

## Anthropogenic impacts on continental surface water fluxes

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[1] Impacts of reservoirs and irrigation water withdrawals on continental surface water fluxes are studied within the framework of the Variable Infiltration Capacity (VIC) model for a part of North America, and for Asia. A reservoir model, designed for continental-scale simulations, is developed and implemented in the VIC model. The model successfully simulates irrigation water requirements, and captures the main effects of reservoir operations and irrigation water withdrawals on surface water fluxes, although consumptive irrigation water use is somewhat underestimated. For the North American region, simulated irrigation water requirements and consumptive irrigation water uses are 191 and  $98 \text{ km}^3 \text{year}^{-1}$ , while the corresponding numbers for the Asian region are 810 and  $509 \text{ km}^3 \text{year}^{-1}$ , respectively. The consumptive uses represent a decrease in river discharge of 4.2 percent for the North American region, and 2.8 percent for the Asian region. The largest monthly decrease is about 30 percent, for the area draining the Western USA in June. The maximum monthly increase in streamflow (28 percent) is in March for the Asian Arctic region. **Citation:** Haddeland, I., T. Skaugen, and D. P. Lettenmaier (2006), Anthropogenic impacts on continental surface water fluxes, *Geophys. Res. Lett.*, 33, L08406, doi:10.1029/2006GL026047.

### 1. Introduction

[2] Anthropogenic impacts on the land surface water balance are known to be locally and even regionally important. Dams result in the trapping of freshwater runoff and modified timing of river discharge. Diversion of water between rivers, for example for hydropower purposes, alters natural streamflow regimes, and water withdrawals contribute to increased evaporation. Vörösmarty *et al.* [1997] estimated that 20 percent of global mean annual runoff can be retained in reservoirs, and that the mean age of global terrestrial runoff likely has tripled to well over one month because of water storage in reservoirs. Estimates of irrigation water requirements globally range from  $1100 \text{ km}^3 \text{year}^{-1}$  [Döll and Siebert, 2002] to  $2300 \text{ km}^3 \text{year}^{-1}$  [Shiklomanov, 1997]; numbers that while large in absolute magnitude are much smaller than global mean annual runoff estimated at  $\sim 40,000 \text{ km}^3 \text{year}^{-1}$  [Postel *et al.*, 1996]. Hence, the impact of irrigation on the global water balance might seem small. However, Postel

*et al.* [1996] concluded that over 50 percent of globally accessible runoff is currently used by humans.

[3] Several regional and global studies have been performed on the impact of irrigation on evapotranspiration [Döll and Siebert, 2002; de Rosnay *et al.*, 2003], and modifications on the hydrologic cycle caused by dams and reservoirs [Vörösmarty *et al.*, 1997; Hanasaki *et al.*, 2006]. Here we go one step further and study the combined effects of reservoirs and irrigation (surface water withdrawals only) on surface water fluxes using a macroscale hydrology model. Macroscale hydrology models, or land surface schemes, are usually structured to simulate naturalized streamflow, that is, the streamflow that would occur in the absence of reservoirs, diversions, or water withdrawals. In this study, we specify a set of simple reservoir operating policies which are related to stated operating purposes for large reservoirs. The effects of irrigation and large reservoirs on the water balance are studied with the objective of obtaining plausible reproductions of observed flows at the outlets of large river basins, with a special emphasis on river basins affected by irrigation. The approach can be contrasted with representation of the specific operating strategy or rules for individual reservoirs, which requires detailed site specific data and models, implementation of which is not feasible for large continental areas.

### 2. Approach

[4] The grid-based Variable Infiltration Capacity (VIC) model [Liang *et al.*, 1994] represents the hydrologic response of large areas through parameterization of the partitioning of precipitation into direct runoff and infiltration, and the nonlinear effects of base flow depending on subsurface moisture storage. Land cover variability is represented by partitioning each grid cell into multiple vegetation types. Runoff is routed from each grid cell to the basin outlet as described by Lohmann *et al.* [1998]. Irrigation water withdrawals are represented using a scheme described by Haddeland *et al.* [2006].

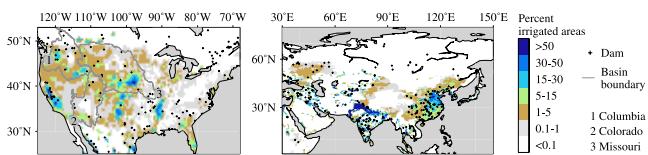
[5] The regions studied include most of Asia (including parts of Eastern Europe), and parts of North America (Figure 1). The North American region coincides with the area studied in the North American Land Data Assimilation System (NLDAS) project [Mitchell *et al.*, 2004], and is hereafter referred to as the NLDAS region. The regions studied include some of the most heavily irrigated areas in the world, and account for nearly 80 percent of the areas equipped for irrigation globally [Siebert *et al.*, 2002]. The hydrology model is run at daily time steps at 0.5 degrees spatial resolution for a period of 20 years (1980–1999). The model's soil moisture was initialized by running the model to equilibrium prior to performing the model simulations.

[6] Daily atmospheric forcing data were obtained from Adam *et al.* [2006] for Asia, and from Maurer *et al.* [2002]

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**Figure 1.** Location of the study areas. The location of three North American river basins evaluated in Section 4 is included.

for the NLDAS region. The *Maurer et al.* [2002] land surface characteristics were used for the NLDAS region, while topography and land cover classification for Asia were taken from *Nijssen et al.* [2001]. Information about irrigated areas was obtained from *Siebert et al.* [2002], while crop information was prepared using the method described by *Haddeland et al.* [2006]. Dam information was obtained from the *International Commission on Large Dams (ICOLD)* [2003] and *Vörösmarty et al.* [1997, 2003]. Globally this combined data set georeferences 633 of the world's largest reservoirs. Stream networks were taken from *Maurer et al.* [2002], and from the global Simulated Topological Network (STN-30p, available at <http://www.watsys.sr.unh.edu/>).

### 3. Reservoir Model

[7] The overall modeling strategy was to develop a generic reservoir model and implement it within the *Lohmann et al.* [1998] routing model. Reservoir characteristics and operating purposes were taken from *ICOLD* [2003]. An optimization scheme based on the SCEM-UA algorithm [Vrugt et al., 2003] was used to calculate optimal releases given reservoir inflow, storage capacity and downstream water or power demands (see also Table 1 and auxiliary materials<sup>1</sup>). A single-reservoir algorithm was used, that is, it does not consider the simultaneous operation of multiple reservoirs in a river basin. The reservoir model was run at a daily time step. However, water demands were calculated on a monthly basis, and within each month releases were kept constant if possible. The economic value of reservoir releases for hydropower and water supply was assumed to be constant throughout the year.

[8] Irrigation demands were calculated based on simulated irrigation water requirements downstream of the dam, that is, the grid cell elevation must be lower than that of the dam grid cell, and maximum 5 grid cells (~250 km) from the dam's downstream river course. If there were multiple dams upstream of an irrigated area, but the dams themselves were located in separate tributaries, demands were divided based on reservoir capacity. For dams located on the same river course, irrigation demands for shared downstream areas were used to represent water demands for all dams. Flood damages are expected when river discharge exceeds bankfull discharge, which has a recurrence interval on the order of once in 1.5 to 10 years [Mosley and McKerchar, 1993]. In this study, the mean annual flood (the mean of the annual maximum daily discharges) was used as a rough approximation of bankfull

discharge. For hydropower dams, the optimization scheme was used to maximize hydropower production. When a dam had multiple purposes, irrigation demands were given priority, followed by flood control. Any excess water was used to maximize hydropower production, if applicable.

[9] The reservoir model is retrospective – that is, it assumes perfect knowledge of future reservoir inflows. At the beginning of each operational year, the next 12 month's inflows were used to determine reservoir releases. The start of the operational year was defined as the time when mean monthly simulated naturalized streamflow shifts from being higher than the mean annual flow to being lower than mean annual flow, following the convention of *Hanasaki et al.* [2006]. Minimum release ( $Q_{\min}$ ) was set as 7Q10, the seven-day consecutive low flow with a ten year recurrence period, and was calculated based on simulated naturalized flow at the dam location. The maximum volume of water ( $Q_{\max}$ ) released for the current day ( $i$ ) can be written:

$$Q_{\max_i} = \min \left[ (S_{i-1} + Q_{in_i}), \left( S_{i-1} - S_{end} + \sum_{day=i}^{365} Q_{in_{day}} - \sum_{day=i+1}^{365} Q_{\min} - \sum_{day=i}^{365} E_{res_{day}} \right) \right] \quad (1)$$

where  $S_{i-1}$  is reservoir storage at the end of previous day,  $S_{end}$  is storage at the end of the operational year,  $Q_{in}$  is simulated inflow to the reservoir, and  $E_{res}$  is reservoir evaporation, which is calculated using the Penman equation.  $S_{end}$  varies between 60 and 80 percent of maximum reservoir capacity, depending on water demands during the current 12-month simulation period.

### 4. Model Evaluation

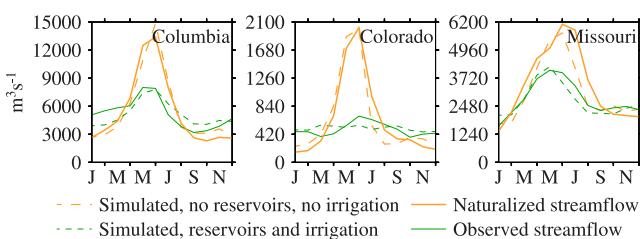
[10] The reservoir model is intended for use in large-scale hydrologic modeling, and particularly in cases where reservoir operation information and physical data are limited. Evaluating the reservoir model is, however, easiest in river basins where both naturalized and observed streamflow data are available. The simplicity of the reservoir model implies lower performance than for a detailed reservoir model that utilizes site specific operating rules. Hence, the evaluation presented here is based on the accumulated effects of several reservoirs in the river basins, which is consistent

**Table 1.** Objective Functions Used in the Reservoir Model<sup>a</sup>

Purpose	Objective Function
Irrigation	$\min \sum_{i=1}^{365} (Q_{d_i} - Q_r), Q_d > Q_r$
Flood control	$\min \sum_{i=1}^{365} (Q_{r_i} - Q_{flood})^2, Q_r > Q_{flood}$
Hydropower	$\min \sum_{i=1}^{365} \frac{1}{Q_r \rho \eta h g}$
Water supply, navigation	$\min \sum_{i=1}^{365}  (Q_{r_i} - Q_{mean}) $

<sup>a</sup> $Q_d$ : water demands;  $Q_r$ : reservoir releases;  $Q_{flood}$ : mean annual flood, calculated based on simulated naturalized discharge;  $Q_{mean}$ : mean annual flow;  $\rho$ : density of water;  $\eta$ : efficiency of the power generating system;  $h$ : hydrostatic pressure head;  $g$ : acceleration due to gravity.

<sup>1</sup>Auxiliary material is available at <ftp://ftp.agu.org/pend/g1/2006gl026047>.



**Figure 2.** Simulated (with and without reservoirs and irrigation water withdrawals), naturalized, and observed streamflow near the outlets of the Columbia and Missouri Rivers. In the Lower Colorado River basin, diversions affect streamflow significantly, and hence the model evaluation is performed for the Upper Colorado River basin at Glen Canyon.

with our overall objective. Three river basins where both naturalized and observed streamflow are available were selected for evaluation of the reservoir model; specifically the Columbia, Colorado and Missouri river basins (see Figure 1). Figure 2 shows mean annual simulated, naturalized and observed streamflow values for the three river basins. Although there are discrepancies between simulated and observed reservoir releases, the agreement is quite good considering the rudimentary nature of the reservoir operating rules used.

[11] The ratio of reservoir storage capacity to mean annual streamflow is low in many Asian river basins, meaning that the shape of the hydrographs does not change much because of river regulation. Simulated streamflow changes caused by river regulations in the Lena and Yenisei River basins (see auxiliary material) are somewhat smaller than concluded by *Ye et al.* [2003] and *Yang et al.* [2004]. The reservoirs in these river basins are mainly used for hydropower generation. The assumption of constant economic value of hydropower through the year probably explains why simulated winter flows increase slightly less than expected, which results in a lower spring flood reduction.

[12] FAO's database AQUASTAT (<http://www.fao.org/ag/aglw/aquastat/main>) reports irrigation water requirements, defined as the water required in addition to precipitation for optimal plant growth during the growing season. For validation purposes, we assumed that water availability was not a limiting factor. The results for Asia are compared to the FAO values in Figure 3, which shows a reasonable agreement. Irrigation water requirements for the USA are not included in FAO's database. Hence, simulated irrigation water use (water availability is limited) was compared to the U.S. Geological Survey (USGS) reported numbers (<http://water.usgs.gov/watuse/>) on irrigation consumptive water use (i.e., actual water consumed because of irrigation practices), see Figure 3c. Simulated consumptive irrigation water use for the USA is  $80 \text{ km}^3 \text{ year}^{-1}$ , which is somewhat lower than the USGS reported number of  $112 \text{ km}^3 \text{ year}^{-1}$  (of which surface water was the source for 63 percent of the water withdrawals) in 1995. In most states, simulated consumptive water use is somewhat underestimated. The significant underestimation in California can, at least partly, be explained by the fact that California imports water from neighboring states, which is not taken into the account in the modeling scheme. The underestimation of consumptive

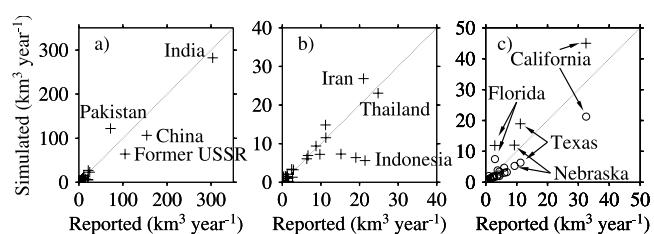
water use in some other states (e.g., Nebraska and Texas) can be explained by groundwater withdrawals, which are not taken into account in the modeling scheme.

## 5. Results

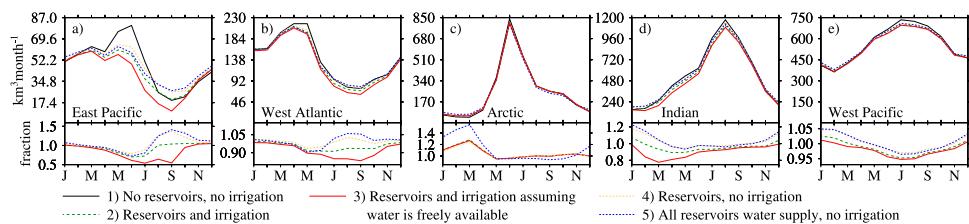
[13] Simulated mean monthly runoff to the receiving oceans is shown in Figure 4. In addition to the naturalized streamflow simulations (labeled “1” in Figure 4); results for the above described reservoir and irrigation schemes are shown (2). The maximum relative decrease in monthly runoff occurs in area draining to the East Pacific Ocean (line number 2 in Figure 4a) in June; a result of flood management combined with irrigation water withdrawals. The maximum relative increase is in the Arctic region (line number 2 in Figure 4c) in March, when naturalized winter flows are low.

[14] For comparison purposes, Figure 4 includes simulation results for three alternative model configurations. These include: 3) the reservoir model is implemented, and irrigation water is assumed freely available, 4) the reservoir model is implemented, but the irrigation scheme is not, and 5) all reservoirs are assumed to be used for water supply purposes only, and there is no irrigation. The streamflow differences between alternatives 2 and 3 in Figure 4 indicate that the storage volumes and locations of the reservoirs are not sufficient to meet the irrigation water requirements. This is especially apparent for the areas draining to the East Pacific and the West Atlantic Oceans. Simulated irrigation water requirements (alternative 3) for Asia and the NLDAS regions are  $810$  and  $191 \text{ km}^3 \text{ year}^{-1}$ , respectively. The corresponding consumptive uses (alternative 2) are  $509$  and  $98 \text{ km}^3 \text{ year}^{-1}$ , representing a decrease in model simulated flow of  $2.8$  and  $4.2$  percent.

[15] The results for alternative 5 show the least streamflow variations over the year, which is caused by the objective function used. The results for alternatives 4 and 5 are fairly similar for all regions except the Asian Arctic, which is dominated by dams built mainly for hydropower purposes. The simulation results for alternatives 4 and 5 do not include irrigation withdrawals, and can hence be compared to the simulations of *Hanasaki et al.* [2006]. In general, the results shown in Figure 4 have somewhat weaker signals than the *Hanasaki et al.* [2006] results, although the relationship among the receiving oceans is similar. Differences in the operating rules explain some of the differences – for instance, *Hanasaki et al.* [2006] only



**Figure 3.** (a) Mean annual simulated and reported irrigation water requirements for countries in Asia. (b) The lower values shown in Figure 3a. (c) Mean annual simulated and reported irrigation water use (o) in the conterminous USA. Simulated irrigation water requirements (+) for four states are included for comparison purposes.



**Figure 4.** Effects on freshwater fluxes reaching the oceans. (a and b) Rivers draining the NLDAS region to the Pacific and Atlantic Oceans. (c) Rivers draining northward to the Arctic Ocean in the Asian region, while (d and e) rivers draining Asia to the Indian and Pacific Oceans. The bottom section of each figure show the results of simulations 2 through 5 divided by simulation 1.

distinguished between irrigation and non-irrigation reservoirs. Another reason is that the *Hanasaki et al.* [2006] streamflows are generally lower than the ones simulated in this study, meaning the reservoir storage capacity is relatively smaller in this study. The spatial resolution of the routing model may also be an explanatory factor, since reservoirs in the most upstream river reaches at one degree spatial resolution [used by *Hanasaki et al.*, 2006] have the possibility of overestimating the reservoir's drainage area more than for the 0.5 degree spatial resolution we used.

[16] Globally, 60–75 percent of water withdrawals are for irrigation purposes [Shiklomanov, 1997], while the remainder is withdrawn mostly for municipal and industrial use. Groundwater withdrawals, which are estimated to account for 30 percent of global water withdrawals [Gornitz, 2001] are not accounted for in our scheme. It should also be kept in mind that not all reservoirs in the study area are included. However, the data set used includes about 70 percent of the global storage volume in the ICOLD [2003] database.

## 6. Conclusions

[17] In this study, a simple reservoir model is implemented in the VIC model, which combined with an irrigation scheme, is used to model the effects of anthropogenic impacts on surface water fluxes. The model does a reasonable job of reproducing the effects of management on selected large rivers. Model simulations demonstrate storage reservoirs' ability to alter natural hydrographs, although the mean annual effect of river regulations and irrigation on freshwater fluxes reaching the oceans is relatively minor. Simulated maximum monthly increases in streamflow, as a result of river regulations, are less than 30 percent, and are for Arctic rivers where winter flows are quite low. The largest monthly decrease in streamflow is about 30 percent, and is a result of flood control management and irrigation in the Western USA. Averaged over the NLDAS region and Asia, simulated consumptive irrigation water uses are 4.2 and 2.8 percent of simulated naturalized runoff, respectively. Given freely accessible irrigation water, the corresponding numbers are 7.6 and 4.4 percent.

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