Impact of reservoirs on river discharge and irrigation water supply during the 20th century

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[1] This paper presents a quantitative estimation of the impact of reservoirs on discharge and irrigation water supply during the 20th century at global, continental, and river basin scale. Compared to a natural situation the combined effect of reservoir operation and irrigation extractions decreased mean annual discharge to oceans and significantly changed the timing of this discharge. For example, in Europe, May discharge decreased by 10%, while in February it increased by 8%. At the end of the 20th century, reservoir operations and irrigation extractions decreased annual global discharge by about 2.1% (930 km^3 yr^{-1}). Simulation results show that reservoirs contribute significantly to irrigation water supply in many regions. Basins that rely heavily on reservoir water are the Colorado and Columbia River basins in the United States and several large basins in India, China, and central Asia (e.g., in the Krishna and Huang He basins, reservoirs more than doubled surface water supply). Continents gaining the most are North America, Africa, and Asia, where reservoirs supplied 57, 22, and 360 km^3 yr^{-1} respectively between 1981–2000, which is in all cases 40% more than the availability in the situation without reservoirs. Globally, the irrigation water supply from reservoirs increased from around 18 km^3 yr^{-1} (adding 5% to surface water supply) at the beginning of the 20th century to 460 km^3 yr^{-1} (adding almost 40% to surface water supply) at the end of the 20th century. The analysis is performed using a newly developed and validated reservoir operation scheme within a global-scale hydrology and vegetation model (LPJmL).

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1. Introduction

[2] Water is an essential resource for life on earth. As a result of population and economic growth, global water demand will continue to increase in the near future. At the same time, climate change will alter the global water cycle, reducing water availability in critical locations [see *Bates et al.*, 2008; *Kabat et al.*, 2004]. For centuries people have been intervening in the natural water cycle to make more water available for anthropogenic use. Irrigation systems have made dry areas suitable for agricultural production, and reservoirs were built for multiple purposes: to use the energy potential of rivers for electricity production, to reduce discharge variability for improved navigation, or to supply water for irrigation and other users [*International Commission on Large Dams* (*ICOLD*), 2007; *World Commission on Dams* (*WCD*), 2000]. Most of the profound changes that humans have made to the hydrological cycle took place in the 20th century. The total global irrigated area has increased from around 40 Mha in 1900 to 215 Mha in 2000 [*Fader et al.*, 2010] and the total cumulative storage capacity of large dams has increased from less than 100 km^3 in 1900 to around 8300 km^3 in 2000 [*Chao et al.*, 2008; *ICOLD*, 2007].

[3] Current estimates of the total global annual water demand for irrigation around the year 2000 range from 1900 to around 3800 km^3 yr^{-1} [*Döll and Siebert*, 2002; *Rost et al.*, 2008, and the references therein; *Vörösmarty et al.*, 2005; *Wisser et al.*, 2008], depending to a large extent on the data sets used for irrigated area and climate [*Wisser et al.*, 2008]. *Gerten et al.* [2008] have estimated that expansion of irrigation has decreased global river discharge to the oceans by 0.3% (equaling 118 km^3) between 1901 and 2002, with pronounced regional effects, including regional increases due to increased return flows to the river system.

[4] *Nilsson et al.* [2005] showed that currently over half of the world's global river systems are regulated by dams, which mostly lie in basins where irrigation and economic activities take place. The total cumulative storage of large dams is about 20% of global annual runoff [*Vörösmarty et al.*, 1997]. However, there are large regional differences: in the United States, for example, the total storage capacity of large dams is more than 75% of the mean annual runoff [*Graf*, 1999]. The global standing pool of rivers has

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increased sevenfold as compared to a situation without artificial reservoirs [*Vörösmarty et al.*, 1997], and consequently reduced global sea level rise by 30 mm [*Chao et al.*, 2008]. For African countries, a correlation has been found between the water storage capacity of the country and its economic development [*Ludwig et al.*, 2009].

[5] In addition to the positive effects that large infrastructural water projects like dams can have on water supply for different sectors and on flood risk reduction, there are also negative effects. These negative effects include alteration of the natural river dynamics of water, sediments, and nutrients; habitat fragmentation; and loss of biodiversity [*Graf*, 2006; *Poff et al.*, 2007; *Rosenberg et al.*, 2000; *Syvitski et al.*, 2005; *Vörösmarty et al.*, 2003].

[6] In the assessment of current and future water resources it is important to account for large reservoirs and their impact on water availability for different sectors [e.g., *Biemans et al.*, 2006]. The available water resources for human use, and potential (future) water stress, can be evaluated only when human alterations to the hydrological cycle are taken into account. However, only a few global water resources assessments have accounted explicitly for the operation of large reservoirs. On the continental and global scale those studies have mainly focused on the influence of dams on discharge patterns [*Döll et al.*, 2009; *Haddeland et al.*, 2006; *Hanasaki et al.*, 2006]. At basin scale, especially in the United States, information on the management of dams is readily available, making it possible to simulate the impact of dams on river systems in more detail [see, e.g., *Christensen et al.*, 2004; *Graf*, 2006; *Payne et al.*, 2004]. Studies also exist on the influence of dams on discharge in specific river basins outside of the U.S. [*Adam et al.*, 2007; *Yang et al.*, 2004; *Yang et al.*, 2008; *Ye et al.*, 2003].

[7] The potential contribution of rainwater harvested in small local reservoirs to global irrigation supply has been quantified to range between 1847 and 2511 $km^3\ yr^{-1}$ by *Wisser et al.* [2010]. However, the contribution of large reservoirs to irrigation has to our knowledge never been quantified at the global scale before.

[8] The objective of our research was to estimate the impact of large reservoirs on water availability and irrigation water supply during the 20th century. Therefore, a reservoir operation scheme has been developed within the dynamic global vegetation and hydrology model Lund-Potsdam-Jena managed Land (LPJmL). All analyses were performed at global, continental, and river basin scale, focusing both on the increasing impact of reservoirs during the 20th century and on the intra-annual dynamics during the last part of the 20th century.

2. Methods

2.1. LPJmL

[9] The LPJmL model is designed to simulate the global carbon and water balances in conjunction with the dynamics of natural and agricultural vegetation. It runs at 0.5° spatial resolution at daily time steps. Originally the model was developed as a dynamic global vegetation model (LPJ), simulating changing patterns of potential natural vegetation based on soil properties and climate [*Gerten et al.*, 2004; *Sitch et al.*, 2003]. In recent years, the model has been extended to LPJmL, which includes a dynamic representation of cropland and grazing land in order to simulate the growth, production, and management regime of the world's major crop types [*Bondeau et al.*, 2007; *Fader et al.*, 2010], as well as a global routing and irrigation module [*Rost et al.*, 2008]. The river routing and irrigation module has been efficiently implemented on a parallel cluster, speeding up the simulations [*von Bloh et al.*, 2010]. LPJmL has been systematically validated against discharge observations for 300 globally distributed river basins [*Biemans et al.*, 2009] and against irrigation water use and consumption [*Rost et al.*, 2008].

[10] For each crop LPJmL calculates a growing season, which is defined as the period between sowing date and harvest date. Once a year, sowing dates are determined as a function of climate- and crop-specific thresholds regarding temperature and/or precipitation. Sowing dates determined by temperature (temperate cereals, sunflower, and rapeseed) are modeled based on the 20 previous years' average date on which temperature drops below (for winter types) or rises over (for spring types) a crop-specific threshold value. Sowing dates determined by precipitation (tropical cereals, tropical roots, and groundnut) require 40 mm (110 mm in tropical Asia) of precipitation accumulated over the previous 10 days. For maize, the temperature and/or precipitation threshold depends on the latitude. For rice, pulses, temperate roots, and soybean the sowing dates are fixed. Phenological development toward maturity is modeled using heat unit theory, and harvest occurs as soon as maturity is reached. Rice is assumed to grow twice a year in tropical Asia (for more details, see *Bondeau et al.* [2007]).

[11] The irrigation algorithm is described in detail by *Rost et al.* [2008]. Irrigation only occurs during the growing season. The net irrigation demand of an agricultural field is defined as the amount of water needed to either fill the soil to field capacity, or to fulfill the atmospheric evaporative demand. The gross water demand is determined by multiplying the net irrigation demand with a country-specific efficiency factor, which depends on the irrigation system (estimated by *Rohwer et al.* [2007]). This gross irrigation demand is first fulfilled by taking water from the cell's lakes and rivers. Second, if the local cell cannot fulfill the demand, water is taken from the adjacent grid cell with the highest discharge. Third, in the expanded LPJmL containing the reservoir module (described below), if there is still a remaining irrigation demand, water is requested from the reservoir. The reasoning behind this assumption is that it is probably easier and cheaper for farmers to access their locally produced runoff or to use a local river than to be supplied from a reservoir. Fourth, if irrigation supply is assumed not to be restricted by availability of renewable water, the remaining demand can be filled up assuming unlimited supply (e.g., from fossil groundwater). Figure 1 illustrates the irrigation algorithm.

[12] Not all the water that is extracted reaches the agricultural fields, and transport losses are accounted for by applying a country-specific conveyance efficiency factor. The conveyance efficiency varies between 0.7 and 0.95 depending on the irrigation system used (open canals or pipeline systems) [see *Rohwer et al.*, 2007; *Rost et al.*, 2008]. Fifty percent of the water lost during conveyance is assumed to evaporate, and 50% is assumed to return to the river.

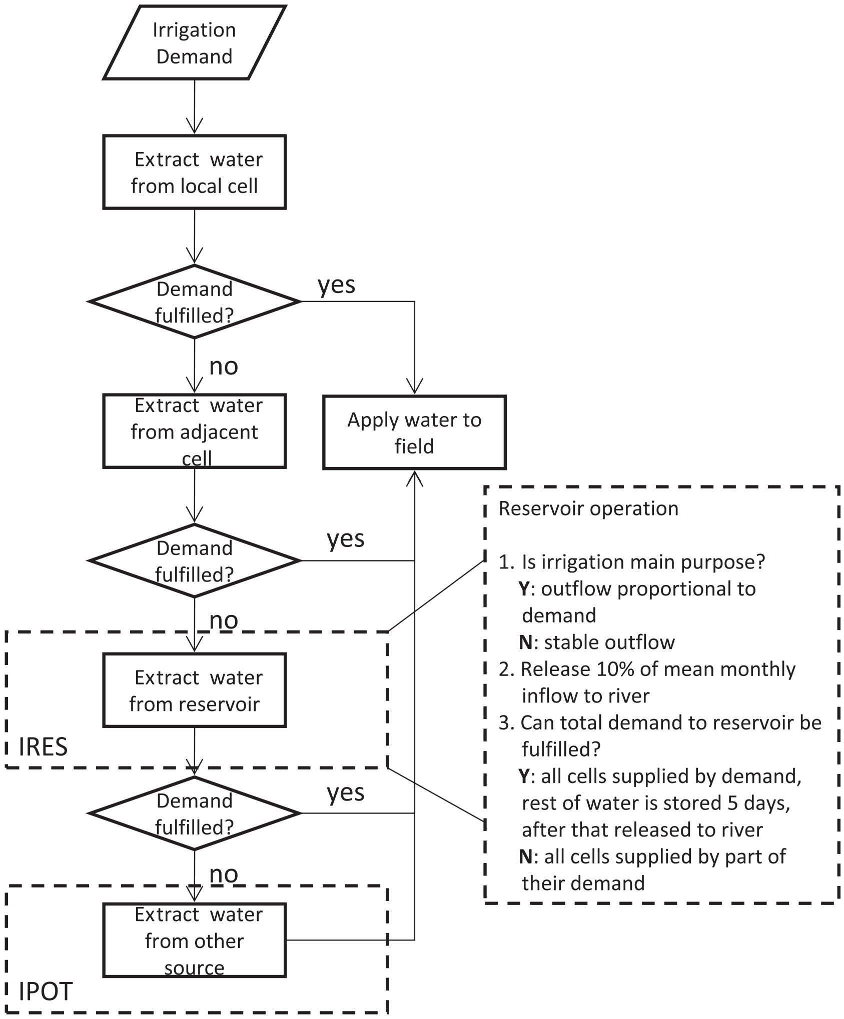


Figure 1. Schematic representation of the reservoir and irrigation algorithm in LPJmL. Water from reservoirs can only be extracted in a simulation which includes reservoir operations (IRES). The right box contains a summary of the rules for reservoir operation. Water from other sources can only be applied in a simulation that assumes unlimited supply (IPOT).

2.2. Reservoir Module

[13] For this study, the LPJmL model has been extended with a new reservoir module and an expanded irrigation module, affecting the seasonal timing of discharge and the amount of water locally available for irrigation. Since there is no global data set on the management of dams, it was necessary to develop a generic reservoir operation model based on known functions of the reservoir. Two reservoir operation schemes used in large-scale hydrological models previously have been described. *Haddeland et al.* [2006] developed an optimization algorithm, in which information regarding inflow, downstream water demand, and reservoir evaporation is used to optimize reservoir outflow, depending on the purposes of the reservoir. The algorithm has been tested and applied for North America and Asia [*Haddeland et al.*, 2007]. The advantage of this scheme is that it simulates the operation of reservoirs with different purposes (irrigation, hydropower, flood protection, water supply/navigation), and it can take into account multipurpose reservoirs. Further, it simulates not only reservoir outflow, but also extractions from reservoirs for irrigation during water-scarce periods, based on estimated irrigation demand. Irrigation efficiency and conveyance losses are not taken into account. Furthermore, in this scheme the optimization algorithm is applied retrospectively [*Haddeland et al.*, 2006], which means that it uses information on river flow and water demand for the whole operational year in a postprocessing step. This scheme was developed for a model running in the spatial domain (cell by cell), and therefore not directly applicable in LPJmL, which is operated in discrete time-step mode.

[14] The second algorithm can be run within a routing model, time step by time step [*Hanasaki et al.*, 2006]. However, this algorithm only accounts for two different purposes (irrigation and other) and is not integrated with an irrigation scheme. This means it does not simulate water extractions from the reservoir, but only addresses the redistribution of river water in time. In a more recent application of this scheme, water extractions are accounted for, but only from the local river and not directly from the reservoir [*Hanasaki et al.*, 2008a, 2008b]. To overcome the limitations of these

two model approaches, a new reservoir scheme within LPJmL is developed by combining parts of both schemes and adding new functionalities.

[15] A reservoir is considered in the model from the (simulation) year that it was built. This makes the model suitable to study the impacts of dams over time. The reservoir is filled daily with discharge from upstream and with precipitation. Subsequently, the start of an operational year for a reservoir is defined similar to the way *Hanasaki et al.* [2006] and *Haddeland et al.* [2006] described it, as the month when mean monthly inflow shifts from being higher than the mean annual inflow to being lower than the mean annual inflow. If there is a reservoir upstream, this can influence the start month of the operational year for the downstream reservoirs. This definition is slightly different from that of *Hanasaki et al.* [2006] and *Haddeland et al.* [2006], who defined the start of the operational year based on natural flow simulations. At the beginning of the operational year, the actual storage in the reservoir is compared with the maximum storage capacity of the reservoir. To adjust the reservoir release to interannual fluctuations in inflow, a release coefficient is calculated as:

$$k_{rls,y} = S_{first,y} / \alpha C, \tag{1}$$

where $S_{\mathrm{first,y}}$ is the actual reservoir storage at the beginning of the operational year y, C is the maximum storage capacity of the reservoir, and α is a dimensionless constant that can be interpreted as the preferred storage level at the start of the new operational year. For the study presented in this paper, α is set to 0.85, following *Hanasaki et al.* [2006].

[16] A monthly target release $r'_{m,y}$ (L d^{-1}) for month m in operational year y can be interpreted as the optimal release of the reservoir if reservoir capacity is not limited. The target release depends on the function of the reservoir, as in the work by *Hanasaki et al.* [2006]: for a reservoir that is not built primarily for irrigation (e.g., for hydropower, flood control, navigation), the target release is assumed to be constant

$$r'_{m,y} = i_{mean} \tag{2}$$

where i_{mean} is the mean annual inflow (L d^{-1}) over the last 20 years. The target release for irrigation reservoirs is defined as:

$$\begin{aligned} r'_{m,y} &= \frac{i_{mean,m}}{10} + \frac{9}{10} \cdot i_{mean} \cdot \frac{d_{mean,m}}{d_{mean}} \quad \text{if } d_{mean} \geq 0.5\, i_{mean} \\ r'_{m,y} &= i_{mean} + d_{mean,m} - d_{mean}, \quad \text{if } d_{mean} < 0.5\, i_{mean}, \end{aligned} \tag{3}$$

where $i_{\mathrm{mean,m}}$ is the mean monthly inflow, and d_{mean} and $d_{\mathrm{mean,m}}$ are the mean annual and mean monthly irrigation demand to the reservoir, respectively (all in L d^{-1} calculated over the last 20 years). This release algorithm is based on *Hanasaki et al.* [2006], but has been slightly adjusted here so as to account only for irrigation water use while neglecting domestic and industrial extractions. Further, from *Hanasaki's* [2006] scheme, the minimum release was set to 50% of the mean inflow (environmental flow requirement). In rivers with a strong seasonality, this means that the outflow in low-flow months is much higher than in the natural situation, leaving no water available for irrigation. Therefore in the LPJmL scheme the minimum release is set to 10% of the mean monthly inflow, allowing the outflow to follow the irrigation demand as much as possible, but always leaving 10% of the mean monthly inflow in the river, following the natural intra-annual flow variability.

[17] The actual reservoir release $r_{m,y}$ in month m of year y (L d^{-1}) depends on the relative size of the reservoir, as described by *Hanasaki et al.* [2006]:

$$r_{m,y} = \begin{cases} k_{rls,y} \times r'_{m,y}, \ (c \geq 0.5) \\ \left(\frac{c}{0.5}\right)^2 k_{rls,y} \times r'_{m,y} + \left\{1 - \left(\frac{c}{0.5}\right)^2\right\} i_{m,y}, \ (0 \leq c \leq 0.5) \end{cases}, \tag{4}$$

where c equals maximum storage capacity/mean annual inflow.

[18] If the reservoir is not built for irrigation purposes, the water is released directly into the river. Otherwise, part of the released water can be diverted to irrigated land, except for the water needed to fulfill the environmental flow requirements. The area that can be supplied from a reservoir is estimated according to the rules of *Haddeland et al.* [2006], slightly modified. All cells requesting water from a reservoir must lie at lower altitudes than the cell with the reservoir. Further, they must either be situated along the main river downstream of the reservoir, or within reach of this main river at a maximum distance of 5 cells upstream (approximately 250 km at the equator). Consequently, an irrigated cell can be supplied by two or more reservoirs, in which case the irrigation demand of that cell is shared between the reservoirs proportional to their mean volumes. The mean volume of water stored in a reservoir can change from year to year, and hence shares are updated annually.

[19] Irrigation demands vary from day to day, and water that is released for irrigation is made available for a 5 day period. If the water is not used within these 5 days, it is released back into the river, and thus storage possibilities in the conveyance system are simulated. A reservoir's total water demand is compared with the water that was released from the reservoirs for irrigation. If the total demand can only partly be fulfilled, all cells get the same percentage of the water they requested. A summary of the operational rules for water supply from reservoirs can be found in Figure 1.

2.3. Model Setup and Simulation Protocol

[20] LPJmL was run for the period 1901–2000, after a 990 year spin-up period (forced by repeating the 1901–1930 climate and without irrigation and reservoirs), needed to bring carbon and water pools into equilibrium. The model was forced with monthly gridded values for temperature, precipitation, number of wet days, and cloud cover from the CRU TS 2.1 climate data set [*Mitchell and Jones*, 2005]. To get daily input forcings, those data were temporally downscaled: temperature and cloud cover were linearly interpolated, and daily precipitation values were obtained by applying a stochastic distribution method using the number of wet days [see *Sitch et al.*, 2003].

[21] The land use input consists of annual fractions of irrigated and nonirrigated crop types within each grid cell for the 20th century. This global crop and irrigation input

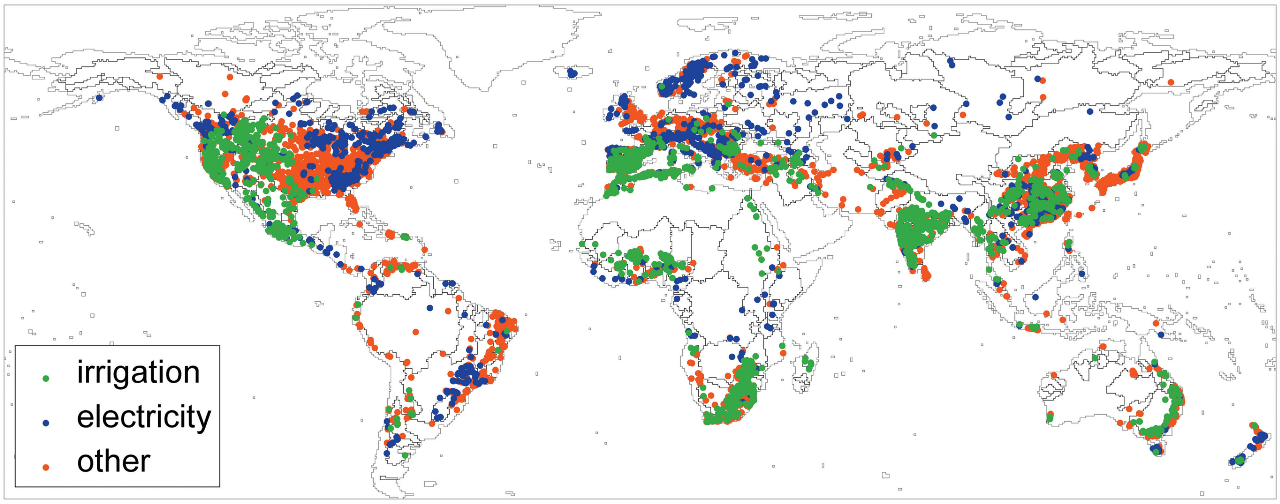


Figure 2. Reservoirs included in the GRanD database and their main function. If reservoirs have multiple functions, the most important function is shown. Included are all reservoirs built before 2008.

data set was developed by combining recently compiled data sets on rainfed and irrigated agriculture [*Portmann et al.*, 2010], current crop distributions [*Monfreda et al.*, 2008; *Ramankutty et al.*, 2008], and historical land use information [*Klein Goldewijk and van Drecht*, 2006]. For details see *Fader et al.* [2010].

[22] Information on natural lakes is obtained from the global lake and wetland database (GLWD) [*Lehner and Döll*, 2004]. The locations of the reservoirs are obtained from the recently released GRanD database [*Lehner et al.*, 2011]. This global database contains geographical locations for approximately 7000 dams, including information on construction year, maximum storage capacity, surface area, and functions (see Figures 2 and 3).

[23] The representation of the river system is simplified to a 0.5° grid network [*Vörösmarty et al.*, 2000]. Therefore, not all reservoirs (which have exact geographical locations) are placed on the right tributary in the modeled river system. The locations of all reservoirs with a capacity greater than 5 km^3 (190) have been checked and, if necessary, relocated on the network. Observed discharge data, to compare with simulated discharge values, were obtained from the Global Runoff Data Centre (available at http://grdc.bafg.de).

[24] In this study the following four simulations are performed: (1) A model run without irrigation or reservoirs, as in [*Biemans et al.*, 2009], simulating discharge without human extractions and river flow alterations (INO). (2) A model run with irrigation extractions, assuming that there are no managed reservoirs and that irrigation is limited to the local surface water available in natural lakes and rivers (ILIM) [see also *Rost et al.,* 2008]. (3) A model run with irrigation extractions and reservoir operation, assuming that this irrigation is limited to the local surface water available in lakes, rivers, and reservoirs (IRES). (4) A model run with irrigation extractions and without reservoir operations, assuming that irrigation water can always be supplied, regardless of the source of the irrigation water (IPOT).

2.4. Analyses

[25] For model validation purposes, discharges simulated by the runs INO and IRES are compared. The difference between those two runs shows the combined impact of reservoir operations and irrigation withdrawals on discharge in these basins. To evaluate whether the reservoir model improves the discharge simulations, mean monthly discharge results and discharge time series for seven large affected basins are presented and compared with observations. The model is further validated by comparing simulated discharge with observations at 522 gauging stations (as in the works by *Biemans et al.* [2009] and *Fekete et al.* [2002]) for both INO and IRES simulations. The quality of the simulation is estimated by calculating the root-mean-square error, normalized by the mean of the observations as

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(o_i - s_i)^2}{n}}\,\frac{1}{\bar{o}}, \tag{5}$$

where n is the amount of observations, o_i is the observed discharge, s_i is the simulated discharge at time step i, and $\bar{o}$ is the mean of all observations. After the validation, the model was applied to calculate the impact of irrigation extractions and reservoir operations on mean monthly global and continental discharge.

[26] Another measure to quantify the hydrological effect of flow regulations on rivers spatially is the amended annual proportional flow deviation (AAPFD) indicator [*Ladson*

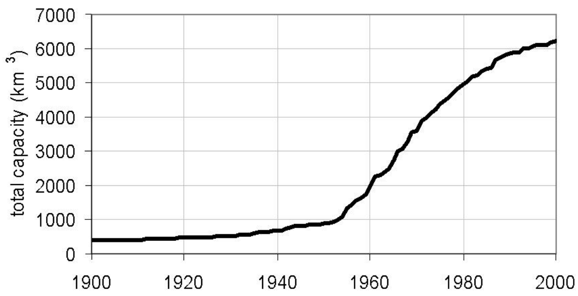


Figure 3. Cumulative storage capacity of large reservoirs during the 20th century, derived from the GRanD database.

and White, 1999; *Marchant and Hehir*, 2002]. The AAPFD expresses changes in monthly flow as a proportion of the natural flow, averaged over a number of years (*nyears*):

$$AAPFD = \frac{1}{nyears} \sum_{j=1}^{nyears} \left(\sum_{j=1}^{12} \left(\frac{(c_{ij} - n_{ij})}{\overline{n_j}} \right)^2 \right)^{\frac{1}{2}}, \quad (6)$$

where c_{ij} is the actual discharge in month i year j, n_{ij} is the natural discharge in month i year j, and $\overline{n_j}$ is the mean natural discharge in year j. The AAPFD indicates the level of modification of a river system and can be calculated at every arbitrary point in the river basin if both modified and natural discharge data are available. The AAPFD is calculated in every grid cell, based on the INO and IRES simulations. It gives a good spatial overview of the river stretches most affected by reservoirs and irrigation extractions.

[27] Subsequently this study evaluates the contribution of reservoirs to irrigation water supply during the 20th century, by comparing simulated irrigation extractions of the runs ILIM, IRES, and IPOT. The ILIM run estimates the water that is available for irrigation in the natural system of lakes and rivers. The IRES simulation estimates availability including the water in managed reservoirs. The IPOT simulation estimates extractions under unlimited supply and can be interpreted as the total water demand for irrigation.

[28] Total global water extractions for irrigation as simulated by ILIM, IRES, and IPOT during the 20th century were compared to estimate the contribution of reservoirs to irrigation supply. Because the reservoir model uses only one set of rules to simulate reservoir operations globally, the sensitivity of the estimated water supply from reservoirs for the chosen model parameters was tested. One by one, three main parameters were varied: the size of the area that can be supplied by the reservoir, the time water can be stored in the conveyance system, and the environmental flow requirement. For comparison, the influence for reservoir capacity was also tested.

[29] Finally, the contributions of reservoirs to irrigation were calculated for continents and basins. For some specific basins, the effect of reservoirs on intra-annual water supply was analyzed.

3. Results

3.1. Discharge Validation

[30] Figure 4 shows a comparison of simulated discharge with observations at seven locations that are known to be influenced by reservoir operations and irrigation extractions. The construction of the Glen Canyon reservoir (completed in 1963) just upstream of the Lees Ferry stream gauging station in the Colorado River basin is clearly visible in both the observed and simulated time series. In other basins the effect of the introduction of a large reservoir is less obvious, because the stream gauge is not located directly downstream of the reservoir or because streamflow is less affected by reservoirs. The mean monthly figures show that the reservoir module changes the discharge timing significantly. In all example basins both the timing and the total of the IRES simulation is closer to the observed discharge than that of the INO simulation.

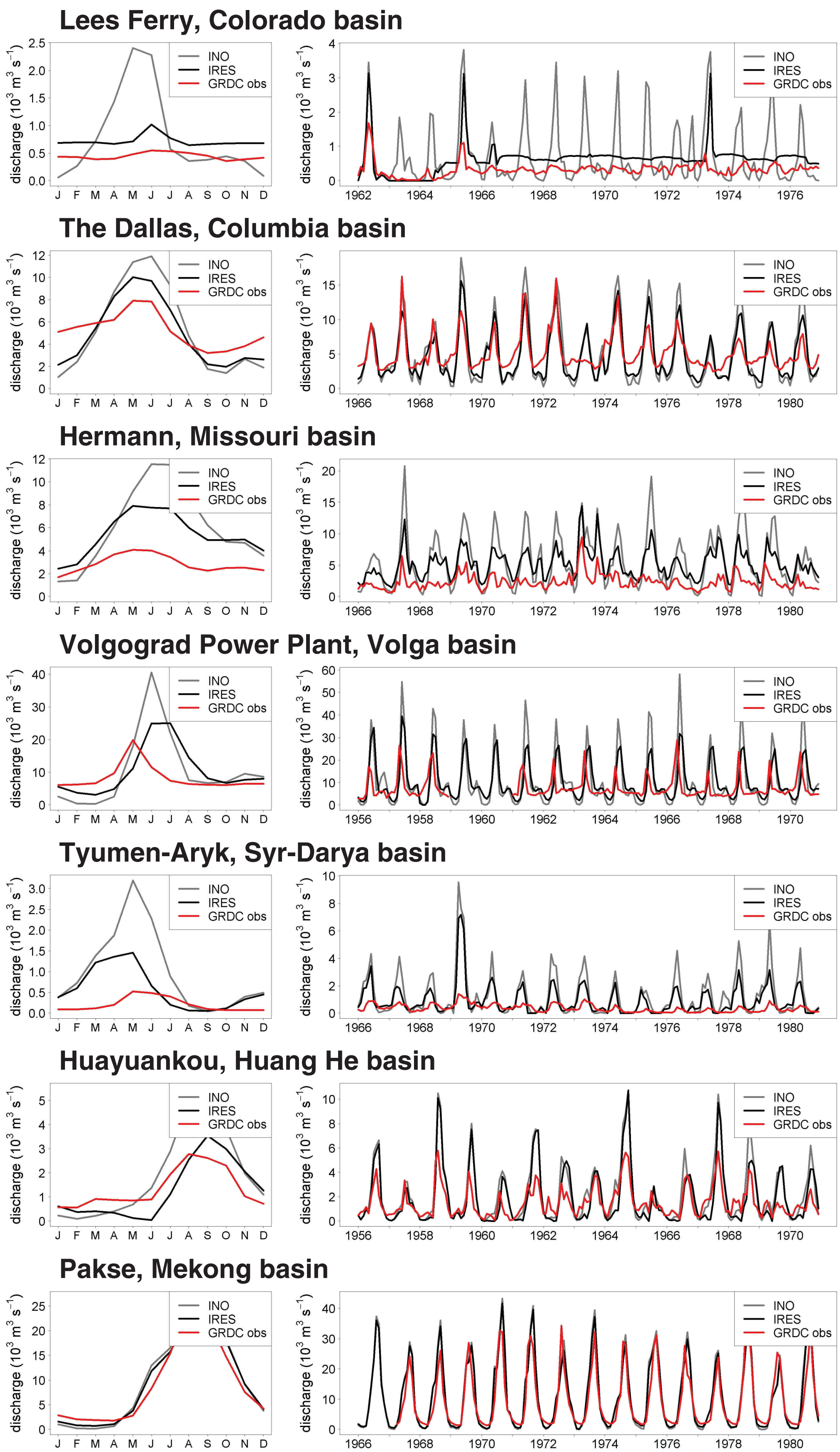
[31] For a broader analysis of the performance of the model at global scale, the root-mean-square error (RMSE) (normalized to the mean of the observations) was calculated for 522 GRDC stations, both for the INO and for the IRES run. For 304 stations there was a difference in RMSE between the two simulations, because the basin was impacted by reservoirs and irrigation (the gray shades in Figure 5 show the storage capacity to mean annual runoff ratio). At 279 locations the RMSE improved when including the impact of reservoirs and irrigation in the simulation, at 104 stations this improvement was more than 0.25, and for 37 cases the improvement factor was more than 1 (Figure 5). In some basins in South and Southeast Asia, the red dots suggest that including reservoir operations in the calculations has decreased model performance in those basins.

3.2. Effects of Reservoirs and Irrigation on Discharge

[32] Figure 6 shows that the global annual discharge into oceans and large inland water bodies is reduced by human activities. Simulation results indicate that, without reservoirs, the irrigation extractions only (ILIM) decrease the total global discharge by about 1 to 2% per month, with the strongest relative effect in the period from May to August (Figure 6). The total mean annual decrease in discharge (1981–2000) is 1.2% or 540 km^3 (but note that additional supply from other sources than surface water is not taken into account, as was done in the study of *Gerten et al.* [2008]). The effect of irrigation extractions and reservoir management together (IRES), however, shows a more profound pattern. From May to August, global discharge is lowered up to 5%, due to increased irrigation water withdrawals from reservoirs. This is partly offset by an increase in the October to March discharge of up to 2% caused by extra releases from nonirrigation reservoirs during low-flow months. The cumulative effect of reservoir management and irrigation extractions leads to a mean annual decrease in global discharge of 2.1% or 930 km^3.

[33] The largest effect of extractions for irrigation only (ILIM) on discharge fluxes can be seen in the summer in Europe (June to September) and North America (July, August) and in spring in Asia (March, April, May) (Figure 6). When reservoir operations are included in the simulations (IRES), the effect on discharge is much larger in all continents. Simulation results indicate that there is cumulative effect of reservoir operations and irrigation extractions on discharge in all continents. The strongest effects are again seen in the continents with large irrigated areas and many

Figure 4. Streamflow simulations for test basins: (left) mean monthly and (right) time series. Note that not all time series are plotted for the same period. Presentation of results focuses on periods when complete data sets were available or when a big dam was built upstream of the station (as, for example, in 1963 the Glen Canyon Dam just upstream of Lees Ferry station), or a period that has complete data availability. The mean monthly discharge calculations are based on the period 1981–2000 for all stations, but only include the years for which data was available in this period.



Lees Ferry, Colorado basin
The Dallas, Columbia basin
Hermann, Missouri basin
Volgograd Power Plant, Volga basin
Tyumen-Aryk, Syr-Darya basin
Huayuankou, Huang He basin
Pakse, Mekong basin
discharge (10^3 m^3 s^{-1})
INO
IRES
GRDC obs
J F M A M J J A S O N D

Figure 4

human-built reservoirs (Europe, Africa, Asia, and North America), where increases up to 5% and decreases up to 10% are estimated in different months of the year (Figure 6). At the annual timescale, the decrease in discharge is largest in North America (on average 2% or 138 km^3 lower than in the natural situation) and in Asia (4.0%, 607 km^3 lower).

[34] Comparing of the Amended Annual Proportional Flow Deviation (AAPFD) for the first two (1901–1920) and the last two decades (1981–2000) of the 20th century clearly shows that the river systems are much more modified in the late 20th century than in the early 20th century (Figure 7). During the course of the century reservoirs have been built in Scandinavia, northern Russia, the Nile basin, and North America, and the effects on discharge are obvious. Further, it can be seen that in the heavily irrigated areas in India, Southeast Asia and the United States, reservoir operations also influence river branches. This is mainly caused by the effect irrigation has on redistributing water, increasing the discharge in dry areas because of inefficient irrigation (return flows). The reservoirs not built for irrigation purposes have a strong impact on discharge, but the effect is restricted to the main river (Figure 7). It can also be seen that the effect is greatest close to the dams and dampens out further downstream (see, for example, in the northern Russian river basins).

3.3. Effects of Reservoirs on Water Availability for Agriculture

[35] During the 20th century a rapid increase in the number of large reservoirs has significantly increased the available water resources for irrigation (Figure 8). LPJmL simulations indicate that between 1981–2000, average irrigation water demand was 2650 km^3 yr^{-1}. If there were no artificial reservoirs, 1250 km^3 yr^{-1} of this demand could be extracted from surface water. Another 460 km^3 yr^{-1} (which is an extra 37%) has been made available from managed reservoirs. The remaining 940 km^3 yr^{-1} might have been supplied from other sources (e.g., groundwater) or not have been supplied because of water shortages. At the beginning of the 20th century (1901–1920), reservoirs supplied only 19 km^3 yr^{-1} (5% more than surface water supply without reservoirs).

[36] Results of the parameter sensitivity analysis (given in Table 1) demonstrate that this estimated mean annual reservoir withdrawal of 460 km^3 (for 1981–2000) would be 17 km^3 yr^{-1} higher under the assumption that the reservoirs could distribute their water 8 cells upstream of the main river (but still lower than the reservoir in altitude) instead of 5. Similarly, restricting the area to 2 cells upstream of the main river would decrease the estimated annual withdrawal by 80 km^3. Application of a larger environmental flow requirement of 20% decreased the estimated reservoir withdrawals by 16 km^3 yr^{-1}, versus an increase of 13 km^3 yr^{-1} when the total reservoir outflow could be used for irrigation. The effect of assuming a longer (8 days) or shorter period (2 days) of conveyance storage is only 5 km^3 yr^{-1} or -7 km^3 yr^{-1}, respectively. The factor most influencing the estimate of reservoir supply is the reservoir capacity; doubling or halving all reservoirs' capacities changes the total annual supply by + 92 km^3 or -99 km^3, respectively.

[37] Asia is by far the largest user of irrigation water in terms of volume (Figure 9). During the second half of the 20th century, Asia has built many reservoirs and almost tripled its surface water withdrawals for irrigation. Partly, this additional water is supplied from new reservoirs: the contribution of reservoirs to irrigation water supply increased from around 40 km^3 yr^{-1} (8%) in 1941–1960 to 360 km^3 yr^{-1} (38%) in 1981–2000 (Figure 9). In North America, most reservoirs are older. The contribution of reservoirs was already large in the 1950s and has increased from 19 km^3 yr^{-1} (25% of usage) to 57 km^3 yr^{-1} (38% of usage) during the second half of the 20th century. In relative terms, Africa, North America, and Asia have gained the most from their reservoirs, which have increased the water supply by around 40%.

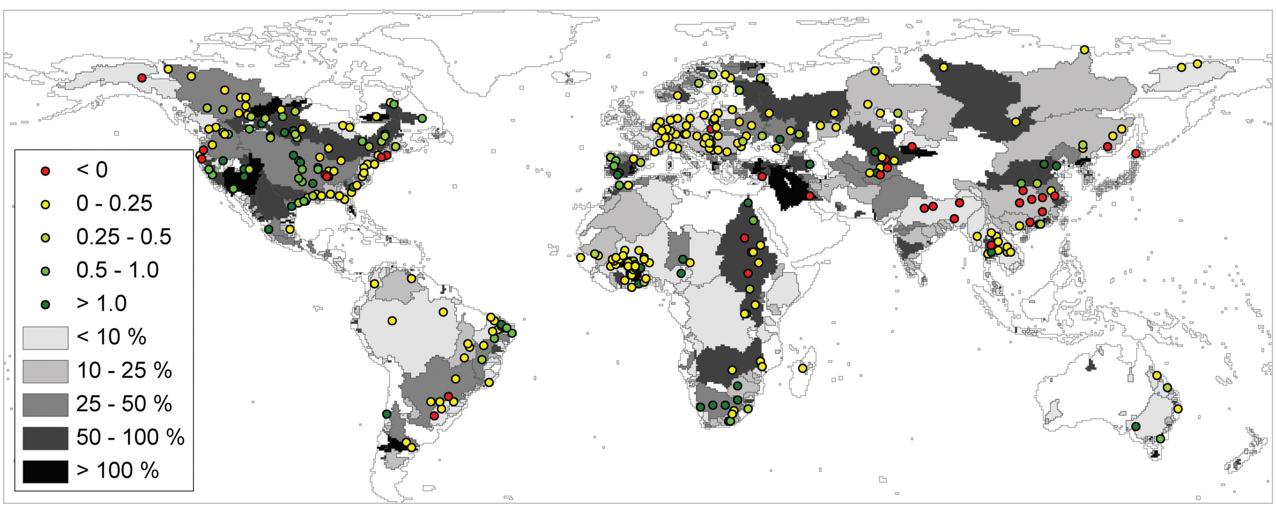


Figure 5. Gray shades: total reservoir storage in the basin (2000 from GRanD data) compared to the mean annual runoff (1981–2000, LPJmL simulations) in percentage. Circles: Absolute difference between the normalized root mean square errors (RMSE) of the INO and IRES run (1981–2000). Yellow to green dots reflect an improvement of the NRMSE when reservoir operation and irrigation extractions are included in the simulations. Only results for affected basins are shown.

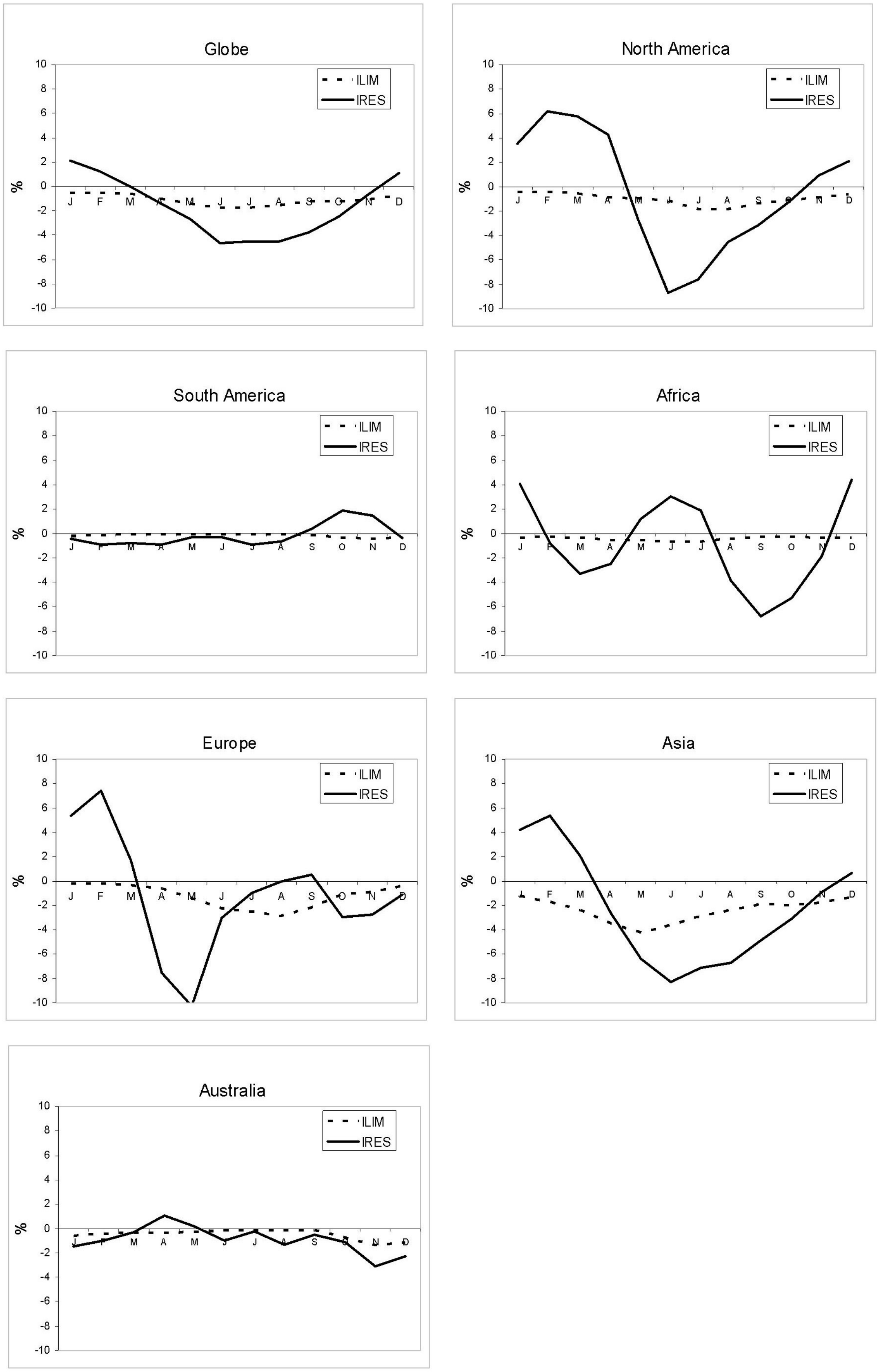


Figure 6. Relative difference in mean monthly discharge at river mouths (in percentage, compared to the natural situation simulated by INO) for the period 1981–2000. Dashed line shows the effect of irrigation extractions alone, solid line shows the cumulative effect of reservoir operations and irrigation extractions.

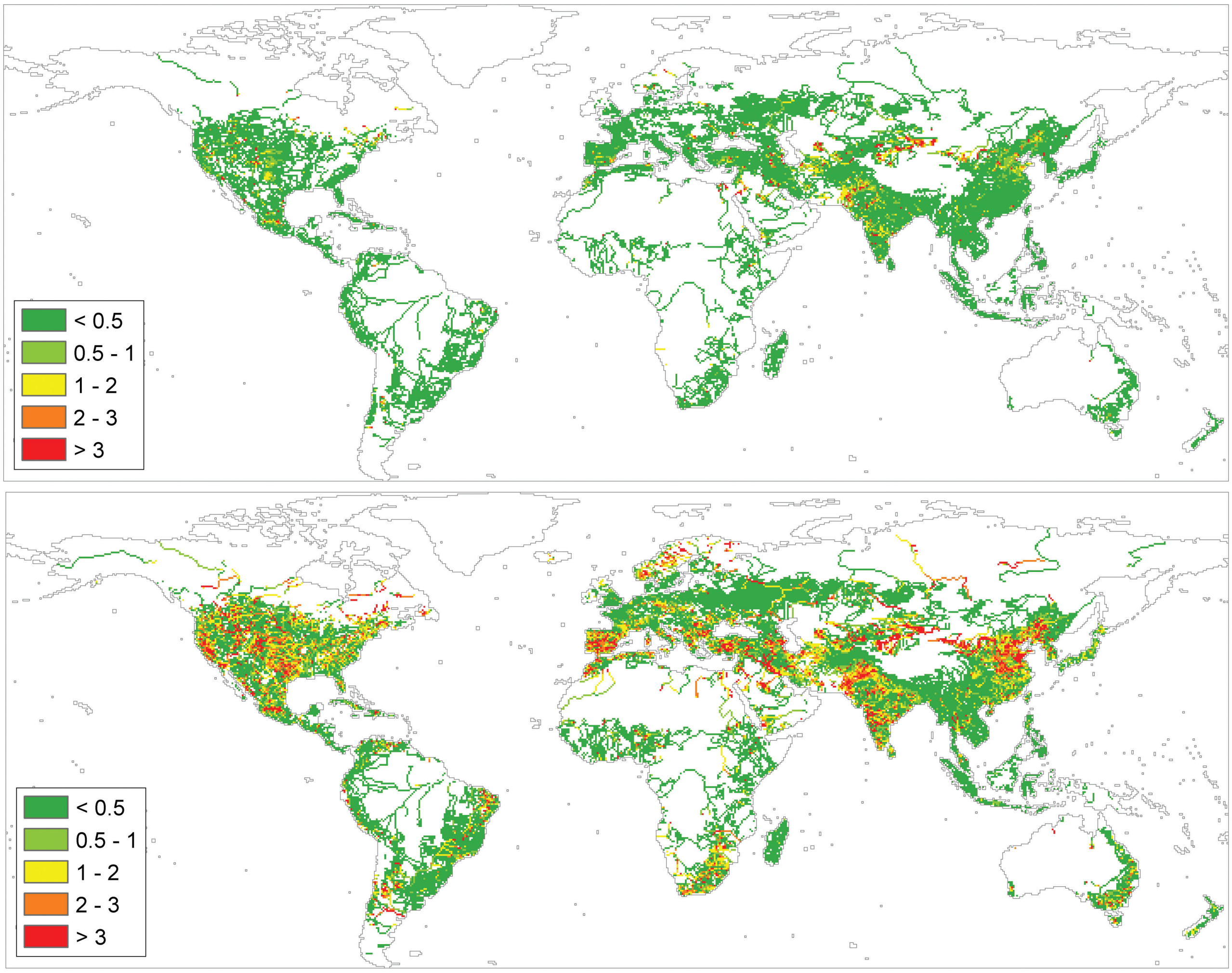


Figure 7. Average amended annual proportional flow deviation (AAPFD) for (top) 1901–1920 and (bottom) 1981–2000.

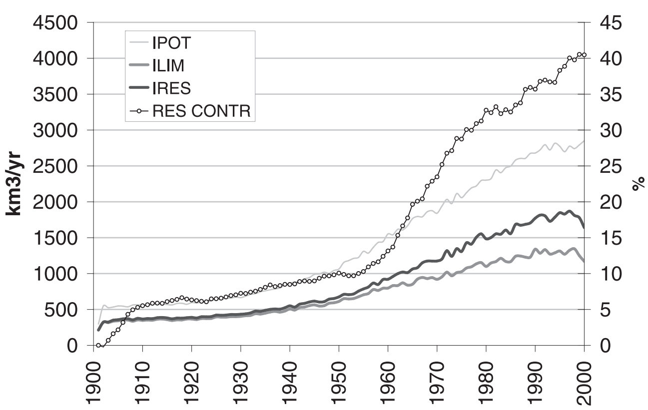


Figure 8. Twentieth century development in annual global irrigation withdrawal as simulated by LPJmL for ILIM, IRES, and IPOT. IPOT can be interpreted as the total irrigation water demand. The circles (right axis) show the additional supply contributed by reservoirs (smoothed average over previous 5 years), compared to a simulation without reservoirs.

Table 1. Sensitivity Analysis on Model Parameters in the Reservoir Operation Model: Irrigation Water Withdrawals

Simulation	Mean Annual Total Irrigation Withdrawal From Reservoirs 1981–2000 (km^3 yr^{-1})	Difference With Respect to IRES (km^3 yr^{-1})
IRES	460	-
Area +[a]	477	+ 17 (3.6%)
Area −[a]	380	− 80 (−17.4%)
Days +[b]	465	+ 5 (1.1%)
Days −[b]	453	−7 (−1.5%)
Env flow +[c]	444	−16 (−3.5%)
Env flow −[c]	473	+13 (2.8%)
Capacity +[d]	552	+92 (20.0%)
Capacity −[d]	361	− 99 (−21.5%)

[a]The amount of cells that can get water from the reservoir is increased to 8 cells or decreased to 2 cells upstream of the river below the reservoir (compared to 5 cells in IRES).

[b]The time that released water from the reservoir is stored in the conveyance system is increased to 8 days or decreased to 2 days (compared to 5 days in IRES).

[c]The minimum flow that is required in the river is decreased to 0% or increased to 20% of the mean monthly inflow (compared to 10% in IRES).

[d]The capacities of all reservoirs are doubled or divided by 2.

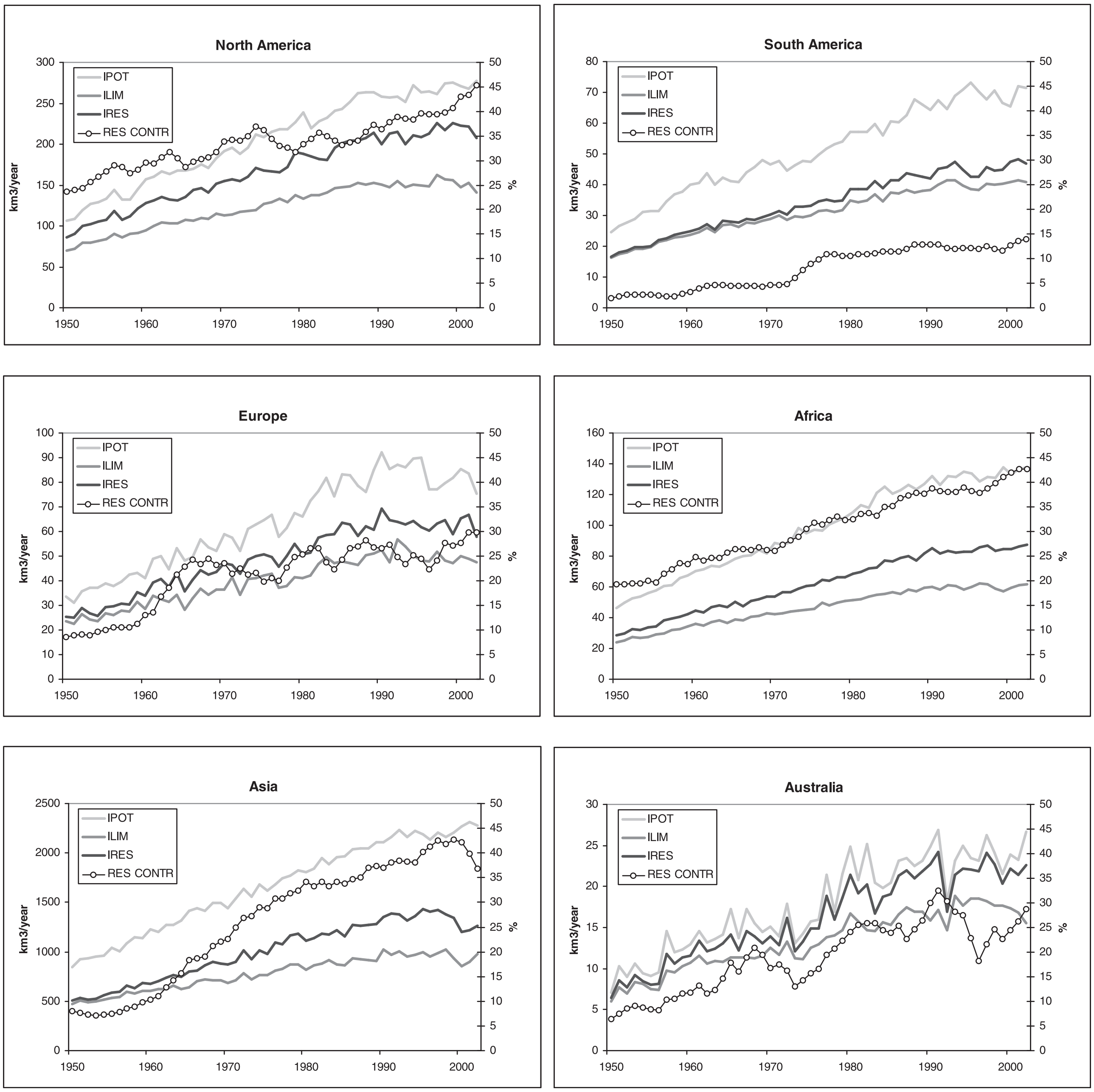


Figure 9. Same as Figure 8 but for different continents: 1950–2000 development in total continental annual irrigation withdrawals as simulated by LPJmL; circles show the additional supply contributed by reservoirs compared to a simulation without reservoirs (right axis).

[38] The contribution of reservoirs to irrigation water supply differs considerably more on the basin scale (Figure 10). Basins that experienced the largest increase in supply by reservoirs are the Colorado and Columbia River basins in the United States, several basins in India and central Asia, and some large basins in East Asia and Africa. In Europe, basins in Spain have gained the most water from their irrigation reservoirs.

[39] Figure 11 focuses on a few basins that supply a large part of their irrigation water from reservoirs. In the Colorado and Columbia River basins, reservoirs have significantly increased irrigation water supply compared to a situation without reservoirs. In both these basins, with additional supply from reservoirs, the irrigation demand (derived from the IPOT simulation) can almost be met by surface water extractions only.

[40] In the Asian basins, the picture is different. In these basins, there is large intra-annual variability in water supply due to a distinct dry and wet season. Reservoirs (partly) mitigate these seasonal differences in water availability. As a result, with reservoirs, more water becomes available for irrigation. This is especially the case in the Krishna basin (Figure 11).

4. Discussion

[41] This study demonstrated that introducing a reservoir operation and irrigation module in the LPJmL global

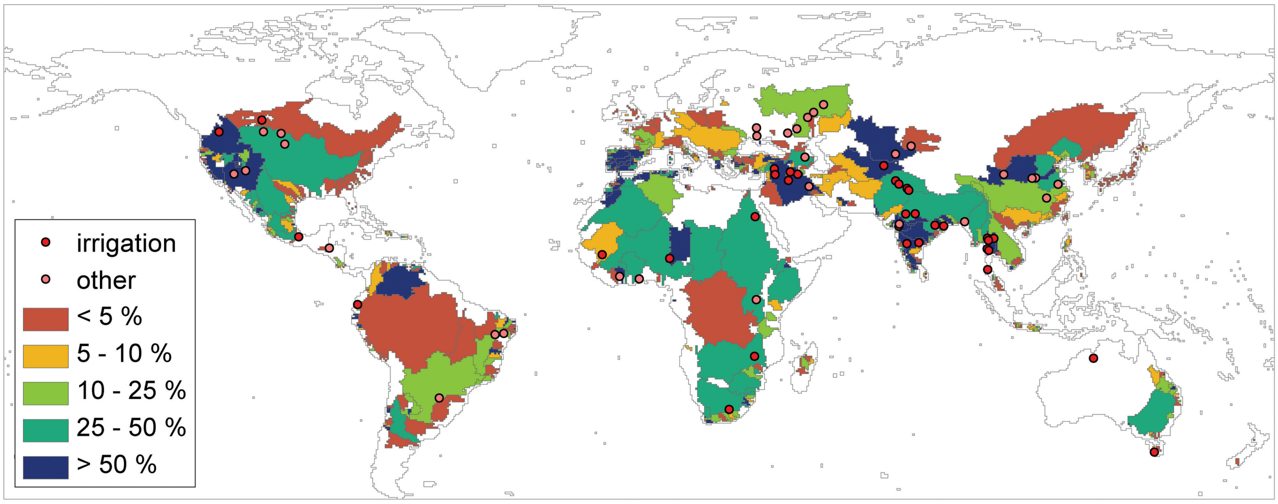


Figure 10. LPJmL simulated contributions of reservoirs to total irrigation water supply (average over the period 1981–2000). Colors represent the percentage of extra water used for irrigation in the reservoir simulation compared to a simulation without reservoirs (IRES versus ILIM) for the period 1981–2000. The dots represent all reservoirs larger than 5 km^3 from which irrigation water is supplied: red for irrigation reservoirs, pink for reservoirs that are primarily for other purposes, but do supply irrigation water.

hydrology and vegetation model significantly improves the simulation of discharge in basins where human impacts on the natural hydrology are known to be large. A validation was performed by showing simulated time series and mean monthly discharge values of affected rivers. Further, an analysis of simulated discharge at 304 gauging station locations with reservoirs upstream showed an improvement of the RMSE in 91% of the cases.

[42] The reservoir model used in this study generalizes the operation of large reservoirs at the global scale, and does not include local information on the management of individual reservoirs. A sensitivity analysis showed that the reservoir model is more sensitive to total reservoir capacity than to chosen model parameters. This result increases confidence in the estimate of global irrigation supply from reservoirs. However, there might be stronger sensitivities in particular basins.

[43] Since the model is flexible and rules can be changed, the model can easily be adjusted to include specific local information on management or irrigation practices in large river basins, and could therefore be made more suitable for river basin studies. Further, the model can now be used to study the combined impacts of climate change and reservoir scenarios both on discharge and on regional water supply.

[44] There are several other uncertainties regarding model input and model algorithms that could have influenced the results. As discussed by *Biemans et al.* [2009] some overestimations or underestimations in simulated streamflow (see Figure 4) are inevitable, and might be attributed to forcing data. From Figure 5 one can conclude that adding the reservoir module does not improve the simulation of discharge in some basins, mainly in India and China. This might have different reasons. India and China are among the countries with the highest irrigation water demands. Simulated outflow of irrigation reservoirs is to a large extent dependent on simulated growing season, because it follows irrigation water demands. Therefore, the right representation of sowing dates is essential. A new sowing date algorithm is currently being developed that could possibly improve the timing of the growing season. Further, although rice is allowed to grow twice a year in tropical Asia, there is no simulation for multiple cropping systems like the rice-wheat systems in South Asia, or the wheat-soybean or maize-soybean systems in North America [*Bondeau et al.*, 2007]. Ignoring multiple cropping might underestimate irrigation water demand in those areas.

[45] Globally, groundwater withdrawals are estimated at 600–700 km^3 yr^{-1} [*Foster and Chilton*, 2003] and in many countries groundwater forms an important contribution to irrigation water supply. Although there is no explicit representation of (fossil) groundwater in the model, the difference between surface water irrigation (IRES) and unlimited irrigation (IPOT) could partly be attributed to groundwater extraction. However, with the current model, it is not possible to evaluate actual groundwater availability and its limits. First attempts to include groundwater in global-scale hydrological models are currently being made [*Döll and Fiedler*, 2008].

Figure 11. (left) The 1950–2000 development in the total annual irrigation withdrawal water as simulated by LPJmL; (right) mean monthly irrigation withdrawal in 1981–2000. The IPOT line represents the withdrawal if water was not limited, the ILIM line represents the water withdrawal from rivers and natural lakes only, and the IRES line represents the supply from rivers, natural lakes, and operated reservoirs. Dotted line is the percentage of additional water supplied in the simulation with reservoirs compared to a simulation without reservoirs.

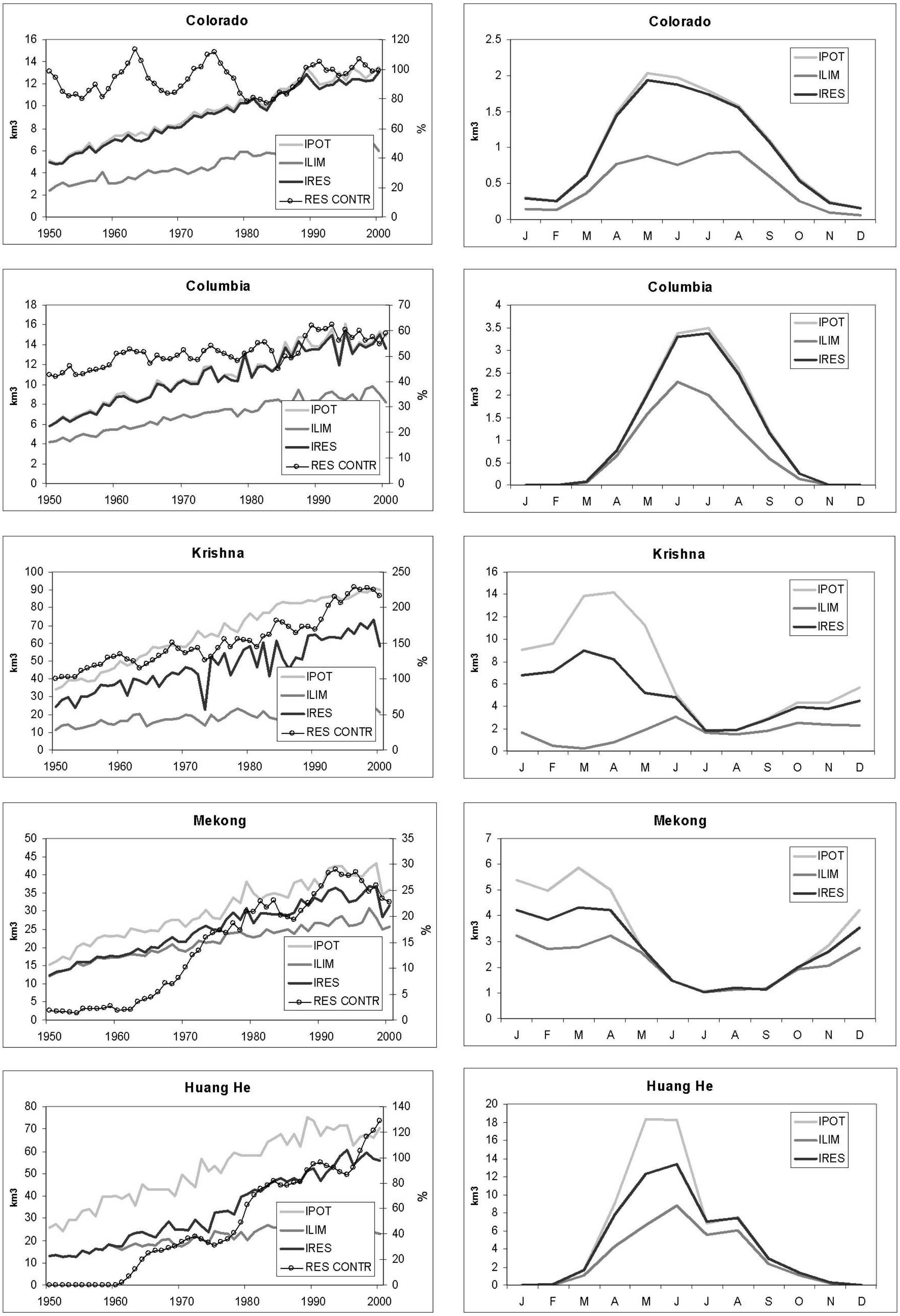

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Figure 11

[46] The most complete global list of large dams is provided by *ICOLD* [2007]. However, this list does not contain information on geographical locations, and is therefore not suitable for use in hydrological models. The cumulative capacity estimated by *Chao et al.* [2008], based on ICOLD) is 8300 km^3, whereas the GRanD database used in this study includes 6300 km^3 of storage. This means that the contribution of large reservoirs to irrigation water supply might be even higher than the 460 $km^3\ yr^{-1}$ reported here.

[47] The total area used for irrigation in 2000 in the land use data set used here [*Fader et al.*, 2010] is estimated at 215 Mha. This estimate is derived from the global map of areas equipped for irrigation (GMIA) [*Siebert et al.*, 2005] but is significantly lower than their reported 270 Mha. This is because the areas that are not actually in use for irrigation (e.g., because of damaged infrastructure or water shortage) were excluded. *Wisser et al.* [2008] showed that estimates of global irrigation demand are very sensitive to the selected data sets for irrigated area and climate. This means that using another land use data set, e.g., another map of areas suited for irrigation [e.g. *Thenkabail et al.*, 2008], could lead to a much higher or lower estimation of irrigation water demand, and consequently to a different assessment of the impact of reservoirs.

5. Conclusions

[48] In this study, a global-scale model was developed that can simulate the impact of large reservoirs on the global water cycle. This model was tested and applied to quantify the impact of reservoirs on discharge and irrigation water supply in the 20th century.

[49] At continental and global scale, irrigation extractions and reservoir operation affect both the timing and the total amount of discharge reaching the oceans. Impacts of large reservoirs are most profound in Asia, Europe, and Africa, where in some months the total flux of freshwater into the ocean is 10% less compared to a naturalized situation. Averaged over the year, irrigation (including irrigation from reservoirs) decreases global discharge by 2.1%, or approximately 930 km^3.

[50] It was also shown that global surface water extractions for irrigation have significantly increased through the construction of large reservoirs during the 20th century. At the beginning of the century, reservoirs added around 5% to irrigation supply from surface water; at the end of the century this had increased to 40%. In absolute terms, the global annual average irrigation extractions from reservoirs increased from 18 $km^3\ yr^{-1}$ at the beginning of the century (1901–1920), to 460 $km^3\ yr^{-1}$ at the end of the century (1981–2000). This increase occurred mostly in continents with large irrigated areas and many irrigation dams.

[51] A more detailed analysis at river basin scale confirmed that irrigation reservoirs are able to make more water available in specific seasons, especially in some Asian basins such as the Krishna and Huang He (around 200% and 130% more, respectively), where natural water availability is highly variable throughout the year. These reservoirs retain water to be released during a water-scarce period.

[52] The analysis performed in this study showed the importance of reservoirs for sustaining irrigated agriculture. By storing and redistributing water, reservoirs significantly increase water availability for irrigation. As an effect of climate change and socioeconomic change, however, irrigation and other water demands are expected to grow and put more pressure on available water resources [e.g. *Alcamo et al.*, 2007; *Döll*, 2002]. In some regions, the current reservoir system might not be able to fulfill an increase in demand, or might not be able to continue the same supply because of a change in reservoir inflow. On the other hand, reservoirs might have an increasing role in meeting future water requirements in regions where water stress is an issue of distribution rather than of absolute shortage.

[53] The ability of the model developed here to quantify the effect of large reservoirs on 20th century irrigation water supply makes it also a very useful tool to estimate the impact of global change scenarios, e.g., to assess the changing role of reservoirs in sustaining water supply for irrigation.

[54] **Acknowledgments.** This research was partly undertaken under the European Union (FP6) funded projects WATCH and SCENES. Part of the research was funded by the Netherlands Environmental Assessment Agency (PBL). Thanks to Bernhard Lehner for the provision of the GRanD data, and to the Global Runoff Data Center for the streamflow observation data. The authors would also like to thank three anonymous reviewers for their very useful comments on an earlier version of this paper.

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