al. 2003; Hanasaki, et al. 2006]*, or about 1/5 of average annual global river runoff *[Vörösmarty et al. 1997; White, 2005]*. These reservoirs have vastly changed the variability of runoff in many of the world's rivers, at time scales ranging from daily (or less) to seasonally and interannually. *Vörösmarty and Sahagian [2000]*, for instance, showed the aging of water in the largest rivers of the world; water now takes as much as three months longer to reach the mouths of some of the largest rivers than it did prior to dam construction, and most of the largest rivers have experienced increases in aging of at least a month. This increased aging has a number of deleterious consequences, including substantial reduction in transport of sediment through the river systems which support the hydro-ecological functioning of river systems; reduction of transport of nutrients which provide critical support for life forms in the river mouth plumes of the rivers; change in predator/prey dynamics (especially near the outlet of major reservoirs); and alteration in streamside vegetation (due to changes in bank erosion and other manifestations of streamflow variability).

Despite the widespread use of reservoir models for planning of water management at seasonal and longer time scales, the effects of reservoirs on rivers at continental and global scales have only recently been studied. *Hanasaki et al. [2006]* implemented a generic global reservoir model that inferred operating strategies based on the seasonal cycle of unregulated streamflow, and reservoir size. They assumed that the primary operating purpose of all reservoirs was agricultural or domestic water supply. *Haddeland et al. [2006; 2007]* developed a generic reservoir operations model based on three primary reservoir uses: agricultural water supply, hydropower generation, and flood control. The model was implemented over North America and most of Eurasia using information available in the *ICOLD [2003]* World Register of Dams and *Vörösmarty et al. [1997; 2003]*. The authors point out that while the generic reservoir model cannot reproduce details of specific systems given the generic rules, their model does reproduce long-term variations in streamflow at the mouths of the Colorado and Mekong Rivers.

In addition to their direct effects on river discharge, the storage of river discharge has had a substantial effect on global sea level rise as newly constructed reservoir storage (mostly during the 2nd half of the 20th century) has filled. *Lettenmaier and Milly [2009]* for instance, estimate that this effect reduced global sea level by about 0.5mm/yr, or roughly 15% of net sea level increase during the period of maximum reservoir construction in the mid-20th century.

In this paper, we review the status and results of modeling-based estimates of the water management impacts on global runoff. We summarize estimates of global consumptive use of water, from both modeling-based and accounting-based studies. We also review the best current understanding of interseasonal and interannual variations in reservoir storage globally based on model estimates.

2.0 Macroscale water management models and intercomparisons

As noted above, models that are capable of representing the effects of water management at large scales are a recent development. Model intercomparisons have been used to evaluate the performance of such models, and to create consistent and comprehensive simulation results based on standardized simulation protocols. Two such recent projects are WaterMIP (Water Model Intercomparison Project; *Haddeland et al., 2011*) and ISI-MIP (Inter-Sectoral Impact Model Intercomparison Project; *Warszawski et al., 2014*). These projects (which in a sense are an evolution of the same effort) were intended to analyze, quantify and predict components of the current and future global water cycles and related resources as they are and have been affected by water management activities. As shown in Table 1, many of the participating models take into account anthropogenic impacts such as water withdrawals and dams. Comparisons of these models with model setups that represent the "natural" hydrologic systems offer the opportunity to assess the effects at large scale of water management activities. In both WaterMIP and ISI-MIP, the spatial resolution of the simulations was 0.5 degrees latitude-longitude, and the modeling domain was the global land area as defined by the Climate Research Unit of the University of East Anglia (CRU) global land mask. The global river channel network as represented for purposes of streamflow routing was the DDM30 river network of *Döll and Lehner [2002a]*.

In WaterMIP, the extent of irrigated areas was kept constant (at 2000 levels) throughout the simulation period. The hydrological models used global maps of irrigated areas as shown in Figure 1 *[based on Siebert et al. 2005]*. Global potential irrigation water consumption (defined as water that would be consumed by the irrigated areas if the water supply, when added to water from precipitation, was unlimited) was estimated based on results simulated by the models for the period 1985-1999. Model meteorological forcing data were from the so-called WATCH data set described by *Weedon et al. [2011]*. As shown in Figure 2, the models' estimated mean potential irrigation water consumption globally ranged from about 1000 km^3/yr to about 1500 km^3/yr.

The results shown in Figure 2 for Eurasia and North America as well as the global totals are dominated by the largest areas equipped for irrigation. The Indian subcontinent and China account for most of the Eurasian total, while the U.S. accounts for most of the North American total (Figure 1. It is not surprising that the hydrological models simulate the highest potential irrigation water consumption in these areas (see also Figure 3). The irrigation water demand on the Eurasian continent accounted for more than 70 percent of the global total in all model estimates (Figure 2). North America was second in irrigation water consumption, with 10 to 15 percent of the global total numbers. Hence, these two continents are responsible for up to 90 percent of the global total potential irrigation water consumption. High irrigation demands were also found on the Iberian Peninsula, in the lower reaches of the Nile River basin, and to a smaller degree in Australia.

The global pattern of irrigation water consumption, represented by the model mean numbers in Figure 3a, is fairly similar among the models. Some inter-model differences exist, though, and these are reflected in the coefficients of variation (CV) shown in Figure 3b. In general, the inter-model differences are small in areas with high irrigation water demands, and larger in areas with lower irrigation water demands. Some of these differences are likely caused by discrepancies among the irrigation maps and cropping calendars used by the models (which varied somewhat from model to model). However, parameterization choices in the models' representation of water withdrawals and use, and other assumptions as to the physics incorporated in the models, lead to dissimilarities in evaporative demand and soil moisture levels, and these also influence irrigation water consumption. In addition, there are major differences among the models in the seasonal distribution of irrigation water consumption (Figure 4). The WaterGAP, LPJmL and MPI-HM models assume one cropping period per year, but use different methods when defining this period. H08 and VIC have the option of including multiple cropping periods if desired, and globally this leads to two distinct irrigation water consumption peaks (Figure 4).

Water storage, water withdrawals and consumption affect annual evapotranspiration and runoff volumes. It has previously been demonstrated that, in some river basins, human interventions can have larger impacts on the annual water cycle than does climate change (e.g., +2K global temperature rise, see *Haddeland et al. 2014*). However, both climate change and (direct) human interventions in the water cycle have much larger manifestations on water fluxes at the seasonal as compared with the annual level. This is demonstrated clearly in Figure 5, which shows monthly streamflow at the outlet of two river basins for a control period (1971-2000) and a future period with +2K temperature increase. The simulation results shown in the figure represent naturalized streamflow as well as streamflow where human interventions (both the effects of man-made reservoirs and water withdrawals) were taken into account. Four of the five hydrological models summarized in Table 1 are included (MPI-HM was excluded because it does not represent reservoirs). Output from eight global climate models, bias corrected to the WATCH forcing data *[Weedon et al., 2011]*, were used to force the hydrological models in both naturalized and human impact modes. More information on these simulations, and results at the annual level, can be found in *Haddeland et al. [2014]*.

Not surprisingly, water consumption always results in decreased streamflow volumes, whereas reservoir operations usually reduce seasonal variations in streamflow. On the other hand, the climate change signal can be in both directions. In the Indus River basin, for instance (Figure 5a), the human impact signal is much larger than the climate signal throughout the year, and is a result of extensive water consumption within the basin. In the Colorado River basin (Figure 5b), the impact of climate change adds to the human impact signal at the annual scale, and the combined effect is enhancement. However, the signal varies throughout the year, and in some months the climate signal is in the opposite direction of the human induced signal. In general, the climate and human impact signals for each model show similar behavior, but the magnitude of the signals vary (not shown). Differences in evapotranspiration, runoff and snow parameterizations, which are major contributors to the model spread for the naturalized simulations in the control period, will inevitably impact the inferred climate signal (see e.g. *Hagemann et al. [2011]* and *Schewe et al. [2014]*). Subsequently, these differences impact both the need for, and availability of, water for irrigation. Inter-model differences in assumptions about reservoir operations and cropping calendars also contribute to the model spread.

Most of the models that participated in WaterMIP and ISI-MIP take into account water availability when simulating streamflow, meaning that human-induced impacts depicted in Figure 5 might be larger if water was not a limited resource. 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. Also, groundwater extractions are poorly represented in most models. According to *Gornitz [2000]*, groundwater withdrawals account for about 30 percent of global water withdrawals, and hence the effect of irrigation water consumption on streamflow is most likely somewhat underestimated in both WaterMIP and ISI-MIP. On the other hand, the models assume that the water needed to meet irrigation demand in the areas equipped for irrigation is derived from surface water, thus fulfilling some of the irrigation demand that is served by groundwater sources in the real world. Consequently, while the source of the irrigation water may be incorrect in some cases, the total water used for irrigation should be represented properly.

3.0 Global consumptive use of water

Consumptive use of water can be defined as the additional amount of water that is evaporated and transpired because of human intervention (and that otherwise would not be evaporated). In the models summarized in Section 2.0, this is the amount of irrigation water applied, since the simple irrigation algorithms used in these models do not account for return flows. The return flows account for excess water that is applied, but which is not transpired or evaporated (the application of excess water is required in many situations to avoid the buildup of salts in soils). Our main focus here is the human impacts on the entire water cycle, hence we are interested in the total water consumption from all water uses including not only irrigation, but other agricultural practices (e.g., livestock), as well as municipal and industrial withdrawals. In Table 2, we synthesize the findings from WaterMIP and ISI-MIP as well as previous studies of global water use over the past ~40 years (Table 2).

The previous studies mostly focus on four variables related to water use: 1) irrigation withdrawal (IW), which is the amount of irrigation water diverted from the source; 2) irrigation consumption (IC), which is the amount of irrigation water reaching the field and eventually transpired by the crops; 3) total withdrawal (TW), which is IW plus livestock, municipal and industrial water withdrawals; and 4) total consumption (TC), which is the portion of water withdrawn for all sectors that is not returned to the original water source.

The studies summarized in Table 2 can be grouped into two different types based on the approaches they use to estimate water withdrawals and consumption: accounting-based approaches and modeling-based approaches. The accounting-based approach attempts to estimate water used by for different sectors to satisfy the needs per person and year for food, drinking water, and industrial purposes. In many cases, these studies also attempt to project future water needs (usually as TW). Due to their assumptions about future population, crop land, GDP, and industrial water growth, the TW estimated from accounting-based studies vary widely (over a range from -50% - +100% based on different assumptions) *[Gleick 2003]*. For example, the very high TW (>6000 km^3/yr) accounting-based estimate from *Falkenmark and Lindh [1974]* is projected to 2015 (from 1974) on the basis of a population estimate of 8.15 B, and estimates of water use globally that correspond to a standard of living in the industrialized countries.

Modeling-based approaches began to appear from about 2000 on, and as in Section 2.0, they simulate global irrigation water requirements using models based on climate, cropping intensity, crop types, and (in some models) water availability. In general, the results from model estimates are somewhat lower than those from the accounting-based estimates, whereas the estimates published from the various modeling studies are roughly similar – that is, the differences between accounting and modeling estimates are generally larger than those among modeling studies. This might be attributable to 1) water availability is considered in most of the models which limits irrigation water use; 2) the irrigation maps used in the modeling studies come from the same or similar sources. It may be, therefore, that there is a common bias in the estimates of irrigation area used in the modeling studies; 3) the model structures are somewhat similar, and in the various studies the models have been forced by the same or similar climate data.

We focus primarily on irrigation water consumption because a) other sources of water consumption are not represented in the models, and b) IC accounts for most of TC (about 90% according to *Shiklomanov [2000]* and *Rost et al. [2008]*). Hence, TC can be estimated reasonably accurately from IC. In cases where IC was not available, IW was used to estimate IC based on the average IC/IW ratio (about 0.5) derived from previous estimates or forecasts across late 20th century to early 21st century (Table 2 taken from *Postel et al. [1996]; Döll and Siebert; [2002], Hanasaki et al. [2006]; Rost et al. [2008]; Döll et al. [2009]; Wada et al. [2011]; and Pokhrel et al. [2012]*). As shown in Table 2, our estimated global TC from the modeling studies is about 1300 km^3/yr, and from the accounting-based methods is almost

2600 km^3/yr (projected from TW using averaged TC/TW taken from *Postel et al. [1996] and Shiklomanov [1998, 2000]*), or nearly double the modeling results. Here we use the median rather than the mean in both cases to minimize the effects from outliers. Note that although the variation across the modeling-based estimates is smaller than for the accounting-based methods, the water consumption estimates from a single model can vary by as much as ±30% depending on the selection of climate forcing and irrigation maps *[Wisser et al. 2008]*.

4.0 Reservoir contributions to global land surface water storage variations

In Section 3.0, we compared modeling-based studies of water withdrawals and consumption on continental and global scales. In this section we analyze global reservoir storage, which is another important component of human-induced changes in the water cycle. We simulated the seasonal variation of global reservoir storage during the past half century and compared with natural storage variations including soil moisture and snow based on results from one of the models (VIC) that participated in the two studies (WaterMIP and ISI-MIP) summarized in Section 2.0. *Zhou et al. [2015]* provide details of the study from which the results summarized below are taken.

The reservoir model (see *Haddeland et al. [2006, 2007]* for details) used here includes a soil-moisture-deficit-based irrigation scheme (as in the VIC results reported in Section 2.0), and a reservoir module which optimizes dam releases based on multiple dam functions, including irrigation, hydropower, flood control, and (municipal and industrial) water supply. As in *Zhou et al. [2015]*, we focus on 32 global river basins which include a total of 166 reservoirs using simulations for the 63-year period 1948 to 2010, at a daily time step. The spatial resolution was 0.25 degree (Figure 6), which is double the 0.5 degree spatial resolution used in WaterMIP and ISI-MIP. The simulated reservoirs were selected based on their capacity (> 3 km^3) and the drainage area of the river basins (> 600,000 km^2). The 166 reservoirs have a total capacity of 3900 km^3, or nearly 60% of the global total as estimated by White (2005). The percentage of irrigated area and the crop calendar used to specify irrigation demand were obtained from the International Water Management Institute (IWMI) Global Irrigated Area Mapping (GIAM) database *[Thenkabail et al., 2009]*, which is different from the one used in the WaterMIP project. We determined the primary uses of each reservoir from the Global Reservoir and Dam (GRanD) database *[Lehner et al., 2011]*. The reservoir storage time series, as well as other natural storage terms simulated by VIC including soil moisture (aggregate of three soil layers), and snow water equivalent (SWE) were averaged to monthly, and were analyzed for each basin.

We evaluated the simulated storage variations for 23 of the 34 reservoirs for which satellite-based estimates or reservoir storage variations were reported by *Gao et al. [2012]* based on a combination of satellite altimetry elevations and surface area from Moderate Resolution Imaging Spectroradiometer (MODIS) image classifications. The seasonal storage variation comparisons (Figure 7) suggest that the simulated seasonal cycle was in general agreement with the satellite-derived estimates in both magnitude and variability.

Based on the storage changes simulated for the 166 reservoirs, we estimated the total reservoir storage change for each basin by projecting the simulated reservoir storage values to the total reservoir storage values within that same basin (i.e., including those not simulated) using a simple multiplier. The inferred seasonal reservoir storage variations from reservoirs (man-made) were then compared with combined SWE and soil moisture storage (natural) for each basin (Figure 8). A term F was computed to represent reservoir storage variation as a fraction of natural storage variation for each basin. Here the term "variation" denotes the difference between the maximum and minimum values of the mean seasonal cycle.

The results show that the F value varies strongly among the basins. For instance, in some relatively dry and intensively regulated basins such as the Yellow River basin, F was as large as 0.72. Other basins with large F values are the Yangtze, Nelson, Krishna, Indus, Volga, and Yenisei. In most of these basins (with F values ranging from 0.2 to 0.5), dams were built for either hydropower or irrigation purposes. In contrast, for a number of the basins, reservoir storage variations are negligible compared to the natural storage terms. These appear to be cases where a) the drainage areas are relatively large and reservoir storage capacity, expressed as a spatial average, is small (e.g. Mississippi, Nile); b) relatively small installed reservoir storage capacity compared to runoff (e.g. Mekong); or c) both (e.g. Amazon, Lena).

From a global perspective, we compared the seasonal reservoir storage with VIC-simulated seasonal natural storage (SWE and soil moisture) for the five continents as well as the Northern and the Southern Hemisphere separately due to the reversed seasonality (see Figure 9, re-plotted from Figure 9 of *Zhou et al. [2015]*). For each continent, the simulated reservoir storages were aggregated and extrapolated to the entire continent by multiplying a projection factor P (P = total reservoir capacity in the continent/simulated reservoir capacity in the continent). The results suggest that the largest (>90% of total) seasonal storage variations in South America, Africa, and Australia are from soil moisture. In contrast, reservoir storage variations are very low (<3mm) for these continents because reservoir capacity is small compared to the mean annual flow in most of the large basins in these continents. SWE variations are almost negligible in the Southern Hemisphere continents. North America and Eurasia have similar patterns for the three storage components with the largest storage variation from seasonal snow (60 mm in North America and 45 mm in Eurasia), followed by soil moisture (40 mm in North America and 12 mm in Eurasia). The reservoir variation is the smallest contributor to storage variations in both continents with about 10 mm in North America and 7 mm in Eurasia. Compared to the combined natural storage variations, reservoir variations as a fraction are about 10% in North America and 15% in Eurasia.

In the Northern Hemisphere (excluding Greenland), the reservoir storage variation is about 6.3 mm, equivalent to about 40% of the soil moisture variation and 17% of the SWE variation, or 22% of the combined natural storage variation. Note that all variations presented here are differences between seasonal maximum and minimum values, which means that if the SWE and soil moisture have different seasonalities, the variation of the combined natural storage might be less than that for one of the components (SWE in this case). In the Southern Hemisphere (excluding Antartica), the reservoir storage variation is 3.5 mm, or about 2.5% of the soil moisture variation. Because the Southern Hemisphere has little snow and the result is areally-averaged, the simulated SWE variation is only 0.03 mm, as the snow storage is essentially negligible in the Southern Hemisphere.

During the second half of the 20th century, an estimated 33,000 reservoirs were constructed globally *[ICOLD, 2003]*, and about 7000 km^3 water was impounded *[Vörösmarty et al. 2003, Hanasaki, et al. 2006]*. Our simulated monthly global reservoir storage time series suggests that the mean absolute inter-annual storage variation, which quantifies the global reservoir storage change between every two consecutive years, is about 89 km^3. This is quite small as a fraction of total storage probably because most reservoirs are operated on a fixed seasonal cycle (especially if reservoir storage is less than the mean annual flow of the river on which it is located in which case its purpose is primarily for seasonal flow regulation). The relatively small total interannual variation also probably results in part from global averaging in the same way that variations in total global precipitation or runoff are relatively small.

We also calculated the total mean annual potential irrigation water consumption (IC, as defined in Section 3.0) for the 32 basins, which is about 780 km^3/year. In some highly agriculturalized basins, such as the Brahmaputra-Ganges and Yangtze, the mean annual potential irrigation water consumption is as high as 200 km^3/year, while this number is negligible in some under-developed basins such as the Lena and Amazon. Given that the area equipped for irrigation in the 32 basins is approximately 48% of the global irrigation area (according to FAO Global Map of Irrigation Areas (GMIA) V5.0), the extrapolated total global potential irrigation consumption is about 1600km^3/yr, which is slightly higher than the high end of the range reported in the WaterMIP project (1000-1500km^3/yr). The model we used here (VIC) is one of the participating models of WaterMIP and ISI-MIP projects, however the applications of different spatial resolution, climate inputs, and soil parametric settings could account for the differences in global potential irrigation consumption estimates, and the extrapolation doubtless plays a role as well.

5.0 Conclusions

We have reviewed current knowledge of how human effects on global water cycle dynamics through a) water consumption for irrigation, municipal, and industrial purposes, and b) water management structures. Our main findings are:

1) Based on two recent multi-model estimates (WaterMIP and ISI-MIP) global irrigation water consumption estimates range from about 1000 to 1500 km^3/yr, of which more than 90% is contributed by Eurasia and North America.

2) Comparisons of the model-based estimates (from current WaterMIP, ISI-MIP, and other recent modeling studies) with accounting-based estimates indicated that the model-based estimates of total global water consumption (including irrigation, and inferred industrial and municipal water use) are approximately half of the (mostly earlier) accounting-based estimates (median from the modeling-based studies is about 1300 km^3/yr).

3) Dam constructions impounded ~7000 km^3 water globally in man-made reservoirs over the past ~75 years. Based on model results, the seasonal signature of reservoir storage relative to combined soil moisture and snow storage is about 22% in the Northern Hemisphere (and as high as 70% for some intensively regulated basins such as Yellow River basin), but is much smaller (about 2.5%) for the Southern Hemisphere.

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Table 1: Parameterization of human impacts in the hydrologic models (after *Haddeland et al., 2014*). The institution names identifies what modeling group was responsible for the simulation results included here.

Model name	**Human impact parameterizations**
H08 (National Institute for Environmental Studies, Japan)	Two-purpose reservoir scheme (irrigation and non-irrigation). 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.
LPJmL (Potsdam Institue for Climate Research, Germany)	Multi-purpose 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.
MPI-HM (Max Planck Institute for Meteorology, Germany)	Potential irrigation water consumption. Irrigation water extracted from nearby river and from a hypothetical aquifer if needed. No reservoirs.
VIC (Norwegian Water Resources and Energy Directorate, Norway)	Multi-purpose reservoir scheme. Potential and actual irrigation water withdrawals and consumption. Irrigation water extracted from nearby river and from reservoirs.
WaterGAP (University of Kassel, Germany)	Two-purpose reservoir scheme (irrigation and non-irrigation). Potential irrigation water withdrawals and consumption. Potential water withdrawals and consumption for domestic and industrial sectors.

Table 2: Comparisons of previous estimates (km^3) about irrigation withdrawal (IW), irrigation consumption(IC), total withdrawal (TW), and total consumption (TC). The TC values with parentheses were estimates based on averaged IC/IW (0.5) or IC/TC (0.9) ratios.

Author(s)	**Estimate year**	**Irrigation withdrawal (IW)**	**Irrigation consumption (IC)**	**Total withdrawal (TW)**	**Total consumption (TC)**	**Notes**
			Accounting-based approaches			
Nikitopoulos [1967]	2000			6730	(3778)	
L'vovich [1974]	2000			6325	(3551)	Rational water use
				12270	(6889)	Conventional water use
Falkenmark and Lindh [1974]	2000			6030	(3385)	With water reuse
				8380	(4705)	Without water reuse
Postel et al. [1996]	1990	2880	1870	4430	2285	
Raskin et al. [1997]	1995			3700	(2077)	
	2025			5000	(2807)	Mid-range growth rate
Shiklomanov [1998]	1995			3765	2265	
	2000			3927	2329	
Shiklomanov [2000]	1995	1753		3788	2074	
	2000			3973	2182	
Median					**2568**	
			Modeling-based approaches			
Döll and Siebert [2002]	1961-1990	2452	1092		(1213)	
Hanasaki et al. [2006]	1987-1988	2254	1127		(1252)	
Oki and Kanae [2006]	not specified	2660	(1330)	3800	(1478)	
Rost et al. [2008]	1971-2000	1161	636	-	(707)	Without nonlocal water
		2555	1364	-	(1516)	With nonlocal water
Wisser et al. [2008]	1963-2002	3100	(1550)	-	(1722)	CRU forcing, FAO irrigation
		3800	(1900)	-	(2111)	CRU forcing, IWMI irrigation
		2200	(1100)	-	(1222)	NCEP forcing, FAO irrigation
		2700	(1350)	-	(1500)	NCEP forcing, IWMI irrigation
Döll et al. [2009]	1998-2002	2900	1200	4020	1300	
Hanasaki et al. [2010]	1985-1999		1530	-	1690	
Wada et al. [2011]	1958-2001	2057	1176	-	(1307)	
Pokhrel et al. [2012]	1983-2007	2158	906	-	(1007)	
	2000	2462	1021	-	(1134)	
Wada et al. [2013]	1980-2010	2945	(1473)	-	(1636)	ISI-MIP
Median				**-**	**1307**	

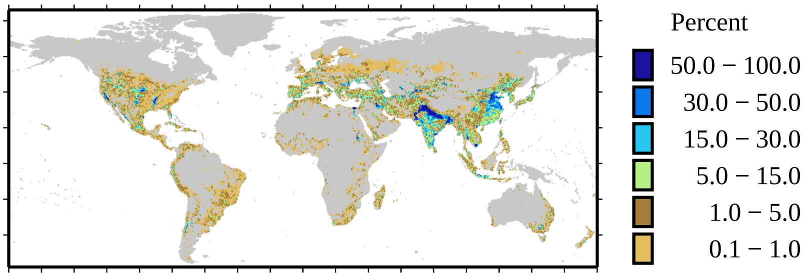

Figure 1: Percent of area equipped for irrigation. Source: *Siebert et al. [2005]*.

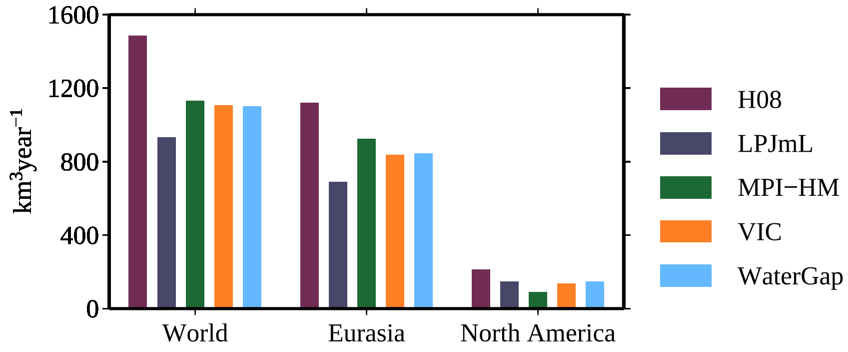

Figure 2: Estimated mean annual potential irrigation water consumption (km^3 year^{-1}), 1985-1999. Source: WaterMIP archive (http://www.eu-watch.org).

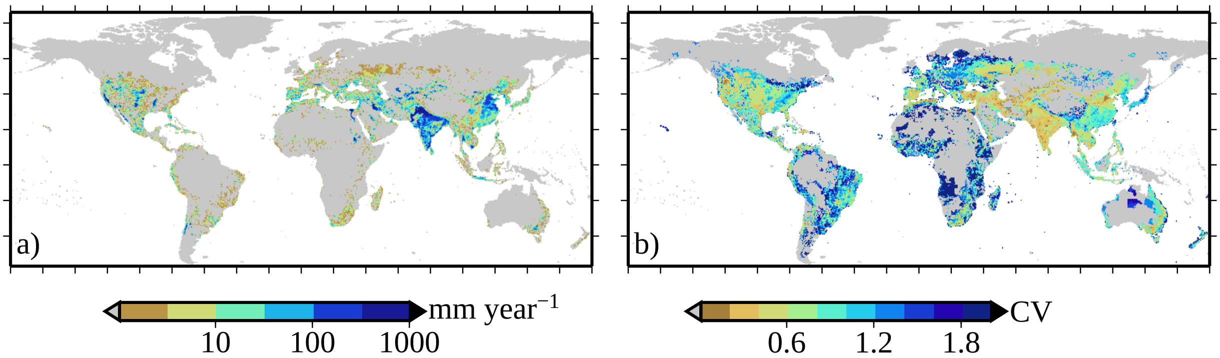

Figure 3: a) Mean annual (1985-1999) potential irrigation water consumption for the five models, and b) coefficient of variation of the model means. Source: WaterMIP archive (http://www.eu-watch.org)

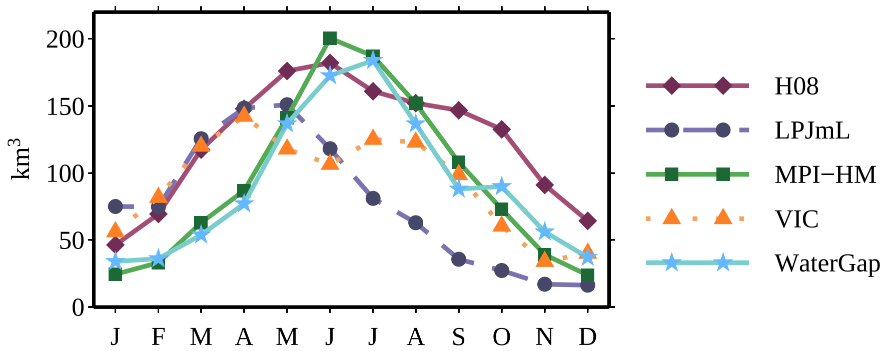

Figure 4: Monthly mean global potential irrigation water consumption, 1985-1999. Source: WaterMIP archive (www.eu-watch.org)

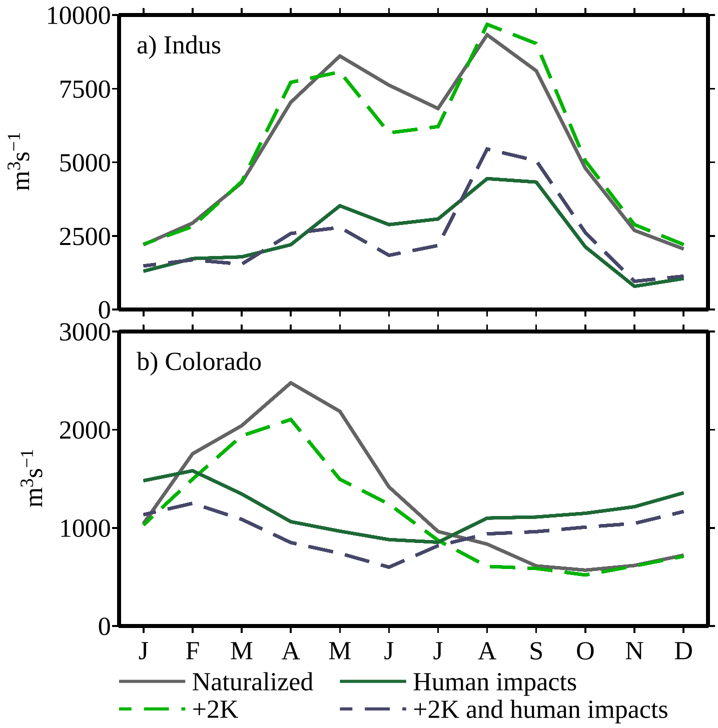

Figure 5: Ensemble mean monthly streamflow for naturalized and human impact simulations in the a) Indus River basin and b) Colorado River basin. Simulation results represent the control period (1971-2000), and the period representing a +2K global temperature rise compared to pre-industrialized levels. Source: WaterMIP (http://www.eu-watch.org/) and ISI-MIP (www.isi-mip.org) archives

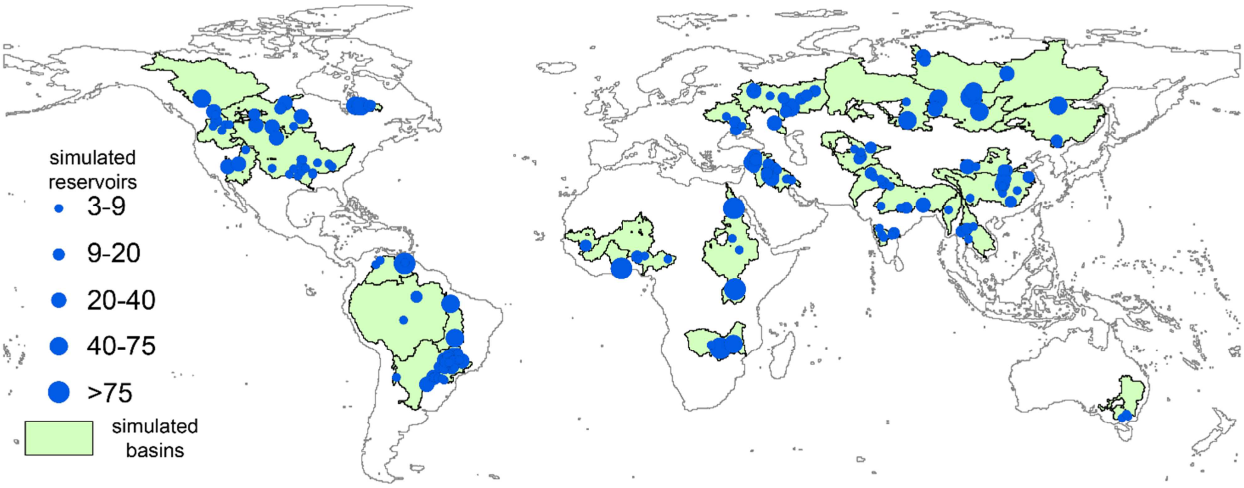

Figure 6: Location of river basins and 166 simulated reservoirs (blue dots give reservoir capacities in km^3). *Source: Zhou et al. [2015]*.

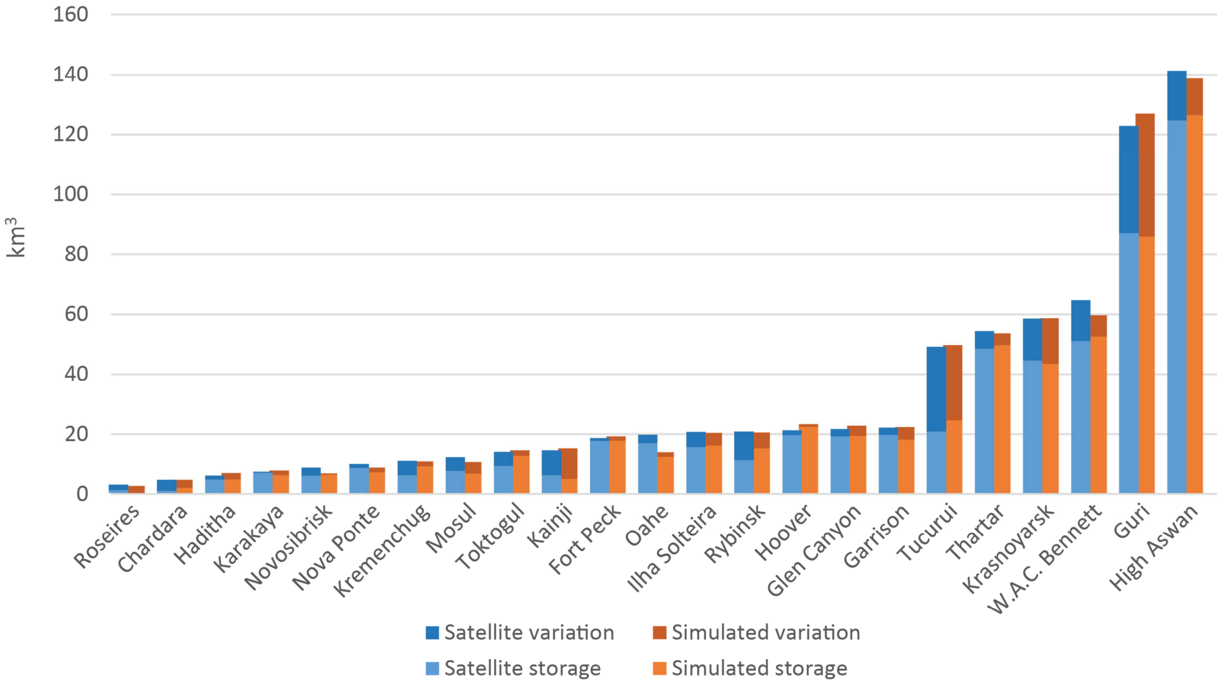

Figure 7: Comparison of model-simulated and satellite observations of reservoir storage in 32 major river basins by storage capacity and inter-seasonal storage variations (from *Gao et al., [2012]*).

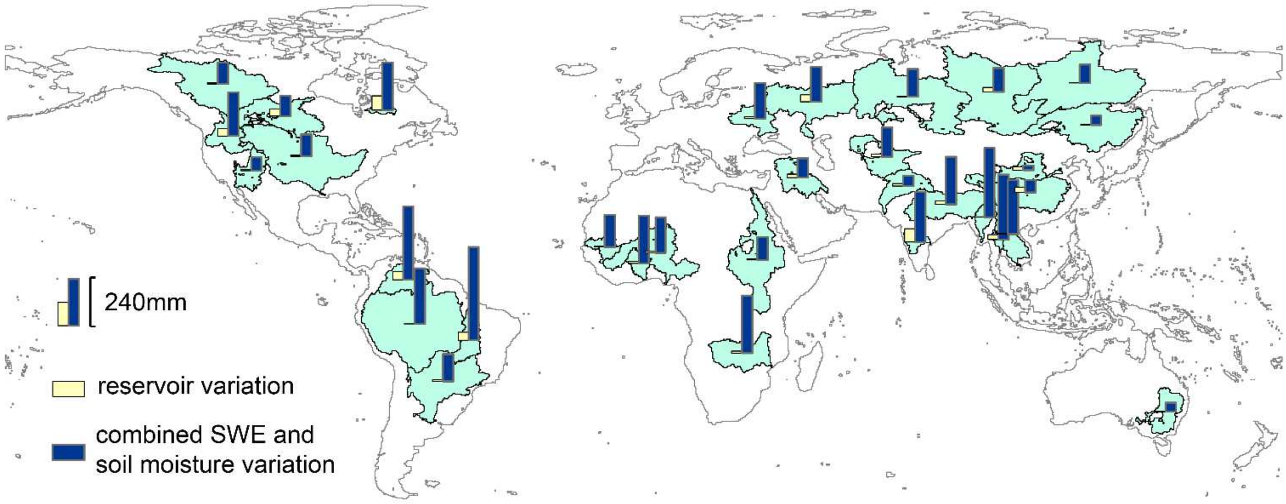

Figure 8: Simulated seasonal variations from reservoir compared with combined SWE and soil moisture storage variation for 32 major river basins.

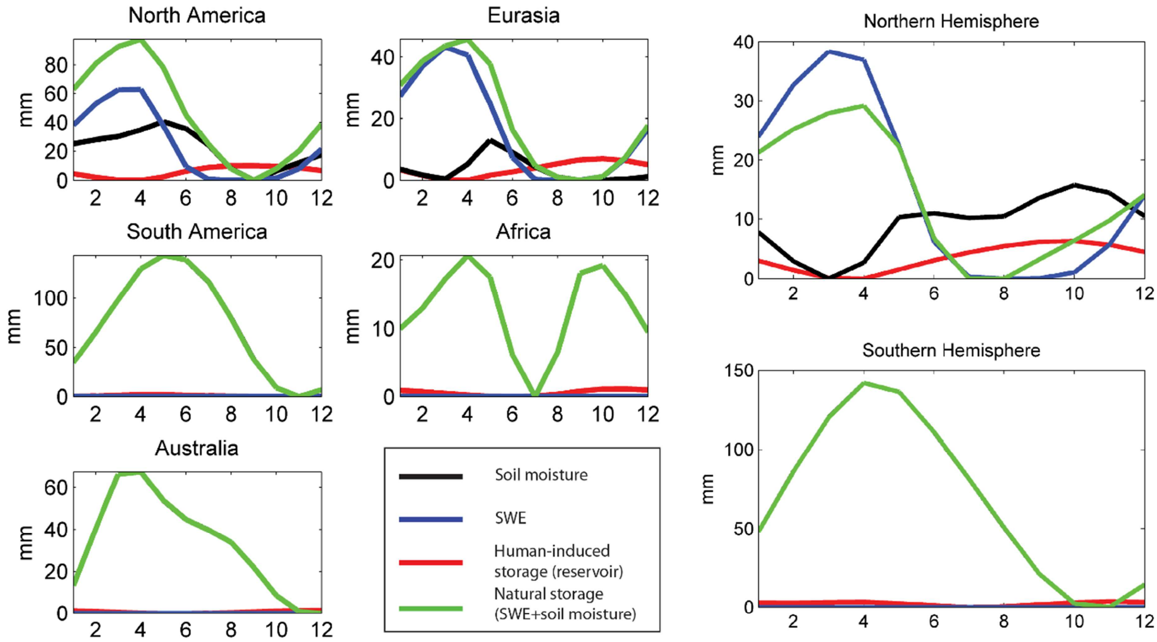

Figure 9: Mean seasonal reservoir storage variations compared with seasonal SWE and soil moisture in Northern (a) and Southern (b) Hemisphere.